OPEN ACCESS

Int. J. Agr. Ext. 14 (02) 2026. 101-118.

DOI:-10.33687/ijae.014.01.5653

Check for updates

Available Online at EScience Press

International Journal of Agricultural Extension

ISSN: 2311-6110 (Online), 2311-8547 (Print)

https://esciencepress.net/journals/IJAE

FROM CONVENTIONAL COTTON FARMING TO CLIMATE-RESILIENT PRODUCTION SYSTEMS: COMPARATIVE INSIGHTS FROM UZBEKISTAN AND A TRANSFORMATION FRAMEWORK FOR PAKISTAN

[a]Muhammad Abubakar*, [b]Iqbal Hussain, [b]Shahid Saleem, [a]Adnan N. Shah, [a]Mumtaz Ahmad, [c]Bilal Hussain, [c]Muhammad I. A. Rehmani, [c]Aman Ullah

[a] *Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Pakistan.*

[b] *Rural Education and Economic Development Society (REEDDS), Pakistan.*

[c] *Ghazi University Dera Ghazi Khan, Pakistan.*

ARTICLE INFO

Article History

Received: January 21, 2026

Revised: March 17, 2026

Accepted: April 04, 2026

Keywords

Cotton productivity

Climate change adaptation

Regenerative agriculture

Resource-use efficiency

Technological modernization

Institutional transformation

ABSTRACT

Cotton is a strategic fiber and cash crop that supports millions of livelihoods and contributes substantially to the economies of many developing countries. However, despite comparable agro-climatic conditions and sustained investments in cotton research, Pakistan has experienced stagnant or declining productivity under increasing climate variability, whereas Uzbekistan has achieved consistent gains through comprehensive agricultural transformation. This review critically examines the ecological, technological, and institutional pathways underpinning Uzbekistan's superior cotton productivity and identifies lessons applicable to Pakistan. A structured literature review was conducted using Web of Science, Scopus, Google Scholar, CAB Abstracts, and authoritative reports from FAO, ICAC, USDA, the World Bank, and national government agencies. Studies published between 2010 and 2026 were screened using predefined eligibility criteria, resulting in the synthesis of more than 100 high-quality publications and policy documents. The evidence indicates that Uzbekistan's productivity gains stem from coordinated improvements in water-use efficiency, conservation-oriented farming, climate-resilient cultivars, mechanization, digital agriculture, effective extension services, and institutional reforms, particularly the cotton-textile cluster system. In contrast, Pakistan continues to face inefficient resource use, weak seed and extension systems, fragmented policy implementation, slow technology adoption, and increasing climate vulnerability. Based on these comparative insights, this review proposes a Pakistan Cotton Transformation Package (PCTP) that integrates evidence-based ecological, technological, and institutional interventions to enhance productivity, climate resilience, resource-use efficiency, and long-term sustainability. The proposed framework offers researchers, policymakers, and development agencies a practical roadmap for accelerating sustainable cotton transformation in Pakistan and other climate-vulnerable cotton-producing regions.

Corresponding Author: Muhammad Abu Bakar

Email: abmazari@gmail.com

© The Author(s) 2026.

INTRODUCTION

Enhancing cotton productivity under accelerating climate change has become one of the foremost challenges to sustainable agriculture. Rising temperatures, frequent heat waves, erratic rainfall, prolonged droughts, declining freshwater availability, soil degradation, salinity, and increasing pest and disease pressures increasingly threaten cotton productivity, profitability, and resilience worldwide

(Lal, 2020). These challenges are particularly severe in arid and semi-arid regions, where cotton production depends heavily on irrigation and efficient soil and water management (Hatfield and Dold, 2019; Ullah et al., 2024). Heat stress during flowering and boll development reduces boll retention, lint yield, and fibre quality, while water scarcity further limits production efficiency and farm profitability (Singh et al., 2023). Consequently, sustaining cotton productivity under climate change has evolved beyond a breeding challenge into a multidimensional issue requiring coordinated ecological adaptation, technological innovation, effective institutions, and farmer-centred management strategies (Pretty et al., 2018; IPCC, 2023).

Cotton (*Gossypium* spp.) is one of the world's most important natural fibre crops, supporting more than 100 million farming households and supplying raw material for the textile, edible oil, and livestock feed industries (FAO, 2023; ICAC, 2024). It is cultivated on approximately 32–34 million hectares worldwide and produces about 24–26 million tonnes of lint annually, with China, India, Brazil, the United States, Pakistan, and Uzbekistan among the leading producers (FAOSTAT, 2024; USDA-FAS, 2024). Although advances in breeding, biotechnology, irrigation engineering, precision agriculture, and mechanization have improved cotton production globally, productivity gains remain uneven across countries (OECD/FAO, 2023). These contrasting trends indicate that technological innovation alone is insufficient; sustained productivity depends on integrating ecological resource management, technological modernization, institutional governance, and farmer adoption within the production system (Lal, 2020; Pretty et al., 2018).

Among major cotton-producing countries, Pakistan and Uzbekistan provide a compelling comparison for understanding contrasting productivity under climate change. Both cultivate cotton predominantly in arid and semi-arid environments characterized by irrigation dependence, rising temperatures, water scarcity, salinity, and increasing climatic variability (World Bank, 2022; FAO, 2023). Cotton remains strategically important to both economies, contributing to agricultural GDP, rural employment, export earnings, and the textile industry (ICAC, 2024; USDA-FAS, 2024). However, their productivity trajectories have diverged markedly during the past decade. Pakistan continues to face stagnant yields, declining cultivated area, fragmented seed systems, limited mechanization, inefficient resource use, and increasing climate vulnerability (Government of Pakistan, 2025; Ahmad et al., 2024; Ali et al., 2019). In contrast, Uzbekistan has achieved relatively higher and more stable productivity through improved irrigation efficiency, widespread mechanization, digital agriculture, strengthened seed systems, effective research–extension linkages, and institutional reforms, particularly following agricultural liberalization and the introduction of the cotton cluster model after 2017 (World Bank, 2022; Bekchanov et al., 2015). These contrasting outcomes suggest that productivity differences are shaped not only by climate but also by the interaction of ecological management, technological innovation, institutional effectiveness, and farmer adoption.

This divergence raises two important scientific questions: Why is Uzbekistan outperforming Pakistan in cotton productivity under climate change, and which transformation pathways can be adapted to improve Pakistan's cotton sector? Addressing these questions is essential for identifying evidence-based strategies that enhance productivity, climate resilience, resource-use efficiency, and long-term sustainability.

Although extensive research has examined cotton breeding, irrigation, regenerative agriculture, mechanization, climate adaptation, and agricultural policy, these components have largely been investigated independently (Lal, 2020; Fang et al., 2021; FAO, 2022; IPCC, 2023). Likewise, comparative studies of Pakistan and Uzbekistan have primarily focused on production trends, irrigation systems, or policy reforms without integrating the ecological, technological, and institutional drivers that collectively determine productivity (ICAC, 2024;). Consequently, existing reviews provide limited understanding of how interactions among resource management, technological modernization, institutional governance, and farmer participation influence long-term cotton productivity under climate change. This lack of an integrated systems perspective represents the principal knowledge gap addressed by this review.

To bridge this gap, the present review adopts a Cotton Transformation Framework (CTF) that integrates three interconnected pathways: ecological transformation**,** encompassing resource-use efficiency, regenerative agriculture, irrigation management, and climate adaptation; technological transformation**,** including improved genetics, certified seed systems, mechanization, precision agriculture, and digital technologies; and institutional transformation**,** comprising governance, policy reforms, extension services, research–industry linkages,

market incentives, and farmer participation. By examining the interactions among these pathways, the framework provides a more comprehensive explanation of productivity differences than conventional descriptive comparisons. Building on this synthesis, the review proposes a Pakistan Cotton Transformation Package (PCTP) comprising evidence-based, context-specific interventions tailored to Pakistan's agroecological conditions, farming systems, and institutional realities.

Accordingly, this review aims to: (i) evaluate whether Uzbekistan is outperforming Pakistan in cotton productivity under climate change using evidence from scientific literature and international databases; (ii) compare the ecological, technological, and institutional transformation pathways responsible for the contrasting productivity of the two countries; and (iii) synthesize these findings into an evidence-based Pakistan Cotton Transformation Package (PCTP) to guide sustainable cotton production, climate resilience, and future policy and research priorities in Pakistan.

REVIEW METHODOLOGY

Literature Search Strategy

This comparative review followed the PRISMA 2020 guidelines to ensure a transparent and systematic literature selection process. Scientific literature was retrieved from Web of Science, Scopus, Google Scholar, CAB Abstracts, and AGRICOLA, complemented by authoritative datasets and reports from FAOSTAT, the International Cotton Advisory Committee (ICAC), the United States Department of Agriculture (USDA), the World Bank, the Intergovernmental Panel on Climate Change (IPCC), and relevant government publications from Pakistan and Uzbekistan. The search covered studies published between 2010 and June 2026. Boolean operators were used to combine keywords related to cotton (Gossypium spp.), Pakistan, Uzbekistan, climate change, productivity, climate adaptation, regenerative agriculture, conservation agriculture, resource-use efficiency, irrigation, mechanization, precision agriculture, digital agriculture, seed systems, extension services, and institutional reforms to ensure comprehensive coverage of the ecological, technological, and institutional dimensions of cotton production.

