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REVIEW ARTICLE

SWOT analysis of cotton in India

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Abstract

Cotton production plays an important role in India's farming and industry, supporting the country's economy, jobs and textile exports. This review looks at the Strengths, Weaknesses, Opportunities and Threats (SWOT) of cotton farming in India. Some key strength includes suitable weather, large areas of farmland and help from research centres like CICR (Central Institute for Cotton Research) and ICAR (Indian Council of Agricultural Research). Government support through subsidies and minimum price guarantees also adds value. On the other hand, there are several weaknesses such as too much reliance on rain, insufficient irrigation, low crop yields, pest problems, high costs for seeds and fertilizers, small land sizes and limited use of machines. These problems reduce the quality and quantity of cotton thereby makes it harder to compete globally. Still, there are many opportunities to improve. Using better seeds, modern farming tools and smart practices like precision farming can boost production. There is also growing demand for organic and eco-friendly cotton, which India can take advantage of adding value through better processing, branding amidst government initiatives that augment farmers' earnings. However, there are threats that need attention *viz*; climatic changes, water shortages, vermin pests and price swings in the market that could impact farmers. The rise of synthetic fibres and unclear policies also bring challenges. Environmental concerns and the need for standards like Fair Trade and GOTS (Global Organic Textile Standard) are becoming more important. To face these issues, the focus should be on saving water, reducing waste and employing better technological advancements. In the end, the cotton sector in India needs a careful mix of modern tools, strong policies and eco-friendly steps to stay strong and succeed in the future. This review underscores the need for a balanced approach integrating technological advancements, policy support and sustainable practices to navigate challenges and leverage opportunities that ensuring the long-term viability and competitiveness of India's cotton industry.

Keywords: climate resilience; cotton production; Indian textile industry; organic cotton; sustainable agriculture; SWOT analysis

Introduction

Cotton, often referred to as "white gold," plays a vital role in shaping Indian agricultural, industrial and economic landscape. Its cultivation is deeply connected to the country's agricultural history and spanning diverse agro-climatic zones, making India the largest global producer of cotton (1). Cotton cultivation in India covering approximately 5 % of the nation's arable land, which equates to 122.38 lakh hectares and its farming is particularly concentrated in Maharashtra, Gujarat and Telangana. These three states account for nearly 70 % of the total cultivation area and production, underscoring their significance in this sector. According to Committee on Cotton Production and Consumption (COCPC), (2023 - 2024) Maharashtra leads with 4.23 million hectares under cotton cultivation, followed by Gujarat with 2.68 million hectares in the central zone and Telangana with 1.91 million hectares in the southern zone. Other states, including Andhra Pradesh, Punjab, Karnataka and Rajasthan also contribute substantially, showcasing the extensive reach of cotton cultivation across India.

Economically, cotton serves as the backbone of Indian textile industry which is the largest industrial sector within the country. This sector contributes significantly to the GDP, export earnings and employment generation. Cotton alone accounts for approximately 30% of the agricultural GDP and over 4 % of the national GDP. In the 2021-22 period, India's cotton exports peaked approximately around ₹ 1.37 lakh crores, highlighting the crop's significant role in commerce and revenue generation. But, in 2022 - 23, export value declined to around ₹ 88000 crores due to global price shifts. Exports recovered in 2023 - 24, reaching nearly ₹ 98000 crores with rising global demand. Raw cotton exports increased by 80 %, touching 28 lakh bales during the 2023 - 24 crop year (2). Export revenues from cotton exceed ₹ 45000 crores annually, solidifying India's position as a leading exporter of raw cotton and yarn. The India-Australia ECTA (Economic Cooperation and Trade Agreement) eased tariffs and improving the cotton market access. A trade agreement with Oman is in progress, aiming to boost exports to the Middle East (3). Employment generated by the cotton

industry is equally impressive, directly supporting around 6 million farmers and indirectly sustaining the livelihoods of an additional 40-50 million individuals involved in processing, manufacturing and trade (4). From a production perspective, Gujarat leads with 9.06 million bales, followed by Maharashtra in the central zone and Telangana in the southern zone with 5.08 million bales. As a cornerstone of India's economy, cotton fosters rural livelihoods, strengthens trade and contributes to poverty alleviation.

Despite its immense potential, the cotton sector faces several challenges that threaten its growth and sustainability. Agricultural issues such as dependency on unpredictable monsoon, inconsistent rains and limited irrigation infrastructure results in low productivity and crop failures (5). India's average cotton yield remains lower than global standards due to regional disparities in farming practices, soil fertility and rainfall distribution (6) whereas, Gujarat exhibits the highest productivity at 574.06 kg·ha^{-1}, followed by Odisha in the central zone. Telangana demonstrates superior productivity in the southern zone with 475.03 kg·ha^{-1}, while Punjab leads the northern zone with an output of 499.67 kg·ha^{-1}. Economic constraints, including rising input costs for seeds, fertilizers and pesticides place financial burdens on small and marginal farmers. The widespread division of land into smaller plots makes cotton farming less efficient and prevent farmers from the benefits of large-scale production (7).

Climate change and environmental degradation were additional threats to cotton farming. Rising temperatures, erratic rainfall patterns and depleting water resources have adversely affected yields and quality. Excessive groundwater usage, particularly in Maharashtra and Gujarat has reduced cropping intensity and forcing farmers to adopt less water-intensive crops (8). Furthermore, the industry's reliance on chemical pesticides the most pesticide-intensive crop and fertilizers has led to soil and water pollution, amplifying ecological concerns (9). These challenges underscore the urgent need for sustainable and adaptive practices in cotton production.

The increasing global demand for organic and sustainable cotton offers India a great opportunity to boost its position in international markets. India is already the largest producer of organic cotton, contributing nearly 70 % of the global supply (10). Programs like the Better Cotton Initiative (BCI) promote sustainable farming practices ensuring environmental and economic benefits for farmers. Technological advancements such as precision agriculture, genetically modified (GM) seeds and pest-resistant cotton varieties further promise to improve productivity while reducing environmental impact (11). However, India's cotton productivity measured as yield per hectare or GDP per hour worked remains comparatively low. For instance, India produces around 450 kg of lint per hectare, whereas China and the United States average over 1500 kg/ha and 950 kg/ha respectively. This disparity underscores the need for continued investment in agritech and infrastructure to close the gap. This review article aims to provide a comprehensive analysis of India's cotton sector exploring its strengths, weaknesses, opportunities and threats. It evaluates the economic significance of cotton, the supportive ecosystem facilitated by government policies and research institutions along with the sector's role in global trade. The article also highlights the environmental and social dimensions of cotton farming toward sustainability. Strategies such as circular economy practices, efficient water management and the adoption of voluntary sustainability certifications like BCI are discussed as pathways to ensure long-term growth and resilience.

Status of cotton cultivation in India

Cotton plays a key role in India's agriculture and industry, being a major fibre crop. Known as the "King of Fibre Crops" and "White Gold," it holds great economic importance. About 67 % of India's cotton grows in rain-fed areas, while the rest is grown on irrigated lands. Cotton farming in India is spread across three different regions, located between 8°-32°N latitude and 70°-80°E longitude. These regions have varying conditions such as elevations from sea level to 950 m, annual rainfall between 250 and 1500 mm and a wide variety of soils differing in colour, texture and nutrients.

Fig. 1.

The Northern region faces tough weather with high temperatures of 40-45 °C and dry conditions. Cotton in this area is grown with irrigation on alluvial soils, but water shortages have led to a 20 % drop in cotton farming in Rajasthan in recent years. The central region, covering about 65 % of the total cotton-growing area, relies mostly on rain-fed farming. Maharashtra alone accounts for nearly 30 % of this area. While irrigation is limited, the region benefits from good temperatures, plenty of sunshine during key growth stages and dry weather from October to February which helps boost yields. Here, cotton is grown in black soils. In the southern region, conditions are suitable for growing extra-long staple cotton, but high-quality production depends on irrigation. Cotton in this region is cultivated on vertisols and red soils (12).

