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Review Article

Sustainable Cotton Production in the Era of Climate Change: Challenges and Adaptive Measures

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ABSTRACT

Climate change is impacting agriculture, particularly cropping systems, in Pakistan due to rising temperatures and changing precipitation patterns. The cultivation of cotton (*Gossypium spp.*), a globally significant fiber crop, is becoming increasingly vulnerable to the adverse impacts of climate change. Cotton crops face various stresses due to climate change, including extreme temperature stress, drought stress, and salinity stress. Elevated temperatures during the reproductive phase of cotton adversely affect its growth and productivity by disrupting critical physiological processes, including germination, root development, and fruit formation. Similarly, drought stress remains a major limiting factor, particularly in arid and semi-arid regions where cotton is predominantly cultivated, resulting in suppressed plant growth and significant yield losses. Plants employ their mechanisms to adapt to drought conditions, but excessive moisture can also negatively impact growth and yield. Excessive salts in the soil profile and irrigation water trigger salinity stress, which adversely impacts cotton's vegetative and reproductive growth, with young seedlings being especially sensitive. Air pollution stress, particularly ozone, can damage cotton plants, affecting yield and photosynthetic efficiency. Sustainable management practices, including mulching, cover cropping, and improved irrigation, play a pivotal role in minimizing stress-induced losses in cotton. Simultaneously, breeding for enhanced heat and drought tolerance is imperative for cultivar development. The chapter underlines the crucial role of water management, timely irrigation scheduling, and the strategic use of plant growth regulators (PGRs) in optimizing cotton productivity. Furthermore, the application of Decision Support Systems (DSS) and ICT tools supports efficient resource utilization and improves cotton growers' capacity to adapt to climatic challenges. Climate-smart agriculture (CSA) practices, aimed at boosting productivity, enhancing adaptability to climatic stresses, and curbing greenhouse gas emissions, are crucial for the sustainability of cotton farming. Climate-smart cotton practices and technologies can enhance production, improve farmers' livelihoods, and mitigate the adverse impacts of climate change on cotton cultivation. Adopting a climate-smart cotton production system is crucial for ensuring the sustainability of cotton cultivation in the face of the climate change challenges of this era.

Keywords: Climate change, Agriculture, Cotton, Drought, Salinity, Heat stress, Climate-smart agriculture.

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INTRODUCTION

Cotton, also known as 'white gold,' is one of the world's most important fiber and cash crops that significantly contributes to the Gross Domestic Product (GDP) developing countries (Khan et al., 2020). It serves as a main source of natural

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cellulose-based textile fiber, contributing to a range of industrial and agricultural applications and providing economic stability for millions of farmers worldwide (Shahrajabian *et al.,* 2020). Cotton being a climate-sensitive crop, requires specific temperature, soil conditions, and water for optimal growth. Rising climate variability and environmental stress factors pose a significant threat to the sustainable production of cotton. In cotton-dependent economies, failure to develop tolerant varieties will disrupt the supply chain and increase financial pressure, as global demand is projected to rise.

Commercial cultivation on a global scale is limited to only four out of the fifty identified species of wild cotton. These species are exclusively found in tropical and subtropical regions. The four most predominant species of cotton are *Gossypium arboreum*, *Gossypium barbadense*, *Gossypium herbaceum*, and *Gossypium hirsutum*. Regions located above thirty degrees' north latitude primarily cultivate cotton. Cotton growers exclusively cultivate cotton in non-tropical areas, especially during summer (Afzal *et al.,* 2020). Varying species of cotton exhibit variations in the micronaire, maturation, length, and strength of their fibers. The level of adaptation of a species to a certain habitat is contingent upon the genetic composition of the crop and the prevailing environmental conditions. G. *hirsutum* species is responsible for producing high-quality cotton and accounts for almost 90% of global cotton production. The plant is extensively cultivated because of its enhanced productivity and excellent adaptability to several agro-environmental conditions (Yang *et al.,* 2020). Conversely, in certain regions, elevated temperatures can lead to the sterilization of cotton and result in boll shedding (Sable *et al.,* 2018). Alternative cotton species are more prevalent in Asia and Africa due to their low productivity and limited ability to adjust to changing climatic conditions (Saleem *et al.,* 2021). The climate and environment of the region impact cotton production.

In the textile industry, it makes a minimum annual contribution of $600 billion to global economic activity. Its cultivation covered over 33 million hectares of land in over 100 countries (Khan *et al.,* 2020). The leading cotton-producing countries include Burkina Faso, India, China, United States, Pakistan, Brazil, Australia, Uzbekistan, Turkey, and Turkmenistan (Tokel *et al.,* 2022). China cultivates cotton as its primary agricultural product in 24 provinces out of its 35 provinces. The United States of America is the global leader in cotton exports, where the states of Mississippi, Louisiana, and Arkansas are among the primary producing states of cotton. Likewise, Brazil is the fourth-largest exporter of cotton globally, with most of its agricultural land dedicated to cotton farming (Matloob *et al.,* 2020). Pakistan is a significant producer and consumer of cotton. The cultivation of cotton has a lengthy historical background, commencing with the Indus Valley Civilization (Prasad, 2018).

Cottonseed is highly valued and plays a crucial role in animal feed, paper production, pharmaceuticals, and cooking oil industries. (Kumar *et al.,* 2021). Cotton fiber is extensively used in a diverse range of products due to its numerous advantageous characteristics, such as comfort, color retention, absorbency, and strength (Khan *et al.,* 2020). Weather conditions significantly influence the growth and development of crops. Temperature is the main factor that decreases agricultural productivity, making it an important variable in crop growth. Erratic weather patterns frequently impede cotton production, with high heat becoming a significant concern. Most cotton farmers in developing countries persist in using conventional methods and technology for managing their crops, hence worsening the significant issues and difficulties arising from their failure to embrace contemporary production practices and technologies (Zulfiqar and Thapa, 2021).

Cotton fields use a greater amount of fertilizer, leading to an increase in greenhouse gas (GHG) emissions, specifically carbon dioxide (CO_2) emissions, thus contributing to global warming (Hedayati *et al.,* 2019). The perpetuation of conventional plowing practices among farmers is a causative element in the increase of greenhouse gas emissions. The primary issue is the inefficient use of pesticides, water, fertilizers, and radiation in the present cotton cultivation technique. Conventional cotton cultivation results in substantial resource inefficiency and increased production expenses (Zulfiqar and Thapa, 2021).

