

Original Article

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**Inheritance Pattern and Combining Ability of Yield and Yield-Related Traits in *Gossypium hirsutum* L.**

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*Corresponding author: Haiqa Mustafa; haiqamustafa217@gmail.com**Abstract**

Gossypium hirsutum L. is a significant fibre crop and is a key element in the textile industry. The present study investigated the inheritance and combining ability of yield and yield related traits in upland cotton in a complete 3×3 diallel mating design. The three genetically different parental genotypes Cyto-608, CIM-343 and MNH-1026 were crossed in all possible combinations to generate six F_1 combinations with 9 genotypes; these were then tested for plant height, monopodial branches, sympodial branches, bolls per plant, boll weight, seed cotton yield per plant and lint percentage. Analysis of variance showed significant differences between genotypes for all traits, thus statistically significant variation in the material evaluated was noted. Several traits had significant GCA and SCA effects, indicating a contribution from additive and non-additive genetic effects, per Griffing's Model I analysis. MNH-1026 was superior for a number of traits, but exhibited mixed breeding value for the different traits, with boll number, seed cotton yield, plant height, and lint percentage being superior. Specific crosses also exhibited beneficial SCA effect for certain traits. The differences in the reciprocal crosses were significant for boll number, seed cotton yield, and lint percentage, suggesting direction-specific differences, but the effects cannot be definitely classified as maternal or cytoplasmic inheritance. Interpretation of the relative magnitude of variance components was done in conjunction with statistical significance of GCA and SCA but not as proof of gene action by only the magnitude of the variance components. The overall results suggest that there is a preliminary indication that both additive and non-additive gene effects are involved in the inheritance of yield and yield related traits in the cotton material evaluated. The results are, however, based on only three parents and two replications, and need to be replicated in other genetic material, locations, and growing seasons.

Keywords: Quantitative, Combining Ability, Additive, Non-Additive, Heterosis, Hybrid**How to cite this article:** Mustafa H., Ali K., Wahab A. Inheritance Pattern and Combining Ability of Yield and Yield-Related Traits in *Gossypium hirsutum* L. J. Genet. Appl. Biotechnol. 2026: e2026037. <https://doi.org/10.66432/hdch8293>

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Introduction

Cotton is one of the most significant natural fiber crops and is a significant contributor to the international textile industry (1). The high yield potential, general adaptability, and desirable fiber qualities make upland cotton over 90 percent of global cotton fiber production (2). According to the United States Department of Agriculture (USDA) estimates, in 2025–26, global production may be around 119–120 million bales (3). In spite of its economic significance, the production of cotton is not high in Pakistan and the current arrivals are estimated at about 5.5 million bales (4). Some of the key challenges to cotton productivity are climatic variability, pest infestation, water scarcity, and viral diseases (5). Furthermore, genetic progress has been slow and there is a relatively low genetic diversity available for yield and associated attributes (6,7).

Breeding of cotton is important to develop more productive and other economically important traits (8). For the agronomic and fiber properties, most of them are quantitative with polygenic inheritance and environmental effects (9,10). These traits may be additive and/or non-additive and their genetic control may be complex. Selection may give rise to additive effects, while dominance and other interactions may give rise to non-additive effects and contribute to variations among combinations of hybrids (11,12,13). Thus, knowledge of the genetic control of desirable characteristics is necessary to develop successful breeding programmes.

One of the common methods of determining the genetic potential of parental lines and crosses is to combine ability analysis (14). GCA is usually related to additive genetic effects while specific combining ability (SCA) is related to non-additive genetic effects such as dominance and epistatic

effects (15,16). Diallel mating designs are a systematic method for testing combining ability of parents and determining the genetic components of quantitative traits (17,18). Some earlier research has shown that the additive and non-additive components of the genetic architecture of yield and fibre traits of cotton can differ by trait, genetic composition and experimental conditions (19,20,21).

The study was undertaken to study the genetic control of selected yield and yield related characters of upland cotton with complete diallel mating design. Specific goals were to estimate general combining ability, specific combining ability and reciprocal effects; to select parental genotypes with desirable GCA for individual traits; and to identify cross combinations with desirable SCA effects that should be considered for additional testing in cotton breeding programs.

