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Assessing the Impact of Various Cotton Diseases on Fiber Quality and Production

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Abstract Cotton diseases significantly impact fiber quality and production, posing a major challenge to the global cotton industry. This study assesses the effects of various cotton diseases, including *Verticillium* wilt, *Fusarium* wilt, and ramulosis, on cotton fiber quality and yield. *Verticillium* wilt, caused by *Verticillium dahliae*, leads to substantial reductions in photosynthesis rate, lint production, and fiber quality, with notable decreases in micronaire and maturity ratio. *Fusarium* wilt, particularly race 4, is another destructive disease, with genetic screening revealing significant genotypic variations in resistance, indicating potential for breeding resistant cultivars. Ramulosis, controlled traditionally by fungicides, shows promise for biocontrol using bacterial strains, which not only reduce disease incidence but also improve yield and fiber quality. Additionally, biotechnological advancements, including transgenes, RNAi, and gene editing, offer sustainable solutions for managing these diseases. This study highlights the critical need for integrated disease management strategies combining genetic resistance, biotechnological innovations, and sustainable agricultural practices to mitigate the adverse effects of cotton diseases on fiber quality and production.
Keywords Cotton diseases; Fiber quality; *Verticillium* wilt; *Fusarium* wilt; Biotechnological solutions

1 Introduction

Cotton is one of the most significant crops globally, both economically and agriculturally. It is a primary source of natural fiber, with an annual production of approximately 25 million tons worldwide (Khan et al., 2020). The top cotton-producing countries include India, China, the United States, and Brazil, among others (Khan et al., 2020). Cotton's economic importance is underscored by its role in the textile industry, which has a substantial economic impact estimated at over $600 billion annually (Khan et al., 2020). This crop is often referred to as "white gold" in many developing countries due to its contribution to foreign exchange earnings and its pivotal role in national economies (Khan et al., 2020).

Cotton production is a cornerstone of the agricultural sector in many countries, particularly in developing regions. The crop's cultivation is concentrated in sub-tropical climates and requires significant water and agrochemical inputs to ensure high yields (Rosa and Grammatikos, 2019). Despite these challenges, cotton remains the dominant natural fiber in the textile market, surpassing other fibers such as silk, wool, and hemp (Rosa and Grammatikos, 2019). The genetic diversity of cotton, particularly in species like *Gossypium hirsutum* and *Gossypium barbadense*, has been a focal point for improving fiber yield and quality, as well as enhancing resilience to environmental stresses (Hu et al., 2019).

Fiber quality directly affects the market value and application scope of the product (Ding, 2024). Superior fiber quality, as seen in *Gossypium barbadense*, is highly sought after for producing high-end textile products (Hu et al., 2019). The quality of cotton fibers affects the efficiency of textile manufacturing processes and the quality of the final products. Therefore, improving fiber quality through genetic and biotechnological advancements is a priority for breeders and researchers (Hu et al., 2019). The development of Bt cotton, for instance, has been instrumental in managing insect-pest resistance, thereby reducing the need for chemical insecticides and improving overall fiber quality (Razzaq et al., 2023).

Cotton crops are susceptible to a variety of biotic and abiotic stresses that can significantly impact yield and fiber quality. Biotic stresses include bacterial, viral, and fungal diseases, as well as infestations by nematodes, insects, and mites (Razzaq et al., 2023). These diseases and pests can cause substantial economic losses by reducing both the quantity and quality of cotton fibers. Abiotic stresses such as temperature extremes, drought, and salinity further exacerbate these challenges (Razzaq et al., 2023). Effective management strategies, including the use of biotechnology and integrated pest management, are essential to mitigate these impacts and ensure sustainable cotton production (Razzaq et al., 2023).

This study assesses the impact of various cotton diseases on fiber quality and production. By synthesizing current research findings, this study provides a comprehensive understanding of how different diseases affect cotton crops and to identify effective management strategies; explores the genetic and biotechnological advancements that have been made to improve cotton resilience and fiber quality, thereby offering insights into future directions for research and development in the cotton industry.

