

Fungal Diseases of Cotton in Pakistan: Trends, Threats, and Strategic Interventions for Sustainable Management

Karamat Ali Zohaib^{1*}, Sumra Ashraf², Ghzanfar Ali Khan³, Beenish Rasheed¹, Adnan Akhter¹, Waheed Anwar¹, Muhammad Taqqi Abbas¹, Samina Hassan⁴, Alia Batool⁵

¹Department of Plant Pathology, Faculty of Agricultural Sciences, University of the Punjab, Lahore, Pakistan

²Department of Entomology, Faculty of Agricultural Sciences, University of the Punjab, Lahore, Pakistan

³Guard rice Lahore, Pakistan.

⁴Kinnaird College for Women, Lahore, Pakistan.

⁵Department of Plant Breeding and Genetics, Faculty of Agricultural Sciences, University of the Punjab, Lahore, Pakistan.

*Correspondence: Karamat Ali Zohaib, karamatzohaib.dpp@pu.edu.pk

ABSTRACT

Cotton (*Gossypium hirsutum*) is a vital cash crop and a foundational pillar of Pakistan's economy, particularly for its textile sector. Despite being among the top cotton producers globally, the country's cotton yields are persistently hampered by fungal diseases. These pathogens significantly affect cotton throughout its growth stages, resulting in considerable yield losses, fiber degradation, and economic setbacks. This document describes the past and present scenario of cotton fungal diseases in Pakistan, detailing key pathogens, their epidemiology, and transmission. Additionally, the present work integrates recent findings, describes the integrated disease management strategies, examines technical developments, and discusses prevailing challenges. The paper is aimed to outline strategic suggestions for the reduction of disease effects and ensuring the long-term sustainability of Pakistani cotton production.

Keywords: Climate change, cotton, Disease management, fungal pathogens, sustainable agriculture.

INTRODUCTION

Cotton (*Gossypium hirsutum* L.) is one of the most important fiber crops worldwide and holds a central place in Pakistan's economy, where it sustains millions of farmers and provides the raw material for the textile industry, the country's largest export sector (Arshad et al., 2022; Chohan et al., 2020). Despite Pakistan being ranked among the leading cotton-producing nations, average yields per hectare remain much lower than the global average, largely due to a combination of abiotic and biotic constraints (Iftikhar et al., 2025).

Among the latter, fungal diseases represent the most persistent and devastating challenges, compromising

yield, fiber quality, and farmer income. These pathogens affect cotton plants at every growth stage, from seed germination and seedling establishment to boll maturation, leading to chronic yield suppression and significant economic losses (Javed et al., 2024). The occurrence and severity of fungal diseases are closely linked with the country's climatic variability, the widespread practice of monoculture, the use of uncertified and untreated seeds, and the limited availability of resistant cultivars (Asma et al., 2025). Morphological and pathological investigations of these pathogens, although often overshadowed by modern molecular diagnostics, remain critical in the Pakistani context where resource constraints and infrastructural limitations restrict access to advanced technologies (Luneja & Mkindi, 2025). The integration of morphological features with molecular characterization ensures accurate identification of fungal pathogens, which is fundamental for devising sustainable management strategies.

Economic Impact and Historical Perspective

The economic significance of cotton fungal diseases in Pakistan is reflected in recurrent epidemics that have severely affected production at both regional and national levels. At a global level, if even a conservative disease-induced yield reduction of 10% is applied to the FAO-reported annual production baseline of ~25–26 million tonnes of cotton lint, this suggests a potential production deficit of 2.5–2.6

Article History

Received: [December 19, 2025](#), Revised: [February 09, 2026](#), Accepted: [March 01, 2026](#), First Online: [March 08, 2026](#),



Copyright: © 2026 by the authors. Licensee Roots Press, Islamabad Pakistan.

This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

<https://creativecommons.org/licenses/by/4.0/>

million tonnes per year attributable to biotic stresses such as fungal pathogens (ICAC, 2025; OECD-FAO, 2025). However, reported losses vary in scale (per hectare, district-level, and national estimates), and therefore must be interpreted within defined economic contexts. At the regional level, root rot caused by *Macrophomina phaseolina* resulted in approximately 25% yield loss on affected fields in South Punjab during 2010, primarily impacting smallholder farmers (Iftikhar et al., 2025). Likewise, in 2015, a recurrence of Bahawalpur and Vehari districts' *Verticillium* wilt resulted in extensive plant death, defoliation, and reductions in yields which together cost over PKR 10 billion (Shuli et al., 2018). These incidents are not standalone but are instead components of a repeating trend of fungal disease outbreaks, which are frequently fueled by climatic abnormalities of irregular rainfall and prolonged wet periods (Eastburn

et al., 2010). During 2020-2023, abnormal monsoon trends provided conducive conditions for foliage diseases, especially *Alternaria* and *Ramularia* leaf spots, which propagated in a very short period in Sindh and southern Punjab and resulted in premature defoliation, shedding of bolls, and heavy losses in the quality of lint (Chaudhari et al., 2020). At the national level, according to the reports by the Pakistan Cotton Ginners Association, cotton yields in 2024–2025 dropped by 39% below last season's levels, which were the lowest in four decades (PCGA, 2025). Most of these losses resulted from a mixture of disease pressure, adverse weather conditions, and management inefficiencies. Long-term data also reveal that fungal diseases contribute 20–30% to the loss of yield on an annual basis in Pakistan, with localized outbreaks causing still greater losses at times (Chohan et al., 2020).

Table 1. Major fungal diseases of cotton in Pakistan, regional yield losses, and control measures.