In India, Maharashtra leads in cotton cultivation area with 4.23 million hectares, followed by Gujarat in the Central zone with 2.68 million hectares. Telangana has the highest cultivation area in the southern zone at 1.91 million hectares, followed by Karnataka with 0.7 million hectares. Rajasthan cultivates the most cotton in the northern zone with 1.0 million hectares followed by Haryana with 0.5 million hectares during 2023-2024 (Fig. 1).

From a production standpoint, Gujarat leads in India with 9.06 million bales, followed by Maharashtra in the central zone. Telangana has the highest production in the southern zone at 5.08 million bales, followed by Karnataka. Rajasthan records higher output in the northern zone with 2.62 million bales, followed by Haryana during 2023-2024 (Fig. 2).

Regarding productivity, Gujarat leads with 574.06 kg/ha, followed by Odisha in the central zone. Telangana exhibits higher productivity in the southern zone at 475.03 kg·ha^{-1}, followed by Karnataka. In the northern zone, Punjab records higher productivity at 499.67 kg·ha^{-1}, followed by Rajasthan during 2023–2024 (Fig. 3).

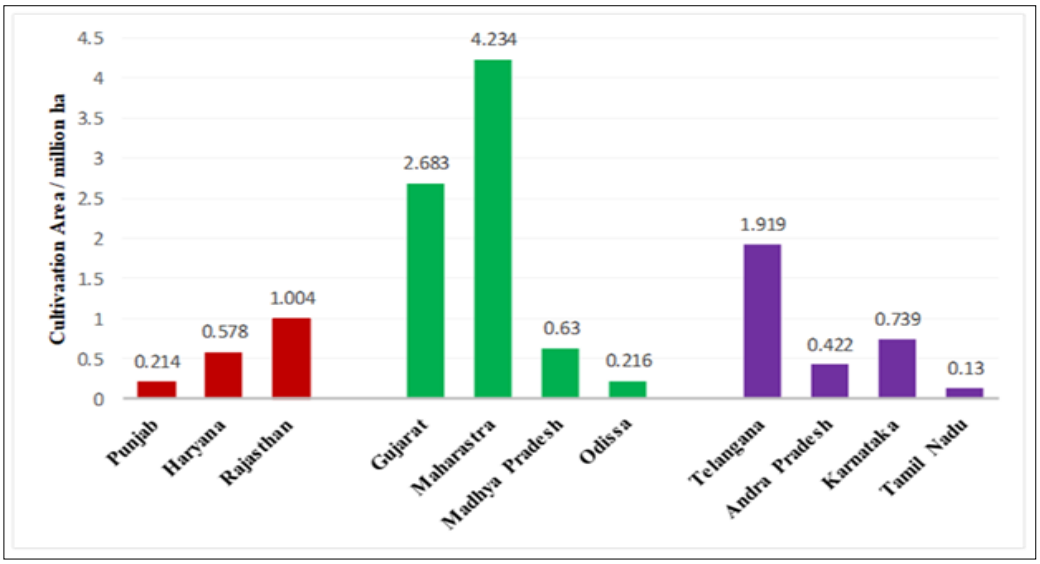

Fig. 1. Cotton cultivated areas in different zones of India in 2023-2024. (Data from COCPC)

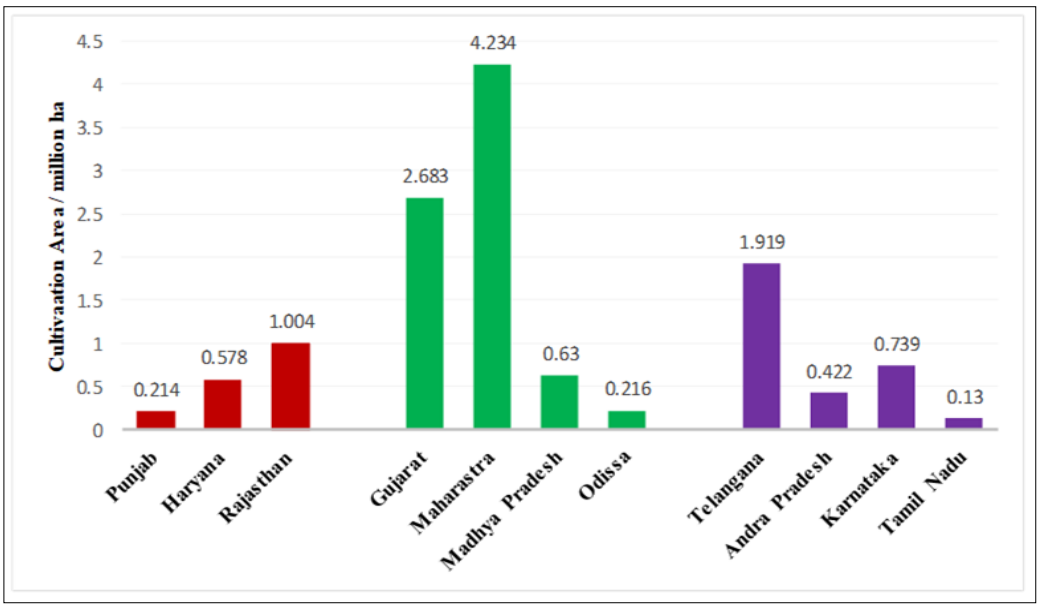

Fig. 2. Cotton production in different zones of India in 2023-2024. (Data from COCPC)

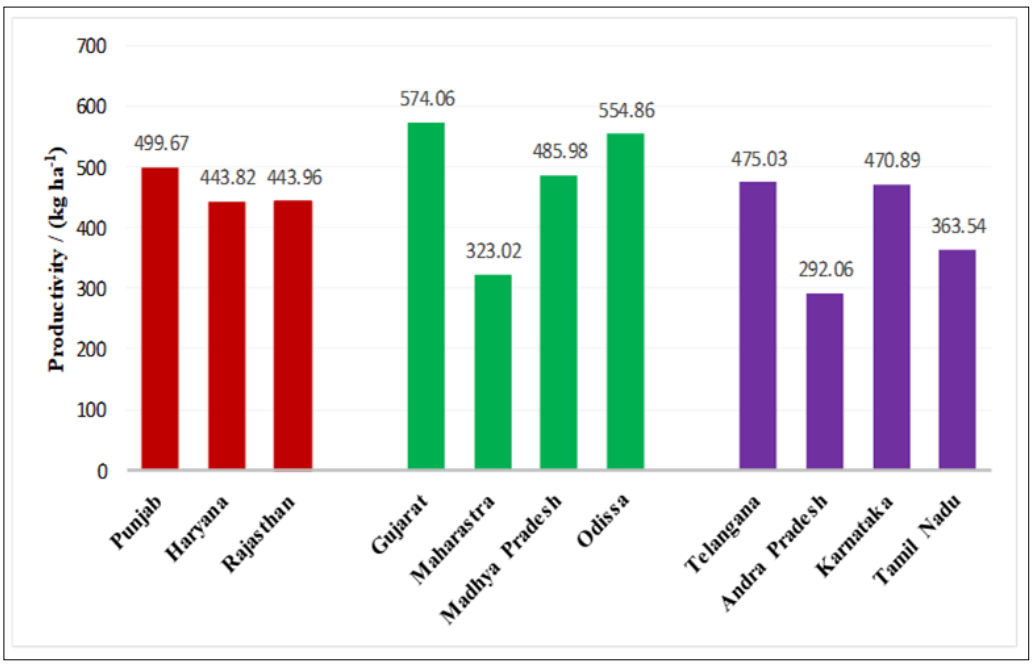

Fig. 3. Productivity of cotton in different zones of India in 2023-2024. (Data from COCPC)

Strengths of cotton production in India

Agronomic Advantages

Suitable climatic conditions for cotton cultivation: Cotton cultivation in India thrives under diverse climatic conditions across its northern, southern and central regions with temperature, rainfall, sunlight, humidity and soil playing crucial roles in its growth and productivity. In northern India, like Punjab benefits from optimal temperatures ranging from 25 to 32 °C, along with extended sunshine hours exceeding 9 ° C daily, which promote plant health and effective pest management. Accumulated Growing Degree Days (AGDD) in North India, particularly in Punjab and Haryana reach a high of 24.41 °C day indicating excellent growth potential (13). Low relative humidity during critical growth phases minimizes pest outbreaks, while balanced water availability through rainfall and irrigation supports robust development. However, rising temperatures and shorter thermal growing periods create challenges, necessitating adaptive strategies to mitigate projected yield declines of up to 477 kg/ha under severe climate scenarios (14, 15).

