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Genetics of Cotton Fiber Color: Unveiling the Mechanisms and Exploring Gene-Based Approaches for Color Expression

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ABSTRACT

Cotton is a vital natural fiber, and its color significantly impacts its commercial value and marketability. Traditional cotton cultivation focuses on white fibers, but naturally colored cotton (NCC) is gaining attention due to its potential for sustainable and environmentally friendly textile production. This review explores the genetics and molecular mechanisms underlying cotton fiber color, focusing primarily on anthocyanins and gossypol pigments. We discuss the role of key genes involved in pigment biosynthesis and regulatory pathways. Additionally, we analyze the potential of gene-based color expression approaches, including traditional breeding and genetic engineering. We highlight the advantages and limitations of each approach and discuss future research directions for developing NCC varieties with improved fiber quality, yield, and color diversity.

INTRODUCTION

Cotton is one of the most important natural fibers in the world, and its color is a critical quality trait that influences its commercial value and marketability. Traditionally, cotton has been cultivated for its white fibers, but there is growing interest in developing colored cotton varieties for use in various textile applications. Gene-based color expression offers a promising approach to achieving this goal. Throughout the world, in the 1990s, polyester and other man-made fibers faced strong competition. This competition increased further in the early 2000s [1]. Cotton fibers or cotton lint are mostly used in fabrics today [2]. There is a unique way of fiber formation during cotton plant growth. Fiber is created when Smaller cells on the surface of the cotton seed stretch outward. Inner structure breakdown during fiber maturation, and the cell walls shrink, leaving behind a flat, twisted shape [3]. Cotton is a key material in the textile industry. Different dyes are added during production to color fabrics. However, the use of these dyes is causing pollution, which is harmful to human beings [4]. Naturally colored cotton has its color built into the fibers [5, 6]. Scientists are creating improved versions by breeding white cotton with colorful cotton types to produce different colors in cotton fibers naturally. These plants have better color retention, longer fibers, and stronger material than the original colorful cotton. These days, naturally colored cotton is becoming popular

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because of the demand for organic, eco-friendly products. Its biggest advantage of naturally colored cotton is that there is no need to add dyes, which is the most polluting step in fabric production, so it is cleaner and safer for both people and the environment [7, 8]. There are many benefits of naturally colored cotton; it serves as a crucial raw material for eco-friendly textiles [9]. It may cut down on chemical residue, pollution, and processing costs. it may also be less flammable and have a higher UV protection rating than regular white cotton [10, 11]. This colored cotton has been grown for many years, but it hasn't improved as fast as regular white cotton. The biggest reasons are that colored cotton plants produce fewer fibers than white cotton, and their colors look faded. These flaws are making them less practical for large-scale farming [9]. Scientists want to fix this by making the fibers stronger, longer and finer [12]. When the cotton bowl opens, the color in the cotton fibers appears. These natural colors come from pigments which are mixed with the cotton's cellulose. This color trait is passed to the next generation through genes. However, traditional breeding struggles to improve both the cotton's quality (like fiber strength) and its yield at the same time; if one gets better, the other might get worse. These days, scientists are using genetic approaches to create these cotton varieties.

Genetics of Cotton Fiber Color

The color of cotton fibers is determined by the accumulation of pigments, primarily anthocyanins and gossypol. These pigments are synthesized through a complex network of biochemical pathways that are regulated by genes. Several genes have been identified that play important roles in cotton fiber color. For example, the MYB113 gene is a transcription factor that regulates the expression of genes involved in anthocyanin biosynthesis. Targeted Mutations in the MYB113 gene can lead to the production of brown or green cotton fibers [13]. Natural compounds called proanthocyanidins (PAs) and related substances are responsible for the brown color in cotton fibers. Early research found that these flavonoid compounds are responsible for the brown shades [14]. Brown shades, for example, come from compounds made through the plant's natural processes, similar to how flowers or fruits get their colors [15-17]. Pathways by which colored cotton is produced are shown in Figure 1.

