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Review

An update on conventional and molecular breeding approaches for improving fiber quality traits in cotton - A review

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The cultivated *Gossypium* spp. represents the most important, natural fibre crop in the world. India is the only country cultivating all the four cultivated species of cotton. Among the *Gossypium* spp., *Gossypium hirsutum* is the most cultivated species in many countries. Breeding for high cotton yield is still the primary goal of cotton breeding programs, but improving fibre quality has become increasingly important. The enhancement of fibre quality traits like fibre length, strength, and fibre fineness is an essential requirement for the modern textile industry. *G. hirsutum* is characterized by its high lint yield while *Gossypium barbadense* has good fibre quality. Through a conventional breeding strategy, introgression of useful alleles for fibre quality from wild species and *G. barbadense* to *G. hirsutum* will be the effective way to improve the fibre quality traits. The identification of the stable quantitative trailt loci (QTLs) affecting fiber traits across different generations will be very helpful in molecular marker-assisted selection to improve fiber quality of cotton cultivars. In this review, we present an overview of the genetics and conventional and molecular breeding techniques that have been used to increase the favorable fibre quality traits in cotton.

Key words: Cotton, fibre quality traits, simple sequence repeat (SSR), restricted fragment length polymorphism (RFLP), amplified fragment length polymorphism (AFLP), quantitative trait loci (QTLs).

INTRODUCTION

Cotton is an important fibre-producing crop, and it plays an important role in the Indian economy. India ranks first in the world in terms of area under cotton cultivation, but occupies third rank in total production. In India, cotton is a major agricultural commodity and a large part of the Indian economy. Worldwide, India is the only country producing that cultivates all four cultivated species of cotton. Cotton production in India is 355 lakh bales during 2011-12 India is the first country throughout the world to exploit hybrid vigor by developing *hirsutum x hirsutum*

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Abbreviations: AFLP, Amplified fragment length polymorphism; **CSR,** complex sequence repeat; **RFLP,** restricted fragment length polymorphism; **RAPD,** random amplified polymorphic DNA; **SRAP,** sequence related amplified polymorphism; **SSR,** simple sequence repeat; **QTL,** quantitative trait loci; **PHB,** polyhydroxybutyrate; **PHA,** polyhydroxyalkanoate; **HPLC,** high performance liquid chromatography; **GC,** gas chromatography; **PCR,** polymerase chain reaction; **MAS,** marker assisted selection.

Table 1. Categories of fibre length in cotton in India (Singh, 2004).

Fibre length			Fibre strength		
Category	**Mean stable length**	**2.5% Span length (mm)**	**Category**	**3.2 mm gauge (g/t)**	**Tenacity (g/tex)**
Short	19.0 and below	Below 20	Very low	Below 17	Below 34.5
Medium	20 - 21.5	20 - 24.5	Low	17-19.5	34.5- 37.4
Superior medium	22 - 24	25 - 27.5	Average	19.6 - 25	37.5 - 43.0
Long	24.5 - 26	28 - 31.5	Good	25.1 - 29.9	43-.1- 47.4
Superior long	27 and above	32 and above	Very good	29.1 & above	47.5 & above

and *hirsutum x barbadense* hybrids which combined high yield potential and superior fibre quality (Alkuddsi et al., 2013).

Fibre quality parameters of cotton, fibre length and fineness have a vital influence the yarn strength. Fibre length is the most important cotton fibre character which determines the amount by which fibres can overlap with one another. The greater overlapping, the easier it is for the fibres to be bound together and result in better yarn strength (Ahmad et al., 2003). Fibre fineness is another important fibre character affecting yarn strength. It contributes to the number of fibres in the cross-section of yarn. The better the fineness of cotton, the more fibres there are per cross-section resulting in higher yarn strength. Broughton et al. (1992) acknowledged that increasing fibre length results in improved yarn strength because a long fibre generates a greater frictional resistance to an external force. Broughton et al. (1992) stated that at high fibre length, the tensile strength of the fibres becomes the controlling factor of yarn strength.