Disease	Region	Yield Loss (%)	Control Measures	Resistant Varieties
Fusarium wilt	Punjab	18–22	Trichoderma, fungicides	CIM-496, CIM-707
Verticillium wilt	Bahawalpur, Vehari	10–15	Crop rotation, fungicides	NIAB-111, MNH-886
Root rot complex	Central Punjab	20–25	Deep plowing, <i>Bacillus</i> spp.	NIAB-Kiran
Anthracnose	Sindh, South Punjab	5–10	Seed treatment	Under evaluation
Boll rot	Countrywide	10–15	Vector control, hygiene	Not specified
Alternaria/Ramularia	Sindh	8–12	PGPR, sprays	No full resistance

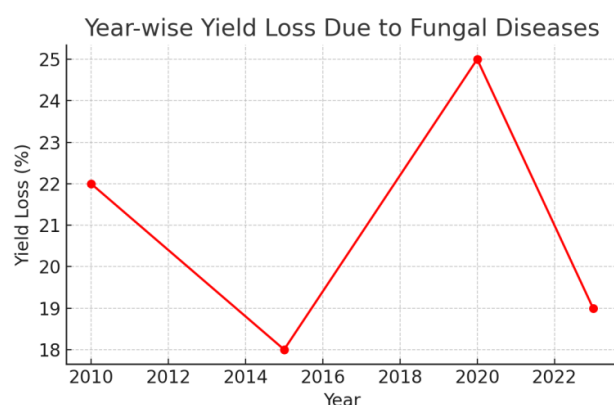


Figure 1. Year-wise regional loss estimates due to fungal diseases

Major Fungal Diseases of Cotton in Pakistan

Fungal diseases infecting cotton in Pakistan are highly diverse and are influenced by the intersection of crop biology, environmental aspects, and management practices. The most lethal among them are vascular wilts caused by *Fusarium oxysporum* f. sp.

vasinfectum and *Verticillium dahliae*, both of which have become a long-term challenge in Pakistan's cotton belt. Morphologically, *Fusarium* wilt is distinguished by the production of sickle-shaped macroconidia, oval-shaped microconidia, and thick-walled chlamydospores that enable the pathogen to remain viable in the soil for extended periods of time (Waqar Akhtar et al., 2024). Disease is manifested by yellowing, vascular tissue discoloration, stunting, and ultimately wilting, wherein yield losses of up to 45% are realized during epidemic years (Khan et al., 2024). *Verticillium dahliae*, on the other hand, forms microsclerotia that are viable in soil for more than a decade and develop best in cooler temperatures such as those prevalent in central Punjab. Seed-borne fungal complexes worldwide are a reflection of those seen in Pakistan. *Verticillium* wilt-infected plants exhibit interveinal chlorosis, vascular browning, and early defoliation, resulting in extensive yield and fiber quality losses (Ashraf et al., 2024). Besides the vascular wilts, root rots also contribute to the substantial decline in cotton productivity.

Macrophomina phaseolina, the pathogen responsible for charcoal rot, forms black microsclerotia and is extremely aggressive under hot and dry conditions, which are on the rise in arid parts of Pakistan (Shahzadi et al., 2023). *Rhizoctonia solani*, recognized by its right-angled branching hyphae, is responsible for damping-off and hypocotyl rot in seedlings, while *Pythium* spp. cause pre- and post-emergence damping-off through sporangia and motile zoospores production (Ali et al., 2018). Together, these pathogens constitute a root rot complex which can decimate crop stands, with losses of 20–30% having been reported in many places (Khatun, 2023).

Seed-borne fungal diseases introduce an extra layer to the disease syndrome. *Colletotrichum gossypii*, the anthracnose pathogen, is disseminated mainly by infected seed and forms acervuli bearing dark setae and falcate conidia. Infected seeds have reduced germination and often seedlings present with cotyledonary lesions and stunted growth. Germination declines of over 30% in Pakistan have been reported following the sowing of untreated infected seed lots (Syed et al., 2022). Other fungi associated with seeds, such as *Fusarium* spp., *Alternaria alternata*, and *Aspergillus* spp., have been recovered from cotton seeds and are responsible for seedling blights and poor plant stands (Ashraf et al., 2021). Relative accounts from Brazil, China, and Ethiopia reveal these seedborne diseases are worldwide in significance, necessitating effective seed health systems (Silva,

Araújo, & Cardoso, 2023). Indian and Chinese experience has shown that systematic certification of seeds, farmer education initiatives and the introduction of climate resistant varieties is a potent way of enhancing IDM uptake. Such practices are localized to Pakistani agroecologies, which might be useful in the management of the diseases and a stable yield.

Foliar diseases like *Alternaria* leaf spot, *Ramularia* leaf blight, and *Cercospora* leaf spot add to the complexity of cotton pathology. *Alternaria* produces pigmented, beaked conidia with both transverse and longitudinal septa, which allow extensive dispersal and survival under changing conditions (Chaudhari et al., 2020). *Ramularia areola* is most severe in humid weather and leads to early defoliation, whereas *Cercospora gossypina* yields narrow, septate conidia that result in typical circular leaf spots with ragged white centers (Ashok, 2023).

Other foliar pathogens include *Myrothecium roridum*, which induces concentric ring lesions, and *Ascochyta gossypii*, which thrives under prolonged wet conditions and leads to wet weather blight (AARI; Ahmad et al., 2023). Boll rots caused by *Colletotrichum*, *Diplodia gossypina*, *Fusarium* spp., and *Aspergillus* spp. also represent a significant threat, as they not only reduce yield but also degrade lint quality, especially when facilitated by insect damage (Ali et al., 2022).

Table 2. Estimated yield and economic losses of cotton crop in Pakistan caused by fungal pathogens.