Following predefined eligibility criteria, 108 peer-reviewed journal articles, institutional reports, and government publications providing quantitative or qualitative evidence relevant to cotton productivity, climate resilience, technological innovation, and policy development were included. Conference abstracts, duplicate records, non-English publications, and studies lacking methodological rigor or direct relevance were excluded. The retrieved records were screened through title, abstract, and full-text evaluation, and their methodological quality was critically assessed based on publication quality, data reliability, and relevance to the objectives of this review.

Publication and Citation Trends

Figure 1 presents the temporal distribution of publications and citation trends related to cotton productivity systems in Pakistan and Uzbekistan between 2010 and 2026. The available evidence indicates relatively limited research during 2010–2016, whereas publication output increased markedly after 2017, reflecting growing scientific and policy interest in climate-resilient cotton production, precision agriculture, mechanization, and institutional reforms. Despite this upward trend, comparatively few studies have evaluated Pakistan and Uzbekistan within an integrated ecological–technological–institutional framework. This highlights a significant knowledge gap and underscores the need for interdisciplinary evidence synthesis to better understand the drivers of sustainable cotton productivity under climate change. The present review addresses this gap by integrating evidence from multiple scientific and institutional sources into a comprehensive comparative framework for guiding future research, policy development, and climate-smart cotton transformation.

Global Cotton Distribution and Production Trends under Changing Climate

Studies have shown that commercial cotton cultivation is concentrated primarily between 37° N and 32° S, where warm temperatures (20–35 °C), long frost-free periods, abundant solar radiation, and adequate water availability provide favourable conditions for crop growth and fibre development (Oosterhuis & Snider, 2014; Constable & Bange, 2015). Cotton is cultivated in more than 75 countries, although global production is concentrated in a relatively small number of producers, including India, China, Brazil, the United States, Pakistan, Uzbekistan, Türkiye, Australia, and several West African countries (FAOSTAT, 2024; USDA-FAS, 2024). Production systems vary considerably across regions. Irrigated cotton predominates in Central Asia, northwestern China, Australia, and the western United States, whereas rainfed production is more common in Sub-Saharan Africa, central India, and parts of Brazil (Constable & Bange, 2015; FAO,

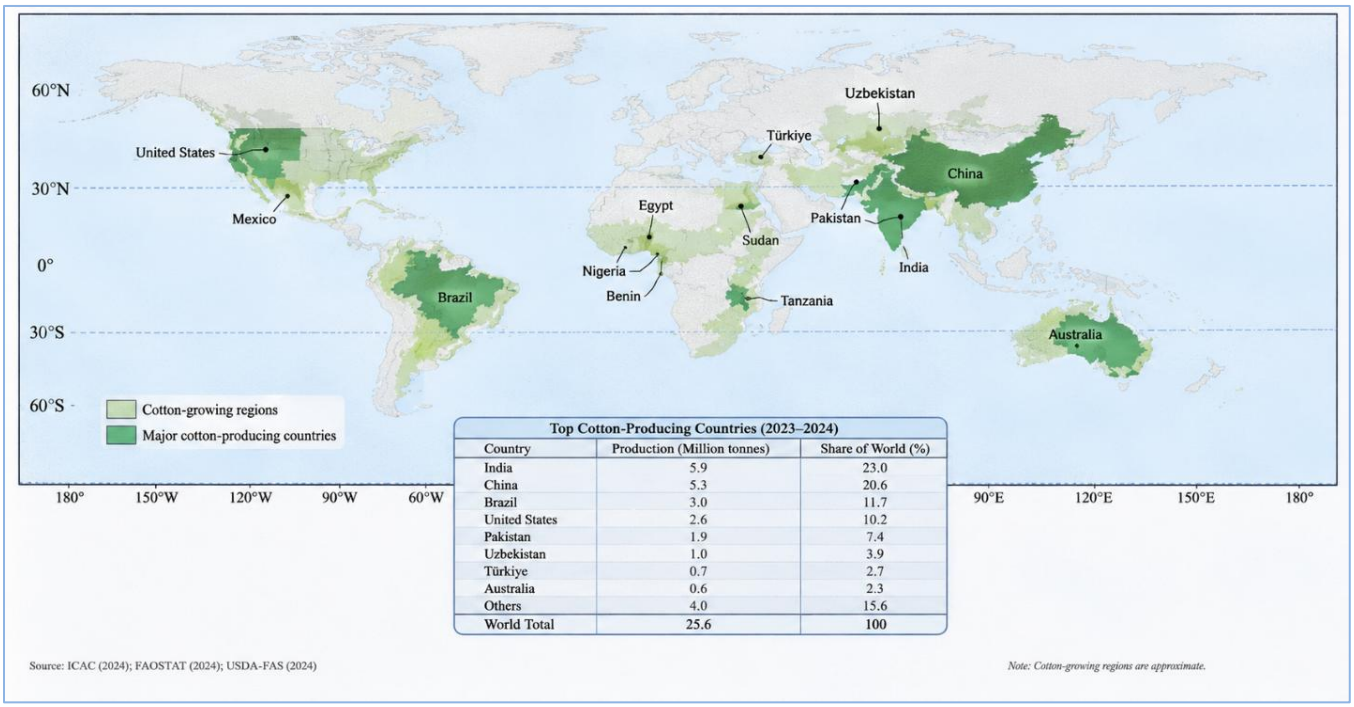
2021). Consequently, differences in irrigation practices, mechanization, nutrient management, and production systems contribute substantially to regional variation in cotton productivity.

Recent evidence indicates that climate change has become one of the major constraints to global cotton production. Rising temperatures, erratic rainfall, prolonged droughts, increasing salinity, and more frequent extreme weather events adversely affect crop growth, fibre quality, and yield stability (Lobell et al., 2021). Although cotton is relatively drought tolerant, reproductive growth remains highly sensitive to heat and moisture stress during flowering and boll development (Bange et al., 2010). Furthermore, increasing evapotranspiration elevates irrigation requirements, while declining freshwater availability threatens the sustainability of irrigated production systems, particularly in arid and semi-arid regions (FAO, 2024; World Bank, 2024). Soil salinization has also intensified in many irrigated landscapes of Central and South Asia because of inadequate drainage and long-term irrigation, further constraining cotton productivity (Qadir et al., 2026). Collectively, these studies demonstrate that sustaining cotton production under climate change requires integrated ecological management, efficient resource utilization, and adaptive production technologies rather than reliance on single stress-tolerance traits.

Figure 1. Publication and citation trends of studies on cotton productivity systems in Pakistan and Uzbekistan (2010–2026).

Despite these climatic challenges, global cotton production has remained relatively stable because advances in breeding, irrigation, mechanization, and precision agriculture have improved productivity without major expansion of cultivated land (Fischer et al., 2022; Bange et al., 2010). During the 2023–2024 production season, approximately 32–33 million hectares were cultivated worldwide, producing 25–26 million tonnes of lint with an average lint yield of about 780 kg ha^{-1} (FAOSTAT, 2024; USDA-FAS, 2024). International statistics indicate that India, China, Brazil, the United States, and Pakistan collectively account for more than three-quarters of global cotton production, while countries such as Brazil, Australia, the United States, and Uzbekistan consistently achieve higher national yields through the integrated adoption of improved cultivars, efficient irrigation, mechanization, precision agriculture, and effective research and extension systems (Constable and Bange, 2015).

Overall, the available literature indicates that global differences in cotton productivity are determined not only by climatic conditions but also by the extent to which ecological sustainability, technological innovation, and institutional capacity are integrated within production systems. This global perspective provides the scientific foundation for the following comparative analysis of Pakistan and Uzbekistan, where contrasting responses to similar climatic challenges have resulted in markedly different productivity trajectories and offer valuable insights for sustainable cotton transformation.



Top Cotton-Producing Countries (2023–2024)

Country	Production (Million tonnes)	Share of World (%)
India	5.9	23.0
China	5.3	20.6
Brazil	3.0	11.7
United States	2.6	10.2
Pakistan	1.9	7.4
Uzbekistan	1.0	3.9
Türkiye	0.7	2.7
Australia	0.6	2.3
Others	4.0	15.6
World Total	25.6	100

Figure 2. Global distribution of cotton-growing regions and major producing countries.

Comparative Cotton Production Dynamics of Pakistan and Uzbekistan

Studies have consistently shown that although Pakistan and Uzbekistan are both major cotton-producing countries with semi-arid production environments, their cotton sectors have followed markedly different development trajectories during the past decade (FAOSTAT, 2024; ICAC, 2024). Long-term production statistics reveal that Pakistan generally cultivates a larger cotton area than Uzbekistan; however, this advantage has not translated into higher productivity or stable production.