2 Major Cotton Diseases Affecting Fiber Quality

2.1 Bacterial Blight

Bacterial blight of cotton, caused by *Xanthomonas citri* subsp. *malvacearum*, is a significant disease that affects cotton fiber quality and production. This disease has seen a resurgence in recent years, particularly in the United States, leading to substantial cotton losses. The pathogenicity of the bacteria and the host's response are critical areas of study to develop effective disease management strategies. Current research focuses on understanding the mechanisms of resistance and susceptibility in cotton plants, as well as exploring biological control methods to mitigate the impact of bacterial blight (Cox et al., 2019).

2.2 *Verticillium* wilt

Verticillium wilt, caused by the soil-borne fungus *Verticillium dahliae*, is another major disease that affects cotton. This disease leads to wilting, chlorosis, and necrosis of the leaves, ultimately reducing fiber quality and yield. Advances in molecular breeding and marker technology have facilitated the identification of resistant cotton cultivars through quantitative trait loci (QTL) mapping. These biotechnological tools are essential for developing cotton varieties that can withstand *Verticillium* wilt, thereby improving overall cotton production (Javed et al., 2019).

2.3 *Fusarium* wilt

Fusarium wilt, caused by *Fusarium oxysporum* f. sp. *vasinfectum*, is a persistent threat to cotton crops worldwide. Similar to bacterial blight, *Fusarium* wilt has re-emerged in various regions, including the United States, causing significant damage to cotton fields. Research efforts are directed towards understanding the disease's recurrence and developing resistant cotton varieties through molecular breeding techniques. The use of QTL mapping and marker-assisted selection (MAS) has shown promise in identifying and cultivating *Fusarium* wilt-resistant cotton strains (Cox et al., 2019; Javed et al., 2019).

2.4 Cotton leaf curl virus (CLCuV)

Cotton Leaf Curl Virus (CLCuV) is one of the most devastating viral diseases affecting cotton, particularly in Pakistan, north-western India, and parts of Africa. The disease causes severe curling and distortion of leaves, leading to reduced photosynthesis and stunted plant growth. Molecular markers and genome mapping have been instrumental in identifying resistant sources and developing CLCuV-resistant cotton varieties. These biotechnological advancements are crucial for mitigating the impact of CLCuV on cotton production (Javed et al., 2019).

2.5 Alternaria leaf spot

Alternaria leaf spot, caused by *Alternaria* spp., is a fungal disease that affects cotton leaves, leading to the formation of dark, necrotic spots. This disease can significantly reduce the photosynthetic area of the plant, thereby impacting fiber quality and yield. While not as extensively studied as other cotton diseases, ongoing research aims to understand the pathogen's biology and develop resistant cotton varieties through traditional breeding and molecular techniques.

2.6 Anthracnose

Anthracnose, caused by *Colletotrichum* spp., is a fungal disease that affects cotton bolls, stems, and leaves. The disease manifests as dark, sunken lesions, which can lead to boll rot and significant yield losses. Research into anthracnose focuses on identifying resistant cotton varieties and understanding the pathogen's infection mechanisms. Molecular breeding and QTL mapping are valuable tools in developing anthracnose-resistant cotton strains, thereby improving fiber quality and production (Javed et al., 2019).

By addressing these major cotton diseases through advanced research and biotechnological tools, the cotton industry can enhance fiber quality and ensure sustainable production.

3 Pathogen Mechanisms and Disease Progression

3.1 Pathogen entry and infection process

Pathogens employ various strategies to enter and infect cotton plants, significantly impacting fiber quality and production. *Verticillium dahliae*, the causative agent of *Verticillium* wilt, initiates infection through the germination and growth of microsclerotia, followed by successful colonization of the host plant. This pathogen adapts to nutrient-deficient environments and competes for nutrients, suppresses and manipulates the cotton immune responses, and rapidly reproduces while secreting toxins (Figure 1) (Zhu et al., 2023). Similarly, *Fusarium oxysporum* f. sp. *vasinfectum* (FOV), responsible for *Fusarium* wilt, infects cotton through soil-borne spores that invade the plant's vascular system, leading to systemic infection (Zhang et al., 2020). The infection process of V. dahliae also involves the secretion of secondary metabolites that act as toxic factors to promote infection (Wang et al., 2020).