Fungal Disease	Estimated Yield Loss (%)	Pakistan: Economic Loss ha ⁻¹ (PKR)	Global: Yield Loss (%)	Global: Economic Loss (USD year ⁻¹)	References
<i>Fusarium</i> spp.	30–45%	50,000–75,000	15–30%	\$1.0–1.5 Billion	(Khan et al., 2024)
<i>Verticillium dahlia</i>	35–50%	25,000–55,000	10–20%	\$500–900 Million	(Shuli, 2023)
<i>Macrophomina phaseolina</i>	20–30%	35,000–50,000	10–25%	\$600–800 Million	(Gupta, 2023)
<i>Rhizoctonia solani</i>	5–25%	10,000–35,000	5–15%	\$400–700 Million	(Khatun, 2023)
<i>Pythium</i> spp.	5–15%	8,000–20,000	5–10%	\$300–500 Million	(Ali et al., 2018)
<i>Colletotrichum gossypii</i>	5–10%	8,000–15,000	3–8%	\$150–250 Million	(Chohan et al., 2020)
<i>Diplodia gossypina</i>	5–10%	8,000–15,000	2–5%	\$100–200 Million	(Khatun, 2023)
<i>Helminthosporium</i> spp. (<i>Drechslera</i>)	5–8%	6,000–12,000	2–4%	\$100–180 Million	(Ashok, 2023)

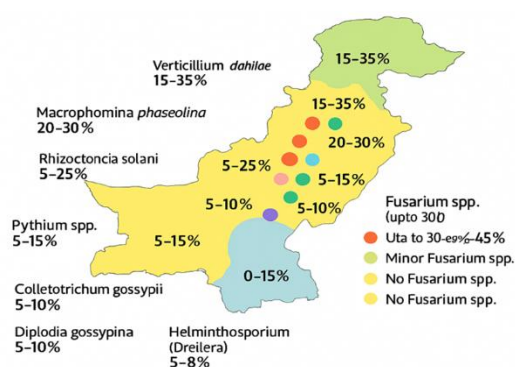


Figure 2. Map highlighting incidence of fungal diseases on cotton crop in different regions of Pakistan.

Seed-Borne Pathogens

Seed-borne fungi are a major but often underestimated constraint in cotton production systems of Pakistan, contributing to poor germination, weak plant stands, and the early establishment of inoculum in the field. The reliance of farmers on saved or uncertified seed, often untreated and stored under suboptimal conditions, exacerbates the risk of pathogen carryover from one season to the next (Shuli, 2023). Among the most important seed-borne pathogens is *Colletotrichum gossypii*, the causal agent of anthracnose, which produces acervuli bearing dark setae and falcate conidia. Infected seeds exhibit reduced germination, and seedlings that emerge frequently develop necrotic lesions on the cotyledons, hypocotyls, and young stems. In severe infections,

anthracnose progresses to boll rot, compromising both yield and lint quality (Asif et al., 2020). Surveys conducted in Sindh and Punjab have reported infection levels as high as 40% in untreated seed lots, with germination losses exceeding 30% (Maqbool et al., 2023). *Fusarium* species, including *Fusarium oxysporum* and *F. solani*, are also commonly seed-borne, causing pre- and post-emergence damping-off and wilt symptoms in later growth stages (Javed et al., 2024). *Alternaria alternata* and *Aspergillus niger* are frequently isolated from stored seed and are associated with reduced seed vigor, poor seedling establishment, and in some cases aflatoxin contamination, which poses additional health risks (Abbas et al., 2022). Research done in Brazil, China, and Ethiopia all point to *Fusarium* spp., *Rhizoctonia solani*, *Aspergillus* spp., and *Colletotrichum gossypii* being the most important seedborne pathogens (Silva, Araújo, & Cardoso, 2023). These findings highlight the worldwide issue of seed health in cotton and necessitate stringent seed certification and seed health testing schemes. Institutional inadequacies in seed certification, combined with limited access to fungicidal seed treatment for small farmers, still allow these pathogens to be carried over from one season to the next in Pakistan (Luqman, 2023). Seed disease problems are addressed through certified seed systems, seed testing laboratories, and farmer awareness programs as a crucial but unexplored part of cotton disease management in the country.

Table 3. Global yield and economic losses due to various fungal diseases on cotton crop.

Country	Major Fungal Diseases	Avg. Yield Loss (%)	Economic Loss (USD/year)	References
Pakistan	<i>Fusarium</i> , <i>Verticillium</i> , <i>Macrophomina</i> , <i>Rhizoctonia</i>	20–35%	\$175–250 million	(Ahmed et al., 2023)
India	<i>Fusarium</i> , <i>Rhizoctonia</i> , <i>Macrophomina</i> , <i>Colletotrichum</i>	10–25%	\$800 million–1.2 billion	(Singh, 2023)
China	<i>Verticillium</i> , <i>Fusarium</i> , <i>Rhizoctonia</i>	10–20%	\$600–900 million	(Abbas et al., 2022)
USA	<i>Verticillium</i> , <i>Fusarium</i> , <i>Pythium</i> , <i>Rhizoctonia</i>	5–12%	\$300–500 million	(National Research Council, 1996)
Brazil	<i>Macrophomina</i> , <i>Rhizoctonia</i> , <i>Colletotrichum</i> , <i>Fusarium</i>	8–18%	\$250–400 million	(Silva, Araújo & Cardoso, 2023)
Uzbekistan	<i>Verticillium</i> , <i>Fusarium</i>	10–20%	\$100–180 million	(Khasanov et al., 2023)
Turkey	<i>Fusarium</i> , <i>Verticillium</i>	5–10%	\$80–150 million	(D’Onghia, 2015)
Egypt	<i>Fusarium</i> , <i>Pythium</i>	8–15%	\$70–100 million	(Palmer, 2013)
Sudan	<i>Fusarium</i> , <i>Macrophomina</i>	10–20%	\$50–90 million	(Haile & Rao, 2023)
Tanzania	<i>Fusarium</i> , <i>Rhizoctonia</i> , <i>Colletotrichum</i>	10–25%	\$30–60 million	(Kabissa, 2015)
Ethiopia	<i>Fusarium</i> , <i>Rhizoctonia</i>	15-25%	\$40-70 million	(Terefe & Tesfaye 2009)