Between 2015 and 2025, Pakistan experienced substantial fluctuations in cotton area, production, and yield due to recurrent heat waves, floods, droughts, insect pest outbreaks, cotton leaf curl disease, declining seed quality, inefficient irrigation, and inconsistent policy implementation (Ahmad et al., 2024;). In contrast, Uzbekistan maintained relatively stable production despite gradually reducing its cultivated area, indicating that productivity gains were achieved through improvements in yield rather than expansion of land. It is therefore evident from comparative studies that sustainable cotton production depends more on efficient management of available resources than on increasing cultivated area alone (Lal, 2020; FAO, 2023).

Further studies using national production datasets have revealed a widening yield gap between the two countries during 2015–2025. Pakistan's average lint yield generally remained between 550 and 650 kg ha^{-1} (approximately 1.8–2.4tha^{-1} seed cotton) with considerable annual variability, whereas Uzbekistan consistently achieved 700–800 kg ha^{-1} lint yield (approximately 2.5–3.2 t ha^{-1} seed cotton) under commercial farming conditions (FAOSTAT, 2024; ICAC, 2024). More recent evidence indicates that Uzbekistan accelerated these gains after the implementation of major agricultural reforms, with national seed cotton yields increasing by more than 40% between 2021 and 2025 despite a reduction in cultivated area, demonstrating a remarkable increase in land productivity. Practical comparisons further indicate that many progressive Uzbek cotton farmers routinely obtain yields exceeding 3.5–4.0 t ha^{-1} under irrigated conditions through integrated crop management, while yields on many Pakistani farms remain substantially below attainable levels because improved varieties are often cultivated under suboptimal agronomic, irrigation, and crop protection practices (FAO, 2023; ICAC, 2024).

Table 1. Comparative Status of Cotton Production in Pakistan and Uzbekistan (2024/25).

Sr.	Indicator	Pakistan	Uzbekistan	Relative Interpretation
1	Cotton Area Harvested (million ha)	2.00	1.00	Pakistan cultivates about twice the cotton area
2	Cotton Production (million 480-lb bales)	5.50	3.00	Pakistan produces more total cotton due to larger area
3	Average Yield (kg ha^{-1})	599	653	Uzbekistan achieves higher productivity per unit area
4	5-Year Average Yield (kg ha^{-1})	550	638	Uzbekistan shows more stable productivity

The insights gained from numerous studies underscore that Uzbekistan's superior farm-level productivity is not attributable to a single technological innovation but rather to coordinated reforms across the entire cotton production system. Since 2016, the Government of Uzbekistan has implemented comprehensive agricultural restructuring by replacing the traditional quota-based system with cotton-textile cluster farming, encouraging vertical integration between farmers, ginneries, textile industries, researchers, and private investors (Bekchanov, 2024; World Bank, 2025). Simultaneously, substantial investments were made in irrigation rehabilitation, laser land levelling, drip and water-saving irrigation technologies, mechanized sowing and harvesting, certified seed production, digital field monitoring, precision nutrient management, biological pest control, and farmer training programmes supported by the Ministry of Agriculture, FAO, the World Bank, and other international development partners. These interventions improved input-use efficiency, reduced production costs, enhanced water productivity, strengthened technology transfer, and increased farmers' capacity to respond to climatic stresses. Moreover, reforms aimed at eliminating forced labour, strengthening rural institutions, and promoting value-added textile industries further enhanced producer incentives and encouraged adoption of modern production technologies.

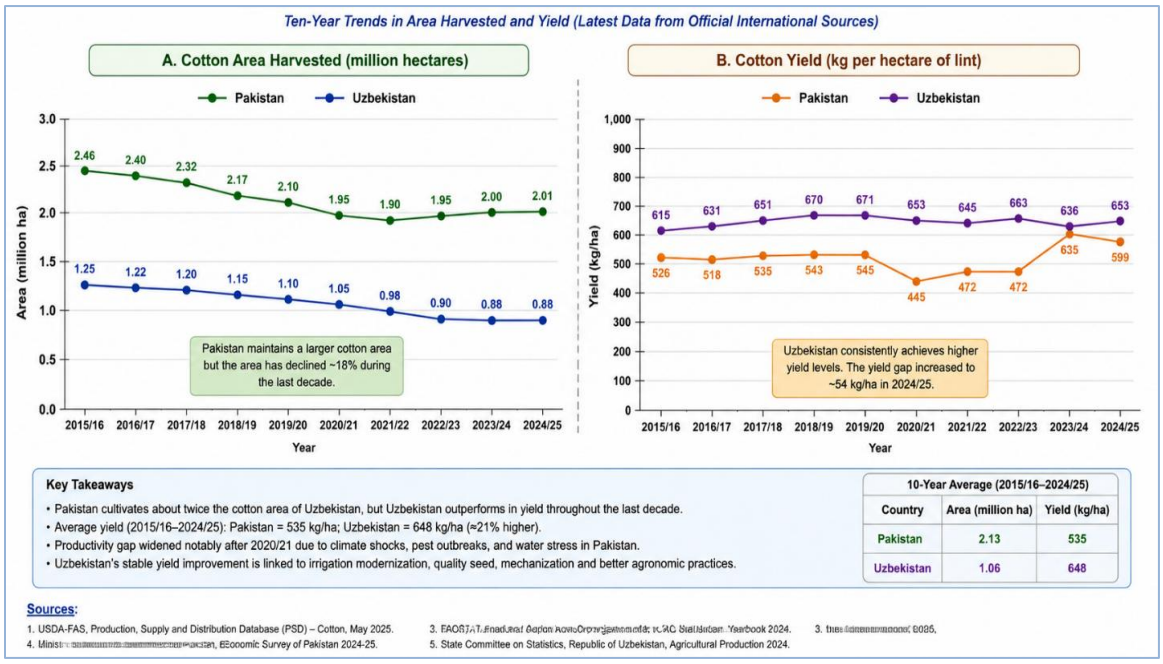


Figure 3. Cotton area and yield comparison: Pakistan and Uzbekistan (2015/16 – 2024/25).

Table 2. Comparative impacts of regenerative agriculture on soil health and cotton productivity.

Sr. No.	Parameter	Pakistan	Uzbekistan
1	Soil organic carbon (SOC)	5–15%	8–18%
2	Soil organic matter (SOM)	0.1–0.4%	0.2–0.6%
3	Water infiltration	10–25%	15–30%
4	Water-use efficiency	10–20%	20–35%
5	Cotton yield	8–18%	10–20%

Lal (2020); FAO (2023); Abbas et al. (2023); Irshad et al. (2025); World Bank (2024); ICARDA (2023); Abdullaev et al. (2007)

In contrast, numerous reviews have reported that Pakistan continues to face structural constraints that limit the translation of scientific advances into farm-level productivity, including fragmented landholdings, weak seed certification and quality assurance systems, premature commercialization of varieties, low mechanization, inefficient irrigation practices, inadequate extension services, increasing pest resistance, and fragmented policy implementation (Ahmad et al., 2022; Bakhsh et al., 2019). Consequently, despite considerable progress in cotton breeding and biotechnology, the realized productivity of Pakistani farmers has remained well below the crop's genetic potential. The comparative evidence therefore indicates that the productivity gap between Pakistan and Uzbekistan reflects differences in the efficiency of the entire production system rather than differences in genetic resources or climatic conditions alone. This synthesis provides the conceptual foundation for the following sections, which critically examine how climate change, resource-use efficiency, regenerative agriculture, technological innovation, and institutional reforms have collectively shaped cotton productivity in both countries.

Comparative Study of Ecological Transformation Pathways

The comparative production trends discussed in the previous section indicate that the sustained productivity gains achieved in Uzbekistan are closely associated with the ecological transformation of its cotton production system rather than with increases in cultivated area or genetic improvement alone. A growing body of research has shown that resilient cotton production under climate change depends on the integration of climate-smart water management, restoration of soil health, efficient resource utilization, and regenerative agricultural practices that collectively enhance the capacity of agroecosystems to withstand environmental stresses while sustaining long-term productivity (Lal, 2020; IPCC, 2023; FAO, 2023). These findings suggest that ecological resilience has become a critical determinant of yield stability in modern cotton production systems. Comparative studies have further revealed that Pakistan and Uzbekistan have adopted contrasting approaches to ecological resource management during the past decade. In Pakistan, declining soil organic carbon, increasing salinity, inefficient flood irrigation, nutrient imbalances, residue burning, and continuous monocropping have progressively reduced soil fertility, water-use efficiency, and ecosystem resilience, thereby widening the gap between potential and realized cotton yields (Ahmad et al., 2024; Ashraf et al., 2024). In contrast, Uzbekistan has implemented integrated ecological interventions through irrigation modernization, improved drainage, residue incorporation, crop diversification, conservation agriculture, balanced nutrient management, and precision water delivery supported by national agricultural reforms and international development programmes (Bekchanov et al., 2015; World Bank, 2023; FAO, 2024). These complementary interventions have improved soil functioning, optimized resource use, and strengthened farmers' adaptive capacity under increasing climatic variability. It is increasingly evident from recent studies that ecological transformation is most effective when multiple resource-management practices operate synergistically rather than independently. Research conducted across irrigated cotton systems has demonstrated that combining efficient irrigation with improved soil management, organic amendments, residue retention, reduced tillage, crop rotations, and site-specific nutrient management enhances water productivity, nutrient-use efficiency, soil carbon sequestration, microbial activity, and overall system resilience more effectively than isolated interventions (Lal, 2020; Rhodes, 2022; FAO, 2023). Consequently, Uzbekistan has been able to translate ecological improvements into sustained farm-level productivity, whereas the adoption of similar practices in Pakistan has remained fragmented and localized, limiting their impact at the national scale (Ahmad et al., 2024).

