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REVIEW

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Exploring the impact of high density planting system and deficit irrigation in cotton (*Gossypium hirsutum* L.): a comprehensive review

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Abstract

Lessons learned from past experiences push for an alternate way of crop production. In India, adopting high density planting system (HDPS) to boost cotton yield is becoming a growing trend. HDPS has recently been considered a replacement for the current Indian production system. It is also suitable for mechanical harvesting, which reducing labour costs, increasing input use efficiency, timely harvesting timely, maintaining cotton quality, and offering the potential to increase productivity and profitability. This technology has become widespread in globally cotton growing regions. Water management is critical for the success of high density cotton planting. Due to the problem of freshwater availability, more crops should be produced per drop of water. In the high-density planting system, optimum water application is essential to control excessive vegetative growth and improve the translocation of photoassimilates to reproductive organs. Deficit irrigation is a tool to save water without compromising yield. At the same time, it consumes less water than the normal evapotranspiration of crops. This review comprehensively documents the importance of growing cotton under a high-density planting system with deficit irrigation. Based on the current research and combined with cotton production reality, this review discusses the application and future development of deficit irrigation, which may provide theoretical guidance for the sustainable advancement of cotton planting systems.

Keywords Deficit irrigation, High density planting system, Ultra narrow row, Cost saving, Mechanical harvesting, Yield optimization

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Background

Cotton (*Gossypium hirsutum* L.) is one of the major cash crops in India, sustaining the country's largest organized industry, the textile industry, and is popularly known as "White Gold" for its role in the national economy in terms of foreign exchange earnings and employment generation (Smith, 1999). It plays a pivotal role in the livelihoods of millions of farmers, traders, millers, and the global textile industry. It needs to develop new technologies that can assist farmers in generating adequate income without suffering losses brought on by the ever-changing climate, labor shortages, and increased pest and disease incidence in cotton. The high-density planting system (HDPS) aids farmers in overcoming these obstacles. It is a narrow row spacing system that uses early-maturing semi-compact cotton varieties. This method restricts the number of bolls per plant but maximizes bolls per unit area, thereby enabling the farmers to achieve high yields.

The HDPS technologies promote early maturity in cotton, facilitate rapid canopy closure, and minimize soil water evaporation, which avoiding excessive vegetative growth. Given the growing global population and the increasing demand for food and clothing (Khan et al., 2019), the HDPS has emerged as an alternative strategy to conventional methods, proving to be a well-established agronomic technique for enhancing yield, profitability, input use efficiency, and complete mechanization including mechanical harvesting (Nalayini et al., 2018). Promoting plant density is particularly advantageous for cotton yield in low fertility plots (Dong et al., 2010; Sankaranarayanan et al., 2018). Optimizing plant population stands out as a cost-effective practice with the potential to significantly boost cotton production (Severino et al., 2021; Li et al., 2020).

Water stress significantly affect cotton production. Inadequate irrigation during critical growth stages such as flowering and fruit setting can result in water stress, decreasing fruiting positions, boll shedding, and underdeveloped bolls (Aujla et al., 2005). On the contrary, excessive irrigation in cotton can result in excessive vegetative growth, potentially reducing cotton yields (Karam et al., 2006). Effective irrigation management enhances water productivity and nutrient uptake of cotton (Zonta et al., 2016). Water deficit impact on cotton plants can bring about alterations across various levels of cellular organization. In terms of physiology, it prompts the accumulation of abscisic acid (ABA) in the plant, which is a compound associated with stomatal closure, reducing photosynthesis and hampering most gas exchange processes (Nazim et al., 2021; Kholliyev et al., 2020). Consequently, there are decreases in cell division and expansion, affecting the formation and growth of plant structures like leaves and stems. Biochemical alterations in plants also occur, alongside disruptions in water potential, leading to the acceleration of senescence and the premature shedding of leaves (Makamov et al., 2023; Wahab et al., 2022).

Implementing deficit irrigation strategies at various growth stages enhances the ability of cotton genotypes to tolerate water scarcity, leading to heightened growth and improved yield components. Furthermore, the seeds of these genotypes exhibit increased resistance to water deficit when used in subsequent production cycles (Chen et al., 2021; Veloso et al., 2023). The cotton crop showed a nearly 15% increase in water use efficiency (WUE) when subjected to moderate water stress (Basal et al., 2009).

Hybrid types of cotton are characterized by their extended growing period, tall stature, and expansive growth habit, which contribute to higher cultivation costs because they require more manual harvesting (Gunasekaran et al., 2020). Therefore, recent research proposes that the optimal solution for mechanical harvesting lies in the contemporary approach known as the high-density planting system (Singh et al., 2012). Implementing HDPS in cotton also serves as an alternative method to boost the productivity and profitability of cotton cultivation. Thus, this review paper synthesizes various studies to highlight the impact of HDPS cotton under deficit irrigated conditions for sustainable cotton production.

Major cotton growing countries in the world

China is the leading cotton producer in the world, followed by India, the United States, and Brazil, etc., as analyzed based on the production data in 2022–2023 (Fig. 1).

Global cotton production from 2011 to 2024

Cotton production volume from 2011 to 2024 was analyzed and briefed that, 2011–2012 recorded highest production volume during 2011–2024 (Fig. 2).

Status of cotton cultivation in India

Cotton is crucial in India's agricultural and industrial landscape, serving as a vital commercial fibre crop. It is known as the 'King of fibre crops' and 'White Gold' due to its substantial economic value. Approximately 67% of India's cotton is produced in rain-fed areas and 33% on irrigated lands. Cotton cultivation in India spans three distinct agro-climatic regions, situated between 8°–32°N latitude and 70°–80°E longitude. These regions exhibit diverse characteristics such as elevation ranging from sea level to 950 m, annual rainfall varying from 250 to 1 500 mm, and a wide range of soil conditions in terms of colour, texture, and nutrient composition. The Northern zone experiences harsh climatic conditions with