Climate Change and Emerging Threats

Temperature fluctuations, changed rainfall patterns, and prolonged humidity have established conditions strongly favorable for fungal sporulation, dispersal, and infection (Eastburn et al., 2010). For instance, the occurrence of *Macrophomina phaseolina* epidemics has grown over the last few decades because of repeated droughts and increased temperature in the southern parts of Punjab and Sindh. This pathogen grows well in warm, dry soils, and climate models indicate that its distribution will increase further into new regions, heightening losses (Gupta, 2023). On the other hand, heavy rainfall and long durations of wetness during recent monsoons have promoted intensification of *Alternaria* and *Ramularia* leaf spots, which need prolonged leaf wetness to develop infections (Baird et al., 2003). The unusual intensity of the 2024 monsoon season, one of the wettest in four decades, was associated with widespread foliar disease epidemics across multiple cotton-growing districts (PCGA, 2025). Another dimension of climate

change lies in its impact on pathogen virulence and adaptation. *Fusarium oxysporum* pathogens are also known to have evolved very quickly with changing environmental conditions, and new aggressive strains have been reported in many cotton-producing nations, including Pakistan (Khan et al., 2024). Selection pressure-driven mutations resulting from fungicides, host resistance genes, and varying environmental conditions have given rise to pathotypes with improved pathogenicity and resistance-breaking features (Haile & Rao, 2023).

In the same manner, *Verticillium dahliae* has shown to alter its geographic distribution, with frequent occurrence reported in areas previously regarded as marginal for the disease (Hussain et al., 2025). Climate change also indirectly increases fungal disease incidence by degrading host plant physiology. Heat stress, drought stress, and nutrient disorders predispose cotton to infection, incorporating a subtle interplay between abiotic and biotic stresses that amplifies yield loss (Eastburn et al., 2010).

Table 4. Climatic factors affecting onset of various fungal diseases on cotton crop.

Climate Change Factor	Impact on Fungal Disease	Example Diseases
Temperature Rise	Faster pathogen life cycles; wider distribution	<i>Fusarium</i> wilt, <i>Verticillium</i> wilt
Increased Rainfall	Higher foliar disease pressure	<i>Alternaria</i> , Anthracnose
Drought	Root and stem rots	Charcoal rot
Elevated CO ₂	Canopy density, altered defense	Leaf spots
Extreme Events	Physical damage + new infections	Boll rot, opportunistic fungi

These facts emphasize the imperative of integrating climate-smart approaches into cotton pathology

research and disease management systems.

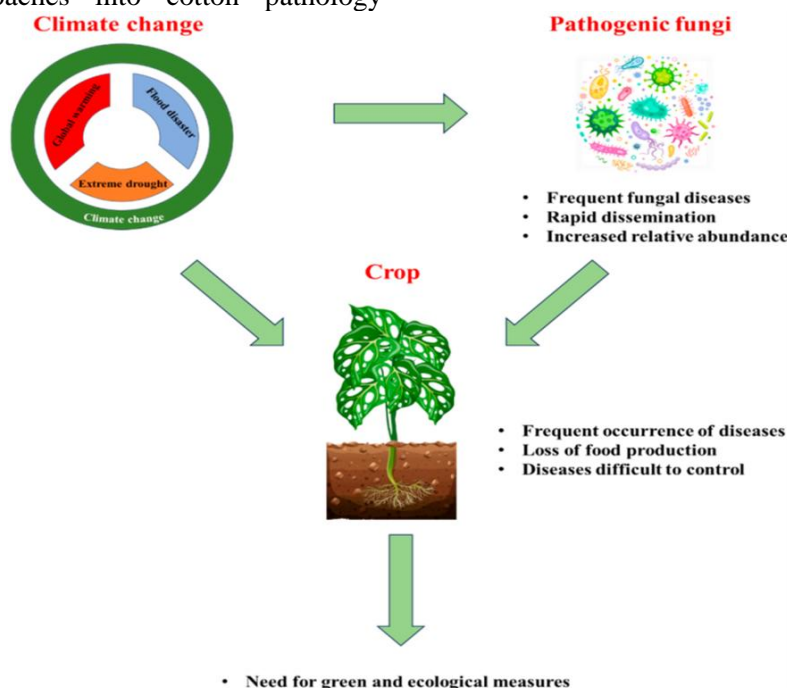


Figure 3. Pictorial representation of the impact of climate change on fungal diseases of cotton.

Integrated Disease Management

The management of fungal diseases in cotton requires a comprehensive, integrated approach that combines host resistance, chemical control, biological methods, and cultural practices. In Pakistan, the use of resistant cultivars such as CIM-496, CIM-707, NIAB-111, and MNH-886 has provided partial relief against major pathogens like *Fusarium* and *Verticillium*, though resistance breakdown under high disease pressure remains a persistent challenge (Shah et al., 2022). Chemical fungicides, including thiophanate-methyl, carbendazim, and triazoles, have historically been relied upon, but indiscriminate use has led to fungicide resistance in pathogen populations, reducing their long-term effectiveness (Ashok, 2023).