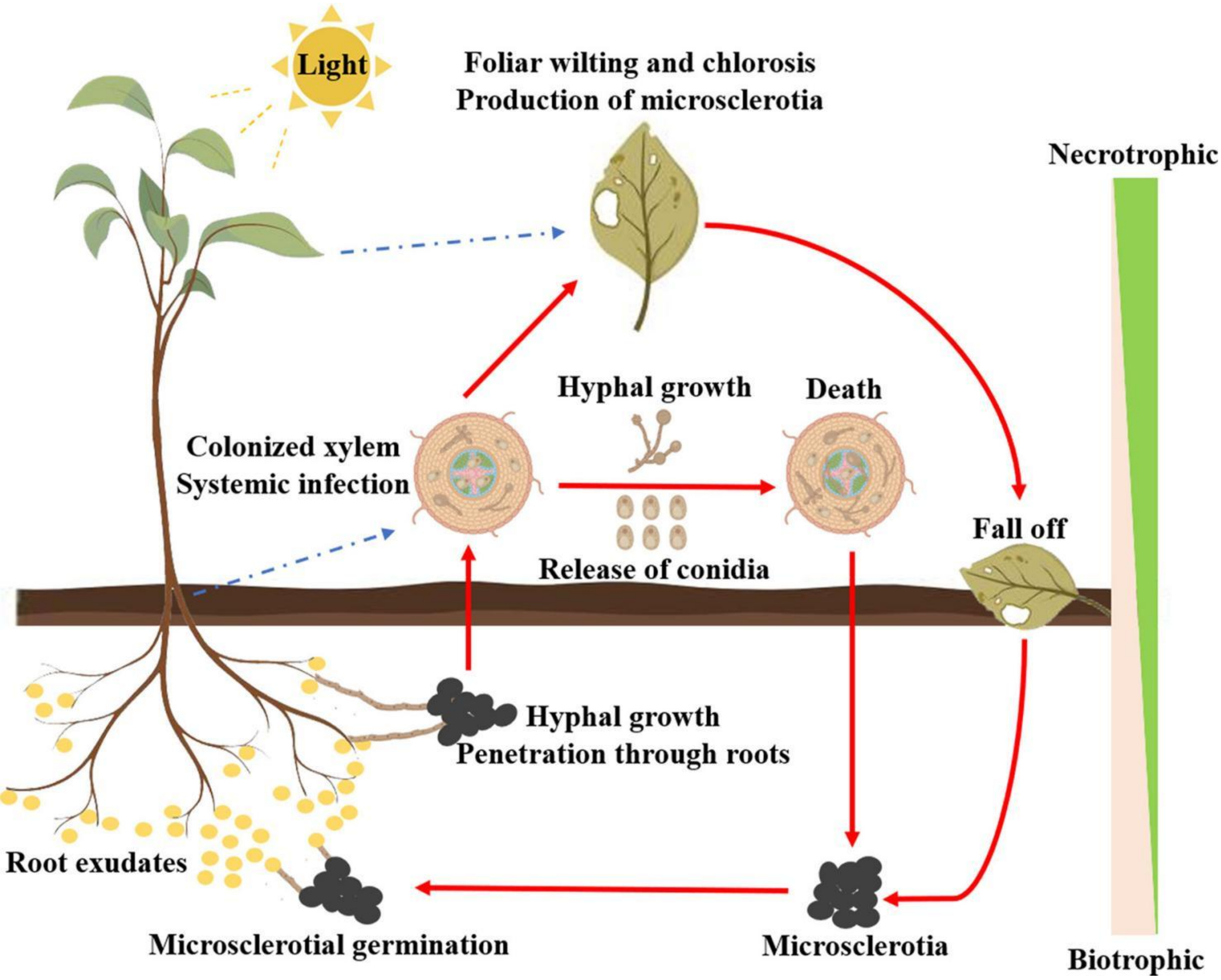

Figure 1 Infection cycle of *V. dahliae* in generic host plants (Adopted from Zhu et al., 2023)

