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Review Article

BRIDGING COTTON RESEARCH GAPS FOR A RESILIENT AND SUSTAINABLE COTTON SECTOR IN PAKISTAN

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Abstract

This review identifies and prioritizes key research gaps in the global cotton sector, with a specific focus on challenges facing Pakistan's cotton production. The article synthesizes gaps found in existing literature, methodologies, theoretical frameworks, data verification, and practical implementation. It highlights that the most critical issues facing Pakistan's cotton sector include genetic limitations, poor seed quality, pest management failures, and the impacts of climate change. The review also notes that these challenges are compounded by weak institutional support, insufficient investment, and a lack of effective farming practices. This analysis emphasizes that addressing these interconnected gaps requires strengthening collaborations, adopting innovative research techniques, and implementing targeted policy interventions to foster a more sustainable and equitable cotton sector.

Keywords: *Cotton Research, Sustainable cotton, interconnected gaps.*

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1. INTRODUCTION

To identify a research gap is to pinpoints an unanswered question related to either insufficient data or conflicting findings emphasizing the need for deeper exploration (Armstrong and Shimizu, 2007; Creswell, 2018; Bryman, 2021; Booth *et al.*, 2016). Addressing these multifaceted gaps (Fig. 1) is fundamental for the amplification of missing sustainability, efficiency, and equity across different sectors, ultimately bringing transformation into the whole tangible relevant field (Hart, 2018; Snyder, 2019; Webster and Watson 2002). Nevertheless, within the realm of agriculture research, a thorough gap analysis is unavoidable to illuminate existing impediments and latent prospects, coupled with scientifically informed recommendations aimed at attaining national self-sufficiency and food security (Keller *et al.*, 2024; Wang *et al.*, 2022; Huang *et al.*, 2021; Kohli *et al.*, 2015; Gaddi and Mundinamani, 2002). However, in a specific crop like cotton a comprehensive gap analysis is required to provides a strategic roadmap for targeted interventions and advancements across the entire cotton value chain (Nachimuthu and Webb, 2017; Zhao *et al*., 2023; Khandave *et al*., 2017; Mollaee *et al*., 2019).

2. LITERATURE GAPS

A research lacuna in the field of agriculture science is an indication that the particular scholarly investigation has not sufficiently explored, highlighting the specific deficiency in that identified domain. This knowledge gap necessitates further rigorous scientific inquiry to enhance our understanding and inform evidence-based agricultural practices and policies (Gebrehiwot, and Van, 2013; Sumberg, and Okali, 1997; Robinson and Petrov, 2016)). Addressing literature gaps in cotton research need to fill in some spaces current research literature about what problems farmers face when growing it, how cotton moves from the farm to the final product, what farmers need to know, and how to take care of our resources for the long term (Pan, *et al*., 2021; Khan *et al*., 2017). Research on climate change impacts on cotton mainly focuses on yield, leaving a gap in understanding its effects on fiber quality across varieties and regions (Reddy *et al*., 2017). The application and effectiveness of digital agriculture technologies in cotton production, especially for smallholder farmers, requires more comprehensive research (FAO, 2019). A limited understanding exists regarding the specific cotton microbiome under different management practices and its influence on yield and fiber quality (Manzotti *et al*., 2020). Consumer awareness and willingness to pay for sustainable cotton products remain under-researched across various global markets (United Nations Conference on Trade and Development, 2015). We also need to learn more about how to help cotton farmers learn new ways of farming and use new technologies effectively (Ahmed *et al*., 2018). Finally, to use things like fertilizers and water in the best way and protect the environment, we need more research that looks at both the money side and the environment (Iqbal *et al*., 2022). One big problem is that we can't easily track cotton all the way from the field after it leaves the spinning factory, especially when cotton from different places gets mixed together (King, 2024). Also, we need to do more studies in specific areas to figure out exactly why cotton production is going down in places like Pakistan (Raza *et al*., 2021).

