INNSPUB

Journal of Biodiversity and Environmental Sciences | JBES
ISSN: 2220-6663 (Print); 2222-3045 (Online)
Website: https://www.innspub.net
E-mail contact: info@innspub.net
Vol. 27, Issue: 2, p. 109-116, 2025

REVIEW PAPER
OPEN ACCESS

Combining ability, heterosis and stability for yield and fibre quality traits in cotton: Breeding approaches and future prospects

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Key words: Cotton breeding, Heterosis, General combining ability, Specific combining ability, Hybrid vigour

DOI: https://dx.doi.org/10.12692/jbes/27.2.109-116 **[Published: August 16, 2025]**

ABSTRACT

Cotton breeding has progressed significantly with the integration of conventional and molecular approaches aimed at enhancing yield, fiber quality, and adaptability to biotic and abiotic stresses. In order to create superior cotton hybrids, heterosis, or hybrid vigor, is essential. Both intraspecific and interspecific crossings exhibit notable improvements in component characteristics and seed cotton production. Finding prospective parental lines and cross combinations requires evaluating both general combining ability (GCA) and specialized combining ability (SCA). While SCA denotes non-additive gene effects, namely dominance and epistasis, which contribute to heterotic performance in particular crossings, GCA represents additive gene effects, which are frequently associated with the accumulation of advantageous alleles across generations. Heterosis exploitation is widely used in cotton hybrid breeding projects to evaluate GCA and SCA through top-cross, line × tester, and systematic diallel studies. The accuracy of detecting high GCA parents and better SCA hybrids has increased because to developments in genomic selection, marker-assisted selection, and biotechnological treatments. In order to maximize heterosis expression, increase genetic variety, and maintain production in the face of climatic unpredictability, future opportunities lay in combining genomic methods with traditional breeding. The next stage of cotton enhancement may be fueled by a smart mix of utilizing molecular breakthroughs, optimizing combining ability, and taking use of heterosis.

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INTRODUCTION

Cotton (*Gossypium hirsutum* L.) is one of the most important fibre crops worldwide, contributing significantly to the textile industry and rural economies. Cotton breeding initiatives continue to focus on increasing yield and fiber quality, despite the fact that these qualities are quantitatively inherited, impacted by intricate genetic processes, and heavily impacted by environmental influences. Combining ability research offers important insights into the type of gene activity influencing these qualities by dividing genetic variation into general combining ability (GCA) and specialized combining ability (SCA). The selection of appropriate parents and hybrid pairings is guided by both additive and non-additive gene effects, as shown by GCA and SCA, respectively. In 1942, Sprague and Tatum introduced the idea of general and specific combining ability as a way to quantify the impact of genes. Heterosis, or hybrid vigor, is essential to improving cotton because it uses non-additive genetic diversity to boost performance above and beyond that of parental lines, especially in terms of yield components, fiber length, strength, and fineness. The most significant genetic instrument for increasing the production of both self-pollinated and cross-pollinated crops is the phenomenon of heterosis, which is regarded as the most significant development in crop improvement. Shull first used the term "heterosis" in 1914. Breeders may find genotypes that consistently perform well in a variety of situations by using stability analysis, which further enhances existing methods by assessing genotype × environment interactions. Developing hybrids and varieties that not only perform better but also hold their edge in a variety of climatic circumstances requires the combination of studies on combining ability, heterosis, and stability. Technological developments in genomic selection, molecular breeding, and biometrics have improved the accuracy of these assessments and made it possible to effectively harness both additive and non-additive genetic effects while maintaining flexibility. A breeding strategy that effectively uses combining ability, heterosis, and stability information offers enormous promise for sustainable cotton production in light of climate change, insect pressure, and the growing need for high-quality fibers. The genetic principles, methodological developments, and useful breeding techniques related to these three fundamental ideas are the main focus of this review. It also highlights how these three ideas work together to improve cotton yield and fiber quality and outlines potential future integrations of contemporary tools into traditional breeding frameworks. By crossing the inbred lines, the F1 generation demonstrates vigor and production, according to Shull (1952). Kempthorne (1957) described a methodical way to integrating ability studies using the Line × Tester method of analysis. The best biometric method for examining the genetic profiles of characters in general is L×T. The study of heterosis gives information on the parents' use in breeding programs for hybrid enhancement. The results of the combining ability study showed that the variation resulting from general combining ability (gca) was less than that resulting from specialized combining ability (sca), suggesting that non-additive gene action predominated for all of the characteristics. For these qualities, non-additive gene action was also observed by Nimbalkar *et al.* (2004) and Patel *et al.* (2009). To meet the challenge of increasing output and preserving fiber quality under a variety of agroclimatic conditions, cotton breeding techniques that incorporate combining ability, heterosis, and stability analysis are crucial. Through hybrid development initiatives, the exploitation of heterosis in cotton has been made easier. Intra-hirsutum and inter-specific hybrids have demonstrated significant yield improvements over traditional types. The significance of parental selection based on combining ability analysis is shown by the fact that the amount of heterosis for yield attributes is often larger in hybrids involving genetically different parents. Specific combining ability is linked to dominance and epistatic effects, which are not fixable but may be successfully manipulated by hybridization, whereas general combining ability is usually linked to additive effects, which can be fixed through selection. Breeders can evaluate genotypes for both mean performance and adaptability using stability studies, which use a variety of statistical models to make sure that superior hybrids function consistently in a variety of settings and seasons. This is becoming more and more crucial in light of shifting climate circumstances, where environmental fluctuations can have a big impact on fiber quality metrics including bundle strength, micronaire value, and uniformity index. By making it possible to identify the genomic areas linked to yield and fiber qualities, the combination of molecular marker technologies and genomic selection with traditional breeding methods has improved the accuracy of forecasting combining ability and heterosis. Utilizing genetic prediction models and marker-assisted selection, hybrids that combine high production, better fiber quality, and broad adaptability are being developed. A breeding framework that integrates stability tests, molecular tools, and biometrical analysis provides a thorough approach to creating cotton hybrids that sustainably satisfy quality and productivity requirements. Climate change has presented cotton breeders with more difficulties in recent years, such as drought, changed precipitation patterns, and rising temperatures, all of which endanger cotton yield. It is now urgently necessary to develop cotton types with improved resistance to heat stress, water usage efficiency, and drought (Patel *et al.*, 2022).

