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ADVANCES IN COTTON FIBER QUALITY IMPROVEMENT: GENETIC AND AGRONOMIC PERSPECTIVES: A REVIEW

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ABSTRACT

Cotton is one of the world's most important fibre crops and is a key raw material for the textile industry, as well as being an important contributor to the global economy. The quality of fibers is an important attribute and has a significant influence on spinning efficiency, yarn quality, and market value, as reflected in their length, strength, fineness, uniformity, and maturity. The genetic control of these traits and their susceptibility to environmental influences improve fiber quality while maintaining high yield, a great challenge. The genetic, molecular biological, and agronomic advances in recent years have opened up new possibilities for improving cotton fibre quality. Conventional breeding methods and marker-assisted selection, quantitative trait loci (QTL) selection, genomic selection, and genome editing technologies have made the process of developing better cotton cultivars that produce superior cotton fiber properties a much faster process. In addition, transcriptomics, proteomics, and metabolomics research have led to a greater understanding of the molecular mechanisms involved in the development and elongation of fiber. Other agronomic treatments like balanced nutrient management, optimized irrigation scheduling, plant growth regulators, high-density planting, and stress management also have a significant influence on fibre quality attributes. The adoption of sustainable agricultural practices and precision agriculture technologies further supports this in order to ensure better fibre quality and reduce environmental impacts. This review focuses on the recent advances in genetic and agronomic strategies for improving fibre quality and discusses genotype-environment interactions, with a view to the future in developing climate-resilient, high-quality cotton varieties for use in modern cotton-based textile industries and sustainable agricultural systems.

Keywords **:** Cotton fiber quality, Genetic improvement, Agronomic management, Genome editing, Sustainable cotton production.

Introduction

Cotton is the world's major natural fibre, cultivated on over 30-34 million hectares in over 30-85 countries, and accounting for approximately one third of global fibre demand (Saini *et al*., 2023; Tlatlaa *et al*., 2023; Yasir *et al*., 2022). It produces mainly upland cotton (Gossypium hirsutum), which accounts for about 95% of the production due to its wide adaptability and high-yielding potential (Tlatlaa *et al*., 2023; Yasir *et al*., 2022). In addition to textiles, the cotton industry is also a source of food and feed production, due to cottonseed oil and meal, and is a source of livelihood for the tens of millions of farming households, especially in developing countries (Saini *et al*., 2023; Khan *et al*., 2025). As a result, the cotton value chain, which spans from the farm to the textile industry, has significant implications for rural income, trade, and sustainable development (Saini *et al*., 2023; Tlatlaa *et al*., 2023; Khan *et al*., 2025).

The spinning performance, processing cost, and fabric quality of cotton in the downstream textile industry directly depend on the quality of fibre in the cotton lint, which is the main component of cotton's economic value (Zhang & Wedegaertner, 2021; Yasir *et al*., 2022). With the rising demands of the market for high-performance and “green” products, mills are willing to pay higher prices for lint with higher and consistent quality, and fiber quality is one of the most important factors in differentiating price differences among cultivars and regions (Zhang & Wedegaertner, 2021; Yasir *et al*., 2022). Meeting the high-quality standards required for access to high-value textile markets is becoming as important as yield in many production systems (Zhang & Wedegaertner, 2021; Van Der Sluijs, 2022; Sapkota *et al*., 2023).

Cotton fiber quality traits such as fiber length, strength, fineness (micronaire), uniformity, and color collectively influence the spinnability and yarn strength of cotton (Zhang & Wedegaertner, 2021; Yasir *et al*., 2022). The genetics underlying these traits are polygenetic and complex, involving multiple pathways that are influenced by phytohormones and environmental conditions, including pathways to fibre cell initiation and elongation, and secondary wall deposition (Qanmber *et al*., 2024; Wu *et al*., 2022; Jan *et al*., 2022; Zhai *et al*., 2023; Yasir *et al*., 2022). Due to this complexity, coordinated genetic and agronomic measures are required to improve quality and involve both the regulatory molecular genetics of fibre development and field management (nutrients, plant density, stress mitigation) (Qanmber *et al*., 2024; Van Der Sluijs, 2022; Arinaitwe *et al*., 2026; Sapkota *et al*., 2023).

One of the biggest problems is the negative or negative and fluctuating fiber quality/yield relationship. Fiber traits have been tightly selected by historical breeding, reducing genetic variation and sometimes creating trade-offs, such as an increase in yield and a decrease in length/stretch and vice versa (Wu *et al*., 2022; Jan *et al*., 2022; Zhai *et al*., 2023; Yasir *et al*., 2022). In addition, climate change, primarily heat and drought stress, further increases the tradeoff between yield and quality (Saini *et al*., 2023; Khan *et al*., 2025; Abro *et al*., 2023). The agronomic management of nitrogen rate, plant population, and micronutrients also affects the quality, but must not be done at an excessive cost and with environmental impacts, and must be balanced with yield targets (Van Der Sluijs, 2022; Arinaitwe *et al*., 2026; Sapkota *et al*., 2023; Shah *et al*., 2022). The challenge of simultaneous improvement of high yield and premium fiber quality has been an ongoing hurdle in cotton breeding and production (Wu *et al*., 2022; Jan *et al*., 2022; Zhai *et al*., 2023; Yasir *et al*., 2022).

In this context, the purpose of this review is to emphasize some recent advances in genetic and agronomic methods of enhancing cotton fiber quality without sacrificing or reducing yield. The genetic side of the review will focus on some of the recent discoveries relating to fiber developmental biology, quantitative genetics, and genome-wide association studies, and new tools such as genomic selection and genome editing that target the fiber traits (Qanmber *et al*., 2024; Wu *et al*., 2022; Jan *et al*., 2022; Ghorbanzadeh *et al*., 2025; Yasir *et al*., 2022). The agronomic perspective will focus on maximising the quality of fibre in various production environments through nutrient management, plant population, stress mitigation, and precision technologies (Saini *et al*., 2023; Van Der Sluijs, 2022; Arinaitwe *et al*., 2026; Sapkota *et al*., 2023; Shah *et al*., 2022). A holistic approach to the review will contribute to the development of practical approaches and future research directions to develop and manage cotton cultivars to satisfy the changing needs of the world's cotton textile industry in the context of climate and market change.