Materials and Methods

Experimental Plant and Site Material

The experiment was carried out at the Research Area, Department of Plant Breeding and Genetics, University of Agriculture, Faisalabad, Pakistan in 2024-2025 growing season. The parental material consisted of three genetically diverse upland cotton (*Gossypium hirsutum* L.) genotypes Cyto-608, CIM-343 and MNH-1026 which were selected for the variation in yield and yield related traits.

Diallel Crossing

All three possible direct and reciprocal crosses were generated in a 3×3 diallel mating design. The analysis was carried out using Griffing's Model I which assumed that the parents and the crosses were fixed effects (14). The crossing program resulted in six F_1 combinations (3 direct crosses plus their reciprocal crosses). The experimental material was comprised of nine genotypes along with the three parents. Hybridization was done in the glasshouse with conventional emasculation and hand pollination. F_1 seed was collected separately by cross direction, labeled and planted in the field for evaluation.

Field Experiment

The 9 genotypes (three parents, three direct F_1 crosses and three reciprocal F_1 crosses) were tested in two replications Randomized Complete Block Design (RCBD) (22). Each genotype was planted in a 10-foot row and row to row and plant to plant spacing was 75 and 30 cm respectively. Within each replication, treatments (genotypes) were randomly distributed. Phenotypic evaluation of plants was done for 5 plants from each experimental row. All experimental units were treated alike, with the usual agronomic practices employed in their production (grs, irrigation, fertilizer, weed control, plant protection). The experiment was carried out at one location for one growing season with only two replications and the results were interpreted under the condition of the present experiment and were not considered to indicate stability or general environmental adaptation.

Data Collection

The data included seven yield and yield-related traits: plant height (cm), number of monopodial branches per plant, number of sympodial branches per plant, number of bolls per plant, boll weight (g), seed cotton yield per plant (g), and lint percentage (%). The plants were measured for height (cm),

monopodial and sympodial branches and bolls per plant. The boll weight was taken in gram and seed cotton yield was measured in Gram/plant. Seed cotton was ginned from the samples and lint percentage was calculated as lint weight divided by seed cotton weight.

Statistical Analysis

The experimental data was analyzed by analysis of variance (ANOVA) which was done according to Steel et al. (1997) (25). Ability analysis was carried out by combining ability using Griffing's Model I, parental genotypes and their crosses as fixed effects (14). The GCA effects were estimated for the parental genotypes, while the specific combining ability (SCA) effects were estimated for the direct cross combinations. Reciprocal effects were examined separately in order to see if there was any difference in performance dependent on the direction of crossing.

The statistical significance of mean squares for GCA, SCA and reciprocal effects was assessed by comparison with the appropriate error mean square. The mean squares of the fixed-effect diallel design were used to estimate variance components for GCA, SCA and reciprocal effects. Values of * and respectively were considered as statistically significant at 5% and 1% significance level, and NS indicates a non-significant effect. The interpretation of genetic effects was mainly statistical in terms of statistical significance, rather than just numerical size of the variance components. For that reason, when the SCA effect was not significant, a larger variance related to the dominance component was not viewed as an indication of the predominance of non-additive gene action. Non-significant GCA effects were also deemed to be non-significant additive effects, even though the numbers differed in variance estimates, simply because they were not significant.

Phenotypic genotype means were not analyzed with GCA, SCA and reciprocal effects. The observed performance of a cross is classified as genotype, the average observed performance of the two parents as GCA, the deviation observed for the cross from the average of the two parents as SCA, and the difference in performance observed with the two cross directions as reciprocal effects. Standard errors were determined for comparison between GCA, SCA and reciprocal effects. If the effects were not significant, then numerical differences were considered as indicative but not substantiated differences. If there were significant reciprocal effects, they were taken to indicate differences in the direction of inheritance and were not regarded as proof of maternal or cytoplasmic inheritance. Only three parental genotypes, two replications, one location and growing season were used in the experiment; estimates of combining ability and genetic components, therefore, were interpreted in the context of the experimental material and conditions of this study.

Results and Discussion

Number of Monopodial Branches per Plant

Analysis of variance showed highly significant differences between the genotypes for monopodial branches per plant ($P \leq 0.01$), with statistically significant differences among the

parents and F₁ hybrids, but not among the replications. The GCA and SCA effects were highly significant, suggesting that the two parents together contributed to the variation and the cross combinations contributed, also that the effect of cross direction was not statistically detectable, so that reciprocal effect was non-significant (Table 1). Parental means and the GCA effects are illustrated in Figure 1, direct-cross means and the SCA effects in Figure 2, and the reciprocal means and the reciprocal effects in Figure 3. Table 2 presents standard errors used for comparing GCA, SCA and reciprocal effects.

