PLANT SCIENCE TODAY
Vol 12(sp1): 01–14
https://doi.org/10.14719/pst.9908

eISSN 2348-1900

REVIEW ARTICLE

Breeding for coloured cotton for a sustainable environment: Progress and prospects

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Received: 08 June 2025; Accepted: 28 July 2025; Available online: Version 1.0: 26 September 2025

Cite this article: Aditi K, Nallathambi P, Alagesan S, Narayanan MB, Chitra N, Ritik R, Yash B, Vimal R VV. Breeding for coloured cotton for a sustainable environment: Progress and prospects. Plant Science Today. 2025;12(sp1):01–14. https:/doi.org/10.14719/pst.9908

Abstract

Coloured cotton has gained significant attention as an eco-friendly alternative to conventionally dyed cotton, offering a sustainable approach to textile production. This review explores recent advances and future prospects in the breeding of naturally coloured cotton, highlighting its role in promoting sustainability within the environment intensive textile industry with the specific objective of identifying genetic and biotechnological strategies that can overcome current agronomic and commercial limitations. Traditional and modern breeding techniques have been employed to enhance fibre quality, yield, and colour stability, accelerating the development of cultivars with improved agronomic traits and diverse pigmentation. Compared to conventional cotton, coloured cotton reduces water usage by up to 90% and eliminates the need for synthetic dyes, decreasing chemical pollution by approximately 85%. Despite these benefits, challenges such as limited fibre quality, lower yield potential, and market acceptance hinder its large-scale adoption. Future breeding strategies should prioritise overcoming these constraints by leveraging biotechnology, tapping into genetic diversity, and enhancing climate resilience. Advancing research in fibre enhancement, pigment stabilisation, and commercial viability will be crucial in establishing coloured cotton as a mainstream sustainable textile resource.

Keywords: climate resilience; coloured cotton; fibre quality; natural pigmentation; yield improvement

Introduction

Textile manufacturing contributes to approximately 20% of global industrial water pollution, largely due to untreated dye effluents discharge, and accounts for around 10% of global carbon emissions, more than the aviation and shipping sectors combined (1).

Synthetic dyes used in textiles release hazardous substances such as azo dyes, heavy metals, and formaldehyde, contaminating rivers and lakes, particularly in major textile-producing countries like China, India, and Bangladesh (2, 3). Over 70% of rivers in China are polluted by textile wastewater, rendering water unfit for consumption, while in India, textile hubs like Tirupur and Surat discharge large volumes of untreated dye effluents, significantly contaminating local water sources (4). Conventional cotton farming, while occupying just 2.5% of global agricultural land, consumes 16% of insecticides and 6% of pesticides worldwide, resulting in soil degradation, groundwater contamination, biodiversity loss, and health risks for farming communities. Water consumption is another critical issue. Dyeing and finishing textiles require 100–200 litres of water per kilogram of fabric, and producing one kilogram of cotton fabric can use up to 10,000 litres of water (5). This exacerbates water scarcity in drought-prone regions such as India's Punjab and China's Xinjiang province (4).

In response, naturally coloured cotton is gaining attention as an eco-friendly alternative. Unlike conventional white cotton, which requires chemical dyeing and bleaching, naturally coloured cotton grows in shades of brown, green, and reddish hues, eliminating the need for synthetic dyes (6).

The inherent pigmentation of coloured cotton can significantly reduce water consumption reportedly by up to 90% and eliminate the need for synthetic dyes, thereby preventing the discharge of toxic dye effluents. However, while such environmental benefits are promising, they are often based on estimations and lack robust, comparative Life Cycle Assessment (LCA) data (7).

Comprehensive LCA studies are essential to validate these claims and quantify the full environmental advantages of naturally coloured cotton across its entire production cycle. Naturally pigmented cotton also requires fewer chemical treatments, making it safer for both consumers and textile workers (8), and when grown organically, further reduces pesticide and fertilizer use. However, the adoption of naturally coloured cotton faces agronomic and market-related challenges that must be addressed through targeted breeding programs.

Consumer demand for sustainable textiles is rising rapidly, with the global sustainable fashion market projected to reach $15 billion by 2030. Demand for organic and naturally dyed textiles has surged by 45% in the past five years, driven by preferences for biodegradable, non-toxic, and ethically produced fabrics. Leading fashion brands such as Patagonia, Stella McCartney, and Levi's are incorporating naturally coloured cotton into their collections, reflecting the preferences of the 65% of millennials and Gen Z consumers who prefer eco-friendly clothing (9).

In summary, naturally coloured cotton offers a promising path toward sustainable textile production. Strategic breeding initiatives, coupled with collaboration among farmers, scientists, policymakers, and industry, stakeholders, can help overcome current limitations and establish coloured cotton as a mainstream, scalable solution.

Historical perspective

The history of naturally coloured cotton spans over 5,000 years, with its earliest cultivation traced to ancient civilisations. Archaeological finds in Central Coastal Peru reveal brown and reddish *Gossypium barbadense* fibres from around 2500 BCE, while textiles from Huaca Prieta in the Andes suggest the use of cultivated cotton as far back as 7,800 years ago (10,11). In South Asia, the Indus Valley Civilisation, particularly at Mohenjo-Daro and Harappa, integrated naturally coloured cotton into daily and ritual life (12). Similarly, ancient Egyptians used brown cotton in pharaonic textiles, and West African communities traditionally wove brown and green cotton into culturally significant fabrics.

Historically, naturally pigmented cottons were valued for their durability and aesthetic appeal, offering robust fibres without the need for dyeing. However, the rise of industrial textile production and colonial policies led to a preference for high-yield white cotton, displacing indigenous coloured varieties and reducing genetic diversity. This shift created breeding challenges that persist today, as naturally coloured cotton often has lower fibre quality and yields compared to high-yield white cotton (13).

Despite these obstacles, growing interest in sustainable textiles has renewed efforts to conserve and improve naturally coloured cotton. Modern breeding programs aim to enhance fibre properties while preserving natural pigmentation, supporting both environmental sustainability and the preservation of cultural heritage. Table 1 represents uses of naturally coloured cotton across different regions, showcasing its historical and cultural significance.

Industrialisation and global trade prioritised uniformity and large-scale production, making white cotton more commercially attractive due to its adaptability to mechanised dyeing processes and longer fibres, which were easier to spin and weave. Colonial powers and European textile industries promoted the mass cultivation of white cotton. In regions such as India, Africa, and China, colonial agricultural policies disrupted local economies by imposing foreign cotton varieties, resulting in a loss of genetic diversity and the marginalisation of indigenous farming practices.

Farmers were further incentivised to cultivate white cotton because of its higher yields, accelerating the transition away from naturally pigmented varieties. In China, for instance, this shift nearly drove traditional coloured cotton to extinction. As a result, many unique coloured cotton strains that once thrived in diverse cultures faded into obscurity. Only recently have conservation efforts and sustainable textile movements begun working to revive these ancient varieties, recognizing their ecological and cultural significance.

As awareness of sustainability grows, more consumers are choosing eco-friendly fashion, with studies showing that environmental consciousness directly influences purchasing decisions for naturally dyed clothing. Educational initiatives are also helping younger generations understand the environmental benefits of coloured cotton and encouraging more sustainable consumption habits. Innovations in textile embellishment techniques, such as tie-dye, have further enhanced the appeal of naturally pigmented cotton, allowing it to find a place in contemporary fashion while preserving its traditional essence. The increasing demand for ethical and environmentally responsible apparel reflects a broader shift in the fashion industry toward sustainability (6, 7, 9).

Origin and evolution

Naturally coloured cotton, with origins over 5,000 years ago in ancient South and Central America, Africa, and Asia, was domesticated by indigenous peoples who selectively bred varieties exhibiting natural pigments that produce fibres in shades of brown, green, red, and tan (16,17).

The expression and stability of these pigments are significantly influenced by environmental factors. Temperature, for instance, plays a key role in anthocyanin and tannin biosynthesis pathways, where higher day/night temperatures can reduce pigment intensity or alter hue uniformity**.** UV radiation has been reported to induce flavonoid accumulation, enhancing pigmentation but potentially affecting fibre development. Likewise, soil composition, particularly pH, micronutrients (e.g., Fe, Mn, Cu), and organic matter, can influence pigment expression by modulating enzymatic activities involved in phenolic and flavonoid biosynthesis.

Table 1. Uses of naturally coloured cotton across different regions, showcasing its historical and cultural significance

Region	Naturally Coloured Cotton Use	Cultural & Historical Significance	Reference
Peru	*Gossypium barbadense* cotton exhibits remarkable fibre colour variability.	Essential in traditional textile manufacturing for centuries; conservation efforts protect unique genetic varieties.	(13)
Asia (Shangjia ethnic group)	Cultivation of brown-coloured cotton.	Used primarily for mourning garments, signifying deep spiritual and cultural traditions.	(14)
Africa (Sotho-Tswana people)	Coloured cotton integrated into textile traditions.	Specific hues reflect community values and social identity.	(15)
Peru (archaeological discoveries)	Evidence of cultivated cotton use dating back over 7,800 years.	Highlights the long-standing importance of naturally coloured fibres in indigenous communities.	(11)

These environmental variables not only impact the intensity and uniformity of colour but may also affect fibre quality traits such as fineness, elongation, and strength, due to trade-offs in metabolic allocation between pigment production and fibre development. Therefore, understanding and optimising agro-environmental conditions is crucial for maintaining colour consistency and fibre performance in coloured cotton cultivation. (18). Table 2 shows the comparative analysis of coloured cotton and conventional white cotton.

Throughout history, naturally coloured cotton has been valued for its unique aesthetic and practical qualities. During periods of dye shortages, such as World War II, the use of naturally coloured cotton increased due to its inherent hues, reducing the need for synthetic dyes (19). In recent decades, breeders and innovators have worked to improve fibre quality and expand the colour range, supporting a resurgence of interest in these sustainable and historically significant cotton varieties (20,21).