3. DISAGREEMENT GAP

A key disagreement in cotton research revolves around the sustainability of conventional, organic, and Bt cotton. Some argue conventional cotton is unsustainable due to its environmental impact from pesticides and fertilizers (Horowitz *et al*., 2005 (A); Aktar *et al*., 2009). Others prefer organic cotton for its ecological benefits, though can’t deny its lower yields (Scialabba and Hattam, 2002; Ton and Bijman, 2005). Genetically modified Bt cotton is reclaim for reducing insecticide use (Qaim and Zilberman, 2003) however the issues like insect resistance and super weeds are far alarming (Tabashnik *et al*., 2009A; Tabashnik *et al*., 2009B). On one side organic cotton is considered more environmentally friendly but its water footprints as compared to conventional or even Bt cotton in certain regions are discouraging. This is due to its potentially lower yields that it might require more water per unit of output in water-scarce areas (Chapagain *et al*., 2006). One the other side this contrasts with arguments that the reduced use of synthetic fertilizers in organic systems can lead to better soil health and water retention in the long run (Scialabba and Hattam, 2002). This motivates a researcher to conduct more localized and comprehensive water footprint analyses, considering irrigation practices, rainfall patterns, and soil types across different production systems to seek the hidden truth. While numerous studies have reported the economic benefits of Bt cotton in terms of reduced pesticide costs and increased yields (Qaim and Zilberman, 2003), a contrasting body of research highlights negative socio-economic consequences for small land holder farming community, particularly in developing countries e.g., India. These concerns pinpoint increased dependence on expensive hybrid seeds, instability in yield potential and the worsening farmers lives due to debt (Shiva and Jafri, 2004; Stone, 2012). Research gaps exist in evaluating a true picture of socio-economic impacts of Bt cotton across diverse farming systems and to develop strategies accordingly to ensure benefits for all scales of farmers. This disagreement stems from varying prioritizations of environmental, economic, and social factors. Furthermore, relevant future research should be focused on overall life cycle assessments. The long-term impacts of each individual system should also be considered to bridge these gaps. The key disagreement in cotton research stems from the fact that no single production system, conventional, organic, or Bt cotton has been definitively proven to be superior across all environmental, economic, and social metrics, necessitating further localized and long-term research to understand the true trade-offs and impacts.

4. CONTEXTUAL GAP

A significant contextual gap exists in cotton research encompassing various areas. The impact of climate change on small land holder farmers particularly in vulnerable regions is one of them (Raza *et al*., 2021; 2014 IPCC reports, 2014). There is a history of socio-cultural norms in the region which significantly influence cotton farming decisions and technology adoption which is often overlooked in research findings (Scoones, 1999; Richards, 1985). The advantages and disadvantages of dynamics and importance of informal seed systems in maintaining cotton diversity and resilience require further investigation (Almekinders *et al*., 1994; Louwaars and de Boef, 2012). The deep rooted land tenure systems and it's critically impacts on farmer's investment in sustainable cotton practices must be considered and necessitating more research on these linkages (Feder and Feeny, 1991; Besley, 1995; Ton and Bijman, 2005). A comparison study regarding the specific factors influencing youth engagement in cotton agriculture and aging farmer populations is essential to study (White, 2012; Sumberg and Okali, 2000). Furthermore, the adoption of sustainable practices by women farmers, who face unique barriers and gender discrimination effects, must be evaluated (Knowler *et al*., 2007; Doss, 2002). There are considerable gaps to fill in areas related to digital agriculture's effectiveness in low-connectivity areas, searching considering issues of accessibility and limited local community literacy (Wolfert *et al*., 2017; Unwin, 2009). Finally, historical analyses of cotton production practices and their environmental consequences in specific regions are often lacking (Crosby, 2004; Worster, 1979). More précised and innovative approaches are crucial to robustly address the gaps.

5. THEORETICAL GAP

The whole process and throughout study of adaptation of latest technology by farming community is lacking. A unified theory especially explaining small land holder cotton farmers' cooping various challenges is crucial for future planning (Agarwal, 1988; Moser and Barrett, 2003). Seed system is basic and a theoretical framework for its resilience with formal and informal interactions is. These loopholes are there therefore whole system is undeveloped (Weltzien *et al*., 2004; McGuire and

Sperling, 2016). An integrated such type of model linking various important factors like soil health, plant health, and fiber quality in cotton crop research seems untouched and underdeveloped (Doran, 2002). Similar efficient models are required to address the social and ethical implications of cotton technology and its adoption (Kloppenburg, 2004; Thompson, 2007). A poor history of theoretical understanding exists developing a huge gap between the integrated interplay of fiber development and environmental cues at a molecular level (Haigler *et al*., 2007). Furthermore, work need to be done to report the theoretical frameworks explaining farmers' complex decision-making regarding sustainability trade-offs (Ajzen, 1991). Cotton research and development is linked with comprehensive modeling for predicting pest resistance evolution. The theoretical point of view explaining their spread in cotton agro-ecosystems also require further development (Tabashnik and Croft, 1982). Additionally, it is impossible to bring out global change unless these gap barriers are not removed which hinder our analysis of the resilience of cotton-based livelihoods (Holling, 1973). Addressing these gaps through the development of theoretical frameworks of interdisciplinary approaches and innovative thinking is crucial for advancing the field of cotton research.

