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A RECENT REVIEW ON COTTON AND CLIMATE CHANGE IN PAKISTAN: IMPACTS, MITIGATION, AND ADAPTATION

Original Research

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ABSTRACT

Background: Cotton (Gossypium spp.), a key member of the Malvaceae family, is one of Pakistan's most important cash crops, often referred to as "white gold" due to its significant contribution to the national economy and rural livelihoods. However, the sustainability of cotton production is increasingly threatened by the effects of climate change, including altered temperature patterns, irregular rainfall, pest outbreaks, glacial melting, and extreme weather events such as the catastrophic floods of 2010 and 2022.

Objective: This narrative review aims to explore the impact of climate change on cotton production in Pakistan and to examine mitigation and adaptation strategies that can enhance the crop's resilience under changing climatic conditions.

Main Discussion Points: The review discusses the various climate-induced stressors affecting cotton yields, such as heatwaves, drought, unpredictable monsoons, pest invasions, and soil degradation. It highlights the vulnerability of small-scale, rain-fed cotton farmers and underscores the urgent need for adaptive interventions. Climate-smart agriculture (CSA) is presented as a robust approach, encompassing water-smart practices (e.g., micro-irrigation, rainwater harvesting), weather-smart tools (e.g., agro-met advisories, stress-tolerant varieties), nutrient-smart inputs (e.g., precision fertilizers, IPM), and carbon-efficient methods (e.g., zero tillage, crop rotation), alongside institutional and educational supports.

Conclusion: Integrating CSA strategies into cotton farming practices presents a promising pathway to mitigate climate-related risks. However, broader adoption requires institutional support, farmer education, and further research to develop scalable, region-specific solutions.

Keywords: Cotton, Climate Change, Climate Smart Agriculture, Mitigation, Adaptation, Pakistan.

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INTRODUCTION

Cotton, a natural fiber derived from plants of the genus Gossypium in the family Malvaceae, plays a pivotal role in the global textile economy. Revered for its unique combination of softness, breathability, and durability, cotton remains unmatched among natural fibers, sustaining millions of livelihoods worldwide. Approximately 250 million people are engaged directly or indirectly in the cotton industry, making it a cornerstone of rural economies, particularly in developing nations where it accounts for nearly 7% of the labor force (1). As a non-food cash crop of critical economic importance, cotton contributes substantially to international trade and national revenue streams in producer countries, serving as both a raw material for industrial processing and a source of foreign exchange earnings.

In Pakistan, cotton holds an unparalleled economic and agricultural stature. Often referred to as “white gold,” its contribution extends beyond textiles, underpinning a vast industrial complex that includes textile mills, ginning units, and oil expelling facilities. With over 60% of the country’s export revenue attributed to cotton-based products, the crop serves as a vital economic driver and a source of sustenance for millions in the agrarian community (2). Pakistan stands among the global leaders in cotton-related metrics, ranking second in cotton exports, fourth in yarn production, and seventh in fabric manufacturing (1,2). This scale of engagement underscores the centrality of cotton in Pakistan’s socio-economic fabric.

Despite its enduring significance, the cotton sector in Pakistan is facing unprecedented challenges. Over the past five years, the contribution of cotton to Pakistan’s GDP has declined from around 1% to 0.6%, and its share in agricultural value addition has diminished from 3.1% to lower levels (3). A significant portion of this decline is attributable to the increasingly severe impacts of climate change. Rising temperatures, erratic precipitation, altered pest dynamics, and more frequent extreme weather events have collectively undermined the crop’s productivity and quality. Cotton cultivation is predominantly concentrated in Punjab and Sindh, which together account for 99% of national production. In Punjab, 66% of cotton is produced, while Sindh contributes 33%. In these regions, an overwhelming majority of farmers—90% in Punjab and 82% in Sindh—rely on cotton for their primary income (4). This heavy dependence amplifies the vulnerability of rural livelihoods to environmental shocks.

Several cultivars dominate the cotton landscape in Pakistan, most notably Gossypium hirsutum (upland cotton) and Gossypium odelled (tree cotton). While G. hirsutum is widely cultivated across Pakistan for its higher yield and commercial value, G. odelled, locally known as “Narma,” is favored in Sindh for its superior fiber quality and resistance to certain pests and climatic stressors (5). The domestic cotton industry includes around 430 textile mills, over 1000 ginning factories, and 350 oil expelling units. Notably, cotton accounts for 84% of all oilseed output in Pakistan, reflecting its multidimensional utility beyond textiles (5,6).