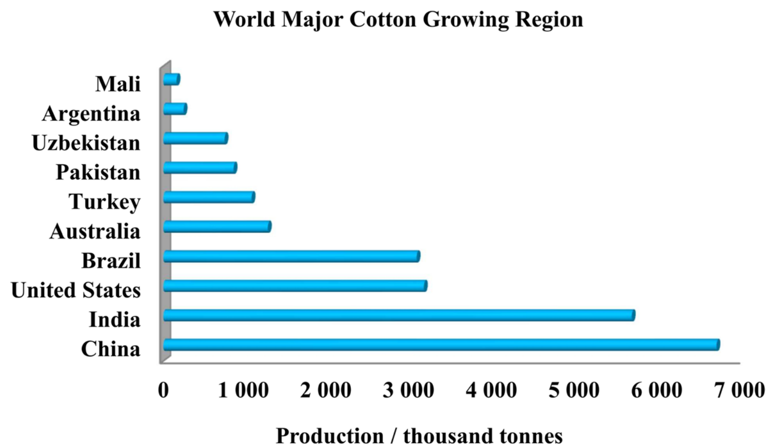

Fig. 1 Major cotton growing countries in the world 2022-2023. Data from statista database (https://www.statista.com/statistics/263055/cotton-production-worldwide-by-top-countries/)

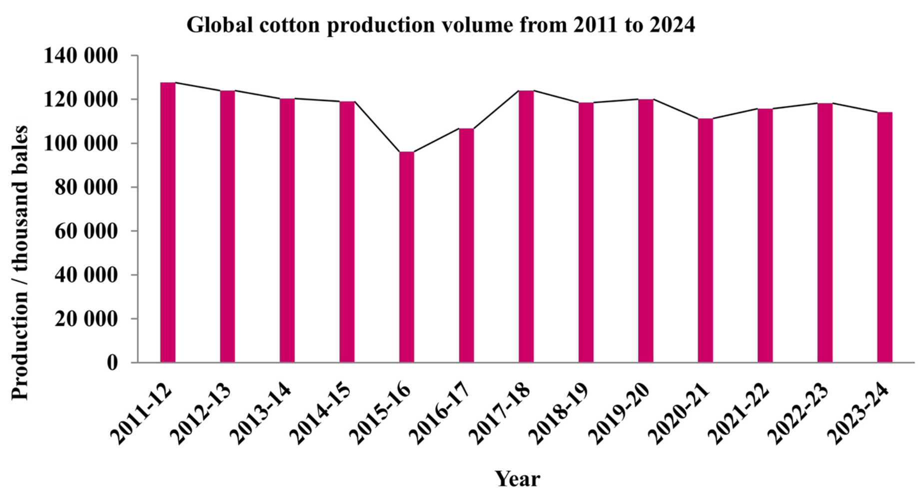

Fig. 2 Global cotton production volume from 2011 to 2024. Data from Statista Database (https://www.statista.com/statistics/259392/cotton-production-worldwide-since-1990/)

high temperatures ranging from 40°–45 °C and aridity, leading to limitations in canal water irrigation, which is grown under irrigation in alluvial soils. In Rajasthan, there has been a 20% decrease in cotton cultivation area in recent years due to a shortage of irrigation water supply. The Central zone accounts for approximately 65% of the total cotton cultivation area, with Maharashtra contributing nearly 30%. Despite limited irrigation sources, the Central zone benefits from favourable temperatures, abundant sunshine during crucial growth and maturity stages, and extended periods of moderately cool, rain-free dry weather from October to February, which create conducive conditions for achieving higher cotton yields. In the Central zone, rainfed crops were cultivated in black soil. In the Southern zone states, cultivation of extra long staple cotton varieties is favourable, but quality assurance is only guaranteed under irrigated conditions. In this region, cotton is grown in vertisols and red soils.

In India, Maharashtra leads in cotton cultivation area with 4.18 million hectares, followed by Gujarat in the Central zone. Telangana has the highest cultivation area in the Southern zone at 1.97 million hectares, followed by Karnataka. Rajasthan cultivates the most cotton in the Northern zone with 0.81 million hectares, followed by Haryana during 2022–2023 (Fig. 3).

From a production standpoint, Gujarat leads in India with 8.79 million bales, followed by Maharashtra in the Central zone. Telangana has the highest production in the Southern zone at 5.74 million bales, followed by Karnataka. Rajasthan records higher output in the Northern zone with 2.77 million bales, followed by Haryana during 2022–2023 (Fig. 4).

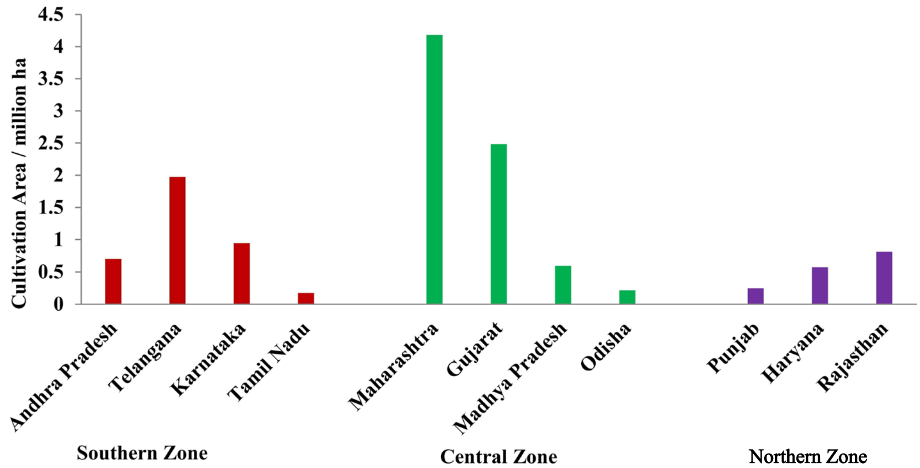

Fig. 3 Cotton cultivated areas in different zones of India in 2022-2023. Data from Committee on Cotton Production and Consumption

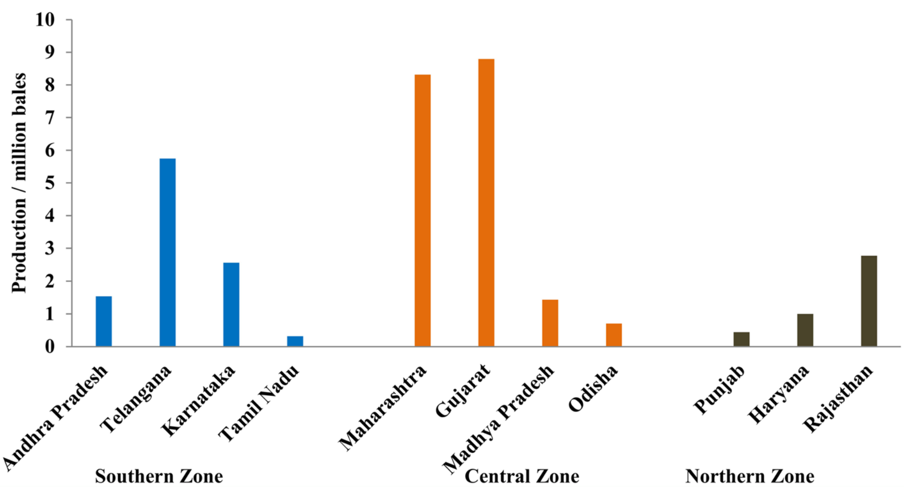

Fig. 4 Cotton production in different zones of India in 2022-2023. Data from Committee on Cotton Production and Consumption

Regarding productivity, Gujarat leads with 601.9 kg·ha^{-1}, followed by Odisha in the Central zone. Telangana exhibits higher productivity in the Southern zone at 495 kg·ha^{-1}, followed by Karnataka. In the Northern zone, Rajasthan records higher productivity at 578.6 kg·ha^{-1}, followed by Punjab during 2022–2023 (Fig. 5).