6. EMPIRICAL GAP

A throughout reporting system and successful practical implementation of all related cotton research can only fill empirical gaps undermining the system. This gap filling requires real-world data. Long-term socio-economic impacts of sustainable initiatives in relation with farms and farming community require comprehensive empirical assessment (Lohano *et al*., 2017; Pretty, 2008). Extensive, long-term field data and its empirical validating along with the multifaceted benefits of agroecological practices in diverse cotton-growing regions is almost unavailable (Gliessman, 2015; Altieri, 1999). Empirical data on the adoption and real-world impact of specific IPM techniques in smallholder cotton farming systems remains limited (Dhaliwal *et al*., 2010; Horowitz and Ishaaya, 1994). Empirical studies documenting the large-scale implementation and benefits of circular economy practices within the cotton value chain are also lacking (Korhonen *et al*., 2018). More empirical research framework is needed to understand the socio-economic impacts of new agricultural technologies on farmer's livelihood influencing the whole system. Empirical gaps addressing labor and equity within cotton-producing communities are vital for future planning (Barrett *et al*., 2001; Brynjolfsson and McAfee, 2014). Field-level data identifying influence of change in global policies on the overall research framework and especially the effectiveness of digital agriculture solutions across diverse farming systems is often limited (Wolfert *et al*., 2017; Unwin, 2009). The real-world validation of laboratory-based pest and disease management strategies and its comparison under field conditions is also insufficient (Paterson *et al*., 2012). Furthermore, empirical data on climate change impacts on cotton fiber quality in different effected regions is though lacking which is a very important factor in textile industry (Messina *et al*., 2006). Finally, almost every area that hinders circular economy practices in the cotton value chain needs more empirical investigation. Addressing these contextual gaps will ensure cotton research is more relevant and equitable across diverse settings.

7. METHODOLOGICAL GAP

Methodological gaps in cotton research hinder the field's progress. Cotton research inadequately employs systems thinking and integrated modeling to grasp the interconnectedness of agronomic, economic, social, and environmental factors (Checkland, 1999; van Ittersum *et al*., 2003). The limited use of participatory research methods hinders the relevance and applicability of findings by overlooking farmer involvement and indigenous knowledge (Pretty, 1995; Cornwall and Jewkes, 1995). A lack of standardized data collection and reporting protocols across cotton studies impedes synthesis and robust global conclusions (Nelson *et al*., 2018). Sophisticated economic and policy analysis tools are underutilized in evaluating the impacts of cotton systems, technologies, and policies, hindering evidence-based decisions (Sadoulet and de Janvry, 1995; Alston *et al*., 1995). Over-reliance on small-scale, short-term trials limits generalizability (Edmeades, 2003). The potential of advanced remote sensing and precision agriculture for comprehensive data collection remains underexploited (Weiss *et al*., 2020; Lowenberg-DeBoer and Erickson, 2019). Complex interactions are not always captured by simpler statistical methods (Piepho *et al*., 2012; Messina *et al*., 2006). Furthermore, farmer perspectives are often overlooked due to limited qualitative research (Chambers, 1994; Scoones, 2009). Finally, challenges in data sharing and reproducibility impede knowledge verification and advancement (Baker, 2016; Wilkinson *et al*., 2016). Addressing these gaps with more robust and innovative approaches is crucial.

8. THEORETICAL GAP

A unified theory explaining smallholder cotton farmers' complex innovation and adaptation processes to various challenges is lacking (Agarwal, 1988; Moser and Barrett, 2003). A theoretical framework for the resilience of the entire cotton seed system, considering formal and informal interactions, is yet to be developed (Weltzien *et al*., 2004; McGuire and Sperling, 2016). An integrated theoretical model linking soil health, plant health, and fiber quality in cotton remains underdeveloped (Doran, 2002). Robust theoretical models addressing the social and ethical implications of cotton technology adoption are needed (Kloppenburg, 2004; Thompson, 2007). A theoretical gap exists in understanding the integrated interplay of fiber development and environmental cues at a molecular level (Haigler *et al*., 2007). Furthermore, robust theoretical frameworks are needed to explain farmers' complex decision-making regarding sustainability trade-offs (Ajzen, 1991). Comprehensive theoretical models for predicting pest resistance evolution and spread in cotton agro-ecosystems also require further development (Tabashnik and Croft, 1982). Additionally, underdeveloped theoretical frameworks limit our analysis of the resilience of cotton-based livelihoods to global change (Holling, 1973).

9. PRACTICAL GAP

Climate-resilient cotton varieties face practical limitations in availability and affordability for vulnerable smallholder farmers (FAO, 2019; IPCC reports, 2014). Inadequate agricultural extension services hinder the widespread adoption of sustainable cotton farming practices (Anderson and Feder, 2007; Rivera *et al*., 2000). Weak farmer organization and limited collective marketing mechanisms pose a practical gap for smallholder cotton farmers (World Bank report, 2016). Limited access to affordable and timely credit remains a significant practical barrier for smallholder cotton farmers (Financial inclusion reports, 20250. A practical gap exists in the limited adoption of IPM strategies by smallholder farmers due to access, cost, and complexity (Dhaliwal *et al*., 2010). Scaling up and commercializing promising biocontrol agents for cotton pests faces hurdles in mass production and cost-effectiveness (Glare *et al*., 2012).

