Review

Not peer-reviewed version

Technological Advancements in Cotton Agronomy: A Review and Prospects

Adeyemi Adeleke *

Posted Date: 23 February 2024

doi: 10.20944/preprints202402.1342.v1

Keywords: Environmental impact; Hybrids; Remote sensing; Robotic platforms; Sustainable agronomy; Technological innovations; Precision cotton farming; Water management;

Review

Technological Advancements in Cotton Agronomy: A Review and Prospects

Adeyemi Adegoke Adeleke

Department of Biological and Agricultural Engineering, Texas A&M University, College Station, TX 77843, USA; yemadeleke@tamu.edu

Abstract: Cotton is the most ubiquitous and profitable fiber with diverse industrial and domestic applications. Grown in over 100 countries, it has a global market value of about $40 billion and employs over 350 million people from fields to textile mills, contributing about 7% of total labor-force recruitment in developing economies. Cotton has an indeterminate growth habit and an extensive tap root system affected by soil physicochemical and environmental conditions. There is a consensus among experts that conventional cotton cultivation still has a long way to attain sustainability, which is essential if cotton will maintain its competitive edge over other natural and synthetic fibers like hemp, polyesters, and rayon. Despite several efforts already committed to growing cotton sustainably, sustainability has eluded cotton cultivation globally because of the intense farm inputs (freshwater, pesticides, and heavy-duty equipment) needs, especially in developing economies. Some of the technological advancements towards achieving the goal of sustainable cotton cultivation include the development of new varieties, improved irrigation and mulching and precision agriculture techniques, application of remote sensing and Unmanned Aerial Systems (UAS) combined with image processing, and the introduction of autonomous and multi-purpose robotic platforms for growing and harvesting cotton. This review attempts to evaluate the successes already achieved by stakeholders in moving cotton towards sustainable production and identify areas where efforts are still needed to reach sustainable production and improved profitability goals for cotton with projections for future research directions.

Keywords: environmental impact; hybrids; remote sensing; robotic platforms; sustainable agronomy; technological innovations; precision cotton farming; water management

---

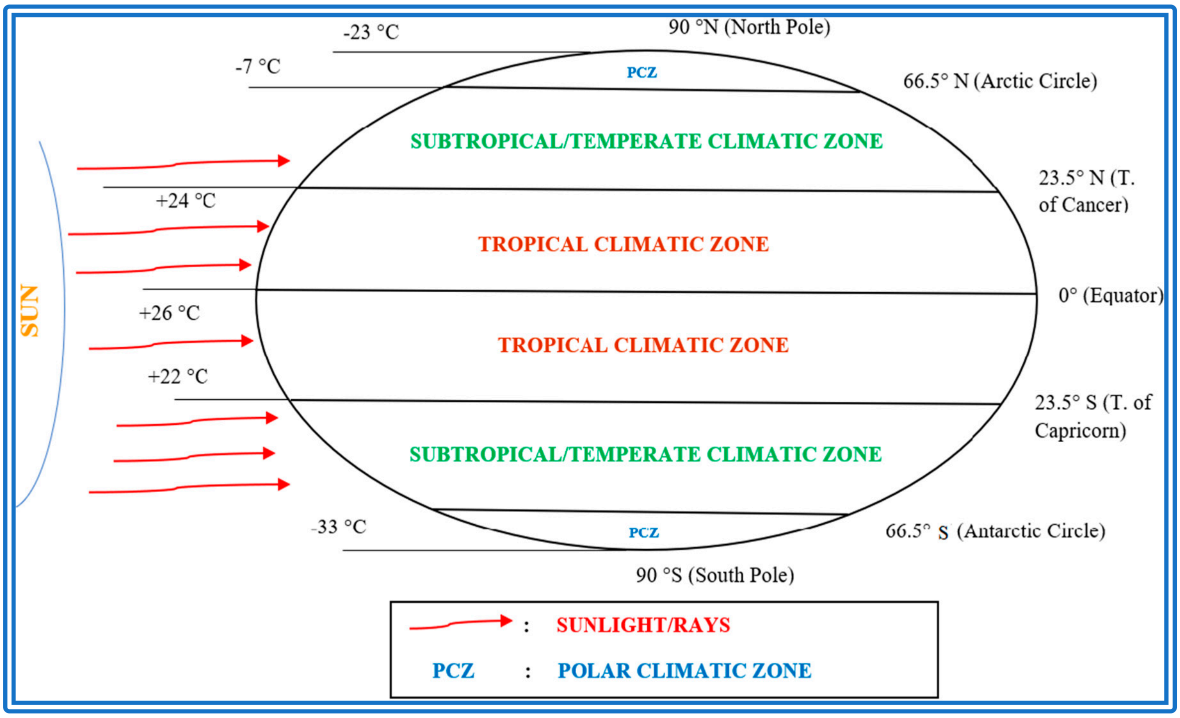
1. Introduction

Cotton is the natural fiber of choice cultivated in over 100 countries, with China, India, and the USA leading in the global production ranking. It is a perennial crop with an indeterminate growth pattern and a complex tap root system significantly affected by physicochemical and environmental conditions but is often grown as an annual crop[1]. It is a globally significant agricultural crop that supplies raw materials for diverse purposes in industry and has many domestic uses[1–3]. Cotton fiber finds uses in many textile products production, healthcare, and minting of diverse financial securities[2]. On the other hand, cottonseeds, separated from the fiber through a series of operations collectively called ginning, are a good source of edible oil, protein for animal feed, and soil amendment products[2]. The cotton industry employs about 7% of total labor in developing economies[4] and directly and indirectly employs over 350 million people globally, from primary cultivation to textile manufacturing[3]. The global cotton market has an estimated value of over $44 billion, and in the US alone, official estimates indicated that cotton provides an annual revenue of over $21 billion, employing over 125,000 people[5,6]. In China, cotton is grown in about 70% of the 35 provinces, employing almost 300 million people[7]. This background emphasizes the importance of cotton to the global economy.

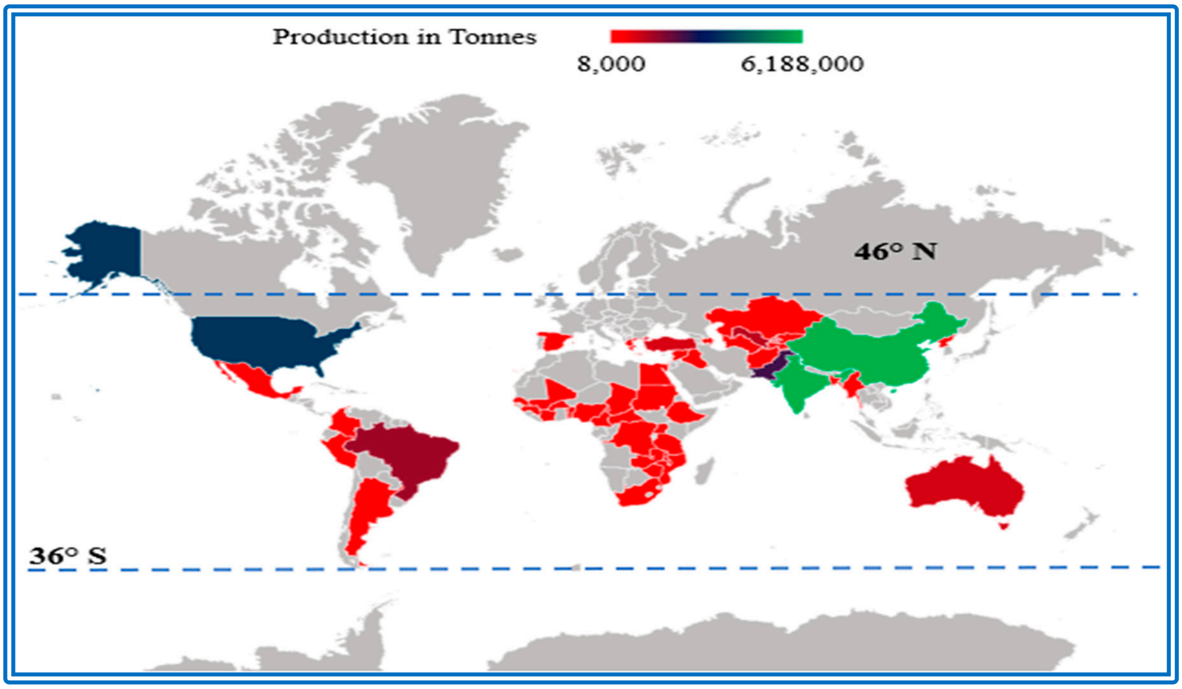
Traditionally, as shown in Figure 1b, cotton is grown in the generally tropical and subtropical regions between 46° N latitude and 36° S latitude because of the favorable climatic conditions enabled

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 23 February 2024 doi:10.20944/preprints202402.1342.v1

by the substantial quantity of solar radiation received annually (Figure 1a)[8]. Also, over decades, conventional cotton production practices have been a major consumer of global freshwater supply (as a significant sector of agriculture that uses a substantial portion of world freshwater for irrigation)[4,9]. About 73% of global cotton production is under irrigation from freshwater sources, while the remaining 27% is under rainfed cultivation. Cotton agronomy is also a notable source of ground- and surface-water pollution and land degradation (conversion of habitat to agricultural use) because of the large consumption of chemicals (pesticides, herbicides, etc.) and heavy-duty machinery (for tillage, management, and harvesting)[9].



(a)



(b)

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 23 February 2024 doi:10.20944/preprints202402.1342.v1

Figure 1. Global maps showing (**a**) regions of the world and the relationship between latitude, irradiation, and average regional temperature and (**b**) the top 50 cotton-producing countries and their 2017 production. All are geographically located in the warm tropical or subtropical regions between 36° S and 46° N. *Production data was extracted from the FAO database (see the supplementary material)*.

Over the years, towards more sustainable cotton cultivation, several practices and technological innovations and advancements have been proposed and adopted by the cotton industry to enhance yield, minimize farm input use, improve disease and stress resistance, reduce drudgery in cotton agronomy, and encourage consumer acceptability of cotton which has moved from a merely 4% of global market share of fibers used for textiles production in the 18th century to about 48% in modern times[9]. Among these innovations and technological advances are the continuous development of new varieties (cultivars) of cotton by multinational seed companies and researchers and the widespread adoption by the growers, improved mulching and irrigation methods, precision agriculture technologies leading to reduced input (pesticide/chemical) use, application of unmanned aerial systems (UAS)/remote sensing systems, image processing techniques, machine learning algorithms for improved soil nutrient and weed management and crop health, autonomous harvesters with various onboard module building capabilities, and the recently proposed small robotic harvesting technology to enable multiple-pass harvesting of seed cotton [10–24].

These efforts towards making cotton a more sustainable crop have yielded some results, but they have also encountered many challenges and difficulties that still need to be fully resolved before sustainable benefits can be derived from the efforts of all the stakeholders. ***Therefore, this review article aims to highlight the successes already achieved by the cotton industry in making cotton agronomy a more sustainable and environmentally friendly venture and identify other germane areas where efforts are still needed to achieve the overall goal of making cotton a continuously competitive natural fiber***.

The remainder of this review is structured as follows: firstly, I identified the main sustainability issues in cotton agronomy, followed by a detailed analysis of the technological evolutions and advancements in cotton agronomy, then a summary and projections of future trends and enabling technologies for repositioning cotton as a sustainably grown crop and competitive fiber follows. Finally, the article ends with a concluding-remarks section.

2. Key Sustainability Issues in Conventional Cotton Farming

Agricultural production is arguably the largest consumer of global freshwater supply, consuming up to 70% of freshwater withdrawn from natural sources in some world regions and presents the single most significant risk to the natural freshwater environment and biological variety[3,9]. Cotton agronomy is one of the three crop production systems (others are rice and wheat) that consume most of the freshwater used for agriculture. For many years, farmers have conventionally cultivated cotton (like many other major cash crops) mainly to achieve high yields without much consideration for the environmental impacts of agronomical practices[3]. From China to Pakistan, the US, and other countries, extensive groundwater use for agricultural production (of which cotton agronomy takes a significant share) has resulted in a detectable drop in the water table levels[3,9,25]. Runoff from cotton-grown fields, land reclamation for cotton farming, drainage contamination, large-scale soil compaction, and chemical use are a few of the effects of cotton agronomy on freshwater ecology and environmental diversity.

Runoff from cotton-cultivated fields can cause environmental issues like eutrophication and wildlife contamination when fertilizer and other agricultural chemicals (pesticides: fungicides, microbicides, insecticides, and herbicides) are washed away from farmland into waterbodies, killing different aquatic life species, as there have been recorded cases in Uzbekistan, Egypt, and China, land reclamation for cotton production causes changes in natural vegetation cover and loss of the natural habitat for some wildlife[3,9]. Extensive irrigation and dam constructions, which restrict/regulate water flow and sometimes cause water logging, negatively impact the environment by causing changes in water table level, salination of the soil surface by leaching away non-salt nutrients and leaving behind salt on the soil surface (e.g., in Uzbekistan, Australia, Pakistan, and Indus River valley). See a detailed summary of the various impacts of cotton production on freshwater biodiversity and ecosystem in Table 2.2 of Radhakrishnan, 2017[3,9].