Biological control offers a sustainable alternative, with organisms such as *Trichoderma harzianum*, *T. viride*, and *Bacillus subtilis* showing strong antagonistic activity against *Rhizoctonia solani*, *Fusarium* spp., and *Macrophomina phaseolina* (Mehmood et al., 2025). These biocontrol agents not only suppress pathogens but also enhance plant vigor through mechanisms of induced systemic resistance. Several field trials in Pakistan have demonstrated significant reductions in disease incidence with the use of *Trichoderma*-based formulations, though their adoption among farmers remains limited due to cost and awareness barriers (Bajwa et al., 2024). Cultural practices such as crop rotation with non-host crops, deep plowing to bury inoculum, the removal of infected residues, and optimized irrigation scheduling are also critical in reducing disease inoculum and improving plant health (Chohan et al., 2020). Together, these strategies form the basis of integrated disease management (IDM), which is gaining ground as the most sustainable and eco-friendly method of managing cotton fungal diseases (Eastburn et al., 2010). Although the efficacy of using integrated disease management (IDM) strategies has been proved and extensive research has been carried out, most Pakistani cotton farmers are reluctant to adopt it because of the high cost of inputs, lack of awareness, lack of extension services and access to certified seeds and biocontrol agents.

Challenges

In spite of tremendous advancement in the knowledge of cotton fungal diseases, their control in Pakistan also suffers from various challenges that reduce the efficacy of measures and maintain yield losses. Overdependence on chemical fungicides is one of the greatest challenges. Although fungicides like carbendazim, benomyl, thiophanate-methyl, and triazoles have been widely used to inhibit *Fusarium*, *Verticillium*, and foliage pathogens, indiscriminate and largely uncontrolled use has led to the development of populations resistant to fungicides

(Ashok, 2023). This not only reduces the effectiveness of chemical control but also poses environmental and human health risks. Compounding this is the limited availability of affordable and accessible alternatives for resource-constrained smallholder farmers, who form the backbone of Pakistan's cotton industry.

Another major constraint is the absence of a robust seed certification and testing system. The widespread practice of using uncertified or farmer-saved seed allows seed-borne pathogens such as *Colletotrichum gossypii*, *Fusarium* spp., and *Alternaria* spp. to persist from season to season, leading to recurring epidemics (Chohan et al., 2020). Although research institutions have developed protocols for seed health testing, their implementation at the field and farmer level remains weak. This gap between research outputs and on-ground adoption is symptomatic of a larger challenge: the lack of strong extension services and effective dissemination of knowledge. Farmers often lack access to timely and accurate information on disease diagnosis and management, which results in delayed or inappropriate interventions (Ashraf et al., 2024). The limited adoption of biological control agents represents another challenge. While promising results have been documented with antagonistic fungi such as *Trichoderma harzianum* and bacterial agents like *Bacillus subtilis*, large-scale commercial formulations remain scarce in local markets, and awareness among farmers is low (Luqman, 2023). Additionally, weak regulatory frameworks and quality control mechanisms hinder the commercial success of biocontrol products. Climate change adds further complexity by introducing new pathogen pressures and altering the epidemiology of established diseases. Pathogens previously confined to some agro-ecological zones, like *Verticillium dahliae*, are now spreading to new areas, while heat- and drought-loving fungi like *Macrophomina phaseolina* are becoming increasingly virulent (Gupta, 2023). All together, these problems emphasize the systemic limitations that need to be filled to obtain effective and sustainable control of cotton fungal diseases in Pakistan. To the efficient application of IDM in the field, policy constraints such as ineffective systems of seed certification, quality assurance of biocontrol products, and lack of regulatory protection to new technologies are still seen as a key bottleneck to the successful implementation of the IDM system.

Biotechnological Interventions and Future Prospects

Recent epidemiological data (2022-2024) show that the number of major cotton fungal diseases in Pakistan is increasing especially vascular wilts, which are caused by *Fusarium oxysporum* f. sp. *vasinfectum* and *Verticillium dahliae*. Field surveys in central and southern Punjab indicate disease occurrence of 1832

and yield loss of localized areas of 30-40 percent under extreme infection. The *Macrophomina phaseolina* has proliferated in drought-prone areas as the charcoal rot, which is a symptom of high temperatures and pathogen aggressiveness. The finding of new virulent strains of *Fusarium*, and an adaptation change in *Verticillium* populations, have also indicated a loss of resistance in most of the commercially grown varieties, with many of them being tolerant instead of genetically resistant. Also, the use of benzimidazole and triazole fungicides repeatedly is of concern since it has led to decreased sensitivity of the pathogen, the necessity of molecular surveillance and resistance monitoring programs.

Cotton pathology is changing to symptom identification to early detection based on precision rather than symptom as advances in pathogen detection and molecular diagnostics are made. Although classical morphological identification still plays an essential role in Pakistan, it is becoming more frequently supplemented by PCR, qPCR, DNA barcoding, ITS sequencing and even loop-mediated isothermal amplification (LAMP) assays of high diagnosis rates in the field. Epidemiological modeling is being coupled with remote sensing, hyperspectral imaging, and GIS-based mapping in forecasting disease outbreaks in a changing climatic environment. Image recognition tools based on artificial intelligence also facilitate a large-scale surveillance of foliar disease. On the breeding level, QTL wilt resistance-related marker-assisted selection and genomic studies have been used to identify quantitative trait loci, and CRISPR-based genome editing provides an opportunity to provide a specific change to the susceptibility gene. The quantitative trait loci (QTLs) related to *Fusarium* wilt resistance in cotton are qFWR1 and qFWR2 in *Gossypium hirsutum* and Ve1 and Ve2 loci in *Verticillium* wilt resistance (Li et al., 2022; Zhang et al., 2021). Controlled knockout of the susceptibility genome, e.g. GhDREB2 in cotton, by CRISPR/Cas9, has resulted in increased resistance to *Fusarium oxysporum* (Wang et al., 2023). The same type of genome editing that was used to target Ve-like genes has been demonstrated to work in tomato and has been used as a possible breeding model in cotton, which is resistant to cotton leaf roll disease (Bai et al., 2020). Despite the fact that these technologies are still in their initial adoption phase in the country, they offer a guideline towards the development of multi-pathogen resistance which is durable. Research, field trials and commercialization of genetically modified crops, including genome-edited plants, are regulated by the National Biosafety Guidelines and the Pakistan Biosafety Rules (2005, updated 2021). The National Biosafety Committee monitors adherence to the

safety, environmental and socio-economic standards (Ministry of Climate Change, Pakistan, 2021).