In India, the cotton industry plays a crucial role in the livelihoods of millions. Approximately 6 million farmers depend on cotton cultivation, while the broader cotton trade and processing sector employs around 40–50 million individuals. Additionally, cotton cultivation has been gaining traction in the Eastern state of Odisha. Some non-traditional states like Uttar Pradesh, West Bengal, and Tripura also engage in cotton cultivation, albeit in smaller areas.

Cotton in India: a journey through time and innovation

India is believed to be one of the birthplace of cotton because its early development of cotton cloth manufacturing. Cotton, integral to India's fabric heritage since ancient times, traces its roots back over 5 000 years to the Indus Valley civilization. Excavations at Mohenjodaro reveal a sophisticated mastery of spinning and weaving with cotton, showcasing early artistic endeavours with the material. India emerged as a significant hub for the cotton industry around 1 500 BC, with its cultivation subsequently spreading to Egypt, Spain, and Italy. Among the 20 wild and cultivated cotton species, only four cultivated species yield spinable lint, while the wild variants produce short fuzz or smooth seeds. The cotton growing system in India has evolved over centuries and has been

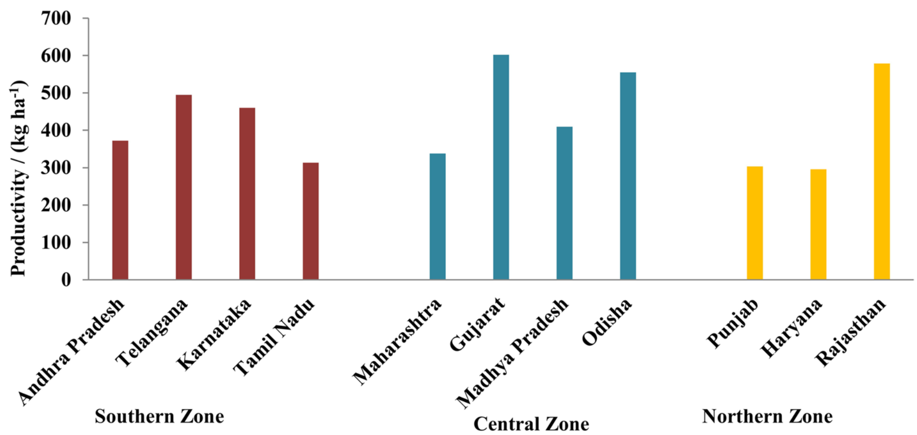

Fig. 5 Productivity of cotton in different zones of India 2022-2023. Data from Committee on Cotton Production and Consumption

influenced by historical, socio-economic, technological, and environmental factors. From its ancient origins to the colonial period, where British interests spurred modernization efforts and, later, the green revolution, which introduced high-yielding varieties and modern agricultural practices, the sector has continually adapted. Moreover, environmental concerns such as water scarcity and soil degradation have prompted a shift towards sustainable practices like deficit and micro-irrigation (Ranapanga et al., 2023). This intricate interplay has led to the diverse landscape of cotton cultivation in India today, blending tradition with modern approaches to address many challenges (Table 1).

Effect of high density planting system in cotton

The introduction of the high density planting system was pioneered by Briggs et al. (1967), who implemented narrow-row planting. Adopting HDPS with compact and early-maturing cotton varieties presents a sustainable production approach at reduced costs in the Indian

Table 1 Shortcomings of cotton cultivation in India

Shortcomings	Reasons	References
Soil type	Growing cotton in clay soils leads to abundant vegetative growth because of their excellent water retention and nutrient richness, rendering them inappropriate for HDPS.	Khan et al., 2019
Selection of suitable cultivars	Cotton varieties with long growth cycles and dense branching structures are not well-suited for HDPS because there is limited space available for each plant, and they are more prone to suffering from terminal drought.	Kumar et al., 2020
More time required for manual sowing	In HDPS, manual sowing requires additional time because of the closer spacing between plants.	Venugopalan, 2019
Higher seed rate	HDPS requires a higher seed rate because of the closer spacing between plants, leading to elevated seed expenses. Nevertheless, the improved yields obtained from HDPS farming can balance these increased costs.	Ranapanga et al., 2023
Canopy management	In HDPS cotton, effective canopy management is essential. Plant growth regulators such as mepiquat chloride are necessary to minimize excessive vegetative growth and retain the first-formed bolls in HDPS.	Kumar et al., 2020
Nutrient management	HDPS requires an additional 25% of fertilizers due to the increased plant population compared with traditional planting methods.	Venugopalan, 2019
Soil moisture stress	The greater plant density in HDPS cotton exacerbates drought stress. Therefore, it is imperative to research and identify cost-effective osmoprotectants to mitigate drought effects.	Ranapanga et al., 2023
Weed management	HDPS facilitates rapid canopy closure and enhances the cotton crop's competitiveness against weeds.	Prasad et al., 2023
Pest & disease incidence	Implementing tighter plant spacing generates a microclimate conducive to the proliferation of pests and diseases.	Prasad et al., 2019
Labour availability	Cotton cultivation in India encounters notable hurdles stemming from ineffective labour practices, escalating labour expenses, and shortages in labour availability.	Ramanjaneyulu et al., 2021

context. The utilization of the HDPS is increasing, particularly in rainfed areas due to less productive soils. HDPS involves planting short-duration, semi-compact cotton varieties at densities ranging from 110 k to 245 k plants per hectare. The spacing between rows varies between 45 cm and 90 cm, and the distance between plants within a row is 10 cm, with adjustments made based on the soil type and prevailing growth conditions (Venugopalan et al., 2016).

