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# Impacts of Climate Change on Cotton (Gossypium hirsutum L.): Growth, Yield and Resilience Strategies- A Global and Pakistan Perspective

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***Abstract:*** *Cotton (Gossypium hirsutum L.) is an important fiber crop which plays a vital role in industries, economics and rural livelihoods, globally and especially in Pakistan. But current climate change is increasingly becoming a threat to cotton productivity due to increased temperatures, variability in rainfall, droughts, flooding, salinity and increased infestation of pest and diseases. Heat and drought stress affects the rate of photosynthesis, maturation of the plant, boll retention and fiber development with significant yield and quality losses. Physiological instability and oxidative damage are exacerbated by combined stresses. Climate variability also increases the occurrence of key pests and diseases such as pink bollworm (Pectinophora gossypiella) and Cotton Leaf Curl Virus (CLCuV) with devastating consequences to crop yields, particularly in South Asia. New opportunities are provided by recent progress in biotechnology such as CRISPR-Cas genome editing, genomic selection, genome-wide association studies (GWAS) and multi-omics approaches to develop cotton cultivars that are more climate-resilient, have enhanced stress resistance and have more stable fiber properties. Besides that, climate-smart agriculture (CSA) techniques like deficit irrigation, conservation agriculture, integrated pest management, agroforestry and digital agriculture are gaining increasing significance as adaptation strategies. This review provides a summary of the physiological, agronomic, molecular, ecological and socio-economic climate change effects on cotton at the global and Pakistan perspectives and integrated approaches for sustainable and climate resilient cotton production. This work was supported by the Government of Pakistan, Ministry of Science and Technology, under the program Climate Resilient Agriculture with a seed grant from the ASL. This work was funded by Government of Pakistan, Ministry of Science and Technology under the program Climate Resilient Agriculture, with a seed grant from the ASL.*

***Keywords:*** *industries, economics, productivity, rainfall, droughts, flooding, salinity, Cotton Leaf Curl Virus, CRISPR-Cas, genome, agronomic, molecular, ecological.*

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## 1. Introduction

Cotton (Gossypium spp.) is one of the main fiber crops of the world and has a significant importance in the textile industry, agricultural trade and rural livelihood. In 2023, the global cotton crop totaled over 25 million metric tons, with the top producers being China, India, Pakistan, Brazil and the United States. Cotton is a strategic cash crop that is grown by almost 1.7 million farming households in Pakistan and plays a prominent role in the agricultural gross domestic product (GDP), foreign exchange earnings and textile industry which is one of the largest industries in Pakistan (Mehmood et al., 2024). Cotton also has a role in food and feed systems via cottonseed oil and livestock feed (by-products).

Cotton, an important crop, is more and more affected by climate change and environmental variability. With the rise in temperature, irregular rainfall, droughts, floods, salinity and increasing pest and disease pressure, sustainable cotton production is a major constraint for cotton cultivation in all parts of the world (Shahzadi et al., 2024). Climate change has exacerbated the impacts of extreme weather events, especially in South Asia, where the growing areas of cotton lack adequate water, soil quality and tolerate high temperature stress. The climatic changes lower productivity yields and fiber quality and endanger farmers livelihoods and the sustainability of cotton production systems.

Heat stress is one of the more serious climatic stresses that restricts growth and productivity of cotton. The temperature range that is best for cotton is from 21 to 30 °C, but temperatures above 35 °C during flowering and boll development greatly affect lint yield and reproductive success (Han et al., 2023). High temperatures limit photosynthetic activity, accelerate leaf senescence, alter assimilate partitioning, cause flower drop and lower boll drop which leads to loss of pollen viability (Zafar et al., 2018). Experimental results show that for every 1 °C increase above optimum conditions, there is a decrease in lint yield by almost 110 kg $ha^{-1}$ (Yousaf et al., 2023). Likewise, drought stress can cause disruption of physiological and biochemical processes that affect boll retention, seed

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cotton production and fiber quality such as the interference of photosynthesis, nutrient transport, fiber elongation, etc. (Poffenbarger et al., 2023; Ul-Allah et al., 2021).

The effects are even more severe when heat is combined with drought. The combined effect of the stresses helps to increase oxidative damage, membrane instability and metabolic disruptions which result in serious reproductive failure and reduction in lint quality (Zafar et al., 2023). Moreover, climate change is also contributing to more extreme rainfall events and flooding, especially in countries that experience mostly monsoon rains like Pakistan. The waterlogging causes limitations in root respiration, nutrient uptake and hormonal balance which ultimately restricts growth and yield formation (Beegum et al., 2023). The devastating floods in 2022 in Pakistan also exposed the fragility of cotton production systems with respect to the alternating drought–flood climate change cycles (Rathore and Khuwaja, 2022).

Climate variability also affects the dynamics of pests and diseases in cotton farms. The survival, reproduction and spread of insect pests like pink bollworm, whiteflies, thrips and leafhoppers are increased under the increasing temperatures (Shahzad et al., 2022). The climatic conditions are favorable for the transmission of Cotton Leaf Curl Virus (CLCuV) which is one of the most devastating viral pathogens of cotton in South Asian countries (Ali et al., 2019). These stresses add up to production risks and economic losses in Pakistan, especially for the smallholder population in the provinces of Punjab and Sindh.