Table 1 shows that the estimated additive variance ($\sigma^2A = 17.21$) was smaller than the dominance-related variance ($\sigma^2D = 59.49$). But the magnitude of the variances was not the only criterion used to infer predominant gene action. The large GCA and SCA effects confirmed statistically that there were additive and non-additive genetic effects that contributed to the variation in monopodial branch number. Cyto-608 and MNH-1026 showed positive GCA effects (+0.11), whereas CIM-343 showed a negative effect (−0.22) (Figure 1). The results showed that the average combining ability of Cyto-608 and MNH 1026 was more favorable than the other tested material for this trait. Specific combining ability of cross combinations varied among direct crosses with MNH-1026 × Cyto-608 having the highest positive SCA effect (+0.25) and CIM-343 × MNH-1026 the lowest (−0.25) (Figure 2).

The effect was non-significant on the other side (Table 1). The numerical reciprocal effect in the case of MNH-1026 × CIM-343 was highest (−0.50) but was not statistically supported and so should not be inferred as a cross-direction, maternal or cytoplasmic effect (Figure 3). Based on the positive GCA effects, Cyto-608 and MNH-1026 can be used to improve monopodial branching; the positive SCA effect for MNH-1026 × Cyto-608 suggests this hybrid may be worthy of further research (Figures 1 and 2). It is important to note that this SCA effect is not a representation of heterosis as it was not directly estimated. The results are consistent with the previous reports showing additivity and non-additivity contribution towards monopodial branching in cotton (23,24). The results, however, reported here are preliminary due to the small number of parents, replications and environment.

Number of Sympodial Branches per Plant

Analysis of variance revealed significant difference among the genotypes for number of sympodial branches per plant, implying that there exists a statistically detectable difference among the parents and F₁ hybrids. Replication effect was not significant. The average ability of both parents (GCA) and the specific cross combinations (SCA) were significant, while the effect of cross direction(reciprocal) was not significantly different (Table 1), suggesting that both average parents and specific cross combinations have an effect, but that the cross-direction effect itself is not observable.

Table 1. Analysis of Variance, Combining Ability and Variance Components for All Studied Traits

Trait	Source	DF	MS	F-value	Variance (σ^2)	Genetic Effect
MBP	GCA	2	95.20	13.32**	17.21	$\sigma^2A = 17.21$
	SCA	3	66.64	9.32**	59.49	$\sigma^2D = 59.49$
	Reciprocal	3	28.55	3.99NS	21.40	$\sigma^2R = 21.40$
	Error	8	7.15			
SBP	GCA	2	6.875	7.97*	1.203	$\sigma^2A = 1.203$
	SCA	3	4.8125	5.58*	3.95	$\sigma^2D = 3.95$
	Reciprocal	3	2.0625	2.39NS	1.20	$\sigma^2R = 1.20$
	Error	8	0.8625			
BP	GCA	2	103.15	14.43**	19.20	$\sigma^2A = 19.20$
	SCA	3	72.20	10.09**	65.05	$\sigma^2D = 65.05$
	Reciprocal	3	30.95	4.33*	23.80	$\sigma^2R = 23.80$
	Error	8	7.15			
BW	GCA	2	0.615	2.46NS	0.073	$\sigma^2A = 0.073$
	SCA	3	0.431	1.72NS	0.181	$\sigma^2D = 0.181$
	Reciprocal	3	0.185	0.74NS	≈0	$\sigma^2R \approx 0$
	Error	8	0.25			
SCYP	GCA	2	526.29	24.54**	100.97	$\sigma^2A = 100.97$
	SCA	3	368.40	17.17**	346.95	$\sigma^2D = 346.95$
	Reciprocal	3	157.89	7.36**	136.44	$\sigma^2R = 136.44$
	Error	8	21.45			
PH	GCA	2	91.26	12.76**	13.69	$\sigma^2A = 13.69$
	SCA	3	22.82	3.19NS	15.67	$\sigma^2D = 15.67$
	Reciprocal	3	7.50	1.05NS	0.35	$\sigma^2R = 0.35$
	Error	8	7.15			
LP	GCA	2	32.55	7.23*	5.61	$\sigma^2A = 5.61$
	SCA	3	22.79	5.06*	18.29	$\sigma^2D = 18.29$
	Reciprocal	3	9.77	2.17NS	5.27	$\sigma^2R = 5.27$
	Error	8	4.50			

Parental means and effects and SCA effects and means of direct crosses, plus cross means and effects, and reciprocal cross means and effects are presented in Figures 1, 2 and 3, respectively, with standard errors provided in Table 2 for comparisons.