Implementing effective traceability systems throughout the fragmented cotton supply chain is challenging due to blending and technological limitations (Textile Exchange; King, 2024). Many smallholder farmers lack access to affordable and high-quality cotton seeds (FAO, 2019). Insufficient infrastructure and market access in remote areas further hinder the translation of research into improved farmer livelihoods (Ali and Hussain, 2017). Targeted interventions and policy support can successfully address these practical gaps. Several interconnected gaps across literature, conflicting findings, contextual limitations, methodological weaknesses etc., are the reasons behind the weaknesses in Cotton research. These gaps hinder the development of comprehensive theoretical frameworks and the process of sufficient real-world data acquisition for scientific and field validation. This results in the challenges of practical application of research findings and slowing down the implementation throughout the cotton value chain. Prioritizing the fulfillment of these multifaceted gaps is crucial for fostering a more sustainable, efficient, and equitable cotton sector.

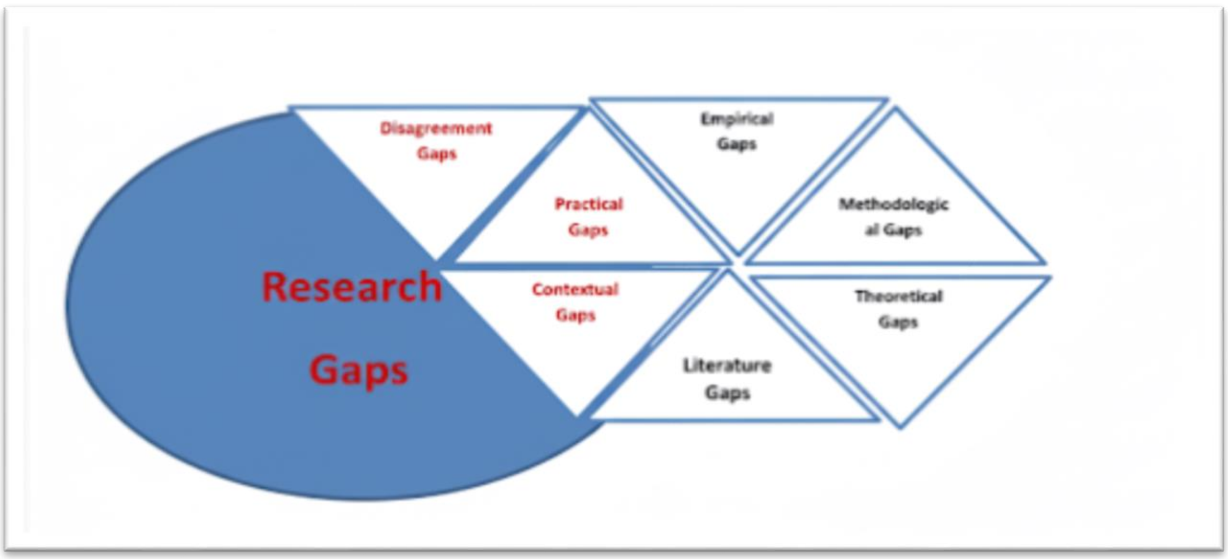

Figure 1: Components of research gaps for comprehensive gap analysis

IDENTIFYING RESEARCH GAPS

The first crucial step in the process of research gaps filling is to identify those gaps. In the dynamic field of agricultural science this identification process will not only contributes to the existing body of knowledge but also addresses practical challenges ahead. This whole exercise will foster innovation. A more detailed look at the strategies for identifying these gaps is discussed here:

1. **Conduct a Thorough Literature Review**

This involves exploring scientific studies across various domains with close attention and systematically analyzing existing research's foundation. While conducting a literature review following areas are essential to consider Table (2). Areas to explore during a literature review process.

2. **Examine Recent Trends and Developments**

Emerging issues and innovations often create new research questions which later change into gaps. Without bridging these gaps scientific research and development can't proceed further. Few of these are under

Table (3). Recent agricultural advancements which can be future research gaps

3. Analyze Existing Theories

Evaluating the strengths and weaknesses of theoretical frameworks can reveal limitations and areas for refinement. Table (4). Identifies of research gaps through the theoretical frameworks analysis.

4. Consult Experts and Practitioners

Agriculture research activities hold an amalgam of different stakeholders. They all carry part of information before it is reported