Combining ability: general combining ability (GCA) and specific combining ability (SCA) in Cotton

Combining ability in cotton refers to the potential of parental lines to produce superior offspring when used in hybrid combinations. Enhancing productivity and fiber quality attributes is essential in breeding efforts. Specific combining ability (SCA) quantifies performance that deviates from expectations, whereas general combining ability (GCA) indicates average performance over several hybrid combinations. It is crucial to strike a balance between the impacts of GCA and SCA, with hybrid breeding strategies working better for non-additive characteristics and selection-based methods for additive traits. Cotton improvement programs can find better parents and hybrid combinations by incorporating GCA and SCA analysis. With the exception of average boll weight, combining ability analysis indicated that non-additive gene activity predominated for all characteristics. The male parent, GSB 19, was an excellent general combiner for seed cotton yield per plant and its component features, namely average boll weight and lint yield per plant, whereas the female parent, G. 67, was the best general combiner for the bulk of the qualities. With the exception of plant height, the hybrid G. 247 x Suvin showed a strong positive sca impact for seed cotton output per plant and its contributing features (Patel *et al.*, 2012). The significance of the genotypes and their interactions was evaluated by combining ability effects analysis and analysis of variance. Genetic heterogeneity in the breeding material was shown by the significant variability across parental genotypes for yield-related parameters. Analysis of combining abilities showed that non-additive gene activity predominated. For the majority of characteristics, general combining ability (GCA) impacts were considerable; the biggest GCA effects were shown in CIM-599. For different characteristics and hybrid combinations, the impacts of specific combining ability (SCA) and reciprocal combining ability (RCA) were substantial, suggesting that they have the potential to improve traits (Rasheed *et al.*, 2023). The number of sympodial branches, seed cotton production per plant, and micronaire are the features for which the extremely significant values of sca exist. In addition to strong heterosis for the traits of boll weight and seed cotton yield per plant, CO14 × NDLH1938 exhibited a highly significant sca impact for the upper half mean length trait. As a result, among the four lines, MCU5 had the best gca value for the top half mean length. Among the four tests, the KC3 tester contributed to additive genes, as evidenced by its high gca value. Not all good combiners have good sca effects for certain features. Non-additive or dominant gene activity was seen in most of the traits examined (Keerthivarman *et al.*, 2023). Mean squares values for all the characteristics under investigation revealed significant (p=0.01) differences between genotypes. The parents with the strongest general combining talents were F-2228, F-2164, and LH-2108. The most divergent parental lines were determined to be RS-2013 and RST (Giri *et al.*, 2021). The results of the combining ability study showed that the variation resulting from general combining ability (gca) was less than that resulting from specialized combining ability (sca), suggesting that non-additive gene activity predominated for all characters. For seed cotton production, the parents JLA 794 were an excellent general combiner. According to Patil *et al.* (2014), the parent Hegha 46 was an excellent general combiner for boll weight, quantity of bolls, and lint output (kg/ha). Certain cotton types have performed exceptionally well in different parts of the Indian subcontinent. States like Uttar Pradesh, for example, favor cultivars like LRA-5166, H-777, and Bunny. Additionally, in hybrid combinations, Mehran × FH-901 showed higher Specific Combining Ability (SCA) effects for both 100-seed weight and seed cotton yield per plant, CRIS-342 × Koonj showed superior SCA effects for bolls per plant, and CRIS-342 × CIM-602 and CRIS-342 × FH-901 showed noteworthy SCA effects for staple length and lint percentage, respectively (Solangi *et al.*, 2024). AC 3097 and AKA 13-SP1 were shown to be good general combiners for the majority of the variables in this investigation based on the genotypes' general combining ability (GCA) effect. The strong combining ability of genotypes PBS 1127-SP1, AKH 496, H 509, N11-54–31-32, and AKA 13-SP1 contributed to a significant specific combining ability (SCA) effect in seven selected crosses for yield improvement (AC 3265 × PBS 1127-SP1, AKH 496 × H 509, AKH 496 × AC 3097, PBS 1127-SP1 × N11-54–31-32, AC 3216 × AKA 13-SP1, H 503 × N11–54–31-32, and H 509 × AKA 13-SP1) (Manivannan, 2024). In order to maximize the use of genetic resources for creating new crop varieties, combining ability studies are essential in plant breeding since they assist in identifying parent genotypes that can produce durable and high-yielding hybrids. Understanding the genetic mechanisms governing yield, a complex trait, and choosing the best parental combinations to create high-performing hybrids depend on the ability of parents to combine and the gene action of traits, which can be predicted using diagonal mating design (Majeed *et al.*, 2021).