Table 3. Comparative resource-use efficiency indicators in the cotton production systems of Pakistan and Uzbekistan.

Sr.	Indicator	Pakistan	Uzbekistan	Implications for Productivity
1	Irrigation efficiency (%)	35–40	60–70	Higher water productivity
2	Nitrogen-use efficiency (%)	30–40	45–55	Better nutrient recovery
3	Phosphorus-use efficiency (%)	10–20	20–30	Improved fertilizer utilization
4	Soil organic matter (%)	0.3–0.8	1.0–2.0	Greater soil resilience
5	Soil pH	7.8–8.5	7.2–8.0	Better nutrient availability
6	Salinity severity	High	Moderate	Reduced yield constraints
7	Mechanization level	Moderate	High	Greater operational efficiency

The insights gained from these comparative studies underscore that ecological transformation constitutes the foundation upon which technological innovation and institutional reforms generate sustainable productivity gains. Therefore, understanding how climate-smart water management, soil restoration, resource-use efficiency, and regenerative agriculture interact within cotton production systems is essential for identifying practical strategies capable of narrowing the productivity gap between Pakistan and Uzbekistan. The following sections critically examine these ecological components and their contribution to enhancing cotton productivity, climate resilience, and environmental sustainability under changing climatic conditions.

Technological Transformation Pathways

Cotton Genetics and Breeding

Comparative studies consistently demonstrate that genetic improvement forms the foundation of sustainable cotton productivity, particularly under increasing climatic variability. However, the productivity advantage achieved by Uzbekistan extends beyond the development of improved cultivars to the effective integration of modern breeding, certified seed systems, and efficient technology dissemination. Pioneering studies by Abdurakhmonov et al. (2008) established the application of molecular markers in cotton breeding, while subsequent research highlighted Uzbekistan as one of the leading countries translating genomic discoveries into practical cultivar development through genome-wide association studies (GWAS), genomic prediction, and systematic multi-environment evaluation (Kushanov et al., 2021; Abdurakhmonov, 2026). These breeding strategies have accelerated the development of early-maturing, climate-resilient cultivars with improved fibre quality and enhanced tolerance to heat, drought, salinity, and major diseases. Evidence further indicates that cultivars such as Porloq, Bukhara-102, and Sultan**,** when integrated with certified seed systems and improved crop management, have provided approximately 10–20% higher farmer-level yields than older cultivars, together with improved boll retention, fibre quality, and yield stability under climate-induced stresses (Abdurakhmonov et al., 2008, 2009; FAO, 2023; ICAC, 2024). Consequently, commercial cotton farms in Uzbekistan frequently produce 3.5–4.0 t ha^{-1} of seed cotton, while national lint yields have remained comparatively stable despite reductions in cultivated area (FAOSTAT, 2024; ICAC, 2024). In contrast, although Pakistan has released numerous improved cultivars, including CIM-598, CIM-602, CIM-678, NIAB-878, FH-326, and VH-383**,** the realized genetic gains at farmers' fields remain comparatively limited (Shahzad et al., 2022;). The literature indicates that breeding programmes continue to rely predominantly on Bt-based cultivars and conventional phenotypic selection, with relatively limited integration of genomic selection and predictive breeding for heat, drought, salinity, and cotton leaf curl disease resistance (Tester and Langridge, 2010;). Moreover, although newly released cultivars often exhibit 5–10% higher yield potential under experimental conditions, these gains are frequently undermined at the farm level by poor seed purity, premature commercialization of varieties, weak enforcement of seed certification by the Federal Seed Certification and Registration Department (FSC&RD), and inconsistent crop management (Ahmad et al., 2024; Bakhsh et al., 2019). Likewise, the initial yield advantage of Bt cotton has progressively declined because of resistance development, deterioration in seed quality, secondary pest outbreaks, and inadequate technology stewardship (Qaim and Zilberman, 2003; Brookes and Barfoot, 2020).

Collectively, these studies indicate that the genetic superiority observed in Uzbekistan is driven not only by advanced breeding technologies but also by an integrated breeding–seed–farmer delivery system that efficiently converts genetic innovation into sustained farm-level productivity. By comparison, Pakistan's productivity gap reflects constraints in the translation of genetic advances into farmers' fields rather than a lack of breeding potential, highlighting the need to strengthen modern breeding approaches, seed quality assurance, and technology dissemination.

Seed Systems

Comparative evidence reveals substantial differences in the organization and performance of seed systems between Uzbekistan and Pakistan, which largely explain the contrasting farm-level productivity of the two countries. Following agricultural reforms, Uzbekistan established an integrated breeding–seed–farmer delivery system in which public research institutions, certified seed enterprises, cotton clusters, and extension services operate in close coordination. Improved cultivars undergo rigorous multi-location evaluation before commercial release, while certified seed multiplication, quality testing, and distribution are implemented under strict regulatory supervision (Abdurakhmonov et al., 2008; FAO, 2023;

World Bank, 2023). Consequently, certified seed adoption exceeds 80–90%, with high varietal replacement rates enabling the rapid dissemination of newly developed climate-resilient cultivars.

This coordinated system has substantially reduced varietal admixtures, improved seed quality, ensured uniform crop establishment, and contributed to stable cotton productivity under changing climatic conditions (ICAC, 2024; FAOSTAT, 2024). In contrast, Pakistan's cotton seed system continues to face several structural and regulatory constraints despite the release of numerous improved varieties. Studies consistently report low certified seed use (approximately 30–40%), slow seed replacement, widespread marketing of uncertified seed, and inadequate quality assurance as major barriers to productivity (Ahmad et al., 2024). Although the Federal Seed Certification and Registration Department (FSC&RD) is responsible for varietal registration, certification, and quality control, weak regulatory enforcement, limited post-registration monitoring, and premature commercialization of varieties have reduced the effectiveness of the seed system (Bakhsh et al., 2019). Consequently, many farmers cultivate seed with reduced genetic purity and inconsistent Bt expression, resulting in poor germination, uneven crop establishment, variable pest resistance, and substantial yield losses under field conditions (Shahzad et al., 2022 ;).

Collectively, these studies indicate that Uzbekistan's productivity advantage is attributable not only to superior genetic improvement but also to an efficient breeding–seed–farmer delivery system that ensures high-quality seed reaches producers rapidly and reliably. In Pakistan, strengthening certified seed production, increasing seed replacement rates, improving regulatory enforcement by FSC&RD, and fostering greater collaboration among public breeding institutions, responsible private seed companies, and extension services will be essential for translating genetic advances into sustained farm-level productivity. These improvements will become even more effective when integrated with precision agriculture and digital technologies, discussed in the following section.

Table 4. Comparison of cotton seed systems in Pakistan and Uzbekistan.

Indicator	Pakistan	Uzbekistan	Key References
Certified seed use	Generally30–40% (varies by province and year)	Generally>80–90% through organized seed multiplication and cotton clusters	FAO (2023); ICAC (2024); World Bank (2023)
Seed replacement rate	Low to moderate; farmers often reuse seed	High; regular replacement with newly released cultivars	FAO (2023); Abdurakhmonov et al. (2008)
Seed quality regulation	FSC&RD responsible, but enforcement and post-registration monitoring remain weak	Strong government-led certification and quality control integrated with cotton clusters	Bakhsh et al. (2023); World Bank (2023)
Private sector role	Expanding, but quality varies among suppliers	Regulated participation integrated with public breeding and certified multiplication	FAO (2023)
Farmer-level outcome	Variable germination, inconsistent varietal purity, unstable yields	Uniform crop establishment, high varietal purity, stable and higher yields	ICAC (2024); FAOSTAT (2024)