The colour of naturally pigmented cotton is genetically determined by specific genes, often recessive, that regulate pigment production. MYB transcription factors play a key role in activating or suppressing enzymes responsible for colour formation; genes in the flavonoid biosynthesis pathway are more active in coloured cotton than in white cotton, resulting in stronger pigmentation (22). Modern genetic improvements in naturally coloured cotton which originates from wild species of the *Gossypium* genus such as *G. hirsutum*, *G. arboreum*, and *G. herbaceum*, domesticated since the fourth millennium BCE in regions like South Asia aim to enhance fibre colour intensity, stability, and quality through techniques like selective breeding, hybridisation, gene editing (CRISPR-Cas9) and genomic selection.

Centuries of selective breeding have improved pigmentation and fibre traits, and current breeding programs in China, India and the United States use advanced genetic studies, including Genome-Wide Association Studies (GWAS), to boost fibre yield, colour intensity and resistance to environmental stresses, transforming cotton breeding through biotechnology and genomics. However, coloured cotton typically suffers a 50-70% yield penalty compared to white cotton cultivars. This substantial reduction in yield is largely attributed to the pleiotropic effects and genetic linkage drag associated with pigmentation genes (23).

Many of the natural pigment-producing genes are closely linked with loci that negatively affect fibre development and boll size, leading to reduced lint yield. Additionally, metabolic resources in coloured cotton plants are often diverted toward pigment biosynthesis such as flavonoids, tannins, and quinones, at the expense of fibre elongation and cellulose deposition. Moreover, due to limited breeding focus and the narrow genetic base of coloured cotton germplasm, these varieties generally lack the heterosis, vigour, and high-performing traits observed in commercially cultivated white cotton hybrids. (24). Fig.1 represents Advancements in Cotton Genomics and Breeding Strategies.

Naturally coloured cotton faces challenges due to its shorter fibre length, lower tensile strength, and 50-70% lower yields compared to white cotton, limiting its industrial and economic viability. This significant yield penalty is primarily due to genetic linkage drag, where genes responsible for pigment production are tightly linked to loci that negatively influence fibre development and boll size. Additionally, the metabolic cost of pigment biosynthesis diverts energy and resources from fibre growth, further reducing yield. The limited availability of high-yielding coloured cotton cultivars and the lack of intensive breeding for yield traits have also contributed to this productivity gap (18,24). Market competition from consistently coloured, mass-produced synthetic fabrics further restricts its appeal (25). Additionally, regulations to prevent contamination of white cotton fields create barriers for farmers (19). Despite environmental benefits and rising demand for sustainable textiles, these factors hinder the widespread adoption of naturally coloured cotton.

Table 2. Comparative Analysis of Coloured Cotton and Conventional White Cotton

Trait / Feature	Coloured Cotton	White (Conventional) Cotton	Reference(s)
FibreColour	Naturally pigmented (e.g., brown, green, reddish)	Requires synthetic dyes for colouration	(18)
FibreQuality	Lower strength and length; often coarser	Higher strength, uniformity, and fineness	(18)
Yield Potential	30-70% lower yield due to pigment-related gene linkage drag	High-yielding varieties available	(18)
Genetic Diversity	Limited number of improved cultivars	Broad genetic base; many commercial hybrids and varieties	(18)
Input Requirements	Low; less fertiliser and pesticide use in some cases	Moderate to high, depending on variety and system	(18)
Water Use	Potentially lower due to reduced processing steps (e.g., dyeing)	Higher due to cultivation and industrial dyeing processes	(18)
Environmental Impact	Lower-eliminates the need for chemical dyes and reduces pollution	High-dyeing and finishing processes cause water and soil contamination	(18)
Processing Requirements	Minimal; no dyeing or bleaching required	Extensive processing and chemical treatment are needed	(18)
Market Acceptance	Niche eco-conscious market; demand increasing	Well-established global market	(18)
Economic Value	Currently lower, but premium price possible with certifications (e.g., organic)	Economically dominant with mature supply chains	(18)
Breeding Challenges	Yield and fibre quality improvement without compromising colour	Focus on stress resistance, fibre quality, and yield	(18)
Pigment Stability	May vary with environmental conditions (UV, soil, temperature); colour may change after washing	Uniform white fibre	(18)

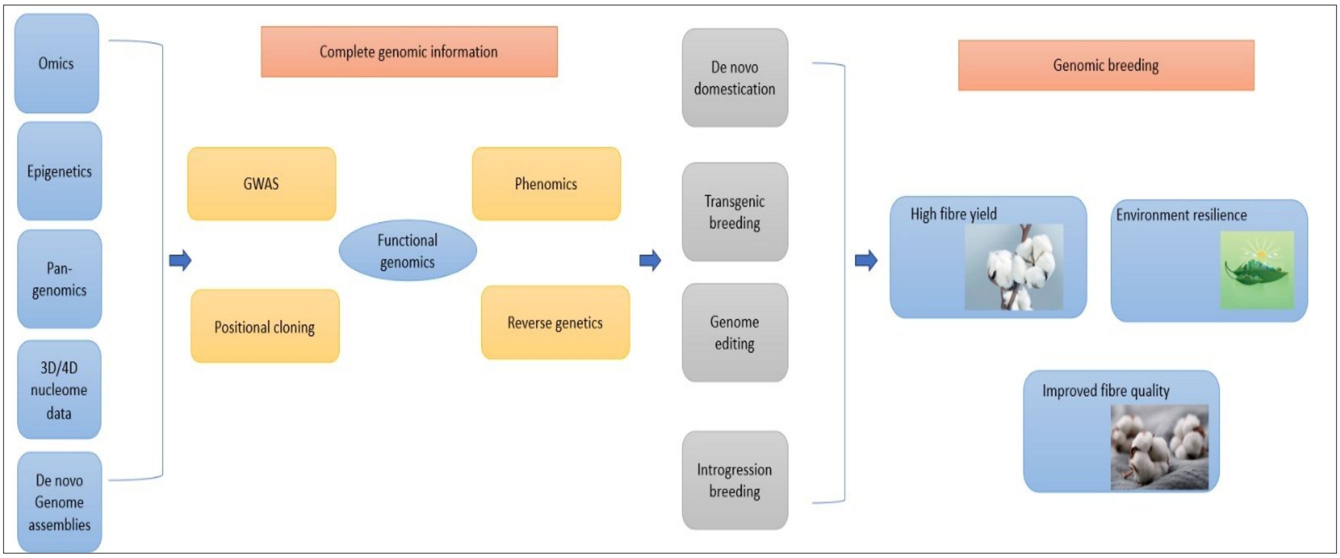

Fig. 1. Advancements in cotton genomics and breeding strategies.

Advancements in molecular breeding and genetic engineering have significantly improved the fibre quality, yield, and colour consistency of naturally coloured cotton. Techniques such as quantitative trait loci (QTL) mapping and transcriptome analysis have enabled researchers to identify and enhance key traits (26). Through interspecific and intraspecific crosses, stable genotypes with superior fibre quality and uniform colouration have been developed (27).

Ongoing research aims to broaden the natural colour palette of cotton while also improving pest resistance and environmental adaptability. Molecular markers and specific gene expressions have been linked to the stability of fibre colour and quality (28). Advanced genetic engineering methods, including CRISPR and RNA interference, are being used to enhance fibre properties without sacrificing yield (29). Further studies on fibre-specific gene expression and promoter functions are providing insights for improving cotton traits at the molecular level, supporting the development of varieties with greater resilience to environmental stress (30).

These scientific advancements are paving the way for more sustainable, high-quality, and commercially viable naturally coloured cotton. By leveraging genomic tools and targeted breeding strategies, researchers can continue to enhance fibre yield, quality, environmental resilience, and the unique traits that make coloured cotton valuable in the textile industry. Comparative analysis of coloured and white cotton

Coloured cotton and conventional white cotton differ significantly in terms of fibre characteristics, agronomic performance, environmental impact and market acceptance. The most obvious distinction lies in fibre pigmentation: coloured cotton produces naturally pigmented fibres in shades of brown, green and reddish tones, whereas white cotton requires synthetic dyeing, contributing to greater chemical usage during processing. However, coloured cotton typically suffers from lower fibre quality, including shorter length and reduced tensile strength, which limits its suitability for high-end textile manufacturing without further genetic improvement.

Yield is another major constraint in coloured cotton, with reported reductions of 30-70% compared to conventional cultivars. This is largely attributed to genetic linkage drag, where genes responsible for pigment biosynthesis are closely associated with traits negatively affecting boll size and lint output. In addition, the breeding focus for coloured cotton has historically been limited, resulting in a narrower genetic base and fewer high-yielding, improved cultivars. In contrast, white cotton benefits from decades of intensive breeding, leading to a broader genetic pool, numerous commercial hybrids, and higher levels of stress resilience and productivity.

From an environmental standpoint, coloured cotton holds distinct advantages. It eliminates the need for synthetic dyes and extensive finishing processes, reducing water usage and chemical runoff. Some studies suggest that the overall environmental footprint of naturally pigmented cotton is considerably lower, especially when combined with organic farming practices. Input requirements such as fertiliser and pesticide usage are also reported to be lower in coloured cotton, although this may vary by genotype and growing conditions.

Economically, white cotton dominates global markets due to its scalability, established supply chains, and consistent quality. However, consumer demand for sustainable and eco-friendly textiles is opening niche markets for coloured cotton, especially when certified under schemes such as GOTS, OEKO-TEX®, or Fair Trade. Despite its lower current market value, coloured cotton has potential for premium pricing, particularly when marketed as part of sustainable fashion lines. Bridging the gap between ecological benefits and agronomic shortcomings through advanced breeding tools remains essential for the future of coloured cotton.

Cotton Processing and Manufacturing

The journey from cotton fields to fabric involves several key stages. First, ginning separates the fibres from the seeds. Next, the fibres are spun into yarn through the spinning process. This yarn is then transformed into fabric by weaving or knitting. Finally, dyeing and finishing techniques are applied to enhance the aesthetics and functionality of the textiles.