Fibre length and fibre strength properties have influenced textile processing (Kohel, 1999; Amjad, 1999). With this thrust, breeders must always develop new elite cultivars with both high yield and improved quality. One-third of foreign exchange is earned by export of cotton. In total, cotton production contributes to 30% of the Indian agricultural gross domestic product and accounts for 30% of all export earnings. Current modernized spinning mills fibre standards sets mainly based on greater fibre quality, especially strength (Arioli, 2005). Strong fibres survive the rigours of ginning, cleaning, opening, carding, combing and drafting (Guo et al., 2003). Ahuja (2003) also suggested that developing high fibre length and strength cultivars or hybrids is required for current modernized spinning mills. Based on the above, this review summarizes the updated results of conventional and molecular breeding techniques that have been used for the development of favorable fibre quality traits in cotton.

FIBRE QUALITY PARAMETERS

Fibre length

The crucial index of fibre quality in cotton is determined by the spinning performance. Among the fibre properties which contribute most to spinning value are staple length, fibre fineness and strength. The staple length constitutes the basic norm for evaluating quality of cotton in the trade and by the consuming textile industry. Fibre length has been directly correlated with the spinning capacity. The worth of cotton is mainly determined based on the fibre length. Fibre length is generally measured by three ways, as halo length, mean length, and 2.5% span length. Halo length is the length of fibre with attached seed, and it can be measured with the help of halo disc. The mean halo length is the arithmetic mean of the length of all the fibres present within the sample. 2.5% span length is the distance from the clamp on fibre beard to a point up to which only 2.5% of the fibres extend. This is the fibre length representing the majority of the fibres and expressed in millimeter, and measured by the digital fibre graph. Five stable length categories were used for the classification of cotton in India proposed by Singh (2004) (Table 1).

Fibre strength

Of the fibre quality traits, fibre strength is the second most important property of cotton fibre and it determines the yarn strength. The fibre strength is essential for high speed spinning such as rotobar and jet spinning. Fibre strength is generally measured by stelometer. Fibre strength can be determined either on individual fibre or on a bundle fibre. Fibre strength is also known as tensile strength, and expressed as tenacity in gram per tex at 1/8” gauge. Based on the bundle strength and tenacity values, cotton can be classified into five categories (Table 1).

Other fibre quality parameters

Fibre finess is the relative measure of size, diameter and linear density of fibres, which denotes the finess of fibres. It’s also known as micronaire. The ratio between 50 and 2.5% span length is known as uniformity ratio, and it is expressed as percentage. Uniformity ratio denotes the percentage of longer fibres. Fibre elongation percentage is the elongation of the fibre bundle. It is a measure of the per cent increase in jaw separation of instrument under load.

GENETICS STUDIES OF FIBRE QUALITY IMPROVEMENT IN COTTON

The comparison of *Gossypium hirsutum* cultivars for genetically diverse genotypes for fibre quality traits is essential for developing high fibre quality cultivars. Ashokkumar and Ravikesavan (2011) reported, highest 2.5% span length in *G. hirsutum* cultivar SURABHI (32.90 mm), and the lowest 2.5% span length were found in accession SOCC 11 (23.00 mm) and Copur (2006) and Khan et al. (1989) also observed similar results for fiber length in cotton. The bundle strength was lowest in (18.9 g/tex-1) and highest in (22.9 g/tex-1). Fibre fineness or micronaire is very important characteristic of the fiber quality of cotton and is very useful for textile industry. The comparison of treatment mean indicated that *hirsutum* cultivars varied significantly for fiber fineness. SURABHI had fine fibres (3.4 µg inch-1) SOCC17 registered coarse fibre (4.6 µg inch-1) reported by Ashokkumar and Ravikesavan (2011). Differences between the *hirsutum* cultivars with respect to fiber fineness were also found significant by Copur (2006) and Ehsan et al. (2008). Therefore, genetic studies of gene action and association studies were important for fibre quality traits improvement in cotton.