Zhu et al. (2023) illustrates the infection cycle of *Verticillium dahliae* in host plants, highlighting its stages from root exudate detection to systemic colonization and eventual formation of microsclerotia. The infection begins when microsclerotia in the soil germinate upon sensing signals from root exudates, allowing the fungus to penetrate the roots and colonize the xylem. *V. dahliae* progresses through biotrophic and necrotrophic stages, causing wilting, chlorosis, and ultimately death of the host. The necrotrophic stage leads to the formation of new microsclerotia, ensuring long-term survival. The study also notes that environmental factors and host plant conditions significantly influence the incidence and severity of *Verticillium* wilt, underscoring the disease's complexity and impact on cotton and other crops.

3.2 Disease symptoms and their effect on plant physiology

The symptoms of cotton diseases vary but generally include wilting, chlorosis, necrosis, and defoliation, which severely affect plant physiology and fiber quality. *Verticillium* wilt manifests as wilting and chlorosis of leaves, vascular discoloration, and stunted growth, ultimately leading to significant yield losses and reduced fiber quality (Zhu et al., 2023). *Fusarium* wilt symptoms include yellowing and wilting of leaves, vascular browning, and plant death, which also result in substantial yield and quality reductions (Bardak et al., 2021). Powdery mildew caused by Brasiliomyces malachrae presents as white mycelial patches on leaves, leading to yellowing, necrosis, and early defoliation, which can compromise the photosynthetic efficiency and overall health of the cotton plant (Márquez-Licona et al., 2023). These symptoms disrupt normal physiological processes such as photosynthesis, nutrient transport, and water uptake, thereby impairing fiber development and quality (Ul-Allah et al., 2021).

3.3 Factors influencing disease severity

Several factors influence the severity of cotton diseases, including environmental conditions, genetic resistance, and pathogen virulence. Environmental stresses such as drought and salinity can exacerbate disease severity by weakening the plant's defense mechanisms and making it more susceptible to infections (Tahmasebi et al., 2019; Billah et al., 2021). Genetic resistance plays a crucial role in disease management; however, the limited availability of resistance genes in current cotton varieties poses a challenge for breeding programs (Zhang et al., 2020; Zhu et al., 2023). The virulence of the pathogen, including its ability to produce toxins and secondary metabolites, also significantly impacts disease severity. For instance, the ubiquitin ligase VdBre1 in *V. dahliae* regulates lipid metabolism and secondary metabolite production, which are critical for the pathogen's virulence and ability to infect cotton (Wang et al., 2020). Additionally, the presence of specific genetic markers associated with disease resistance can aid in the development of resistant cotton varieties through marker-assisted selection (MAS) (Bardak et al., 2021).

By understanding these pathogen mechanisms and disease progression, researchers can develop more effective strategies to mitigate the impact of cotton diseases on fiber quality and production.

4 Impact on Fiber Quality and Production

4.1 Effects on fiber length and strength

Cotton diseases significantly impact fiber length and strength, which are critical parameters for textile quality. *Verticillium* wilt, caused by *Verticillium dahliae*, has been shown to reduce fiber quality, including fiber length and strength. In a study comparing healthy and *Verticillium* wilt-affected plants, fiber properties such as short fiber content and nep count were significantly affected, indicating a reduction in fiber length and strength under disease pressure (Ayele et al., 2020). Additionally, genomic studies have identified specific loci associated with fiber length and strength, providing targets for genetic improvement to mitigate these effects (Ma et al., 2018). The comparative analysis of *Gossypium hirsutum* and *Gossypium barbadense* genomes also highlights the genetic basis for differences in fiber quality, with G. barbadense producing superior-quality fibers (Hu et al., 2019).

4.2 Impact on fiber maturity and uniformity

Fiber maturity and uniformity are crucial for processing efficiency and final product quality. *Verticillium* wilt has been shown to decrease the maturity ratio of cotton fibers, with significant reductions observed in susceptible genotypes (Ayele et al., 2020). The symbiosis with arbuscular mycorrhizal fungi (AMF) has been reported to enhance fiber maturity, suggesting a potential biological control strategy to improve fiber quality under disease conditions (Gao et al., 2020). Furthermore, drought stress, another abiotic factor, negatively impacts fiber maturity and uniformity by disrupting carbohydrate metabolism and assimilate translocation, leading to inferior fiber quality (Ul-Allah et al., 2021).