Cotton Fiber Development and Quality Traits

Stages of Cotton Fiber Development

Cotton fibers are single cells with a very long length that emerge from the epidermis of the ovule and go through four overlapping development phases: initiation, elongation, secondary cell wall synthesis, and maturation (Jan *et al*., 2022; Zhai *et al*., 2023). Fibre initiated from about 3 days before anthesis until 3 days after; the number of fibre initiation cells is a good indicator of the final fibre yield (Zhai *et al*., 2023). Elongation begins around flowering and continues for ~20–25 days, during which lint fibers grow to ~25–30 mm, and then strongly overlaps with the deposition of secondary cell wall (SCW) material (Jan *et al*., 2022; Zhai *et al*., 2023; Saini *et al*., 2023). SCW synthesis and thickening usually begin around 20-45 (up to 60) days after flowering and are mainly controlled by cellulose deposition, accounting for ~85% of the fiber composition (Zhai *et al*., 2023; Saini *et al*., 2023). The last maturation/dehydration stage (≈ 45-50 days after) consists of dehydration and consolidation of the cellulose wall, which finally confers strength, fineness, maturity, and elongation (Table 1, Jan *et al*., 2022; Zhai *et al*., 2023; Saini *et al*., 2023).

Table 1 : Cotton Fiber Quality Traits and Their Sensitivities

Fiber parameter	What it reflects / why important	Major sensitivities and controls	Citations
Fiber length & uniformity	Extent and evenness of cell elongation; key for spinning and yarn strength	Primarily genetic; strongly shaped by the elongation phase. High temperatures (>35 °C) and sub-optimal night temperatures reduce length and uniformity; N level has a variable, often small effect compared with genotype and weather (Van Der Sluijs, 2022; Saini *et al*., 2023)	(Van Der Sluijs, 2022; Saini *et al*., 2023)
Fiber strength	Integrity of SCW is critical for yarn performance	Mainly genetic; determined during SCW thickening. Heat during cell wall thickening (20–60 days) and reduced cellulose synthesis impair strength; N rate usually has little consistent effect if not extreme (Van Der Sluijs, 2022; Saini *et al*., 2023)	(Van Der Sluijs, 2022; Saini *et al*., 2023)
Fineness / micronaire	A combination of fiber fineness and maturity influences dye uptake and handle	Strongly affected by temperature during SCW formation; micronaire deteriorates above ~28–33 °C, and heat can cause rough, high-micronaire fibers via altered wall condensation (Abro *et al*., 2023; Saini *et al*., 2023)	(Abro *et al*., 2023; Saini *et al*., 2023)
Maturity & elongation	Wall development (maturity) and fiber extensibility both affect spinning performance.	Elongation depends on proper early temperature and hormonal control; high day/night temperatures reduce elongation. Maturity depends on adequate cellulose synthesis, which is optimal at ~25–30 °C and declines at higher temperatures (Jan *et al*., 2022; Abro *et al*., 2023; Saini *et al*., 2023)	(Jan *et al*., 2022; Abro *et al*., 2023)

Factors Affecting Fiber Quality

Genetic Factors

Fibre traits, which are influenced by Fibre length, strength, elongation, fineness, uniformity, etc., are largely genetically determined, where many associated SNPs and QTLs are positively selected for good fibre quality (Yasir *et al*., 2022). There are different Gossypium species with varying profiles (e.g., G. barbadense has longer, finer, and stronger fibres), and many genes involved in the initiation, elongation, and SCW synthesis have been identified, such as transcription factors and hormone-related genes (Jan *et al*., 2022; Zhai *et al*., 2023; Yasir *et al*., 2022).

Environmental Conditions

Temperature is an important environmental factor. Proper development of fiber has been observed at the average daily temperatures within the range of 26 °C, which is below 35 °C. The higher the temperature, the more fiber length, strength, uniformity, elongation, maturity, and micronaire are reduced due to the reduction of photosynthesis, sucrose supply, and cellulose synthesis (Abro *et al*., 2023; Saini *et al*., 2023). Heat stress also causes changes in the biochemical composition of fibers and may result in increased roughness and micronaire (Abro *et al*., 2023). Respiration increases and carbohydrate supply decreases (Saini *et al*., 2023) when night temperatures are outside of ~15–21 °C, which leads to a decline in fiber length and weight.

Agronomic Management Practices

Nutrient management, particularly nitrogen rate, has the greatest influence on yield rather than fibre quality, and has inconsistent and often limited effects on fibre length, strength, and elongation compared to genotype and weather (Van Der Sluijs 2022). Optimization of agronomic practices (such as irrigation optimization and exploitation of other inputs as soil, water, and light) are expected to maintain plant health and maintain fiber quality under stress conditions, while hormone focused and genomic breeding approaches (e.g., targeting brassinosteroid and other hormonal pathways) are proposed to improve fiber development, and quality resilience (Jan *et al*., 2022, Qanmber *et al*., 2024, Shah *et al*., 2022).

Genetic Approaches for Cotton Fiber Quality Improvement

Conventional Breeding Approaches

Traditional breeding of fiber quality is carried out through selection in segregating populations and through crosses between contrasting parents, and it is common to cross G. hirsutum with G. barbadense to obtain high-yielding fiber plants with better fiber quality. Crosses between species of different fiber qualities have been used to map quantitative trait loci (QTL) for fiber properties to identify regions of the genome linked to elongation, strength, and fineness, and to select phenotypically superior lines, which will give breeders a guide for the regions to select.