Central India, encompassing regions like Vidarbha and Maharashtra, also provides favourable conditions due to its moderate AGDD of 2,276.8 °C day and the presence of black soils (*Vertic Haplustepts*) with excellent moisture retention properties (16). While erratic precipitation poses challenges, the annual rainfall of 500 -1200 mm supports healthy growth, especially with strategic irrigation during critical phases such as flowering and boll formation (15). Soil management practices including organic manure application and crop diversification enhance fertility and resilience thereby ensuring sustainable cotton cultivation (17). These favourable climatic and soil characteristics make central India highly suitable for cotton cultivation underscoring its adaptability and potential for sustainability.

South India offers highly favourable conditions for cotton farming, with a stable temperature range of 20 to 30 °C that supports healthy growth and productivity. Maximum air temperatures significantly influence flower and boll production while higher minimum relative humidity enhances flower and boll formation, ensuring better yields (18). The region's reliance on the northeast monsoon provides essential moisture for rainfed cultivation, complemented by the moisture-retentive properties of Tamil Nadu's black soil, which is particularly suitable for cotton farming. Diverse climatic zones, such as the southern zone (Tirunelveli, Ramanathapuram) and the central zone (Coimbatore, Tiruchirapalli, Perambalur) allows cultivation of various cotton varieties tailored to local conditions (18), making south India a promising area for sustainable and productive cotton farming.

Across India, cotton demonstrates remarkable adaptability to varying climatic conditions, thriving in temperatures between 25 - 30 °C and tolerating saline soils within specific thresholds (18). While cotton is drought-resistant, supplemental irrigation and optimal rainfall during early growth stages significantly enhance productivity. Short sunshine duration and higher relative humidity positively influence flower and boll formation, while tailored practices in coastal saline-alkaline regions mitigate challenges like rotted bolls and improve fibre quality (17).

These strengths position cotton as a versatile crop capable of thriving in diverse environments, offering substantial potential for sustainable production in the face of shifting climatic patterns.

Large arable land area dedicated to cotton farming: Cotton cultivation in India occupies about 5 % of the country's arable land, which is approximately 122.3 lakh hectares. Major contributors to this area are Maharashtra, Gujarat and Telangana accounting for around 70.4 % of the total cotton-growing area and 62.6 % of production (19). Other significant contributors include states like Andhra Pradesh, Madhya Pradesh, Punjab, Haryana, Karnataka, Rajasthan, Tamil Nadu and Odisha (1). Maharashtra leads the country with 4.23 million hectares under cotton cultivation, followed by Gujarat in the central zone. Telangana tops the southern zone with 1.91 million hectares, followed by Karnataka. In the northern zone, Rajasthan has the highest cultivation area with 1.0 million hectares, followed by Haryana with 0.57 million hectares during 2023 - 2024.

Cotton's resilience and tolerance to salinity renders it a suitable crop for challenging environments, including salt-affected soils and wastelands. India has an estimated 6.73 million hectares of salt-affected land which offers a significant opportunity to expand cotton cultivation in these areas (20). Utilizing these underutilized lands can boost cotton production whilst restoring soil vitality and improving the livelihoods of farmers. Research shows that salt-tolerant cotton varieties combined with soil management techniques such as gypsum application and the use of organic amendments can enhance yields in saline soils (21). By adopting these practices, India can optimize the use of degraded lands, strengthen its position as a global leader in cotton production and address land degradation challenges effectively.

Economic significance

Contribution to GDP and employment: Cotton production plays a crucial role in India's economy, significantly contributing to both GDP and employment. As a primary raw material for the textile industry, cotton is integral to the livelihoods of millions and the overall economic framework of the country. It accounts for approximately 4 % of India's GDP (2) and about 30 % of the agricultural GDP (22), with export earnings exceeding Rs. 45000 crores annually (3). The compound growth rate of cotton production from 1951 to 2020 was a notable 3.31 % (23) and India has emerged as the leading global cotton producer surpassing China in 2021 (24). The textile industry which is heavily reliant on cotton is the largest industrial segment in India, generating substantial export earnings and contributing significantly to the national economy. In terms of employment, cotton cultivation and its associated industries provide direct employment to around 6 million farmers and indirectly support approximately 40-50 million jobs in trade and processing (25). The textile sector employs over 4.5 crore people (26) while the cotton sector alone generates direct and indirect employment for over 8 million individuals (3). The introduction of Bt. cotton technology has further

enhanced productivity and stability, supporting job creation across the sector (24, 27).

Backbone of India's textile industry: The economic significance of cotton production in India's textile industry is profound, serving as the primary raw material for this sector and directly impacting employment, trade and agricultural practices. Cotton farming supports around 6 million farmers and employs approximately 40 - 50 million individuals in related processing and manufacturing activities, emphasizing its critical role in job creation and poverty alleviation (25). Accounting for about 59 % of the raw materials used in the textile industry, cotton sustains this labour-intensive sector amplifying household incomes through significant backward linkages and multiplier effects (28, 26). The Cotton Corporation of India plays a pivotal role in stabilizing prices and ensuring fair compensation for farmers, which is essential for maintaining production levels and fostering economic stability (29). Additionally, the sector's performance is closely tied to global market dynamics, influencing trade policies and contributing to economic growth (30). Mechanization and modern agronomic practices are increasingly being adopted to improve yields, address labour shortages and enhance efficiency, ensuring sustainability and competitiveness in both domestic and global markets (28, 29).

Supportive ecosystem

Role of research institute in improving yield

Research institutes in India have played a pivotal role in enhancing cotton yield through innovative approaches and advancements in genetic improvements, agronomic practices and transgenic technologies. Genetic research has been instrumental, with genome-wide association studies identifying 205 SNPs and 134 QTLs linked to fibre yield traits in Indian upland cotton, alongside the discovery of 39 novel QTLs and 40 candidate genes, forming a strong foundation for future breeding programs (24). Agronomic advancements, driven by the CICR and the All India Coordinated Cotton Improvement Project (AICCIP) have standardized practices, improved nutrient and water management and facilitated cotton-wheat double cropping across 14 lakh hectares, significantly boosting productivity and reducing costs. Moreover, the introduction of Bt. cotton has revolutionized Indian cotton farming, leading to an 80 % augmentation in yield and a substantial reduction in pesticide use, helping the farmers effectively to combat pest losses and elevating India to a leading position in global cotton production (31).

Availability of government subsidies and Minimum Support Prices (MSP).

Government subsidies and MSP are pivotal in creating a supportive ecosystem for cotton production in India, aiming to stabilize farmers' incomes and encourage production. Subsidy schemes introduced by the Indian government address high input costs and technological obsolescence, playing a crucial role in enhancing cotton mill usage and supporting the overall growth of the cotton industry (32). MSP serves as a vital safety net, ensuring farmers receive a minimum price for their cotton, particularly during periods of price volatility and has shown growth trends over time (33). While low awareness of MSP reported at only 20 % among cotton farmers limits its reach, it remains an essential policy tool for mitigating distress sales and providing financial stability (34). Despite challenges like delays in payments, insufficient procurement centres and market price fluctuations often exceeding MSP, these interventions form the backbone of support for cotton farmers. Strengthening awareness and addressing systemic inefficiencies can further enhance the impact of these policies on cotton producers.