The cotton yield is very vulnerable to climate extremes, and its reduced capacity to adapt severely undermines its resilience to climate change. Decades of breeding efforts have focused on yield improvement and pest resistance, particularly after the introduction of Bt cotton. While these advancements have enhanced insect resistance**,** they have not provided sufficient tolerance to climate extremes. The existing agricultural system is worsening the problem by utilizing excessive irrigation water and applying excessive quantities of pesticides and fertilizers to cotton crops (Rahman *et al.,* 2020). Investing in climate-smart cotton breeding is essential to safeguarding farmer livelihoods, ensuring stable global cotton production, and sustaining the textile industry. Given the heightened susceptibility of Pakistan's existing agricultural infrastructure to the impacts of climate change, it is imperative to prioritize the sustainable cultivation of cotton to adequately address the country's future requirements.

COTTON PRODUCTION AND CLIMATE CHANGE

The growth and development of the cotton (*Gossypium spp.*) plant progresses through distinct stages, each defined by specific physiological and morphological transitions. These developmental phases are critical for effective crop management, optimizing yield potential, and enhancing fiber quality. Cotton plants go through four major growth stages: germination stage, vegetative stage, reproductive phase, and maturity stage, as represented in Figure 1. Climate significantly impacts crop productivity, affecting development, growth, phenological phases, and yield (Khan *et al.,* 2020) which is described in Figure 2.

As a C3 crop, cotton may benefit from an increase in CO_2 levels; however, higher temperatures may reduce cotton yield. In Indian Punjab, cotton production decreased by 51% as temperatures rose from 28 to 32°C (Jaglan *et al.,* 2012). Researchers observed severe injury throughout the entire process, from seeding to anthesis. Seed cotton output is significantly impacted by elevated summer temperatures in the Punjab and Sindh regions, which surpass 45°C. This is primarily due to the heightened susceptibility of the boll development phase due to heat stress (Ahmad, 2017).

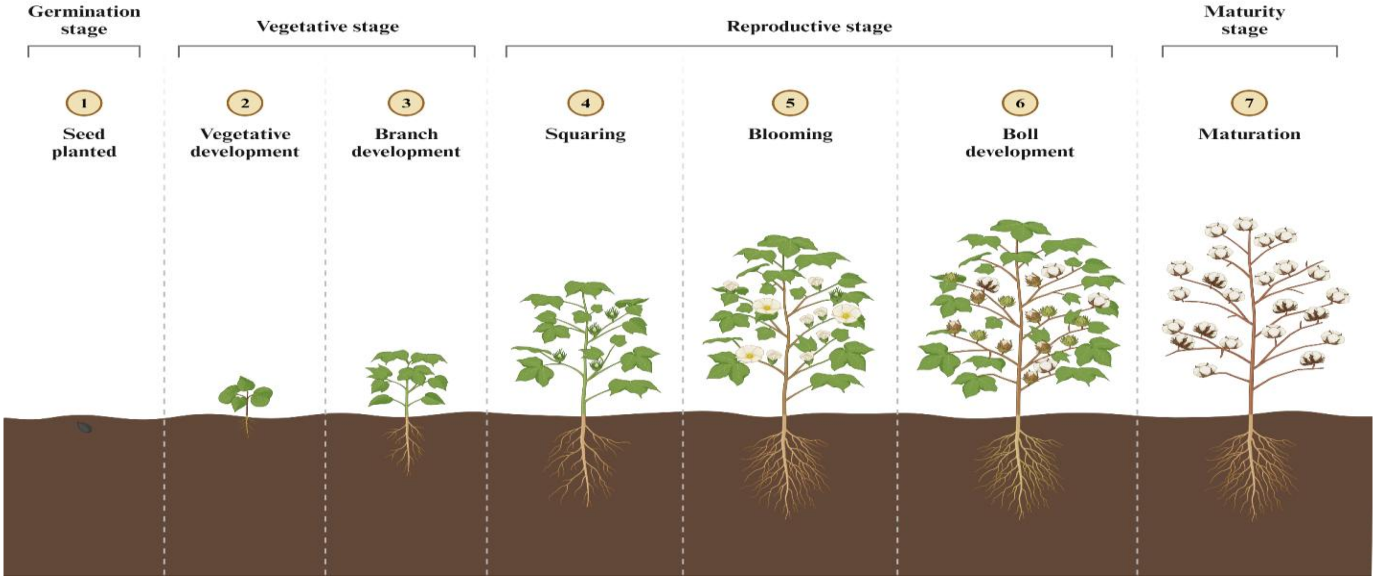

Figure 1. Cotton plant growth and development under normal conditions.