The future needs to be focused on standardized epidemiological reporting, national seed health fortification and systems of climate-linked disease forecasting. According to recent estimates, fungal diseases still cause about 20-30 percent yield losses in the infested regions every year, and economic losses of more than PKR 50,000 on a per-hectare basis are experienced in disease outbreaks. It is necessary to strengthen certified seed systems, keep track of the emergence of new pathogen races, introduce omics-based resistance discovery into breeding pipelines, and scale up proven biocontrol agents like *Trichoderma* and *Bacillus*. A shift in management towards reactive fungicide-based management to predictive, technology-oriented, and climate-friendly disease surveillance would prove vital in ensuring cotton productivity and reduced long-term economic losses.

CONCLUSION

Fungal diseases of cotton remain among the most formidable biotic challenges to sustainable cotton production in Pakistan. Their persistence and severity, exacerbated by monoculture, seed health issues, fungicide resistance, and climate variability, underscore the urgent need for a comprehensive and integrated approach to disease management (Chohan et al., 2020; Eastburn et al., 2010). Morphological identification, though sometimes undervalued in the era of molecular biology, continues to serve as a critical tool for accurate diagnosis, especially in resource-limited settings (Ashraf et al., 2024). However, the future lies in combining classical approaches with advanced molecular diagnostics, digital tools, and biotechnology to ensure timely, precise, and cost-effective disease detection and management (Maqbool, 2023). Integrated disease management strategies that combine resistant cultivars, judicious use of fungicides, biological control agents, and cultural practices must be mainstreamed and supported through strong extension services and farmer education (Luqman, 2023). Resistant varieties of cotton that are currently grown in Pakistan are usually tolerant and not resistant; they can endure the infection of the pathogen, but the yield losses might still occur when the disease pressure is high and hence the breeding and molecular characterization of the resistant -type cotton are necessary and continuous.

The path forward will require systemic reforms in seed certification, investments in molecular breeding and biotechnology, and the development of climate-smart surveillance systems that integrate artificial intelligence and geospatial technologies (Ahmed et al., 2023). Strengthening research-extension linkages

and fostering public–private partnerships will be key to translating scientific advances into tangible field-level solutions (Haile & Rao, 2023). By adopting these strategies, Pakistan can reduce the heavy economic toll of fungal diseases, safeguard the productivity and quality of cotton, and secure the livelihoods of millions of farmers who depend on this vital crop. Ultimately, the resilience of Pakistan’s cotton sector against fungal pathogens will depend on the integration of science, technology, policy, and farmer participation in building a sustainable Plant health management system.

COMPETING OF INTEREST

The authors declare no competing interests.

REFERENCES

- Abbas, A., Mubeen, M., Sohail, M. A., Solanki, M. K., Hussain, B., Nosheen, S., ... & Fang, X. (2022). Root rot a silent alfalfa killer in China: Distribution, fungal, and oomycete pathogens, impact of climatic factors and its management. *Frontiers in microbiology*, 13, 961794. Adeleke, A. (2024). Technological Advancements in Cotton Agronomy: A Review and Prospects. MDPI AG. <https://doi.org/10.20944/preprints202402.1342.v1>
- Adeleke, A. (2024). Technological Advancements in Cotton Agronomy: A Review and Prospects. MDPI AG. <https://doi.org/10.20944/preprints202402.1342.v1>
- Ahmad, S., Ahmad, I., Ahmad, B., Ahmad, A., Wajid, A., Khaliq, T., Abbas, G., Wilkerson, C., & Hoogenboom, G. (2023). Regional integrated assessment of climate change impact on cotton production in a semi-arid environment. *Climate Research*, 89, 113–132. <https://doi.org/10.3354/cr01710>
- Ahmed, M., et al. (2023). *Advances in molecular breeding and CRISPR-based editing for cotton resistance to fungal pathogens*. *Plant Biotechnology Journal*, 21(4), 765–782.
- Ali, H., et al. (2018). *Characterization of Pythium spp. causing damping-off in cotton seedlings in Pakistan*. *Pakistan Journal of Agricultural Sciences*, 55(2), 321–328.
- Ali, M. A., Hassan, M., Mehmood, M., Kazmi, D. H., Chishtie, F. A., & Shahid, I. (2022). The Potential Impact of Climate Extremes on Cotton and Wheat Crops in Southern Punjab, Pakistan. *Sustainability*, 14(3), 1609. <https://doi.org/10.3390/su14031609>
- Arshad, M. U., Zhao, Y., Hanif, O., & Fatima, F. (2022). Evolution of overall cotton production and its determinants: implications for developing countries using Pakistan case. *Sustainability*, 14(2), 840.
- Ashok, P. (2023). *Fungal pathogens of cotton: Global distribution, impact, and management*. *Indian Phytopathology*, 76(2), 201–212.
- Ashraf, S., & Ashraf, I. (2024). Comprehensive Factor Analysis of Cotton Production Challenges in the Cotton Zone of Punjab, Pakistan. *Pakistan Journal of Agricultural Sciences*, 61(4).
- Ashraf, S., Ch, K. M., Ashraf, I., & Akbar, N. (2024). A phenomenological inquiry into farmers’ experiences growing cotton in Punjab, Pakistan. *Scientific Reports*, 14(1). <https://doi.org/10.1038/s41598-024-62950-y>
- Asif, R., Khan, M. A., & Iqbal, M. (2020). Evaluation of fungicides and bioagents against cotton wilt disease. *Pakistan Journal of Phytopathology*, 32(2), 101–108.
- Asma, Illyas, M., Neelam Zeb, Arooj Javed, Iqra Shabbir, & Ayesha Bibi. (2025). A recent review on cotton and climate change in Pakistan: impacts, mitigation, and adaptation. *Insights-Journal of Health and Rehabilitation*, 3(2 (Health&Rehab)), 631–638. <https://doi.org/10.71000/j14pen89>
- Ayub Agricultural Research Institute. Cotton diseases (Cot-Dis). Agriculture Department, Government of the Punjab. <https://aari.punjab.gov.pk/Cot-Dis>
- Bai, Y., Smith, J., & Chen, L. (2020). Genome editing for disease resistance in tomato: CRISPR/Cas applications and future prospects. *Plant Biotechnology Journal*, 18(4), 735–749. <https://doi.org/10.1111/pbi.13234>
- Baird, R. E., Wadl, P. A., & Mueller, J. D. (2003). Disease and insect pests of cotton under variable rainfall. *Crop Protection*, 22(3), 453–459.
- Bajwa, K. S., Ali, M. U., Rao, A. Q., Kiani, S., Ahmad, F., Bakhsh, A., Noor, S., Abbas, Z., Ali, S., & Ali, G. M. (2024). From genes to fields: Environmental compatibility of herbicide tolerant transgenic cotton. *Industrial Crops and Products*, 209, 117903. <https://doi.org/10.1016/j.indcrop.2023.117903>
- Bilal, M., & Jaghdani, T. J. (2024). Barriers to the adoption of multiple agricultural innovations: Insights from Bt cotton, wheat seeds, herbicides and no-tillage in Pakistan. *International Journal of Agricultural Sustainability*, 22(1). <https://doi.org/10.1080/14735903.2024.2318934>
- Chaudhari, R. J., Bhale, U. N., & Khadse, A. C. (2020). Effect of weather parameters in relation to occurrence and development of leaf blight (*Alternaria macrospora*) of cotton. *Biological*