Fibre quality parameters

Coloured cotton fibres are generally shorter than white cotton fibres, with brown-fibred varieties having longer fibres than green ones due to slower early fibre development (31). Breeding for longer fibres while maintaining colour intensity is challenging, as flavonoid accumulation responsible for pigmentation can interfere with cellulose synthesis and fibre growth (32). Although fibre length, strength, and micronaire are highly heritable, balancing these qualities with pigmentation requires careful genetic selection. Application of plant growth regulators like gibberellic acid (GA3) has shown promise in enhancing fibre elongation without compromising colour, but achieving optimal fibre length and colour intensity remains a major challenge for breeders (33). Fig. 2 represents Key Fibre Quality Traits in Cotton.

Pigmentation and colour stability traits

Natural fibre pigmentation in cotton varies widely due to genetic factors. Flavonoid biosynthesis is central to determining fibre colour, and genetic modifications can improve colour stability and intensity across generations (34). However, maintaining colour stability is challenging, as factors like UV exposure and laundering can cause significant pigment loss; for example, green cotton fibres lose much of their radical scavenging capacity and fade noticeably after repeated alkaline washing (35). Breeding strategies focus on selecting genes involved in flavonoid and phenolic compound synthesis to enhance pigment retention and colour stability, while also increasing resistance to environmental stress (36). These compounds not only provide colour but also contribute to the structural integrity, antioxidant and antimicrobial properties of the fibres (34,36).

Continued advancements in breeding and fibre processing are essential for developing naturally coloured cotton fibres with improved durability and functional properties, supporting their use as sustainable textile materials (37).

Naturally coloured cotton varieties, such as brown and green types, have historically produced lower yields and inferior fibre quality compared to white cotton, mainly due to lower cellulose content and limited fibre elongation (38). Recent breeding advancements, especially in China, have narrowed this gap, with hybrid techniques and the use of eco-friendly fertilisers further improving productivity and fibre quality (39).

Compact plant types are now favoured for efficient mechanical harvesting and better boll retention (40), though a decline in public breeding programs raises concerns about genetic diversity (41). Maturity duration is also important; breeding efforts now focus on early-maturing varieties to suit diverse cropping systems and climates (42).

Overall, advances in breeding and agronomy have improved the yield, fibre quality, and adaptability of coloured cotton, making it a more viable and sustainable alternative to conventional white cotton.

Biotic and abiotic stress resistance traits

Genetic improvement in coloured cotton starts with extensive germplasm screening to identify and integrate traits such as superior fibre quality, higher yields, and resilience to environmental stress. By tapping into the genetic diversity of *Gossypium spp.*, including wild relatives, breeders introduce valuable variations that strengthen breeding programs and support long-term crop improvement (43). A major advancement in cotton breeding is the identification of quantitative trait loci (QTLs) and the application of marker-assisted selection (MAS). These molecular techniques, using markers like SSRs and SNPs, allow breeders to efficiently track and incorporate beneficial traits, accelerating the development of improved cultivars (44). Table 3 represents biotic and abiotic stress-resistant traits in cotton

Modern genetic engineering and molecular breeding have also pinpointed specific genes and pathways that enhance resistance to pests, diseases, and environmental stresses. These innovations are vital for creating resilient, high-performing cotton varieties that support sustainable and productive cultivation (45).

Germplasm screening is essential not only for improving fibre quality but also for developing stress-resistant cotton varieties (46). Studies have shown that selecting for traits like root length, shoot growth, and biomass accumulation enables breeders to identify and develop salt-tolerant cotton plants suited for saline environments (47). With rising demand for high-quality textiles, breeding programs are also enhancing fibre length, strength, and fineness by introducing beneficial alleles from wild cotton species and using marker-assisted selection (48).

Advances in biotechnology, including transgenic methods and genome editing tools like CRISPR/Cas9, have accelerated cotton breeding by enabling the precise introduction of genes that improve fibre characteristics and stress resistance (49). Overall, germplasm screening remains central to coloured cotton breeding, supporting the development of high-quality, high-yielding, and resilient

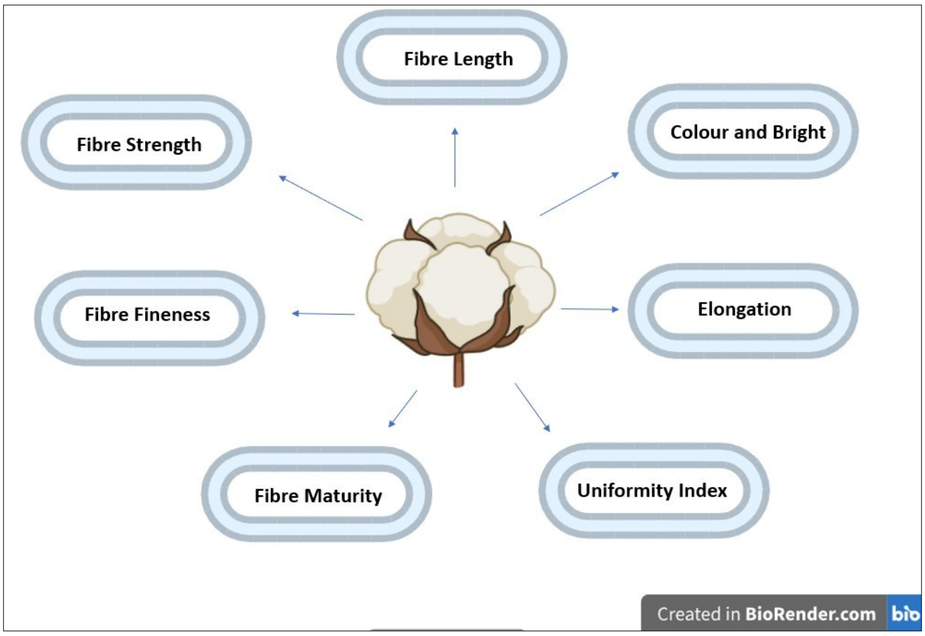

Fig. 2. Key fibre quality traits in cotton.

Table 3. Biotic and Abiotic Stress-Resistant Traits in Cotton

Stress Type	Trait	Genetic Basis / Mechanism	Reference
Biotic Stress	Pest Resistance (e.g., *Helicoverpa armigera*)	Bt (Bacillus thuringiensis) gene integration	(44)
	Resistance to Whiteflies	Increased phenolic compound production	(45)
	Bacterial Blight Resistance	Presence of Xa genes (Xa21, Xa23)	(46)
	Fusarium Wilt Tolerance	Overexpression of GhNPR1 gene	(46)
	Verticillium Wilt Resistance	Activation of PR (pathogenesis-related) proteins	(17)
Abiotic Stress	Drought Tolerance	Upregulation of DREB2A and GhMYB transcription factors	(47)
	Heat Tolerance	Enhanced expression of HSP70 and HSP90 proteins	(48)
	Salinity Tolerance	Overexpression of NHX1 sodium transporter gene	(49)
	Waterlogging Tolerance	Increased expression of GhADH1 (Alcohol Dehydrogenase)	(50)
	Cold Tolerance	Activation of CBF (C-repeat binding factor) genes	(51)

cultivars. The integration of traditional breeding with modern biotechnological innovations promises a bright future for coloured cotton, balancing sustainability with the evolving needs of the textile industry.

Eco-friendly and sustainable traits

Naturally pigmented fibres, such as brown and green cotton, offer significant environmental benefits by eliminating the need for synthetic dyes, a major source of industrial pollution. These fibres inherently possess colour, reducing harmful chemical use, water consumption, and energy during textile production, and aligning with consumer demand for sustainable, chemical-free clothing (50). Research also shows that their colours often become more vibrant with repeated washing, further decreasing the need for chemical treatments (51).

Additionally, naturally coloured cotton varieties require fewer inputs and are well-suited to organic farming. Their greater pest and disease resistance reduces reliance on pesticides and fertilisers, benefiting soil health, biodiversity, and minimising chemical runoff (52). The absence of a dyeing process also lowers production costs, making these fibres attractive to eco-conscious manufacturers.

With rising demand for sustainable textiles, naturally pigmented fibres are emerging as a viable alternative to conventional cotton. They support sustainability by reducing water and chemical use, promoting organic agriculture, and offering a natural, non-toxic solution for eco-friendly fashion (18). Their environmental advantages and cost-effectiveness position them as a key component of a greener textile industry.

Types of cotton and their uses

There are several types of cotton, each with distinct characteristics, end uses, and breeding objectives. Upland cotton (*Gossypium hirsutum*), accounting for approximately 90% of global cotton production, is favoured for its adaptability to diverse agro-climatic conditions, high yields, and ease of mechanical harvesting. Breeding efforts for upland cotton primarily focus on improving fibre length, strength, yield potential, and resistance to biotic (pests and diseases) and abiotic stresses such as drought and salinity. These improvements support its widespread use in everyday textile applications and maintain its dominance in global markets (18).

Pima cotton (*Gossypium barbadense*) is renowned for its exceptional fibre fineness, softness, and durability, making it the preferred choice for luxury fabrics and high-end clothing. Breeding programs for Pima cotton emphasise enhancing fibre uniformity, length, and tensile strength, along with improving resistance to pests and diseases. Additionally, efforts are underway to adapt Pima varieties to various agro-ecological zones, ensuring consistent quality and dependable supply chains for premium textile industries (27).

Naturally coloured cotton, though offering significant environmental benefits such as eliminating the need for chemical dyes and reducing water usage, still faces challenges related to market acceptance. These challenges stem from relatively lower yields, shorter fibre length, and colour stability issues. However, increasing consumer demand for sustainable and ethically produced textiles is driving renewed interest. Certification systems such as GOTS (Global Organic Textile Standard), OEKO-TEX®, and Better Cotton Initiative (BCI) provide assurance of chemical-free and socially responsible production. Eco-labels like EU Ecolabel, Cradle to Cradle Certified™, and Fair Trade Cotton enhance traceability, promote environmentally friendly practices, and enable producers to access premium markets. Promoting coloured cotton through robust certification frameworks, consumer education, and transparent labelling can substantially enhance its commercial viability and policy support (6 - 9).