Export competitiveness

India plays a pivotal role as a major exporter of raw cotton and cotton yarn, significantly impacting both its economy and the global textile market. The country's cotton production has witnessed substantial growth with a production growth rate of 3.5 % annually and productivity increasing by 2.75 % per annum driven by effective government policies (35). Institutions like the Cotton Corporation of India (CCI) ensure fair compensation for farmers, stabilize prices and promote exports (29). Cotton exports contribute significantly to bridging trade deficits with yield and export prices positively influencing economic performance (36). The sector supports over 4.5 crore jobs, showcasing strong backward linkages to household income and production activities (26). Government initiatives aimed at developing high-yielding cotton varieties and providing robust farmer support has further enhanced India's export capabilities. Collaborative efforts among stakeholders are instrumental in addressing challenges such as price volatility and ensuring sustainability, strengthening India's position in the global cotton market (29). These strengths underscore the pivotal role of cotton exports in driving economic growth and sustaining India's competitiveness on the global stage.

Weaknesses of cotton production in India

Agricultural challenges

Dependence on monsoons and lack of irrigation infrastructure: The weaknesses of cotton production in India are largely influenced by dependence on the monsoons and inadequate irrigation infrastructure which lead to low productivity and greater vulnerability to climate variability, causing severe economic consequences for farmers. Cotton is mostly cultivated during the monsoon season with around 60 % of the crop grown under rainfed conditions (5). Variability in monsoon rainfall affects both irrigation demand and crop yield, significantly impacting both wet and dry seasons (37). This dependence on unpredictable monsoon patterns increases the risk of crop failure particularly in drought-prone areas like Marathwada, where farmers often face severe financial difficulties (38). Furthermore, only 40 % of cotton cultivation is irrigated, leaving a large portion of the crop vulnerable to water scarcity (5). Inefficient irrigation management results in suboptimal water usage, especially during critical stages of cotton growth (39). The lack of a reliable irrigation system further limits farmers' ability to cope with drought conditions, contributing to a rise in farmer suicides in affected regions (38). Despite these challenges, some researchers argue that the use of alternative cotton varieties and improved irrigation practices could help increase resilience and productivity, offering potential solutions to the ongoing issues faced by cotton farmers (40).

Low productivity compared to global standards: Cotton production in India faces challenges in terms of low productivity compared to global standards. Although growth rates in cotton production and yield have improved over time, there are still factors that prevent India from being more competitive in the global cotton market. From 1951 to 2020, India's cotton production grew at an average rate of 3.31 %, with yields increasing at 2.6 % (23). Between 1980 and 2019, production grew at 4.74 %, while productivity grew at 3.17 % (41). However, there are significant regional differences in cotton yield. States like Punjab, Haryana and Gujarat show high yield efficiency while other states like Maharashtra and Karnataka face challenges such as uneven rainfall and poor soil quality leading to lower productivity (6). The coefficient of variation for cotton yield in India stands at 25.83 % showing instability in production (23). To improve cotton production, technological advancements and government policies are essential. These measures should focus on promoting high-yield varieties and shifting cultivation to more productive regions (6). Despite progress, India's cotton productivity remains below its potential necessitating targeted interventions to enhance it. At the same time, the environmental sustainability of cotton farming particularly with the use of Bt. cotton and organic practices, presents an opportunity for growth while mitigating ecological concerns (41).

India's cotton sector also faces challenges in mechanization and technological adoption. Cotton farming in India has low levels of mechanization, which reduces efficiency and productivity (28). However, there is significant potential for improvement through mechanization, such as using cotton pickers and precision planters which can boost yields and reduce labour costs (28). High-density planting systems (HDPS) could also help by optimizing plant density and resource use thereby improving yields (28). Another major challenge is rainfed farming, which leads to variable yields due to unpredictable monsoon patterns (40). Additionally, the emergence of pest resistance in Bt. cotton has resulted in increased pesticide use, complicating cotton production and affecting yields (40). Regional differences also remain, with states like Punjab and Gujarat having higher yields due to better soil fertility and farming practices while Maharashtra and Karnataka experience lower productivity (6). To address these issues, government initiatives should focus on promoting cotton farming in regions with higher yield potential and supporting sustainable farming practices to improve productivity across the country (6).

Economic constraints

High input costs for seeds, fertilizers and pesticides: The economic challenges in cotton production in India are largely driven by high input costs for seeds, fertilizers and pesticides which significantly affect farmers' profitability and sustainability. The introduction of hybrid Bt. cotton has led to a substantial increase in seed costs with farmers experiencing a 2.5-to-3-fold rise in production expenses without proportional improvements in yield. Bt. cotton initially boosted yields and reduced pesticide use but over time, pests like bollworms have developed resistance and reducing its effectiveness. This highlights the need for next-generation transgenic solutions such as gene stacking or CRISPR-based traits to maintain long-term pest control and crop sustainability (42). Fertilizers and pesticides also add to the burden as their rising prices make them unaffordable for many farmers impacting both small and large-scale producers (43). Alongside these input costs, labour expenses are another major constraint. Increasing wages and the reliance on labour-intensive farming methods further strain the financial resources of cotton growers (43).

Market-related issues also play a major role in the economic difficulties faced by cotton farmers. Price volatility and uncertain market conditions make it challenging to predict profits and manage costs effectively (44). Many farmers lack access to regulated markets which reduces their chances of securing fair prices for their produce leading to financial instability. Even in cases of contract farming, high input costs and difficulties in meeting quality standards often negate the benefits of these arrangements (44).

A lack of knowledge about improved agricultural practices and insufficient training programs worsens the challenges of managing high input costs effectively (45). While the introduction of Bt. cotton has shown potential to reduce pesticide use and improve yields, the persistent issues of high seed costs and market access remain critical barriers to realizing its full benefits. Some researchers suggest that transitioning to non-GM high-density short-season cotton varieties could help reduce costs and enhance productivity offering a possible solution to alleviate these financial challenges (42).

Fragmented landholdings and limited access to credit: The economic challenges faced by cotton farmers in India are deeply influenced by fragmented landholdings and limited access to credit, which together hinder productivity and financial stability. Fragmented landholdings reduce efficiency as smaller plots are harder to manage and often lead to higher travel times and supervision challenges (7). While some believe that smaller farms allow farmers to diversify risks, the inefficiencies caused by fragmentation such as limited economies of scale and reliance on family labour often outweigh these potential benefits (46).

Limited access to institutional credit adds to the problem by restricting farmers' ability to invest in essential inputs like seeds, fertilizers and modern equipment. Without affordable credit, many farmers are forced to rely on high-interest loans from informal sources, trapping them in a cycle of debt that negatively impacts their financial stability and, in some cases, results in severe social consequences such as suicides. Access to institutional credit has been shown to significantly improve crop productivity, emphasizing the importance of providing financial support to small and marginal farmers (47).

In addition to these challenges, high input costs for seeds, fertilizers and pesticides along with fluctuating market prices further strain the profitability of cotton farming any farmers also lack timely access to technical advice and market information, which limits their ability to optimize production and cope with changing market conditions (4). Addressing these interconnected issues is

essential for improving the efficiency and sustainability of cotton farming in India.

Technical gaps

Adoption of mechanization and modern farming techniques: Adoption of mechanization and modern farming techniques in cotton production in India is largely due to economic and technical challenges that significantly affect productivity and profitability. High initial costs of purchasing machinery such as cotton pickers and planters remain a major barrier for smallholder farmers who often cannot afford these investments (28). Limited access to institutional credit further restricts farmers from financing mechanization leaving them dependent on traditional labour-intensive methods that increase costs and reduce efficiency (48). Additionally, farmers often perceive mechanization as a costly option with uncertain immediate benefits discouraging its adoption (49).

Another significant hurdle is the lack of knowledge and awareness among farmers about the advantages of mechanization and modern farming practices. Many farmers have insufficient training and limited understanding of how to use advanced machinery effectively which leads to underutilization (48). Studies highlight that only a fraction of farmers are familiar with techniques like micro-irrigation, emphasizing the need for training programs to bridge this gap and promote technology adoption (49).