Precision Agriculture

Several studies indicate that Uzbekistan has integrated precision agriculture into its broader cotton modernization programme through coordinated investments in digital infrastructure, irrigation modernization, and institutional support. Satellite-based crop monitoring, UAV surveillance, soil moisture sensing, GPS-guided machinery, AI-assisted decision-support systems, and digital irrigation scheduling are increasingly used to optimize crop management and resource utilization (Abdurakhmonov, 2026). Satellite monitoring based on the Normalized Difference Red-Edge (NDRE) vegetation index has demonstrated high accuracy (R^2 up to 0.96) for estimating cotton yield, enabling timely management interventions and more precise production forecasting. Field studies further indicate that sensor-based irrigation scheduling, variable-rate nutrient application, and remote sensing have reduced irrigation water use by 20–40%, increased nitrogen-use efficiency by 15–30%, and improved cotton yields by 10–25%, while enhancing water productivity and farm profitability under increasingly variable climatic conditions (Ibragimov et al., 2021; Zhu et al., 2025). National evidence further shows that the

integration of precision technologies with improved cultivars and agronomic management increased average seed cotton yield from 3.24 to 4.55 t ha^{-1} between 2021 and 2025 despite a reduction in cultivated area, demonstrating substantial improvements in production efficiency. In contrast, the adoption of precision agriculture in Pakistan remains largely confined to research institutions, progressive commercial farms, and pilot-scale initiatives. Although studies have demonstrated the technical feasibility of remote sensing, GIS, machine learning, and AI-based cotton monitoring for improving yield prediction and climate-risk assessment, widespread adoption is constrained by fragmented landholdings, limited digital infrastructure, high investment costs, inadequate technical capacity, and weak extension services (Qadir et al., 2026;). Consequently, the productivity and resource-use benefits observed under experimental conditions have not yet been translated into large-scale commercial production. Collectively, these studies demonstrate that Uzbekistan's productivity gains are not attributable to individual precision technologies but to their integration within a broader innovation system encompassing improved genetics, certified seed systems, efficient irrigation, mechanization, and strong institutional support. In Pakistan, similar technologies have shown considerable potential, yet fragmented adoption and institutional constraints continue to limit their contribution to national cotton productivity. Expanding digital infrastructure, strengthening extension services, and promoting investment in precision agriculture will therefore be essential for narrowing the productivity gap and enhancing climate resilience. The following section examines how mechanization has further reinforced these technological gains by improving labour efficiency, harvest quality, and overall farm profitability.

Mechanization

Evidence indicates that Uzbekistan has successfully integrated mechanization into its cotton modernization programme through cotton-cluster farming, supportive government policies, machinery subsidies, and public–private investment. Precision planters, laser-guided land levellers, self-propelled sprayers, mechanical pickers, and defoliation technologies are widely adopted, enabling timely crop establishment and efficient harvesting (Bekchanov et al., 2024; World Bank, 2023). Farm-level studies have shown that mechanization reduces labour requirements by 50–70%, lowers harvesting costs by 30–50%, minimizes fibre contamination, and improves operational efficiency, thereby contributing to higher and more stable yields under climate stress (FAO, 2023; OECD, 2024). In contrast, cotton production in Pakistan remains heavily dependent on manual harvesting despite widespread tractor use for land preparation. Labour shortages, rising wage rates, delayed picking, fragmented landholdings, high machinery costs, limited custom-hiring services, and inadequate technical capacity continue to constrain the adoption of mechanical harvesting and other precision field operations (Ahmad et al., 2024; Bakhsh et al., 2019). Consequently, harvesting inefficiencies and fibre contamination remain major factors limiting productivity and profitability. Collectively, these studies demonstrate that Uzbekistan's mechanization advantage stems from its integration within a broader technological and institutional transformation rather than machinery adoption alone. Expanding affordable machinery access, custom-hiring centres, farmer cooperatives, and technical training could substantially improve operational efficiency and help narrow Pakistan's cotton productivity gap. These gains can be further strengthened through the integration of digital agriculture, discussed in the following section.

Digital Agriculture

Uzbekistan has rapidly incorporated digital technologies into its cotton modernization programme through satellite-based crop monitoring, AI-assisted diagnostics, mobile extension services, digital irrigation scheduling, and electronic farm information systems supported by government agencies and international development partners (Wolfert et al., 2017; Liakos et al., 2018; FAO, 2023). These digital platforms have strengthened irrigation management, nutrient optimization, pest surveillance, and climate-risk forecasting, contributing to 10–15% higher yields, lower production costs, and improved farm profitability under commercial production systems (FAO, 2023). More importantly, digital technologies have enhanced coordination among research institutions, extension services, cotton clusters, and farmers, accelerating the adoption of climate-smart innovations. In contrast, digital agriculture in Pakistan remains at an early stage despite encouraging advances in remote sensing, GIS-based crop monitoring, AI applications, and mobile advisory services.

Studies consistently identify inadequate digital infrastructure, weak extension systems, limited technical capacity, and low digital literacy among smallholder

farmers as major constraints to large-scale adoption (Ahmad et al., 2024). Consequently, the potential of digital technologies to improve climate resilience, resource-use efficiency, and farm-level decision-making remains largely underutilized. Collectively, these studies demonstrate that digital agriculture functions as the integrating platform linking improved genetics, certified seed systems, precision agriculture, mechanization, and extension services into a coordinated innovation ecosystem. Uzbekistan has successfully embedded digital technologies within its broader agricultural transformation strategy, whereas Pakistan must strengthen digital infrastructure, institutional coordination, and farmer capacity to fully realize the benefits of climate-smart cotton production.

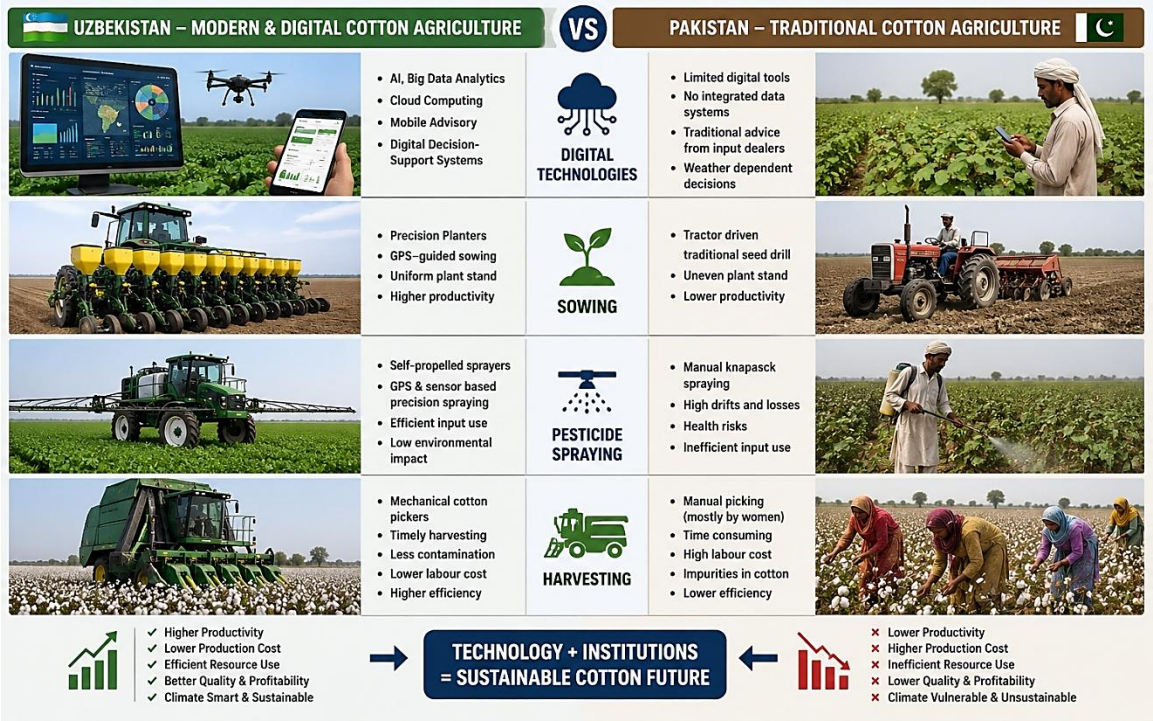


Figure 4. Showing Technological Advancement in Cotton Production.

Technological Outcomes

Collectively, the evidence synthesized in this review demonstrates that Uzbekistan's technological advantage is not attributable to a single innovation but to the coordinated integration of improved genetics, efficient seed systems, precision agriculture, mechanization, and digital agriculture within a supportive innovation ecosystem. Numerous studies have shown that these complementary technologies have collectively enhanced cotton productivity, resource-use efficiency, fibre quality, labour productivity, and climate resilience while improving the economic sustainability of commercial cotton production (FAO, 2023; World Bank, 2023; ICAC, 2024). Rather than functioning as independent interventions, these technological components reinforce one another, enabling farmers to translate scientific advances into consistent field-level productivity gains. In contrast, Pakistan possesses substantial research capacity and has released numerous improved cultivars and production technologies; however, their adoption remains fragmented because of weak seed governance, limited mechanization, slow digital transformation, inadequate extension services, and insufficient coordination among research institutions, regulatory agencies, and farmers (Bakhsh et al., 2019). Consequently, the gap between genetic yield potential and realized farm productivity remains considerably wider than in Uzbekistan.

The insights gained from these comparative studies underscore that sustainable technological transformation depends not only on scientific innovation but also on efficient technology delivery, farmer adoption, and institutional coordination. Therefore, narrowing Pakistan's cotton productivity gap will require an integrated technological transformation strategy in which improved genetics, certified seed systems, precision agriculture, mechanization, and digital agriculture are implemented as complementary components

of a unified production system rather than as isolated interventions. This synthesis provides the foundation for the subsequent analysis of the institutional and policy transformation pathways that have enabled Uzbekistan to convert technological innovation into sustained improvements in cotton productivity and farmer livelihoods.