The utilization of heavy-duty equipment, ranging from tillage implements to large tractors and harvesters (strippers and pickers), which can weigh several tons, is also a significant cause for concern regarding the impact of cotton production on the environment. These heavy machinery compact agricultural soils and consume fossil fuels that release large volumes of greenhouse gases, which contribute to global warming and the associated climate change and particulate matter that pollute the environment, reducing air quality[24,26].

The world is moving towards sustainability—a forward-thinking approach of using the limited available resources for various production activities without causing adverse effects that would jeopardize living on earth for future generations—with the tripartite goals of ensuring social and economic equity, economic profitability, and environmental health[3]. Conventional cotton production has not been sustainable, as evidenced by its diverse near-permanent negative impacts on the natural habitat over the decades. To achieve more sustainable/green cotton production, growers must use land, water, energy, and other natural resources more judiciously[27]. Hence, cotton producers and industry players globally have been taking steps towards responsible cotton production practices that may significantly lower land usage, water consumption, soil loss, and energy consumption while improving soil health and yield. A few of these efforts include improving cotton agronomy management practices and adopting innovative technologies with farm input minimization potentials[27].

In the following section, I detail some of these significant efforts committed by different industry players in the cotton production value chain—researchers, farmers, and government agencies—to make cotton a more sustainable cash crop with a more environmentally friendly production.

3. Technological Evolutions and Advancements in Cotton Agronomy

In this section, I discuss a few enabling technological advancements and efforts that have focused on moving cotton towards more sustainable production, improved profitability, and increased competitiveness with other natural and synthetic fibers. The achieved fruits so far, the difficulties encountered, and the challenges that need overcoming before the emerging ones can gain market acceptance/commercialization are discussed.

3.1. New Cotton Cultivars/Hybrids Developments

Individual countries and total global cotton production has been trending upward in the past few decades (see Figure 2). Each/most cotton-producing country, including the developing countries of the world, has witnessed a significant increase in production volume/productivity, contributing to higher cotton productivity on the global scale. Numerous factors are responsible for this data-backed progress, but successful breeding technologies have a significant effect. For example, it is reported that the introduction and later fast acceptance of new hybrids (Bacillus thuringiensis (Bt) transgenic) certainly qualify as the most significant event in cotton agronomy in India and globally[28,29]. Several hybrids, which are genetically-modified (GM), pest-resistant (boll worms resistant) and herbicide-tolerant (HT) cotton, have since 2002-03 captured the Indian cotton market with over 95% of the cultivated cotton farmland done with them[1]. They have been instrumental in increasing India's cotton output, which is now the leading global cotton producer since around 2019 and one of the topmost countries that grow hybrid cotton[29,30].

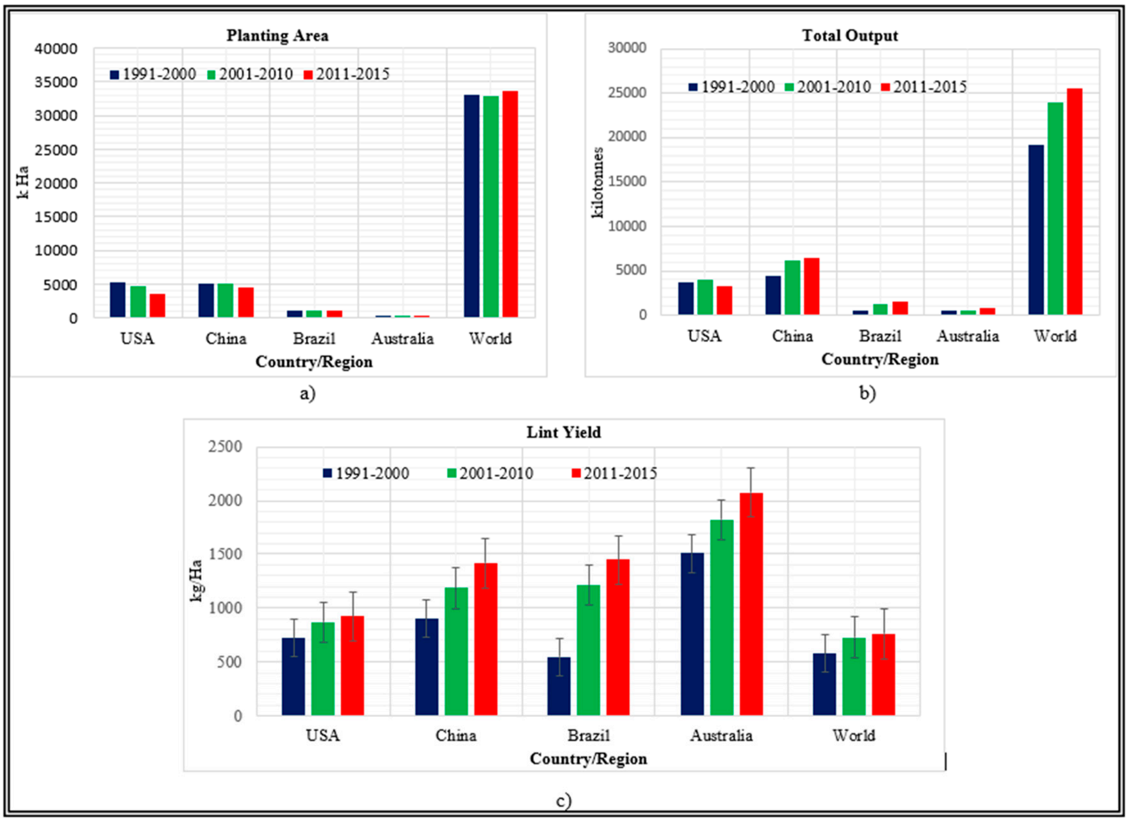


Figure 2. Cotton productivity data in some main cotton growing countries and the world between 1991 and 2015. (Data based on Table 1 of Feng et al.[31].).

Cotton hybrid research started in the USA, but scientists in China created the first successful GM cotton variety in 1993, and it was commercially introduced for cultivation in other countries like the USA, Mexico, Australia, and Argentina in 1996[32–34]. Since then, transgenic cotton has gained widespread global adoption, rising from a cultivated area of only 0.8 m ha in 1996 to 15.5 m ha in 2008[32]. Venugopalan et al. (2009) reported that in 2008, less than 10% of the USA, South Africa, and Australia arable cotton land was uncultivated using genetically modified varieties, while in India and China, about 75% of their cotton production was done using GM cultivars. However, the GE cotton adoption rate data from the USDA for 1993 to 2023 (see Figure 3) shows that the adoption rate in the USA only surpassed the 90% level in 2014[33,35]. However, it is true that India, on the other hand, has long increased the usage of GM cotton cultivars to >90%[1,29,32]. Also, after many years of opposition to GM products, many African countries (Nigeria, Kenya, Sudan, Eswatini, Rwanda, Mozambique, etc.) are opening to cotton cultivation using GM or biotech hybrids[36].

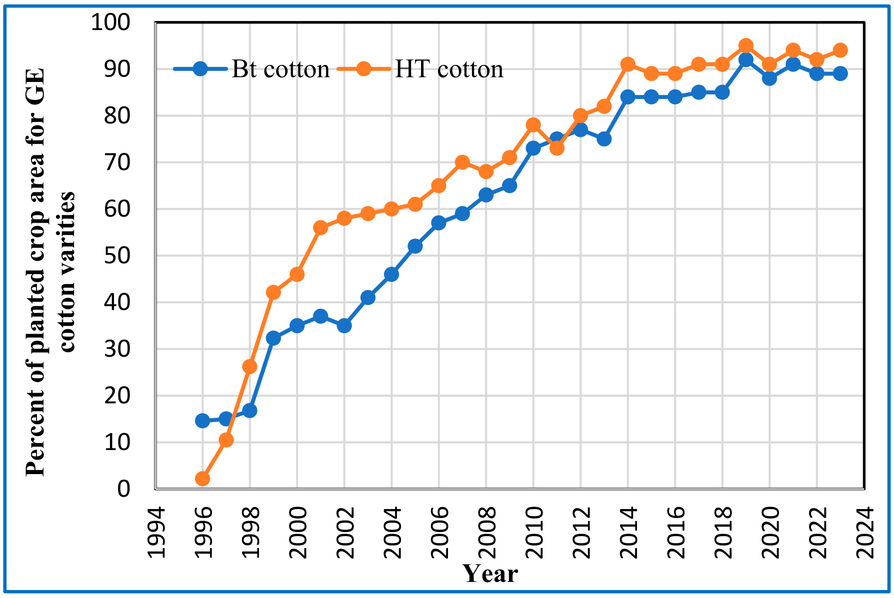


Figure 3. Recent trends in genetically enhanced (GE)/GM cotton adoption rates in US for Bt cotton and herbicide-tolerant (HT) cotton. The adoption rate has increased exponentially since the introduction of the varieties, surpassing the 90% level in the past few years. (Data extracted from the USDA[33].).

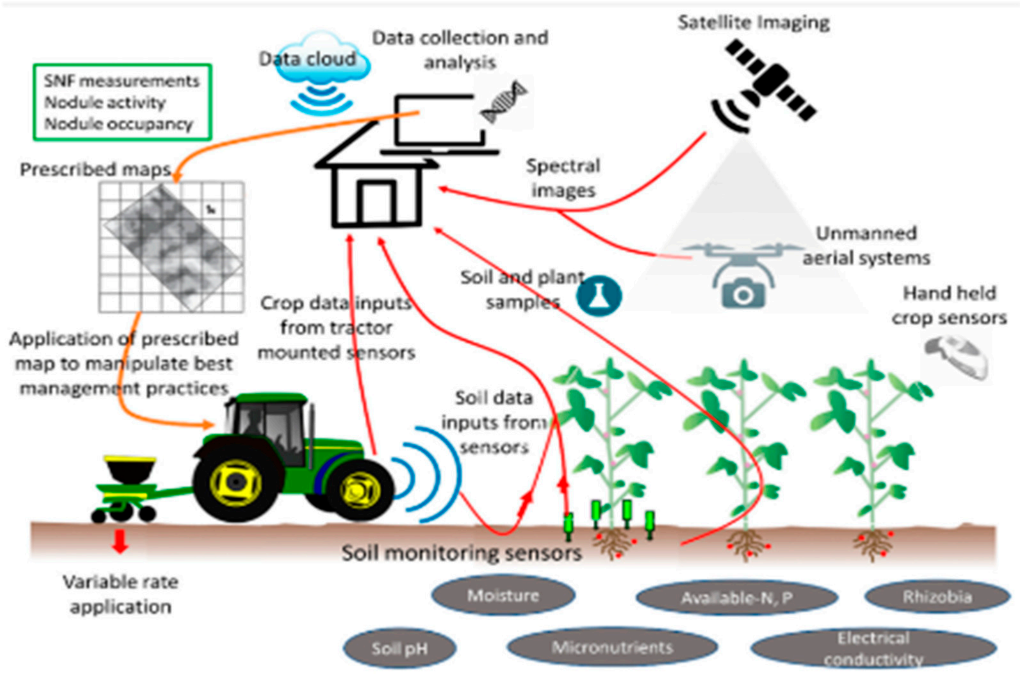
Although Bt and HT traits are the most popular among cotton producers in the USA, India, and other countries, other GE varieties/traits have been developed, including fungus and virus resistance, boosted oil, protein, and vitamin content, drought resistance, early maturing, and dwarf or short stature[29,30,33]. While the Bt cotton hybrid was designed to be resistant/tolerant to insect pests (bollworm/boll weevils, pink bollworm), by incorporating soil bacterium Bt gene into varieties cotton, the HT hybrid was designed to tolerate powerful herbicides (e.g., glufosinate, Trifluralin, dicamba, and glyphosate) and offer growers a wide array of options of effectively manage weeds[30,33,34]. There are newer stacked GM varieties that combine these traits of HT and Bt and other similar traits combinations, and they are more commonly used in the US than the individual GM traits[33]. There are varied reasons for adopting each of these GM cotton hybrids. For instance, where they have been adopted, like the US, India, China, etc., the adoption rate of Bt cotton may not be unconnected to the severity of tobacco budworm, bollworm, and pink bollworm infestations in those regions, the adoption of HT cotton hybrid may correlate with producers' desire to reduce the expensive and time-consuming dependence on soil tilling operations for controlling pests and diseases[29,33,34]. Regardless of farmers' rationale for their adoption, these technological shifts towards GM cotton hybrids have immensely contributed to moving cotton cultivation to a more sustainable, environment-friendly future.