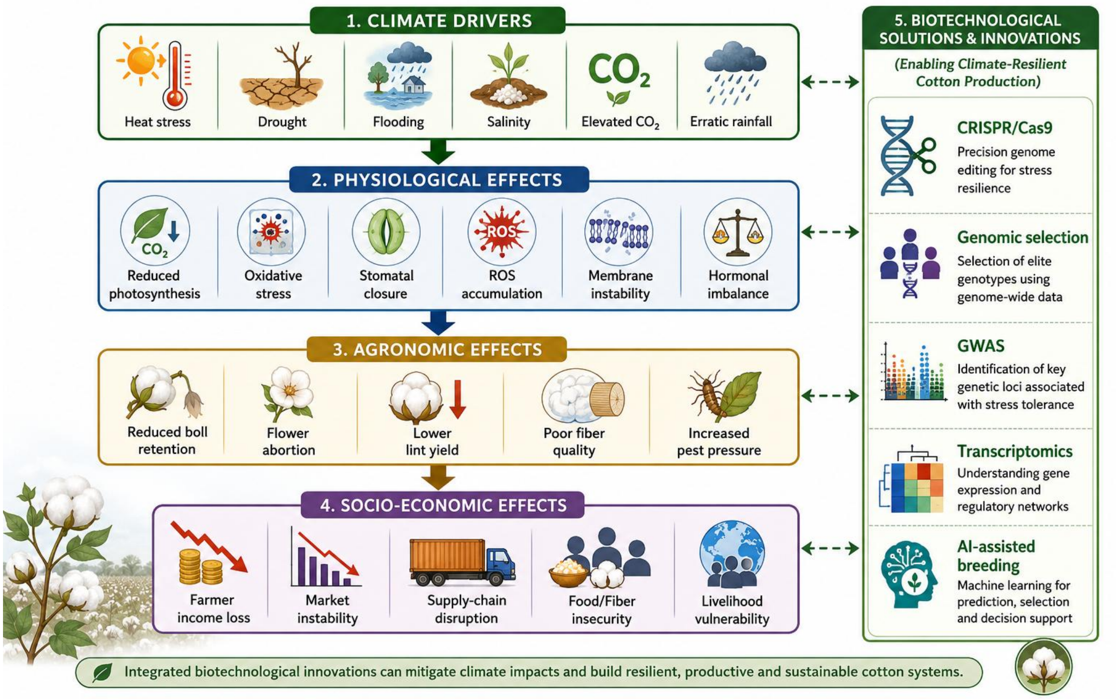
New tools in the biotechnology and molecular breeding toolbox offer hope for increasing the climate resilience of cotton. Genome-wide association studies (GWAS), genomic selection, transcriptomics, metabolomics and CRISPR-Cas genome editing technologies are used to accurately identify and manipulate key stress responsive genes that control heat tolerance, drought resilience, osmotic adjustment and fiber-quality stability (Luqman et al., 2025). Meanwhile, climate-smart agriculture (CSA) approaches such as deficit irrigation, conservation agriculture, integrated pest management (IPM), agroforestry and digital agriculture technologies are gaining traction as adaptation solutions to the impacts of climate change (Asma et al., 2025).

The present review aims to provide a comprehensive overview of the available recent evidence at global and Pakistan specific level on the physiological, agronomic, socio-economic and molecular impacts of climate change on crop management systems of cotton. It also underscores the need for diversified adaptations and mitigation measures using biotechnology, climate-smart agronomy, digital agriculture and policy measures to enhance the resilience and sustainable cotton production in future climate scenarios.

## 2. Impacts of the climate change on the growth and production

Climate stresses such as heat, drought, flooding, salinity, pest attack, soil degradation and other disasters can adversely impact cotton crops and crop quality and productivity, creating a high vulnerability for cotton production systems. These stresses can cause physiological, biochemical and molecular changes that hinder cotton development and productivity. Heat and drought are among the several stresses, which are thought to be the most important limiting factors for cotton yield in the world's large cotton-producing regions (Arshad et al., 2021). The multi-faceted potential relationship between climatic stress and cotton physiology, productivity and socio-economic sustainability are summarized in Figure 1.

Figure 1: Conceptual Framework of Climate Change Impacts on Cotton Production Systems



## 2.1 Heat Stress

Cotton is a thermophilic crop which is best grown between 21°C and 30°C; but temperatures over 35°C during flowering and boll development will adversely affect reproductive success and lint production (Han et al., 2023). The heat stress causes decrease in photosynthesis, disintegration of chloroplast membranes, premature aging of leaves and decreases assimilate flow to reproductive organs. The low viability of pollen and higher drop of flowers lead to low boll retention and loss of yield (Zafar et al., 2018). The experimental studies show that lint yield (Yousaf et al., 2023) can be significantly affected by raising the temperature up to 1 °C from the optimum. Heat stress also impacts fiber development by affecting the biosynthesis of cellulose and the organization of the cytoskeleton which leads to shorter fibers with a lower tensile strength and uniformity (Jareczek et al., 2023). In Pakistan and Australia, significant impacts on boll formation and lint yield due to heat waves during flowering stages have been reported (Bista et al., 2025; Schwenk et al., 2022).

In recent years, scientists have been focusing on pathways which are heat-sensitive and using biotechnology to increase thermotolerance in cotton. The application of genomic selection, transcriptomic analysis and CRISPR-based genome editing are helping to

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identify genes that respond to stress, including membrane stabilization, antioxidant defense and reproductive tolerance to high temperatures.

## 2.2 Drought Stress

Another significant limitation of cotton production is drought, especially in the arid and semi-arid areas. In periods of water deficiency, leaf growth rate, nutrient transport, photosynthetic rate and plant growth rate (biomass) are all decreased (Poffenbarger et al., 2023). A reduction in water supply due to drought leads to stomatal closure to retain water, but it also reduces fibre growth and carbon uptake. The combined action of heat × drought stress causes greater oxidative damage, membrane instability, disruption of metabolic pathways and reproductive failure and lint quality degradation (Zafar et al., 2023).