Table.5. Comparison of Technological Advancement in Uzbekistan and Pakistan.

Technology	Uzbekistan (Farmer-level outcomes)	Pakistan (Current status)	Key References
Climate-resilient cultivars	10–20% higher yield, improved heat and drought tolerance	Slow genetic gain; Bt dependence	Abdurakhmonov et al. (2008); Hickey et al. (2019)
Certified seed systems	Better germination, uniform crop stand, 8–18% higher yield	Weak seed quality regulation, low seed replacement	Louwaars & de Boef (2012); FAO (2023)
Precision agriculture	20–40% water saving, 15–30% higher NUE, 10–25% yield gain	Limited adoption, mainly pilot projects	Gebbers & Adamchuk (2010); FAO (2023)
Mechanization	50–70% labour saving, reduced harvest losses, improved fibre quality	Predominantly manual harvesting	OECD (2024); World Bank (2023)
Digital agriculture	10–15% higher yield, improved decision-making and climate resilience	Emerging adoption with limited field-scale implementation	Wolfert et al. (2017); FAO (2024)

Institutional Transformation Pathways

Institutional transformation has emerged as a fundamental driver of sustainable cotton productivity under climate change because technological innovations achieve lasting benefits only when supported by effective governance, research, extension, markets, and enabling policy frameworks. Comparative studies consistently demonstrate that countries integrating institutional reforms with technological modernization achieve greater productivity, resource-use efficiency, and climate resilience than those relying on technological interventions alone (World Bank, 2022; FAO, 2023; OECD, 2023). Uzbekistan has pursued a coordinated institutional transformation linking production, financing, processing, and marketing, whereas Pakistan continues to face fragmented governance, inconsistent policy implementation, and weak institutional coordination, limiting the widespread adoption and impact of improved technologies (Bekchanov et al., 2021; World Bank, 2022).

Policy and Cotton Cluster Reforms

Agricultural policies play a decisive role in shaping farmer investment, technology adoption, and long-term productivity. Studies have shown that stable policy environments combined with institutional coordination encourage private investment and accelerate agricultural modernization (OECD, 2023; World Bank, 2022). Following a series of reforms initiated after 2017, Uzbekistan gradually abolished the state procurement quota system, liberalized agricultural markets, improved land tenure arrangements, strengthened digital governance, and encouraged private-sector participation (Bekchanov et al., 2021; OECD, 2023). A central component of these reforms has been the cotton cluster model, which integrates input supply, certified seed, mechanization, irrigation services, technical advisory, and finance, processing, and marketing within a single institutional framework. This integrated approach has reduced transaction costs, improved technology dissemination, enhanced production efficiency, and strengthened farmer incentives to adopt climate-smart practices (Djanibekov et al., 2018; World Bank, 2022).

In contrast, Pakistan's cotton sector remains constrained by fragmented policy implementation, inconsistent seed regulation, weak institutional coordination, and limited integration among research organizations, extension services, input suppliers, processors, and markets (Government of Pakistan, 2025; Ahmad et al., 2024;). These institutional weaknesses have slowed technology adoption and reduced the effectiveness of investments in improved cotton production.

Research–Extension–Innovation Systems

The effectiveness of agricultural innovation depends on strong linkages among research institutions, extension services, and farmers. Evidence consistently indicates that integrated research–extension systems accelerate

technology dissemination, improve climate adaptation, and enhance productivity (FAO, 2023). Although Pakistan continues to develop improved cotton varieties and production technologies, field-level adoption remains limited because of inadequate extension coverage, weak coordination among institutions, insufficient farmer training, and limited on-farm demonstrations (PARC, 2023; Ahmad et al., 2024;). By comparison, Uzbekistan has strengthened institutional integration by linking research organizations with cotton clusters, demonstration farms, digital advisory platforms, mechanization training, and irrigation management programmes. Continuous technical support from cluster agronomists has accelerated the adoption of certified seed, precision agriculture, integrated pest management, and water-efficient irrigation practices, contributing to greater productivity and climate resilience (Bekchanov., 2024; World Bank, 2022; OECD, 2023).

Market and Value Chain Integration

Efficient market institutions are essential for improving farm profitability and encouraging investment in advanced production technologies. Studies have shown that vertically integrated value chains strengthen coordination among input suppliers, producers, processors, and exporters, thereby enhancing efficiency, product quality, and market competitiveness (World Bank, 2022). Uzbekistan has successfully integrated cotton production with ginning, textile manufacturing, and export-oriented industries through the cotton cluster system, providing farmers with timely access to production inputs, mechanization services, institutional finance, and guaranteed markets (OECD, 2023; World Bank, 2022). In contrast, Pakistan's cotton value chain remains fragmented, characterized by limited institutional credit, weak quality-based pricing, inadequate coordination between producers and the textile industry, and poor market incentives for technological investment (Government of Pakistan, 2025; Ahmad et al., 2024). These institutional differences have significantly influenced technology adoption, production efficiency, and value addition in the two countries.

Table 6. Comparative institutional transformation pathways in Pakistan and Uzbekistan.

Institutional component	Pakistan	Uzbekistan
Policy framework	Inconsistent and short-term	Stable, long-term reforms
Production model	Fragmented smallholder farming	Integrated cotton cluster system
Institutional coordination	Weak inter-agency coordination	Coordinated public–private governance
Research–extension linkage	Limited technology transfer	Cluster-based continuous advisory services
Market structure	Fragmented value chain	Vertically integrated value chain
Farmer support	Limited mechanization, finance and extension	Integrated input, finance, mechanization and advisory services

Overall, comparative evidence indicates that Uzbekistan's coordinated institutional reforms have created an enabling environment for rapid technology adoption, efficient resource utilization, and value-chain integration, whereas fragmented institutional arrangements continue to limit productivity gains in Pakistan despite the availability of improved production technologies.

Pakistan Cotton Transformation Plan (PCTP): Lessons and Future Transformation Pathways

The comparative evidence synthesized throughout this review demonstrates that the productivity gap between Pakistan and Uzbekistan cannot be attributed to a single technological limitation or climatic constraint. Instead, it reflects differences in the integration of ecological management, technological innovation, and institutional governance within national cotton production systems. Experiences from Uzbekistan and other major cotton-producing countries consistently indicate that sustainable productivity gains are achieved when these three dimensions operate synergistically rather than independently (FAO, 2023; World Bank, 2022; OECD, 2023; IPCC, 2023). Based on this evidence, this review proposes a Pakistan Cotton Transformation Plan (PCTP) as a comprehensive, systems-based roadmap for revitalizing Pakistan's cotton sector under climate change. Rather than recommending isolated interventions, the PCTP integrates ecological restoration, technological modernization, institutional strengthening, and future research into a coordinated national strategy designed to improve productivity, profitability, climate resilience, and resource-use efficiency. The proposed plan is not intended to replicate Uzbekistan's production system, but to adapt its successful transformation principles to Pakistan's distinct agroecological, socio-economic, and institutional conditions. Collectively, these interconnected

transformation pathways provide a practical evidence-based framework for achieving sustainable cotton intensification and restoring the global competitiveness of Pakistan's cotton sector.

Ecological Transformation Pathways

The evidence identifies ecological sustainability as the foundation of long-term cotton productivity under climate change. Global studies consistently demonstrate that conservation agriculture, efficient irrigation, improved soil health, crop diversification, and regenerative agricultural practices enhance resource-use efficiency while increasing resilience to climatic extremes (Lal, 2020; FAO, 2023; IPCC, 2023). The experience of Uzbekistan further illustrates that investments in laser land levelling, water-saving irrigation technologies, conservation tillage, residue management, and improved soil fertility can simultaneously improve irrigation efficiency, reduce land degradation, and stabilize cotton yields under water-limited conditions (Bekchanov et al., 2024;). For Pakistan, future ecological transformation should prioritize integrated watershed management, conservation agriculture, precision irrigation, crop diversification, biochar application, integrated nutrient management, residue recycling, and other regenerative agricultural practices through coordinated national programmes. These interventions would improve soil health, increase water productivity, enhance carbon sequestration, and strengthen resilience against climate-induced production risks.

Technological Transformation Pathways

The comparative literature demonstrates that technological innovation contributes to sustained productivity only when scientific advances are efficiently translated into farm-level adoption. International experience shows that productivity improvements are driven by the combined deployment of improved genetics, certified seed systems, mechanization, precision agriculture, remote sensing, artificial intelligence, and digital decision-support platforms rather than by varietal improvement alone (FAO, 2023; ICAC, 2024). Uzbekistan provides a practical example of this integrated technological transition through the coordinated use of certified seed, mechanized field operations, precision irrigation, digital advisory services, and climate-smart crop management (Bekchanov et al., 2013; World Bank, 2022).

Accordingly, Pakistan should accelerate investments in climate-resilient cotton breeding, certified seed systems, mechanization suited to smallholder farming, precision agriculture, unmanned aerial vehicles, remote sensing, artificial intelligence, and digital extension services. Integrating these technologies within farmer-oriented advisory systems will substantially improve input-use efficiency, reduce production costs, and enhance cotton productivity under changing climatic conditions.