3.2. Precision Agriculture Techniques

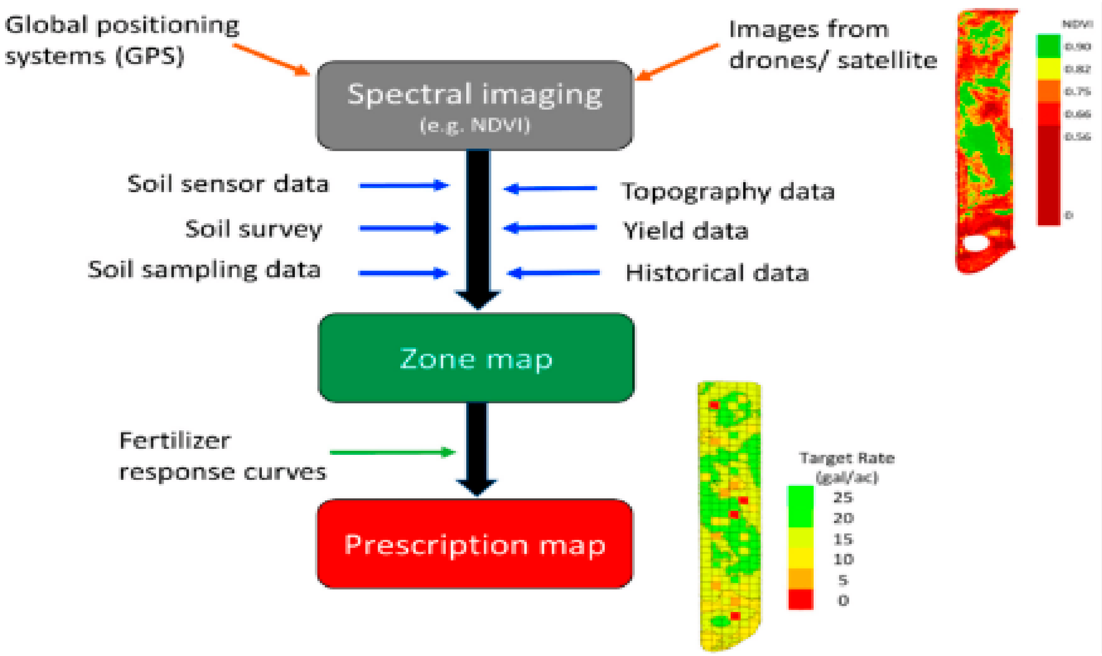
Realizing how unnecessarily input-intensive and unsustainable cotton agronomy has been practiced over the years, the research community and the agriculture industry (in which cotton is a major player), through series of efforts came up with frameworks to precisely time and use seeds, schedule/apply irrigation water, and agricultural chemicals with the hope of increasing agricultural yields and creating enhanced economic value to producers and other agricultural industry players, this framework is generally referred to as *precision agriculture (PA)* or *site-specific crop management (SSCM)*[15]. See Figure 4 for a conceptual overview of what a PA entails. Thus, the agriculture industry in most advanced economies (like the US, Australia, Israel, etc.) that transitioned from a small-scale labor-intensive venture to large-scale, capital-intensive conglomeration enterprises because of rapid

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 23 February 2024 doi:10.20944/preprints202402.1342.v1

advancements in farm machinery technology some decades ago has shifted back towards smaller individually managed units, known as management zones, thanks to PA[15].



(a)



(b)

Figure 4. PA (a) conceptual overview of the processes involved in a PA framework where a large field is divided into smaller units and different sensors collect data (moisture, nutrients, foliage health, yield, etc.) that can be used for managing crop field on a site-specific or zone map need basis as in (b). (Adapted from Thilakaranthna and Raizada, 2018[37].).

Therefore, recently, especially in developed economies, cotton agronomy and field practices have been primary receivers of the benefits of PA because cotton is grown with different cultivars in diverse climatic and soil conditions, which requires unique management between and even within sites. PA offers a means of optimizing cotton production inputs according to the plant requirement within specific management zones in a field instead of applying inputs at uniform rates for all plants regardless of the differences in their needs[17]. PA relies on numerous sensors and information technologies and systems to acquire and analyze field spatial-temporal data for interpretive, factual, and interpretive crop management decisions, which usually entails some variable rate technology (VRT) applications[15,17]. Thus, only data acquisition capability is not sufficient for effective SSCM because it must be combined with a deep knowledge of interpreting relationships between variables, which most times are nonlinear and elusive, and much research has been done using machine learning models to decipher field data and support SSCM decisions[17,38].

Generally and more specifically for cotton, PA has benefitted from advances in many enabling technologies, including the global positioning system (GPS), sensor technologies (e.g., soil moisture sensors, low-cost and accurate GPS receivers/sensors), precision equipment for variable rate (VR) seeding, chemical, and irrigation applications[15,17]. For instance, the development and availability of precision irrigation systems like pivot or linear move machines with diverse resolutions from the 90s until now have granted more water efficiency to cotton production. Although the cost of these equipment, which increases with their resolutions and complexities, may still be prohibitive to cotton farmers in developing economies in Asia and Africa[17,39–41].

As time progresses and sensor development advances and becomes cheaper and more available to cotton growers, even smallholder farmers in developing economies, integrated PA will keep playing a significant role in repositioning cotton farming in good light as a sustainable and environmentally friendly cash crop/fiber that uses the minimally sufficient input for production and maintaining the reputation of cotton as the natural fiber of choice.

3.3. UAV Inspections and Remote Sensing Techniques

One key enabling technology for PA is the rapid development and evolution of sensor technologies ranging from optical RGB cameras to light detection and ranging (LiDAR) technology/systems and ultrasonic transducer (UT) sensors[42]. These technologies have gained widespread adoption and applications in cotton agronomy practices globally because they bring immense benefits and capabilities to farmers. These sensors are used mainly for remote sensing purposes in acquiring data on plant growth, development, health status, and yield[19,38,42,43]. During crop data acquisition, the sensors must be placed on a platform(s) that "carry" them about. Often, these platforms are tagged unmanned systems to indicate their autonomous (self- or remote-driving) nature. Unmanned systems with flying capabilities are called UAVs; otherwise, they are called Unmanned Ground Systems (UGVs) and offer potential farm management efficiency enhancements[19,24]. Using these systems with remote sensors reduces/eliminates the tediousness, labor-intensiveness, and occasionally destructive nature of manual cotton agronomical practices, like phenotyping[43–45].

Although widespread adoption and commercialization of these systems are yet to be achieved, especially in the two leading cotton-producing nations, India and China, significant research efforts have been committed to developing them for cotton production in those two countries, and some reports say cotton planters in China favor them[45]. While Yeom et al. (2018) successfully investigated the use of UAV-acquired image dataset for detecting boll opening and subsequent yield prediction, Han et al. (2020) investigated an improvement method for UAV-based data collection process to enhance the usability of UAV data for PA management purposes by incorporating UGV-based ground control points with UAV[19,42]. Also, Hardin et al. (2018) and Zhai et al. (2022) investigated the use of UAV image data for the characterization and detection of plastic, a primary cotton contaminant, in cotton fields so they can be retrieved before harvesting[46,47]. Sun et al. (2018) successfully demonstrated the use of LiDAR technology for fast in-field cotton plant growth and analysis[43]. These are only examples of how UAVs (and UGV) combined with advanced multispectral/hyperspectral optical and non-optical sensors are transforming cotton cultivation field management.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 23 February 2024 doi:10.20944/preprints202402.1342.v1

However, aside from the current prohibitive cost, the associated security risks, and the advanced expertise/certification required to use UAVs in agriculture, specifically cotton agronomy, UAVs offer one of the most compelling technologies that would drive the future of sustainability-compliant cotton production.

3.4. Effective Water Management Strategies

Cotton as a crop is not water intensive because cotton plants are genetically drought- and heat-tolerant and are cultivatable in regions of limited water supply[27]. However, rainfed cotton cultivation is a risky venture, as it is always universally challenging to maintain good cotton growth and productivity (yield) performance under rainfed agronomy because rainfall patterns are not static and too unpredictable for good crop management strategies[48]. Thus, often, farmers produce cotton with substantial reliance on freshwater sources for irrigation in most of the arid and semi-arid climatic regions (Pakistan, Australia, Uzbekistan, Egypt, US, some provinces of China, etc.) where cotton production occurs, and freshwater supply is limited[9]. Irrigated cotton farming accounts for about 53% of the world's arable cotton farmlands, mostly in dry, semi-arid and arid areas[9]. Essentially, all cotton growth in Uzbekistan, Egypt, and Xinjiang province of China gets irrigated from freshwater sources, and about 31% of cotton irrigation water comes from groundwater sources in Pakistan, which has resulted in receding water tables as is the case in China and recently the US[9,25].

Because most cotton irrigation systems utilize traditional flood irrigation technique, where freshwater is conveyed out of water sources (dam, lake, river, or reservoir) through open channels and delivered to the surface of the cotton cultivated fields, these traditional systems are water inefficient because of the high seepage and evaporation rates and other inherent inefficiencies[9]. These sustainability-unfriendly characteristics of conventional cotton irrigation management techniques have led to research on finding more effective cotton irrigation and water conservation techniques globally. Some of the main techniques include:

Plastic Film Mulching

From the US to Asia, numerous research studies have suggested that plastic film mulching can be highly beneficial in cotton agronomy[3,31,49]. That is so because plastic films have thermal properties suitable for increasing the soil temperature in the pre-germination period (when cottonseeds need high soil temperature for effective germination), seedling establishment, and root growth[31,49]. Mulching is considered a significant constituent of a combination agricultural principle for sustainably cultivating cotton[3] because of its potential to minimize water utilization in cotton production.

Fereres and Goldhamer (1991) investigated the effect of plastic mulching (PM) on cotton yield and pre-season irrigation needs in California, USA, against the backdrop that the surface (furrow) irrigation method used for pre-season irrigation is the largest source of drainage problems that affected the study area in California and concluded that although plastic mulch did not eliminate soil dryness, the plastic mulch acted as a solar still that raised the soil moisture to level needed for effective timely germination without need for pre-season irrigation, compared to non-mulched treatment where irrigation is mandatory for germination to occur[49]. The soil moisture level in the study was conducive for germination under PM treatment without requiring artificial irrigation because the plastic trapped the evaporating water vapors, condensing and returning them to the soil.

Similar investigations in other countries like China have established that PM combined with furrow-bed seeding minimizes soil salinity effects on plants and is a good agronomy practice for weed control[31]. They also reported PM as capable of adjusting the cotton flowering and boll stages to meet with the local best photothermal intervals[31,50]. Many consider PM a crucial technology for promoting early emergence and maturation in the northwest inland cotton-growing China region[31].

However, there are significant challenges associated with PM use in cotton agronomy. Apart from the generally acknowledged non-sustainability-compliant nature of plastic in every industry, plastic seriously threatens the reputation of cotton as a natural fiber and should be cautiously applied

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 23 February 2024 doi:10.20944/preprints202402.1342.v1

in the cotton value chain[2]. When available, fully biodegradable or thicker plastic films should be used instead of thin polyethylene ones to reduce plastic contamination threat from PM technology by enhancing biodegradation, reducing the speed of film aging, or enhancing pre-harvest retrieval, which eliminates chances of picking them up with seed cotton during harvesting[31].

Drip and Center Pivot Irrigation and Fertigation Methods

Given the need to apply irrigation water as and when needed in the appropriate quantity, in most developed economies since the early 90s, most cotton irrigation practices have moved from the furrow/flooding irrigation technique to more environmentally friendly and sustainable irrigation water management using VR technologies (Figure 5)[39–41]. These site-specific irrigation techniques, including center pivot (also known as linear move machines) and drip irrigation, have demonstrated their water-saving capabilities since they have been widely used in crop cultivation[51]. By water efficiency, drip irrigation is the best available technology used in cotton and agriculture generally because it applies the minimal amount of water required for optimal plant growth, saves fertilizer through fertigation, increases cotton yield, and saves labor costs[51,52].

Figure 5. An example of modern irrigation system—center pivot (or linear move machine). It is more suitable for variable rate irrigation water application on a larger scale compared to drip irrigation method which is more suitable for smaller farms. (Source: Valley Irrigation).

Because of their high water-use efficiency, which supports the sustainability drive, there are recent research efforts to utilize these irrigation systems for autonomous variable rate fertigation using low-cost electronics and controllers and to enhance their satisfactory performance and prospects[53]. Also, in China, where they irrigate about 3.33 million ha of farmland with drip irrigation, continuous research studies are being conducted to improve the irrigation technique for durability and higher performance[54]. And because most cotton farms are still furrow-irrigated in many countries (especially in developing economies), the combination of these new more water-efficient irrigation systems with machine learning algorithms, biodegradable PM, vegetation indices computed in real-time with remotely sensed data, and modern electronics presents hope/near-term solution for cotton water sustainability drive[53].

Also, these modern irrigation systems permit the integration of solid or liquid fertilizer application and irrigation (i.e., "fertigation") technology, which is a good way of killing two birds with one stone in cotton agronomy. This technique has proven to be a necessity/requirement rather than a cotton agronomical choice in some world regions, e.g., in China, to conserve water usage in cotton production[55].

However, some issues still need to be solved before these advanced irrigation methods (drip and center pivot) may fully benefit the cotton industry's sustainability drive. Firstly, these advanced irrigation systems are costly. Hence, their speedy adoption can be hindered by that factor until it is affordable to cotton farmers, even in developing countries. Also, research has correlated their

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 23 February 2024 doi:10.20944/preprints202402.1342.v1

adoption to a significant drop in water table levels in locations where they have been adopted, for example, the Ogallala Aquifer in the Southern High Plains (SHP) of Texas, US. Thus, we need modalities for preventing the depletion of groundwater sources following the adoption of these irrigation systems by experts and regulators to prevent future water crises[51].