Flowering and boll filling drought results in significant boll drop, seed cotton production and fiber quality parameters like micronaire, fiber length and tensile strength (Ul-Allah et al., 2021). In Pakistan, seed cotton yield losses up to 50% have been observed in some areas due to drought stress and it was reported that there was a 37.9% lint yield loss under drought stress for 60 days in China (Schwenk et al., 2022; Poffenbarger et al., 2023). In response to these challenges, breeding programmes have been developed to improve root architecture, osmotic adjustment, water-use efficiency and mechanisms of antioxidant defence, with the help of genomic selection and the manipulation of genes by CRISPR.

## 2.3 Excess rainfall and flooding

Consequences of excess rainfall and flooding are also being a huge challenge for cotton production, especially in monsoon dominated areas. Waterlogging leads to hypoxic soils which affects root respiration, nutrient uptake and hormonal imbalance, which in turn results in growth inhibition and reduced yield potential (Beegum et al., 2023). The anatomical characteristics of cotton are not well adapted to long duration of waterlogging, making it very sensitive to waterlogging stress.

The floods in Sindh, Pakistan in 2022 revealed the sensitivity of cotton systems to extreme rainfall events resulting in significant losses in cotton system and also in the expected

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harvest of cotton (Rathore and Khuwaja, 2022). Flooding causes postponement of sowing/transplanting, reduction in fibre development time and vulnerability to pest/disease (Haider et al., 2025). Recent research in biotechnology is directed towards better understanding hypoxia-responsive pathways, root engineering and rhizosphere microbes with positive effects on waterlogging tolerance of cotton.

### 2.4 Phenological Shifts

The phenology of cotton is greatly affected by climate warming, as evidenced by the increased rate of flowering, boll development and maturity. Rising temperature speeds up heat-unit accumulation, reducing crop duration and putting reproductive stages at risk of terminal heat and water stress (Zanre and Combary, 2024). Earlier flowering can minimise late season pest damage, but also mean increased exposure to heatwaves during flowering. In Pakistan, often there are mismatches between the phenology of crops and favorable atmospheric conditions due to irregular distribution of rainfall and changes in the sowing schedule (Syed et al., 2022).

The genetic and transcriptomic characterization of flowering-time and stress responses is advancing in recent years and enhancing the knowledge of how to make more climate-resilient cultivars with optimal phenological strategies.

### 2.5 Biotic Pressures and Soil Degradation

Pest dynamics is greatly affected by climate warming in cotton systems. An increase in temperature can boost the survival, reproduction and geographic distribution of insect pests like pink bollworm, whiteflies and leafhoppers (Syed et al., 2022). Multiple pest generations per year may occur with warm weather and these may overlap with the reproductive stages of cotton. A rise in humidity and shifts in precipitation also tend to amplify pest outbreaks and increase the spread of disease. Thus, the importance of climate-informed integrated pest management (IPM) systems that involve predictive climate models, pheromone monitoring and digital surveillance systems is growing.

Climate variability also increases soil degradation by salinizing soils, reducing soil organic matter, leading to nutrient depletion and reducing soil water holding capacity (Wu et al.,

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2025). The salinity stress is emerging as a serious problem for cotton crop productivity in Pakistan and affects the cotton crops in terms of reduction in water absorption, root development and photosynthesis capacity of cotton. Conservation agriculture practices and organic amendments and microbiome-based interventions are new emerging ways of soil health restoration and stress resilience.

### 2.6 Impacts on Fiber Quality and Future Yield Projections

The cotton fiber quality traits such as fiber length, strength, fineness and uniformity are extremely affected by environmental stresses during the reproductive and boll development stages (Abro et al., 2023). The heat and drought stress cause disturbances in cellulose deposition, fiber elongation, decrease tensile strength and decrease fiber uniformity (Zafar et al., 2018). Too much humidity at boll maturity also lowers the quality of the lint, by causing it to discolor and suffer microbial damage. These losses can be reduced, to some extent, by balanced nutrient management and by optimizing irrigation scheduling (Beegum et al., 2024).

Despite potential benefits of increasing the atmospheric $CO_2$ concentration, climate-crop simulation models suggest productivity of cotton will be reduced in many climate regions in the future. In Pakistan, cotton production can be reduced by as much as 20% under extreme climate scenarios due to reproductive failure caused by heat and due to evapotranspiration (Lio et al., 2016). Combined heat, drought and water-scarcity stress are expected to cause similar reductions in India, Australia and the U.S. Yield losses can reach up to 30% when the extreme condition of combined heat × drought is met (Sabagh et al., 2020). The potential of AI-driven crop models, genomics and digital agriculture tools to enhance the assessment of risks associated to climate conditions and the creation of climate-resilient cotton production systems seems to be promising for future. Table I shows the major losses in yield and fibre quality reported in regions around the world growing cotton due to climate change.

*Table I. Global Evidence of Climate-Induced Yield and Fiber Losses in Cotton*

| Country/Region | Climate Stress | Yield/Fiber Impact | Key Findings | Reference |
|---|---|---|---|---|

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| | | | | |
|---|---|---|---|---|
| Pakistan | Heat + drought | 20–50% yield loss | Reduced boll retention | Han et al., 2023 |
| China | Drought | 38% lint reduction | Reduced fiber length | Chen et al., 2019 |
| Australia | Heatwaves | 12–18% lint loss | Floral sterility | Saleem et al., 2023 |
| India | Heat + pests | 15–22% decline | Pest intensification | Ul-Allah et al., 2021 |
| USA | Water scarcity | 15% yield reduction | Irrigation limitation | Somaddar et al., 2023 |

## 3. Higher pest and disease pressure.

The biotic stress is significantly increasing due to climate change, which affects the dynamics of pest populations, raises the disease burden and makes plants less resilient. An increase in temperature, changes in rainfall pattern, increased duration of humidity and change in seasonal conditions provide conducive conditions for insect outbreak and transmission of viral diseases, especially in the South Asian region and Pakistan (Shahzad et al., 2022). Climate stress also affects cotton physiology, which makes it more vulnerable to herbivory and pathogen attack and affects the survival and reproduction of pests and pathogens.