The suitability of HDPS for cotton cultivation varies across regions due to climatic conditions, soil quality, and infrastructure availability. Cotton from HDPS thrives in favourable temperatures, humidity, and soil conducive to robust root development and nutrient uptake. Larger farms with mechanized equipment may find HDPS more feasible, while smaller operations could face challenges (Konduru et al., 2013).

The strategy focuses on planting 7–8 plants per meter of row length. Its purpose is to restrict the number of bolls per plant to 6–8 while optimizing the total boll count per unit area, aiming for a significant yield within a relatively short duration (Venugopalan, 2019). The HDPS technology enables swift canopy closure, decreasing soil water evaporation and encouraging early maturity, particularly in soils unsuitable for excessive vegetative growth. This approach is especially beneficial in shallow to medium soils in rainfed environments, offering an advantage over conventional late-maturity hybrids susceptible to terminal drought challenges (Jost et al., 2001).

In HDPS, scientists strive to reshape the crop architecture as an agronomic strategy to increase yields. This approach involves increasing plant density (Paslawar et al., 2015; Parlawar et al., 2017; Madavi et al., 2017; Meena et al., 2017). The increased availability of more determinate cultivars, advanced weed control, and insect pest management options, growth regulators for modifying the morphological structure, and improved planting and harvesting equipment have led to the widespread adoption of high density cotton planting systems in numerous countries. Closer plant spacing resulted in significantly higher seed cotton yields, increased crop productivity and enhanced profitability than wider plant spacing (Shukla et al., 2013).

In HDPS for cotton, climatic conditions like heat, light radiation, and rainfall play a crucial role. Heat management involves spacing plants adequately and promoting airflow within the canopy to prevent stress. Ensuring sufficient light penetration through practices like canopy management is essential for proper growth and development. Timely irrigation becomes critical in HDPS due to increased water demand from densely planted crops. Balancing these factors is essential to maximizing yield and fibre quality while adapting to varying climatic conditions.

The HDPS offers option for complete mechanization in cotton. Mechanization offers significant benefits to small-scale farmers, although its necessity depends on various factors such as the size of the farm, available resources, and specific agricultural practices. While small farmers may not require large-scale mechanization, introducing equipment tailored to their needs can enhance productivity, efficiency, and overall farm management. Mechanization can help small farmers save time and labour, increase production yields, reduce post-harvest losses, and improve the quality of agricultural produce. Additionally, mechanization can enable small farmers to adopt more sustainable farming practices and remain competitive. Therefore, while not always essential, mechanizationcan holds potentail to substantially benefit small-scale farmers by improving their livelihoods and contributing to agricultural sustainability (Nimbalkar et al., 2022).

The ultra-narrow row (UNR) system is employed in Brazil, China, Australia, Spain, Uzbekistan, Argentina, the United States, and Greece. The primary benefit of narrow row planting is its ability to promote early maturity (Rossi et al., 2007; Latha et al., 2011). With the adoption of narrow planting, there is a reduction in the number of bolls per plant. However, this approach yields a higher proportion of the total bolls in the first sympodial position and a lower proportion in the second sympodial position (Vories et al., 2006). This is attributed to enhanced light interception, efficient leaf area development, and ability to meet elevated crop requirements under HDPS (Narayana et al., 2018). Adopting narrow-row planting has gained popularity in various countries, leading to increased cotton production (Ali et al., 2010).

Ultra narrow row cotton production is a promising approach to reducing production costs by shortening the growing season (Rossi et al., 2004). Utilizing genotypes suitable for UNR allows for an increase in the plant population per unit area, leading to enhanced productivity. Furthermore, the early maturation of these genotypes renders this system suitable for marginal soils in rainfed environments (Thatikunta et al., 2018).

Simply increasing planting density in cotton cultivation doesn't guarantee high yields. It needs to be accompanied by improved cultivation techniques and suitable cultivars. Proper spacing, timely irrigation, nutrient management, and pest control are vital. Additionally, selecting cultivars with disease resistance, early maturity, and high yield potential can significantly enhance productivity in high density plantings. Effective management practices combined with appropriate cultivar selection are essential for maximizing yield potential in densely planted cotton fields.

Crop canopy management under HDPS

Mepiquat chloride, a plant growth regulator, is extensively utilized to regulate cotton plant morpho-frame, control growth, and expedite maturation within HDPS (Stuart et al., 1984). Despite extensive testing of plant growth regulators in Indian cotton cultivation, specific recommendations for dosage and timing to tailor crop morpho-frame for Indian varieties in high planting densities are lacking. Applying mepiquat chloride results in a more compact architecture with reduced node count, shorter internodes, and decreased reproductive branching (Reddy et al., 1990; Bogiani et al., 2009).

Furthermore, applying mepiquat chloride decreases leaf area but increases the number of bolls per unit area under HDPS. It also aids in boll retention on lower sympodia and enhances the synchronicity of boll maturation (Gwathmey et al., 2010). However, the impact of mepiquat chloride on cotton is influenced by environmental factors, particularly temperature, which may lead to varying responses across different environments. Applying mepiquat chloride increased seed cotton yields from 1 330–1 530 $kg \cdot ha^{-1}$ among cultivars. A significant interaction effect was observed between cultivars and mepiquat chloride application. Taller cultivars, such as TCH 1608 and TCH 1705, showed more essential benefits from applying mepiquat chloride than other cultivars with a more compact growth habit. Cultivars exhibiting a more indeterminate growth pattern responded positively to mepiquat chloride application (Rosolem et al., 2013).

Opportunities of HDPS

Promising opportunities exist for the adoption of HDPS for cotton cultivation.

1. With the expanding textile industry and sustained consumer demand for cotton products, Indian cotton farmers can capitalize on this opportunity by boosting production through the adoption of HDPS (Ranapanga et al., 2023).
2. Initiatives by the government to promote innovative and sustainable agricultural practices should encompass support for adopting HDPS, recognizing its role in enhancing cotton farming (Kumar et al., 2020).
3. Given the limited arable land in India, HDPS emerges as a solution for making more effective use of available land resources. This approach allows for increased cotton production without expanding into new areas (Venugopalan, 2019).
4. For farmers seeking to diversify their agricultural practices or income streams, embracing HDPS allows them to explore novel techniques and markets within the cotton industry.
5. Cotton grown using HDPS cotton has demonstrated the potential to yield 30% to 40% higher than traditional methods, allowing farmers to realize higher profits.

Details of cotton varieties released for HDPS are mentioned in Table 2,

and some of the varieties released from the Indian Council Agricultural Research-Central Institute for Cotton Research for HDPS are mentioned in Table 3.