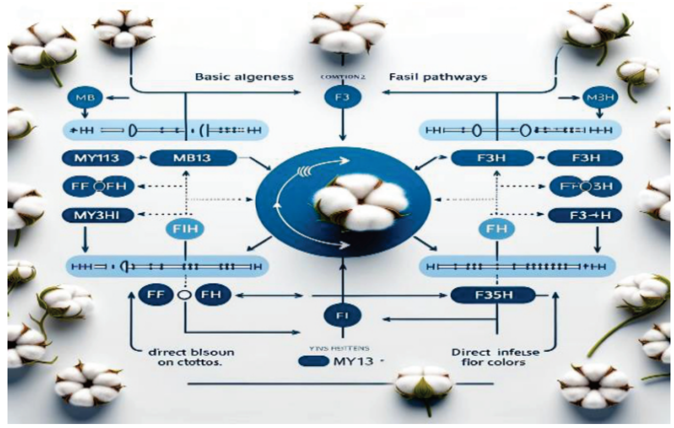

Figure 1: Genetic pathways in Cotton Fiber Coloration

Cotton gets natural brown or green shades from pigments in the fibers. There is a chemical pathway for the production of pigments. Proanthocyanins pigments are responsible for the brown color, and anthocyanins pigments are responsible for other colors. Gene directly controls the formation of these pigments. MYB, bHLH, and WD40 are important genes that switch to turn on the production of color-related compounds. Different enzymes such as F3H, F3'H, and F3'5'H add chemical groups to naringenin and create different forms of modified naringenin, which results in the production of pigments like pelargonidin (involved in red color formation), cyanidin (involved in magenta color formation), and delphinidin (involved in blue color formation) [18]. In the anthocyanin pathway, one of the important steps of pigments like pelargonidin, cyanidin, and delphinidin formation is the addition of a hydroxyl group to naringenin to create dihydrokaempferol, which gives colors to flowers, and is added by flavanone 3-hydroxylase enzyme., F3H's role is most important in color formation, while other enzymes like F3'5'H modify pigments later [19]. These enzymes play a role in the formation of anthocyanins, which are involved in red, blue, and purple shades in plants [20]. When the F3H enzyme is less active, it changes the color of cotton petals. F3'H and F3'5'H enzymes are involved in red and blue pigments and use the same starting materials in a color production process. Different colors are produced by the rise and fall of the level of these enzymes. For example, Brown cotton fibers have more active GhF3H genes linked to this color process as compared to white fibers [21]. In contrast to white cotton fiber, there is a greater level of GhCHS, GhC4H, GhF3`H, and GhF3`5`H enzymes in brown cotton fiber expression during flavonoid synthesis. It is studied the expression of the GhCHS, GhANR, and GhLAR genes affects the concentration of anthocyanidin and fiber color [22]. Finding the key genes, their roles in pigment synthesis, and the specific pigments they influence in cotton fiber coloration (Table 1).

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Table 1: Summarizing Key Genes Involved in Cotton Fiber Coloration

Gene	Role in Pigment Synthesis	Influenced Pigments	References
MYB113	Regulates anthocyanin biosynthesis	Anthocyanins	[23]
F3H	Catalyzes hydroxylation in the anthocyanin pathway	Dihydroflavonols, leading to pelargonidin, cyanidin, delphinidin	[24]
F3'H	Involved in flavonoid B-ring hydroxylation for cyanidin synthesis	Cyanidins (red hues)	[20]
F3'5'H	Facilitates hydroxylation for delphinidin synthesis	Delphinidins (blue hues)	[25]
GhMYB113	post-anthesis (DPA) fibers with tissue-specific promoter	brown mature fibers	[26]
GhPIF4	Regulate the flowering time of cotton	–	[27]
GhCHS	Colored fiber formation	–	[22]
GhANR, and GhLAR	affect anthocyanidin content and fiber color	–	[22]
GhF3H	anthocyanin biosynthesis and fiber color formation	–	[15]
GhDFR1	brown color formation of cotton fiber	–	[15]
GhANS	strongly associated with brown color	–	[29]