Egyptian cotton, characterised by its extra-long staple fibres, is prized for producing exceptionally smooth and durable yarns. It is widely used in premium bedding and high-quality garments. Breeding strategies in Egyptian cotton aim to preserve these elite fibre traits while improving yield stability and resilience to regional pests and environmental fluctuations. Conservation of traditional Egyptian cotton landraces also remains a critical focus for maintaining unique genetic traits and fibre attributes (18).

Organic cotton is cultivated without the use of synthetic fertilisers, pesticides, or genetically modified seeds. Its production supports sustainable farming practices by enhancing soil health and reducing chemical runoff. Breeding programs for organic cotton prioritise developing varieties that are naturally resistant to pests and diseases, efficient in nutrient use, and capable of performing well under low-input or marginal conditions. These traits align with the principles of organic farming and contribute to the long-term sustainability of cotton production systems (6).

Fibre colour

Brown cotton is the most common naturally coloured variety, rich in tannins that enhance its durability and resistance to environmental factors. Its pigmentation comes from proanthocyanidins, a group of flavonoids that provide both colour and ultraviolet protection. Brown cotton is widely cultivated for its superior fibre properties and natural flame-retardant capabilities.

Less common than brown cotton, green cotton gets its colour from chlorophyll-based pigments and lignin derivatives, rather than flavonoids. Its fibres are softer and preferred for applications requiring comfort and flexibility, but they are less durable, limiting their use in high-stress textiles. These varieties are considered subsets of brown cotton, displaying hue variations due to genetic and environmental factors. They are valued for their natural, earthy tones and are often used in speciality, organic textiles. Like brown cotton, they contain tannins that provide antioxidant and antibacterial properties, but their fibres are generally shorter and weaker, requiring further breeding and processing improvements (18). Fig. 3 Biosynthetic pathway of flavonoids: anthocyanin and proanthocyanidin formation.

Gossypium hirsutum (Upland cotton) dominates commercial naturally pigmented cotton due to its high yield and adaptability (53), while *G. barbadense* is valued for superior fibre quality and pigmentation in premium textiles (54). *G. arboreum* and *G. herbaceum*, native to South Asia and Africa, offer natural pigmentation, pest resistance, and suitability for marginal soils, contributing to sustainable and traditional textile production (54). Cotton fibre colouration arises from the flavonoid biosynthesis pathway, which produces pigments like anthocyanidins and proanthocyanidins. Starting from phenylalanine, key enzymes such as PAL, CHS, CHI, F3H, DFR, and ANS synthesise anthocyanidins (e.g., pelargonidin, cyanidin), while ANR converts them into catechin and epicatechin, forming proanthocyanidins that give brown and reddish hues. Modern breeding programs in China, India, and the U.S. use genomic tools like GWAS and CRISPR to enhance pigment intensity, fibre quality, and stress resilience in naturally coloured cotton (18).

Genetics of coloured cotton

Fibre pigmentation in naturally coloured cotton is primarily controlled by single genes with incomplete dominance. Brown and green fibre colours are regulated by different genes: brown cotton often shows dominant inheritance, while green cotton exhibits incomplete dominance (55). The transcription factor MYB113 is crucial for anthocyanin biosynthesis in brown cotton, with its overexpression leading to increased pigment accumulation (18).

Genetic diversity in coloured cotton is relatively narrow, making hybridisation and marker-assisted selection important for improving fibre quality. In Xinjiang, China, genetic studies revealed that brown cotton is closely related to upland cotton (Gossypium hirsutum), whereas green cotton is more distantly related, indicating distinct evolutionary origins (56). Breeding programs have identified genotypes with improved lint percentage and fibre strength (27). Environmental factors, such as water and processing conditions, also impact fibre colour stability, influenced by enzymatic gene activity in fibre cells (51).

Key genetic studies using molecular markers (AFLP, SSR, RFLP) have mapped quantitative trait loci (QTLs) for fibre traits like length, strength, fineness, and elongation. These efforts have led to the development of high-quality varieties such as Suvin, Narasimha, MSH-53, and Xinhai 21, demonstrating the effectiveness of molecular breeding in cotton improvement programs.

Genetic studies using various molecular markers such as AFLP, SSR, and RFLP in tetraploid cotton have led to the identification of multiple QTLs, particularly in the A-subgenome, contributing to superior fibre traits, as seen in the Indian variety *Suvin*

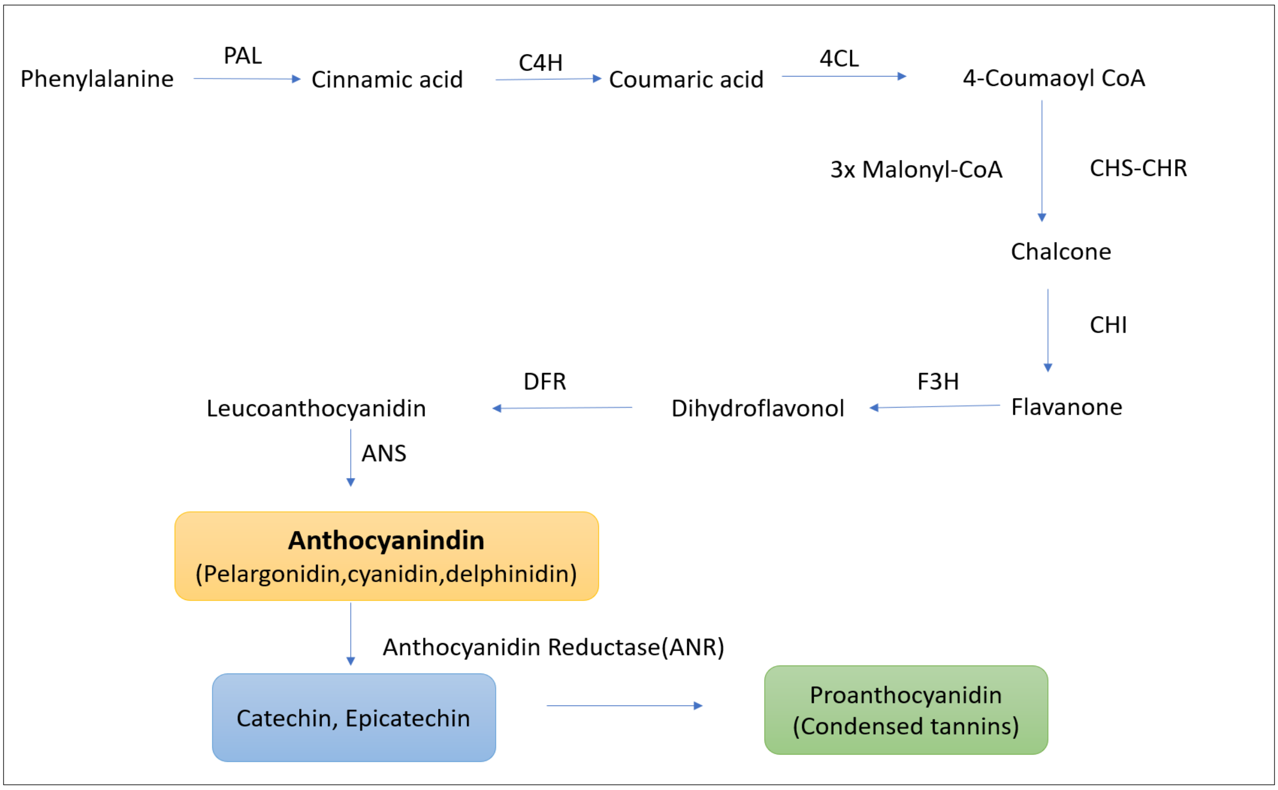

Fig. 3. Biosynthetic pathway of flavonoids: anthocyanin and proanthocyanidin formation.

(57). Comparative mapping between *Gossypium hirsutum* and *G. barbadense* revealed 28 QTLs linked to 11 fibre-related traits, aiding the development of high-yielding varieties like *Narasimha* (58). Backcross mapping in *G. hirsutum* × *G. barbadense* populations identified QTLs for fibre length, strength, and fineness, leading to pest-resistant, dark brown varieties such as *MSH-53* (59). Additionally, RFLP-based linkage maps detected QTLs for fibre strength and elongation, contributing to improved coloured cotton lines like *Xinhai 21* in China (60).

Genetic improvement for trait improvement in coloured cotton

Germplasm screening

Genetic improvement in coloured cotton relies on extensive germplasm screening to identify and incorporate traits such as superior fibre quality, higher yields, and enhanced stress tolerance. By exploring genetic diversity within Gossypium species, including wild relatives, breeders introduce novel alleles that enrich breeding programs and drive crop improvement (58).

A major advancement has been the identification of quantitative trait loci (QTLs) and the use of marker-assisted selection (MAS). Molecular markers like SSRs and SNPs enable precise tracking and incorporation of beneficial traits, accelerating the development of improved varieties (57).

Germplasm screening is also vital for developing stress-resistant cultivars. For example, selecting for traits such as root length and biomass accumulation has led to the development of salt -tolerant cotton suitable for saline environments. Breeding programs increasingly focus on enhancing fibre length, strength, and fineness to meet textile industry demands, often by integrating beneficial alleles from wild species (59).

Recent biotechnological advances, including transgenic methods and genome editing tools like CRISPR/Cas9, further expand the potential for cotton improvement by enabling targeted enhancement of fibre properties and stress resilience (49).

Overall, germplasm screening remains central to developing high-quality, high-yielding, and stress-tolerant coloured cotton cultivars for sustainable agriculture and the evolving textile industry.

Conventional breeding

Hybridisation and selection

Conventional breeding, hybridisation, and selection are foundational plant breeding techniques used to improve crop traits such as yield, disease resistance, and environmental adaptability. Conventional breeding involves crossing parent plants with desirable traits and selecting superior progeny over multiple generations, following Mendelian principles and using methods like mass selection, backcrossing, and pedigree breeding. While effective, this process is time-consuming and influenced by genotype-environment interactions, often taking 8–10 years to develop a new variety (60).