Recurrent selection and pedigree breeding have led to cultivars with better fiber length and fiber strength over time, but progress is slow and limited due to the low genetic diversity and high genotype × environment interactions of the cultivars (Ghorbanzadeh *et al*., 2025; Jan *et al*., 2022). Conventional breeding schemes are being supplemented by speed breeding and better phenotyping to reduce breeding cycles and boost selection intensity, ensuring the development of better cultivars to match the requirements of the textile industry (Ghorbanzadeh *et al*., 2025) (Figure 1).

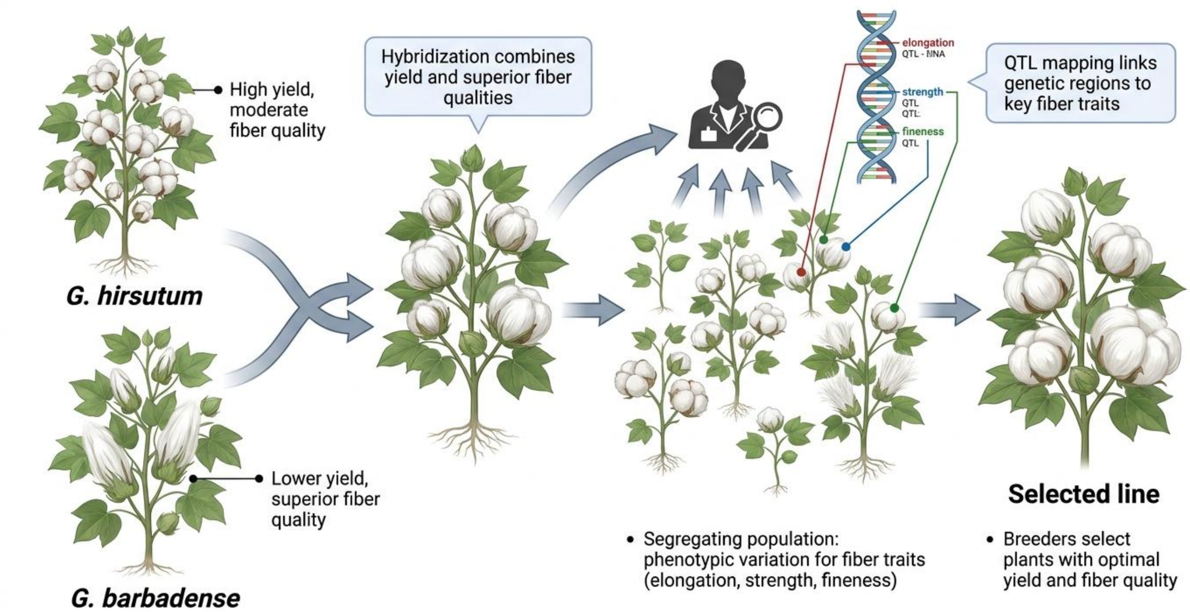

Fig. 1 : This diagram shows the integration of conventional breeding and QTL mapping in cotton. By breeding *Gossypium hirsutum* (high yield) with *Gossypium barbadense* (superior fiber quality), it is possible to identify and select progenies that have desirable fiber properties, for example, elongation, strength, and fineness, which results in the development of improved cotton lines with both high yield and excellent fiber quality.

Molecular Breeding Techniques

Marker-Assisted Selection (MAS) takes advantage of closely linked DNA markers associated with major QTL for fiber traits for early-generation selection and decreases the co-transfer of undesirable DNA markers linked to the major QTLs (Jan *et al*., 2022; Khan *et al*., 2025). These genetic loci have been identified in cotton, and hundreds of markers are now known for this trait; a genome-wide marker panel will enable introgression of desirable alleles from a variety of germplasm (Jan *et al*., 2022). Under extreme G x E interaction, the use of genomic selection (GS) is more efficient than MAS for highly polygenic traits, as the genome-wide markers and prediction models give better estimates of breeding values (Ghorbanzadeh *et al*., 2025; Khan *et al*., 2025). Combined with GTK's high-throughput phenotyping and machine-learning capabilities, GS can also be used to predict ideotypes having optimal yield, fiber quality, and stress resistance (Ghorbanzadeh *et al*., 2025; Khan *et al*., 2025).

Genome Editing and Biotechnology

The precise modification of candidate genes that regulate fiber development and adaptation in the complex tetraploid cotton genome is possible by using genome editing tools, notably CRISPR/Cas and its variants (base and prime editing) (Ghorbanzadeh *et al*., 2025). These tools have the potential to quickly validate the function of a gene for longer, stronger fiber and/or environmental adaptation without a lot of linkage drag. Historically, pest resistance and seed composition have been the two areas targeted with transgenic approaches and gene stacking (trait pyramiding), but in the case of fibres, similar approaches are being suggested for simultaneously enhancing fibre yield and quality via the incorporation of hormone signalling components and structural proteins (Ghorbanzadeh *et al*., 2025). However, there are significant infrastructure costs, regulatory uncertainty, and concerns about the risk of a decrease in allelic diversity in the event of highly targeted editing coupled with limited use of germplasm to address large-scale deployment (Ghorbanzadeh *et al*., 2025).

Omics Approaches in Fiber Quality Improvement

The revolution in knowledge of fiber development has been brought about by genomics, transcriptomics, proteomics, and metabolomics. Polymorphism mapping by chromosome-scale genomes, pan-genomes, and haplotype-resolved resequencing identifies causal variants and non-reference alleles linked to the fiber traits and adaptation to the environment in cotton (Ghorbanzadeh *et al*., 2025; Jan *et al*., 2022). Comparing gene expression between developmental stages and fiber quality variation among different genotypes reveals gene expression patterns and regulatory networks that can be associated with the initiation, elongation, and secondary wall thickening stages of fiber development (Jan *et al*., 2022; Khan *et al*., 2025). Combined proteomic and metabolomic analyses, along with genomics ("multi-omics") analysis, provide insight into the relation between enzymes, structural proteins involved in cell wall biosynthesis, and metabolites and their responses to stress, thus providing candidate genes and pathways for breeding and editing (Ghorbanzadeh *et al*., 2025; Jan *et al*., 2022). High-throughput phenotyping coupled with multi-omic integration is used to create and simulate a digital "ideotype" fibre under different climates (Ghorbanzadeh *et al*., 2025).