Although cotton exports experienced a steady rise between 2003 and 2008, a declining trend was observed thereafter, with notable drops in productivity and export revenue between 2008 and 2018 (7,8). This downturn has been linked with a series of climatic anomalies, including excessive heatwaves, water scarcity, and pest outbreaks—factors that were once seasonal but have now become systemic due to global warming. In addition to climatic pressures, institutional challenges such as outdated agricultural practices, limited access to genetically improved seed varieties, and inadequate farmer education further compound the crisis (9).

Despite a growing body of literature on the agronomic and economic aspects of cotton, critical gaps remain in understanding the multifactorial impacts of climate change on cotton physiology, disease resistance, fiber quality, and yield stability. While some studies have addressed individual aspects—such as temperature effects or pest dynamics—there is a lack of integrative analyses that consider compound risks and regional disparities in vulnerability. Furthermore, research on localized adaptation measures, such as heat-resistant cultivars, precision irrigation techniques, and integrated pest management, remains fragmented and underutilized.

Given the magnitude of cotton’s contribution to Pakistan’s economy and the severity of climate-induced threats, a comprehensive understanding of the climate-cotton nexus is urgently needed. The objective of this narrative review is to explore the multidimensional effects of climate change on Pakistan’s cotton sector. This includes an assessment of agronomic stressors such as temperature extremes, water stress, and biotic invasions; economic ramifications; and existing as well as emerging adaptation strategies. The review draws upon recent empirical studies, government reports, and global climate models to synthesize current knowledge and identify feasible interventions.

The scope of this review is focused on peer-reviewed articles, national policy documents, and scientific reports published in the last five years, with a particular emphasis on studies relevant to South Asia and arid agricultural systems. By doing so, this synthesis aims to inform stakeholders—including policymakers, agronomists, climate scientists, and the farming community—about effective mitigation strategies and evidence-based policy interventions.

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This review holds particular significance in the current global context, where agriculture is increasingly under threat from climate volatility. Cotton, as a climate-sensitive crop, offers a compelling case study to examine how sectoral adaptation can be achieved through a combination of technology adoption, policy reforms, and community-level resilience building. Through a critical synthesis of recent findings, this review seeks to bridge the knowledge gap between climate projections and field-level realities, thereby contributing to the formulation of sustainable cotton production strategies under changing climatic conditions.

Thematic Discussion

Climate change has emerged as a pressing threat to cotton production globally, with developing countries like Pakistan facing the brunt due to fragile agro-ecological systems and limited adaptive capacity. The thematic discussion of this review explores the multifaceted impacts of climate change on Pakistan's cotton industry, emphasizing temperature shifts, precipitation variability, extreme weather events, pest and disease outbreaks, and the responses—both current and proposed—that aim to mitigate these risks and adapt the system sustainably.

Impact of Temperature Fluctuations on Cotton Growth and Yield

One of the most immediate threats to cotton productivity in Pakistan is temperature variability, especially the increase in frequency and intensity of heatwaves. Cotton is sensitive to temperature during critical developmental stages, including flowering, boll setting, and lint formation. It is reported that a 1°C rise in temperature above the optimal threshold can reduce lint yield by approximately 110 kg/ha (10). Recent summers in Sindh and Punjab have frequently crossed 45°C, compromising boll development and leading to increased flower and square abscission (10,11). Heat stress also affects physiological traits such as stomatal conductance, photosynthetic efficiency, and root elongation, thus reducing biomass accumulation (12). Notably, the 2022 heatwaves significantly hampered germination and pollination, contributing to yield losses in the major cotton belts (13). While the physiological implications of temperature extremes are increasingly well-understood, empirical data on varietal performance under high-heat conditions in Pakistan remains limited, pointing to a significant research gap.

Altered Precipitation Patterns and Water Scarcity

Climate-induced changes in precipitation have led to two contrasting but equally destructive outcomes for cotton: flooding and drought. Excess monsoon rainfall in 2022 led to one of the worst floods in Pakistan's history, affecting over 33 million people and causing a 41% decline in cotton production (Pakistan, 2023). The inundation of fields caused root hypoxia and reduced seedling survival, especially in low-lying areas (14). Conversely, chronic water scarcity continues to afflict southern Punjab and parts of Sindh, where over 73% of irrigation relies on depleting groundwater sources (15). Cotton's high water demands, particularly during flowering and boll development, make it highly vulnerable to irrigation stress. Data suggests a pronounced yield drop in areas with irregular water availability, exacerbated by poor water governance (16). Despite growing awareness, technological adoption for water-efficient irrigation systems like drip and sprinkler methods remains low, especially among smallholders (15,16).