There is recent evidence that biotic stress is on the rise as one of the most critical factors that limits sustainable cotton production, especially as a result of climate change. Warming also drives the spread of pests globally, leads to higher pest numbers and increases the speed of resistance evolution, which diminishes the efficacy of Bt technologies and promotes secondary pest infestations. For this reason, a shift towards a more climate-informed approach to pest and disease management will be more and more needed to ensure cotton productivity in the future climate scenarios.

### 3.1 Accelerated Pest Invasions under Climatic Stress

Pink bollworm (Pectinophora gossypiella), is one of the most damaging insect pests of cotton fields of Pakistan. Pest incidence, abundance and infestation severity are significantly affected by rising temperatures and changes in the precipitation regime

(Shahzad et al., 2022). Warming effects can significantly elevate the level of pink bollworm infestation (Hussain et al., 2023) and simulation studies suggest that warming effects can significantly increase the level of pink bollworm infestation.Experimental studies indicate that about 28 °C is optimum for the development and reproduction of pink bollworm (Hussain et al., 2023), whereas simulation studies suggest that warming effects can significantly increase the level of pink bollworm infestation. Longer diapause periods are observed at low night temperatures while higher night temperatures lead to a shorter duration of diapause and better overwinter survival, resulting in a higher number of pest generations during the cropping period.

Pakistan's cotton agroecosystems are home to almost 145 insect pest species such as bollworms, whiteflies, thrips and leafhoppers. The population explosion of pink bollworm and sucking pests has been positively correlated with the rise of temperatures during the autumn season (Shahzad et al., 2022). In recent years, green leafhopper (Amrasca biguttula biguttula) infestations in South Asia also showed that high humidity and rainfall levels could worsen infestations and result in significant crop losses (Azrag et al., 2025). Heat and drought stress also compromise jasmonic acid and salicylic acid defense pathways, thereby decreasing the plants natural resistance to herbivory and pathogen attack.

The results show that climate warming influences the abundance, geographical distribution and resistance dynamics of pests and thus makes traditional pest management more complicated. Therefore, IPM systems based on predictive climate analytics, pheromone monitoring, remote sensing and digital surveillance platforms are becoming increasingly relevant. Other approaches that are promising for enhancing cotton resilience to climate-driven pest outbreaks include biotechnology-based strategies such as CRISPR-mediated insect resistance, RNA interference (RNAi) and genomics-assisted resistance breeding.

### 3.2 Cotton Disease Spread and Viral Losses

Cotton diseases, especially viruses, also are significantly affected by climatic factors. Of these, Cotton Leaf Curl Virus (CLCuV) is one of the most devastating diseases of cotton

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crops in South Asian countries and accounts for up to 30-35% yield loss in Pakistan during an epidemic (Ali et al., 2019).

Whiteflies are the main vector of CLCuV, whose populations are greatly influenced by high temperature and humidity. The effects of climate variability on vectors' capacity to survive, reproduce and enhance their efficiency to transmit viruses increases the severity of the disease. Warm winter weather can also exacerbate the survival of the whitefly and increase the disease pressure during the growing season. In the coming few years, due to climate variability, pest infestation and viral disease outbreaks, severe reductions in cotton arrivals had been reported from Pakistan (Ali et al., 2019).

Additionally, the vulnerability of first-generation Bt cultivars and widespread adoption of uncertified seed contribute to susceptibility to pests and diseases in the future under changing climatic conditions (Ojdowska et al., 2025; Nagaraj et al., 2024). New opportunities are opening up in viral disease management thanks to the recent progress in genomics and biotechnology. CRISPR-based genome-editing technologies addressing genes involved in host susceptibility and transcriptomic studies of host–virus interactions are becoming promising technologies to enhance resistance against CLCuV and related pathogens.

### 3.3 Pest resistance and management strategies

Pesticide overuse and climate variability are driving the rise of pest resistance in cotton systems, especially in Pakistan (Nagaraj et al., 2024). Overuse of pesticides puts pressure on pest populations to develop resistance and also disturbs ecology and decreases beneficial insect populations. With warming temperatures, the rate of pest reproduction increases and their life cycles shorten, further increasing the likelihood of the development of resistance, which will limit the effectiveness of pest control measures over time.

An integrated approach to pest pressures (Integrated Pest Management, or IPM) is more sustainable than others. IPM incorporates resistant cultivars, biological control, cultural control, pheromone traps and judicious pesticide applications to reduce pest populations and minimize ecological damage. The cultivars relatively resistant to the major sucking

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pests (CKC-6 and MNH-Shan) were identified in Pakistan and found to show better yield stability in the presence of sucking pests (Ullah et al. 2025). Similarly, surveys further report that numerous cotton farmers in Pakistan have encountered repeated infestations by pests due to climate anomalies like heat waves, irregular rainfall and extended humid conditions (Arshad et al., 2021).

A digital agriculture approach to monitoring and management, including the use of remote sensing, AI-based pest monitoring and surveillance, predictive climate models and early-warning systems, is gaining increasing momentum in modern IPM systems. Furthermore, new biotechnology techniques, such as genomics-assisted resistance breeding, RNAi-mediated pest suppression and engineering insect-resistance pathways using CRISPR, will help ensure the sustainability and effectiveness of future cotton protection systems in the face of climate change. The most significant expected changes in important cotton pests and diseases in response to climate change are summarized in Table 2.