Genetic Regulation of Fiber Development

The initiation and elongation of cotton fibers are regulated by large gene networks and hundreds of QTLs, with cotton fibers being single cells from the epidermis of the ovule (Jan *et al*., 2022; Zhai *et al*., 2023). Variation in fiber length and strength has been associated with genes that are part of the cytoskeleton organization, cell expansion, and secondary wall deposition (Jan *et al*., 2022). Multiple phytohormones, such as brassinosteroids, are involved in the regulation of initiation and elongation of fibre cells at low concentrations, and genes involved in biosynthesis and signalling pathways have been identified to modulate fibre development (Jan *et al*., 2022; Qanmber *et al*., 2024). Brassinosteroids in particular form a well-studied signaling cascade with other pathways that regulate cell elongation and wall mechanics during fiber growth, with biosynthetic enzymes, receptors, kinases, and transcription factors all interacting with one another and other pathways (Qanmber *et al*., 2024). Omics research has uncovered numerous genes involved in cell wall biosynthesis pathways, including those for cellulose and matrix polysaccharide synthesis and remodeling, that are well-integrated into the suite of genes for hormonal and transcriptional regulation and are excellent targets for gene discovery and precision breeding for increased fiber strength and fineness (Ghorbanzadeh *et al*., 2025; Jan *et al*., 2022) (Table 2).

Table 2 : Largest Table: Genetic Tools and Their Roles in Cotton Fiber Quality

Approach / Tool	Main role in fiber quality improvement	Citations
Marker-assisted & genomic selection	Track QTL and genome-wide variants; design ideotypes combining yield and quality.	(Ghorbanzadeh *et al*., 2025; Jan *et al*., 2022; Khan *et al*., 2025)
CRISPR/Cas and advanced editing	Precisely modify fiber-development genes for length, strength, and resilience.	(Ghorbanzadeh *et al*., 2025; Qanmber *et al*., 2024)

Agronomic Perspectives for Fiber Quality Enhancement

Nutrient Management

Nitrogen, phosphorus, and potassium are the three elements that are essential for sustaining cotton growth, but their role in production. Nitrogen requirements are well understood, and inadequate nitrogen supplies are responsible for reduced growth and boll set; however, excessive N use can result in reduced lint yield, lint quality, and N use efficiency, making correct N rate, source, timing, and method critical to profit from optimal lint yield and acceptable fibre properties (Van Der Sluijs, 2022; Shah *et al*., 2022). N–P–K programs need to be adjusted according to soil moisture status, as phosphorus and potassium facilitate root growth, energy metabolism, and osmotic balance, and this deficiency is exacerbated by drought, and drought alone can cause an impairment of N and P uptake, causing ionic imbalance and membrane damage (Shah *et al*., 2022). The micronutrients (boron, iron, manganese, and zinc) are all essential for photosynthesis and hormone signaling, boll retention, and cell wall integrity, and deficiencies can greatly impact the quality of the fibre even if macronutrients are sufficient (Arinaitwe *et al*., 2026). Balanced fertilization is thus a combination of nutrients N–P–K, alongside some essential micronutrients, and focuses on nutrient use efficiency rather than high nutrient doses, knowing when and how much of the nutrients are required by the crop, and how much will be available in the water (Van Der Sluijs, 2022; Shah *et al*., 2022; Arinaitwe *et al*., 2026) (Table 3).

Table 3 : Key Agronomic Levers for Fiber-Relevant Physiology

Management area	Main roles for fiber-related performance	Notes for cotton systems	Citations
Nutrient supply (N, P, K + micronutrients)	Supports canopy, boll load, photosynthesis, and cell-wall formation; over- or under-supply of N can lower lint yield and quality; micronutrients (B, Fe, Mn, Zn) sustain boll retention and fiber development.	Focus on N use efficiency; correct hidden micronutrient deficiencies to close yield and fiber-quality gaps.	(Van Der Sluijs, 2022; Shah *et al*., 2022; Arinaitwe *et al*., 2026)
Water and irrigation (incl. deficit)	Determines nutrient transport, boll filling, and micronaire; moderate deficit irrigation can save water, but severe stress shortens and weakens fibers.	Local calibration of the deficit level and irrigation termination is essential to avoid fiber-quality penalties.	(Koudahe *et al*., 2021)

Irrigation and Water Management

The relatively drought-resistant nature of cotton allows deficit irrigation to be used to reduce water use without affecting yield, with water stress in the growing season usually resulting in lower micronaire (Koudahe *et al*., 2021) and shorter, weaker fibers. The water use efficiency and the fiber response are dependent on climate, cultivar, and irrigation method, and local crop coefficients and site-specific deficit levels are required (Koudahe *et al*., 2021). Precision irrigation (drip or mulched drip irrigation and evapotranspiration or soil moisture scheduling) increases water efficiency, leading to better water distribution, matching water demand with crop demand, and can lead to better fiber quality while decreasing the overall amount of water used and energy inputs (Vitale *et al*., 2024; Koudahe *et al*., 2021).

Plant Density and Crop Geometry

Canopy microclimates, light distribution, and boll distribution are greatly influenced by plant density. A high or low population rate will result in a reduction in yield, and the best density will depend on the location, while the quality of the fibre varies in response to different population rates and different stresses, which affect the boll position. High-density planting systems (HDPS) can facilitate mechanical harvesting and promote weed suppression due to quick canopy closure, but might worsen soil moisture stress and be advantageous for certain pests and diseases; careful row spacing, fertilizer adjustment, and canopy management are essential to account for this (Vitale *et al*., 2024).