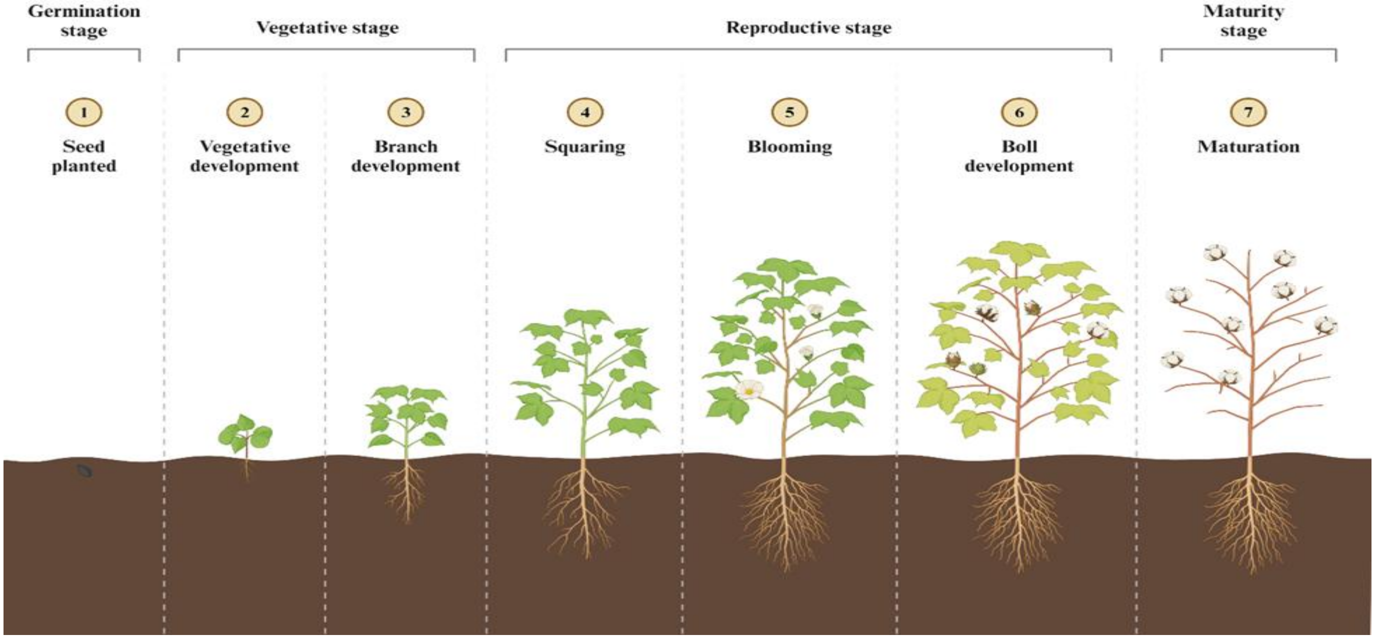

Figure 2. Cotton plant growth and development under climate stress.

THE COTTON CROP EXPERIENCES VARIOUS STRESSES INDUCED BY CLIMATE CHANGE

Cotton yield is predicted to be greatly influenced by moderate and severe climate change. Cotton crop can be affected by extreme temperature stress, drought, salinity, mineral nutrient stress and air pollution stress which is demonstrated in Figure 3.

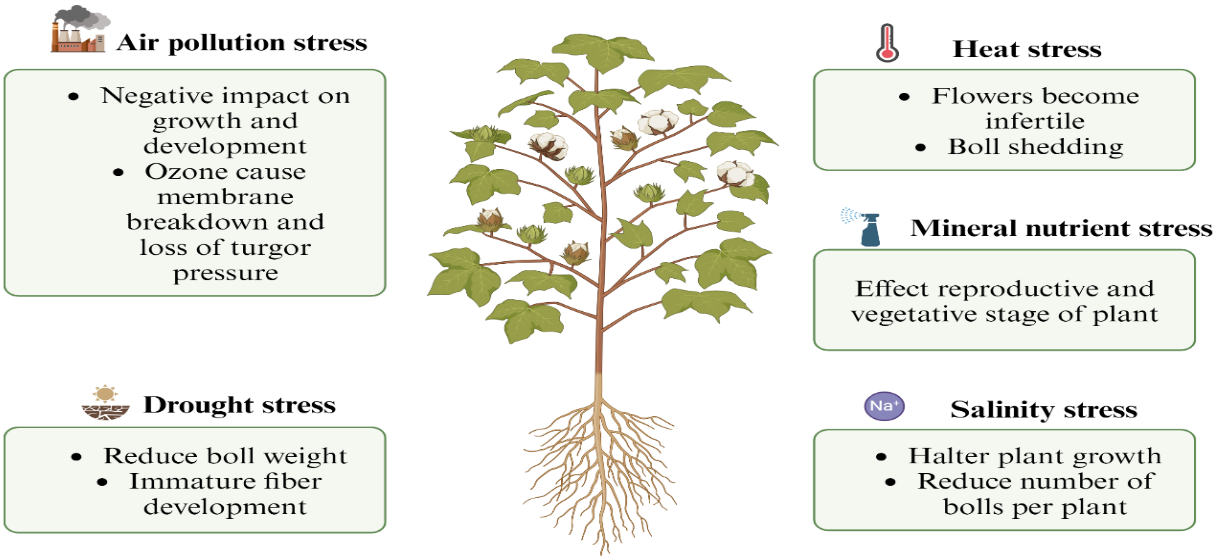

Figure 3. Abiotic stresses faced by cotton due to climate change.

Extreme Temperature Stress

Temperature is the most significant ecological determinant of crop development. The intensification of global climate change has resulted in erratic temperature regimes which is a considerable challenge for cotton productivity.

Its impact starts from the germination/emergence stage onward. Cotton, despite its inherent temperate climates, is significantly compromised by elevated temperatures, particularly at reproductive stage (Saleem *et al.,* 2021). According to (Bange *et al.,* 2022), Literature suggests that 15.5°C (60°F) temperature is required for germination. The ideal temperature for facilitating root development in moist cotton is 35°C. The thermal kinetic window for rainfed cotton is characterized by a temperature range of 23.5 to 25°C. A decrease in temperature from 30 to 18 °C hinders root development due to the reduction in the roots' hydraulic conductivity (Meshram *et al.,* 2021). A temperature increase of just 1°C, as reported by Ahmad et al. (2020), can result in flowering occurring 3.1 days sooner. During the reproductive phase, temperatures increase from 18 to 28°C, during which five to sixteen fruiting branches are produced: however, Pima cottons cease producing fruiting branches at temperatures above 36°C. When temperatures exceed 38°C and the reproductive structure develops, flowers become infertile. Elevated temperatures not only induce oxidative stress but also diminish photosynthetic activity, resulting in the depletion of ATP and carbohydrates. The optimal temperature range for upland cotton metabolic activity efficacy is between 23°C and 32°C. Metabolic activity and membrane functions subsequently decline below 15°C and between 20 and 23°C.

Pakistan has recently experienced a discernible shift in its weather patterns, characterized by elevated mean temperatures and increased night temperatures. The intensity of these changes has escalated in tandem with the rise in greenhouse gas emissions over the past few decades. The influence of climate change on cotton productivity can be pictorially visualized in Figure 4. During 2022-23, the cotton crop was drastically damaged due to the climatic changes. Cotton season started with a 7-10°C rise in temperatures from the last few years in March till May coupled with a shortage of irrigation water, causing severe heatwave, which affected cotton germination, seedlings growth and leaf wilting problem (Economic survey of Pakistan 2022-23).