Gene action

The inheritance of fibre quality characters of fibre properties in cotton may be governed by oligogenes with distinct effect of individual gene, and polygenes with small additive effect of each gene. The inheritance of fibre characters, viz., fibre length and strength is governed by polygenes. In polygenic inheritance, the variation for character is continuous from one extreme to another. The fibre length, fibre strength, fibre fineness and uniformity ratio were mainly governed by additive gene action with some of the degree of dominance. Several studies were reported gene action for fibre quality traits in cotton, and it is summarized in Table 2.

Association studies

In path coefficient analysis, indirect effect of seed cotton yield was influenced positively by ginning outturn, lint index, seed index, 2.5 per cent span length, bundle strength and seed protein. The direct effects of seed cotton yield were influenced in negative direction by uniformity ratio, fibre fineness, and elongation percentage (Ashokkumar and Ravikesavan, 2008). Fibre length and strength were negatively associated with seed cotton yield as reported by Amudha et al. (1996), Gururajan and Sunder (2004) and Ahuja et al. (2006). The reviewed up to date research reports of association analysis for fibre quality traits are summarized in Table 3.

SOURCES OF FIBRE QUALITY TRAITS IMPROVEMENT IN COTTON

Wild species

Wild species are the potential sources of fibre quality in cotton. Besides the four cultivated species of *Gossypium*, 50 species have been reported for fibre quality sources. Among them, four species are cultivated for their spinnable fibre and the remaining 46 species are distributed throughout the tropical and subtropical countries in wild forms. Wild species possess useful genes for fibre quality traits like fibre length and strength in cotton. *Gossypium thurberi* is one of the important sources of fibre strength; it's successfully transformed to the cultivated varieties of *G. hirsutum*. Some wild species can serve as possible donors for fibre quality traits and are presented in Table 4. Meanwhile, the variability available from the cultivated species is limited and has been thoroughly exploited for breeding programmes. Therefore, to develop basic germplasm materials enriched with rare useful genes from wild species through introgression is essential. For example, long stable variety AKA 8401 has been obtained from the cross between *Gossypium arboreum* cultivars and *Gossypium anomalum* (Tayyab, 1990). Phenotypic variation between wild species of cotton is shown in Figure 1.

Induced mutation

Mutations are the potential source of creating genetic variability in the plant breeding material. Since the spontaneous mutations having the extremely low frequency and the induced mutation provides a tool for the rapid creation of variability in crop species. In cotton breeding, while hybridization and selection have stood the test of times, of late mutation breeding techniques has come in handy for improvement of specific characters. Fibre quality traits can also be improved through the use of induced mutations. However, this source is rarely used in the improvement of fibre quality traits. In upland cotton, some of the x ray induced mutants showed better fibre quality than their parents (Thompre and Mehetre, 1982). For example: MCU 7 cotton variety is the x rays irradiation of L1143; it increased the yield and spinning performance.

BREEDING APPROACHES

The breeding methods like introduction, selection, hybridization followed by mass selection, pedigree selection, back cross method, mutation breeding,

Table 2. Gene action for fibre quality traits in cotton.