Traditional Breeding

This approach involves crossing cotton varieties with different fiber colors to introduce desirable color traits into new varieties. So far, varieties of colored cotton have been developed mostly by selection and recurrent crossing approaches from the germplasm [30]. Selection, the discrimination among variability, is the oldest method of plant improvement [31]. However, this approach is time-consuming and can be challenging due to the complex inheritance patterns of cotton fiber color. The use of statistical genetics and biometrical techniques such as principal component analysis (PCA) and correlation analysis can help in the selection and evaluation of breeding material, optimizing the breeding process, and identifying parental pairs for hybridization [32, 33]. Complex hybridization methods, such as double, complex, and double crossing, have been studied in cotton selection research and have shown promising results in collecting valuable traits from different genetic origins in a single genotype [34].

Genetic Engineering

This approach involves directly introducing genes into cotton plants that control the production of pigments. The science of genetics revolutionized the selection process, taking the guesswork out of it, facilitating it and making it more efficient [35]. Modern plant breeders follow standard methods to create variability, discriminate among the variability, and develop cultivars for release to farmers [36]. This approach can be more efficient than traditional breeding methods, but many ethical concerns and regulatory hurdles need to be addressed (Table 2).

Table 2: Traditional Breeding and Genetic Engineering

Aspect	Traditional Breeding	Genetic Engineering
Time Required	Time-consuming due to multiple breeding cycles	Faster, direct introduction of desired genes
Efficiency	Variable, depends on genetic variability and inheritance patterns	Highly efficient, precise targeting of traits
Challenges	Complex inheritance patterns, lower yield of colored fibers	Regulatory approvals, public acceptance, and possible unintended effects
Potential Outcomes	New varieties with desired color traits and possible yield improvements	Consistent color expression, potential for enhanced fiber qualities
Ethical and Regulatory Concerns	Generally accepted, no significant ethical concerns	Ethical concerns require regulatory approvals

Current Status and Future Prospects

Remarkable progress has been made in understanding the genetic basis of cotton fiber color throughout the world. Many key genes have been identified that play important roles in pigment synthesis in cotton, and transgenic cotton lines with altered fiber colors have been developed by using advanced genetic engineering techniques. Large-scale colored cotton production would be possible if we could overcome the following challenges. Improving the color Expression: Improvement in stability and color expression is needed as the color of transgenic cotton fibers can be variable and sensitive to environmental conditions. Ensuring the safety of colored cotton: Colored cotton fibers must be as safe as white cotton fibers and must not cause any health or environmental risks. Addressing regulatory hurdles and ethical concerns: Genetically edited cotton cultivars must pass regulatory, safety and gain regulatory approval before they can be adopted on a large scale. Many more colors in cotton can be produced once these issues are resolved, and in this way, consumers will be safe from the negative effects which are caused by artificial dyes. This could also lead to new opportunities for textile manufacturers, and it could reduce the extensive cost on use of using dyes.

CONCLUSIONS

If naturally colored cotton varieties are produced, it may be beneficial for both the textile industry and the environment. By understanding the genetics of cotton fiber colors, their formation and applying advanced breeding and genetic engineering such as CRISPR Cas9 and RNAi techniques, scientists can overcome the limitations of traditional methods and can produce a wider spectrum

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of sustainable colors. Naturally colored cotton has the potential to reduce environmental pollution which are associated with dyeing processes, in this way it may be the eco-friendly solution for the fashion industry. Not only can above mentioned benefits be obtained from them they also have other qualities as well, such as improved flammability resistance and UV protection. Once these issues are resolved and new genetic engineering techniques are used, gene-based color expression can transform the cotton industry so in the future, textiles will be eco-friendly.

Authors Contribution

Conceptualization: MNA
Methodology: MNA, MAQ, MR, RB, AA, NS
Formal analysis: RB, AA
Writing review and editing: MAQ, MR, NS

All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

All the authors declare no conflict of interest.

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