- Forum – An International Journal*, 12(1), 483–487.
- Chohan, S., Perveen, R., Abid, M., Tahir, M. N., & Sajid, M. (2020). Cotton diseases and their management. In A. Jabran & B. Chauhan (Eds.), *Cotton production and uses: Agronomy, crop protection, and postharvest technologies* (pp. 239–270). Singapore: Springer.
- D'ONGHIA, A. M. (2015). the Joint International Congress: 14th Congress of the Mediterranean Phytopathological Union and International Society of Mycotoxicology (Mediterranean Branch) meeting, Istanbul, Turkey, 25–29 August 2014. *Phytopathologia Mediterranea*, 54(1), 140-196.
- Eastburn, D. M., DeGennaro, M. M., DeLucia, E. H., Dermody, O., & McElrone, A. J. (2010). Climate change and plant disease management. *Annual Review of Phytopathology*, 48, 269–291. <https://doi.org/10.1146/annurev-phyto-080508-081747>
- Food and Agriculture Organization of the United Nations (FAO). (2025). FAOSTAT: Production data for cotton. Rome: FAO. Retrieved from <https://www.fao.org/faostat/en/#data/QCL>
- Haile, T., & Rao, M. S. (2023). *Emerging fungal pathogens of cotton in Sub-Saharan Africa under climate change*. *African Journal of Plant Protection*, 29(2), 87–99.
- Hussain, I., Butt, T. M., Fatima, N., Rahman, W. U., & Ullah, M. K. (2025). Causes of cotton decline in pakistan: A comprehensive review. *Acad Int J Social Sci*, 4(1), 1191-1203.
- Iftikhar Hussain, Tahir Munir Butt, Noor Fatima, Waqee Ur Rahman, & Muhammad Kaleem Ullah. (2025). Causes of Cotton Decline in Pakistan: A Comprehensive Review. *ACADEMIA International Journal for Social Sciences*, 4(1), 1191–1203.
- International Cotton Advisory Committee. (2025). World cotton market projections 2025/26. Washington, DC: International Cotton Advisory Committee. Retrieved from <https://icac.org/the-icac-releases-its-2025-26-world-cotton-market-projections>
- Javed, I., Khan, M. A., Riaz, H., Saeed, S., Ali, H., Bashair, M., & Haider, I. (2024). Sustainable management of *Fusarium* wilt in cotton through biological applications. *Frontiers in Sustainable Food Systems*, 8, 1–12.
- Kabissa, J. C. (2015). *Cotton in Tanzania: Breaking the jinx*. Tananzia Educational Publishers.
- Kaur, S., Behera, L., & Chandel, A. (2020). Climate change-induced shifts in fungal pathogen distribution. *Frontiers in Plant Science*, 11, 561.
- Khan, M. A., et al. (2024). *Epidemiology and management of Fusarium wilt of cotton in Pakistan*. *Plant Disease*, 108(6), 1401–1412.
- Khasanov, B. A., Sherimbetov, A. G., Adilov, B. S., & Khakimov, A. A. (2023). Crop diseases in Uzbekistan caused by the species of the genus *Fusarium*: an Overview. *Fusarium-Recent Studies*.
- Khatun, S. (2023). *Soil-borne fungal diseases of cotton: Pathology and management*. *Bangladesh Journal of Plant Pathology*, 39(1), 33–46.
- Li, R., Zhao, Q., & Wang, H. (2022). Mapping and validation of QTLs for *Fusarium* wilt resistance in *Gossypium hirsutum*. *Euphytica*, 218(3), 45. <https://doi.org/10.1007/s10681-022-03105-8>
- Luneja, R. L., & Mkindi, A. G. (2025). Advances in botanical-based nanoformulations for sustainable cotton insect pest management in developing countries. *Frontiers in Agronomy*, 7. <https://doi.org/10.3389/fagro.2025.1558395>
- Luqman, M. (2023). *Plant growth-promoting rhizobacteria and AI applications in cotton disease management*. *Journal of Crop Protection*, 12(2), 99–118.
- Malik, M. W. I., Usman, K., Hamza, A., & Saad, M. (2024). Optimizing Cotton-Wheat System Productivity Through Resource Conserving Techniques. *Communications in Soil Science and Plant Analysis*, 55(4), 536–549. <https://doi.org/10.1080/00103624.2023.2274037>
- Maqbool, S. (2023). *Remote sensing and GIS in mapping fungal diseases of cotton*. *Precision Agriculture*, 24(5), 1121–1136.
- Mehmood, H. Z., Abbas, A., Ullah, R., & Wudil, A. H. (2025). Sustainability analysis of better cotton: a cleaner and sustainable production alternative in Pakistan. *The Journal of Animal and Plant Sciences*, 1, 80–89. <https://doi.org/10.36899/japs.2025.1.0006>
- Ministry of Climate Change, Pakistan. (2021). National biosafety guidelines for genetically modified organisms. Government of Pakistan. <http://www.mocc.gov.pk/biosafety>
- National Research Council, Committee on Pest, Pathogen Control Through Management of Biological Control Agents, Enhanced Cycles, & Natural Processes. (1996). *Ecologically based pest management: new solutions for a new century*. National Academies Press.
- Organisation for Economic Co-operation and Development & Food and Agriculture Organization of the United Nations. (2025).