Fibre character	Gene action	Species	Reference
Fibre length	Additive	*G. hirsutum*	Pavasia, et al. (1989); Mandloi et al. (1998); Muthuswamy et al. (2003); Haq and Azhar (2004); Subramanian et al. (2005)
	Non-additive	*G. hirsutum*	Tuteja et al. (1995); Ahuja and Tuteja (1999); Hassan et al. (2000); McCarthy et al. (2004); Ahuja and Dhayal (2007); Ashokkumar et al. (2010)
	Non-additive	*G. barbadense*	Gururajan and Manickam (2002)
	Additive	*G. arboreum*	Sandhu and Singh (1989)
	Partial dominance	*G. hirsutum*	Krishna Rao (1998)
	Dominance	*G. hirsutum*	Patel et al. (1997)
	Additive and dominance	*G. hirsutum*	Nadarajan and Sree Rangasamy (1992)
	Additive and non-additive	*G.hirusutum*	Gupta (1993)
		G. arboreum	Tomar and Singh (1992)
Fibre fineness	Additive	*G. hirsutum*	Nadarajan and Sree Rangasamy (1990); Amudha et al. (1997); Bharad et al (1999); Mandloi et al. (1998); McCarthy et al. (2004); Subramanian et.al. (2005); Lukonge et al. (2007); Azhar et al. (2004)
	Non-additive	*G. hirsutum*	Krishna Rao, 1998; Hassan et al. (2000); Muthuswamy et al. (2003); Ahuja and Dhayal (2007); Ashokkumar et al. (2010).
	Non-additive	*G. barbadense*	Gururajan and Manickam (2002)
	Additive and dominance	*G. hirsutum*	Nadarajan and Sree Rangasamy (1992); Nageshwara Rao et al. (2002).
Uniformity ratio	Additive	*G. hirsutum*	Nadarajan and Sree Rangasamy,(1990)
	Non-additive	*G. hirsutum*	Muthuswamy et al. (2003); Preetha and Raveendran (2008); Ashokkumar et al. (2010)
	Non-additive	*G. barbadense*	Gururajan and Manickam (2002)
Fibre strength	Additive	*G. hirsutum*	Amudha et al. (1997); Swati et al. (1999); McCarthy et al. (2004; Azhar et al. (2004); Lukonge et al. (2007)
	Additive and non-additive	*G. hirsutum*	Rao and Reddy (2002)
	Non - additive	*G. barbadense*	Gururajan and Manickam (2002)
	Non -additive	*G. hirsutum*	Valarmathi and Jehangir (1998); Ahuja and Dhayal (2007); Hassan et al. (2000); Muthuswamy et al. (2003); Ashokkumar et al. (2010).

heterosis breeding and molecular breeding, among others can be used to breed new varieties/ hybrids combining high yield potential and superior fibre quality. Of them, briefly discussed few breeding techniques utilized for exploitation of fibre quality enhancement in cotton was given under below.

Progeny selection

Superior plants are selected from a heterogeneous population as the basis of their progeny performance is referred association progeny selection. Singh et al. (1988), reported improvement in fibre length and strength in the progenies originally selected from open pollinated Bikaneri Narma. The improvement was more in the progenies isolated from segregating populations of the cross between Bikaneri Narma and Pusa-734. One genotype Pusa GH 95-33-47-2-2 has been registered as germplasm with NBPGR, New Delhi for high fibre length and strength of 26.2 g/tex at 3.2 mm gauge and high

Table 3. Genotypic and phenotypic correlation studies for fibre quality traits cotton.

S/N	Character	Correlation	Reference
A	Seed cotton yield with		
1	Ginning outturn	Positive	Choudhary et al. (1988); Krishna Rao and Mary (1990); Swati Bharad et al. (19990; Kaushik et al. (2003); Ashokkumar and Ravikesavan,(2010)
2	Lint index	Positive	Valarmathi, 1996; Echekwu, 2001; Kowsalya and Raveendran (1996), Murthy et al. (1995); Kaushik et al. (2003); Ashokkumar and Ravikesavan, 2010.
3	Fibre length	Negative	Valarmathi (1996); Swati Bharad et al. (1999); Ahuja et al. (2006); Ashokkumar and Ravikesavan,(2010)
4	Bundle strength	Positive	Swati Bharad et al. (1999)
		Negative	Valarmathi (1996); Rao et al. (2001); Ashokkumar and Ravikesavan (2010)
5	Seed index	Positive	Faqir et al. (1984); Tomar and Singh (1992) Sambamurthy et al. (1995); Ashokkumar and Ravikesavan (2010)
6	Fibre fineness	Positive	Kowsalya and Raveendran (1996), Murthy et al. (1995); Kaushik et al. (2003); Ashokkumar and Ravikesavan (2010)
B	Fibre length with		
1	Fibre strength	Positive	Echekwu, 2001, Basang and Gencer, 2007; Ashokkumar and Ravikesavan, 2010; Magadum et al.(2012).
2	Fibre fineness	Negative	Rajarathinam et al. (1993); Swati Bharad et al. (1999); Basang and Gencer (2007); Ashokkumar and Ravikesavan (2010)
3	Lint index	Positives	Kadambavanasundaram (1980); Magadum et al. (2012).
4	Uniformity ratio	Negative	Rajarathinam et al. (1993); Preetha and Raveendran (2008); Magadum et al. (2012).
C	Fibre fineness with		
1	Strength	Negative	Singh et al. (1990); Basang and Gencer (2007); Ashokkumar and Ravikesavan (2010)
2	Fibre length	Negative	Krishna Rao and Mary (1990)
3	Uniformity ratio	Positive	Rajarathinam et al. (1993)
D	Fibre strength with		
1	Fibre length	Positive	Ashokkumar and Ravikesavan (2010)
		Negative	Larik et al. (1999); Desalegn et al. (2009); Magadum et al.(2012).
2	Fibre fineness	Negative	Singh et al. (1990); Desalegn et al. (2009); Ashokkumar and Ravikesavan (2010); Magadum et al. (2012)
3	Elongation percentage	Positive	Basang and Gencer (2007)
4	Uniformity ratio	Negative	Desalegn et al. (2009)