Plant Growth Regulators

Growth retardants like mepiquat chloride have been extensively incorporated into HDPS cotton to manage excessive vegetative growth, improve canopy structure, and maintain early boll retention, which helps to ensure yield and lint quality in dense stands and when water supplies vary from year to year (Vitale *et al*., 2024; Liu *et al*., 2025). At a broader level, plant growth regulators interact with the endogenous hormones under stress and affect root growth and flowering, as well as partitioning assimilates and their utilization in the plant, which in turn can affect boll size, boll retention, and fiber development (Sodhi *et al*., 2025; Liu *et al*., 2025).

Weed, Pest, and Disease Management

Biotic stresses can result in a decrease in photosynthetic area, disruption of source–sink relationships, and boll shed, which can have a negative effect on lint yield and fiber quality. Denser canopies may be preferred by a specific pest and/or disease issue in HDPS that will necessitate Integrated Pest and Weed Management (IPWM) with competitive canopies, crop rotation, and targeted chemical and biological control to ensure yield and fiber properties are maintained (Vitale *et al*., 2024).

Environmental and Climate Effects on Fiber Quality

Plant growth and development of cotton fiber are highly influenced by environmental and climatic factors, including temperature, water availability, and salinity, affecting significant fiber characteristics like fiber length, fiber strength, fiber fineness, and micronaire. With the continuous change in climatic conditions, high fiber quality will become a challenge in the future due to more frequently occurring heat waves, droughts, and soils affected by salt (Abro *et al*., 2023; Saini *et al*., 2023) (Figure 2).

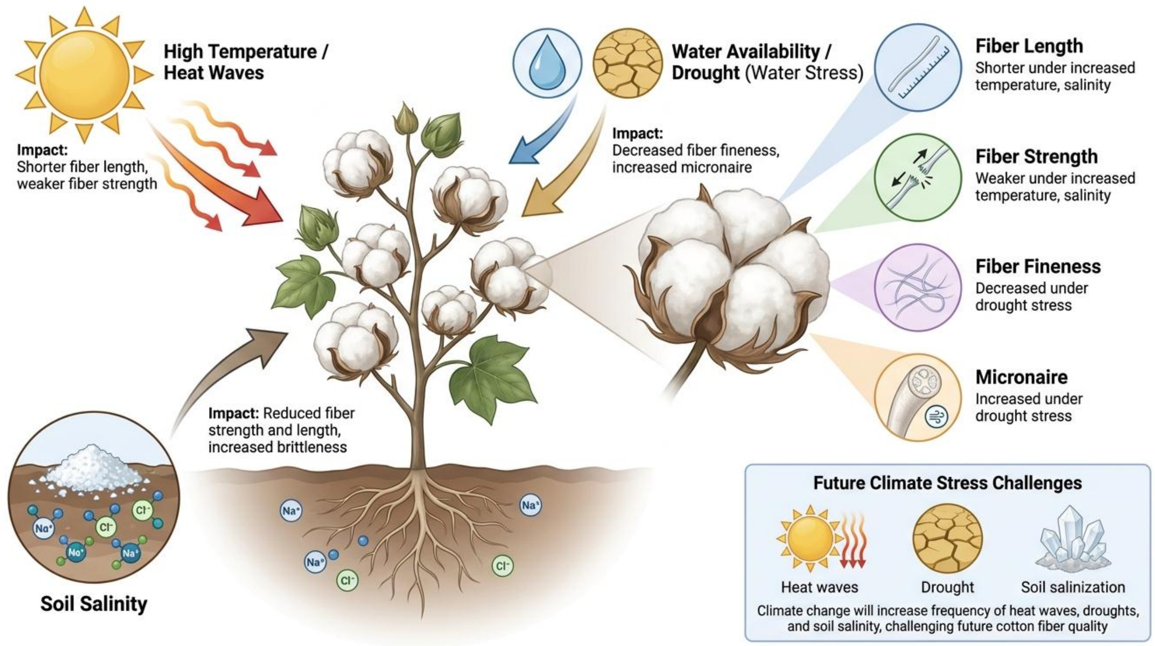

Fig. 2 : This graph illustrates how the stresses of climate change (high temperatures, drought, salinity) affect cotton fiber quality. These stresses have a negative impact on important fiber characteristics such as fiber length, strength, fineness, and micronaire, which are important to cotton productivity and quality in the future climate scenario.

Photosynthesis, stomatal conductance, membrane integrity, and carbohydrate supply are essential for fiber elongation and secondary cell wall formation and are affected by temperature stress (particularly high temperatures in flowering and boll development) (Abro *et al*., 2023; Saini *et al*., 2023). Heat stress decreases the amounts of cellulose and alters the biochemical composition of fiber "juice" (phosphorus, soluble proteins, lactate), resulting in shorter, weaker fibers and degradation of properties like width, resilience, elongation, and micronaire (Abro *et al*., 2023). Fiber consistency and micronaire are best at around 16 °C, while fiber strength is best at 18–22 °C, and fiber production can decrease by up to 110 kg ha^{-1} at temperatures significantly higher than these ranges (30–35 °C) (Abro *et al*., 2023).

The effects of drought and salinity, also frequently co-occurring with heat, are additional and further degrade fiber traits by their effect on plant water status and photosynthetic capacity. Drought causes a decrease in stomatal conductance, photosynthesis, leaf water potential, and assimilate supply, growth suppression, boll number, and lint yield, and is explicitly reported to affect fiber quality of cotton (Saini *et al*., 2023). When the combined effect of elevated temperature and drought occurs during the fiber thickening stage, fiber biomass accumulation and cellulose synthesis are adversely affected, reducing fiber length, sometimes impacting cultivar and environment-dependent fiber strength and micronaire (Saini *et al*., 2023). Salinity mainly affects the partitioning of photoassimilates into bolls, photosynthesis, and leaf area, which indirectly decreases photoassimilates available for fibre development and hence reduces yield and quality (Saini *et al*., 2023).