Deficit irrigation

Adopting the deficit irrigation method in crops was driven by recognizing the sensitivity of crucial crop stages to soil moisture stress. The use of permanent, pressurized irrigation systems has facilitated the application of minimal amounts of water at regular intervals,

Table 2 Details of cotton varieties released for HDPS

Name of the cotton varieties	Released year	Released institution
CO 17	2020	Tamil Nadu Agricultural University, Coimbatore
RS 2818	2020	Swami Keshwanand Rajasthan Agricultural University, Sriganganagar
ARBC 1601	2020	University of Agricultural Sciences, Dharwad
ARBC 1651	2020	University of Agricultural Sciences, Dharwad
ARBC 1651	2020	University of Agricultural Sciences, Dharwad
DSC 1651	2020	University of Agricultural Sciences, Dharwad
Cotton CO 15 (TCH 1705)	2018	Tamil Nadu Agricultural University, Coimbatore
CSH 3075	2017	CICR, Sirsa
ARBC 19	2016	University of Agricultural Sciences, Dharwad
F 2381	2016	Punjab Agricultural University, Faridkot
F 2383	2016	Punjab Agricultural University, Faridkot

The data source from Kumar et al. (2020)

Table 3 Indian Council Agricultural Research-Central Institute for Cotton Research (ICAR-CICR) released cotton varieties for HDPS

Name of the cotton varieties/hybrids	Released year	Area of adaptability
Bt Cotton 61	2022	Rainfed condition of the Central zone
Bt Cotton 62		
Bt Cotton 63	2022	Rainfed condition of the Southern zone
Suraksha	2021	Madhya Pradesh, Maharashtra, Gujarat, Tamil Nadu, Karnataka, Andhra Pradesh, South Rajasthan
Subiksha	2018	Tamil Nadu, Karnataka, Andhra Pradesh
PKV- 081 Bt	2017	Maharashtra
Rajat Bt		
CSH 3075	2017	Punjab, Haryana, and Rajasthan
Roja	2011	Rainfed area of the Southern zone
Suraj	2008	Irrigated area of the Southern zone
H Cotton 54	2002	The Central and Southern zone
Anjali	1992	Maharashtra, Gujarat, South Rajasthan

The data source from ICAR- CICR, statistics until September 2023

providing an additional tool for stress management (Fereres et al., 2007). Abdelkhalik et al. (2019) asserted that deficit irrigation encourages a shift from vegetative growth to reproductive growth, leading to improvements in the harvest index, stem diameter, and overall water use efficiency.

Prior to enacting a deficit irrigation plan, it is essential to understand how crops respond to water stress, whether at specific growth stages or across the entire growing season (Kirda et al., 1999). High yielding varieties exhibit greater water stress sensitivity than low-yielding varieties. The most suitable crops or varieties for deficit irrigation are those with a brief growing season and drought tolerance (Stewart et al., 1982). To achieve effective deficit irrigation, it's crucial to consider the soil water retention capability. Plants may experience rapid water stress in sandy soils when subjected to deficit irrigation. In contrast, those in deep soils with fine texture may have sufficient time to adapt to low soil water metric pressure, remaining unaffected by low soil water content.

Consequently, the likelihood of success in deficit irrigation is higher in finely textured soils. Adjustments to agronomic practices may be necessary under deficit irrigation, such as reducing plant population, minimizing fertilizer usage, adopting flexible planting dates, and selecting varieties with shorter growing seasons (English et al., 1990). In addition, the reductions in yield caused by disease, pests, harvest, storage losses, and inadequate fertilizer application are considerably more significant than the decreases anticipated from deficit irrigation.

Optimizing water use is crucial for sustaining agriculture in arid regions with limited irrigation resources. Monitoring soil moisture levels regularly and employing water conservation techniques like drip irrigation and mulching can enhance water efficiency. Timing irrigation to coincide with critical growth stages, such as flowering or fruit set, ensures water is used most effectively. Additionally, selecting drought-tolerant crop varieties and implementing crop rotation practices can help mitigate water stress. By integrating these strategies, farmers can maximize crop yields while conserving precious water resources in arid environments. Deficit irrigation gives the crop less water needed to replenish consumed entirely water (Azad et al., 2016).

Importance of deficit irrigation

Deficit irrigation is a sustainable approach that enhances the effectiveness of irrigation water utilization. The primary goal of deficit irrigation is to improve crop water use efficiency by omitting irrigations that minimally affect yield (Anac et al., 1999). Although there may be a slight reduction in yield, the advantages gained by redirecting the saved water to other crops, which would typically face water scarcity in traditional irrigation, outweigh the minor yield decrease (Kovacs et al., 1999). Conversely, when practised appropriately, deficit irrigation can enhance crop quality. As an illustration, the length and strength of cotton fibre tend to rise under deficit irrigation.

The objective of implementing deficit irrigation techniques is to sustain soil moisture at a level that it does not substantially restrict crop yield while avoiding complete saturation of the soil profile (Chai et al., 2016). The advantage of deficit irrigation approach, compared with other restricted irrigation methods, lies in its ability to supply water throughout the entire crop growth cycle. Deficit irrigation methods deviate from conventional water supply approaches. Hence, it is essential to be aware of the acceptable level of transpiration deficiency that won't lead to a substantial decrease in crop yields (Waheed et al., 1999).

Partial root zone drying

Aside from deficit irrigation, partial root-zone drying (PRD) also presents a viable method for inducing stress tolerance in various agricultural and horticultural crops. Both PRD and deficit irrigation techniques involve manipulating the distribution of irrigation water and maintaining a moisture deficit in the root zone (Sampathkumar et al., 2013). Therefore, deficit irrigation and PRD demand proficient management skills and the implementation of micro-irrigation technology facilitate their application. In the case of PRD, as a portion of the root zone experiences drying, there is an increase in the level of ABA. This rise in ABA signals the leaves to close the stomata in response to water stress, shoot growth reducing, and evaporation from the leaf surface. Notably, the plant continues to grow without adversely affecting crop development, as other roots still access water.

Effect of deficit irrigation in cotton

In general, cotton requires approximately 600 mm of water during its growth period. The concept of deficit irrigation practices for cotton was first introduced in the 1970s (Capra et al., 2008). Effectively implementing deficit irrigation techniques can significantly reduce water usage, and crops such as cotton are suitable for deficit irrigation, whether applied consistently during the entire growth period or at specific stages of development (Kirda et al., 2002).