Table 4. Wild species utilized for fibre quality traits improvement in cotton (Gotmare et al., 2000).

Fibre quality	Species
Fibre length	*G. anomalum, G. stochsii, G. raimondii, G. areysianum and G. longicalyx*
Fibre strength and elongation	*G. stochsii, G. areysianum, G. thurberi, G. anomalum, G. sturtianum, G. raimondii, and G. longicalyx*
Fibre fineness	*G. longicalyx, G. anomalum, and G. raimondii*
Fibre yield	*G. stochsii, G. areysianum, G. anomalum, G. sturtianum, and S. australe*
High ginning	*G. austral*

elongation of 7% (IGNR No. 0.3099). Furthermore, Singh et al. (1988) identified six promising genotypes namely; P56-2, P56-4, P56-6, C4-9-2-1, C4-9-2-1-2 and P4515-1 have been identified for high fibre strength at IARI. These

Figure 1. Genetic variation of the flower in between the cotton wild species *G. hirsutum X G. barbadense G. hirsutum x G. anomalum* Arogya (NISD 2) TCHB 213, MCU 2, MCU 5, Varalaxmi, DCH 32, and HB 224.

genotypes were showed fibre strength ranging from 24.3 g/tex (P56-2) to 29.4 g/tex (P56-4).

Intra and inter-specific hybridization

Hybrids of two genotypes of the same species are referred to association intra specific hybridization. A number of varieties belonging to different cultivated species have been developed through intra specific hybridization. For example, LRA 5166, Suman and DH-286 of *G. hirsutum* were developed from single, three way and double cross, respectively. Variety MCU 5 having high yield potential and spinning to 60 counts and its origin form a multiple cross-involving five parents. Progeny of a cross-between two different species of the same genus are referred association inter specific hybridization (Nijagun and Khadi, 2001). It can be readily made between the cultivated teraploid cottons, that is, *G. hirsutum* and *Gossypium barbadense* and *Gossypium arboreum* and *G. herbaceum.* Interspecific crosses amongst the wild species within a genome, between different genomes and between diploid species and cultivated tetraploid species are successful in varying degrees. Tetraploid species hybridizes are mostly successful for the majority of diploid species. Interspecific crosses between *G. arboreum* and *G. hirsutum* have also been successfully used to develop *G. aboreum* varities with fibre quality at par with, besides high-yield potential. Examples, the varieties like MCU 2 and MCU 5 were developed by introgression from *G. barbadense* and the world first interspecific commercial hybrid Varalaxsmi and DCH-32 (Jayakaksmi) has extra-long stable cotton production and TCHB 213 also have fibre quality with yield were reported by (Gotmare and Singh, 2004) and shown in Figure 2.