Table 1: The different types of research gaps in cotton sector

Sr. No.	Types of Research Gaps	Research Gaps in Cotton Sector	References
1.	**Literature Gap** (A specific topic or question has not been adequately addressed by previous research)	Climate change impacts on fiber quality, the problem farmers face from cotton farms till final products etc	(Pan, *et al*, 2021; Khan *et al*., 2017; Manzotti *et al*., 2020; Iqbal *et al*., 2022; King, 2024).
2.	**Disagreement Gap** (This highlights the need for further research to reconcile any discrepancies and arrive at more definitive conclusions)	For example the sustainability debate of conventional, organic, and Bt cotton etc	(Horowitz *et al*., 2005 (A); Scialabba and Hattam, 2002; Ton and Bijman, 2005; Tabashnik *et al*., 2009A; Chapagain *et al*., 2006; Qaim and Zilberman, 2003; Shiva and Jafri, 2004)
3.	**Contextual Gap** (Ample research exists on a topic, but it lacks investigation in)	Climate change impacts on smallholder farmers, the effectiveness of digital agriculture in low-connectivity areas etc	(Raza *et al*., 2021; 2014 IPCC reports, 2014; Scoones, 1999; Richards, 1985; Wolfert *et al*., 2017; Unwin, 2009)
4.	**Methodological Gap** (This gap arises from limitations or weaknesses in the methodologies used in previous studies)	integrated modeling, research and farmer involvement, a lack of standardized data collection, underutilization of advanced economic and policy analysis tools, over-reliance on small-scale trials etc	(Checkland, 1999; van Ittersum *et al*., 2003; Cornwall and Jewkes, 1995; Sadoulet and de Janvry, 1995; Piepho *et al*., 2012; Baker, 2016; Wilkinson *et al*., 2016)
5.	**Theoretical Gap** (Lack of a suitable theoretical framework to explain a phenomenon)	The resilience of cotton seed systems, the integrated link between soil health, plant health, and fiber quality, pest resistance evolution, and the resilience of cotton-based livelihoods to global change etc	(Weltzien *et al*., 2004; McGuire and Sperling, 2016; Doran, 2002; Kloppenburg, 2004; Thompson, 2007; Ajzen, 1991; Tabashnik and Croft, 1982; Holling, 1973).
6.	**Empirical Gap** (When a hypothesis lacks sufficient empirical testing or validation through real-world data)	The validation of agro-ecological and IPM practices in diverse farming systems, necessity of real-world data, an in-depth investigation for circular economy and the cotton value chain etc	(Lohano *et al*., 2017; Pretty, 2008; Gliessman, 2015; Altieri, 1999; Dhaliwal *et al*., 2010; Horowitz and Ishaaya, 1994; Korhonen *et al*., 2018; Paterson *et al*., 2012)
7.	**Practical Gap** (When research findings have not yet been translated into practical applications)	Climate-resilient cotton varieties' accessibility and affordability, weak farmer organization, limited credit access, low IPM adoption, fragmented supply chain traceability issues, lack of access to quality seeds etc	(FAO, 2019; IPCC reports, 2014; World Bank report, 2016; Dhaliwal *et al*., 2010; Glare *et al*., 2012; FAO, 2019; Ali and Hussain, 2017)

or not reported anywhere. These information carriers include farmers, extension workers, scientists, agri-industry reporters etc. These direct engagements bridge the gap between theory and real-world agricultural practices.

5. Attend Conferences and Seminars

Agricultural science conferences and seminars showcase preliminary research, emerging areas, and debates (Lansbury, 2019; Schäfer, 2010), revealing potential research gaps. Networking with researchers and practitioners at these events fosters

Table 2: Areas to explore during a literature review process

Sr. No.	Literature Review	Examples	References
1.	Unanswered Questions (Future research areas suggested by authors)	Future research should explore soil micro-biome-nitrogen interactions in various cropping systems	King (2024)
2.	Limitations of Previous Studies. (The constraints of prior work highlight avenues for new research)	The effects of phosphorus on crop growth are related to the soil types or geographical regions.	Edmeades (2003),
3.	Contradictions in literature (Conflicting findings needs reconciliation)	One researcher reported positive impacts of a certain tillage practice on soil carbon sequestration however other could present contrasting results under different environmental conditions.	Horowitz *et al*. (2005, B); Scialabba and Hattam (2002)
4.	Under-Researched Contexts (certain areas might not have received adequate attention)	Agricultural extension services concentration on high-income countries, indicating a need for research in low-income contexts.	Unwin (2009)
5.	Outdated Research	studies on older pesticides, traditional irrigation, older fertilizer use, pre-climate change crop varieties, and chemical-only pest control	Smith and Jones, 1985; Brown, 1970; Green and White, 1965; Taylor, 1990; Clark and Hill, 1975

Table 3: Recent agricultural advancements which can be future research gaps

Sr. No.	Advancement	Research opportunities	Reference
1.	AI's rapid advancement in agriculture	AI-powered image recognition for broad and early disease detection, for adoption across farming communities, for knowledge transfer etc., need investigations.	(Weiss *et al*., 2020) (Kamilaris and Prenafeta-Boldú, 2018; Mahlein, 2016; McKinney *et al*., 2020) (Carolan, 2020) (Fielke *et al*., 2022) (Rotz *et al*., 2019)
2.	Crop Varieties tolerant to combine heat and drought	Demand investigations under different climates in climate change scenarios.	(Bita and Gerats, 2013)
3.	Precision irrigation techniques	Demands optimize water use and reduce agricultural water consumption significantly	(Pereira *et al*., 2017).