Hybridisation crosses genetically diverse parents to produce offspring with hybrid vigour (heterosis), making it especially valuable for both self- and cross-pollinated crops. The success of hybrid breeding depends on careful parental selection, as seen in crops like rice and maize (61). Selection, whether phenotypic or marker-assisted, is critical for choosing desirable traits. Genomic selection now complements traditional methods, increasing breeding efficiency and genetic gain (62). Mutation breeding, which induces genetic variation through physical or chemical agents, further enhances crop diversity and trait improvement, especially when integrated with genomic tools. This approach enables the development of resilient, high-yielding varieties suited to changing environmental conditions.

Overall, these breeding methods, enhanced by modern molecular tools, are accelerating the creation of improved crop varieties essential for global food security.

Backcross breeding

Backcross breeding is particularly effective for integrating fibre colour from Gossypium barbadense into high-yielding Gossypium hirsutum cultivars. Interspecific hybridisation followed by backcrossing improves fibre quality and yield while retaining natural pigmentation. This approach has led to the development of backcross inbred lines (BILs) that combine enhanced fibre traits with stable colour, supporting the commercial production of naturally coloured cotton (63).

Quantitative trait loci (QTL) mapping has been instrumental in identifying genetic regions responsible for fibre colour and quality. Advanced backcross populations have enabled the discovery of QTLs linked to fibre length and strength, which are essential for market competitiveness. Introgression lines developed through backcrossing have shown improved fibre uniformity, enhancing yarn quality and textile applications (64).

A major challenge in backcross breeding for coloured cotton is maintaining fibre yield while enhancing colour intensity. Researchers have developed BIL populations with high heterosis for fibre production that also retain pigmentation, demonstrating the feasibility of commercialising coloured cotton through this method (65). Marker-assisted selection (MAS) further accelerates breeding by enabling efficient identification and selection of plants with desirable fibre colour and agronomic traits.

Recent research highlights the role of QTL mapping and advanced breeding techniques, such as backcrossing and the development of introgression lines, in improving fibre quality and pigmentation traits. MAS has proven valuable for efficient trait selection, helping to balance fibre yield with colour intensity. These advancements significantly enhance the agronomic and commercial value of naturally coloured cotton.

Quantitative trait loci (QTL) mapping has been instrumental in identifying key genetic regions associated with fibre colour and quality traits in coloured cotton (66). Advanced backcross populations have revealed specific QTLs that contribute to improvements in fibre length and strength, thereby enhancing the competitiveness of coloured cotton fibres (67). The use of introgression lines through backcrossing has shown promise in improving fibre uniformity, which is critical for better yarn quality and wider textile applications (68). However, a major challenge in backcross breeding lies in balancing fibre yield with enhanced colour intensity, as improving one trait often compromises the other (69). Interestingly, breeding introgression lines (BILs) have demonstrated heterosis, or hybrid vigour, leading to increased fibre production without compromising natural pigmentation (69). Marker-assisted selection (MAS) continues to play a vital role in accelerating the breeding process by enabling the precise selection of desirable fibre colour and agronomic traits (69).

Mutation breeding

Conventional breeding for coloured cotton focuses on hybridisation and selection to improve fibre length, strength, and yield while preserving natural pigmentation. However, a key challenge is the negative correlation between fibre colour and agronomic traits like strength and length, complicating simultaneous improvement (66).

Mutation breeding overcomes these limitations by inducing genetic diversity. Chemical mutagens like EMS and techniques such as TILLING generate mutant populations with enhanced fibre quality, stress resistance, and yield, expanding the genetic base of coloured cotton (67).

Molecular advances, including marker-assisted selection (MAS), quantitative trait loci (QTL) mapping, and CRISPR gene editing, enable precise identification and incorporation of favourable mutations while maintaining natural colouration (49). Backcross breeding complements these methods by transferring desirable traits such as improved fibre strength, yield, and colour intensity from donor parents into elite coloured cotton lines, ensuring retention of beneficial genetics and pigmentation. Combined with MAS and genomic tools, these strategies accelerate the development of high-performing, naturally pigmented cotton varieties that meet agronomic and industrial demands for sustainable textiles.

Molecular breeding and biotechnological approaches

Marker assisted selection

Marker-Assisted Selection (MAS) is a vital tool in molecular breeding for improving fibre quality and pigmentation traits in naturally coloured cotton (Gossypium spp.). By enabling breeders to identify genetic markers linked to desirable traits, MAS enhances fibre strength, length, and colour stability key challenges that have limited the broader adoption of coloured cotton.

Recent advances in MAS have led to the identification of key quantitative trait loci (QTLs) for fibre length, strength, micronaire, and uniformity. The successful introgression of superior fibre QTLs into new upland cotton varieties has resulted in improved fibre properties (68). Stable QTLs on chromosomes 3, 7, 9, 11, and 12, along with the use of KASP markers, have further increased breeding precision and efficiency (70).

MAS has also advanced the understanding and improvement of fibre pigmentation. It enables the identification and selection of genes involved in pigment biosynthesis, such as GhTT2-3A, F3'5'H, ANS, CHS, and DFR, which regulate the development and stability of brown and green pigmentation. Integrating transcriptomic and metabolomic data has enhanced MAS-based breeding strategies, supporting the development of coloured cotton varieties with more intense and consistent fibre colouration. Overall, MAS accelerates the breeding of high-quality, eco-friendly coloured cotton by targeting both fibre and pigmentation traits. Marker-assisted selection (MAS) plays a significant role in coloured cotton breeding by aiding in the identification and selection of genes associated with pigmentation. In brown cotton, pigmentation is primarily due to the presence of proanthocyanidins (PAs), whereas green cotton derives its colour from caffeic acid (CA) derivatives (70). A key gene involved in flavonoid biosynthesis is GhTT2-3A, which is crucial for MAS-based breeding programs focused on improving colour traits (70). Transcriptomic and metabolomic studies have identified several differentially expressed genes that influence pigment formation in coloured cotton fibres (71). Notably, genes such as F3'5'H, ANS, CHS, and DFR play essential roles in the biosynthesis and stabilisation of pigments (71). These genetic insights have enabled the development of MAS-based breeding strategies aimed at enhancing colour stability and intensity in coloured cotton (71).

Genomic selection in coloured cotton

Genomic selection (GS) is revolutionising modern plant breeding by enabling more efficient improvement of fibre quality and yield in naturally coloured cotton. As demand for sustainable textiles grows, coloured cotton is valued for reducing reliance on synthetic dyes, making it an eco-friendly choice for the textile industry. Recent research in Brazil and elsewhere has revealed significant genetic diversity among coloured cotton genotypes, highlighting opportunities for targeted breeding to enhance fibre characteristics (72).

Advanced genomic selection models, especially Bayesian approaches like BayesB, have demonstrated high accuracy in predicting fibre quality traits. Marker-assisted selection (MAS) further supports these efforts by identifying genetic loci linked to fibre colour, enabling breeders to improve colour uniformity and fibre strength without compromising natural pigmentation (73).

Genetic diversity studies show a strong correlation between fibre strength and colour stability, suggesting that both traits can be improved simultaneously through selective breeding (73). Public breeding programs have also found that GS can significantly enhance fibre quality, yield, and adaptability to diverse environments. By accelerating the breeding process and integrating genomic prediction with MAS, breeders can rapidly develop high-quality, resilient, and visually appealing coloured cotton varieties. As consumer demand for sustainable and ethically produced textiles rises, genomic selection will be essential for ensuring coloured cotton meets both environmental and industry standards.

Genetic engineering and CRISPR

Genetic engineering, especially using CRISPR/Cas9, has revolutionised cotton breeding by enabling precise modification of fibre quality genes to enhance traits like length, strength, and fineness (49). This technology also opens new possibilities for expanding cotton's natural colour range by targeting pigment-related genes. Key QTLs and candidate genes identified through marker-assisted selection and gene editing are paving the way for more targeted improvements (74).

CRISPR-based modifications are also being used to increase yield while preserving desirable fibre properties. Genome-wide association studies (GWAS) have identified genetic variations influencing fibre traits, providing additional targets for improvement. Together, these advances are making cotton breeding more sustainable and efficient, supporting the production of high-quality, naturally pigmented fibres (49).

Transcriptomics

Gene regulation in cotton fibre development and colour expression involves transcription factors, genetic variations, and epigenetic modifications. Myogenic regulatory factors (MRFs) like MyoD and Myf5 influence fibre differentiation, while SNPs affect fibre composition and quality. Growth regulators such as IGF-1 promote fibre elongation and structural development (75). Pigment biosynthesis is controlled by genetic and epigenetic factors, environmental conditions, and even dietary influences, all impacting fibre colour and traits (76). Advances in transcriptomics and genomics are helping optimize fibre quality for agricultural and industrial use.

Integration of traditional and modern breeding tools in coloured cotton improvement

The improvement of coloured cotton varieties has traditionally relied on phenotypic selection and conventional hybridisation techniques, which are time-consuming and often limited by environmental influence, low heritability, and linkage drag. While these methods have contributed to developing naturally pigmented cotton lines, they face limitations in overcoming the trade-offs between pigment expression and agronomic traits such as yield and fibre quality.

In contrast, modern molecular breeding tools such as Marker-Assisted Selection (MAS), Genome-Wide Association Studies (GWAS), Genomic Selection (GS), and CRISPR/Cas9 genome editing offer precise, rapid, and efficient approaches to address these challenges. Table 4: Comparison of 13. Traditional and modern breeding tools in coloured cotton improvement

Recent GWAS studies in *Gossypium* have identified QTLs associated with fibre length, strength, and pigmentation, enabling breeders to make informed selections (22). MAS has already been deployed to pyramid fibre strength and disease resistance loci into coloured cotton lines. Furthermore, CRISPR-Cas9 technology has the potential to uncouple undesirable gene linkages and directly enhance colour expression without compromising yield.