Exploitation of heterosis

India is the first country in the world to exploit heterosis in cotton at the commercial level. Inter-specific and Intra specific hybrids have been developed, which combine high yield and superior fibre quality. Besides this, hybrids also have wide adaptability and perform well under varied agro-climatic situations. Inter-specific hybrids between *G. hirsutum* and *G. barbadense* like DCH-32, DHB-105, and HB-224 have fine quality and spin to 80 counts. Ano et al. (1983) reported that *G. barbadense* parent played a dominant role in determining the fibre quality of the hybrids. Inter specific hybrids between *G. hirsutum* and *G. barbadense* have produced high frequency of fibre quality traits (Ano et al., 1983). Therefore, choice of *the G. barbadense* parents is very important in developing *G. hirsutum* x *G. barbadense* hybrids. The summarized up to date research reports of exploitation of heterosis for fibre

Figure 2. Examples of cotton cultivars developed through interspecific hybridization breeding technique for fibre quality.

quality traits are presented in Table 5.

BIOTECHNOLOGICAL APPROACHES

Biosynthesis of cotton fibre

Cotton fibre cells are the tubular outgrowth of single celled trichomes, which arise in near synchrony from the epidermis of the ovule, and it may elongate ate peak rates in excess of 2 mm per day during rapid polar expansion phase of development (Basra and Malik, 1984). There has been a substantial progress in our understanding of cellulose synthesis in developing cotton fibers. However, little is known about the early events controlling fibre cell initiation. Morphologically, the initiation of each fiber cell is associated with the spherical expansion and protrusion of one epidermal cell above the ovular surface during anthesis (Basra and Malik, 1984). Cotton fibre grows in four distinct phases of development viz., fibre initiation, elongation, secondary deposition and maturation and dehydration (Graves and Stewart, 1988). Ultra structural evidence indicates that expansion occurs through a diffusion mechanism, albeit with some bias for deposition of newly synthesized cell wall materials at the tip (Tiwari and Wilkins, 1995). Fibre elongation per se involves the deposition of the primary cell wall via secretory mechanism involving the dictyosomes and a protein synthesis mechanism sufficient to supply the proteins required in the expansion of plasma membrane and tonoplast, while the rate of biosynthesis of degradation.

Fibre modification through Genetic engineering

The fibre properties of cotton arise from the manifestation of thousands of genes. The conventional breeding, part of the gene pool from one cultivar is exchanged with that of another compatible cotton cultivar. Nevertheless, their diversity of fibre quality traits among different cotton cultivars is limited. Hence, recombinant DNA technology and new genetic transformation techniques can over-come this limitation. The critical task is to identity genes that can modify relevant fiber properties. There are several general strategies were used for fibre in cotton.

Table 5. Heterosis, heterobeltiosis and standard heterosis for fibre quality improvement in cotton.

Character	Species	Relative heterosis (%) di	Heterobeltiosis (%) dii	Standard heterosis (%) diii	References
Fibre length (mm)	*G arboreum*	-	-10.9 - 41.5 *	-	Singh and Narayanan (1990a)
		-	-23.0 -26.2*	-	Duhoon (1990)
	G. hirsutum	-	-19.42**-6.86*	-	Siddique (1993)
	G. hirsutum	-	-12.5**-3.4*	2.7 - 28.3	Kumar et al. (1992)
	G arboreum *G. hirsutum*	-16.39** -14.40**	-19.42**-6.86*	-	Siddique and Patil (1994)
	G. hirsutum	(-12.0) - 28.1	(-20.7) - 27.6	(-23.7) - 0.6	Krishnadoss and Kadambavasundaram (1997)
	G. hirsutum	-6.72 to 8.31	-6.23 to 8.21	-7.15 to 8.78	Reddy (2001)
	G. hirsutum	-11.19 to 16.79	-16.29 to 10.60	-11.54 to 16.78	Neelima (2002)
	G. hirsutum	3.70*-4.30*	-0.23- (-7.29)	-	Khan (2002)
	G. hirsutum	-	-	-4.17 to 15.53	Tuteja et al. (2005)
	G. hirsutum	-	-	7.35*- (-20.69**)	Pushpam and Raveendran (2005)
	G. hirsutum	-7.19* to -11.30**	-	-	Preetha and Raveendran (2008)
	G. hirsutum	5.3*-9.6**	-	-	Basal et al. (2011)
Fibre fineness	*G. hirsutum*	10.34* - 24.14**		-	Preetha and Raveendran (2008)
	G. hirsutum	-	-	-12.70*- (-25.40**)	Pushpam and Raveendran (2005)
	G. hirsutum	-0.12 - (-14.40)	-	-	Karademir et al. (2009)
Bundle strength (g/tex)	*G. hirsutum*	-	-	-7.59*- (-18.62**)	Pushpam and Raveendran (2005)
	G. hirsutum	-6.78* - 15.25**	-	-	Preetha and Raveendran (2008)
	G. hirsutum	0.55-24.67	-	-	Karademir et al. (2009)
	G. hirsutum	-5.1* to 9.9*	-	-	Basal et al. (2011)
Uniformity ratio (%)	*G. hirsutum*	-	-	6.21*-8.97**	Pushpam and Raveendran (2005)
	G. hirsutum	0.00-3.10	-	-	Karademir et al. (2009)
	G. hirsutum	1.8* -2.7**	-	-	Basal et al. (2011)
Elongation (%)	*G. hirsutum*			-13.45*-(-30.04**)	Pushpam and Raveendran (2005)
	G. hirsutum	0.53 - (-11.58)	-	-	Karademir et al. (2009)
	G. hirsutum	-0.3 - (-5.5)	-	-	Basal et al. (2011)