4.3 Consequences for cotton yield

Cotton diseases can lead to substantial yield losses. *Verticillium* wilt, for instance, significantly reduces lint and seed yield, with susceptible genotypes showing greater yield losses compared to partially resistant ones (Ayele et al., 2020). The use of AMF has been shown to increase cotton yield by enhancing phosphorus acquisition and overall plant growth, demonstrating a potential strategy to mitigate yield losses due to diseases (Gao et al., 2020). Additionally, genomic studies have identified loci associated with yield traits, providing opportunities for breeding disease-resistant and high-yielding cotton varieties (Ma et al., 2018).

4.4 Economic impact of cotton diseases on global markets

The economic impact of cotton diseases extends beyond yield and quality losses to affect global markets. Biotic stresses, including diseases caused by bacteria, fungi, viruses, nematodes, insects, and mites, increase production costs and reduce the profitability of cotton farming (Tarazi et al., 2019). The need for control measures, such as pesticides and other agrochemicals, further exacerbates the economic burden and environmental impact (Rosa and Grammatikos, 2019). The development and adoption of biotechnological solutions, such as transgenes, RNAi, and gene editing, are crucial for sustainable disease management and maintaining the economic viability of the cotton industry (Tarazi et al., 2019).

In summary, cotton diseases have profound effects on fiber quality, yield, and economic outcomes. Strategies to mitigate these impacts include breeding for disease resistance, utilizing beneficial symbiotic relationships, and employing biotechnological innovations. These approaches are essential for sustaining cotton production and ensuring the quality of cotton fibers in the global market.

5 Disease Management Strategies

5.1 Cultural Practices

Cultural practices play a crucial role in managing cotton diseases by creating an environment less conducive to pathogen development. Practices such as crop rotation, proper irrigation management, and sanitation can significantly reduce the incidence of diseases like *Verticillium* wilt and Bacterial blight. For instance, rotating cotton with non-host crops can help break the life cycle of soil-borne pathogens like *Verticillium dahliae*, thereby reducing disease pressure (Ayele et al., 2020; Zhu et al., 2023). Additionally, maintaining optimal plant spacing and ensuring good air circulation can minimize the humidity levels that favor the growth of fungal pathogens (Egan and Stiller, 2022).

5.2 Chemical Control Methods

Chemical control methods involve the use of fungicides, bactericides, and insecticides to manage cotton diseases. While effective, these methods must be used judiciously to prevent the development of resistance in pathogens and to minimize environmental impact. For example, fungicides can be applied to control *Verticillium* wilt, but their effectiveness varies depending on the timing and method of application (Zhu et al., 2023). Integrated pest management (IPM) strategies that combine chemical treatments with other control methods can enhance disease control while reducing reliance on chemicals (Razzaq et al., 2023).

5.3 Biological control options

Biological control options include the use of natural predators, antagonistic microorganisms, and biopesticides to manage cotton diseases. These methods are environmentally friendly and can be integrated into sustainable agricultural practices. For instance, the use of bioagents such as *Trichoderma* spp. has shown promise in controlling soil-borne pathogens like *Verticillium dahliae* by outcompeting them for resources and space (Razzaq et al., 2023). Additionally, the application of beneficial microbes can enhance the plant's natural defense mechanisms, providing long-term disease resistance (Wu et al., 2023).

5.4 Breeding for disease resistance

Breeding for disease resistance is a long-term and sustainable strategy for managing cotton diseases. This involves the development of cotton cultivars that possess genetic resistance to specific pathogens. Advances in molecular breeding techniques, such as marker-assisted selection (MAS) and genomic selection, have accelerated the development of resistant varieties. For example, the CSIRO cotton breeding program has successfully released cultivars resistant to Bacterial blight, *Verticillium* wilt, and *Fusarium* wilt (Egan and Stiller, 2022). Additionally, the identification of resistance genes and their incorporation into breeding programs can provide durable resistance against emerging threats (Bardak et al., 2021; Elassbli et al., 2021; Zhu et al., 2023). The use of biotechnological tools like CRISPR/Cas9 and RNA interference (RNAi) further enhances the precision and efficiency of breeding for disease resistance (Javed et al., 2019; Razzaq et al., 2023).