Table 4: Identifies of research gaps through the theoretical frameworks analysis

Sr. No.	Examples	Strengths and Weaknesses (future gaps)	References
1.	Theory of planned behavior	Reveals limitations in explaining farmers' technology adoption, particularly regarding social networks and risk perception within diverse cultural settings.	(Centola, 2015; Slovic, 1987; Hofstede, 2001)
2.	Resilience Theory	Offers a framework for understanding agricultural systems' response to shocks, prompting further research into specific factors enhancing resilience against climate change and market volatility in various farming systems.	(Nelson *et al*., 2007; Tilman *et al*., 2002)

conversations that can uncover unaddressed questions and practical agricultural problems requiring investigation (Kadushin, 2012; Katz, 1997). This direct interaction facilitates the identification of cutting-edge research needs.

6. Pay Attention to Calls for Research

Funding agencies and journals have always highlighted research priorities, such as sustainable cotton (Scialabba and Hattam, 2002; WWF, 2020), specifying needs in organic methods, water conservation (FAO, 2017), and socio-economic impacts (ICAC, 2021). Journal editorials and special issues further delineate key challenges and future research directions within agricultural sub-disciplines (Crona *et al*., 2023; Ahmed *et al*., 2024). Paying attention to these calls can guide researchers toward impactful and funded projects.

Challenges and Research Needs for Cotton Production in Pakistan

1. Genetic Improvement and Breeding

Limited Genetic Diversity: The narrow genetic base of cultivated cotton varieties in Pakistan makes them vulnerable to diseases, pests, and environmental stresses (Abbas *et al*., 2020; Khan, 2018; Ali *et al*., 2022). Research is needed to introduce and utilize diverse germplasm, including wild relatives and exotic varieties, to broaden the genetic pool (Hussain, 2019; Malik and Shah, 2021).

Inefficient Breeding Techniques: There is a need for the widespread adoption and integration of modern, efficient breeding techniques such as marker-assisted selection (MAS), genomic selection, and transgenic breeding to accelerate the development of superior varieties (Ahmad *et al*., 2020; Iqbal, 2023).

Fiber Quality Improvement: Development of varieties with good fiber quality should be focused along with high yielding. Research efforts need to be intensified to meet the specific fiber quality requirements keeping in view the textile industry and international markets standards (Soomro *et al*., 2022).

Adaptation to Different Agro-Ecological Zones: The first preference should be cultivation of zone-specific cotton varieties. A zone should be a blend of certain well adapted varieties however different from the varieties of other zone that are well-adapted to Pakistan's diverse agro-ecological zones for optimal performance (Baloch *et al*., 2020; Cheema, 2023).

Integration of Biotechnology: Further research and development are needed in areas of biotechnology beyond Bt cotton is totally lacking e.g., drought and heat stress tolerance with are vital threats in climate change scenario. This should be after dressing biosafety concerns and ensuring proper regulatory frameworks (Mansoor *et al*., 2019).

Mechanization Suitability: Varieties that are suitable for mechanical picking can be a game changer in improving efficiency and harvesting losses reduction. In case of manual picking issues of labor availability are increasing with urbanization. Varieties promoting mechanical picking should be focused. (Ali and Khan, 2023).

2. Seed Quality and Delivery Systems

Good quality seed is foremost for high yield. The availability of best quality, certified seeds of approved varieties is a major constraint in our country (CABI, 2021). A well rooted framework of policy delivery, extension network, farmer’s vibrant involvement, efficient seed production and multiplication, quality control, and efficient delivery systems is essential to ensure the best planting material (Ahmed and Tanveer, 2021; Hussain, 2024; Ali *et al*., 2017; Hussain, 2022).

3. Pest and Disease Management

Climate change has increased pest threat to an already pest loving crop in the region. Pests like pink bollworm, whitefly, aphids, jassids and emerging pests like the mealybug are not only hurdles in good production but are reasons of high inputs. Cotton leaf curl virus (CLCuV) is already prevailing and no variety is still fully resistant, Research is crucial for overcoming these biotic stresses and developing durable resistance. Implementing integrated pest management (IPM) strategies is still a less explored field

Table 5: Research gap identification through experts and practitioner's identification

Sr. No.	Source	Information	Reference
1.	Extension agents	Can unveil practical IPM adoption barriers not fully covered in literature	(Dhaliwal *et al*., 2010; Feder and Slade, 1986)
2.	Farmer	Farmers' insights can highlight emerging pest/disease issues needing research and context-specific solutions	(Bentley and Andrews, 1991)
3.	Agribusiness professionals	Can illuminate supply chain inefficiencies and quality control challenges warranting investigation	(Fearne and Hughes, 1999; Porter, 1985).