Extreme Weather Events: Floods, Droughts, and Cyclones

Pakistan's cotton fields are increasingly exposed to extreme weather events such as floods, droughts, and cyclones. Floods, particularly in 2010 and 2022, resulted in massive crop failures, with financial damages running into billions. These events also washed away topsoil, essential nutrients, and standing crops, impairing subsequent cultivation cycles. Drought, on the other hand, affects cotton's physiological processes by reducing photosynthesis and fiber quality. Studies have shown that drought stress impairs sucrose metabolism and pollination efficiency, resulting in poor boll retention and reduced lint quality (17). Despite this, Pakistan's policy and infrastructure for disaster risk reduction in agriculture remain underdeveloped. Early warning systems and crop insurance schemes are inadequate, exposing farmers to repeated financial losses and discouraging investment in adaptive technologies.

Pest and Disease Proliferation Under Changing Climatic Conditions

Climate variability has altered the life cycles and geographical distribution of several cotton pests, including whiteflies, thrips, jassids, and bollworms. Warmer temperatures and extended growing seasons have enabled more generations of pests per year, leading to increased crop vulnerability and pesticide usage. The spread of cotton leaf curl disease (CLCuD), driven by whitefly vectors, continues to devastate fields in Punjab and Sindh (18). American cotton (Gossypium hirsutum), the dominant variety, is more susceptible to these pests than desi cotton, which raises questions about varietal selection under climate stress (17,18). Integrated Pest Management (IPM) has been suggested as a viable alternative to pesticide overuse, but its adoption remains inconsistent due to lack of training and awareness.

Emerging Mitigation Strategies: Technological and Agronomic Innovations

To address the challenges of climate change, Pakistan's cotton sector has begun exploring climate-resilient practices such as precision agriculture, biofertilizers, and conservation tillage. Studies have demonstrated that precision irrigation can reduce water use by up to 65% while maintaining yield. Similarly, the use of biochar and farmyard manure (FYM) has been shown to improve soil health, carbon sequestration, and water-holding capacity, thereby enhancing crop resilience. Conservation tillage methods like zero-till farming are increasingly recognized for their capacity to mitigate greenhouse gas emissions while improving soil structure and microbial health (19). However, socio-economic constraints, such as lack of access to credit and extension services, remain a barrier to scaling up these practices.

Genetic Approaches and Cotton Variety Improvement

Recent research has focused on developing genetically engineered cotton varieties with enhanced drought and pest resistance. CRISPR-Cas9, RNA interference (RNAi), and marker-assisted selection are being deployed to create climate-smart cotton cultivars with improved yield potential and tolerance to CLCuD and lepidopteran pests (20). Transgenic cotton currently accounts for over 90% of Pakistan's cotton area, but its long-term ecological and socio-economic impacts are still debated. Moreover, the concentration of seed production among few players raises concerns about genetic diversity and farmer autonomy. While biotechnological solutions offer promise, their deployment should be supported by robust regulatory oversight and farmer education to ensure equitable and safe usage.

Adoption of Adaptation Strategies and Farmer-Centric Approaches

Adoption of climate adaptation strategies such as crop rotation, early maturing varieties, and improved soil management remains uneven across Pakistan. In Muzaffargarh, for instance, the uptake of sustainable cotton practices was found to be higher among farmers with access to extension services and off-farm income (21). Comparative studies in Rajanpur and Bahawalpur also revealed higher benefit-cost ratios for sustainable cotton producers over conventional ones (22). However, barriers such as illiteracy, financial constraints, and lack of institutional support continue to hinder widespread adoption. Strengthening agricultural extension systems, offering farmer training, and expanding access to affordable credit are vital to bridge this implementation gap.

Conclusion of Thematic Insights

Collectively, these themes underscore the complex and multi-layered vulnerabilities of Pakistan's cotton sector to climate change. While the sector is gradually adapting through technological innovations, varietal improvements, and agronomic practices, systemic constraints and inconsistent policy implementation hinder transformative change. The review identifies an urgent need for integrated, cross-sectoral strategies that combine climate forecasting, technological adoption, and farmer empowerment. A holistic approach rooted in sustainability, inclusivity, and resilience will be key to safeguarding Pakistan's cotton future in a rapidly warming world.

Critical Analysis and Limitations

The current body of literature examining the effects of climate change on cotton production in Pakistan offers valuable insights into the multifaceted vulnerabilities of the sector. However, several methodological and conceptual limitations diminish the robustness and generalizability of the findings. One of the most notable limitations is the predominance of observational and descriptive study designs with minimal use of experimental or randomized controlled trials (RCTs). Many studies focus on correlation-based outcomes without testing interventions under controlled conditions, limiting the capacity to infer causality between specific climate stressors and yield outcomes (23). The absence of RCTs or quasi-experimental frameworks also constrains the development of standardized mitigation protocols that can be tested and replicated in different agro-climatic zones.