Due to the challenges posed by scarce water resources and the expenses involved, researchers are investigating ways to improve WUE. This includes adjusting farming systems and adopting enhanced crop management practices, such as deficit irrigation (Dagdelen et al., 2009). A deficit irrigation strategy was employed to reduce deep percolation and investigate the ability of cotton to utilize water from the soil profile and lower groundwater (Cohen et al., 1995).

In cotton, water stress notably decreased plant height (Saimaneera et al., 1997). Du et al. (2008) outlined that less irrigation water significantly reduced the plants' height. Turner et al. (1986) demonstrated that water stress led to a reduction in both leaf area and leaf area index. Drip irrigation had a beneficial effect on the leaf area index of the cotton crop (Yazar et al., 2002). Dagdelen et al. (2009) narrated that irrigation had a notably positive impact on the leaf area index of cotton. Farre et al. (2009) examined the effect of moderate deficit irrigationby extending irrigation intervals during various growth stages. The study revealed a significant reduction in leaf area index at all stages of the imposed water stress.

Under deficit irrigation conditions, the soil water supply function can be fully utilized, enabling the implementation of appropriate deficit irrigation. This supports the transfer of dry matter accumulation to the reproductive organs, resulting in a notable improvement in the number and weight of bolls per plant. Therefore, adjusting irrigation levels by 12% based on water consumption during the cotton growth period does not significantly reduce cotton yield; instead, WUE is increased WUE (Lin et al., 2021).

Irrigation scheduling, whether based on crop developmental stages or deficit irrigation strategies, is a fundamental technique involving precise and timely application of water to the crops. This approach plays a crucial role in water conservation, improving irrigation efficiency and enhancing the sustainability of irrigated agriculture (Lascano et al., 2017). Deficit irrigation entails the deliberate imposition of water stress on crops, with the potential outcome of reduced crop yields (Smith et al., 2002).

Several studies have shown that deficit irrigation practices increase yield and WUE (Wen, 2017). In contrast, certain studies revealed no positive changes or, in some cases, a decrease in these indicators (Zhang et al., 2016). When appropriately handled, deficit irrigation has the potential to maintain profitability while decreasing the use of irrigation water, especially in times of limited water availability for irrigation (Suleiman et al., 2007). This is evident in cases where water conservation is achieved by refraining from applying additional irrigation water when it only brings about a slight increase in crop yield (Kirda et al., 2002).

Deficit irrigation management in cotton

The response of cotton to deficit irrigation is complex due to factors such as its deep root system, capacity to sustain low leaf water potential, and the ability to regulate leaf turgor pressure, known as conditioning osmotically (Grimes et al., 1982). Thomas et al. (1976) conveyed that plants experiencing mild water stress in the vegetative phase exhibited increased resilience to subsequent water deficits, demonstrating an adaptation to the prevailing soil water conditions. Grimes et al. (1977) elucidated both early and late irrigation applications resulted in decreased cotton yields. However, water stress at the vegetative growth phase caused the leaf water potential to fall below a critical mid-day value of −1.6 MPa. In that case, it adversely influenced the final yield (Grimes et al., 1982). This minimizes substantial water deficit stress during critical growth stages while reducing water usage overall. Conversely, if cotton is over-irrigated, it can lead to undesirable excessive vegetative growth, potentially causing a decline in cotton yields (Wanjura et al., 2002). The imposition of water stress reduced plant foliage cover, with the degree of decrease dependent on the severity of the stress and the specific crop stage affected.

Skillful application of deficit irrigation practices can result in considerable water savings in crops like cotton, which is particularly suitable for this approach (Pawar et al., 2018). Despite the adaptability of cotton to restrict or deficit water conditions, it becomes essential to address the challenges posed by diminishing groundwater resources (Detar, 2008; Himanshu et al., 2019; Ale et al., 2020). Exploring alternative methods is crucial to mitigate cotton irrigation demand. One potential strategy involves identifying optimal irrigation termination periods, aiming for efficient use and conservation of irrigation water, all while maximizing crop yields. The decision on when to terminate irrigation is significant, as it directly influences cotton yield and fibre quality, impacted by factors like the timing and quantity of rainfall and irrigation (Ritchie et al., 2009; Snowden et al., 2013; Sharma et al., 2015; Schaefer et al., 2018).

Effect of deficit irrigation on growth attributes of cotton

There was a progressive increase in plant height with an increase in moisture supply through an irrigation water / cumulative pan evaporation (IW/CPE) ratio of 0.8, as reported by Pandyan et al. (1991). This might be due to the favourable soil moisture supply under this treatment promoting enhanced N, P, and K uptake, which reflected increased plant height and leaf area index. The increased leaf area index helped in efficient photosynthesis and their translocation to various parts of the plant, consequently increasing the dry matter production (Bielorai et al., 1978). Irrigation with an IW/CPE ratio of 0.4 suppressed stem elongation and leaf development, resulting in decreased overall biomass production. In contrast, irrigation with IW/CPE ratio of 0.8 contributed to higher dry matter than irrigation with IW/CPE ratio of 0.4.

Similarly, Prakash et al. (2019) found that irrigation with a 1.0 IW/CPE ratio significantly increased plant height (154.47 cm) at 150 days after sowing (DAS), sympodial branches per plant (20.11) at harvest, leaf area index (3.43) at 120 DAS and dry matter production per plant (376.21 g) at 120 DAS, in comparison to irrigation with a 0.6 IW/CPE ratio (136.28 cm, 14.01, 2.58, and 296.19 g, respectively). However, these parameters were similar to those observed with irrigation with a 0.8 IW/CPE ratio (150.33 cm, 17.54, 3.15, and 347.47 g, respectively). These findings align with the conclusions drawn by Srinivasan et al. (2017) and Yang et al. (2015).

According to Ghongane et al. (2009), employing irrigation at a IW/CPE ratio of 0.8 in conjunction with the application of 150% of the recommended fertilizer rates resulted in the highest plant height, the number of monopodial branches per plant, the number of sympodial branches per plant, and dry matter production. On the other hand, Modhvadia et al. (2016) found that a significantly increased plant height (128.59 cm) as well as numbers of monopodial branches per plant (2.53) and sympodial branches per plant (18.30) when the crop was irrigated with an IW/CPE ratio of 1.2. Mahadevappa et al. (2018) demonstrated that irrigation with IW/CPE ratio of 0.8 resulted in markedly increased plant height (97 cm), dry matter at the first picking (220 g per plant) and the number of bolls per plant (19).