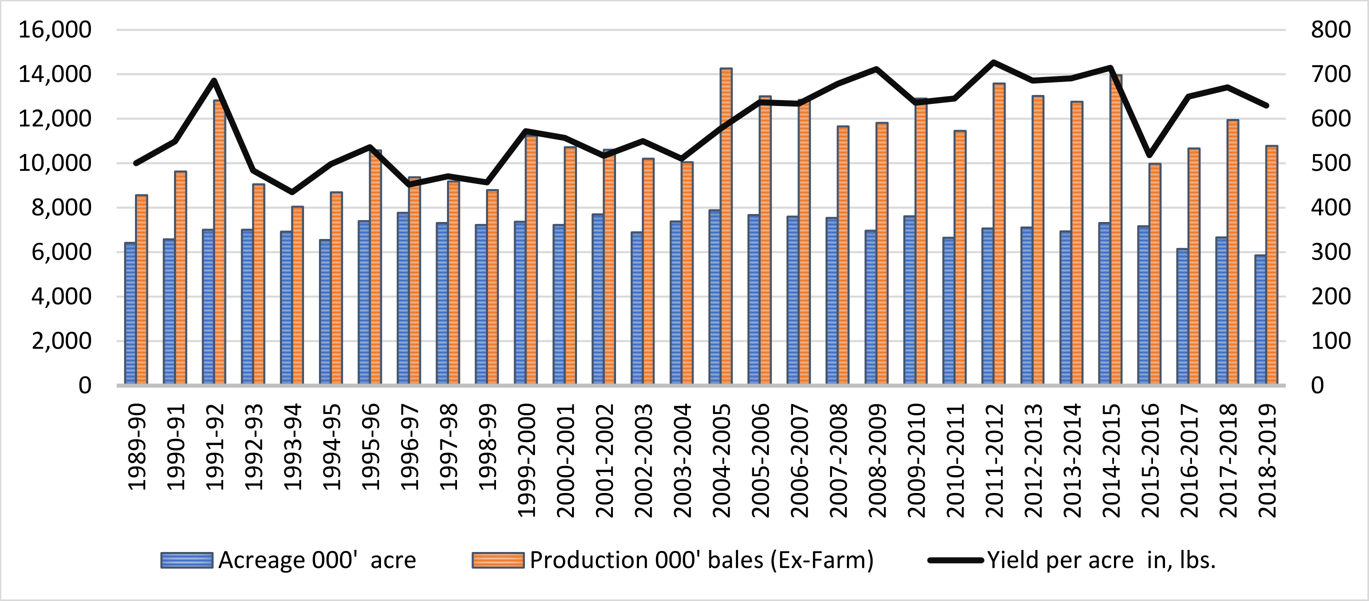

Figure 4. Fluctuations in area, production and yield of cotton in Pakistan due to various biotic and abiotic stresses exacerbated by climate change (Source: http://www.kcapk.com/pakcotstat.htm).

Drought Stress

Drought is the primary abiotic factor that restricts growth. Due to its status as a "xerophyte" Cotton cultivation is prevalent in arid and semiarid regions where irrigation resources are not frequent. It possesses the ability to endure severe weather conditions due to its extensive, deeply ingrained root system and capricious growth pattern. During the life cycle of cotton, water is needed at a rate of 2.0 mm day^{-1} (20,000 L ha^{-1}) during the vegetative stage and 6 to 8 mm day^{-1} (also known as the critical window) during the flowering and early-bulling periods. Despite utilizing 80 to 85 percent of the total water during this "critical window," substantial yield reductions occurred due to moisture stress at this juncture. Despite of addition of nitrogenous fertilizer during the vegetative and boll opening phases, excessive moisture reduces yields and retards growth. Plants employ a variety of coordinated mechanisms, including gene expression, transduction, and stress signaling, to adapt to a stressful environment (Mahmood *et al.,* 2019).

Molecular biological processes and protein synthesis are profoundly altered by drought. Previous studies (Foyer and Noctor, 2009) suggested that oxidative stress happens when the stress signal transduction pathway is activated and reactive oxygen species (ROS) are made at the cellular level at the same time. Drier conditions result in reduced rates of transpiration, stomatal conductance, and net photosynthesis, as well as increased electron transport rates and an effective quantum yield of PSII (pII). Moreover, anthocyanins, malondialdehyde (MDA), and hydrogen peroxide levels increase in response to drought stress (Noreen, *et al.,* 2020). Ethene and abscisic acid synthesis induce the abscission of bolls and other reproductive bodies in unfavorable conditions, resulting in a reduction in fruit retention, boll weight, and yield (Guinn, 1982). Stomatal closure under water-limited conditions limits CO_2 assimilation, reducing carbohydrate synthesis and compromising reproductive development. Consequently, drought stress during flowering and boll formation significantly diminishes boll retention, fiber development, and final yield.

Various reactive oxygen species (ROS) can induce oxidative stress, such as hydrogen peroxide, hydroxyl radicals, and peroxide radicals. When this is the case, antioxidant defense functions act as a scavenger. Antioxidant enzymes, including carotenoids, glutathione reductase (GR), ascorbate peroxidase (AP), and catalase (CAT), function in conjunction with tocopherol to scavenge reactive oxygen species.

The cultivation of one kilogram of fiber and two kilograms of seed requires an average of 1214 liters of irrigation water. Lint deposition necessitates 644 liters of irrigation water per kilogram or roughly 87% of the total agricultural output worldwide. Collecting precipitation and implementing irrigation systems such as alternating furrows, sprinklers, subsurface drip irrigation, and ET-based precision scheduling can increase water flow. In addition to weed suppression, effective insect control, mulching, reduced tillage, intercropping, and cover crops can safeguard soil and its moisture, which ultimately increase yield and water efficiency.

The combined effect of drought stress and elevated temperatures further exacerbates yield losses in cotton. Moreover, climate-induced drought events are often accompanied by increased pest and disease incidences, further amplifying the vulnerability of cotton crops under changing climatic scenarios (Sabagh *et al.,* 2020).