A recurring issue in the reviewed literature is the use of small or region-specific sample sizes, often drawn from single districts or provinces, such as Muzaffargarh or Bahawalpur. While these local insights are valuable, they hinder the extrapolation of findings to broader cotton-growing regions across Pakistan, especially those with varying climatic exposures and socio-economic contexts (24). Furthermore, most studies fail to account for confounding variables, including soil type variability, farmer education levels, and access to extension services, all of which may significantly influence outcomes independent of climatic effects. The lack of multivariate or regression-based statistical analyses in several studies limits the depth of interpretation and the isolation of climate-specific impacts (25).

Performance and selection biases also emerge as notable concerns. For instance, many studies include only farmers who are already engaged in adaptive or sustainable practices, inadvertently excluding those most vulnerable or resistant to change. This skews the data towards more favorable outcomes and creates an overestimation of the success of mitigation strategies (26). Similarly, there is limited use of blinding or standardized outcome measurements in agronomic trials, which raises concerns about performance bias and the objectivity of reported results. This is especially problematic in studies evaluating yield improvements, water use efficiency, or pest resistance, where subjective or farmer-reported data are heavily relied upon without validation through independent field assessments.

Another concern is the potential for publication bias. Much of the existing literature appears skewed towards positive or optimistic evaluations of climate adaptation strategies, such as biofertilizer use, conservation tillage, or precision irrigation (25,26). Negative or inconclusive findings are rarely reported, raising the possibility that unsuccessful interventions or low adoption rates remain underrepresented in the academic discourse. This lack of transparency limits critical appraisal and may contribute to unrealistic expectations regarding the scalability and effectiveness of certain practices.

A significant limitation affecting cross-study comparisons is the variability in how outcomes are measured and reported. For instance, studies assessing cotton yield losses due to drought or pest attacks employ differing metrics—ranging from absolute boll weight reductions to subjective farmer yield estimations—making direct comparisons challenging (27). Similarly, studies evaluating water-saving technologies do not consistently control for variables such as crop cycle duration, rainfall, or soil texture, which compromises the comparability of water use efficiency metrics (16,27). Without standardized methodologies and reporting formats, the collective body of evidence remains fragmented and difficult to synthesize effectively.

Generalizability of findings remains a further challenge. Most studies are conducted in lowland areas of Punjab and Sindh, which are relatively well-resourced compared to arid or marginal regions like Balochistan. Therefore, the applicability of proposed solutions, such as drip irrigation or genetically engineered cotton varieties, may be limited in regions lacking infrastructure or where farming is largely rainfed (28). Moreover, studies seldom account for the socio-cultural barriers to technology adoption, such as gender roles, literacy rates, and land tenure security, which significantly affect the implementation and long-term sustainability of climate adaptation strategies.

In sum, while the current literature provides a valuable foundation for understanding the impact of climate change on Pakistan's cotton sector, its limitations in methodological rigor, sample diversity, and outcome standardization hinder the formulation of universally applicable solutions. There is a pressing need for more rigorous, inclusive, and interdisciplinary studies that not only test interventions at scale but also integrate socio-economic variables into their frameworks. Such research would enhance the reliability of recommendations and support the development of context-specific policies for climate-resilient cotton production.

Implications and Future Directions

The synthesis of recent literature on climate change and its impact on Pakistan's cotton sector offers critical insights with far-reaching implications for agricultural management, policy formulation, and future scientific inquiry. While the findings are agricultural in scope, their implications mirror the clinical discipline's need for preventive, evidence-based, and locally contextualized interventions—particularly in managing climate-sensitive systems that directly affect food security, economic well-being, and public health.

From a practical standpoint, the insights gained underscore the urgency of promoting adaptive agronomic strategies such as precision farming, climate-resilient crop varieties, and sustainable water management among cotton growers. These practices, akin to patient-specific treatment plans in clinical care, must be tailored to regional vulnerabilities, resource availability, and farmer capacity. For instance, cotton producers in Punjab and Sindh, who face recurrent heat stress and erratic rainfall, can benefit from heat-resistant transgenic cultivars and water-saving technologies such as drip and sprinkler irrigation (17,28). The emphasis on early warning systems and spatial crop monitoring also parallels the importance of diagnostic and surveillance systems in healthcare, highlighting a translational approach where timely information leads to timely action. Integrating mobile technology, remote sensing, and geospatial analysis can help forecast crop disease outbreaks and water stress, guiding precision interventions that preserve both yield and farmer income (29).