*Table 2. Climate-Driven Pest and Disease Dynamics in Cotton Ecosystems*

| **Pest/Disease** | **Major Climate Driver** | **Cotton Impact** | **References** |
|---|---|---|---|
| Pink bollworm (Pectinophora gossypiella) | Warmer seasons and mild winters | Increased generations, severe boll damage, reduced lint quality | Hussain et al. (2023) |
| Whitefly (CLCuV vector) | Elevated temperature and humidity | Increased viral transmission and 30–35% yield loss | Ali et al. (2019) |
| Green leafhopper (Amrasca biguttula biguttula) | Increased rainfall and humidity | Severe outbreaks and 20–30% yield reduction | Azrag et al. (2025) |
| Bt resistance | Pesticide misuse and warming | Reduced effectiveness of Bt cotton technologies | Nagaraj et al. (2024) |

## 4. Extreme Events and Socio-Economic Impacts

The production of cotton is being impacted by various extreme events caused by changes in climate globally, which have significant economic and socio-economic consequences,

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such as heatwaves, floods, monsoon variations and droughts (Arshad et al., 2021). Such climatic events have a negative impact on the quality of the fiber and productivity of cotton and have an impact on the entire value chain such as the ginning industries, textile processing, export markets and rural livelihoods. Cotton cultivation is highly climate-sensitive and has been severely impacted in Pakistan by frequent flooding, heat waves and pest attacks, which have significantly lowered yields. Cotton yields are also lower, costs of production have increased and profitability is a concern, which further jeopardizes farmer livelihoods and market stability.

### 4.1 Economic Disruptions in Agriculture

Climate extremes are significant determinants of cotton production instability and have significant economic impacts on agricultural economies (Arshad et al. 2021). The 2022 floods resulted in almost 40% of the cotton productivity reductions in the severely affected parts of Pakistan while the overall cotton production reduced by around 41% during 2022-2023 due to floods, pest attack and climatic variability (Schattman et al., 2023; Mehmood et al., 2024). Other climate disasters have affected crops in the United States and India. This disruption affects farm income, leads to instability of the textile industry and adds to the production cost because of the increased demand for irrigation, pesticides usage and replanting expenses. The smallholder farmers are especially at risk due to their reduced access to adaptation technologies and financial resources. Crop insurance schemes and technologies such as early-warning systems and stress-tolerant cultivars created using molecular breeding and CRISPR-based technology could help lower economic vulnerability in the face of climate change.

### 4.2 Social Vulnerability and Farmer Livelihoods

Climate-induced shocks have a significant impact on rural livelihood and social stability in cotton growing communities (Arshad et al., 2021). Pakistan has almost 1.7 million households directly engaged in cotton farming, which is crucial for their livelihoods and employment (Mehmood et al., 2024). Farmers suffer from distress sale of farm assets, getting into debt and loss of household resilience due to repeated exposure to the effects of heatwaves, flooding, irregular rainfall and pest outbreaks (Ashraf and Iftikhar, 2013).

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Crops repeatedly fail, which also limits the availability of good seed, fertilizers, water facilities and better technologies, thus perpetuating cycles of poverty and vulnerability. Providing farmers with stress-tolerant cultivars produced with biotechnology, digital agriculture platforms and climate-smart extension services can enhance their adaptation and livelihood security in future climatic conditions.

### 4.3 Market Fluctuations and Supply-Chain Challenges

The direct impacts of climate variability on the market instability, price volatility and disruptions in global cotton supply chains (Das et al., 2025). Unpredictability in the availability of cotton because of climate change impacts is a reality for producers, traders, textile industries and export markets. The impact of compound climatic events can also be enhanced upon the disruption of global supply chains as was seen in the 2010 floods in Pakistan and the 2010 Russian wildfires (Arshad et al., 2021). Production uncertainty due to climate change is also making commodities more difficult to price and predict the market. Thus, financial instruments, forecasting systems based on AI and predictive models are increasingly being implemented to mitigate market risks and enhance supply-chain resilience (Mitchell, 2028; Das et al., 2025). Moreover, yield stabilization via biotechnology technologies that produce cotton crops that are more resilient to climate change could also contribute to greater long-term supply security and economic sustainability in the face of future climate variability and change. Figure 2 shows how climate variability affects cotton production and supply-chain systems in cascading socio-economic impacts.