Changing precipitation patterns, including higher frequency and intensity of heat stress, drought, waterlogging, and salinity, are expected to affect cotton production and fiber quality all over the world (Saini *et al*., 2023). Stress on fiber formation will be exacerbated by high temperatures for long periods of time, which will cause irreversible damage to cellulose and repeated water shortages and soil salinization (Saini *et al*., 2023). Preserving future fiber quality will thus rely on the combination of climate-informed breeding (genomic selection and genome editing to create more heat and drought and salinity stress-resilient crop plants) with agronomic practices that reduce impacts from heat, drought, and salinity on photosynthesis, carbohydrate supply, and cellulose deposition in developing fibers, while maintaining as much stability in these processes as possible in the face of increasingly variable climate (Abro *et al*., 2023; Saini *et al*., 2023).

Precision Agriculture and Modern Technologies

Precision agriculture and modern digital tools are changing the way cotton is grown by providing finescale water, nutrient, and crop protection management, while maintaining or enhancing lint and fiber quality and yield. In arable crops, the trend of transitioning from common field management to making decisions at the plant or zone level is being applied and is directly applicable to cotton systems (Miller *et al*., 2025; Mansoor *et al*., 2025). Sensor-based systems take advantage of in situ soil and plant sensors, weather data, and, in some cases, UAV or satellite imagery to measure spatial and temporal variability in the crop water and nutrient requirements and then use that information to manage nutrients and irrigation. Automated drip irrigation or variable rate irrigation systems utilize real-time soil moisture measurements and AI analytics to deliver "the exact amount of water required" to enhance water use efficiency and ensure crop resilience under water-limited conditions (Miller *et al*. 2025). Likewise, smart dispensers for fertilizers analyze soil nutrients and soil growth models and adapt nutrient application to the current growth needs of the plants, avoiding over-fertilization and reducing losses to the environment (Miller *et al*., 2025). Implementing these systems around certain critical periods, like the squaring and boll-filling stages, may help to ensure consistent boll retention and fiber development in cotton under changing circumstances. Crop growth and, indirectly, fiber quality are monitored by the use of AI and remote sensing. Spectral, multispectral, and hyperspectral imagery captured by UAVs and satellites can be used with deep learning models to quantify plant-level metrics of plant vigor, stress, and canopy structure, which thereby allow for targeted irrigation, fertilization, and pest management to optimize both lint quality and yield (Yang *et al*., 2025; Miller *et al*., 2025). Deep learning has also been applied in the cotton value chain to classify fibers and evaluate their quality, which helps to ensure greater uniformity in ginning and provide feedback to the farms (Yang *et al*., 2025). Smart cotton farming technologies are based on IoT-based production systems with a distributed network of sensors (soil moisture, climate, nutrients, pests, etc.) that are connected to a wireless network and then sent to cloud or edge platforms for analysis and control actions. IoT and AI in agriculture reviews highlight the implementation of sensor networks, drones, and automated systems for real-time sensing and decision-making regarding irrigation, fertilization, and pest management, thereby minimizing resource consumption and enhancing sustainability (Miller *et al*., 2025; Mansoor *et al*., 2025). These architectures are also prevalent in cotton for "intelligent irrigation" and selective spraying, and for pest and disease identification, yield estimation, and quality evaluation (Yang *et al*., 2025). Despite these advancements, smart cotton cultivation in a wide range of production areas continues to face numerous barriers, such as high infrastructure and data annotation expenses, connectivity limitations, a lack of generalization in models across different environments, and data privacy and governance concerns that need to be overcome to scale this approach (Yang *et al*., 2025; Miller *et al*., 2025).

Sustainable Approaches for Fiber Quality Improvement

Sustainable ways of enhancing cotton fiber quality involve minimizing environmental effects and optimizing lint quality via system, management, and breeding processes. This trend in the cotton chain has been a movement towards organic, climate-smart, and conservation-oriented systems of cultivation, with policy and innovation incentives (Tlatlaa *et al*., 2023; Xing & Wang, 2024). Despite being water and labour-intensive and only accounting for a small proportion of cotton area globally, organic and eco-friendly cotton production utilises organic inputs and ecological pest management, which can significantly decrease land and freshwater ecotoxicity, CO_2 emissions, and the amount of synthetic fertilizers used compared to conventional cotton and can be valuable benchmarks for sustainability (Xing & Wang, 2024). Adopting conservation agriculture and other conservation management practices like minimum and no tillage, controlled traffic farming, and optimized cropping calendars can lower the rate of greenhouse gas emissions, soil erosion, and nutrient loss; build soil organic matter; and enhance resource use efficiency, thus promoting long-term soil health and stable fiber production (Xing & Wang, 2024) (Figure 3).

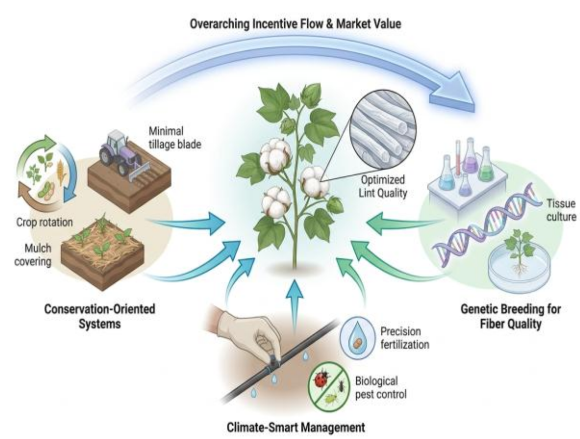

Fig. 3 : The diagram represents an integrated approach to enhancing the quality of cotton fibers by implementing the following practices: implementing conservation farming practices, adopting climate-smart farming methods, and using improved genetic breeding. These methods are all designed to improve the quality of the lint, make the crop more sustainable, and make cotton more profitable.