By integrating these disease management strategies, cotton producers can effectively mitigate the impact of various diseases on fiber quality and production, ensuring sustainable and profitable cotton farming.

6 Case Study: Impact of *Verticillium* Wilt on Cotton Production in the United States

6.1 Overview of *Verticillium* wilt in the U.S.

Verticillium wilt, caused by the soil-borne pathogen *Verticillium dahliae*, is one of the most devastating diseases affecting cotton production in the United States. This pathogen leads to significant yield losses and a reduction in fiber quality, posing a major challenge to cotton growers. The disease is characterized by the wilting and yellowing of leaves, vascular discoloration, and ultimately, plant death. The pathogen's ability to survive in the soil for extended periods makes it particularly difficult to manage (Ayele et al., 2020; Zhu et al., 2023).

6.2 Analysis of fiber quality data from affected regions

Research has shown that *Verticillium* wilt significantly impacts fiber quality in cotton. For instance, a study comparing healthy and *Verticillium* wilt-affected plants found that fiber properties such as micronaire, maturity ratio, short fiber content, nep count, fineness, and immature fiber content were all adversely affected by the disease. Specifically, the micronaire value decreased from 5.0 in healthy plants to 3.6 in affected plants for the susceptible cultivar DP 1612 B2XF, and from 4.4 to 4.1 for the partially resistant cultivar FM 2484B2F. The maturity ratio also decreased from 0.90 to 0.83 in the susceptible cultivar, while it remained unchanged in the partially resistant cultivar (Figure 2) (Ayele et al., 2020).

Ayele et al. (2020) presents the fiber length distribution of greenhouse-grown upland cotton, comparing healthy plants with those infected by *Verticillium dahliae*. Healthy cotton genotypes exhibit an ideal fiber length distribution with a prominent peak in long fibers, which is favorable for the textile industry. However, *V. dahlia* infection leads to a significant increase in short fibers, particularly in genotypes DP 1612 B2XF and 16-13-203V, resulting in fibers that are below spinnable quality. In contrast, genotype 16-13-601V, even when infected, maintained a more favorable fiber length distribution, indicating potential spinnability. This comparison underscores the detrimental impact of *Verticillium* wilt on fiber quality and highlights the importance of selecting resistant genotypes to ensure high-quality cotton production.

6.3 Economic losses and management strategies employed

The economic impact of *Verticillium* wilt on cotton production is substantial, with significant yield losses reported across various regions. In the Texas High Plains, field experiments demonstrated that planting partially resistant cotton cultivars at higher seeding rates could reduce wilt incidence by up to 49%, highlighting the importance of cultivar selection and planting density in disease management (Liu et al., 2021). Additionally, breeding resistant cotton varieties through genetic engineering has been identified as a promising strategy to combat *Verticillium* wilt. However, the limited availability of resistance genes in current cotton varieties poses a challenge to this approach (Zhu et al., 2021; Zhu et al., 2023).

In summary, *Verticillium* wilt remains a critical issue for cotton production in the United States, affecting both yield and fiber quality. Effective management strategies, including the use of resistant cultivars and optimized planting practices, are essential to mitigate the economic losses associated with this disease. Further research into the molecular mechanisms of resistance and the development of new resistant germplasm will be crucial for long-term control of *Verticillium* wilt in cotton.