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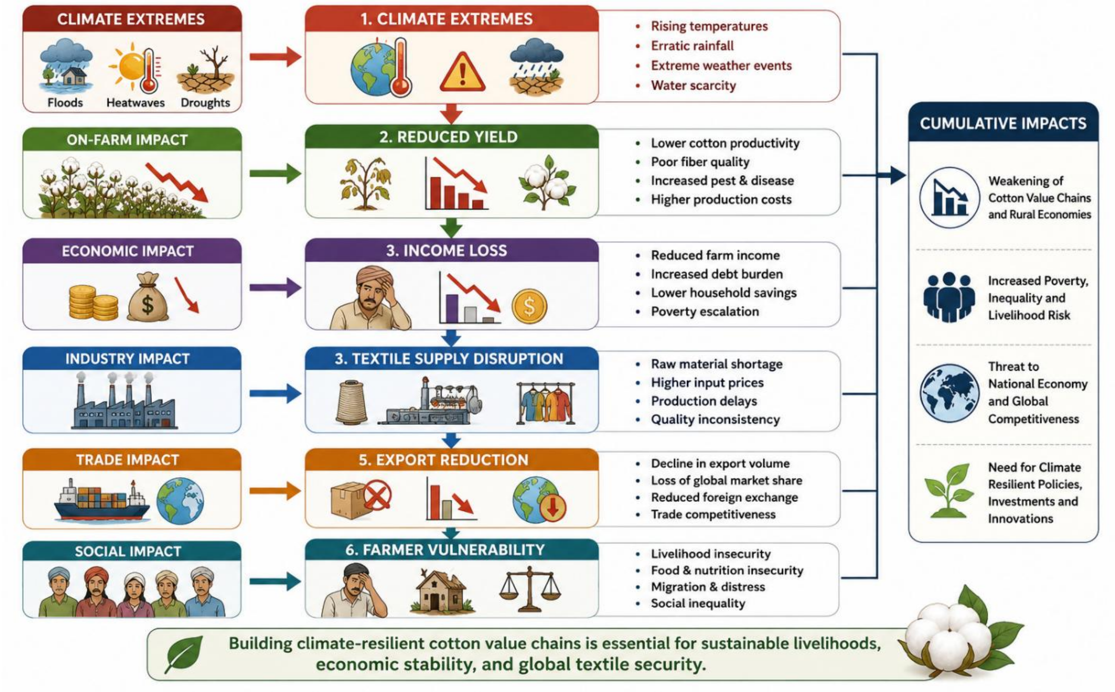
Figure 2: Socio-Economic Impacts of Climate Change on Cotton Value Chains



# 5. Regional Focus

## 5.1 Climate Smart Agriculture (CSA) and Agroforestry Initiatives

Pakistan's cotton belt is facing climate-related stresses and Climate-Smart Agriculture (CSA) is seen as a suitable adaptation measure (Zheng et al., 2024). CSA combines sustainable agronomic approaches, efficient resource use and climate adaptation strategies to boost productivity and resilience. Sowing drought resilient crops, agroforestry and laser land leveling are contributing to better yields, water use efficiency and soil conservation in semi-arid cotton areas. A CSA project in the town of Chakwal and Bhakkar has recorded an almost 22% increase in yield, 45% reduction in water consumption and 60% reduction in soil erosion (Rao and Moharaj, 2023).

Agroforestry systems also provide important environmental and socio-economic benefits. Wind erosion and cotton productivity were decreased by tree planting projects in cotton growing areas, which helped to control the microclimate, increase the soil organic carbon content and conserve soil moisture (Fernandez et al., 2022). These nature-based adaptations increase the adaptability to climate variability in the long-term (Mourad et al., 2020). CSA systems will be even more effective with the integration of genomic selection bred and genome edited stress-tolerant cultivars of cotton.

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### 5.2 Development of Resilient and Low-Input Cotton Varieties

Tolerant cotton cultivars for environmental stresses are increasingly important to ensure cotton producers maintain productivity. In Pakistan, heat and drought-tolerant varieties have been developed by institutions like NIAB and CCRI Multan which have improved yield stability under adverse conditions (Shahzad et al., 2022). The increased yields reported by farmers growing these improved varieties have ranged from around 20–40%.

Multi stress-tolerant cultivars development has been expedited by the recent improvement realized by biotechnology such as marker-assisted selection (MAS), genomic selection, GWAS and genome editing via CRISPR/Cas. Biochar, poultry manure and farmyard manure application are also effective in enhancing soil fertility and cotton production under climate stress (Ahmad et al., 2021). Moreover, the use of biofertilizers and plant growth-promoting rhizobacteria (PGPR) leads to better nutrient uptake, root development and tolerance to stress, which supports sustainability without relying on excessive chemical inputs.

### 5.3 Information, Institutional Support and Farmer Capacity

To support farmer adaptation under climate variability, institutional support and access to agricultural information are key (Ahmed et al., 2019). The implementation of digital agriculture interventions like the Digital Dera program in South Punjab has allowed farmers to receive weather forecasts, pest alerts, irrigation advice and real-time agronomic data, thus enhancing their ability to make informed decisions about their crops (Mehmood et al., 2024).

But, constraints on credit facilities, certified seed, irrigation facilities, crop insurance and extension services persist and limit the adaptive capacity of smallholder farmers (Khan et al., 2020). Enhancing the capabilities of the agricultural extension systems, farmer awareness programmes and conservation agriculture practices is therefore necessary (Mourad et al., 2020). By combining genomic information with digital advisory tools, adoption of climate-smart cultivars and precision-agriculture technologies may be further facilitated in the future under climate scenarios.

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## 6. Approaches to Adaptation and Mitigation

### 6.1 Climate-Smart and Regenerative Agricultural Practices

Climate-Smart Agriculture (CSA) offers a promising approach to enhance cotton resilience under elevated climate risks by implementing water-smart irrigation, precision nutrient management and integrated pest management (IPM) practices (Farah et al., 2025). Deficit irrigation and regulated deficit irrigation (RDI) systems have the potential to reduce water availability while maintaining cotton productivity and simultaneously increasing water-use efficiency (WUE) (Zheng et al., 2024).

In cotton-based systems, regenerative agriculture techniques like intercropping, agroforestry, cover cropping and organic amendment enhance soil structure, microbial activity, carbon sequestration and water retention (Scholar et al., 2023). These practices also help in lowering the input costs and enhance the farm resilience to climatic shocks (Rao and Moharaj, 2023). Genomic selection and CRISPR-based technologies for developing stress-tolerant cultivars can further bolster CSA systems in future climate scenarios.