*, **, Significant at 5 and 1% probability level, respectively.

One approach is to increase or decrease levels of fibre proteins or enzymes (John and Stewart, 1992). The second strategy is to select potential genes from sources other than cotton. The potential gene polyhydroxybutyrate (PHB), and polyhydroxyalkanoate (PHA) identified from biological sources for fibre modification (Steinbuchel, 1991; John and Keller, 1996). These two genes were engineered for expression in fiber by linking them to fiber-specific promoters and introduced into cotton by particle bombardment. Transformants were identified by expression of the marker gene GUS and further confirmation were done by high performance liquid chromatography (HPLC) and gas chromatography (GC); mass spectra for isolation of PHB were presented in fibre (John and Keller, 1996). These developments will lead to improved fiber quality traits in cotton and enable the textile industry to expand its market share (John, 1997).

Molecular mapping studies for fibre quality traits

To understand the genetic basis of cotton fibre traits for the improvement of fibre quality, a genetic linkage map was constructed in the tetraploid cotton using sequence related amplified polymorphism (SRAP) linkage construction, simple sequence repeat (SSR) and random amplified polymorphic DNA (RAPD) (Lin et al., 2005). A total of 238 SRAP primer combinations, 600 RAPD primers and 368 SSR primer pairs were used to screen polymorphisms. Sixty-nine F_2 progeny from inter specific cross of "Handan 208 X Pima 90" were genotyped with 749 polymorphic markers. The identification of the stable quantitative trait loci (QTLs) affecting fiber traits across different generations will be greatly helpful to be used effectively in molecular marker-assisted selection to improve fiber quality of cotton cultivars in the future. Moreover, Lin et al. (2005) observed a total of 566 loci were assembled into 41 linkage groups with at least three loci in each group, and in total 13 QTL was associated with fibre traits among them for QTL were for fibre length and two for fibre strength.

Shen et al. (2005) used three elite fiber lines of upland cotton as parents, three linkage maps were constructed to tag QTLs for fiber qualities using SSR markers and found 11 QTLs for fiber length, 10 for fiber strength, 9 for fineness and 9 for fiber elongation. Gopalakrishnan et al. (2011) studied RAPD-polymerase chain reaction (PCR) analysis for MCU 5, and its mutant MCU 5LL was initially done with 100 primers. Majority of the primers failed to amplify in both the genotypes and observed the only 20 primers gave the best banding pattern. Shaheen et al. (2013) constructed an intraspecific genetic linkage map of the A-genome diploid cotton with SSR and RAPD markers, by 180 F_2 plants were derived from the cross of 2 *G. arboreum* cotton cultivars. Polymorphisms between the two parents were detected using 1089 pairs of SSR primers and 520 RAPD primers. In total, 34 pairs of SSR and 18 RAPD primers were amplified polymorphic loci of F_2 population. The other molecular studies for fibre quality traits were detailed summarized in Table 6.