Labour shortages and the high costs of manual harvesting further underscore the importance of mechanization. Traditional handpicking methods are labour-intensive and inefficient, while mechanized harvesting could reduce labour costs and improve yields. However, resource limitations such as small landholdings and lack of access to machinery make it difficult for farmers to adopt mechanized solutions. Cooperative farming models, where resources and machinery are shared among farmers could help address these constraints and encourage mechanization (50).

Despite these challenges, some argue that traditional farming methods while less efficient may offer sustainability benefits particularly for small - scale farmers reliant on manual labour and local practices. However, addressing the barriers of high costs, knowledge gaps and limited resources remains critical for enabling the broader adoption of mechanization and modern techniques in cotton farming, ultimately improving productivity and reducing labour dependency.

Pest infestations and resistance issues: Pest infestation and resistance issues in cotton production in India pose significant challenges to agricultural productivity and economic stability. The widespread adoption of Bt. cotton, which accounts for 93 % of the cotton-growing area in the country was initially successful in reducing pest-related losses. However, overreliance on this technology has led to increased resistance among pests particularly the pink bollworm which has developed resistance to Cry1Ac and Cry2Ab toxins due to extensive cultivation practices and year-round planting of long-duration Bt. hybrids (51, 52). Resistance has also been observed in sucking pests like leafhoppers and aphids, with neonicotinoid resistance reported to be as high as 2000-fold (53). These developments have complicated pest management and highlight the limitations of current practices.

The inadequacy of existing pest management strategies including improper pesticide application and lack of farmer training has worsened the problem (54). This calls for the adoption of community-based integrated pest management (IPM) approaches which include pheromone technology, crop rotation and better education on pesticide use (55). Furthermore, biotechnological innovations such as RNA interference and CRISPR gene editing show promise in addressing pest resistance effectively (51). Research into pest-resistant cotton genotypes also offers potential solutions for breeding programs aimed at reducing pest impacts (56).

Additionally, promoting eco-friendly practices including the use of biopesticides can reduce reliance on chemical pesticides and slow the development of resistance (56). Despite these advancements, addressing pest resistance in cotton production requires a more sustainable and integrated approach combining innovative technologies with traditional pest management strategies to ensure long-term agricultural productivity and economic stability.

Quality concerns

The lack of uniformity in cotton quality presents a major challenge for India's high-end markets, limiting its competitiveness in the global textile industry. Although India is the second-largest cotton producer its cotton often suffers from quality inconsistencies leading to price discounts on international markets. This issue arises from genetic, environmental and technological factors. For instance, genetic factors like seed selection and breeding practices often emphasize higher yields over fibre quality, creating a trade-off that affects uniformity (57, 58). Additionally, different cotton varieties across regions exhibit varying fibre characteristics such as strength and length further contributing to inconsistencies. Environmental factors like climatic variability, including fluctuations in temperature and weather conditions adversely affect fibre quality, resulting in variations in strength and micronaire levels. Moreover, cultural practices such as irrigation management and fertilization techniques play a crucial role in determining fibre uniformity (59).

Technological challenges worsen these issues as inadequate harvesting and processing methods often compromise cotton quality (57). Furthermore, the existing market pricing mechanisms fail to account for essential attributes like fibre strength and uniformity, putting producers at a disadvantage (60). The introduction of High-Volume Instrument (HVI) measurements has revealed significant disparities in quality assessment with Indian cotton's quality attributes accounting for only 50% of price variation compared to 75 % in the U.S. (61). Contamination and the mixing of different cotton types during cultivation further aggravate quality inconsistencies (62).

On other side, molecular engineering and biotechnology offer promising solutions, with recent studies identifying genes linked to fibre quality that could improve

cotton uniformity and strength (63). Enhanced measurement techniques for fibre length uniformity and targeted breeding programs could help address these issues, creating opportunities to optimize cotton for high-end markets (64). However, addressing entrenched practices and systemic issues in production requires a comprehensive approach to improve quality and sustain global competitiveness.

Opportunities for growth

Technological Innovations

Adoption of precision agriculture and genetically modified seeds: The adoption of precision agriculture and genetically modified (GM) seeds, especially Bt. cotton has brought significant changes to cotton production in India by addressing challenges like low yields, labour shortages and pest management. Precision agriculture technologies optimize the use of resources such as land, water, fertilizers and pesticides improving productivity while reducing costs (11). Tools like remote sensing and data analysis help farmers monitor crop health and soil conditions, allowing for better decision-making and increased yields. Mechanized tools such as seed-cum-fertilizer drills and cotton pickers, further enhance efficiency by reducing labour dependency and operational costs (28). However, the adoption of precision agriculture remains limited due to high costs, a lack of awareness and insufficient infrastructure especially among smallholder farmers (11).

Similarly, GM seeds like Bt. cotton have contributed to higher yields and reduced pesticide use, improving profitability for many farmers particularly in northern India (65). Bt. cotton's pest resistance has lowered input costs and made crops more resilient. Despite these benefits, challenges have emerged over time. Yield and profit growth have stagnated in some regions, raising concerns about the long-term viability of Bt. cotton (66). Smallholder farmers often face additional pressures such as increased vulnerability to market fluctuations and pest resistance which can undermine their ability to sustain production (67). Moreover, the use of GM seeds has raised environmental concerns including potential impacts on soil health and biodiversity, highlighting the need for ongoing crop improvement programs to preserve genetic diversity and sustainability. While precision agriculture and GM seeds hold promise, addressing these challenges is crucial to ensure the long-term success and sustainability of cotton production in India (65).

Development of pest and climate-resilient cotton varieties: The development of pest- and climate-resilient cotton varieties is essential for improving cotton production in India, especially as climate change and biotic stresses pose growing challenges. A combination of genetic engineering and traditional breeding methods is being used to create varieties that can endure drought, heat and pest infestations. Genetic modifications, such as those using CRISPR/Cas9 technology have shown great potential in enhancing cotton's ability to tolerate environmental stresses by enabling precise edits to genes linked to resilience (68). For example, studies have identified genes like heat shock proteins that help cotton plants respond to extreme conditions, paving the way for stress-resistant varieties (69). Similarly, transgenic cotton varieties like Bt. cotton have been successful in combating biotic stresses caused by pests, significantly reducing yield losses that can reach up to 60 % under severe infestations (70).

Traditional breeding techniques, such as field-based phenotyping are also being utilized to select traits that enhance cotton's ability to thrive under heat and drought. These efforts, when combined with genetic insights can lead to cultivars better suited to changing climatic conditions. However, challenges remain including knowledge gaps among farmers about advanced practices like drought and pest management, which limits the widespread adoption of these resilient varieties (49).

In pest management, Bt. cotton has revolutionized the landscape, now accounting for 93 % of cotton cultivation in India. While it initially reduced pesticide use and increased yields; the emergence of pest resistance has highlighted the need for advanced biotechnological solutions such as RNA interference and gene pyramiding to maintain its effectiveness (51). Other innovative methods, like sterile insect release and CRISPR-mediated gene drives, offer promising strategies to address resistance and ensure sustainable cotton production (51). Together, these approaches present a comprehensive path forward to enhance the resilience and sustainability of India's cotton sector.

Export opportunities

Rising demand for organic and sustainable cotton globally: The rising global demand for organic and sustainable cotton reflects increasing consumer awareness of environmental concerns and the harmful effects of conventional cotton farming. Organic cotton grown without synthetic chemicals offers notable environmental, economic and social advantages. For instance, organic farming reduces pollution and soil degradation while preserving biodiversity by avoiding harmful pesticides and fertilizers (71). Additionally, it lowers production costs by eliminating the need for agrochemical inputs and supports healthier ecosystems, thus enduring long-term sustainability (10).

India, as the largest producer of organic cotton, contributing about 70 % of the global supply, has significant potential to benefit from this shift. The textile industry's focus on reducing pollution has further propelled demand for organic cotton, which restores soil fertility and minimizes water usage compared to conventional methods (71). Programs like the Better Cotton Initiative (BCI) encourage sustainable farming practices, improving farmers' incomes while addressing environmental impacts (10).