### 6.2 Enhance Soil Health and Water-use Efficiency

Cotton production systems need to be resilient to climate change and soil health management plays a critical role in achieving this goal. Incorporating no-till, residue retention, cover cropping and soil organic carbon (SOC) into practice can enhance water infiltration, water holding capacity and soil stability during drought and extreme rainfall (Nouri et al., 2021). The improved SOC also contributes to the stability and activity of the rhizosphere, which protects the physiological processes under stress.

Root-system architecture is another adaptation characteristic since greater access to soil water and drought tolerance are achieved with deeper and larger root system (Giband and Kranthi, 2023). More and more traits related to root development, osmotic adjustment and stress-responsive gene expression are under focus via marker-assisted selection, genomic selection and CRISPR/Cas genome editing. Beneficial rhizosphere microorganisms and microbiome engineering also have potential application to enhance nutrient-use efficiency and stress tolerance in degraded soils.

### 6.3 Digital Innovations, Citizen Science and Policy Support

Digital agriculture technologies such as artificial intelligence-based platforms, Internet of Things (IoT) based monitoring systems, remote sensing and predictive climate analytics are revolutionizing the way climate adaptation is being worked out in cotton production systems (Alreshidi, 2019). These tools facilitate real-time weather forecasting, scheduling of irrigation and tracking of pests and climate risks, enhancing precision agriculture and climate-informed decision-making (Farah et al., 2025).

Such participatory methods as tricot trials promote farmer–researcher partnership and promote the adoption of climate-smart cultivars (Mourad et al., 2020). Moreover, policy measures, extension programs and financial support are also crucial for scaling up CSA practices and enhancing farmer adaptation. Digital infrastructure, Biotechnology research, certified seed systems and extension services to promote climate-resilient farming will play critical roles in maintaining cotton productivity in the future. The incorporation of genomic and environmental data into crop models driven by AI can potentially be used to enhance site-specific adaptation and precision-management strategies. The key adaptation and mitigation strategies for cotton production systems to remain climate resilient are summarized in Table 3.

*Table 3. Climate-Smart Agriculture and Adaptation Strategies for Cotton Production*

| **Strategy** | **Major Approach** | **Climate Benefit** | **Biotechnology Link** | **Reference** |
|---|---|---|---|---|
| Deficit irrigation | Water-saving irrigation | Improved WUE | Stress-tolerant cultivars | Ahmed and Schmitz (2011) |
| Agroforestry | Tree integration | Reduced canopy temperature | Climate-resilient genotypes | Luqman et al. (2025) |
| CRISPR breeding | Gene editing | Multi-stress tolerance | Genome editing | Nagaraj et al. (2024) |
| Digital agriculture | AI + IoT | Early warning systems | Predictive genomics | Farah et al. (2025) |

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## 7. Future Directions

There is a need for a more integrated approach to developing cotton-production systems resilient to climate change, which includes genetics and biotechnology, agronomy, digital agriculture, pest management and policies. Further studies should take a systems level approach and multi-stress approach to better mimic field conditions under climate variability.

### 7.1 Developing Multi-Stress Resilience through Breeding

Breeding efforts should focus on cultivars that are heat, drought, salinity, waterlogging and pest resistant, but also have good yield and fiber quality. Stress-tolerance traits could be introduced into elite cotton cultivars at an earlier rate through marker-assisted selection and/or genomic selection. The wild Gossypium species can also serve as valuable genetic resources for the identification of adaptive alleles associated with climate resilience. The combination of genomics, transcriptomics and metabolomics could further complement the identification of multi-stress tolerance trait (Luqman et al., 2025).

### 7.2 Utilization of Genome Editing Technologies

The genome-editing technologies, especially CRISPR-Cas9, offer an excellent toolset to make specific modification in stress-responsive genes of cotton. These technologies can be used to develop heat- and drought-tolerant crops by targeting genes for heat tolerance, antioxidant defense, osmoprotectant accumulation and drought-responsiveness. In addition, new technologies like base editing and prime editing are also being employed in the development of cotton cultivars that are more resistant to climate change without the addition of foreign DNA (Luqman et al., 2025).

The use of genome editing also has the potential to enhance resistance to viral diseases and insect pests by altering host susceptibility genes or defense-related pathways. In Figure 3, a schematic overview of the editing of stress-responsive pathways related to ROS scavenging, osmoprotectant biosynthesis and transcriptional control is shown.

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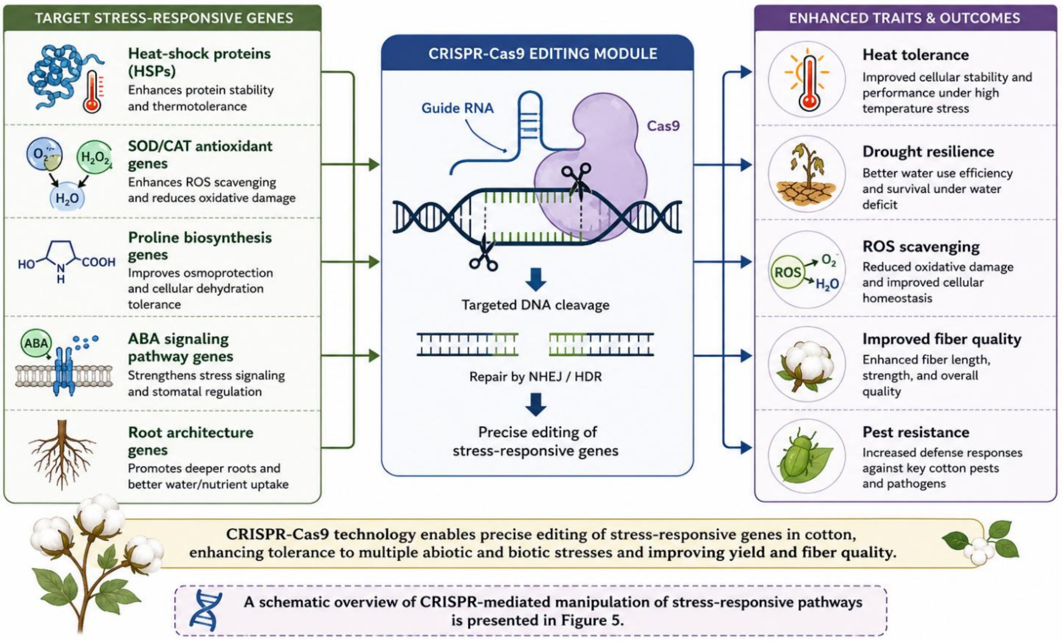
Based on the information provided in Figure 3, the major cotton stress tolerance targets of CRISPR-Cas9 should include heat-shock proteins (HSPs), antioxidant enzymes like SOD, CAT, osmoprotectants such as proline, glycine betaine and regulatory transcription factors of abiotic stress adaptation.