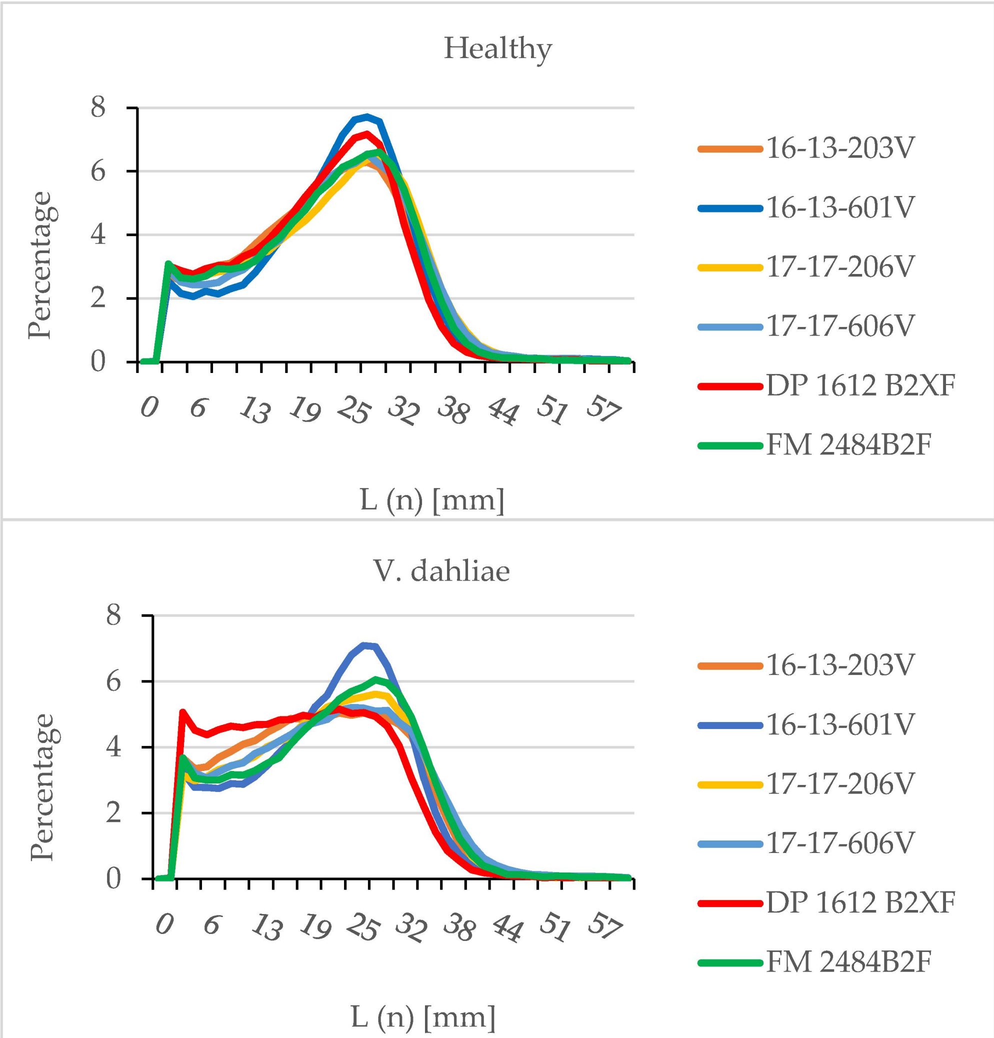

Figure 2 Fiber length distribution of greenhouse-grown upland cotton (Adopted from Ayele et al., 2020)

Image caption: Healthy (top) and inoculated with *Verticillium dahlia* (bottom). L (n) [mm], length by number in millimeters (Adopted from Ayele et al., 2020)

7 Future Directions and Research Gaps

7.1 Emerging cotton diseases and their potential impact

Emerging diseases such as Black root rot and secondary pests are becoming more frequent in cotton production systems, particularly in regions like Australia. These diseases pose significant threats to cotton yield and fiber quality, necessitating the development of new resistant cultivars and advanced breeding techniques (Egan and Stiller, 2022). Additionally, viral diseases in cotton, which often mimic nutrient deficiencies and insect damage, are challenging to identify and manage. The rapid identification and breeding of virus-resistant cotton lines using molecular virology and genomics are crucial to mitigate these threats (Tarazi and Vaslin, 2022).