Other advances and technologies that scholars have applied to minimize water use for cotton agronomy include *dry sowing and wet emergence*, where neither spring nor winter irrigation is applied before sowing and reducing water usage by about 80% and *regulated deficit irrigation practices*, which potentially reduces cotton water use by about 20% in some regions of China[31].

3.5. Advancements in Mechanical Harvesting and General Crop Management Technologies

In the distant past, before 1930, cotton was harvested manually in the US[56]. However, the manual harvesting process, which is still in practice in some countries in Asia and Africa today, is physically demanding and labor-intensive for large-scale cotton farms and thus led to a series of evolutions in the cotton harvesting method[2,57]. In the late 1930s, John Rust invented the first cotton harvester prototype named harvesting locomotive, which, although offered an alternative to manual harvesting, was expensive and fragile and required frequent maintenance. And despite subsequent improvements made to the original model, the harvester first failed commercially[56,58]. In the mid-1940s, International Harvester (IH) introduced their spindle-type mechanical cotton picker that transformed cotton farming from a labor-intensive to a capital-intensive system[57].

Later, in the 1940s, Rust redesigned his spindle-type harvester for durability and commercially succeeded. Further improvements came along in cotton harvesting between the 1950s and 1980s when John Deere (JD) arrived on the scene and changed the cotton harvester into a fully functional harvesting machine with their 4-row cotton picker, which co-operated with tractors, boll buggies, and later cotton module builders to harvest cotton and decoupled harvesting from the ginning operation. Subsequently, in the 1990s, JD produced the 6-row picker, which increased the speed of harvesting cotton and positioned the company as the leader within the cotton harvester manufacturers industry[57].

In 2009, the company introduced another revolutionary product capable of building seed cotton into cylindrical (“round”) modules as they were harvested (onboard module building), thereby eliminating the need for additional investments in tractors, boll buggies, human labor, and conventional module builders in cotton harvesting as was the case with earlier mechanical harvesters, see Figure 6. The new cotton picker machine model 7760 (and subsequent models CP690, CP770, and CS770) wraps the built cylindrical cotton module with a plastic material to protect the seed cotton from rain, wind, and high-frequency radiation from the sun.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 23 February 2024 doi:10.20944/preprints202402.1342.v1

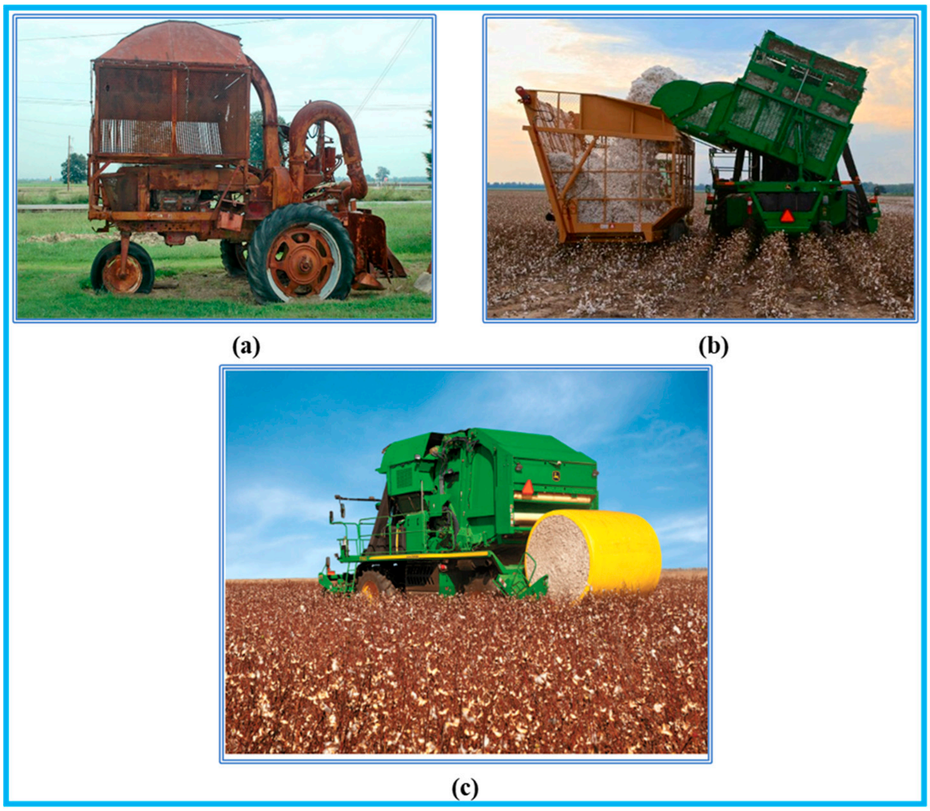


Figure 6. Evolution of mechanized cotton harvesting **(a)** a second generation commercially successful cotton picker M produced in the 1940s **(b)** a boll buggy receiving seed cotton from a cotton picker, an approach that required multiple equipment types and is labor intensive improved by **(c)** a 7760 JD cotton harvester with onboard module building feature, requiring no extra human labor and expensive equipment and tractors to build cotton modules. (Sources: (**a**) Mississippi State University Extension (**b**)West Tennessee Historical Society (c) John Deere, Inc.).

Furthermore, in recent years, cotton agronomy has witnessed numerous other mechanized technologies for cotton seed processing and cultivation. Some of these are mechanical hole sowing devices, which solved the issues of seed breakage and clogging associated with conventional sowing machines, and novel sprayers that solved the problem of pesticide application inside high-density planting areas by breaking the associated bottleneck with uniform defoliant spraying[31].

Heavy-Duty (Stripper And Picker) Harvesters

Cotton mechanization is a complex framework integrating several disciplines with mechanical design, intelligent equipment, and information control as significant components[31]. Cotton harvesting is one of the most tedious processes involved in cotton production, and globally, it was traditionally performed manually even until now in developing economies[2]. With increasing farm sizes and labor costs, cotton harvesting, especially in developed economies, transitioned to using larger and heavier machinery with increased capacity and automation to benefit from the economy of scale they brought into cotton agronomy[24,57]. Countries like Australia, the US, Brazil, and Israel were the early adopters of this fully integrated JD cotton harvesters with onboard module-building capability that decoupled cotton harvesting from ginning[2,59]. Adopting these JD harvesters with onboard module-building capability has reduced the picking time for cotton bales from five to seven person-hours to only eight minutes[57].

However, this motivation towards adopting more efficient heavy-duty harvesting technologies to lower costs and increase work rates has brought about concern because of the undesirable potential higher soil compaction effects and the associated need for tillage repair[57]. Furthermore, while these

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 23 February 2024 doi:10.20944/preprints202402.1342.v1

advanced mechanized harvesting technologies have been widely adopted in developed economies, the required high capital outlay because of the expensive machine price has created a significant impediment to their adoption in developing economies like African countries and India and China, which are the global largest cotton producers[60].

Also, despite the numerous advantages brought to cotton harvesting by JD game-changing harvesters with the onboard module-building feature, plastic from the round module cover has introduced to the cotton value chain another challenge of plastic contamination in addition to the inherent higher trash content of machine-picked cotton, which industry experts and researchers now have the responsibility of solving to prevent further reputational and financial losses to cotton as it repositions itself towards sustainable production.

Finally, it has become a widespread practice to chemically defoliate cotton plants after maturity, before harvesting operation, to make them amenable to mechanical harvesting. If leaves remain on the plants until harvesting, the mechanical harvesters may collect them with seed cotton and introduce high extraneous matter content in the seed cotton module, resulting in losses to producers. Also, the leaves may stain the fiber if not removed before the onset of rain after the bolls open, resulting in farmers' losses because of the low color grade of the processed cotton bales. However, these chemical defoliants for cotton are potential sources of environmental pollution that harm the sustainability drive of cotton and need to be minimized or phased out of cotton agronomy to make it greener.

3.6. Multipurpose Robotic Platforms for Phenotyping, Spaying, Weeding, and Harvesting

Because of the challenges of extensive soil compaction associated with the significant weight and the high capital outlay of heavy-duty mechanical cotton harvesters and other equipment, coupled with advancements in modular robotic platforms that are now commercially available, there have been numerous suggestions for a paradigm shift from the use of single-pass heavy-duty cotton harvesters (pickers and stripper types) to small multi-pass robotic harvesters, which will not only reduce the potential of soil compaction and higher capital investments but can harvest seed cotton continuously as the boll opens, preventing the fiber from exposure to elements of weather for too long[24,59]. Other motivations for these suggestions/recommendations are that commercial UGVs are modular and can be retrofitted with different end effectors to perform diverse precision farm management operations (scouting with multiple sensors, phenotyping, spraying, weeding, etc.) whenever necessary[24,59].

A proof of concept for this cotton agronomy automation paradigm was proposed and investigated by Maja et al. (2021)[24]. They retrofitted a small commercial UGV with a vacuum-type system having a small storage bin and a single harvesting nozzle, see Figure 7[24]. The preliminary performance evaluation of the prototype (named CHAP: cotton harvesting autonomous platform) showed promising results with an average of 57.4% cotton-locks picking rate when locks are around 12 mm from the nozzle (40.7% for row Z and 74.1% for row B for a two-row test arrangement). They are working on further improvement of the system to perfect its functionality and operational modalities.

Figure 7. A 3D model of the CHAP equipped with a suction system, a bin and a harvesting nozzle for picking seed cotton from open bolls. (Adopted from: Maja et al., 2021[24]).

Similarly, in response to the need for an integrated and more sustainable weed management approach, which will reduce the use of herbicides that research has proven can decrease cotton yield and cause environmental pollution risk by drifting to unplanned regions during their application, Lamm, Slaughter, and Gilles (2002) proposed, developed, and tested a weed control system in commercial cotton fields[61]. The designed system was composed of a real-time machine vision subsystem, a precision chemical applicator, and a controlled illumination chamber, all carried on a robotic platform[61]. While traveling continuously at 450 mm/s in commercial cotton fields, the robotics cotton weeding system achieved a reported weed detection-and-spraying accuracy of 88.8% and only sprayed 21.3% of the detected cotton.

3.7. Organic Cotton Production and High Plant Density (Close Planting) Techniques

Organic Cotton Production

Organic cotton farming is a sustainable agricultural practice that prioritizes environmental conservation and the well-being of farmers and consumers. Unlike conventional cotton farming, organic cotton cultivation avoids using synthetic pesticides, genetically modified organisms (GMOs), and chemical fertilizers[62]. Instead, it relies on natural processes to maintain soil fertility and control pests, promoting healthier ecosystems and reducing the environmental impact of cotton production.

One of the significant advantages of organic cotton farming is its positive impact on soil health. By avoiding harmful chemicals, organic farming methods preserve the natural balance of microorganisms in the soil, ensuring soil fertility for future generations. Healthy soil also has higher water retention capacity, reducing the need for excessive irrigation and conserving water resources, a critical concern in many cotton-producing regions.

Furthermore, organic cotton farming promotes biodiversity by encouraging the growth of various plants and insects, creating a balanced ecosystem where natural predators control pest populations, reducing the need for chemical interventions, and making organic cotton farming safer for both the environment and the farmers.

High-Density Planting Technique

High-density planting technique (HDPT) is an innovative approach to cotton cultivation that attempts to optimize the number of plants per unit area. Farmers can achieve higher yields while utilizing resources more efficiently by increasing plant density. This method involves planting cotton plants at closer intervals, allowing the efficient use of available sunlight, nutrients, and water[63].

One of the primary benefits of HDPT is its ability to enhance productivity without expanding the cultivated land. By maximizing the usage of limited space, farmers can meet the growing demand for cotton without further encroaching on natural habitats. Additionally, HDP promotes better weed suppression since the densely planted cotton canopy shades the soil, reducing weed growth and minimizing the need for herbicides[31,63].

Another advantage of HDPT is its potential to improve fiber quality. When cotton plants are grown closer together, they compete for resources, leading to longer and stronger fibers[63]. High-quality cotton fibers are essential for the textile industry because they result in softer, more durable, and luxurious fabrics.

In conclusion, organic cotton farming and high-density planting techniques represent innovative and sustainable approaches to cotton cultivation. By perfecting and embracing these methods, the agricultural industry can minimize its environmental footprint, conserve natural resources, and provide consumers with high-quality, ethically produced cotton products. As consumers become increasingly conscious of the environmental and social impact of their purchases, adopting these sustainable practices is crucial for the future of cotton farming and the well-being of our planet.

3.8. Sowing and Plant Stand Establishment Techniques

One of the significant factors influencing the healthy vegetative and reproductive (lint yield) growths of cotton crops is the choice of planting technique[64]. The choice of planting technique helps in achieving the desired crop stand and root development by accelerating or otherwise impeding the uptake of available root-zone nutrients by the plant. The soil conditions (moisture, texture, and temperature), which are also dependent on the adopted land tillage/preparation and sowing techniques, significantly influence seed germination, cotton plants physical characteristics, and yield[64–66].