Salinity Stress

Climate change is projected to exacerbate soil salinization, particularly in arid and semi-arid regions where cotton is predominantly cultivated. These areas worldwide account for one-third of all agricultural land affected by salinity. Salinity stress adversely affects cotton growth by inducing osmotic stress, ion toxicity, and nutrient imbalances (Pessarakli, 2021). Salt stress has a significant impact not only on the seedlings but also on the early stages of growth and development after germination. Salinity values exceeding 282 mol m^3 (NaCl) are detrimental to root growth. Shoot growth is hampered by a decrease in soil water potential and a deficit in vapor pressure. During reproductive development, the movement of photo assimilates from source to sink is inhibited. As a result, there are fewer fruiting bodies, larger fruit drops, and boll shedding, all of which result in economically significant yield and fiber quality losses. Furthermore, the length, strength, and fineness of the fiber, as well as the oil content of the seed, decrease (Sharif *et al.,* 2019). Salt stress induces rapid senescence, stomatal closure, and increased resistance to CO_2 diffusion. It produces excessive Na+ and Cl accumulation in leaf tissues and disrupts the flow of osmolytes from source to sink. Furthermore, it produces salt stress and impairs the mobility of chlorophyll constituents 'a' and 'b'. Salt-tolerant varieties have a lower K+/Na+ ratio than salt-sensitive varieties (Maryum *et al.,* 2022).

Cotton plants show tolerance to water and salt stress by increasing the synthesis of amino acids, proline, sucrose, glucose, and K+. Cotton has improved resistance to salt stress when it contains an antioxidant defense system composed of glutathione reductase, catalase, ascorbate peroxidase, and superoxide dismutase (Abdelraheem *et al.,* 2019). Several effective agronomic strategies exist for cultivating cotton:

- Using plastic mulching to maintain plant density at 4-5 plants per square meter
- Rotating between saline and non-saline water for irrigation.
- Drip irrigation or furrow irrigation or sprinkler systems.
- Salt-tolerant cultivars may also be more economical and efficient to cultivate

Mineral Nutrient Stress

Eco-edaphic variables, macronutrients, and micronutrients accessible throughout the growing season impact the efficiency of cotton production. In particular, drought and excessive rainfall induced by climate variability can lead to nutrient leaching, reduced nutrient uptake, and imbalanced soil nutrient profiles (Raza *et al.,* 2019; Twumasi *et al.,* 2024). Cotton varieties that exhibit indeterminate growth require a greater quantity of nutrients during the reproductive phase compared to the vegetative phase. The proportion of nutrients transferred and/or reallocated from vegetative to reproductive organs influences cotton yield. To facilitate assimilation between vegetative and reproductive organs, nutrient absorption is greatest during peak flowering, which coincides with the accumulation of 29% nitrogen, 22% phosphorus, and 21% potassium within plant tissues. The disparity in nutrient demand between above-ground tissues and roots plays a critical role in determining nutrient acquisition in cultivars. The concentration of these nutrients is influenced by various agronomic methods, ecosystems and edaphic variables, cultivar genetic composition, temperature and drought pressures, and rhizosphere nutrient concentration. Separating nutrients by harvestable fraction allows for the calculation of the quantity of nutrients required to achieve the intended harvest (Amissah *et al.,* 2022). Understanding the complex interplay between mineral nutrition and climate variables will facilitate the development of adaptive strategies that enhance cotton resilience and maintain soil health.

Air Pollution Stress

Air pollution, an indirect effect of anthropogenic climate change, adversely influences the physiological and developmental processes of cotton. As reported by Noreen et al. (2020), exposure to primary (N_2, O_2, CO_2, CH_4) and secondary pollutants (O_3, peroxyacetyl nitrate, H_2O_2, and other oxygenated compounds) impairs plant growth and ultimately reduces yield potential. When the amount of ozone (O_3) is higher than 0.25 ppm, the membrane breaks down and some or all the turgor pressure is lost. At concentrations greater than 0.20 ppm, net photosynthesis (Pn) decreases considerably. Another important study suggested that decreased CO_2 absorption efficiency results in decreased yield, photosynthetic efficiency, and leaf abscission in response to O_3 exposure (Grulke and Heath, 2020). The cotton plant, on the other hand, has an internal defense system that permits it to tolerate the damaging effects of O_3. Because of its smaller hydraulic capacity, the root organ is more sensitive to O_3 stress than the shoot organ. Mauney (2010) reported a 65% increase in cotton growth and a 50% increase in yield when the CO2 concentration was raised from 550 to 650 ppm. However, rising temperatures and growing carbon dioxide concentrations may cause cotton production to diminish in the context of changing climate conditions (Reddy *et al.,* 1996). Several exogenous approaches have been employed to alleviate ozone (O_3)-induced stress, including the application of antioxidants like citrate, ascorbate, and ethylene diurea (EDU) [N−2−(2−oxo−1−imidazolidinyl)ethyl]−N′−phenylurea along with the use of overhead sprinklers and the development of O_3-resistant cultivars through both traditional breeding and molecular techniques. (Chaudhary and Rathore, 2021).

AGRICULTURAL PRACTICES FOR CLIMATE-RESILIENT COTTON PRODUCTION

Shifting Planting Time

The production of cotton is severely threatened by climate change, and the severity of its impact is influenced by regional environmental conditions and the average daily temperature. For instance, in Northwest China, it was anticipated that a 1ºC increase in the diurnal temperature range spanning from peak bloom to maturation would lead to a 782.6 kg ha^{-1} increase in yield. An average temperature increase of one degree Celsius during the growing season could, conversely, increase yield by 4,764.9 kilograms per hectare. Yield potential in cotton can improve by about 0.0121 kg ha^{-1} for every additional hour of sunshine received between the budding and anthesis stages, highlighting the importance of light during this growth phase (Huang, 2016). Conversely, in regions characterized by elevated temperatures, the correlation between temperature and yield is inverse. It is significant to mention that an increase of 110 kg ha^{-1} in ambient temperature beyond the optimal range adversely impacts yield (Singh *et al.,* 2007). To ensure sustainable crop production, a robust understanding of climate change-driven challenges is necessary for timely agricultural adjustments. Elevated temperatures intensify the decline in reproductive structures (Tariq *et al.,* 2017). As temperatures increase, early sowing indicates the commencement of the planting season. It is critical to conduct extensive research on regional sowing schedules and modify them accordingly in order to maximize the use of heat sources and other meteorological factors. During specific growth seasons, researchers modify the planting schedule to induce a range of climatic conditions. Researchers focus on an adaptation strategy known as planting schedule adjustment to mitigate the adverse effects of changing weather patterns. ENSO, or El Niño-Southern Oscillation, influences the cotton industry in Georgia. One critical management technique suggested to alleviate the impacts of ENSO is the practice of planting at various periods of the year (Paz *et al.,* 2012). An important study (Afzal *et al.,* 2020) concluded that cotton planting should occur 20 days prior to May 10 in the climate of Faisalabad, Pakistan, in order to mitigate the detrimental impacts of inclement weather on crop yield.