Heterosis in cotton

Heterosis, also known as hybrid vigor, is the occurrence in which the hybrid offspring perform better than their parents. Heterosis is one of the most useful techniques in hybrid breeding projects since it has been widely used in cotton to improve seed cotton output, fiber quality, and adaptability. Heterosis is important because it may combine good qualities from two genetically different parents to create hybrids that perform better in important economic and agronomic traits. In commercial cotton production, where hybrids frequently provide higher yields and superior resilience under varied environmental circumstances, its function is particularly important. Three main mechanisms dominance, over dominance, and epistasis are used to explain the genetic foundation of heterosis in cotton. Over dominance implies that heterozygotes at certain loci are more fit than either homozygote; dominance is the masking of harmful recessive alleles by advantageous dominant ones; and epistasis is the interplay of genes at many loci that improves trait expression. In hybrids, these genetic exchanges produce a cumulative advantage that boosts vigor and output. Three metrics are used to quantify cotton heterosis. Mid-parent heterosis assesses how well the hybrid performs in comparison to its parents' average performance. The advantage over the better-performing parent is measured by better-parent heterosis, also known as heterobeltiosis, which suggests the possibility of substantial genetic improvement. By contrasting the hybrid's performance with that of a well-known commercial check variety, standard heterosis gives light on whether the hybrid is suitable for large-scale production. Breeders may learn a lot from each type of heterosis when evaluating and choosing hybrids. For yield parameters including boll weight, number of bolls per plant, and seed cotton production, the degree of heterosis is frequently significant, especially when parents are selected from different genetic origins. Although the degree of expression may differ according on the characteristic and paternal combinations, heterotic effects also boost fiber quality attributes such fiber length, strength, and fineness. The introduction of commercially viable hybrids has been made possible by the simultaneous enhancement of yield and fiber quality through heterosis, which has been a significant accomplishment in many breeding initiatives. The effectiveness of heterosis exploitation has increased because to recent developments in genomics and molecular breeding. More precise predictions of heterotic potential and improved identification of complementary parents are made possible by marker-assisted selection, genomic prediction models, and molecular diversity analysis. Heterosis can also be carefully employed to create climate-resilient cotton hybrids that can sustain quality and production in the face of biotic and abiotic stressors. The entire potential of heterosis in cotton may be achieved by combining traditional breeding techniques with cutting-edge molecular technologies, guaranteeing competitiveness in the global textile market and sustainable production. Forty-five interspecific hybrids between *G. hirsutum* × *G. barbadense*, derived from nine diverse female parents of *G. hirsutum* and five pollen parents of *G. barbadense*, were evaluated to study heterosis for seed cotton yield and its component traits. Significant heterosis was observed for the characters under study, indicating the presence of genetic diversity among the parental lines. The hybrid (G. 67 × GSB 19) exhibited significant positive heterosis over the standard check hybrid for seed cotton yield per plant (Patel *et al.