On a policy level, the review highlights the necessity for climate-adaptive agricultural frameworks that support vulnerable farming communities through targeted subsidies, insurance programs, and extension services. Just as clinical guidelines are essential for standardizing patient care across contexts, national guidelines for climate-smart agriculture can standardize climate resilience protocols and reduce inequities in agricultural adaptation. Given the unequal access to inputs, infrastructure, and education, especially in marginal cotton-producing regions, these guidelines should be region-specific and culturally appropriate. Policymakers should also incentivize the adoption of sustainable practices such as conservation tillage and organic soil amendments, drawing lessons from environmental stewardship in health systems where sustainability and resilience are prioritized (30). Moreover, institutionalizing farmer training programs through agricultural universities and rural development platforms is critical to achieving long-term adaptive capacity.

Despite the growing body of evidence, numerous research gaps remain that warrant further exploration. One major gap is the limited availability of longitudinal studies that evaluate the long-term effectiveness of specific adaptation practices, such as integrated pest management or climate-resilient cultivars. Most current studies are short-term and observational, making it difficult to assess sustainability or cost-effectiveness over multiple crop cycles (29,30). Furthermore, little is known about the psychosocial and behavioral barriers that influence farmer decisions regarding technology adoption—an area that could benefit from interdisciplinary inquiry, merging behavioral economics, rural sociology, and agronomy. Another critical area is the interaction between climate stressors and pest ecology. While several studies have documented increases in pest prevalence under warming conditions, few have 636odelled pest dynamics under future climate scenarios to predict potential outbreaks or shifts in resistance patterns (19,26).

To address these gaps, future research should prioritize the use of robust experimental designs, including randomized field trials, longitudinal cohort studies, and participatory action research models. These methodologies will enhance the validity of findings and facilitate replication across regions and cropping systems. Randomized field trials can assess the comparative effectiveness of various water-saving irrigation techniques or climate-resilient cultivars, while longitudinal studies can provide insight into the durability of farmer behavior change and technology adoption. Moreover, the inclusion of socio-economic variables and stratified analysis based on landholding size, gender, and education can improve the granularity of insights and inform equity-focused policies. Participatory research, where farmers are engaged as co-investigators, can also ensure that interventions are contextually relevant, culturally acceptable, and more likely to be adopted in practice.

Ultimately, the review positions climate-smart cotton production not merely as an agronomic challenge but as a multidimensional issue requiring integrated solutions. The findings suggest that future research and policy should converge towards a systems-thinking approach that incorporates environmental sustainability, economic viability, and social inclusivity. Just as clinical research evolves to meet complex patient needs, agricultural research must evolve to address the intricacies of climate vulnerability, ensuring that interventions are not only effective but also accessible and acceptable to the communities most at risk.

CONCLUSION

This review highlights the profound and multifaceted impact of climate change on cotton production in Pakistan, emphasizing how shifting temperature regimes, erratic precipitation patterns, increasing frequency of extreme weather events, pest proliferation, and water scarcity collectively threaten the sustainability of this vital crop. Small-scale farmers in rain-fed regions are particularly vulnerable due to their limited adaptive capacity and reliance on traditional practices. Despite these challenges, a growing body of literature supports the effectiveness of integrated mitigation and adaptation strategies—such as climate-resilient cotton varieties, water-smart irrigation methods, conservation tillage, and farmer education programs—in enhancing resilience and ensuring long-term productivity. While the current evidence provides a useful foundation, much of it is based on observational data, with limited large-scale, long-term, and controlled evaluations. Therefore, the reliability of existing findings, though promising, must be viewed with caution. It is strongly recommended that policymakers prioritize region-specific climate-smart agricultural policies and that researchers pursue more rigorous, multidisciplinary, and participatory studies to fill critical knowledge gaps. Future research must also explore socio-economic barriers to adoption and test scalable solutions that ensure equity and sustainability in Pakistan's cotton sector under a changing climate.

AUTHOR CONTRIBUTION

Author	Contribution
Asma	Substantial Contribution to study design, analysis, acquisition of Data Manuscript Writing Has given Final Approval of the version to be published
Nazia Shaheen	Substantial Contribution to study design, acquisition and interpretation of Data Critical Review and Manuscript Writing Has given Final Approval of the version to be published
Neelam Zeb	Substantial Contribution to acquisition and interpretation of Data Has given Final Approval of the version to be published
Arooj	Contributed to Data Collection and Analysis Has given Final Approval of the version to be published
Ayesha Bibi*	Contributed to Data Collection and Analysis Has given Final Approval of the version to be published

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