Climate change influences the selection of sowing time. Short-term field experiments spanning two to four years cannot reliably determine estimations of planting windows when long-term climate variability is present. Accordingly, a research team (Anapalli *et al.,* 2016) suggested that thirty years of field research are necessary to account for variations in climatic variables. Notwithstanding the substantial financial outlay and temporal commitment, crop modelling enables the examination of the enduring consequences of climatic conditions by utilizing short-term field investigations as a bedrock.

Water Management

Effective water management is fundamental to sustaining cotton productivity under the increasing incidence of droughts, erratic rainfall patterns, and elevated evapotranspiration rates induced by climate change. Irrigation is the most common practice for growing cotton, according to different scientific findings (Khan *et al.,* 2020). The current adverse weather conditions have changed the need for irrigation. During the monsoon period, irrigation demands decrease significantly due to the unpredictable yet frequent precipitation. Summer cotton is usually planted in the second week of June, coinciding with the start of the monsoon season, and is irrigated by rainfall (Afzal *et al.,* 2020). If ideal precipitation is not present, preplant watering is required to guarantee ideal germination. Cotton needs water to proceed through the pre-budding and blossom growth stages. The cotton season mostly lasts from 150 to 195 days. Two or three further irrigations will take place shortly after the monsoon season to one month later. The needs for irrigation change depending on the region (Wang *et al.,* 2016). Furrow irrigation is typically the most commonly used technique for cotton. Drip irrigation, on the other hand, offers a viable approach to improving irrigation efficiency. Appropriate timing of irrigation in cotton farming plays a key role in reducing water wastage, improving efficiency, and limiting percolation caused by excessive water use. Irrigation is an essential cultural technique that complements precipitation in some locations and gives support in dry and semiarid regions, much like agriculture and the use of fertilizers. Generally speaking, crop water requirements do not align with the temporal distribution of precipitation; as a result, higher irrigation is required to maintain agricultural production. Supplementary irrigation can be used for the following reasons to lessen the stress caused by soil water deficit: incorporating herbicides, enhancing nutrient absorption, promoting plant growth, alleviating water stress, reducing square and boll loss, preserving fiber quality, and maximizing yield potential.

The seasonal demand for water

Similar to other crops, the seasonal water requirement of cotton fluctuates with the changing weather. Plants transpire more water in arid and elevated temperatures to increase biomass production and body temperature regulation. The concept of evaporative demand encompasses the role of environmental factors like air temperature, solar radiation, humidity, wind velocity, and cloudiness in determining the water needs of plants. The moisture content of the soil serves as an indicator of the amount of water necessary to supply the rhizosphere with water for evaporative purposes. Plants cannot obtain sufficient water to fulfil their evaporative requirements when the soil moisture level is inadequate.

Science and Art Applied to Irrigation Scheduling

When, where, and why crops ought to be irrigated constitute the three primary components of crop irrigation scheduling. The primary objective of irrigation is to maintain a moderate level of water consumption throughout the growing season, thereby facilitating unrestricted soil moisture that is essential for the optimal development and growth of plants. Conversely, effective irrigation management maintains inter-cyclical moisture stress levels at a level sufficient to regulate vegetative growth by the requirements of the plants (DeJonge and Thorp, 2017).

Utilization of Plant Growth Regulators to Improve Cotton Yield in Variable Environments

Researchers have made significant progress in the use and development of plant hormones, or PGRs, for horticultural, agricultural, and vinicultural crops worldwidely over the past few decades. Plant growth regulators (PGRs) are important parts of plant systems because they help enzyme networks work, biotic and abiotic stresses are reduced, physiological, biochemical, and anatomical processes speed up or slow down, crop yield and quality are increased, and storage time is extended. Additionally, pest management practices such as defoliating plants and harvesting immature green bolls at maturity are employed to mitigate the occurrence of pest infestations. The application of mepiquat chloride to square and foliar areas of the crop leads to elevated concentrations of gossypol. Consequently, the ingestion of these regions by bollworms results in a reduction in their population. The process of breeding crop cultivars to exhibit increased resistance or tolerance to shifting climate conditions is both labor-intensive and expensive (Noreen, *et al.,* 2020). Utilizing exogenous PGR is not only economical but also harmless to the ecology. A majority of cotton producers are well-equipped with the necessary spraying tools and expertise to manage crop health. PGR utilization is considered a "shotgun" approach to extracting "white gold" through cotton crop manipulation in the context of imminent climate change. Various factors, including formulation chemistry (such as solvents, surfactants, and water quality), growth stage, variety genetic composition, canopy temperature, and epidermal morphology, as well as the concentration of the active ingredient, influence PGR efficacy. In the coming days, there is an increasing need to develop knowledge and implement PGRs in order to realize the potential benefits of the expanding footprints caused by climate change.

Germplasm Improvement for Heat and Drought Stress Tolerance

The imposition of heat and drought stress results in detrimental effects on cotton cultivation by triggering physiological and biochemical disturbances. In general, plant height, boll development, fiber quality, and root growth are all hindered by drought (as represented in Figure 5) and heat stress (Sabagh *et al.,* 2020).