As the genomic resources for cotton continue to expand, integrating omics-assisted breeding with traditional field-based evaluation will be crucial to developing coloured cotton varieties that meet both environmental and commercial demands.

Challenges in coloured cotton

Naturally coloured cotton typically exhibits shorter fibre lengths, lower tensile strength, and reduced elongation properties, limiting its suitability for producing high-quality textiles that demand durability and elasticity.

Coloured cotton generally yields 50–70% less than white cotton due to genetic trade-offs that favour pigment production over traits like fibre strength and length. This lower productivity, combined with the lack of substantial financial incentives or market premiums, makes its cultivation less attractive to farmers. Naturally coloured cotton is limited in its colour range primarily to brown, green, and reddish hues, which makes it less versatile compared to synthetically dyed fabrics that offer a wider spectrum and greater vibrancy. Consumer awareness remains low, and supply chains for coloured cotton are underdeveloped, further restricting market demand and adoption.

There is a significant risk of genetic contamination between naturally coloured and conventional white cotton through cross-pollination, potentially degrading fibre quality. To mitigate this, many regions enforce strict regulations requiring physical isolation of coloured cotton fields, increasing cultivation costs and complicating production logistics. Processing naturally coloured cotton requires specialised spinning and weaving techniques to preserve its pigmentation. Additionally, fibre colour can vary with environmental conditions, leading to inconsistencies in fabric appearance that are less acceptable in standardised textile manufacturing. Compared to white cotton, naturally coloured cotton receives far less attention in breeding programs, slowing progress in improving fibre quality, yield, and pigment diversity. Increased research efforts are needed to overcome these genetic limitations and expand their commercial potential. Overcoming these challenges will require a combination of scientific innovation, supportive policies, and greater consumer education. Only through integrated efforts can naturally coloured cotton become a truly viable and sustainable option for the modern textile industry.

Future prospective

The future of naturally coloured cotton breeding is promising, driven by advances in genetic engineering, sustainable farming, and rising demand for eco-friendly textiles. Innovative techniques like CRISPR/Cas9 gene editing, marker-assisted selection (MAS), and transgenic approaches are being explored to enhance fibre quality, yield and colour consistency while maintaining the cotton's natural pigmentation. Additionally, Researchers aim to broaden the natural colour spectrum to include red, purple and blue, increasing the commercial appeal and design versatility of naturally coloured cotton (49).

Enhancing resistance to drought, pests, and environmental stressors will make coloured cotton more suitable for large-scale farming and adaptable to climate change. However, maintaining genetic purity and preventing cross-pollination with white cotton remain key challenges, necessitating improved seed purification and breeding strategies. These issues necessitate more effective seed purification protocols, spatial isolation techniques and the development of robust breeding strategies that safeguard pigment integrity.

Table 4. Comparison of Traditional and Modern Breeding Tools in Coloured Cotton Improvement

Aspect	Traditional Breeding Tools	Modern Breeding Tools	References
Basis of Selection	Phenotypic performance under field conditions	Genotypic and molecular information	(77, 78)
Speed	Slow (requires multiple generations)	Fast-tracked through marker data or gene editing	(76, 60)
Accuracy	Low to moderate (affected by environment)	High (targets specific genes/QTLs)	(79, 56)
Pigment Trait Improvement	Crosses between coloured landraces and elite lines	Identification of pigment-related QTLs via GWAS; editing flavonoid biosynthesis genes	(22, 34, 76)
Yield Improvement	Limited due to linkage drag	Genomic selection for high-yielding coloured cotton lines	(73, 56)
Disease Resistance	Broad-spectrum resistance via repeated selection	MAS for introgressing specific resistance genes	(44, 56)
Examples	Selection from G. hirsutum landraces for brown fibre lines	CRISPR-mediated editing of MYB transcription factors regulating anthocyanin synthesis	(34, 76)
Limitations	Time-consuming, imprecise, low throughput	Requires high-quality genomic data, technical expertise, and regulatory clarity	(60, 49)

Emerging trends and priorities in the cotton industry reflect a strong shift toward sustainability and technological innovation. Smart cotton farming is gaining traction, with AI-driven systems being used for irrigation, pest control, and real-time crop monitoring to improve efficiency and reduce resource use. At the same time, researchers are focusing on sustainable innovations, such as breeding water-saving cotton varieties and developing biodegradable dyes that minimise environmental impact. Additionally, technology integration through blockchain is being explored to enhance supply chain transparency, ensure fair trade practices and build consumer trust in ethically produced cotton products.

Collaboration among breeders, farmers and the textile industry, along with certification and sustainable branding, will boost commercial adoption and consumer awareness. In addition, government policies that provide incentives, funding, or regulatory support for eco-friendly alternatives can significantly accelerate the adoption and scaling of coloured cotton farming.

As advancements in fibre biotechnology and consumer interest in sustainable fashion accelerate, naturally coloured cotton is poised to emerge as a commercially viable and environmentally responsible alternative. Its adoption can play a pivotal role in reducing the ecological footprint of textile production and fostering a greener future for both agriculture and the fashion industry.

Conclusion

Breeding naturally coloured cotton offers a sustainable alternative to conventional textiles by reducing pollution, water use, and chemical dependency from dyeing. Recent advances in conventional breeding, marker-assisted selection and transgenic technologies have improved genetic diversity, fibre quality, and yield in coloured cotton lines. However, challenges like lower fibre strength, limited colour options, and market acceptance hinder large-scale adoption. Future efforts should prioritise enhancing fibre properties, expanding colour diversity, and boosting climate resilience through advanced genomics. Collaboration among researchers, policymakers and the textile industry is crucial for mainstream adoption. With sustained innovation and institutional support, it can emerge as a leading eco-friendly fibre, aligning with global sustainability goals and promoting a greener future for agriculture and the textile industry.

Acknowledgements

All contributors who do not meet the criteria for authorship should be listed in an 'acknowledgements' section. Examples of those who might be acknowledged include a person who provided purely technical help, writing assistance, or a department chair who provided only general support. Authors must acknowledge the organisations that have provided financial support for their work in the manuscript with grant award number here.

Authors' contributions

AK was responsible for writing the original draft, reviewing and editing, conceptualization, methodology, visualization, and utilizing software to prepare figures. NP, AS, NMB and CN contributed to reviewing and editing, conceptualization and methodology. RR, YB and VR were involved in reviewing and editing, data curation and supervision.

All authors read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

References

1. Islam T, Repon MR, Islam T, Sarwar Z, Rahman MM. Impact of textile dyes on health and ecosystem: a review of structure, causes, and potential solutions. Environ Sci Pollut Res. 2022;30(4):9207–42. https://doi.org/10.1007/s11356-022-24398-3
2. Atanassova D, Kefalas P, Petrakis C, Mantzavinos D, Kalogerakis N, Psillakis E. Sonochemical reduction of the antioxidant activity of olive mill wastewater. Environ Int. 2005;31(2):281–7. https://doi.org/10.1016/j.envint.2004.10.004
3. Dutta S, Adhikary S, Bhattacharya S, Roy D, Chatterjee S, Chakraborty A, et al. Contamination of textile dyes in aquatic environment: Adverse impacts on aquatic ecosystem and human health, and its management using bioremediation. J Environ Manage. 2024;353:120103. https://doi.org/10.1016/j.jenvman.2024.120103
4. Kant R. Textile dyeing industry: An environmental hazard. Nat Sci. 2012;4(1):22–6. https://doi.org/10.4236/ns.2012.41004
5. Uddin MA, Begum MS, Ashraf M, Azad AK, Adhikary AC, Hossain MS. Water and chemical consumption in the textile processing industry of Bangladesh. PLOS Sustain Transform. 2023;2(7):e0000072. https://doi.org/10.1371/journal.pstr.0000072
6. Madhu A. Naturally Coloured Cotton: A Sustainable Innovation. 2024. https://doi.org/10.5772/intechopen.113290
7. Garcia S, De Alencar Nääs I. Textile industry can be less pollutant: introducing naturally coloured cotton. Int J Prod Manag Eng. 2014;2(2):85. https://doi.org/10.4995/ijpme.2014.1744
8. Tounsadi H, Metarfi Y, Taleb M, El Rhazi K, Rais Z. Impact of chemical substances used in textile industry on the employee's health: Epidemiological study. Ecotoxicol Environ Saf. 2020;197:110594. https://doi.org/10.1016/j.ecoenv.2020.110594
9. Palomo-Domínguez I, Elías-Zambrano R, Álvarez-Rodríguez V. Gen Z's Motivations towards Sustainable Fashion and Eco-Friendly Brand Attributes: The Case of Vinted. Sustainability. 2023;15(11):8753. https://doi.org/10.3390/su15118753
10. Stephens SG, Moseley ME. Cotton Remains from Archeological Sites in Central Coastal Peru. Science. 1973;180(4082):186–8. https://doi.org/10.1126/science.180.4082.186
11. Splitstoser JC, Dillehay TD, Wouters J, Claro A. Early pre-Hispanic use of indigo blue in Peru. Sci Adv. 2016;2(9):e1501623. https://doi.org/10.1126/sciadv.1501623
12. Li Z, Liu S, Conaty W, Zhu Q-H, Moncuquet P, Stiller W, et al. Genomic prediction of cotton fibre quality and yield traits using Bayesian regression methods. Heredity. 2022;129(2):103–12. https://doi.org/10.1038/s41437-022-00537-x
13. Delgado-Paredes C, et al. Genetic and historical significance of naturally pigmented cotton in Peru. Peruv Agric J. 2024;28(1):55–72.
14. Ke-yi X. Cultivation of brown-coloured cotton and its cultural significance. Chin J Agron. 2009;15(4):250–9.
15. Motsamayi T. Coloured cotton integrated into textile traditions: Specific hues reflect community values and social identity among the Sotho-Tswana people. S Afr J Cult Hist. 2020;34(2):45–58.