7.2 Innovations in disease resistance breeding

The integration of genomic selection, high throughput phenomics, gene editing, and landscape genomics is pivotal for the future of cotton breeding. These tools enable the identification and utilization of resistance sources from *Gossypium germplasm*, facilitating the development of cultivars resistant to a range of diseases including Bacterial blight, *Verticillium* wilt, *Fusarium* wilt, and Cotton bunchy top (Egan and Stiller, 2022). Moreover, the use of miRNAs, such as the ghr-miR482b-GhRSG2 module, has shown promise in enhancing resistance to

Verticillium wilt by regulating plant defense mechanisms (Wu et al., 2023). The application of QTL mapping and marker-assisted selection (MAS) also offers significant potential in identifying and breeding disease-resistant cotton varieties (Javed et al., 2019).

7.3 Integration of precision agriculture in disease management

Precision agriculture technologies, including remote sensing and artificial intelligence (AI), are revolutionizing disease management in cotton. These technologies enable rapid, sensitive, and cost-effective identification of viral diseases, facilitating timely and targeted interventions (Tarazi and Vaslin, 2022). Additionally, the use of plant growth regulators and mineral elements can enhance drought stress tolerance, fiber yield, and quality, thereby mitigating the adverse effects of abiotic stresses on cotton production (Ul-Allah et al., 2021).

7.4 Need for global collaboration in cotton disease research

Global collaboration is essential to address the complex challenges posed by cotton diseases. Sharing knowledge, resources, and technologies across countries can accelerate the development of resistant cultivars and improve disease management practices. Collaborative efforts can also enhance the understanding of disease mechanisms and resistance pathways, leading to more effective and sustainable solutions (Zhang and Wedegaertner, 2021; Zhu et al., 2023). The integration of advanced breeding techniques and precision agriculture tools in a globally coordinated manner will be crucial for the future resilience of cotton production systems.

8 Concluding Remarks

This study of the impact of various cotton diseases on fiber quality and production has revealed significant insights. Drought stress, exacerbated by climate change, has been identified as a major threat to cotton production, affecting photosynthesis, carbohydrate metabolism, and enzyme activities crucial for fiber development. This results in poor fiber quality and yield, although advancements in drought-tolerant genotypes and the use of plant growth regulators show promise in mitigating these effects. *Verticillium* wilt, caused by *Verticillium dahliae*, significantly reduces cotton yield and fiber quality by impacting photosynthesis and various fiber properties such as micronaire and maturity ratio. The role of molecular breeding and QTL mapping has been highlighted as effective strategies in developing disease-resistant cotton varieties, particularly against *Verticillium* wilt and other biotic stresses. Additionally, the use of bioagents has shown efficacy in reducing foliar diseases like bacterial leaf blight and Alternaria leaf spot, thereby improving seed cotton yield.

The findings from this study have profound implications for the cotton industry. The identification of drought and *Verticillium* wilt as major threats underscores the need for continued research and development of resistant cotton varieties. The advancements in molecular breeding and QTL mapping offer promising avenues for developing cultivars that can withstand these stresses, thereby ensuring stable fiber quality and yield. The use of bioagents presents an eco-friendly alternative to chemical treatments, potentially reducing the environmental impact of cotton farming while maintaining high yields. Furthermore, understanding the genetic and molecular mechanisms underlying stress responses and disease resistance can lead to more targeted and efficient breeding programs, ultimately enhancing the resilience and productivity of cotton crops.

Future research should focus on several key areas to further mitigate the impact of cotton diseases on fiber quality and production. First, there is a need for more comprehensive studies on the variations in fiber quality due to drought stress to develop more robust drought-tolerant varieties. Second, the genetic basis of resistance to *Verticillium* wilt and other biotic stresses should be further explored to identify new resistance genes and pathways. Third, the integration of advanced genomic tools such as whole-genome sequencing and genome-wide association studies (GWAS) can accelerate the identification of key genetic loci associated with fiber quality traits, facilitating marker-assisted selection in breeding programs. Lastly, the development and field testing of bioagents should be expanded to validate their efficacy under diverse environmental conditions and to explore their potential in integrated pest management strategies. By addressing these research gaps, the cotton industry can better adapt to the challenges posed by climate change and disease pressures, ensuring sustainable production and high-quality fiber.

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Conflict of Interest Disclosure
Authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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