Since over a century ago, the raised seedbed planting technique has been the conventional cotton row configuration paradigm in the US and some other countries and still is the most sophisticated and lucrative method, typically prepared using raised-seedbed shapers/planters (see Figure 8) and followed by planting at a depth between 12.7 and 38 mm (0.5 and 1.5 in.) depending on the soil conditions[64,66–68]. Raised seedbed planting affords various benefits, including reduced crust formation and the associated improved cottonseed germination rate, optimal crop stands establishment and population resulting from enhanced root propagation, easy rainfall runoff drainage, improved water and nutrient use efficiency, relatively lower lodging and insect/disease stress compared to other bed types and planting methods, and higher lint yield[64,66,69–72].

 doi:10.20944/preprints202402.1342.v1

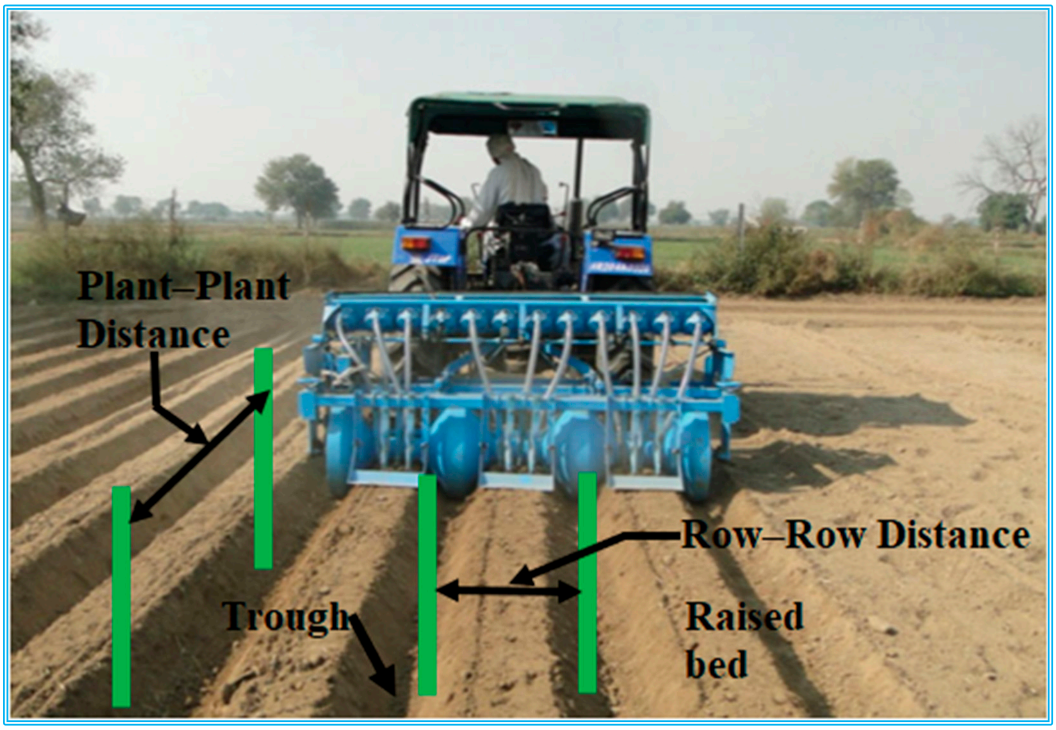


Figure 8. An image showing a multi-crop raised seedbed planter operating on a field with illustrated bed configuration parameters. The machine first creates the raised trapezoidal seedbeds and plants the seeds in its trail. (Image adapted from Kumar et al., 2023[73].).

However, in recent years, that paradigm is changing worldwide, including in the US, as more cotton producers and researchers are adopting/considering alternative seed bed configurations/techniques to gain diverse benefits[64,68,74]. For instance, weeds' growth behavior varies with planting methods, and so whereas weeds grow indiscriminately under flat sowing conditions, they grow at specific locations under the ridge planting method[64]. Similarly, the efficacy of weedkillers changes under different planting techniques[64]. Below, I present some of the most common emerging cotton sowing/planting techniques in literature.

Flat-Sowing Technique

In some US cotton-producing regions (the Sun Belt), many cotton growers are fast adopting the flat (level-ground) planting (with irrigation borders) technique, which had previously been the traditional method for some grain and forage crops, as their favorite because of the perceived benefits of cost-and water-savings on leased farmlands where drip irrigation is infeasible, convenient mechanical harvesting not requiring row-end plow down as in raised-bed planted cotton harvesting, less cultivation/tillage requirements, and faster soil temperature rise for sowed seeds[68]. Most of the lands cultivated with this technique are laser leveled (see Figure 9), and farmers apply the initial fertilizer dosage with tractors followed by fertigation for subsequent fertilizer application(s) without disturbing the field borders between harvests but only cleaning them between crops[68].

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 23 February 2024 doi:10.20944/preprints202402.1342.v1

Figure 9. An image of a farm in the US showing a typical flat-row cotton field with irrigated borders. Most farmlands for the flat planting technique are laser leveled, and the borders are untouched between reaping to maintain the leveling. (Adapted from Cotton Farming, 2015[68].).

This planting technique is not peculiar to the US alone, as reports say it has been widely adopted with excellent outcomes in every cotton-growing region[64]. In this planting method, row spacing is an essential management tool for manipulating cotton yield, with previous research suggesting a positive correlation between plants-spacing width and the trio of boll weight, bolls per plant, and lint yield[75], while pieces of evidence have supported more feasibility of narrow-row spacing for improved lint output[76].

Ridge-Planting Technique

Another significant cotton sowing technique widely used worldwide is ridge-furrow planting[64,77]. With this technique, cotton seeds are planted in ridges made by mechanical ridgers (see Figure 10a) or formed during cultivation of previous growths (Figure 10b), and often a band application of weedkillers trailing the planter offers weed management in the row[64,77]. According to reports, planting cotton (and other crops) with this technique effectively controls between-row weeds, and the cultivated crops help rebuild the ridges for the subsequent year[77]. This ridge-furrow planting method for cotton, which is popular in many countries, including Pakistan, India, and the USA, is also reported to offer enhanced cottonseed germination rate, lint yields, and earliness relative to the flat-sowing technique, excellent erosion control, and increased soil moisture/reduced root penetration resistance[77–79]. It complements furrow irrigation and is generally suitable for adoption on level and gently sloping farmlands, especially when the soil is poorly drained[77].

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 23 February 2024 doi:10.20944/preprints202402.1342.v1

(**a**) (**b**)

Figure 10. The ridge-planting technique for cotton (a) a five-row ridger making fresh ridges in a cotton field, with illustrated general planting geometry and (b) a ridged field cultivated with new crops while the previous year growth/crop residue remains in the furrow, helping with erosion control, typically, 30–50% non-uniformly distributed residue may be found in row-crop rotated ridge-sowing fields[77].

However, the suitability and success of this sowing technique are also significantly influenced by crop rotation practices and ridges must be perennially maintained in well-rounded shapes with a cultivator to ease subsequent planting, and thus is most suited to cotton-based continuous row crops cultivation[77]. Producers must exercise caution not to damage the ridges when wheeled machinery is used, especially during harvesting[77]. Furthermore, studies have indicated that the raised-bed planting technique produces high seed cotton yield relative to flat- and ridge-sowing methods[80].

Early Planting Aided by Transplantation

In arid cotton-growing regions like Pakistan, Uzbekistan, and the Cotton Belt of the US, temperature extremes affect cotton plant emergence and initial seedling establishment[31,81]. In such regions, the early sowing method aided by transplantation, has been emerging in recent years as a promising approach for enhancing cotton production; cotton producers are shifting towards early planting to circumvent the danger of temperature stress on the emergence of cotton seedlings in May and preserve ideal plant density[81]. Although there are alternative techniques for the proper cotton plantlet establishment under high heat, this technique proves superior[81]. This method involves initiating the cotton crop earlier than traditional planting dates, often facilitated by transplanting seedlings instead of direct seeding in the field. Transplanting allows for controlled and uniform plant establishment, offering several potential advantages for cotton growers[81].

Some of the advantages afforded cotton production by this growing technique include optimized growing conditions because transplanting enables the establishment of cotton plants in ideal growing conditions, thereby minimizing exposure to adverse weather conditions and promoting early root development[82], and a reduced weed competition because transplanting allows rapid cotton plants establishment enabling their competitive advantage over weeds during the critical early growth stages[83]. This cotton cultivation technique also permits an extended cultivation season because the early planting affords cotton plants a longer growing period, which can potentially increase vegetative growth, early squaring/flowering, and higher yields[84]. Lastly, because of controlled conditions during transplantation, crop uniformity enhancement is another benefit achievable with the adoption of this technique in cotton production, facilitating management

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 23 February 2024 doi:10.20944/preprints202402.1342.v1

practices and harvest efficiency later in the season[81]. Other benefits and challenges of using this technique for cotton production are available in studies like Ahmad et al., 2018[81].

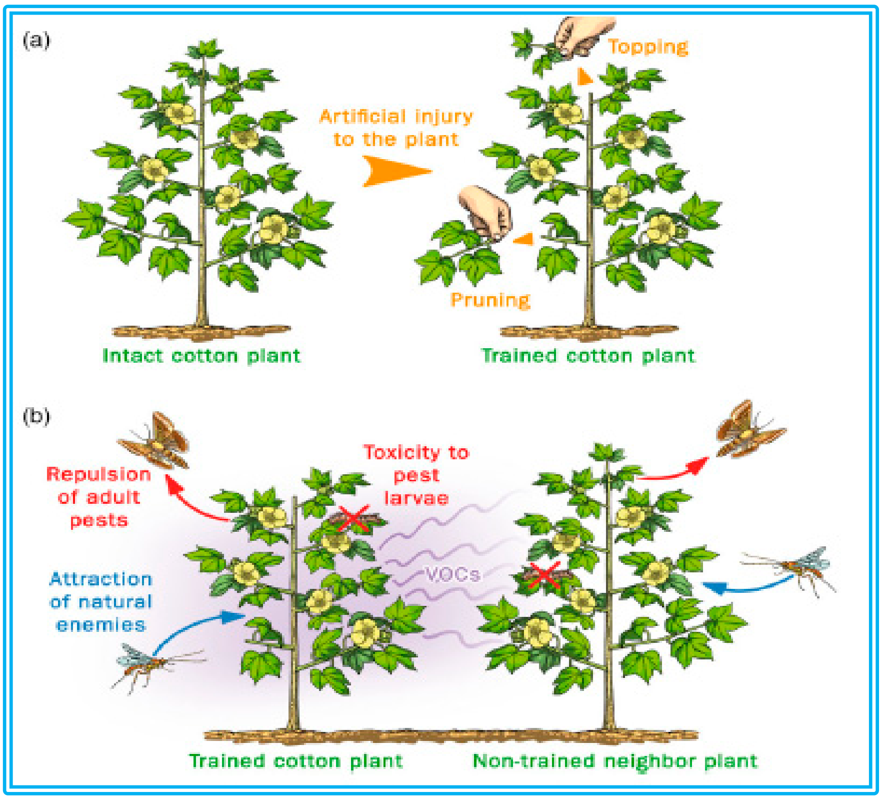
As global warming effects spread aridification across natural cotton-growing habitats where cultivation is by direct seeding, early planting aided by transplantation continues to gain acceptance as a promising approach in cotton production, offering several potential advantages for growers. It is also suitable for successful cotton production adaptation to regions where elevated temperatures generally overlap with May sowing and blooming height days in several traditional cotton-producing areas[81].

Finally, while studies like Ahmad et al. (2018) contributed valuable insights on early planting aided by transplantation by reporting about 14% higher cotton productivity for this method than direct sowing, continued research is essential to refine and optimize the implementation of early planting strategies, considering regional variations and specific crop management practices[81].

Monoseeding/single-seed sowing[85] and cotton-based intercropping[86] are other relevant cotton sowing/plant stand establishment and cropping techniques currently gaining significant attention. I present outlines of these and other advanced methods in the summary of Section 3.

3.9. Chemical and Mechanical Growth Regulation/Topping

Cotton is a perennial crop successfully adopted and grown commercially as an annual crop, yet its indeterminate growth pattern still subsists. So, the advent of mechanical harvesting machines, which require height and ripeness uniformity for efficient performance, has necessitated the need to control the growth of the apical meristem of cotton plants to hasten reproductive maturity and limit the height of plants to those amenable to mechanical harvesting. There have been three main methods widely used for cotton growth regulation (also known as topping), including manual (the traditional method, see Figure 11a), mechanical, and chemical[87–91]. Each of these methods has its advantages and demerits (see Figure 11b) for some merits of the manual topping method), but there have been continuous efforts to shift the cotton-growing industry more towards chemical topping, especially in advanced cotton-producing economies and other countries like China[88–90]. I briefly review the two non-conventional topping methods below.



 doi:10.20944/preprints202402.1342.v1

Figure 11. (a) A representation of cotton plant topping (apical bud removal from the main stem) and pruning (vegetative and fruiting branches apical points removal) and **(b)** a depiction of some benefits of these cotton agronomy practices. (Adopted from Llandres et al., 2018[91].).