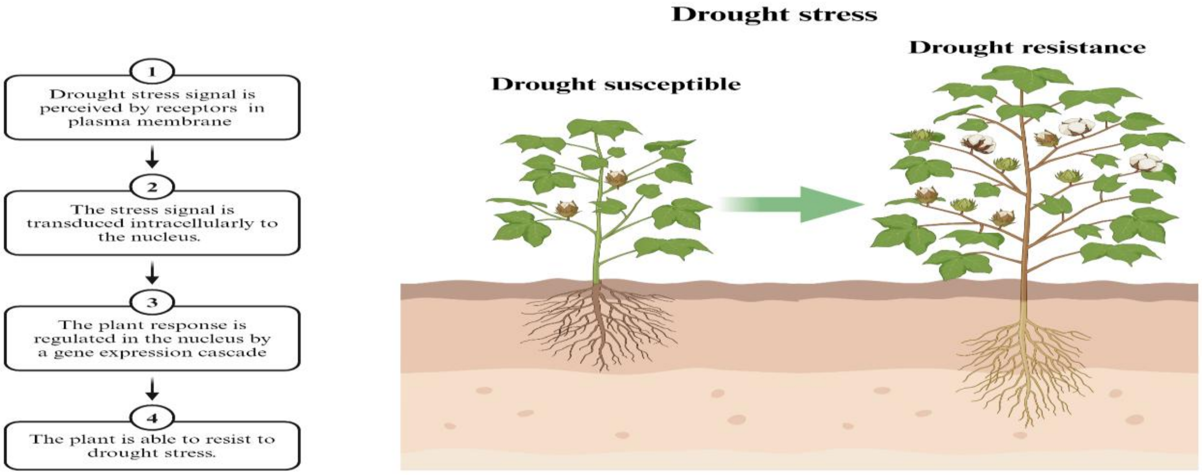

Figure 5. Drought-Induced Constraints on Cotton Growth and Yield.

Cotton must develop resistance mechanisms to heat and drought to withstand numerous shocks and survive in harsh environments. The expected temperature increase in the future would hasten the maturation and blossoming processes of cotton. It is possible that breeding for the phenological event that occurs at elevated temperatures is the most effective method for developing heat-tolerant cultivars (Saleem *et al.,* 2021). An investigation was conducted in Pakistan, utilizing the Decision Support System for Agrotechnology Transfer (DSSAT), with the objective of cultivating climate-tolerant varieties of cotton. A model incorporated forthcoming temperature increases of 3.8 degrees Celsius for the minimum and 3.6 degrees Celsius for the maximum. Elevated temperatures resulted in reduction of 10%, 20%, and 60% anthesis days, maturity, and yield, respectively. The researchers used DSSAT to modify the genetic coefficients of cotton to restore yield and phenology where they observed 10% increase in the proportion of daily growth allocated to seed and shell, along with a 30% reduction in the time, it took for the cotton cultivar to produce its final pod. Furthermore scientists (Ahmad, *et al.,* 2017) modified phenology-related characteristics to produce a drought-resistant cotton cultivar that is tolerant to varying climates. By selecting potential traits that enhance efficacy in water-scarce conditions, it is possible to find out drought-resistant cultivars.

Table 1. List of identified QTLs, genes, transgenes and transcription factors involved in drought tolerance in cotton.

		References
QTLs	*qNSB22*	(Boopathi *et al.,* 2022)
	qCSI01, qCSI02	(Abdelraheem *et al.,* 2018; Shukla *et al.,* 2021)
	qFTD1	(Abdelraheem *et al.,* 2018)
	qPH9 9	(Baytar *et al.,* 2018)
	qBla-Chr5-1	(Zheng *et al.,* 2016)
	qRWC12, qRWC23	(Saleem *et al.,* 2015)
	qtlOA-1	(Saeed *et al.,* 2011)
	qtlPH-1	(Baytar *et al.,* 2018)
Genes	Gohir.A07G058200	(Wang *et al.,* 2022)
	GhYUC22	(Wang *et al.,* 2021)
	Gohir.A07G220600	(Zheng *et al.,* 2022)
	GhDRP1	(Chen *et al.,* 2021)
Transgenes	GhEXLB2	(Zhang *et al.,* 2021)
	pGP1	(Hassan *et al.,* 2021)
	K2-NhaD	(Guo *et al.,* 2020)
	GbWRKY1	(Luo *et al.,* 2020)
	AtHUB2	(Rossi *et al.,* 2019)
	AmDUF1517a	(HAO *et al.,* 2018)
	AtDREB2A-CA	(Lisei-de-Sá *et al.,* 2017)
	GhNAC2	(Gunapati *et al.,* 2016)
	TaMnSOD	(Zhang *et al.,* 2014)
	IPT	(Kuppu *et al.,* 2013)
	AtLOS5	(Yue *et al.,* 2012)
Transcription factors	bZIP (GhABF2, GhABF3, ABF2D, ABP9, GhDBP2, GhNCED2 and AtABI5)	(Zhang *et al.,* 2022)
	TCP (GbTCP4)	(Wang *et al.,* 2022)
	NAC (GhJUB1L1, GhirNAC2, GhNAC79)	(Chen *et al.,* 2021)
	WRKY (GhWRKY21)	(Wang *et al.,* 2021)
	HD-Zip (ICaHB12)	(Basso *et al.,* 2021)
	DREB (StDREB2)	(El-Esawi and Alayafi, 2019)
	Trehelix (Gh_A05G2067)	(Magwanga *et al.,* 2019)
	MYB (GbMYB5)	(Chen *et al.,* 2015)

Several characteristics, such as leaf conductance, leaf water potential, rolling, osmotic adjustment, and soil water extraction, have been associated with drought tolerance. Plant breeders, conversely, possess the ability to analyze these attributes through diverse methodologies with the purpose of creating cultivars that are resistant to adversity. Several researchers have identified various QTLs, genes, transgenes and transcription factors associated with different traits and mechanisms involved in drought tolerance (Table 1).