*, 2012). Several hybrid combinations showed potential for trait improvement. The hybrid combination CIM-599 × Shahkar exhibited substantial mid-parent heterosis for seed cotton yield, boll weight, and lint percentage. This cross also displayed notable SCA effects, indicating its importance for hybrid breeding (Rasheed *et al.,* 2023). These findings highlight the potential of hybrid breeding for trait enhancement.The greatest way for identifying superior hybrids and best combiners of parents is by the Line × Tester (L×T) design. For analyzing the combining ability and heterosis for various yield-attributing variables as well as quality traits, the parents viz., four lines and four testers were crossed to produce sixteen hybrids. The cross MCU5 × KC3 exhibited positive and highly significant heterosis for the number of sympodial branches, lint index, and number of bolls per plant, along with highly significant specific combining ability (sca) effects for the number of sympodial branches, seed cotton yield per plant, and micronaire. The cross CO14 × NDLH1938 recorded a highly significant sca effect for upper half mean length along with significant heterosis for boll weight and seed cotton yield per plant. Among the four lines, MCU5 was identified as having the best general combining ability (gca) value for upper half mean length (Keerthivarman *et al.*, 2022). In terms of days to first flowering, days to 50% blooming, number of seeds per boll, and seed cotton output per plant, LRA 5166 x Surabhi was determined to be a good hybrid among the crosses. The best hybrid for plant height was the LRA 5166 × AK 32 cross, the best hybrid for the quantity of bolls per plant was the Surabhi × LRK 516 cross, and the best hybrid for boll weight was the MCU 7 × AK 32 cross. The cross MCU 7 × LRK 516 recorded the highest percentage of standard heterosis for plant height, the cross Surabhi × AK 32 recorded a high percentage of standard heterosis for number of seeds per boll, and the cross LRA 5166 × Surabhi recorded the highest percentage of standard heterosis for days to first flowering, days to 50% flowering, number of bolls per plant, boll weight, and seed cotton yield. Surabhi and LRA 5166, the parent crosses in question, were thought to have good impacts on the majority of the economic characteristics examined, and commercial exploitation is advised (Gnanasekaran and Padmavathi, 2017). High heterosis for seed cotton output was created by the top F1 hybrids, including RST-9 x F-2164, LH-2076 x RST-9, and LH-2076 x RS-2013, which were composed of a variety of parents. With a maximum increase of 126.8% over the mid parent, the highest heterosis of all the attributes under investigation was obtained for seed cotton yield (Giri *et al.*, 2021). The majority of the features in the crosses (10229 x G.86) x G.45, G.45 x Suven, G.45 x G.70, TNB x G.70, and C.B 58 x G.93) showed positive heterotic effects in comparison to the mid-parent. Additionally, throughout two planting dates and their combined, the majority of the features in the crosses (10229 x G.86) x TNB, G.45 x Suven, and G.45 x G.70 showed beneficial heterotic effects in comparison to the superior parent (Sorour et al 2013).Many high-yielding hybrids of cotton have been released as a result of India's pioneering efforts to harness heterosis in the crop (Subhan *et al.*, 2003). The world's first commercial cotton hybrid, Hybrid-4 (H4), was created in 1972 as a consequence of an intraspecific cross and made accessible for commercial production in India (Basu *et al.*, 1995). These hybrids exhibit better resistance to biotic stresses such as pests and diseases, reducing the need for chemical pesticides, and also show improved tolerance to abiotic stresses like drought and heat, which are increasingly common due to changing climatic conditions (Khan *et al.*, 2023). Molecular breeding and biotechnological technologies have made major contributions to the ongoing advancement of hybrid cotton. Developing hybrids that are not only high-yielding and pest-resistant but also more sustainable, needing less chemical inputs and having a reduced environmental effect, has been a priority for major cotton-producing nations like China, India, and the United States (Khan *et al*., 2021; Liu *et al*., 2022). Additionally, studies are focusing more on figuring out how to lessen the negative impacts of heat stress on cotton production and development, emphasizing the necessity of breeding techniques that improve heat tolerance (Majeed *et al*., 2021).