- OECD-FAO agricultural outlook 2025–2034. Paris: OECD Publishing. Retrieved from https://www.oecd-ilibrary.org/agriculture-and-food/oecd-fao-agricultural-outlook-2025-2034_agr_outlook-2025-en
- Palmer, S. (2013). *Soil-borne diseases of cotton in Egypt: Current status and future threats*. Egyptian Journal of Agricultural Research, 91(3), 201–215.
- PCGA (Pakistan Cotton Ginners Association). (2025). *Annual cotton production report 2024–25*. Multan, Pakistan.
- Shah, A. N., Javed, T., Singhal, R. K., Shabbir, R., Wang, D., Hussain, S., Anuragi, H., Jinger, D., Pandey, H., Abdelsalam, N. R., Ghareeb, R. Y., & Jaremko, M. (2022). Nitrogen use efficiency in cotton: Challenges and opportunities against environmental constraints. *Frontiers in Plant Science*, 13. <https://doi.org/10.3389/fpls.2022.970339>
- Shahzadi, I., Mazhar, N., & Abbas, S. (2023). An assessment of changes and variability of climate impact on cotton production yield over Southern Punjab, Pakistan. *Environment, Development and Sustainability*, 26(11), 29331–29347. <https://doi.org/10.1007/s10668-023-03867-w>
- Sharma, S., Pandey, S., Kulshreshtha, S., & Dubey, M. (2025). Biology and application of *Chaetomium globosum* as a biocontrol agent: current status and future prospects. *Microorganisms*, 13(7), 1646.
- Shuli, F., Jarwar, A. H., Wang, X., Wang, L., & Ma, Q. (2018). Overview of the cotton in Pakistan and its future prospects. *Pakistan Journal of Agricultural Research*, 31(4), 396.
- Silva, J. L., Araújo, L. A., & Cardoso, P. H. (2023). *Seed-borne fungal pathogens of cotton: A global perspective*. *Brazilian Journal of Plant Pathology*, 29(1), 41–53.
- Singh, R. (2023). *Advances in biotechnology for resistance breeding against cotton fungal pathogens in India*. *Indian Journal of Genetics and Plant Breeding*, 83(2), 241–250.
- Syed, A., Raza, T., Bhatti, T. T., & Eash, N. S. (2022). Climate Impacts on the agricultural sector of Pakistan: Risks and solutions. *Environmental Challenges*, 6, 100433. <https://doi.org/10.1016/j.envc.2021.100433>
- Terefe, G., & Tesfaye, D. (2009). Review of research on diseases of fiber crops in Ethiopia. Abraham Tadesse (ed.).
- Ullah, M. I., Hasnain, M., Luqman, M., Hussnain, H., Tauseef, M., Ahmad, A., Shahid, M., Abbas, Q., Hussain, M., Raza, A., Khan, M. M. A., Nadeem, M. K., & Nadeem, S. (2024). Evaluation of New Chemistry Insecticides against Sucking Insect Pests of Cotton. *Sarhad Journal of Agriculture*, 40(3). <https://doi.org/10.17582/journal.sja/2024/40.3.858.865>
- Wang, F., Liu, Y., & Zhang, X. (2023). CRISPR/Cas9-mediated editing of GhDREB2 enhances Fusarium wilt resistance in cotton. *Plant Molecular Biology*, 112(2), 147–159. <https://doi.org/10.1007/s11103-023-01325-6>
- Waqar Akhtar, Muhammad Qasim, Abid Hussain, Nadeem Akmal, Hassnain Shah, Muhammad Ather Mahmood, & Rashid Saeed. (2024). Price Distortions and Competitiveness of Cotton Production in Pakistan. *Proceedings of the Pakistan Academy of Sciences: B. Life and Environmental Sciences*, 61(1). [https://doi.org/10.53560/ppasb\(61-1\)715](https://doi.org/10.53560/ppasb(61-1)715)
- Zhang, Y., Chen, H., & Li, M. (2021). QTL analysis of Verticillium wilt resistance in upland cotton. *Crop Science*, 61(5), 3152–3164. <https://doi.org/10.1002/csc2.20589>