Chemical Topping

Chemical topping, the application of plant growth regulators (PGRs) to control (inhibit or delay) indeterminate growth of cotton plants by terminating the apical dominance/meristem and increasing the boll ratio and lint output, has become a vital practice in modern cotton agronomy, replacing the customary manual topping technique (manual removal of the main stem) and competing with mechanical topping[88,89]. The increasing adoption of mechanical harvesting techniques, which require height and ripeness uniformity for efficient performance, across various countries has necessitated this trend shift in modern cotton production. Although manual topping is still the dominant topping method, especially in developing economies, it is only suitable for use in small- to medium-sized cotton farms because of its intensive labor needs and cannot meet the broad-acre production demands in advanced economies[88,89]. On the other hand, chemical topping offers a low-labor need, harvest efficiency enhancing (through improved plant architecture), a time-efficient, convenient, and easily mechanized technique which does not cause physical damage or missed hitting to plants as with mechanical and manual topping, respectively[92–94].

Some other benefits of chemical topping available in the literature include its ability to replace manual topping at moderate and high plant densities with increased yield via greater assimilates partitioning to fruits and without ecological dependence, enhancement of synchronous cotton fruit maturation, and fiber quality (length, strength, and micronaire) augmentation[89,95,96].

However, some considerations and challenges still need to be addressed before this topping technique properly fits into the overall sustainability agenda for cotton production. These include the environmental impacts and implications (residue concerns and potential effects on non-target organisms) of chemicals like mepiquat chloride used for cotton PGR, economic feasibility that depends on factors such as PGRs costs and application equipment, and resistance in pest and disease issues that may result from the overreliance on some PGRs, which may create problems for integrated pest management (IPM) strategies[91,96–99].

Finally, chemical topping in cotton farming embodies a viable tool for height control, consistent maturation, and increased harvest efficiency. Nonetheless, a balanced approach considering environmental effects, potential weed and pest resistance issues, and economic factors is crucial for sustainable cotton production. Ongoing research and refinement of agronomic practices will further optimize the gains of chemical topping in modern cotton agronomy[88,95,96].

Mechanical Topping

On the other hand, mechanical topping involves physically removing the apical meristem or terminal bud on cotton plants using specialized equipment or machinery other than manually or chemically. The primary aim is to regulate plant height by promoting branching and managing the vegetative growth of plants. However, mechanical topping of cotton has not gained popularity in commercial cotton agronomy, like the chemical topping technique, because of its associated plant and boll damage characteristics[88]. Thus, some have suggested that extensive exploration of more effective and lost-cost mechanical topping technology is still necessary for modern cotton agronomy[88,87].

Although mechanical topping offers the benefits of reducing the overreliance of cotton production on chemical PGRs and the associated environmental and IPM issues, it is relatively more labor-intensiveness than chemical topping on broad-acre farms, and the critical timing challenge that may influence its effectiveness are significant challenges that it must overcome for it to gain more market share[87].

Table 1 itemizes some of these significant technological and methodological advancements in cotton agronomy over the past few decades and their implications for cotton production globally. I

 doi:10.20944/preprints202402.1342.v1

summarize the main advantages and challenges these technologies and methods have introduced in cotton agronomy with specific example territories of application.

Table 1. Summary of some technological and methodological shifts in conventional cotton agronomy, their benefits and associated challenges, and applicable regions.

Change	Key Benefits	Challenges	Prospects	Region of adoption/use
Plastic mulching	• Improved soil temperature and moisture level regulation[3]. • Offers opportunity for early planting, germination, and maturing cotton production[48]. • Minimizes water use and contributes to preserving freshwater sources. • Good for weed control/management[31].	• Increasing in-field residual plastic; plastic contaminant source in value chain[2]. • Potential soil pollution which may affect soil microbes' natural habitat.	• Full development and use of biodegradable plastic instead of polyethylene mulch[2].	China, US[31,49].
Fertigation technique	• Improved fertilizer- and water- use efficiency[52]. • Reduced groundwater contamination from either solid or liquid fertilizers and human labor needs.	• Some expensive equipment, which generally require expensive, skilled maintenance schedules, are needed for these advanced irrigation systems.	• Cost optimization to minimize the associated high capital outlay.	US, China, Australia[51,52].

 doi:10.20944/preprints202402.1342.v1

GM crop/New hybrids	• Resistance to pest and diseases. • Higher yield/acre globally[29,30]. • Ease of selecting desired fiber and seed quality and trait from a growing pool of cultivars. • Improved plant physiology with more tunable features for automation management.	• Large-scale crop growth simulation models now need fine-tuning not only for local environmental conditions, but for genetic variations of which the pool of available cultivars keeps growing exponentially with the continuous introduction of several new cultivars by researchers and seed companies[61]. • High cost of cultivation (especially for seed acquisition). • Seed production is difficult and not reuseable, makes breeding for improved fiber yield and quality challenging.	• Continuous development of new hybrid varieties with stacked traits to meet multiple needs simultaneously. • Higher adoption rate in countries not yet accepting GM crops.	US, India, China, Australia, some African Countries[29,30,33–36].

 doi:10.20944/preprints202402.1342.v1

Heavy-duty mechanical harvesters	• High harvesting efficiency. • Generally reduces labor costs/input. • Minimizes investments in multiple equipment (tractor, boll buggys, module builders, etc.) for harvesting.	• High capital outlay • In regions of cheaper labor, machine-harvested cotton is more expensive and contains higher trash content than manually harvested seed cotton[100].	• Seed cotton module Plastic cover will likely be replaced by another sustainable material[2]. • Will most likely be replaced by smaller, modular and cheaper multipurpose robotic platforms[24].	US, Australia, Israel, Brazil[2,24,59].
Multipurpose robotic platforms	• High modularity and multifunctional systems. • Cheaper compared to large heavy-duty machinery. • Low soil compaction and better steerability[24]. • Enables cost-effective multi-pass, gradual cotton harvesting. • Supports the goals of PA/SSCM.	• Technology has not reached maturity, research ongoing to perfect operational modalities for various agronomy practices. • Usually limited onboard seed cotton storing capacity. • Currently, reported operational efficiencies for many agronomy operations have	• After full development, will mostly replace heavy duty machinery and equipment for in-field agronomy management. • Prospect for cheaper and more precise agronomic practices.	US, Australia, Israel, partly China[24,59].

		significant rooms for improvement.		
Drip/center-pivot irrigation technology	• High water-use efficiency with minimal labor cost[50,51]. • Enable simultaneous application of water and chemicals thereby enhancing chemical use[50,51]. • Suitable for medium and broad-acre farms.	• High capital outlay and sometimes running costs. • A significant source of groundwater depletion which may lead to future water crisis[51].	• When combined with other sustainability-oriented agronomy practices like biodegradable PM, will enhance the continued cotton profitability and appeal of cotton to users. • Creation of official standard for preventing the depletion of groundwater sources when using these technologies[51].	US, China, Australia, Israel[39–41,51,52].
Organic cotton cultivation technique	• Highly environment friendly and sustainability compliant[3]. • Minimal input and no use of	• Uneconomical production in many regions, like Australia, US and other advanced economies with	• Will be more widely acceptable as more people choose sustainable products.	Tanzania, India, China, Turkey, US[62].

	inorganic/synthetic inputs/chemicals in many cases. • Preserves the natural balance of soil microbes, ensuring sustainability for future generations[3].	high land and labor costs[62]. • Highly susceptible to pest damage compared to GM/transgenic cotton[62].		
High-density planting technique	• High input efficiency. • Fast maturity and improved yield[31,63]. • Early crop establishment (high leaf area index) and suitability for rain-fed cultivation[31,63].	• The optimum planting density must be matched to prevent excessive competition among plants, which results in lower lint yield[63]. • Small boll size and squares/bolls shedding because of crowding[31].	• Universal standardization of the protocol for HDPT of cotton cultivation[31].	China, US, Brazil Mexico Australia, India[31,63].
Plastic film mulching combined with drip irrigation and fertigation	• Combines the benefits of PM and the most water-efficient irrigation technology to enhance early cotton planting and plant establishment possibilities[3,50,51].	• Plastic is potentially the most harmful contaminant in the cotton value chain. It should be cautiously used, or its use should be minimized[2].	• Development of fully biodegradable plastic material that can practically reduce contamination of the	US, China[31,48,49].

	• Minimizes water-use costs and helps with weed control, ensuring optimal soil nutrient utilization and crop growth.	• Although drip irrigation is water-efficient, it requires a high capital outlay and strict maintenance.	cotton value chain. • Opportunity to apply high-tech UAV, remote sensing, computer vision, and machine learning for an effective integrated water use system on a large scale.	
Flat-sowing technique	• Offers cost- and water-saving benefits on farmlands where drip irrigation systems are not feasible (e.g., leased farmlands.)[68]. • Supports convenient mechanical harvesting not needing row-end plow down as in raised-bed planted cotton harvesting[64;68]. • When used it helps compensate for yield losses in	• On large-scale farms, it requires laser leveling of the ground to achieve the best outcome[68]. This may be expensive and inaccessible to small scale-farmers and developing economies. • Less efficient than raised-bed sowing method.	• Adoption for higher density planting with narrow-row spacing configuration to gain improved lint output benefits[76]	US, Pakistan, India, and rest of the world (ROW)[64,68].

	HDPT paradigm[64].			
Ridge-planting technique	• High seed-cotton yield than flat-planting technique[64]. • Offers good erosion-and weed-control benefits[77]. • It complements furrow irrigation and is suitable for use on poorly drained level–gently sloping farmlands[77].	• The suitability and success of this sowing technique are also significantly influenced by crop rotation practices. It requires perennial maintenance of ridges [77]. • Produces lower seed cotton yield than raised-bed sowing[80].	• Improving the yield to be on par with the raised-bed planting method.	Pakistan, USA India, ROW[64,77–79].
Chemical topping	• Offers benefits of low-labor need, enhanced harvest efficiency easily mechanized operation[92;93;94]. • Increased Seed cotton yield without quality defect[99].	• Environmental pollution and risk of increased pest and disease resistance[91;96;97;98]. • Despite being less labor-intensive, it is more expensive than other methods.	• Optimizing the rates and time of PGR applications for different regions and growing conditions.	USA, Australia, China, Pakistan[88,95,96].
Mono-seeding/Single-seed planting	• Improves stand establishment with comparable yield to HDPT[85]. • Offers the potential to reduce seed and thinning	• There is bigger pressure on individual seedlings from top-soil during emergence compared to	• Experimentation to adapt the technique to regions with similar growing	China[85]

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 23 February 2024 doi:10.20944/preprints202402.1342.v1

	labor inputs without sacrificing yield of cotton[85].	cluster seeding[85]. • Only works well with good-quality seeds and conducive soil microenvironment[85].	conditions as Yellow River valley of China.	
Early planting assisted by transplanting	• Excellent for enhancing production in regions with temperature extremities (e.g., arid and semi-arid regions) during the prime sowing periods[31,81,82]. • Provides optimal establishment and growing conditions for young cotton seedlings, minimizing exposures to adverse weather that affect root development[82]. • Minimizing the effect of weed competition with seedlings[83].	• Requires investments in additional resources like greenhouses and irrigation facilities[81]. • Coordinating the transplanting process with optimal planting dates can be challenging. • Transplanted cotton plants may experience transplant shock, causing slowed growth and development.	• Research to refine and optimize the implementation of early planting strategies, considering regional variations and specific crop management practices is essential as global warming spreads desertification[81]. • Establishing standard procedures for low-cost seedling production.	Pakistan, China, India; Iran[82–84].

4. Summary and Projections

Over the past few decades, cotton agronomy has witnessed tremendous transformations. There are now many exceptional methods for cotton crop management, but choosing which varieties to cultivate has become a highly imperative component of such management approaches. The foundation for making appropriate variety selection relies on the progress made over the past years in biotechnology and plant breeding technology. Desired traits for healthy growth and development and amenability to highly mechanized cultivation, leading to high-quality fibers and yield, agronomical efficiency, and improved profitability for farmers, have been and are being engineered into conventional cotton cultivar genes to create efficient hybrids suitable for sustainable cotton production.

Next, advanced mechanized harvesting technologies that replaced the labor-intensiveness of cotton agronomy with highly efficient long-term and more profitable capital-intensive methods are notable advancements in cotton agronomy. Although these technologies need high capital outlay that would pay off in the long term against alternatives, they have eliminated the need for investment in multiple tractors, boll buggies, other equipment, and at least four human workers to conduct mechanized harvesting of a large-acre cotton field in the pre-2009 season.

However, with the increasing reliability (and affordability) of mobile robotics platforms for navigating rough terrains as obtained in large cotton fields coupled with numerous research efforts on adopting these platforms for cotton agronomy, the age of large-scale heavy-duty land tillage and harvester machines may be ending in the next decade. In that light, researcher aiming to key into this cotton future may focus their efforts on optimizing the operation of these off-the-shelf or custom-made robotic-platform-based systems for different agronomic practices like weeding, high-throughput/real-time plant physiological stage evaluation/phenotyping, soil sampling, and harvesting, to name a few. After fully developing these robotic platforms for various agronomy practices, they will have comparative advantages over the heavy-duty machinery currently in use, which is not sustainable or environmentally friendly and is cost-prohibitive.

Also, organic production techniques for cotton, which emphasize no use of chemicals and inorganic input and minimal or no-till cultivation, can potentially enhance the image of cotton as a sustainably grown crop. However, efforts are still needed to improve the yield/acre and economic viability of this technique of cotton cultivation to bring it up to par with conventional cotton cultivation, if ever possible.