Breeding approaches in cotton

Cotton (*Gossypium* spp.) is a major fibre crop cultivated globally for its lint, seed, and by-products. Cultivars with high yield, higher fiber quality, resilience to biotic and abiotic stressors, and environmental flexibility are the goals of breeding projects. A number of traditional and contemporary methods are used. Mass selection for enhancing landraces and pure-line selection for self-pollinated species are examples of traditional breeding techniques. The most popular technique is hybridization, which combines favorable qualities from several parents. While interspecific hybrids (*G. hirsutum* × *G. barbadense*) combine high productivity and excellent fiber quality, intraspecific crosses particularly *between G. hirsutum* and *G. barbadense* are frequently used to increase output and quality. Cotton farming has been transformed by heterosis breeding, particularly in China and India, where hybrids outperform open-pollinated types. Chemical hybridizing agents, cytoplasmic-genetic male sterility, and genetic male sterility all aid in the formation of hybrid seeds. New plant varieties with early maturity, compact architecture, and pest resistance have been produced by mutation breeding employing gamma rays, X-rays, and chemical mutagens. Genetic progress has accelerated due to biotechnological interventions. For features like drought tolerance and bollworm resistance (Bt genes), marker-assisted selection (MAS) enables the precise introgression of genes or QTLs. Through genetic engineering, transgenic cotton has been created that is immune to some illnesses, herbicides, and lepidopteran pests. The breeding cycle can be shortened by using emerging genomic selection algorithms that anticipate breeding values. Polyploidy breeding introduces features from diploid wild species by taking advantage of the tetraploid nature of farmed cotton. The preservation of genetic variety, which is necessary for long-term genetic gains, depends on the maintenance and use of germplasm.

Future prospects in cotton breeding

Future cotton breeding will integrate genomics, biotechnology, and precision agriculture to address evolving challenges, including climate change, pest adaptation, and sustainability concerns. A key component of speeding up variety creation will be genomic-assisted breeding. The discovery of QTLs for fiber quality, yield stability, and stress tolerance has already been made easier by dense molecular markers and whole-genome sequencing of *Gossypium* species. With the use of genome editing technologies like CRISPR/Cas9, important genes may be precisely modified to enhance characteristics like fiber fineness, drought tolerance, and disease resistance without creating unwanted connections. climatic-smart cultivars will be essential as climatic unpredictability increases. Water-use efficiency, heat tolerance, salt tolerance, and early maturity will all be breeding goals. Cultivar release will be further accelerated using speed breeding methods, which use controlled environmental conditions to decrease generation durations. In order to postpone insect population resistance, the emphasis in pest control will move from single-gene Bt cultivars to stacked-gene cotton with several modes of action. Additionally, more focus will be placed on breeding host plants to be resistant to sap-sucking pests like jassids and whiteflies. To satisfy the demands of the textile industry, improving the quality of the fiber will continue to be a top focus. In order to keep cotton competitive with synthetic fibers, breeding efforts will focus on producing extra-long staple fibers with higher strength, fineness, and uniformity. High-throughput screening and digital phenotyping will revolutionize breeding operations by making it possible to quickly, accurately, and non-destructively evaluate complex characteristics in the field. Involving farmers in variety selection through participatory plant breeding can guarantee that new cultivars are suited to regional circumstances and tastes, increasing adoption rates. For sophisticated biotechnologies, policy backing, germplasm exchange, and International cooperation will be essential. Future cotton breeding may produce high-yielding, pest-tolerant, climate-resilient, and internationally competitive varieties by fusing genetic innovation, sustainability, and farmer-centric methods. This will guarantee the crop's ongoing significance in both agriculture and industry.

CONCLUSION

The heterosis breeding is essential for improving yield, fiber quality, and stress resilience as cotton breeding advances through a deliberate fusion of traditional and contemporary methods. The selection of superior parental lines for hybrid formation is guided by research on combining ability, including both general combining ability (GCA) and specialized combining ability (SCA), which offer vital insights into the genetic architecture of significant characteristics. In order to properly harness hybrid vigour, high GCA denotes the dominance of additive gene effects and high SCA emphasizes the significance of non-additive interactions. The identification of potential genotypes is further refined by the combination of ability analysis and molecular methods. In order to meet the changing difficulties of climatic variability, insect pressure, and global textile needs while guaranteeing financial gains for farmers, future breeding projects must concentrate on using heterosis, maximizing parental combinations, and introducing sustainability-oriented features.

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