This can be expanded to include coordinated decisions regarding variety choice, sowing time, soil management, fertilization, irrigation efficiency and pest and weed management, as reviewed in the sustainable cotton in smallholder systems, with rotation and intercropping with early maturing food crops being promising methods to drive technology adoption and resilience, but in need of institutional support, extension services and climate resilient practices (Tlatlaa *et al*., 2023). The challenges are compounded by sustainable breeding strategies that aim to develop cultivars with greater resistance to pests and diseases, tolerance to water shortages, and resilience to changing climates, more suitable to reduced use of chemicals, conservation tillage and variable climates, and by policy recommendations that call for investments in research and development for the production of cultivars that are resistant to pests and diseases and resilient to climate change, while supporting the adoption of innovative and sustainability-focused farming technologies as key drivers for environmental protection and competitive cotton quality (Tlatlaa *et al*., 2023). Organic and eco-friendly systems, conservation agriculture, integrated crop management, and sustainability-focused breeding are complementary systems to enhance cotton fiber production using a reduced ecological footprint.

Challenges and Future Perspectives

While the quality of cotton fibers is a complex genetic, environmental, and technological issue, recent developments in genomics, biotechnology, and digital agriculture provide potential avenues for more sustainable, high-quality cotton systems. Cultivar selection and prediction of superior cultivars for future changing climates are complicated by high polygenicity and G×E interactions for fiber yield, fiber properties, and tolerance to stress (Ghorbanzadeh *et al*., 2025; Khan *et al*., 2025). In cotton, genome-wide association studies reveal that fiber traits are polygenetic (many genes) and polyenvironmental (many environments) to some extent, with thousands of SNPs associated over a range of environments and many of these being under strong positive selection, indicating a potential for genetic erosion through breeding efforts in the past (Yasir *et al*., 2022). The molecular and omics studies have revealed that hundreds of genes and QTL are involved in fiber initiation, elongation, and secondary wall biosynthesis, but only a few account for the observed variation, suggesting that there is still some “missing heritability” and these genes may exhibit pleiotropy and gene–gene or gene–environment interactions (Yasir *et al*., 2022; Jan *et al*., 2022). Climate change exacerbates these issues, with increased heat, changing precipitation patterns, and more extreme weather events (such as heat, drought, waterlogging, and salinity) all affecting the yield and quality of cotton fibers, so climate-resilient varieties of cotton are of importance (Khan *et al*., 2025). Genomic selection, marker-assisted selection, genome editing, and integration of multi-omics, along with high-throughput phenotyping and climate-informed breeding, are key strategies highlighted in reviews to improve stress resilience while maintaining fiber traits (Ghorbanzadeh *et al*., 2025; Khan *et al*., 2025). The future holds promise for a wider application of biotechnology and digital agriculture: targeted improvement via precision genome editing (CRISPR, engineering base and prime), pan-genomics and functional genomics; and digital tools like high throughput field phenotyping, machine learning and the “digital twins” that combine genomic, phenomic and environmental data to pre-design, simulate, and manage climate smart cotton ideotypes before deployment to large-scale fields (Ghorbanzadeh *et al*., 2025). To achieve this vision, the need exists for interoperable data systems as well as available infrastructure for resource-limited breeding programs, and science-based regulatory and policy frameworks that enable advanced biotechnologies and digital decision-support systems to be implemented equitably and widely at scale (Ghorbanzadeh *et al*., 2025; Khan *et al*., 2025).

Conclusion

The quality of cotton fiber is a key factor in the performance of cotton-based industries, the competitiveness of cotton in the market, and sustainability. Thus, it is necessary to improve fiber quality to improve the performance of the cotton textile industry. The present review emphasizes that some quality attributes of the fibre, such as length, strength, fineness, and uniformity, are complex traits and highly responsive to environmental and agronomic conditions. The application of conventional breeding, marker-assisted selection, genomic approach, genome editing technology, and omics approach has made remarkable strides in developing superior cotton cultivars with enhanced fiber quality. Meanwhile, agronomic practices, such as balanced nutrient management, precision irrigation, optimized planting density, plant growth regulators, and pest and weed management, are also playing pivotal roles in maximizing the quality of fiber in various production environments. To achieve stable fiber quality in the future while retaining high productivity and environmental sustainability, integration of genetic and agronomic approaches is essential. Economic profitability is not just an objective of sustainable cotton quality improvement; it is also about using resources efficiently and growing cotton in a more climate-resilient way, thus minimizing the environmental impacts. Precision Agriculture, artificial intelligence, molecular breeding, and climate-smart management strategies should be the future focus of cotton production systems to develop high-quality and stress-tolerant cotton varieties. Enhancing multi-disciplinary research and sustainable farming innovations will play an important role in maintaining sustainable productivity, quality of fiber, and future demands of the textile industry.

References

Abro, A. A., Anwar, M., Javwad, M. U., Zhang, M., Liu, F., Jiménez-Ballesta, R., Salama, E. a. A., and Ahmed, M. a. A. (2023). Morphological and physio-biochemical responses under heat stress in cotton: Overview. *Biotechnology Reports*, **40**, e00813. https://doi.org/10.1016/j.btre.2023.e00813

Arinaitwe, U., Yabwalo, D. N., Hangamaisho, A., Kwikiiriza, S., and Akitwine, F. (2026). Advances in boron, iron, manganese, and zinc signaling, transport, and functional integration for enhancing Cotton Nutrient Efficiency and Yield A review. *International Journal of Plant Biology*, **17**(1), 7. https://doi.org/10.3390/ijpb17010007

Ghorbanzadeh, Z., Panahi, B., Purhang, L., Panahi, Z. H., Zeinalabedini, M., Mardi, M., Hamid, R., and Ghaffari, M. R. (2025). Integrative Genomics and Precision Breeding for Stress-Resilient Cotton: Recent advances and Prospects. *Agronomy*, **15**(10), 2393. https://doi.org/10.3390/agronomy15102393

Jan, M., Liu, Z., Guo, C., and Sun, X. (2022). Molecular Regulation of Cotton Fiber Development: A review. *International Journal of Molecular Sciences*, **23**(9), 5004. https://doi.org/10.3390/ijms23095004