Furthermore, research focused on re-engineering cotton module cover materials that do not create cotton contamination sources for harvested seed cotton may be a worthy endeavor that would revolutionize the industry if it can result in a suitable replacement for plastic seed cotton module covers because we cannot achieve cotton sustainability cannot if after fixing all the loose ends in the field management, plastic contaminants in lint bales still deny the producers the maximum benefits for their efforts.

Moreover, we must revisit research on organic biodegradable plastic mulching materials developed to substitute conventional polyethylene plastics, which constitute a significant contamination source for cotton but are yet to gain widespread acceptance. If we need to re-engineer the plastic mulch and combine it with available improved irrigation management systems, researchers and industry experts who desire sustainability for cotton, agriculture, and the earth must dedicate the effort to do that because solving this issue will amount to saving the industry billions of dollars in lost revenue and loss of reputation and make cotton production more environmentally friendly.

Chemical topping is another technological trend that has continued to gain relevance in cotton agronomy worldwide. Manual topping has been the traditional method of plant vegetative growth and height control in favor of reproductive growth and natural pest management. However, with the advent of mechanized cotton harvesting technologies requiring uniform cotton plant height and the increasing average size of cotton farms and labor cost globally, effective alternative methods like chemical and mechanical topping have become essential in profitable cotton production. While the chemical topping technique has been more adopted and effective in the market (US, Australia, Isreal, and gradually China and other countries) than the competing mechanical method, which is still relatively more labor-intensive and time-critical, through rigorous research efforts, it must overcome some concerns/negative perceptions with its environmental impact, cost, and connection to pest and disease resistance. Also, continuous research efforts should soon produce more efficient and less labor-intensive mechanical topping methods that can reduce the overdependence of the cotton industry on chemical PGRs.

Finally, one must note that while it is possible to give a broad overview of recent technological developments and innovations in global cotton agronomy, variabilities in local conditions and factors (e.g., weather, soil, finance, production scale, etc.) typically affect the actual mode of practice of these various techniques in the several cotton producing conditions. Therefore, entities must always consider this fact when adopting or further researching these discussed technologies and other related ones.

5. Conclusions

Cotton must maintain its leadership of fiber market share as the most abundant and natural fiber of choice for various industrial and sundry applications. To achieve this, cotton production, which has traditionally been input-intensive and has an indelible adverse environmental footprint, must continuously be optimized to use minimal inputs while maximizing yield, fiber quality, and profit using existing and emerging technologies and techniques. These enabling tools (such as variety breeding, improved irrigation systems/biodegradable mulching, autonomous aerial systems, computer vision/agricultural remote sensing techniques, robotic harvesters and multipurpose platforms, HDPT, and chemical topping) for cotton agronomy optimization, some of which have been well-researched and commercialized in the global cotton industry, must continuously be improved upon to take full advantage of emerging advanced techniques and technologies as various experts and entities develop them globally.

6. Electronic Supplementary Information

The supporting data (the 2017 production data for the top 50 cotton-producing countries) extracted from FAO database for Figure 1b is provided.

Author Contributions: The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

Acknowledgments: This research received financial support from Cotton Incorporated under agreement No.22-560TX.

Conflict of Interest: The author declares no conflict of interests.

Disclaimer: The mention of trade names or commercial products in this article is solely for the purpose of providing accurate information and does not constitute recommendation, endorsement or otherwise by the authors and his institution.

Data Availability/Electronic Supplementary Information: The supporting data (the production data for the top 50 cotton-producing countries) extracted from FAO database for Figure 1b is available as an addendum.

References

1. Zhang X, Zhang Z, Zhou R, Wang Q, Wang L. 2020. Ratooning annual cotton (Gossypium spp.) for perennial utilization of heterosis. Front. Plant Sci. 11:554970. doi: 10.3389/fpls.2020.554970
2. Adeleke AA. 2023. A review of plastic contamination challenges and mitigation efforts in cotton and textile milling industries. AgriEngineering, 5(1), 193-217. https://doi.org/10.3390/agriengineering5010014

3. Radhakrishnan S. 2017. Sustainable cotton production. In: *Sustainable Fibres and Textiles, (ed. Muthu SS)*. Elsevier, pp. 21–67. https://doi.org/10.1016/B978-0-08-102041-8.00002
4. WWF. N.d. Available online: https://www.worldwildlife.org/industries/cotton (accessed on 25 October 2023).
5. USDA. 2019. Cotton sector at a glance. Washington, DC: USDA National Agricultural Statistics Service. https://www.ers.usda.gov/topics/crops/cotton-wool/cotton-sector-at-a-glance/ (Reviewed on 22 Sept. 2020).
6. Adeleke AA, Hardin IV RG, Pelletier MG. Design of a plastic removal system for a cotton gin module feeder. In Proceedings of the Beltwide Cotton Conferences, Virtual, 5–7 January 2021.
7. Yang Z, Tang J, Yu M, Zhang Y, Abbas A, Wang S, Bagadeem S. Sustainable cotton production through increased competitiveness: analysis of comparative advantage and influencing factors of cotton production in Xinjiang, China. Agronomy **2022**, 12(10), 2239. https://doi.org/10.3390/agronomy12102239
8. Reller A, Gerstenberg J. 1997: Weisses gold, wohin? Stand und aussichten der baumwollnutzung
9. WWF. 1999. The impact of cotton on fresh water resources and ecosystems. Available online: http://d2ouvy59p0dg6k.cloudfront.net/downloads/impact_long.pdf (accessed on 25 October 2023).
10. Zhou RY. (2016). Method of producing hybrid seeds for annual cotton by cultivating perennially. US Patent, US9265206B2.
11. Zhang T, Xuan L, Mao Y, Hu Y. Cotton heterosis and hybrid cultivar development. Theor Appl Genet. 2023 Mar 31;136(4):89. doi: 10.1007/s00122-023-04334-w. PMID: 37000242.
12. Wang J, Du G, Tian J, Jiang C, Zhang Y, Zhang W. Mulched drip irrigation increases cotton yield and water use efficiency via improving fine root plasticity. Agricultural Water Management. 2021 Sep 01; 255. https://doi.org/10.1016/j.agwat.2021.106992
13. Blaise D, Manikandan A, Desouza ND, Bhargavi B, Somasundaram J. Intercropping and mulching in rain-dependent cotton can improve soil structure and reduce erosion. Environmental Advances. 2021 Jul 01;4. https://doi.org/10.1016/j.envadv.2021.100068
14. Iqbal R, Habib-ur-Rahman M, Raza MAS, Waqas M, Ikram MR, *et al.* Assessing the potential of partial root zone drying and mulching for improving the productivity of cotton under arid climate. *Environ Sci Pollut Res* **28**, 66223–41 (2021). https://doi.org/10.1007/s11356-021-15259-6
15. McKinion JM, Jenkins JN, Akins D, Turner SB, Willers JL, Jallas E, Whisler FD. Analysis of a precision agriculture approach to cotton production. Computers and Electronics in Agriculture. 2001 Oct 01;32(3). https://doi.org/10.1016/S0168-1699(01)00166-1
16. Neupane J, Guo W, West CP, Zhang F, Lin Z. (2021). Effects of irrigation rates on cotton yield as affected by soil physical properties and topography in the southern high plains. PLoS ONE 16(10): e0258496. https://doi.org/10.1371/journal.pone.0258496
17. Sui R, Thomasson, JA, Ge Y. Development of sensor systems for precision agriculture in cotton. Int J Agric & Biol Eng, 2012; 5(4). doi: 10.3965/j.ijabe.20120504.00?
18. Hardin IV RG, Searcy SW. 2010. Autonomous module builder. National Cotton Council Beltwide Cotton Conference. CD ROM pp. 558-69.
19. Han X, Thomasson JA, Wang T, Swaminathan V. Autonomous mobile ground control point improves accuracy of agricultural remote sensing through collaboration with UAV. Inventions 2020, 5, 12. https://doi.org/10.3390/inventions5010012
20. Wang Y, Ji C. Study on discrimination of mature cotton in early scenes. Acta Agricultural Jiangxi 2007, vol. 18, no. 6, pp. 141-143.
21. Wang M, Wei J, Yuan J, Xu K. A research for intelligent cotton picking robot based on machine vision. 2008 International Conference on Information and Automation, Changsha, China, 2008, pp. 800-3, doi: 10.1109/ICINFA.2008.4608107
22. Deere and Company. 2014. Products: CP690 Cotton picker. Available online: http://www.deere.com/en_US/products/equipment/cotton_harvesting/cp690_cotton_picker/cp690_cotton_picker.page? (accessed on 26 October 2023).
23. Willcutt MH. 2011. New cotton harvesters benefit growers. Resource: Eng. Tech. Sust. World 18(5):22–23.
24. Maja JM, Polak M, Burce ME, Barnes E. CHAP: Cotton-harvesting autonomous platform. AgriEngineering 2021, 3, 199-217. https://doi.org/10.3390/agriengineering3020013
25. O'Neill C, McCann M, Syam U. 2023. America is using up its groundwater like there's no tomorrow. (ed. Umi Syam): The New York Times. Available online: https://www.nytimes.com/interactive/2023/08/28/climate/groundwater-drying-climate-change.html (accessed on November 4, 2023).
26. Wanjura JD, Parnell CB, Shaw BW, Capareda SC. Source testing of particulate matter emissions from cotton harvesters–system design. In Proceedings of the Beltwide Cotton Conferences, San Antonio, Texas, 3-6 January 2006.

27. CottonWorks. N.d.(b). Sustainable cotton production. Available online: https://cottonworks.com/en/topics/sustainability/cotton-sustainability/cotton-sustainability-basics/ (accessed on November 4, 2023).
28. Blaise D, Venugopalan M., Raju A. 2014. Introduction of Bt cotton hybrids in India: Did it change the agronomy? Indian J. of Agronomy, 59, pp. 1-20.
29. Venugopalan MV, Sankaranarayanan K, Blaise D, Nalayini P, Prahraj CS, Gangaiah B. 2009. Bt cotton (Gossypium sp.) in India and its agronomic requirements - a review. Indian Journal of Agronomy 54(4): 343–360.
30. Drishti (N.d). India's cotton story. Available online: https://www.drishtiias.com/printpdf/india-s-cotton-story (accessed on November 4, 2023).
31. Feng L, Dai J, Tian L, Zhang H, Li W, Dong H. 2017. Review of the technology for high-yielding and efficient cotton cultivation in the northwest inland cotton-growing region of China. *Field Crops Research, 208, pp. 18-26. https://doi.org/10.1016/j.fcr.2017.03.008*
32. James, C. 2006. Global status of commercialized biotech/GMCrops: 2006. ISAAA Briefs No. 35, International Service for the Acquisition of Agri-biotech Applications, Ithaca, NY.
33. USDA. (N.d.). Recent trends in GE adoption. Available online: https://www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-u-s/recent-trends-in-ge-adoption (accessed on November 4, 2023).
34. Pray C, Ma D, Huang J, Qiao F. 2001. Impact of Bt cotton in China. *World Development, 29(5), pp. 813-825.*
35. ICAC. 2009. Biotech cotton and technology fee. ICAC Recorder, 27(1): 4–8.
36. ISAA. 2019. Brief 55: Global status of commercialized biotech/GM crops: 2019. Available online: https://www.isaaa.org/resources/publications/briefs/55/ (accessed on November 5, 2023).
37. Thilakarathna MS, Raizada MN. Challenges in using precision agriculture to optimize symbiotic nitrogen fixation in legumes: Progress, Limitations, and Future Improvements Needed in Diagnostic Testing. *Agronomy*. 2018; 8(5):78. https://doi.org/10.3390/agronomy8050078
38. Xu W, Chen P, Zhan Y, Chen S, Zhan L, Lan Y. 2021. Cotton yield estimation model based on machine learning using time series UAV remote sensing data. Intl. J. Appl. Earth Observation and Geoinf. 104, pp. 102511-. https://doi.org/10.1016/j.jag.2021.102511
39. Duke HR, Sadler EJ. 1992. Linear move irrigation system for fertilizer management research. In: Proc. Int. Exposition and Tech. Conf. Irrig. Assoc., Fairfax, VA, pp. 72–81.
40. McCann IR, Stark JC. 1993. Method and apparatus for variable application of irrigation water and chemicals. US Patent 5,246,164, September 21, 1993.
41. Camp CR, Sadler EJ. 1994. Center pivot irrigation system for site-specific water and nutrient management. ASAE Pap. 94-1586, ASAE, St. Joseph, MI.
42. Yeom J, Jung J, Chang A, Maeda M, Landivar J. 2018. Automated open cotton boll detection for yield estimation using unmanned aircraft vehicle (UAV) data. Remote Sensing. 10(12):1895. https://doi.org/10.3390/rs10121895
43. Sun S, Li C, Paterson AH, Jiang Y, Xu R, Robertson JS, Snider JL, Chee PW. 2018. In-field high throughput phenotyping and cotton plant growth analysis using LIDAR. Front. Plant Sci., 9, https://doi.org/10.3389/fpls.2018.00016
44. Großkinsky DK, Pieruschka R, Svensgaard J, Rascher U, Christensen S, Schurr U, et al. 2015. Phenotyping in the fields: dissecting the genetics of quantitative traits and digital farming. New Phytol. 207, pp. 950–52. doi: 10.1111/nph.13529
45. Wu, J., Wen, S., Lan, Y. et al. Estimation of cotton canopy parameters based on unmanned aerial vehicle (UAV) oblique photography. Plant Methods 18, 129 (2022). https://doi.org/10.1186/s13007-022-00966-z
46. Hardin IV RG, Huang Y, Poe R. Detecting plastic trash in a cotton field with a UAV. In Proceedings of the Beltwide Cotton Conferences, San Antonio, TX, USA, Jan. 3-5, 2018.
47. Zhai Z, Chen X, Zhang R, Qiu F, Meng Q, Yang J, Wang H. 2022. Evaluation of residual plastic film pollution in pre-sowing cotton field using UAV imaging and semantic segmentation. Front. Plant Sci., 13, 91191. https://doi.org/10.3389/fpls.2022.991191.
48. Mandal DK, Mandal C, Venugopalan MV. 2005. Sustainability of cotton cultivation in shrink-swell soils in central India. *Agricultural Systems, 84(1), pp. 55-75.* https://doi.org/10.1016/j.agsy.2004.06.010
49. Fereres E, Goldhamer D. 1991. Plastic mulch increases cotton yield, reduces need for preseason irrigation. Calif Agr, 45(3), pp. 25-28.
50. Dong HZ, Mao SC, Zhang WF, Chen DH. 2014. The theory for optimization of cotton boll cultivation and its development. Sci. Agric. Sin., 47, pp. 441-451. (in Chinese with English abstract).
51. Goebel TS, Lascano R. 2019. Rainwater use by cotton under subsurface drip and center pivot irrigation. Agric. Water Mangt. 215:1-7. https://doi.org/10.1016/j.agwat.2018.12.027