Effects of deficit irrigation on yield attributes and yield of cotton

The diverse deficit irrigation strategies introduced natural variability in growing conditions for the cotton crop, influencing yield and its components through various climatic elements. Prakash et al. (2019) found that irrigation at a 1.0 IW/CPE ratio significantly increased the numbers of bolls per plant (55.55), boll weight (4.70 g), and harvest index (0.42). However, these parameters were comparable with irrigation with a 0.8 IW/CPE ratio (52.47 per plant, 4.52 g, and 0.41, respectively). This resulted from a more frequent irrigation schedule, enhancing the availability and absorption of nutrients and their distribution to various plant tissues. These outcomes align with the discoveries of Yang et al. (2015) and Srinivasan et al. (2017). Adare et al. (2016) found that yield and yield-related traits of cotton were significantly influenced by deficit irrigation.

The increase in dry matter production, the number of bolls, boll weight, and seed index resulting from elevated irrigation frequency can be attributed to heightened moisture absorption, thereby leading to increased cell elongation and turgidity, as observed by Dadgale et al. (2014). Furthermore, the intensified irrigation refers to using advanced, precise, and frequent irrigation methods, such as pressurized systems, to optimize water use efficiency. This approach ensures consistent water delivery directly to plant roots, enhancing crop performance, reducing plant stress, and also supports enhanced photosynthesis, enabling the plant to capture more radiant energy. This facilitates greater translocation of photosynthates to the developing bolls, contributing to the production and retention of a higher number of bolls per plant in the later stages of the crop cycle, as indicated by Ahlawat et al. (2010), Bhunia (2007), and Jadhav (2011). Mahadevappa et al. (2023) demonstrated that irrigation with a 0.8 IW/CPE ratio resulted in significantly more bolls per plant (19), which did not differ considerably from the 0.4 IW/CPE ratio but was significantly superior to rainfed cotton. Additionally, Modhvadia et al. (2014) found that a substantially higher number of bolls per plant and boll weight were recorded when the crop was irrigated with an IW/CPE ratio of 1.2.

Ahlawat et al. (2010) noted that irrigating cotton with a 0.6 IW/CPE ratio, equivalent to the 0.4 IW/CPE ratio throughout the crop cycle, resulted in taller plants with an increased boll count (45.4) and higher boll weight (4.34 g). The application of irrigation through the drip at 0.8 CPE showed significantly superior yield attributes in cotton compared with surface irrigation, alternate furrow method, and drip irrigation at 0.4 CPE (Sagarka et al., 2002). The enhanced performance could be attributed to a more frequent and optimal provision of irrigation water. The boosted nutrient availability in the root zone improved nutrient uptake by the plant, along with a more effective distribution of these nutrients in actively growing plant organs. As indicated by the increased leaf area index and dry matter accumulation with elevated irrigation levels, the heightened growth might have contributed to the observed higher yield attributes in cotton under optimum deficit irrigation of a 0.8 IW/CPE ratio, also reported that application of irrigation through drip method at 0.8 CPE recorded significantly higher seed cotton yield than surface, alternate furrow method, and drip irrigation at 0.4 CPE (Sagarka et al., 2002).

The increased number and weight of bolls, facilitated by a higher count of sympodial branches, contributed to the improved seed cotton yield. Leaf growth persisted even during the boll development stage, and heightened dry matter accumulation in the fruiting bodies during the later stages of crop growth further contributed to the increased yield. These findings align with the conclusions reached by Deepa et al. (2016), Amandeep et al. (2015), and Gundlur et al. (2013).

The rise in seed cotton yield can be credited to higher soil moisture availability, achieved through optimum deficit irrigation levels. Zhao et al. (2010) reported that increased root length density of cotton at shallow soil depth with optimum deficit irrigation might have resulted in better uptake of nutrients, contributing to increased dry matter production. Similar results were reported by different studies with deficit irrigation on cotton yield as mentioned in Table 4.

Scheduling irrigation at an IW/CPE ratio of 0.8 resulted in higher yield attributes and overall yield. Shinde et al. (2009) discovered that implementing protective irrigation for cotton, either at a 0.8 IW/CPE ratio or at three crucial growth stages (square formation, flowering, and boll development), proved advantageous in achieving higher seed cotton yield (Srinivasan et al., 2017). Additionally, Bandyopadhyay et al. (2009) observed that the seed cotton yield (ranging from 1 980 to 2 160 kg·ha^{-1}) and lint yield (ranging from 700 to 772 kg·ha^{-1}) under various irrigation treatments (at 0.6, 0.8, and 1.0 IW/CPE ratio) were statistically equivalent to the benefits seen with protective irrigation.

The highest seed yield of cotton was achieved by irrigating the crop at 0.8 IW/CPE ratio (Sivakumar et al., 2021). This could be attributed to the elevation in kapas and lint yield resulting from enhanced growth and yield attributes. The sustained growth of leaves during the boll development stage and increased dry matter accumulation in the fruiting bodies during the later crop growth were identified as factors contributing to the augmented yield (Prakash et al., 2019). Irrigation at 0.8 IW/CPE ratio significantly increased seed cotton yield (Rajasekar et al., 2016). Irrigating cotton with a 0.7 IW/CPE ratio yielded a substantially higher yield (Virdia et al., 2000).

Effect of deficit irrigation on quality parameters of cotton

Water availability and adopting cultural practices can impact the correlation between seed cotton yield and its components, as well as quality parameters (Ariraman et al., 2022). Appropriately deficit irrigation leads to a

Table 4 Yield of cotton under different irrigated conditions

Deficit irrigation (IW/CPE ratio)	Seed cotton yield/(kg·ha^{-1})	References
0.8	2 210	Gundlur et al., 2013
0.8	3 147	Ghongane et al., 2009
0.8	1 700	Mahadevappa et al., 2018
1.2	3 652	Modhvadia et al., 2016
0.6	2 550	Ahlawat et al., 2010
0.8	1 807	Hallikeri et al., 2010
0.7	1 749	Kaswala et al., 2000
0.4	2 305	Patel et al., 2016
Normal Irrigation		
Furrow irrigation	3 630	Cetin et al., 2002
Drip irrigation	4 380	
Sprinkler irrigation	3 380	

significant enhancement in the quality parameters of cotton. This improvement may be attributed to the increased maturity ratio and uniformity index, resulting from better translocation of assimilated photosynthates due to adequate moisture levels during critical growth stages. The enhanced fibre length results from improved fibre growth, strength, and extension processes, primarily influenced by turgor pressure and carbohydrate supply, both of which are higher under optimal moisture conditions. The refinement in fibre fineness, as indicated by micronaire value, is predominantly influenced by irrigation, with higher irrigation conditions correlating to improved cellulose deposition from seeds to lint (Howell et al., 2004).