Table 6: Cotton production decline statistic in Pakistan due to climate change in the region

Sr. No.	Data/Statistic	Description	Source/Reference
1.	Production Decline	Cotton production has nearly halved in the last decade, falling from 13.6 million bales (2011-2012) to about 7 million (2020-2021).	(Abbas *et al*., 2020)
2.	Yield Loss	A 1°C increase in daily maximum temperature can lead to a loss of 110 kg per hectare in cotton yield	(Abbas *et al*., 2020)
3.	Extreme Weather Impact	The 2022 floods in Sindh Province resulted in an estimated loss of 88% of the total expected cotton production, a direct economic loss of USD 485 million.	(Qamer *et al*., 2022)
4.	Yearly Production Drop	In 2015-2016, production in Punjab dropped by roughly 38% due to erratic rainfall and pest infestation.	(Shuli *et al*., 2018)
5.	Decreased Cropped Area	The land used for cotton cultivation shrunk from 2.8 million hectares to 2.1 million hectares between 2011-2012 and 2020-2021.	(Abbas *et al*., 2020)
6.	2024 Production Decline	Cotton production in 2024-25 season saw a significant year-on-year decline of over 30%, with total arrivals dropping from 8.39 million bales in 2023-24 to around 5.52 million bales.	Monthly Cotton Review from PCCC and Pakistan Bureau of Statistics
7.	2025 Forecast	The production forecast for the 2025-26 season is for 5.5 million bales, a 6% increase from the 2024-25 season, though some reports have lowered this forecast due to water shortages.	(U.S. Department of Agriculture Foreign Agricultural Service, 2025; Pakistan Bureau of Statistics, 2025; Pakistan Central Cotton Committee, 2025)

(Mahmood, 2021; Saleem *et al*., 2024; Iqbal, 2021; Miller, 2009).

4. Environmental and Climate Change Impacts:

Cotton is reportedly most vulnerable crop with climate change so far in the region (Table No. 6). It has posed a significant threat to cotton production in Pakistan through the effect of heat stress, water scarcity, increased pest and disease pressure and their altered patterns. This has opened a new battle field for cotton researchers to overcome (Government of Pakistan, 2023; Agricom, 2025; Abbas, 2020; Saleem *et al*., 2024; Ashraf, 2019; Bhatti *et al*., 2022; Khanzada, 2024). Research is needed to develop cotton varieties that are tolerant to these abiotic stresses and adapted to changing climatic conditions (Hussain, 2022; Nadeem, 2024). Water scarcity and inefficient irrigation methods (reliance on the Indus River and flood irrigation) impact cotton yields (Agricom, January 2, 2025; Maruph, 2022; Ahmad, 2020; Habib-ur-Rehman, 2023). Research should focus on developing water-efficient irrigation techniques and identifying water-efficient cotton varieties. Over-reliance on chemical pesticides and inefficient farming practices contribute to soil degradation (Agricom, January 2, 2025; Ahmad, 2024). Research on sustainable soil management practices is needed.

5. Agronomic Practices

Many farmers still rely on outdated farming practices, leading to lower productivity. Research is needed to optimize agronomic practices, including soil management, fertilizer application, planting methods, and harvesting techniques, for different cotton-growing regions. The role of precision agriculture technologies needs investigation (Ejaz and Ashraf, 2023; Mirza *et al*., 2013; Imtiaz *et al*., 2022).

6. Research and Development (Rand D) and Policy Gaps

There's a significant lack of investment in cotton research and seed improvement (Business Recorder, 2024; Ali, 2023). Poor coordination and linkages exist among research institutions, agricultural universities, extension service providers, and farmers (Ahmad *et al*., 2019; Buttar, 2021; Noor, 2023). Efforts are fragmented due to a lack of a coherent, unified national strategy for cotton (Business Recorder, 2025; Malik, 2022). A disconnect exists between strategic planning and execution (Ahmad, 2024; Aisha, 2024).

7. Knowledge and Skill Gaps among Farmers

Many farmers exhibit knowledge gaps in crucial cotton management practices. Low adoption of modern technology contributes to lower productivity. Weak extension services fail to adequately support farmers (Ahmad *et al*., 2019; Farooq, 2022).

8. Socio-economic and Market Gaps:

Increasing prices of agricultural inputs raise the overall cost of cotton farming (Shahid, 2023; Khan, 2022). The absence of a stable price mechanism creates uncertainty for farmers. Fluctuations in market prices affect the profitability of cotton cultivation. More profitable alternative crops like sugarcane are leading to a decrease in the area under cotton cultivation. Research should consider the socio-economic aspects of varietal development, ensuring new varieties are economically viable and acceptable to smallholder farmers (Hassan, 2020; Iqbal, 2020).

Addressing these gaps

To effectively address the identified research gaps in the cotton sector, a multi-pronged approach is necessary, focusing on enhanced collaboration, innovative methodologies, and targeted interventions:

1. Strengthening Research Focus and Collaboration

Prioritize End-to-End Traceability: Invest in research and development of cost-effective and standardized technologies to track cotton beyond the spinning mill, even with blending. Encourage industry-wide adoption through incentives and policies (Textile Exchange; King, 2024).