**Figure 3: CRISPR-Cas9-Mediated Editing of Stress-Responsive Pathways in Cotton**



CRISPR-Cas9 technology enables precise editing of stress-responsive genes in cotton, enhancing tolerance to multiple abiotic and biotic stresses and improving yield and fiber quality.

A schematic overview of CRISPR-mediated manipulation of stress-responsive pathways is presented in Figure 5.

### 7.3 Omics-Guided Trait Discovery

The transcriptomics, proteomics, metabolomics and phenomics approaches can be of great value to identify genes, proteins, metabolites and regulatory pathways involved in tolerance to heat, drought, salinity, waterlogging and pest pressure. Machine learning will be used to integrate various omic data sets and enhance prediction of traits which will aid in developing climate-resistant cotton cultivars (Luqman et al., 2025).

### 7.4 Field-Level Climate-Smart Agronomic Practices

Climate-smart agronomic practices, including reduced tillage, residue management, cover cropping, organic inputs and irrigation water use efficiency are critical to enhancing soil fertility, water holding capacity and climate stress resilience. It is also recommended that cotton productivity be enhanced under adverse environmental conditions through integrated nutrient management with the application of biochar, poultry manure and

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balanced fertilizers (Ahmad et al., 2021). These cultural practices, in combination with the stress tolerant cultivars, can improve long-term productivity and sustainability.

### 7.5 Digital Agriculture for Adaptive Management

AI, IoT, remote sensing and mobilized advisory systems are some digital technologies that can aid in making real-time decisions based on the climate information used in cotton production (Alreshidi, 2019). Tricot trials and other participatory methods can speed up the speed of uptake of climate-smart varieties and enhance farmers' involvement in adaptation measures (Mourad et al., 2020). The use of digital tools along with site-specific genomic and environmental data can help inform site-specific varietal recommendations and precision management.

### 7.6 Institutional Support Systems

To build smallholder resilience to climate variability, institutional support such as subsidies, crop insurance, certified seeds distribution, extension services and farmer training programmes will be critical (Ahmed et al., 2019). Improving public–private partnerships and extension networks can help speed up the uptake of innovation and climate-smart agriculture practices through biotechnology (Misra et al., 2023).

### 7.7 Climate-Informed Integrated Pest Management

To incorporate resistant cultivars, biological control, pheromone monitoring and a climate-based pest forecasting system into future pest-management strategies (Ullah et al., 2025). Under changing climatic conditions, there is potential for resistance management and avoidance of pesticide and Bt resistance through availability of predictive surveillance systems and genomic monitoring of pest populations (Nagaraj et al., 2024).

### 7.8 Climate-Integrated and Interdisciplinary Research

An interdisciplinary research approach that includes genetics, biotechnology, agronomy, climatology, soil science, pest ecology and socio-economics must be taken up in future research. Crop modeling and experimental research ought to increasingly consider compound stresses, like heat × drought and drought × salinity, as a way to better develop adaptation strategies at the regional level (Das et al., 2025).

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### 7.9 Regional and global cooperation

Regional and international partnerships will play a vital role in enhancing climate resilience of cotton systems. There are collaborative networks that can help with germplasm exchange, sharing of climate data, pest surveillance, biotechnology research and policy coordination. Increased collaboration between cotton-growing regions could help to speed up the progress of cultivating climate-resilient cultivars and adaptation strategies in the future climate scenario (Khan et al., 2025).

## 8. Conclusion

Climate change is a serious threat to the production of cotton (Gossypium hirsutum L.) which is very important for the rural livelihoods and textile industries in developing countries including Pakistan. Temperatures, drought, floods, salt and pest infestation all contribute to the diminishing cotton growth, yield and fiber quality with the growing temperatures and alteration in climate.With the increasing temperature and changing climate, cotton growth, yield and fiber quality are becoming a problem due to rising temperatures, drought, flooding, salinity and pest outbreak. Flooding and soil degradation also decrease productivity and heat and drought stress affect photosynthesis, reproductive growth and fibre development. The increased pressure from pest and disease due to climate warming also poses a threat to the sustainability of cotton-based production system. Another important socio-economic aspect is that the socio-economic vulnerability of farmers and market price fluctuations are greater due to yield fluctuations, growing expenses and climate-induced crop failures. Integrated climate-resilient production systems that integrate CRISPR-based genome editing, omics-guided breeding, genomic selection, climate-smart agriculture, digital decision-support tools, integrated pest management and supportive policy frameworks are needed to address the challenges. Under future climate uncertainty, stress-tolerant cultivars, efficient resource management, farmer-centered innovation and greater institutional and global cooperation will be the key elements for achieving long-term sustainability of cotton production.

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