The economic benefits of organic cotton extend to enhancing livelihoods for farmers through lower input costs and better working conditions. In India, the transition from Bt. cotton to organic methods has shown potential for improving both farmer profits and soil health (72). As global markets increasingly favour eco-friendly products, sustainable cotton production aligns with international sustainability goals creating promising export opportunities for Indian farmers and strengthening their role in the global market (73).

Expanding markets in emerging economies: The expansion of cotton production in India offers significant opportunities in emerging markets fuelled by technological advancements, government policies and increasing global demand. India has witnessed robust growth in cotton production with an annual growth rate of 3.5 % from 1959 to 2019, largely driven by a 2.75 % annual productivity increase (35). The introduction of Bt. cotton in 2002 has been a game-changer with approximately 88.44 % of the cotton-growing area now under Bt. cotton, which has improved pest resistance and reduced production costs (74). High-yielding varieties and government initiatives have also contributed to an impressive 4.47 % growth in production in recent years (75).

India is the second-largest cotton exporter globally, with key markets in Southeast Asia, Japan and Europe. While long and extra-long staple cotton varieties dominate export shares, India also holds a competitive edge in short staple cotton exports to countries like China and Bangladesh. However, challenges such as lower yields compared to other major producers and quality inconsistencies hinder India's export potential with Indian cotton often facing price discounts due to quality issues (61).

To sustain and enhance its position in the global market, India needs to address these challenges through modernization and better agricultural practices such as the adoption of advanced seed varieties and mechanized farming methods. These improvements could help bridge the yield gap and improve quality further boosting India's competitiveness and export potential (30).

Value addition

India's cotton-based products and processing branding offer immense opportunities fuelled by the country's historical connection to cotton cultivation and the increasing global demand for sustainable textiles. Cotton dominates the Indian textile industry, accounting for 73 % of the market share and the country's global textile trade share is expected to rise in the coming years (76). Cotton's popularity has grown significantly, with its share in retail apparel increasing from 34 % in the 1970s to over 60 % today, reflecting a strong market for cotton-based clothing (77). Additionally, the cotton processing sector plays a crucial role in employment generation, supporting over 8 million jobs and contributing significantly to export revenues (3).

Technological advancements in cotton processing have further strengthened the industry, with innovations improving the efficiency of converting raw cotton into high-quality yarns. The establishment of export processing zones (EPZs) and special economic zones (SEZs) has made international market access easier for cotton products, enhancing their global competitiveness (76). At the same time, the implementation of brand-variety information systems has empowered farmers to make better decisions, reducing risks and boosting profitability (78).

Value addition throughout the cotton processing chain underscores the sector's economic potential. From ginning, which adds Rs. 401.24/q seed cotton to garment manufacturing where value addition reaches Rs. 11082.35/q finished fabric, each stage of processing contributes to substantial economic returns. Branding strategies further amplify this potential by creating unique market identities that appeal to consumers prioritizing quality and sustainability (76). The versatility of cotton also supports the development of a diverse product range including textiles, edible oils and byproducts, making it a key driver of economic growth and market differentiation (78).

By focusing on branding, technological improvements and value addition, India can enhance its competitiveness in both domestic and global markets while ensuring sustainable growth in the cotton sector.

Policy support

Government initiatives for improving infrastructure and market linkages: Government initiatives to improve infrastructure and market linkages in India's cotton production are vital for enhancing the sector's competitiveness and fostering economic growth. These efforts include both policy-driven subsidies and infrastructure development to support farmers and ensure better market access. For instance, subsidies for essential inputs like fertilizers significantly impact farmers' incomes and enhance global competitiveness, while policies such as the National Fibre Policy focus on promoting value-added exports rather than raw cotton (79).

Investments in market infrastructure, including transportation and communication networks play a crucial role in reducing transaction costs and improving efficiency. Establishing market information systems ensures farmers receive fair prices and better integrates them into broader markets (79). Furthermore, initiatives targeting smallholders emphasize sustainable supply chain practices and alignment with international standards, improving market access and livelihood opportunities (80).

Infrastructure development also drives broader economic growth by enhancing connectivity and attracting investments. Programs like "Make in India" aim to improve regional integration and capitalize on comparative advantages (81). Public-private partnerships (PPPs) are increasingly used to address infrastructure gaps, leveraging private sector resources for better planning, financing and maintenance of projects (82). These partnerships enhance service delivery and operational efficiency, even in challenging economic environments (83).

A strong policy framework is essential to ensure infrastructure investments yield maximum benefits. This includes fostering competitive pressures, regulatory independence and improving project selection processes to avoid misallocation of resources (84). By addressing these aspects, government initiatives in infrastructure and market linkages can significantly boost the cotton sector's productivity and its contribution to economic development.

Promotion of contract farming and public-private partnerships: The promotion of contract farming and public-private partnerships (PPPs) in cotton production in India offers a promising pathway to enhance agricultural productivity and market access, particularly for small-scale farmers. Contract farming provides a structured framework that ensures income stability through guaranteed prices while reducing

farmers' exposure to market volatility (36). It also addresses resource efficiency by providing essential inputs like seeds and fertilizers, which improve productivity and quality (44). Additionally, the integration of modern agronomic practices and mechanization through such agreements helps achieve higher yields, addressing challenges like labour shortages and aligning with sectoral goals (50).

Similarly, PPPs play a pivotal role in driving technological advancements and fostering innovation in cotton farming. These partnerships facilitate resource sharing between public institutions and private firms leading to improved farming techniques, better seed varieties and enhanced sustainability (85, 86). Private sector involvement also offers farmers financial incentives and better terms, encouraging greater participation and investment in modern practices (87). Moreover, collaborative efforts under PPPs can address environmental concerns by promoting sustainable farming standards, ensuring long-term viability in cotton production (86).

While contract farming and PPPs present significant opportunities for the cotton sector, challenges such as regulatory hurdles, high input costs and compliance with quality standards must be addressed. Equitable agreements and supportive policies are essential to ensure smallholder farmers fully benefit from these initiatives and achieve greater economic resilience (44).

Sustainability Trends

Water-efficient and eco-friendly farming practices in cotton production in India are increasingly essential to address environmental challenges and water scarcity. Adopting sustainable irrigation techniques like drip and mulched drip irrigation has proven to conserve significant amounts of water compared to traditional methods, while mobile applications now enable farmers to make informed irrigation decisions using real-time data further enhancing water use efficiency. Additionally, implementing irrigation strategies based on weather forecasts and reducing reliance on flood irrigation helps optimize water usage and reduces wastage (86).

Eco-friendly practices such as organic nutrient management, which includes double green manuring and the use of well-decomposed poultry manure have shown high resource utilization efficiency contributing to sustainable production (5). Similarly, natural farming techniques like Beejamirit and Ghanajeevamirit improve yields while maintaining ecological balance (17). Integrated Pest Management (IPM) practices, which focus on reducing pesticide use, crop rotation and the proper disposal of crop residues, further enhance soil health and minimize environmental impacts. In India Integrated Pest Management (IPM) is being promoted through farmer training, biological controls and crop monitoring to reduce pesticide use. Scaling it further needs stronger extension services, local demonstrations and affordable eco-friendly alternatives (44).

Moreover, voluntary sustainability standards such as the Better Cotton Initiative and Organic Cotton Standard are driving the adoption of environmentally friendly and socially responsible farming practices. These global initiatives aim to address critical issues by encouraging farmers to embrace sustainable methods while improving their livelihoods (88). However, challenges persist in achieving widespread adoption, necessitating comprehensive training and support systems to ensure that these practices are effectively implemented. With the right interventions, these strategies can significantly contribute to sustainable cotton farming in India.

Threats to cotton production

Environmental Challenges

Climate change and climate resilience: Climate change poses significant threats to cotton production in India, primarily through unpredictable weather patterns and increased stress on crop resilience. Rising temperatures and erratic rainfall patterns have negatively impacted cotton yields, with projections indicating potential yield reductions of up to 39.2 % by mid-century in regions like Punjab and Pakistan, which may reflect similar trends in India (89). In Maharashtra, statistical models reveal significant negative correlations between climatic parameters and cotton production, underscoring the crop's vulnerability to environmental changes (90). High temperatures not only reduce yields but also induce physiological stress, adversely affecting fibre quality and necessitating the development of heat-tolerant cultivars (91).