Support Localized Studies: Foster and fund region-specific research to understand the drivers of production decline (e.g., in Pakistan) and develop tailored solutions (Raza *et al*., 2021).

Enhance Farmer Knowledge and Technology Transfer: Develop and disseminate accessible training programs on modern practices and technologies, utilizing effective extension services and peer-to-peer learning (Ahmed *et al*., 2018; CABI, 2021).

Promote Interdisciplinary Research: Encourage collaboration among molecular biologists, physiologists, environmental scientists, economists, sociologists, and data scientists to address complex issues like fiber development, sustainability trade-offs, and climate resilience.

2. **Bridging Disagreements and Contextual Gaps**

Conduct Holistic Life Cycle Assessments: Fund comprehensive studies that evaluate the long-term environmental, economic, and social impacts of conventional, organic, and Bt cotton systems to provide a clearer understanding of their sustainability (Horowitz *et al*., 2005(A); Scialabba and Hattam, 2002; Qaim and Zilberman, 2003).

Investigate Climate Change Impacts on Smallholders: Prioritize research on the specific vulnerabilities and potential adaptations of smallholder farmers in different regions to climate change (Raza *et al*., 2021).

Undertake Gender-Disaggregated Studies: Increase research focused on the specific challenges and opportunities faced by women farmers in adopting sustainable practices (Knowler *et al*., 2007; Doss, 2002).

Evaluate Digital Agriculture in Low-Connectivity Areas: Develop and test digital solutions tailored to the constraints of low-connectivity regions, considering access, literacy, and infrastructure (Wolfert *et al*., 2017; Unwin, 2009).

Support Historical Environmental Analyses: Mostly scientists focus five or less year's data history and their research is based accordingly. Long-term environmental consequences of past and present must be studied altogether for a better cotton production practices in the specific regions (Crosby, 2004; Worster, 1979).

3. **Strengthening Methodologies and Data:**

Promote Large-Scale, Long-Term Trials: A shift is needed towards the more extensive and longer-duration field trials. This will enhance the generalizability of research findings and long lasting results (Edmeades, 2003).

Integrate Advanced Technologies: A system should be adopted for comprehensive and real-time data collection and analysis with increased utilization of remote sensing, precision agriculture, and AI-powered systems (Weiss *et al*., 2020).

Employ Complex Statistical Methods: Utilize advanced statistical modeling to capture intricate interactions within cotton systems (Piepho *et al*., 2012; Messina *et al*., 2006).

Incorporate Farmer Perspectives: Prioritize qualitative research methods to understand farmer knowledge, practices, and constraints (Chambers, 1994; Scoones, 2009).

Enhance Data Sharing and Reproducibility: Government policies should focus on establishment of such platforms and protocols that facilitate open data sharing and promote transparent research practices. This will improve knowledge verification and advancement for better research practices (Baker, 2016; Wilkinson *et al*., 2016).

4. **Translating Research into Practice**

This will only work when focusing several domains at a time which must efficiently work for a combined influence creating an effective and transparent translation of scientific research into the final goal of productive field practices (Fig. 2).

IPM Programs: Requires farmer-friendly IPM programs targeting smallholders' needs (Dhaliwal *et al*., 2010; Naeem *et al*., 2018).

Supporting Bio-control: Crucial to support bio-control commercialization through R and D and public-private partnerships (khakwani *et al*., 2021; Glare *et al*., 2012; Ahmad *et al*., 2003).

Technologies Adaptation: It is essential to incentivize the adoption of standardized and affordable traceability technologies (Khan *et al*., 2021).

Seed Systems: Strengthening seed production and distribution systems for locally adapted and affordable excellent quality seeds for the farmers (Ali *et al*., 2017).

Rural Infrastructure and Market Access: Investing in rural infrastructure and market access will reduce post-harvest losses and enhance farmer profitability (Government of Pakistan, 2018).

Figure 2: A growing network of different domains can translate the research into field practices

CONCLUSIONS

A comprehensive research gaps analysis in the cotton sector need to be focused. The study reveals several multifaceted, critical research gaps from genetic limitations and pest management to climate change impacts and outdated practices are evident globally and particularly in Pakistan. Future research must prioritize holistic, interdisciplinary approaches, focusing on developing climate-resilient varieties and sustainable practices through advanced technologies and farmer-centric methodologies. Bridging these gaps is vital for enhancing cotton's sustainability can only be achieved after bridging these gaps efficiently and equitably. This will ultimately ensuring a more resilient and prosperous future for the cotton industry and its stakeholders. Insufficient research and development investment along with weak institutional linkages are further aggravating these issues among Pakistani farmers which are already facing knowledge gaps. Therefore, there is a dire need for a targeted oriented research and policy interventions in Pakistan, focusing on collaboration and innovative methodologies for practical solutions. Prioritizing and bridging these gabs is crucial and foremost for fostering a more sustainable and efficient domestic cotton sector.

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