16. Vreeland JM. Revival of coloured cotton. Sci Am. 1999;280(4):112–8.
17. Zhao Y. Colonialism and the Decline of the Cotton Industry in British India (1763–1863). Acad J Manag Soc Sci. 2023;4(3):120–4.
18. Naoumkina M, Hinchliffe DJ, Thyssen GN. Naturally coloured cotton for wearable applications. Front Plant Sci. 2024;15:1350405. https://doi.org/10.3389/fpls.2024.1350405
19. Günaydin K, Karadag R, Yilmaz M. Naturally coloured cotton and its importance in textile history. Text Hist. 2019;50(2):123–37.
20. Atav R, Yüksel MF, Dilden DB, İzer G. Coloured cotton fabric production without dyeing within the sustainability concept in textile. Ind Crops Prod. 2022;187:115419. https://doi.org/10.1016/j.indcrop.2022.115419
21. Schiaroli V, Fraccascia L, Dangelico RM. How can consumers behave sustainably in the fashion industry? A systematic literature review of determinants, drivers, and barriers across the consumption phases. J Clean Prod. 2024;483:144232. https://doi.org/10.1016/j.jclepro.2024.144232
22. Shi S, Tang R, Hao X, Tang S, Chen W, Jiang C, et al. Integrative Transcriptomic and Metabolic Analyses Reveal That Flavonoid Biosynthesis Is the Key Pathway Regulating Pigment Deposition in Naturally Brown Cotton Fibres. Plants. 2024;13(15):2028. https://doi.org/10.3390/plants13152028
23. Viot C. Domestication and varietal diversification of Old World cultivated cottons (Gossypium sp.) in the Antiquity. Rev ethnoécol. 2019;15. https://doi.org/10.4000/ethnoecologie.4404
24. Price JB, Cui X, Calamari TA, Mcdaniel RG. Assessing the Quality of Four Naturally Coloured Cottons. Text Res J. 2001;71(11):993–9. https://doi.org/10.1177/004051750107101110
25. Pizzicato B, Pacifico S, Cayuela D, Mijas G, Riba-Moliner M. Advancements in Sustainable Natural Dyes for Textile Applications: A Review. Molecules. 2023;28(16):5954. https://doi.org/10.3390/molecules28165954
26. Naoumkina M, Kim HJ. Bridging molecular genetics and genomics for cotton fibre quality improvement. Crop Sci. 2023;63(4):1794–815. https://doi.org/10.1002/csc2.20987
27. Sun J, Sun Y, Zhu Q-H. Breeding Next-Generation Naturally Coloured Cotton. Trends Plant Sci. 2021;26(6):539–42. https://doi.org/10.1016/j.tplants.2021.03.007
28. Hamdan MF, Tan BC. Genetic modification techniques in plant breeding: A comparative review of CRISPR/Cas and GM technologies. Hortic Plant J. 2024. https://doi.org/10.1016/j.hpj.2024.02.012
29. Khan Z, Khan SH, Ahmed A, Iqbal MU, Mubarik MS, Ghouri MZ, et al. Genome editing in cotton: challenges and opportunities. J Cotton Res. 2023;6(1):3. https://doi.org/10.1186/s42397-023-00140-3
30. Jiao J, Chang S, Wang F, Yang J, Ismayil A, Wu P, et al. Genes Affecting Cotton Fibre Length: A Systematic Review and Meta-Analysis. Plants. 2025;14(8):1203. https://doi.org/10.3390/plants14081203
31. Xiang Z, Pan LP, Wei DM, Chen Z, Hua WC, Yuan C, et al. Physiological Characteristics Associated with Fibre Development in Two Naturally Coloured Cotton Cultivars. Agron J. 2019;111(3):1190–7. https://doi.org/10.2134/agronj2018.03.0166
32. Tan J, Tu L, Deng F, Hu H, Nie Y, Zhang X. A Genetic and Metabolic Analysis Revealed that Cotton Fibre Cell Development Was Retarded by Flavonoid Naringenin. Plant Physiol. 2013;162(1):86–95. https://doi.org/10.1104/pp.112.212142
33. Jan M, Liu Z, Guo C, Sun X. Molecular Regulation of Cotton Fibre Development: A Review. Int J Mol Sci. 2022;23(9):5004. https://doi.org/10.3390/ijms23095004
34. Liu H-F, Luo C, Song W, Shen H, Li G, He Z-G, et al. Flavonoid biosynthesis controls fibre colour in naturally coloured cotton. PeerJ. 2018;6:e4537. https://doi.org/10.7717/peerj.4537
35. Ma M, Hussain M, Memon H, Zhou W. Structure of pigment compositions and radical scavenging activity of naturally green-coloured cotton fibre. Cellulose. 2016;23(1):955–63. https://doi.org/10.1007/s10570-015-0830-9
36. Feng H, Tian X, Liu Y, Li Y, Zhang X, Jones BJ, et al. Analysis of Flavonoids and the Flavonoid Structural Genes in Brown Fibre of Upland Cotton. PLoS One. 2013;8(3):e58820. https://doi.org/10.1371/journal.pone.0058820
37. Wen T, Luo W, Li Y, Lin Z. Advances and new insights in naturally coloured cotton breeding and research. Ind Crops Prod. 2024;211:118252. https://doi.org/10.1016/j.indcrop.2024.118252
38. Dutt Y, Wang XD, Zhu YG, Li YY. Breeding for high yield and fibre quality in coloured cotton. Zhejiang J Agric Sci. 2004;22(3):301–12. https://doi.org/10.1046/j.1439-0523.2003.00938.x
39. Revanasiddayya R, Nidagundi JM, Fakrudin B, Kuchanur P, Yogeesh LN, Hanchinal S, et al. Genetic diversity among coloured cotton genotypes in relation to their fibre colour and ploidy level based on SSR markers. Czech J Genet Plant Breed. 2023;60(1):12–24. https://doi.org/10.17221/12/2023-CJGPB
40. Yan W, Du M, Zhao W, Li F, Wang X, Eneji AE, et al. Relationships between Plant Architecture Traits and Cotton Yield within the Plant Height Range of 80–120 cm Desired for Mechanical Harvesting in the Yellow River Valley of China. Agronomy. 2019;9(10):587. https://doi.org/10.3390/agronomy9100587
41. Bowman DT. Conventional breeding of cotton: Progress and challenges. J Cotton Sci. 1999;3(3):145–53. https://doi.org/10.1007/978-1-4939-1447-0_10
42. Mostakim M, Mallick D, Gomasta J, Miah MRU, Sultana H, Momtaz MB, et al. Development of ant-based mutualistic and antagonistic biocontrol strategies against cotton mealybugs. Discov Plants. 2025;2(1):60. https://doi.org/10.1007/s44372-025-00146-y
43. Aslam S, Khan SH, Ahmed A, Dandekar AM. The Tale of Cotton Plant: From Wild Type to Domestication, Leading to Its Improvement by Genetic Transformation. Am J Mol Biol. 2020;10(2):91–127. https://doi.org/10.4236/ajmb.2020.102008
44. Kushanov FN, Turaev OS, Ernazarova DK, Gapparov BM, Oripova BB, Kudratova MK, et al. Genetic Diversity, QTL Mapping, and Marker-Assisted Selection Technology in Cotton (Gossypium spp.). Front Plant Sci. 2021;12:Article 672661. https://doi.org/10.3389/fpls.2021.779386
45. Kumar P, Singh R. Economic viability of naturally coloured cotton: A review. J Agric Econ. 2023;78(1):145–63.
46. Feng H, Sun J, Wang J, Jia Y, Zhang X, Pang B, et al. Genetic effects and heterosis of the fibre colour and quality of brown cotton (Gossypium hirsutum). Plant Breed. 2011;130(4):450–6. https://doi.org/10.1111/j.1439-0523.2010.01842.x
47. Abbas G, Ali MA, Khan TM, Kanwal N, Zia MA. Genetic variability for salt tolerance in Gossypium hirsutum L. Afr J Biotechnol. 2011;10(34):6491–501.
48. Baghyalakshmi K, Priyanka RA, Sarathapriya G, Ramchander S, Prakash AH. Genetic improvement of fibre quality in tetraploid cotton: an overview of major QTLs and genes involved in and edited for the quality of cotton fibres. J Cotton Res. 2024;7(1):33. https://doi.org/10.1186/s42397-024-00196-9
49. Sheri V, Mohan H, Jogam P, Alok A, Rohela GK, Zhang B. CRISPR/Cas genome editing for cotton precision breeding: mechanisms, advances, and prospects. J Cotton Res. 2025;8(1):4. https://doi.org/10.1186/s42397-024-00206-w
50. Atav R, Yüksel MF, Dilden DB, İzer G. Coloured cotton fabric production without dyeing within the sustainability concept in textile. Ind Crops Prod. 2022;187:115419. https://doi.org/10.1016/j.indcrop.2022.115419
51. Aliei H, Carrera-Gallissa E, Cayuela D. Evaluating the impact of washing conditions on the colour changes of naturally coloured

cotton fabrics: A focus on detergents, water types, and temperature. Materials. 2024;17(23):5777. https://doi.org/10.3390/ma17235777

52. Günaydin K, Karadag R, Yilmaz M. Naturally coloured cotton and its importance in textile history. Text Hist. 2019;50(2):123–37.

53. Joshi B, Singh S, Tiwari GJ, Kumar H, Boopathi NM, Jaiswal S, et al. Genome-wide association study of fibre yield-related traits uncovers the novel genomic regions and candidate genes in Indian upland cotton (Gossypium hirsutum L.). Front Plant Sci. 2023;14:Article 1252746. https://doi.org/10.3389/fpls.2023.1252746

54. Morales‐Aranibar L, Rivera MYN, Gonzales HHS, Aranibar CGM, Gutiérrez NL, Gomez FG, et al. Comparative analysis of key fibre characteristics in white Pima cotton (Gossypium barbadense L.): Native accessions from the Peruvian Amazon. Agrosyst Geosci Environ. 2024;7(2):Article e20517. https://doi.org/:10.1002/agg2.20517

55. Tonk FA, Tosun M, İştipliler D, İlker E, Reçber A. Genetic analysis of fibre colour using segregations of colour parameters in cotton. J Cotton Sci. 2017;21(4):315–9. http://journal.cotton.org/

56. Wang H, et al. Genomic selection and MAS in cotton breeding. Mol Plant Breed. 2014;12(5):523–40.

57. Kushanov FN, Turaev OS, Ernazarova DK, Gapparov BM, Oripova BB, Kudratova MK, et al. Genetic diversity, QTL mapping, and marker-assisted selection technology in cotton (Gossypium spp.). Front Plant Sci. 2021b;12:Article 779386. https://doi.org/10.3389/fpls.2021.779386

58. Yuan Y, Zhang Z, Li L, Huang J, Wang M, Wang X. Genetic improvement of coloured cotton: Current status and future prospects. Afr J Biotechnol. 2012;11(77):14112–9.