Additionally, climate change exacerbates pest and disease pressures as increased temperatures and rainfall variability create favourable conditions for the proliferation of economically harmful insects and pathogens, further threatening productivity (92). Under RCP 4.5, cotton yields in India are projected to decline by about 25.7 % by the end of the century. Under the more severe RCP 8.5 scenario, losses could reach around 32.2 %, highlighting the urgent need for climate-resilient farming practices (17). Moreover, practices like altering planting dates, improving irrigation methods and implementing integrated pest management are being employed to enhance resilience (93).

While these strategies offer potential solutions, challenges remain in developing climate-resilient cotton varieties that perform well under stress conditions. Certain genotypes show promise and could be pivotal in future breeding programs (94). Comprehensive support systems are essential to help farmers adapt effectively, addressing the socio-economic and infrastructural barriers that hinder widespread adoption of these practices. Although some regions may experience temporary benefits such as altered pest dynamics or extended growing seasons, the broader impacts of climate change on cotton production remain overwhelmingly negative, threatening food security and agricultural sustainability (89).

Depletion of water resources in key cotton-growing areas: The depletion of water resources in key cotton-growing areas of India poses a significant challenge to agricultural sustainability and food security. Groundwater, which provides approximately 80 % of irrigation in India is being overexploited, especially in regions where water-intensive crops like cotton are cultivated. This overuse is compounded

by growing demand for irrigation due to population growth and industrialization with groundwater depletion projected to reduce cropping intensity by 20 % nationwide and up to 68 % in severely affected areas (95). Studies show that a 1 % increase in cotton cultivation area correlates with a notable drop in groundwater levels, highlighting the unsustainable nature of current practices (96).

Water scarcity directly affects cotton production particularly during critical growth stages like flowering where inadequate irrigation can severely reduce yield (39). Regions like Gujarat have experienced diminished cotton yields due to declining groundwater forcing some farmers to reduce cultivation or abandon farming altogether (8). To address these challenges, farmers are adopting efficient irrigation practices such as 'deficit and precision irrigation' which optimize water use and enhance water productivity. Additionally, recommendations to shift towards less water-intensive crop varieties and improve agronomic practices are crucial for sustainable cotton farming (39).

Policy interventions play a vital role in mitigating groundwater depletion. Reforms such as reviewing energy subsidies that encourage water-intensive crops in scarce regions coupled with the promotion of watershed management and rainwater harvesting are critical for reducing groundwater overdraft (96). Moreover, creating water resource structures and harvesting rainwater in rainfed areas have proven effective in improving cotton production (97).

The development of resilient cotton varieties and salinity management strategies are essential for ensuring long-term sustainability in water-stressed regions (98). Effective irrigation scheduling based on local evapotranspiration rates can further mitigate moisture stress, ensuring that cotton production remains viable in the face of diminishing water resources (39). These integrated strategies are essential to secure the future of cotton farming in India amidst escalating water scarcity challenges.

Market dynamics

Price volatility in global and domestic markets: Price volatility in cotton production in India is shaped by a complex interplay of global and domestic market dynamics, presenting significant challenges for stakeholders across the supply chain. The interconnectedness of Indian cotton markets with major global players such as the USA and China leads to heightened price fluctuations particularly during international crises. For instance, events like the Russia-Ukraine conflict and USA-China trade disputes have resulted in long-term volatility spillovers that disrupt price stability in India (99). The reliance on global markets for price determination further increases vulnerability, as international price shocks often transmit to domestic markets impacting producers and consumers alike (46). This dependency is compounded by India's WTO commitments, which limit the ability of domestic farmers to adapt swiftly to global price changes thereby risking crop and income stability (53).

Domestically, the integration of markets in key cotton-growing states such as Gujarat and Maharashtra with international price indices highlights the interconnected nature of cotton pricing in India. Price changes in global markets can influence local markets, exacerbating volatility and its consequences (100). While the Cotton Corporation of India (CCI) plays a vital role in stabilizing prices through minimum support prices, challenges persist due to shifting consumer preferences, sustainability pressures and the limited effectiveness of such interventions during severe price fluctuations (29).

Despite these challenges, some experts argue that the adoption of advanced technologies such as digital trading platforms and predictive analytics alongside robust market strategies could help mitigate volatility and enhance resilience within the cotton sector. These innovations, coupled with well-crafted policy reforms have the potential to stabilize markets and protect vulnerable populations while fostering competitiveness and efficiency in the cotton industry. Understanding and addressing the intricate dynamics of price volatility remain critical for sustaining cotton production in India amid evolving global and domestic challenges.

Competition from synthetic fibres and other cotton-producing countries

India's cotton production faces intense competition from synthetic fibres and other cotton-producing countries, influencing both its market dynamics and agricultural practices. Synthetic fibres like polyester have steadily gained market share due to their lower production costs, durability and versatility often surpassing cotton in production and consumption (46). The affordability of synthetics appeals to cost-conscious consumers, while advancements in their manufacturing technology have further accelerated their adoption in various applications. Although the rising demand for sustainable and eco-friendly textiles has created a specific market for organic cotton, the overall trend continues to favour synthetics due to their cost advantages (72).

In addition to challenges from synthetic alternatives, India faces stiff competition from other cotton-producing countries which leverage advanced technologies, subsidies and more efficient practices to reduce costs and enhance production. Countries like China and the United States exert significant pressure on global cotton markets, influencing prices and trade dynamics (101). Despite being the second-largest cotton producer globally, India struggles with inefficiencies in its agricultural policies, including low minimum support prices and limited support for technology adoption which undermine its competitiveness in export markets (102).

This dual competition from synthetic fibres and international producers necessitates strategic innovation in India's cotton sector. Enhancing production efficiency, improving marketing efforts and adopting sustainable practices are critical to maintaining the relevance and competitiveness of Indian cotton in an increasingly challenging global textile market.

Policy and regulatory risks

Uncertainties in export policies and subsidies: The policy and

regulatory risks associated with uncertainties in export policies and subsidies in India's cotton production are multifaceted, influenced by domestic policy shifts and international trade agreements. These uncertainties significantly affect the competitiveness of Indian cotton in global markets creating challenges for producers and policymakers alike. Export-contingent subsidies have drawn international scrutiny particularly from the United States which argues that such subsidies violate WTO rules reflecting India's increasing reliance on them despite its commitments to reduce these measures under international agreements (103). The WTO's Uruguay Round Agreement on Agriculture mandates reductions in export subsidies posing additional risks as India strives to balance compliance with supporting its cotton sector. Although developing countries like India enjoy temporary exemptions, these are increasingly scrutinized adding to policy uncertainties (104).

Domestically, Indian cotton production faces high input costs and technological challenges, exacerbated by fluctuating subsidy policies that can create inefficiencies and dependency (32). Government-imposed export quotas and requirements such as ensuring mills supply specific products like hank yarn further complicate market access and restrict competitiveness (104). While subsidies are critical in supporting farmers especially through fertilizer subsidies that significantly boost incomes the reliance on such measures creates fiscal pressures and raises questions about long-term sustainability. Additionally, India faces intense global competition particularly from heavily subsidized countries like the United States, which distorts market pricing and access. Despite these challenges, India's resilience is evident in its position as a leading exporter, with opportunities for growth in value-added products offering a pathway to enhance market share and reduce dependency on subsidies (32).

While subsidies and export policies aim to bolster domestic production and protect farmers, they often introduce inefficiencies; hindering technological advancements and perpetuate dependency. Addressing these issues requires a balanced approach that fosters competitiveness, aligns with international trade commitments and ensures sustainable growth for the cotton sector.