Decision Support System Approaches for Sustainable Cotton Management

A Decision Support System (DSS) is a computerized tool designed to facilitate informed and timely decision-making by analyzing data and providing actionable recommendations. Through the integration of sustainable agronomic practices, conservation strategies, efficient nutrient management, and comprehensive pest and disease control, Decision Support Systems (DSS) provide solutions to overcome agricultural constraints and mitigate the impacts of environmental stresses. DSS is potentially applicable to the management of nutrition. The application of fertilizers to fields has been associated with significant losses, which have led to a decline in overall productivity. As a result of future temperature increases promoting volatilization, fertilizer losses will increase. Consequently, DSS was created to advise on the optimal dosages of fertilizer to be applied to crops. An illustration of this is cotton production replication by CROPGRO, which integrates the systems of soil, water, genetics, and environment (Rahman et al., 2018). An additional DSS that aids cultivators in the management of nutrients and irrigation amidst the challenges posed by climate change is Haifa Nutri-Net. Planning Land Applications of Nutrients for Efficiency and the Environment (PLANET) is an additional approach that provides optimal agricultural management strategies and provides recommendations for fertilizer application according to the performance of previous crops (Gibbons et al., 2005). In a shifting climate, DSS can be used to control pests and parasites and increase crop yield. The CLIMEX model examines the distribution patterns of insects and parasites. More than twenty countries have implemented its use for pest and insect management. Scientists (Mir and Quadri, 2009) employed a distinct model called SOPRA to manage insect populations. Decision Support Systems (DSS) have been effectively applied in water resource management and drought forecasting for cotton cultivation. Additionally, climate forecasting serves as a critical scientific basis for developing strategies to address the impacts of climate change. A model utilizing remote sensing and geographic information systems (GIS) was constructed to quantify the risk associated with climate change. Engineered to assess climate change implications, Decision Support System for Agrotechnology Transfer (DSSAT) provides valuable insights into the possible effects of environmental variability on agriculture. It supports crop adaptation by integrating climate forecasting tools.

Use of ICT for Better Cotton Production Under Climate Change

Information and Communication Technologies (ICTs) play a crucial role in facilitating adaptation strategies to address the impacts of climate change (Eakin *et al.,* 2015). Understanding how climate change happens in a particular place, is crucial before undertaking adaptation methods. Sensor-based networks and remote sensing technologies enable observation of climate change using a variety of techniques. To help with inter-institutional communication, the data collected about how climate change is affecting the cotton sector is organized methodically and digitally preserved. In the planning process, computer-based models analyze data to produce decisions. GIS can help with the inclusion of stakeholder observations in the creation of adaptation plans. The adaptation generated shows the influence on farmer decisions. Early warning and predictive systems are useful tools for operations and management. Building capacity can help cotton zone producers better understand and become more conscious of climate adaptation. Implementing ad hoc online and offline solutions can improve training, seminars, and workshops. The last step in networking is to replicate and retry data, enabling the comparison of information with other knowledge partners from various fields and aiding in the formulation of exact conclusions. Attaining GIS technologies for monitoring and assessment purposes is the ultimate goal of ICT integration. It is possible to facilitate georeferenced information and to monitor and evaluate existing adaptive systems.

TECHNOLOGIES FOR CLIMATE-SMART COTTON PRODUCTION

Three key principles underpin climate-smart agriculture (CSA): (i) improving agricultural productivity and financial returns to maintain national food security, (ii) enhancing and reconfiguring agricultural systems to adapt to changing climatic conditions, and (iii) reducing or diminishing greenhouse gas emissions or advancing carbon sequestration mechanisms. Climate-resilient technologies and practices are needed to establish a sustainable cotton farming system. These approaches are designed to address at least one key element of CSA.

Climate-smart agricultural approaches typically achieve increased production, resilience, and efficient resource management by mitigating greenhouse gas emissions. Climate-smart cotton production systems employ strategies and technologies that boost farm income and subsistence, encourage sustainable cotton production, improve water and fertilizer efficiency, strengthen resilience to climate variability, and lower greenhouse gas emissions caused by various inefficient management practices. Implementing CSA technologies and practices can demonstrate the cotton crop sector's inherent capabilities in reducing its vulnerability to climate extremes. A few studies on climate-smart cotton (Rahman *et al.,* 2018) indicate that improvements in resource use efficiency brought about by the adoption of new technologies and practices and strategic adaptations to the current cotton farming system will aid in achieving sustainable production. CSA seeding practices, such as raised beds or ridges, which conserve water, improve fertilizer transport and absorption, and are very effective, may lead to an increase in cotton yield (Imran *et al.,* 2018). Given how important planting density is to cotton productivity, seeding on beds ensures an ideal plant population and a strong crop stand. Furthermore, it protects crops from waterlogging brought on by heavy, irregular monsoon rains and improves germination and crop stand during unfavorable weather. The CSA approach underscores the importance of developing drought- and heat-tolerant varieties, as these can mitigate climate-induced risks and sustain agricultural productivity. Genotypes currently grown in agricultural contexts are not sustainable due to their susceptibility to climate extremes, short lifespan of a few years, rapid exhaustion of potential, and eventual cessation of cotton production.

In cotton production, drip irrigation is employed as a climate-smart practice to optimize water use and limit surface runoff during irrigation. It may also increase the efficiency of nutrient utilization. High irrigation efficiency systems are one of the other water-conserving technologies. Drip irrigation reduces environmental stress and increases agricultural productivity by encouraging strong crop stands and water conservation. This increases cotton yield. To secure sustainable cotton farming amid climate change challenges, the adoption of climate-smart production systems is indispensable.

CONCLUSIONS

Climate change poses significant and multifaceted challenges to global cotton production, threatening its sustainability, profitability, and contribution to rural livelihoods. The increasing prevalence of abiotic stresses such as heat waves, prolonged droughts, soil salinization, mineral nutrient imbalances, and air pollution has adversely affected cotton growth, yield stability, and fiber quality This chapter has comprehensively discussed the direct and indirect impacts of climatic stressors on cotton cultivation and evaluated various adaptive and mitigation strategies to overcome these challenges. Effective approaches such as optimized irrigation scheduling, improved water-use efficiency, precision nutrient management, and the judicious application of plant growth regulators have been highlighted as critical interventions to enhance cotton resilience under adverse environmental conditions. Additionally, the integration of climate-smart agricultural practices, including the adoption of Decision Support Systems (DSS), sustainable pest and disease management, and conservation-oriented soil and water practices, is pivotal to safeguarding cotton production in the face of climatic uncertainties. Continued investment in research and innovation, coupled with capacity-building initiatives and farmer-centric dissemination of climate-resilient technologies, will be instrumental in fostering a more robust, adaptive, and productive cotton sector.

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AUTHOR CONTRIBUTIONS

Muhammad Nouman Khalid and Ifrah Amjad wrote the manuscript and prepared the figures. Dr. Amir Shakeel and Dr. Humera Razzaq reviewed and proofread the manuscript. Noreen Amjad edited and revised the manuscript.

COMPETING OF INTEREST

No conflicts of interest have been disclosed by the authors.

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