Khan, M. A., Anwar, S., Abbas, M., Aneeq, M., De Jong, F., Ayaz, M., Wei, Y., and Zhang, R. (2025). Impacts of climate change on cotton production and advancements in genomic approaches for stress resilience enhancement. *Journal of Cotton Research*, **8**(1). https://doi.org/10.1186/s42397-025-00223-3

Koudahe, K., Sheshukov, A. Y., Aguilar, J., and Djaman, K. (2021). Irrigation-Water Management and Productivity of Cotton: A review. *Sustainability*, **13**(18), 10070. https://doi.org/10.3390/su131810070

Liu, X., Wang, Y., Du, M., Li, F., Tian, X., and Li, Z. (2025). Mepiquat chloride-driven regulation in cotton in China: a review of physiological mechanisms, agronomic integration, and future trajectories. *Journal of Cotton Research*, **8**(1). https://doi.org/10.1186/s42397-025-00243-z

Mansoor, S., Iqbal, S., Popescu, S. M., Kim, S. L., Chung, Y. S., and Baek, J.-H. (2025). Integration of smart sensors and IOT in precision agriculture: trends, challenges and future prospectives. *Frontiers in Plant Science*, **16**, 1587869. https://doi.org/10.3389/fpls.2025.1587869

Miller, T., Mikiciuk, G., Durlik, I., Mikiciuk, M., Łobodzińska, A., and Śnieg, M. (2025). The IoT and AI in Agriculture: The Time Is Now A Systematic Review of Smart Sensing Technologies. *Sensors*, **25**(12), 3583. https://doi.org/10.3390/s25123583

Qanmber, G., Liu, Z., Li, F., and Yang, Z. (2024). Brassinosteroids in cotton: orchestrating fiber development. *New Phytologist*, **244**(5), 1732–1741. https://doi.org/10.1111/nph.20143

Saini, D. K., Impa, S. M., McCallister, D., Patil, G. B., Abidi, N., Ritchie, G., Jaconis, S. Y., and Jagadish, K. S. V. (2023). High day and night temperatures impact on cotton yield and quality—current status and future research direction. *Journal of Cotton Research*, **6**(1). https://doi.org/10.1186/s42397-023-00154-x

Sapkota, B. R., Adams, C. B., Kelly, B., Rajan, N., and Ale, S. (2022). Plant population density in cotton: Addressing knowledge gaps in stand uniformity and lint quality under dryland and irrigated conditions. *Field Crops Research*, **290**, 108762. https://doi.org/10.1016/j.fcr.2022.108762

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., and Jaremko, M. (2022). Nitrogen use efficiency in cotton: Challenges and opportunities against environmental constraints. *Frontiers in Plant Science*, **13**, 970339. https://doi.org/10.3389/fpls.2022.970339

Sodhi, G. K., Wijesekara, T., Kumawat, K. C., Adhikari, P., Joshi, K., Singh, S., Farda, B., Djebaili, R., Sabbi, E., Ramila, F., Sillu, D., Santoyo, G., De Los Santos-Villalobos, S., Kumar, A., Pellegrini, M., and Mitra, D. (2025). Nanomaterials–plants–microbes interaction: plant growth promotion and stress mitigation. *Frontiers in Microbiology*, **15**, 1516794. https://doi.org/10.3389/fmicb.2024.1516794

Tlatlaa, J. S., Tryphone, G. M., and Nassary, E. K. (2023). Unexplored agronomic, socioeconomic and policy domains for sustainable cotton production on small landholdings: a systematic review. *Frontiers in Agronomy*, *5*. https://doi.org/10.3389/fagro.2023.1281043

Van Der Sluijs, M. H. J. (2022). Effect of nitrogen application level on cotton fibre quality. *Journal of Cotton Research*, **5**(1). https://doi.org/10.1186/s42397-022-00116-9

Vitale, G. S., Scavo, A., Zingale, S., Tuttolomondo, T., Santonoceto, C., Pandino, G., Lombardo, S., Anastasi, U., and Guarnaccia, P. (2024). Agronomic Strategies for Sustainable Cotton Production: A Systematic Literature Review. *Agriculture*, **14**(9), 1597. https://doi.org/10.3390/agriculture14091597

Wu, M., Pei, W., Wedegaertner, T., Zhang, J., and Yu, J. (2022). Genetics, Breeding and Genetic Engineering to Improve Cottonseed Oil and Protein: a review. *Frontiers in Plant Science*, **13**, 864850. https://doi.org/10.3389/fpls.2022.864850

Xing, Y., and Wang, X. (2024). Precision Agriculture and water conservation strategies for sustainable crop production in arid regions. *Plants*, **13**(22), 3184. https://doi.org/10.3390/plants13223184

Yang, Z.-Y., Xia, W.-K., Chu, H.-Q., Su, W.-H., Wang, R.-F., and Wang, H. (2025). A comprehensive review of deep learning applications in cotton industry: from field monitoring to smart processing. *Plants*, **14**(10), 1481. https://doi.org/10.3390/plants14101481

Yasir, M., Kanwal, H. H., Hussain, Q., Riaz, M. W., Sajjad, M., Rong, J., and Jiang, Y. (2022). Status and prospects of genome-wide association studies in cotton. *Frontiers in*

Plant Science, **13**, 1019347. https://doi.org/10.3389/fpls.2022.1019347

Zhai, Z., Zhang, K., Fang, Y., Yang, Y., Cao, X., Liu, L., and Tian, Y. (2023). Systematically and Comprehensively Understanding the Regulation of Cotton Fiber Initiation: A review. *Plants*, **12**(21), 3771. https://doi.org/10.3390/plants12213771

Zhang, J., and Wedegaertner, T. (2021). Genetics and breeding for glandless upland cotton with improved yield potential and disease resistance: a review. *Frontiers in Plant Science*, **12**, 753426. https://doi.org/10.3389/fpls.2021.753426