59. Ijaz B, Saleem MF, Raza MA. CRISPR-based genome editing in cotton: A review of progress and potential. Pak J Bot. 2019;51(5):1651–62.

60. Kun W, Shoupu H, Yuxian Z. Cotton2035: From genomics research to optimized breeding. Mol Plant. 2025;18(2):298–312.

61. Labroo MR, Studer AJ, Rutkoski JE. Heterosis and hybrid crop breeding: A multidisciplinary review. Front Genet. 2021;12:Article 643761. Available from: https://www.frontiersin.org/articles/10.3389/fgene.2021.643761

62. Chung P-Y, Liao C-T. Selection of parental lines for plant breeding via genomic prediction. Front Plant Sci. 2022;13:Article 860935. https://doi.org/10.3389/fpls.2022.934767

63. Nie X, Tu J, Wang B, Zhou X, Lin Z. A BIL population derived from *G. hirsutum* and *G. barbadense* provides a resource for cotton genetics and breeding. PLoS One. 2015;10(10):e0141064. https://doi.org/10.1371/journal.pone.0141064

64. Ma X, Zhang Q, Wang L, Li J, Chen Z. QTL mapping for fibre colour and quality traits in coloured cotton using advanced backcross populations. BMC Plant Biol. 2020;20(1):345. https://doi.org/10.1186/s12870-020-02541-x

65. Zhang H, Li Y, Wang J, Liu R, Chen X. Development of backcross inbred line populations with high heterosis for fibre production and pigmentation in coloured cotton. Euphytica. 2016;208(3):521–32.

66. Feng L, Yuan Y, Wang Q, Yang Z, Zheng Y. Breeding progress and genetic analysis of fibre quality and colour in naturally coloured cotton. Euphytica. 2011;181(2):237–45.

67. Brown N, Smith CW, Auld D, Hequet EF. Improvement of Upland cotton fibre quality through mutation of TAM 94L‐25. Crop Sci. 2013;53(2):452–9.

68. Darmanov MM, Makamov AK, Ayubov MS, Khusenov NN, Buriev ZT, Shermatov SE, et al. Development of superior fibre quality Upland cotton cultivar series 'Ravnaq' using marker-assisted selection. Front Plant Sci. 2022;13:Article 942715.

69. Razzaq A, Zafar MM, Ali A, Hafeez A, Sharif F, Guan X, et al. The pivotal role of major chromosomes of sub-genomes A and D in fibre quality traits of cotton. Front Genet. 2022;12:Article 891056.

70. Mikhailova E, et al. Role of MAS in coloured cotton breeding. Mol Breed. 2019;15(4):415–30.

71. Barros MAL, Silva CRCD, Lima LMD, Farias FJC, Ramos GA, Santos RCD. A review on evolution of cotton in Brazil: GM, white, and coloured cultivars. J Nat Fibres. 2022;19(1):209–21.

72. Islam MS, Fang DD, Jenkins JN, Guo J, McCarty JC, Jones DC. Evaluation of genomic selection methods for predicting fibre quality traits in Upland cotton. Mol Genet Genom. 2020;295(1):67–79.

73. Feng H, Guo L, Wang G, Sun J, Pan Z, He S, et al. The negative correlation between fibre colour and quality traits revealed by QTL analysis. PLoS One. 2015;10(6):e0129490. https://doi.org/10.1371/journal.pone.0129490

74. Mangla H, Liu M, Vitrakoti D, Somala RV, Shehzad T, Chandnani R, et al. Identification of favorable alleles from exotic Upland cotton lines for fibre quality improvement using multiple association models. Front Plant Sci. 2025;16:Article 1553514. https://www.frontiersin.org/articles/10.3389/fpls.2025.1553514

75. Grover CE, Jareczek JJ, Swaminathan S, Lee Y, Howell AH, Rani H, et al. A high-resolution model of gene expression during *Gossypium hirsutum* (cotton) fibre development. BMC Genom. 2025;26(1):221.

76. Jiao J, Chang S, Wang F, Yang J, Ismayil A, Wu P, et al. Genes affecting cotton fibre length: A systematic review and meta-analysis. Plants. 2025;14(8):1203.

77. Lv F, Zhang X, Li Y, Wang L, Zhao H. Transcriptomic and metabolomic analyses reveal differentially expressed genes influencing pigment formation in coloured cotton fibres. BMC Plant Biol. 2023;23(1):112.

78. Shi Y, et al. QTL mapping for fibre quality and pigmentation in naturally coloured cotton. Euphytica. 2019;215(7):100.

79. Ma X, Wang L, Zhang Q, Li J, Chen Z. Development and characterization of introgression lines for improving fibre uniformity in coloured cotton. Euphytica. 2017;213(2):45. https://doi.org/10.1007/s10681-016-1802-5

80. Zhang H, Li Y, Wang J, Liu R, Chen X. Development of backcross inbred line populations with high heterosis for fibre production and pigmentation in coloured cotton. Euphytica. 2016;208(3):521–32.

81. Lacape JM, Nguyen TB, Thibivilliers S, Bojinov B, Dumas C, Bourdreau E, et al. QTL analysis of cotton fibre quality using multiple *Gossypium hirsutum* × *Gossypium barbadense* backcross generations. Crop Sci. 2003;43(1):96–106. https://doi.org/10.2135/cropsci2003.9600

82. Jiang C, Wright RJ, El-Zik KM, Paterson AH. Polygenic inheritance of plant height, yield, and fibre quality traits in a recombinant inbred population of cotton. Crop Sci. 1998;38(3):567–75. https://doi.org/10.2135/cropsci1998.0011183X003800030003x

83. Ulloa M, Meredith WR. Genetic linkage map and QTL analysis of agronomic and fibre quality traits in an intraspecific population of cotton (*Gossypium hirsutum* L.). J Cotton Sci. 2000;4(3):161–70. https://www.cotton.org/journal/2000-04/4/161.cfm

84. Zhang J, Lu Y, Adragna PJ, Hughs SE. A molecular linkage map of upland cotton (*Gossypium hirsutum* L.) based on RFLP and SSR markers. Theor Appl Genet. 2002;105(5):786–93. https://doi.org/10.1007/s00122-002-0957-6

85. Chen L, Xu H, Zhao Y, Wang J. Enhanced expression of HSP70 and HSP90 proteins improves heat tolerance in cotton. Environ Exp Bot. 2023;205:105223. https://doi.org/10.1016/j.envexpbot.2023.105223

86. Patel R, Singh P, Sharma D. Overexpression of NHX1 sodium transporter gene increases salinity tolerance in cotton. J Plant Growth Regul. 2022;41(4):1555–68. https://doi.org/10.1007/s00344-021-10522-7

87. Wu Q, Zhang L, Chen Y. Increased expression of GhADH1 (Alcohol Dehydrogenase) enhances waterlogging tolerance in cotton. Front

Plant Sci. 2022;13:876543. https://doi.org/10.3389/fpls.2022.876543

88. Liu F, Zhou X, Li M. Activation of CBF (C-repeat binding factor) genes improves cold tolerance in cotton. BMC Plant Biol. 2023;23:112. https://doi.org/10.1186/s12870-023-04112-7
89. Ahmed M, Zhang Y, Li X, Wang S. Upregulation of DREB2A and GhMYB transcription factors confers drought tolerance in cotton. Plant Physiol Biochem. 2023;198:105621. https://doi.org/10.1016/j.plaphy.2023.105621
90. Sun W, Yu J, Tu J, Zhang W, Zhang X. Breeding and genetic research of naturally coloured cotton in China. Cotton Sci. 2012;24(1):1–7.
91. Mukherjee S. A history of cotton in colonial India. Cambridge: Cambridge University Press; 2018.
92. Niinimäki K, Peters G, Dahlbo H, Perry P, Rissanen T, Gwilt A. The environmental price of fast fashion. Nat Rev Earth Environ. 2020;1(4):189–200. https://doi.org/10.1038/s43017-020-0039-9
93. Shen B. Sustainable fashion supply chain: Lessons from H&M. Sustainability. 2014;6(9):6236–49. https://doi.org/10.3390/su6096236
94. Kim H, Hall ML. Green brand strategies in the fashion industry: Leveraging connections of the consumer, brand and environmental values. Fashion Sustain. 2015;7(3):195–210. https://doi.org/10.2752/175693815X14338504544943
95. Black S. The sustainable fashion handbook. London: Thames & Hudson; 2012.
96. Li X, Zhu L, Zhang X. Advances in genetic improvement of naturally coloured cotton: A review. Front Plant Sci. 2020;11:1234. https://doi.org/10.3389/fpls.2020.01234
97. Smith CW, Coyle GD. Cotton: Origin, history, technology, and production. New York: John Wiley & Sons; 1997.
98. Fang DD, Percy RG. Cotton breeding. In: Janick J, editor. Plant Breeding Reviews. Vol. 38. Hoboken: John Wiley & Sons; 2014. p. 131–200.
99. Ulloa M, Meredith WR. Cotton breeding. In: Fang DD, Percy RG, editors. Cotton. Cham: Springer; 2018. p. 59–85.
100. International Cotton Advisory Committee (ICAC). Cotton production and sustainability. 2023. Available from: https://www.icac.org

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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