Institutional Transformation Pathways

The strongest lesson emerging from this review is that institutional effectiveness determines whether ecological and technological innovations generate measurable improvements in productivity. Evidence from Uzbekistan demonstrates that coordinated policy reforms, integrated cotton clusters, effective extension systems, and vertically linked value chains created an enabling environment for rapid technology adoption, improved resource-use efficiency, and increased farm profitability (World Bank, 2022; OECD, 2023; Bekchanov et al., 2018). Similar findings from international agricultural development studies further emphasize that institutional coordination, stable policy environments, public–private partnerships, and efficient market systems are essential for sustaining agricultural transformation (FAO, 2023; World Bank, 2022).

Future institutional reforms in Pakistan should therefore focus on strengthening coordination among research organizations, extension agencies, seed regulatory authorities, irrigation departments, financial institutions, private enterprises, and the textile industry. Region-specific production clusters, modern digital extension systems, improved seed certification, contract-based service delivery, and stronger research–industry partnerships should be promoted to accelerate technology dissemination and improve value-chain efficiency while adapting successful international experiences to Pakistan's socio-economic and agroecological conditions.

Future Research Priorities

Despite significant advances in cotton research, several critical knowledge gaps remain. Future studies should adopt multidisciplinary systems approaches integrating agronomy, climate science, engineering, economics, data science, and social sciences to evaluate whole-farm performance under changing climatic conditions. Priority research areas include climate-resilient cotton breeding using genomic and phenomic tools, long-term carbon accounting of regenerative production systems, artificial intelligence-based irrigation and nutrient management, digital advisory platforms for smallholder farmers, remote

sensing and Internet of Things applications for precision agriculture, and socio-economic assessments of technology adoption and institutional reforms (FAO, 2023; IPCC, 2023; ICAC, 2024). Long-term comparative studies evaluating the ecological, economic, and social performance of integrated production systems, public–private partnerships, cotton cluster models, and climate-smart value chains across different agroecological regions are also required. Such evidence will strengthen future policy formulation and facilitate the development of resilient, resource-efficient, and internationally competitive cotton production systems in Pakistan and other cotton-producing countries.

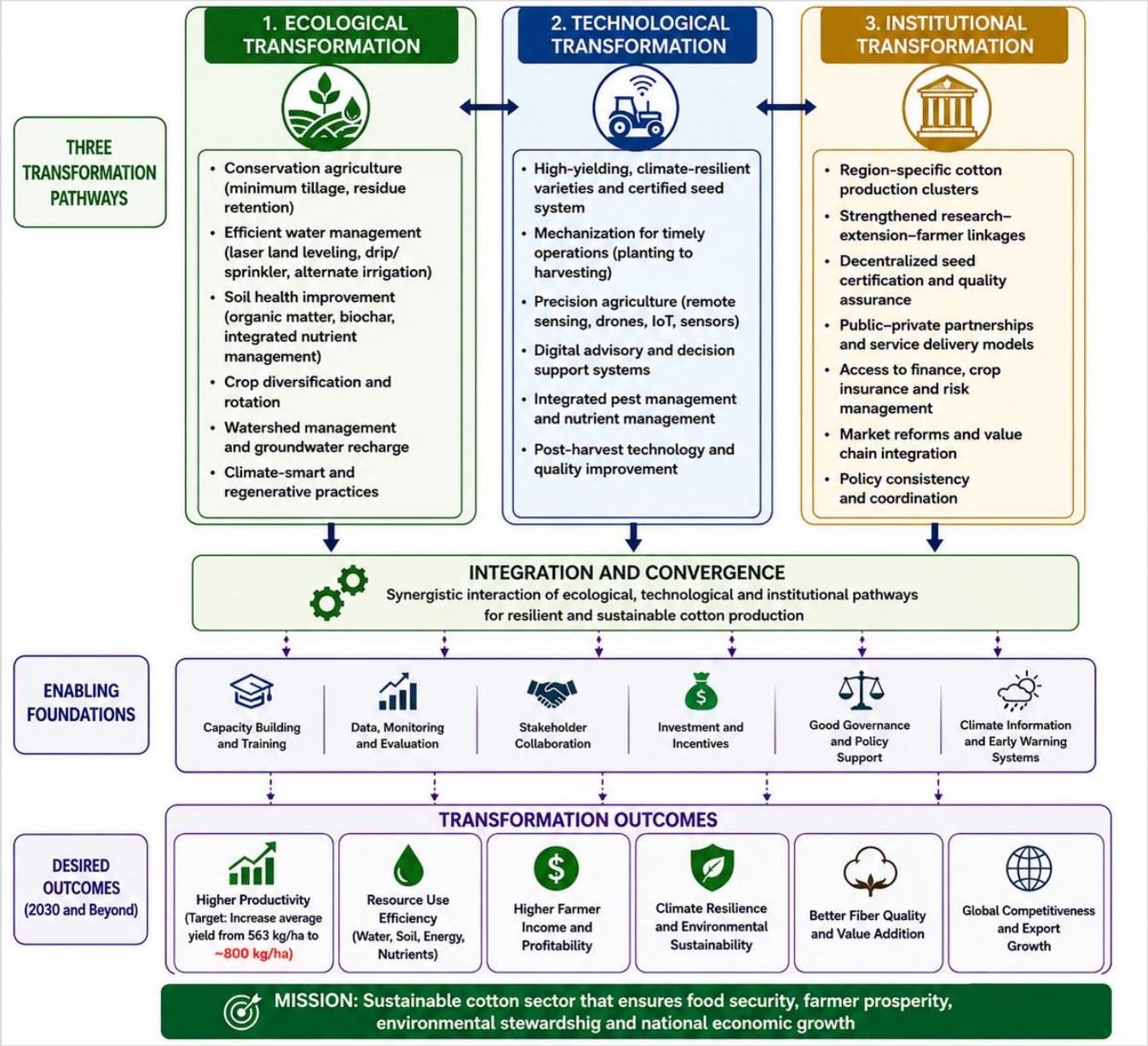


Figure 5. Conceptual framework of Pakistan Cotton Transformation Plan.

CONCLUSION

This review demonstrates that Uzbekistan's superior cotton productivity under climate change is not driven by a single technological innovation but by the coordinated transformation of ecological management, technological advancement, and institutional governance. Comparative evidence consistently indicates that sustainable productivity is achieved when climate-smart agronomic practices, certified seed systems, mechanization, precision agriculture, efficient

water management, digital advisory services, and supportive institutional reforms are implemented as an integrated production system rather than as isolated interventions. In contrast, Pakistan's cotton sector continues to face fragmented implementation of these components, limiting the realization of its substantial production potential despite favourable agroecological conditions and a strong scientific research base.

Based on the evidence synthesized throughout this review, a Pakistan Cotton Transformation Plan (PCTP) is proposed as an integrated roadmap to accelerate sustainable cotton development under climate change. The plan emphasizes three interconnected transformation pathways—ecological restoration, technological modernization, and institutional strengthening—adapted from successful international experiences, particularly Uzbekistan, while considering Pakistan's unique agroecological and socio-economic conditions. Strategic implementation of these coordinated interventions has the potential to increase Pakistan's average cotton productivity from the current 563 kg ha^{-1} to approximately 800 kg ha^{-1} over the medium to long term, while simultaneously improving resource-use efficiency, climate resilience, farmer profitability, and the global competitiveness of Pakistan's cotton sector.

Beyond comparing two major cotton-producing countries, this review provides an integrated scientific synthesis that translates comparative evidence into a practical transformation strategy for sustainable cotton production. The proposed Pakistan Cotton Transformation Plan offers a scientifically grounded framework for policymakers, researchers, development partners, and the farming community to revitalize Pakistan's cotton sector and may also serve as a valuable reference for other cotton-producing countries seeking resilient, productive, and climate-smart agricultural systems under increasingly challenging environmental conditions.

REFERENCES

Abbas, Y., Yun, S., Mehmood, A., Shah, F. A., Wang, K., Eldin, E. T., and Bocchetta, P. 2023. Co-digestion of cow manure and food waste for biogas enhancement and nutrients revival in bio-circular economy. Chemosphere, 311:137018.

Abdullaev, I., Ul Hassan, M. and Jumaboev, K. 2007. Water saving and economic impacts of land leveling: the case study of cotton production in Tajikistan. Irrigation and Drainage Systems, 21(3): 251-263.

Abdurakhmonov, I.Y. 2026. Plant RNA interference from antiviral silencing to multiplex trait engineering for climate-resilient crops. Frontiers in Plant Science, 17:1871239.

Abdurakhmonov, I.Y., Z.T. Buriev, S. Saha, A.E. Pepper, J.A. Musaev, A. Almatov, S.E. Shermatov, F.N. Kushanov, G. Mavlonov et al. 2008. Molecular diversity and association mapping of fibre quality traits in cotton. Genomics, 92: 478–487. https://doi.org/10.1016/j.ygeno.2008.07.013.