52. Okasha AM, Deraz N, Elmetwalli AH, Elsayed S, Falah MW, Farooque AA, Yaseen ZM. Effects of irrigation method and water flow rate on irrigation performance, Soil Salinity, Yield, and Water Productivity of Cauliflower. Agriculture. 2022; 12(8):1164. https://doi.org/10.3390/agriculture12081164
53. Bell S, Koc AB, Maja JM, Payero J, Khalilian A, Marshall M. 2022. Development of an automated linear move fertigation system for cotton using active remote sensing. AgriEngineering, 4, pp. 320-334. https://doi.org/10.3390/agriengineering4010022
54. Ran J, Ren Y, Guo W, Hu C, Wang X. 2023. Aging characteristics of drip irrigation belt in Xinjiang cotton fields and their effects on its recovery and recycling. Sci Rep 13, 16948 (2023). https://doi.org/10.1038/s41598-023-43094-x
55. Liang J. 2015. Xinjiang integration of water and fertilizer technology application present situation and the development countermeasures. Xinjiang Agric. Reclam. Technol., 38 (1), pp. 38-40.
56. Certi-PIK. Available online: https://certipik.com/2017/10/23/a-look-at-the-history-of-cotton-pickers-and-the-advancement-of-cotton-harvester-parts/ (accessed on November 4, 2023).
57. Bennett JMcL, Woodhouse NP, Keller T, Jensen TA, Antille DL. 2015. Advances in cotton harvesting technology: a review and implications for the John Deere round baler cotton picker. J. Cotton Sci, 19, pp. 225-249.
58. EOA. Available online: https://encyclopediaofarkansas.net/entries/john-daniel-rust-2272/ (accessed on November 4, 2023).
59. Barnes E, Morgan G, Hake K, Devine J, Kurtz R, Ibendahl G, Sharda A, Rains G, Snider J, Maja JM, et al. Opportunities for robotic systems and automation in cotton production. *AgriEngineering*. 2021; 3(2):339-362. https://doi.org/10.3390/agriengineering3020023
60. Alish-o'g'li MK, Khusanovna MZ. 2022. Research cotton mechanization in Asian countries. JournalNX, 8(3), pp. 22-30. https://oarepo.org/index.php/oa/article/view/598/593
61. Lamm RD, Slaughter DC, Gilles DK. 2002. Precision weed control system for cotton. Trans. ASAE, 45(1), pp. 231-238. doi: 10.13031/2013.7861
62. Cotton Australia. Organic Cotton. (N.d.). Available online: https://cottonaustralia.com.au/organic-cotton (accessed on November 4, 2023).
63. Khadi BM. 2022. High density planting system–next revolution in cotton farming in India. World Cotton Research Conference 7, Cairo, Egypt, October 5, 2022. Available online: https://www.atpbr.com/doc/webinar/Webinar-19-PPT.pdf (accessed on November 4, 2023)
64. Farooq O, Mubeen K, Khan AA, Ahmad S, 2020. Modern concepts and techniques for better cotton production. In: Cotton Production and Uses. S Ahmad, M Hasanuzzaman (Eds.). Springer, Singapore. https://doi.org/10.1007/978-981-15-1472-2_4
65. Krause U, Koch HJ, Maerlaender B. 2009. Soil properties effecting yield formation in sugar beet under ridge and flat cultivation. Eur J Agron 31(1):20–28.
66. Bayer Group. 2019. Optimum cotton planting conditions and seed placement. Available online: https://www.cropscience.bayer.us/articles/dad/optimum-cotton-planting-conditions-and-seed-placement (accessed 26 January 2024).
67. Silvertooth JC. 2000. Planting methods and soil temperature. Arizona Cotton Comments. Available online: https://ag.arizona.edu/crop/cotton/comments/jan2000cc.html (accessed 26 January 2024).
68. Cotton Farming. 2015. Want to save money? Plant on flat beds. Available online: https://www.cottonfarming.com/special-report/want-to-save-money-plant-on-flat-beds/ (accessed 26 January 2024).
69. Ahmad N, Arshad M, Shahid MA. 2009. Bed-furrow system to replace conventional flood irrigation in Pakistan. In: Proceedings of 59 IEC meeting and 20 ICID conference held at New Delhi, India, pp 6–11.
70. Iftikhar T, Babar LK, Zahoor S, Khan NG. 2010. Impact of land pattern and hydrological properties of soil on cotton yield. Pak J Bot 42:3023–3028.
71. Sayre KD. 2000. Effects of tillage, crop residue retention and nitrogen management on the performance of bed-planted, furrow irrigated spring wheat in northwest Mexico. Presented at the 15th conference of the international soil tillage research organization, 2–7 July 2000, Fort Worth, TX.
72. Hobbs PR, Gupta RK. 2003. Resource conserving technologies for wheat in rice–wheat systems. In: Ladha JK, Hill J, Gupta RK, Duxbury J, Buresh RJ (eds). Improving the productivity and sustainability of rice–wheat systems: issues and impact, vol. 65, paper 7, ASA special publications. ASA, Madison, WI, pp 149–171
73. Kumar N, Upadhyay G, Choudhary S, Patel B, Naresh S, Chhokar RS, Gill SC. 2023. Resource Conserving Mechanization Technologies for Dryland Agriculture. In: Naorem, A., Machiwal, D. (eds.). Enhancing resilience of dryland agriculture under changing climate. Springer, Singapore. https://doi.org/10.1007/978-981-19-9159-2_33
74. JPlovesCOTTON LLC. N.d. Available online: Cotton 101: cotton planting considerations. https://hundredpercentcotton.com/cotton/cotton-101-planting/ (accessed 26 January 2024).

75. Boquet DJ. 2005. Cotton in ultra- narrow row spacing: plant density and nitrogen fertilizer rates. Agron J 97:279–287.
76. Jahedi MB, Vazin F, Ramezani MR. 2013. Effect of row spacing on the yield of cotton cultivars. Cer Agron Moldova 46:31–38.
77. Cropwatch. N.d. Ridge Plant. Available online: https://cropwatch.unl.edu/tillage/ridge (accessed 27 January 2024).
78. Gürsoy S, Sessiz A, Karademir E, Karademir C, Kolay B, Urgun M, Malhi SS. 2011. Effects of ridge and conventional tillage systems on soil properties and cotton growth. Int J Plant Prod 5 (3):227–236.
79. Hussain T, Jehanzeb, Tariq M, Siddiqui BN. 2003. Effect of different irrigation levels on the yield and yield components of cotton (Gossypium hirsutum L.) under two sowing methods. J Biol Sci 3:655–659.
80. Ali M, Ali L, Sattar M, Ali MA (2012) Response of seed cotton yield to various plant populations and planting methods. J Agric Res 48:134–137.
81. Ahmad S, Iqbal M, Muhammad T, Mehmood A, Ahmad S, Hasanuzzaman M. 2018. Cotton productivity enhanced through transplanting and early sowing. Acta Sci Biol Sci 40, e34610.
82. Kumar R, Sharma SK, Yadav S. 2015. Effect of transplanting date on growth and yield of Bt cotton. Indian Journal of Agricultural Sciences, 85(11), 1453–1457.
83. Li X, Zhang Y, Wang L. 2016. Effects of transplanting date on cotton yield and quality. Field Crops Research, 190, 29–36.
84. Yan Y, Liang C, Hou Z. 2018. Influence of transplanting date on cotton yield and fiber quality. Journal of Cotton Research, 1(1), 1–8.
85. Kong X, Li X, Lu H, Li Z, Xu S, Li W, Zhang Y, Zhang H, Dong H. 2018. Monoseeding improves stand establishment through regulation of apical hook formation and hypocotyl elongation in cotton. Field Crops Research, 222:50-58.
86. Lv Q, Chi B, He N, Zhang D, Dai J, Zhang Y, Dong H. 2023. Cotton-based rotation, intercropping, and alternate intercropping increase yields by improving root–shoot relations. Agronomy. 13(2):413. https://doi.org/10.3390/agronomy13020413
87. Aydin I, Arslan S. 2018. Mechanical properties of cotton shoots for topping. Industrial Crops and Products., 112:396-401.
88. Wu Y, Tang J, Tian J, Du M, Gou L, Zhang Y, Zhang W. 2023. Different concentrations of chemical topping agents affect cotton yield and quality by regulating plant architecture. Agronomy, 13(7):1741. https://doi.org/10.3390/agronomy13071741
89. Dai J, Li W, Zhang D, Tang W, Li Z, Lu H, Kong X, Luo Z, Xu S, Xin C, Dong H. 2017. Competitive yield and economic benefits of cotton achieved through a combination of extensive pruning and a reduced nitrogen rate at high plant density. Field Crops Res., 209, 65–72.
90. Byrd S. 2019. Plant growth regulators in cotton. Available online: https://extension.okstate.edu/fact-sheets/plant-growth-regulators-in-cotton.html (accessed 28 January 2024).
91. Llandres AL, Almohamad R, Brévault T, Renou A, Téréta I, Jean J, Goebel F-R. 2018. Plant training for induced defense against insect pests: a promising tool for integrated pest management in cotton. Pest Manag Sci., 74(9), 2004-2012. https://doi.org/10.1002/ps.5039
92. Xu S, Zuo W, Chen M, Sui L, Dong H, Jiu, X, Zhang W. 2017. Effect of drip irrigation amount on the agronomic traits and yield of cotton grown with a chemical topping in northern Xinjiang, China. Cotton Sci., 29, 345–355.
93. Zhao Q, Zhou C, Zhang J, Li S, Yun Y, Tian X. 2011. Effect of Chemical Detopping on the Canopy and Yield of Cotton (Gossypium hirsutum) in South Xinjiang. Cotton Sci., 23, 329–333.
94. Mishra PK, Sharma A, Prakash A. 2023. Current research and development in cotton harvesters: A review with application to Indian cotton production systems. Heliyon, 9: 1-16. https://doi.org/10.1016/j.heliyon.2023.e16124
95. Vistro R, Chachar QI, Charchar SD, Charchar NA, Laghari A, Vitro S, Kumbhar I. 2017. Impact of plant growth regulators on the growth and yield of cotton. Intl. J. Agric. Tech, 13(3), 353-362.
96. Abro GH, Syed TS, Unar MA, Zhang MS. 2004. Effect of application of plant growth regulator and micronutrients on insect pest infestation and yield components of cotton. J. of Entomology, 1(1):12-16. https://doi.org/10.3923/je.2004.12.16
97. Chen L, Hou J, Hu XL, Zhang JZ, Wang HD. 2022. Environmental Behaviors of Plant Growth Regulators in Soil: A Review. 43(1):11-25. https://doi.org//10.13227/j.hjkx.202104051.
98. Paudel KP, Lohr L, Cabrera, M. 2005. Residue management systems and their implications for production efficiency. Renewable Agriculture and Food Systems, 21(2):124-133.

doi:10.20944/preprints202402.1342.v1

99. Gencsoylu I. 2009. Effect of plant growth regulators on agronomic characteristics, lint quality, pests, and predators in Cotton. J of Plant Growth Regulator 28:147-153.
100. Tian JS, Zhang XY, Zhang WF, Li JF, Yang YL, Heng YD, et al. 2018. Fiber damage of machine-harvested cotton before ginning and after lint cleaning. J. Intgr. Agric. 17, 1120–1127. doi: 10.1016/S2095-3119(17)61730-1