ACHIEVEMENTS OF FIBRE QUALITY IMPROVEMENTS IN INDIA

A remarkable success has been achieved in improvement of fibre quality, particularly fibre length and strength of cotton lint during the five decades. MCU 5 is the first extra-long stable variety of *G. hirsutum* and MCU 5 VT, MCU 9, MCU11, and Abhadita are also other extra-long stable varieties. Several *G. barbadense* cultivars have resulted in significant breakthrough in fibre quality improvement in India.

Among them, Sujata and Suvin cultivars resulted in significant capable of spinning 100 counts and 120 counts, respectively, comparable to several Egyptian and Sudan types. This is the distinct landmark in the cotton fibre quality enhancement in India. In addition, inter specific hybrids of Varalaxmi, DCH-32, HB-224; NHB-12, TCHB-123 and Suruthi have the high yield with good fibre quality. *G. herbaceum* cultivars Raichur 51, Sujay, G. Cot 11, 13, 17, 21, and G. Cot 23 varieties had high yielding and medium stable varieties. High yielding and good fibre quality interspecific hybrid is (DH 2, DH 7, DH 9 and Pha 46) milestone of the *G. herbaceum* cotton. The cultivar K 8 is the first long stable variety of *G. arboreum* and K 9, K10, K 11 and AKA 8401 these varieties have fibre length of 25 mm and capable of spinning 36 counts. *G. arboreum* race indicum has been widely used for the improvement of fibre length.

CONCLUSION

India is an only country cultivating all the four cultivated species of cotton. Breeding for high cotton yield is still the primary goal of cotton breeding programmed, but improving fibre quality has become increasingly important. *G. hirsutum* characterized its high lint yield while *G. barbadense* has good fibre quality. In genetic engineering, particle bombardment technology has been developed to introduce and test genes into elite varieties of cotton, without need for regeneration or other tissue culture practices and backcrossing will lead to improved fiber quality traits in cotton and enable the textile industry. Therefore, currently there is an immediate need for a high-density genetic map of cotton anchored with fiber genes to facilitate marker-assisted selection (MAS) for improved fiber traits. Through conventional breeding strategy, introgression of useful alleles for fibre quality from *G. barbadense* to *G. hirsutum* will be the effective way for enhancing fibre length and strength in *G. hirsutum* cultivars.

Table 6. Molecular mapping for fibre quality trait improvement in cotton.

Species	Mapping populations	Markers used	Number of QTLs identified	LOD	QTL in the marker interval (cM)	Total map length coverage (cM)	References
G. hirsutum	F_2, F_2:F_3	SSR	11 QTL for fibre length, 10 QTL for fibre strength 9 QTL for fibre fineness 9 QTL for fibre elongation	≥ 3.0	-		Shen et al. (2005)
G. arboreum	182 F_2	SSR and RAPD	2 QTL for fibre traits	≥ 3.0	-	346	Shaheen et al.(2013)
G. anmolum x G. hirsutum	186 F_2 and F_3	SSR and RAPD	2 QTL for fibre strength	≥ 5.0	4.2	-	Zhang et al. (2003)
G. hirsutum x G. barbadance	F_2	RAPD and RFLP	3 QTL for fibre length 4 QTL for fibre strength 6 QTL for fibre fineness	≥ 2.0	10	-	Kohel et al. (2001)
G. hirsutum	119 F_2:F_3	RFLP	2 QTL for fibre length 3 QTL for fibre strength	-	8.7	700.7	Ulloa and Meredith (2000)
G. hirsutum x G. barbadance	94F_2	AFLP and SSR	7 QTL for fibre traits	≥ 3.0	3.28	5,500	Mei et al. (2003)
G. hirsutum x G. barbadance	183 RILs	SSR and CSR	13 QTL for fibre length, strength and fineness	≥ 2.9	-	1277	Park et al.(2005)
G. hirsutum	F_2, and BC_1	AFLP and SSR	6 QTL for fibre strength	-	10.11	932.9	Chaudhary et al. (2013)

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