Ahmad, A.I., A.I. Khan, M.A. Negm, R. Iqbal, M.T. Azhar, S.H. Khan and I.A. Rana. 2024. Enhancing cotton resilience to challenging climates through genetic modifications. Journal of Cotton Research, 7: 10. https://doi.org/10.1186/s42397-024-00171-4.

Ashraf, S., K. Mahmood, I. Ashraf and N. Akbar. 2024. A phenomenological inquiry into farmers' experiences growing cotton in Punjab, Pakistan. Scientific Reports, 14: 13846.

Bakhsh, A., Hossain, M. J., Yerlikaya, B. A., Ayten, S.and Özcan, S. 2023. An overview of regulations of genetically modified organisms in Türkiye. GMOs and Political Stance, 193-230.

Bakhsh, K., R. Ali and M.A. Yasin. 2019. Impact of urbanization on CO_2 emissions in an emerging economy: Evidence from Pakistan. Sustainable Cities and Society, 48: 101553.

Bange, M.P., S.P. Milroy and P. Thongbai. 2010. Minimizing immature fiber and neps in upland cotton. Agronomy Journal, 12: 218–297.

Bekchanov, M. 2024. Conveyance efficiency and irrigation water productivity under varying water supply conditions in arid lowlands of Central Asia. Agricultural Water Management, 293: 108697.

Bekchanov, M., C. Ringler, A. Bhaduri and M. Jeuland. 2015. How would the Rogun Dam affect water and energy scarcity in Central Asia? Water International, 40(5–6): 856–876.

Bekchanov, M., J.P.A. Lamers, Djanibekov, I. Bobojonov, N., J. Franz-Vasdeki, J. Ruzimov and C. Martius. 2013. Options and constraints for crop diversification: A case study in sustainable agriculture. Agroecology and Sustainable Food Systems, 37(7): 788–811.

Brookes, G. and P. Barfoot. 2020. GM Crops: Global Socio-Economic and Environmental Impacts 1996–2018. PG Economics Ltd., Dorchester, UK.

Constable, G.A. and M.P. Bange. 2015. The yield potential of cotton (Gossypium hirsutum L.). Field Crops Research, 182: 98–106.

Fang, D.D., J.N. Jenkins and R.G. Percy. 2021. Cotton breeding for climate resilience: Recent advances and future perspectives. Theoretical and Applied Genetics, 134: 3571–3591.

Fischer, T., Ammar, K., Monasterio, I. O., Monjardino, M., Singh, R., and Verhulst, N. 2022. Sixty years of irrigated wheat yield increase in the Yaqui Valley of Mexico: Past drivers, prospects and sustainability. Field Crops Research, 283:108528.

Food and Agriculture Organization (FAO). 2023. The State of Food and Agriculture 2023. FAO, Rome, Italy.

Food and Agriculture Organization (FAO). 2024. The State of Food and Agriculture 2024. FAO, Rome, Italy.

Food and Agriculture Organization (FAOSTAT). 2024. FAOSTAT: Crops and Livestock Products Database. FAO, Rome, Italy.

Gebbers, R. and V.I. Adamchuk. 2010. Precision agriculture and food security. Science, 327(5967): 828–831.

Government of Pakistan. 2025. Pakistan Economic Survey 2024–25. Ministry of Finance, Islamabad, Pakistan.

Hatfield, J.L. and C. Dold. 2019. Water-use efficiency: Advances and challenges in a changing climate. Frontiers in Plant Science, 10: 103. https://doi.org/10.3389/fpls.2019.00103.

Hickey, J.M., T. Chiurugwi, I. Mackay and W. Powell. 2019. Genomic prediction unifies animal and plant breeding programs to form platforms for biological discovery. Nature Genetics, 51: 1297–1303.

Ibragimov, N., M. Bekchanov and I. Abdullaev. 2021. Precision irrigation improves water productivity in irrigated cotton systems of Uzbekistan. Agricultural Water Management, 37: 756–897.

Intergovernmental Panel on Climate Change (IPCC). 2023. Climate Change 2023: Synthesis Report. IPCC, Geneva, Switzerland.

International Center for Agricultural Research in the Dry Areas (ICARDA). 2023. Annual Report 2023: Climate-Resilient Agriculture in Dry Areas. ICARDA, Beirut, Lebanon.

International Cotton Advisory Committee (ICAC). 2024. Cotton: World Statistics 2024. ICAC, Washington, DC, USA.

Irshad, M. K., Saleem, S., Ansari, J. R., Noman, A., Aqeel, M., Alshahrani, M. O. and Lee, S. S. 2025. An analysis of impact of soil co-pollution with lead and traditional/biodegradable microplastics on growth characteristics of maize (Zea mays L.). Journal of Environmental Sciences, 166: 197-208

Kumar, R., Srivastava, Y., Muthuramalingam, P., Singh, S. K., Verma, G., Tiwari, S., ... and Tyagi, R. K. 2023. Understanding mutations in human SARS-CoV-2 spike glycoprotein: A systematic review and meta-analysis. 15(4):856.

Kushanov, F.N., I.Y. Abdurakhmonov et al. 2021. Genome-wide association studies accelerate cotton breeding for climate resilience. Frontiers in Plant Science, 16: 115–128.

Lal, R. 2020. Regenerative agriculture for food and climate. Journal of Soil and Water Conservation, 75(5): 123A–124A.

Liakos, K.G., P. Busato, D. Moshou, S. Pearson and D. Bochtis. 2018. Machine learning in agriculture: A review. Sensors, 18(8): 2674.

Lobell, D.B., J.A. Burney and colleagues. 2021. Anthropogenic climate change has slowed global agricultural productivity growth. Nature Food, 2: 6–13.

Louwaars, N.P. and W.S. de Boef. 2012. Integrated seed sector development in Africa: A conceptual framework for creating coherence between practices, programs and policies. Journal of Crop Improvement, 26(1): 39–59.

Organisation for Economic Co-operation and Development (OECD). 2023. Agricultural Policy Monitoring and Evaluation 2023. OECD Publishing, Paris, France.

Organisation for Economic Co-operation and Development (OECD). 2024. Agricultural Policy Monitoring and Evaluation 2024. OECD Publishing, Paris, France.

Organisation for Economic Co-operation and Development (OECD)/Food and Agriculture

Organization (FAO). 2023. OECD–FAO Agricultural Outlook 2023–2032. OECD Publishing, Paris, France.

Pakistan Agricultural Research Council (PARC). 2023. Annual Report 2023. Pakistan Agricultural Research Council, Islamabad, Pakistan.

Pretty, J., T.G. Benton, Z.P. Bharucha, L.V. Dicks, C.B. Flora, H.C.J. Godfray, D. Goulson, S. Hartley, N. Lampkin, C. Morris, G. Pierzynski, P.V.V. Prasad, J. Reganold, J. Rockström, P. Smith, P. Thorne and S. Wratten. 2018. Global assessment of agricultural system redesign for sustainable intensification. Nature Sustainability, 1(8): 441–446.

Qadir, T.A., A. Shabbir, M. Ahmad, M. Hasan and A. Ali. 2026. Artificial intelligence models for high-dimensional and digital biology in plants: Society and environment. Plant Spatial Biology, 96-108.

Qaim, M. and D. Zilberman. 2003. Yield effects of genetically modified crops in developing countries. Science, 299(5608): 900–902.

Rhodes, C.J. 2022. Regenerative agriculture: Soil restoration and climate resilience. Science Progress, 105(2).

Shahzad, K., I. Mubeen, M. Zhang and A. Raza. 2022. Progress and perspective on cotton breeding in Pakistan. Journal of Cotton Research, 5(1): 29.

Tester, M. and P. Langridge. 2010. Breeding technologies to increase crop production in a changing world. Science, 327(5967): 818–822.

Ullah, K., A. Ahmad, I. Khan, M. Hussain, A. Ali and A. Raza. 2024. Sustainability in the face of economic growth, financial development and CO_2 emissions in Pakistan. Journal of Managerial Sciences, 8: 78–92.

United States Department of Agriculture, Foreign Agricultural Service (USDA-FAS). 2024. Cotton: World Markets and Trade. USDA Foreign Agricultural Service, Washington, DC, USA.

Wolfert, S., L. Ge, C. Verdouw and M.J. Bogaardt. 2017. Big data in smart farming: A review. Agricultural Systems, 153: 69–80. https://doi.org/10.1016/j.agsy.2017.01.023.

World Bank. 2022. Uzbekistan Country Economic Memorandum: Toward a More Inclusive and Sustainable Economy. World Bank, Washington, DC, USA.

World Bank. 2023. Uzbekistan Country Climate and Development Report. World Bank, Washington, DC, USA.

World Bank. 2024. Water Security and Climate Adaptation in Agriculture. World Bank, Washington, DC, USA.

World Bank. 2025. Uzbekistan Country Economic Update 2025. World Bank, Washington, DC, USA.

Zhu, Y., S. Zhang and S. Tang. 2025. Research progress and applications of artificial intelligence in agricultural equipment. MDPI, 15(15): 1703. https://doi.org/10.3390/agriculture15151703.

Publisher's note: EScience Press remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/.