The findings were consistent with Patel et al. (2016), who assessed the quality of cotton across various parameters such as fibre length, fibre fineness, breaking strength, uniformity ratio, and maturity ratio. Additionally, cotton seed quality was considered, including seed index, oil content, seed cotton quality, and lint percentage. The study outlined that drip irrigation with a 0.8 IW/CPE ratio resulted in the highest oil content (21.14%), fibre length (26.9 mm), and seed index (6.31 g).

According to Hallikeri et al. (2010), optimal cotton fibre quality was achieved through June sowing with a 0.6 IW/CPE ratio, leading to the highest fibre strength, fibre length, maturity ratio, and uniformity ratio in the transitional tract of Dharwad. In a separate study, Ariraman et al. (2022) demonstrated that irrigating cotton varieties (RCH-659 BG II) at a 0.8 IW/CPE ratio resulted in superior fibre quality, uniformity index, maturity ratio, elongation percentage, breaking strength, and micronaire value compared with other moisture levels. Additionally, Sagarka et al. (2002) observed that applying irrigation through the drip method at 0.8 CPE yielded higher oil content, seed and lint index than another. The 80% of pan evaporation resulted in improved quality of cotton.

Comparison performance of cotton under deficit and full irrigation

Reducing irrigation to 80% of full levels demonstrated an increase in WUE compared with full irrigation. The higher proportion of early harvest in deficit irrigation, as opposed to full irrigation, suggested that a significant portion of the yield was obtained during the initial picking, which could be economically advantageous. As a result of deficit irrigation in cotton plant height, boll number and boll weight were effectively managed, leading to the production of shorter plants. This aligns with similar findings from other studies (Pettigrew, 2004; Tang et al., 2005), indicating successful control of vegetative growth. Additionally, deficit irrigation resulted in only marginal yield reduction, offering the potential for saving 20% of irrigation water. Consequently, this approach improved WUE, emphasizing the benefits of adopting deficit irrigation in cotton production (Hussein et al., 2011).

Deficit irrigation under HDPS cotton

In the HDPS system, optimum water should control excessive growth and improve the reproductive structure. Deficit irrigation is a tool to save water without compromising yield. Deficit irrigation was tested in many crops, with water saving up to 40%–50% and yield improvement up to 30%. Deficit irrigation has been specifically studied in cotton across different regions. Reducing irrigation by 20% through deficit irrigation techniques enhanced the cotton yields through improved WUE. Properly managing cotton growth and achieving a balanced ratio between leaf and boll production is achievable through deficit irrigation, as DeTar (2008) highlighted. Moreover, Basal et al. (2009) observed that deficit irrigation, involving a 25% reduction in applied irrigation water, sustained elevated cotton yields and substantially enhanced WUE under HDPS conditions.

High density planting in cotton can be compatible with deficit irrigation under certain conditions. Choosing drought-tolerant cotton varieties and managing soil moisture levels effectively are crucial for success. Precise irrigation scheduling and monitoring of soil conditions help mitigate the risks associated with deficit irrigation. However, careful consideration of climate factors and implementation of risk management strategies are necessary to optimize yield and quality of cotton in such irrigation systems.

Economic benefits of HDPS and traditional planting pattern

The overall expense of farming has exhibited a direct correlation with farm size, mainly due to increased input utilization on larger farms. Labour costs represent the most significant portion of total expenditures in cultivation, followed by expenses on seeds and fertilizers. Notably, the application of plant protection chemicals was minimal in HDPS cotton compared with non-HDPS cotton. Cultivating HDPS cotton has yielded higher gross and net returns. Moreover, these returns tend to rise with farm size expansion, notably higher on larger farms than on small and marginal ones. Net profits were notably greater in HDPS cotton than non-HDPS cotton due to the substantial gross returns observed in HDPS cotton cultivation (Sam et al., 2023).

Additionally, varieties such as TCH 1822 and CO 17 with a fertilizer application of 125% recommended dose of nitrogen (The application amounts of N, P, and K were 100, 50, and 50 kg·ha^{-1}, respectively) have enhanced economic benefits, including total income, net income, and benefit-cost ratio. It can be inferred from the research that TCH 1822 and CO 17 varieties are highly suitable for HDPS, especially when N, P, and K fertilizer dosages are 100, 50, and 50 kg.ha^{-1}, resulting in increased seed cotton yield, improved economic returns, and superior quality parameters, thus facilitating sustainable cotton production (Veeraputhiran et al., 2021).

Future perspectives

- In the future, continued research is essential for further exploring develop deeper into the dynamics of high density planting system and deficit irrigation in cotton cultivation. Further investigations should focus on assessing these practices' long-term sustainability and resilience under varying environmental conditions, such as different soil types, climates, and water availability scenarios.
- Additionally, there is a need to explore the potential synergistic effects of integrating high density planting with other innovative agricultural practices, such as precision farming techniques, nano-fertilizers, and drone applications.
- Moreover, research efforts should aim to develop advanced modeling approaches and decision support tools tailored specifically for optimizing cotton production using high-density planting and deficit irrigation, thereby facilitating informed decision-making for growers and policymakers alike.
- Future studies by addressing these aspects may enhance cotton farming system efficiency, productivity, and environmental sustainability.

Conclusions

High density planting system is considered the upcoming technology with the potential to fortify India's cotton economy. Widely proven in various countries, this technology is known for boosting productivity and mitigating risks in cotton farming. HDPS, combined with appropriate agronomic techniques, plant protection management, and improved genotypes, offers a promising approach to overcoming stagnant yields in predominantly rainfed cotton-growing regions. To address the growing demand for fibre amidst the declining availability of freshwater for irrigation, cotton cultivation must achieve higher yields with less water. HDPS under deficit irrigation optimizes water usage and land efficiency, maintaining or enhancing crop yields while conserving wter and other resources. This approach promotes economic sustainability by reducing input costs and mitigating production risks. However, effective management is crucial to address challenges like precise irrigation scheduling. Overall, HDPS with deficit irrigation offers a promising strategy for sustainable agriculture in water scarce regions. Adequate funding support has to be provided worldwide to intensify research and raise awareness about the high density planting system along with deficit irrigation in cotton for all regions among small holding farmers to make HDPS and deficit irrigation a tool for improving cotton productivity.

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