Rising concerns over the environmental impact of cotton farming

Cotton farming in India is a key economic activity but comes with significant environmental and social challenges because of its large ecological impact. The cultivation process is highly water-intensive, leading to the depletion of local water resources. Additionally, cotton accounts for nearly 50 % of the country's pesticide usage which contaminates soil and water (9). The dyeing and finishing stages further exacerbate environmental damage which generates hazardous waste that is often improperly disposed of, causing the contamination of soil and water resources. Social issues associated with cotton farming are equally concerning including child labour, poor working conditions and the economic instability faced by communities reliant on this sector. Environmental degradation has forced migration and undermined livelihoods in many areas (96).

In response, sustainable practices such as organic cotton farming have gained attention as eco-friendly alternatives that support healthier farmer livelihoods (72, 41). However, the transition to sustainable methods is complex, as many farmers depend on conventional farming for survival. Furthermore, regulatory risks add another layer of concern. Cotton farming's heavy reliance on pesticides and nitrogen-based fertilizers worsens pollution while importing countries' stringent environmental norms pressure Indian farmers to adopt sustainable practices, which may not always be feasible (9). The absence of a cohesive framework for genetically modified crops like Bt. cotton also raises questions about sustainability and environmental safety. Socially, the sector's ties to child labour in addition to low-income livelihoods draw international scrutiny and regulatory measures to address these issues could further strain smallholder farmers' economic viability (9).

Despite these challenges, regulatory pressures also present opportunities for innovation and sustainable farming practices, which could lead to better environmental outcomes and improved social equity. Addressing these intertwined challenges requires a balanced approach, focusing on environmental protection, farmer support and adherence to international standards.

Sustainability in cotton industry

Role of organic cotton and sustainable farming practices: Organic cotton and sustainable farming practices play a crucial role in improving sustainability within India's cotton industry by enhancing soil health, increasing crop yields and reducing environmental impacts. Organic farming methods, such as the use of organic manures and amendments have been shown to significantly improve soil quality by increasing soil organic carbon and nitrogen content while fostering healthier microbial communities essential for nutrient cycling (42). Long-term application of organic materials like cotton straw and manure has also resulted in yield increases of up to 32.28 % compared to conventional farming methods. Additionally, reducing chemical inputs through the integration of organic fertilizers has been found to promote eco-friendly production and enhance sustainable yield indices (57).

Sustainable farming practices, including crop rotation with legumes and the use of natural farming techniques like Beejamirit and Ghanajeevamirit, offer significant environmental and economic benefits. These methods improve soil health, mitigating resource depletion and deliver better net returns compared to conventional systems. Agronomic strategies such as the adoption of cover crops, drip irrigation and organic nutrient management using double green manuring further enhance input efficiency and sustainability (44). Technological innovations like fuzzy logic-based irrigation systems help conserve water while integrated pest management techniques including pheromone traps and biopesticides reduce pest damage and improve yields (62).

Economically, sustainable farming practices lead to increased profitability for farmers through higher yields and reduced costs associated with pest damage. Socially,

initiatives like the Farmer FIRST (Farm, Innovations, Resources, Science and Technology) program facilitate knowledge sharing and the widespread adoption of sustainable practices, further supporting the industry's growth and resilience (72). These combined efforts are critical for addressing the environmental, economic and social challenges facing the Indian cotton industry, ensuring its long-term sustainability and success.

Impact of certifications

The certification in sustainability within the cotton industry in India has a significant impact on the environment, economy and society. Voluntary Sustainability Standards (VSS) such as the Better Cotton Initiative (BCI) aim to reduce the negative effects of traditional cotton farming, which often involves excessive water use and chemical inputs. Environmental benefits of certification include a reduction in chemical use, as certified farms generally report lower pesticide and fertilizer usage which helps reduce pollution (88). Additionally, sustainable practices promoted by certifications encourage efficient water use, addressing the issue of water scarcity in cotton farming. Economically, farmers participating in BCI often see increased incomes and reduced input costs compared to non-certified farmers. Certification also opens new market opportunities, as many global brands prefer sustainably sourced cotton (88). Socially, while there are economic benefits, labour conditions have not shown significant improvement under BCI which pointing to the need for more attention to social aspects. Certifications can empower smallholder farmers by providing training and resources, but challenges remain in ensuring fair implementation (86). Furthermore, certifications help address social issues such as child labour and wage discrimination, promoting fair labour practice. They also improve the overall quality of life for farmers by giving them access to better resources and training. However, challenges like the high costs and complexity of obtaining and maintaining certifications may discourage some farmers from joining these programs (79). Despite these challenges, certifications like BCI and Fairtrade aim to promote sustainable farming practices and improve the livelihoods of smallholder farmers, influencing environmental sustainability, economic viability and social equity in the cotton industry (87). BCI farmers in Maharashtra and Telangana cut pesticide use by 75 % and saved around ₹ 3500 per season, improving profits and OCA supported organic farmers earned 21 % more income per hectare despite slightly lower yields, due to lower costs and premium prices (105).

Circular economy and waste management in cotton production

The circular economy in cotton production in India offers a promising approach to sustainability that focusing on resource efficiency, waste reduction and material reuse. This model aligns with traditional Indian practices, where reusing textiles within families and adapting garments like sarees and vesti for extended use is common especially in joint family systems (41). These practices help reduce waste and support a more sustainable approach to cotton consumption. Additionally, sustainable farming practices such as organic cotton farming and initiatives like the Better Cotton Initiative (BCI) aim to reduce chemical inputs, benefiting both the environment and the farming community (74). Life cycle assessments show that organic and BCI cotton farming significantly lower the environmental footprint compared to conventional farming methods (74). Innovations in textile processing also contribute to this transformation, as green chemistry and new processing techniques focus on using sustainable materials and energy-efficient methods. Moreover, recycling cotton waste into regenerated fibres or biofuels promotes a closed-loop system further reducing waste (63). However, despite these advancements, challenges like market acceptance and the need for more technological developments still hinder the full potential of the circular economy in cotton production.

Waste management in cotton production is another important issue, as it involves the disposal of agricultural residues, wastewater and the potential for recycling by-products. Cotton cultivation generates substantial waste, including cotton stalks and cotton gin trash (CGT), which often end up being burned or discarded, leading to environmental pollution and nutrient loss. India produces an estimated 10–12 million tonnes of cotton stalks annually, yet less than 30 % is currently utilized for fuel or commercial applications. Likewise, approximately 1.5 million tonnes of CGT are generated each year, with a significant portion left unutilized. Some of the cotton stalks are used for fuel, but much of the residue goes to waste. Innovative uses for cotton waste, such as converting it into bioenergy, animal feed or soil amendments present opportunities to reduce waste and enhance sustainability (57). In addition, wastewater from the cotton-textile industry presents challenges due to its high organic load and colour. However, effective treatment methods such as a combination of anaerobic digestion and activated sludge processes can help manage these challenges while minimizing costs and environmental impacts. The integration of circular economy models in waste management can further enhance sustainability by promoting the recycling and upcycling of cotton waste. Case studies have shown that these strategies can significantly reduce waste and improve the sustainability of the textile sector, highlighting their potential for widespread adoption (45).

Conclusion

In conclusion, the cotton sector remains a cornerstone of India's agricultural and economic framework with immense contributions to employment, trade and rural livelihoods. While the industry boasts significant strengths such as diverse agro-climatic adaptability and global export potential, it also faces considerable challenges including low productivity, environmental concerns and market volatility. Addressing these issues through sustainable practices, technological advancements and policy support can unlock new growth opportunities particularly in organic and value-added cotton production. By fostering innovation and resilience, the Indian cotton sector can sustain its global leadership and continue to thrive in an increasingly competitive and environmentally conscious market. To achieve this, targeted actions such as

increasing public and private investment in agricultural R&D, expanding micro-irrigation infrastructure and promoting the adoption of Integrated Pest Management (IPM) techniques are important. Policymakers should also promote circular economy models by supporting recycling and upcycling of cotton by-products, concurrently improving access to sustainability certifications to enhance global market integration.

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RJP wrote the manuscript draft and SS revised it. NV, PA, SB, SM, MNK contributed to discussion. All authors read, edited and approved the final manuscript.

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