Table 2. Standard Errors (S.E.) for Comparing General Combining Ability ($g_i - g_j$), Specific Combining Ability ($s_{ij} - s_{ik}$) and Reciprocal Effects ($r_{ij} - r_{ik}$) across Studied Agronomic Traits in Upland Cotton (*Gossypium hirsutum* L.)

Trait	S.E. ($g_i - g_j$)	S.E. ($s_{ij} - s_{ik}$)	S.E. ($r_{ij} - r_{ik}$)
MBP	0.25	0.30	0.43
SBP	0.30	0.35	0.52
BP	0.60	0.75	1.04
BW	0.08	0.10	0.14
SCYP	2.50	3.10	4.33
PH	0.50	0.60	0.87
LP	0.70	0.90	1.21

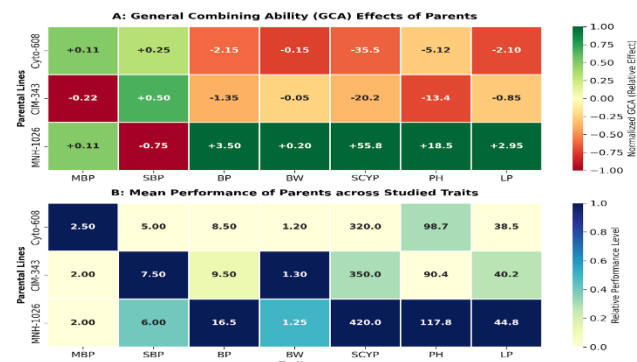


Figure 1: General Combining Ability (GCA) effects (A) and mean performance (B) of parental combinations across seven yield and agronomic traits in *Gossypium hirsutum* L.

The estimated additive variance ($\sigma^2A = 1.203$) was less than the dominance variance ($\sigma^2D = 3.95$) (Table 1). But the greater of the two squares of σ^2D is not necessarily taken as indication of the predominant non-additive gene action. The high GCA and SCA effect suggests that both additive and non-additive genetic effects were involved in the variation of sympodial branch number (Table 1). The mean of 7.5 and the positive GCA effect (+0.50) were obtained with CIM-343, while Cyto-608 had a mean of 5.0 and a positive GCA effect (+0.25). The parental mean for MNH-1026 was higher than the other two (6.0) and the GCA effect was negative (-0.75) (Figure 1). The results demonstrate that parental mean performance and GCA effects are two different measures and should not be confused. Therefore, general combining ability for sympodial branching was better in the tested material in the case of CIM-343 and Cyto-608.

CIM-343 $\times$ MNH-1026 exhibited the highest positive SCA effect (+0.10) while Cyto-608 $\times$ MNH-1026 exhibited the lowest reported value (-0.15) (Figure 2). These differences are significant, due to the importance of SCA, and thus show differences in specific combining ability among the crosses evaluated. Therefore, the favorable SCA of CIM-343 $\times$

MNH-1026 should not be considered as a demonstration of heterosis or hybrid superiority since heterosis was not directly estimated. The reciprocal effect was not significant (Table 1). The largest numerical reciprocal effect was observed for MNH-1026 $\times$ CIM-343 (+0.20) which was not statistically significant (Figure 3). Thus, no statistically significant influence was found due to cross direction, and no evidence can be obtained from the observed reciprocal differences that either maternal or cytoplasmic inheritance is present.

The observations here are in agreement with the previous reports of both additive and non-additive genetic contributions to the sympodial branching of cotton (25, 26, 27). The large GCA and SCA effects indicate that both selection of desirable parents and determination of specific cross combinations could be important in improving this trait. However, the results should be restricted to the three parent, two replication, single environment experiment and tested in additional environments and seasons to validate the stability of the combining-ability effects.

Number of Bolls per Plant

The differences among the genotypes for 'number of bolls per plant' were highly significant ($P \leq 0.01$) and indicated that there was a high level of phenotypic variation among the parents and F_1 hybrids. Replication was non-significant. All of GCA, SCA and reciprocal effects were significant, suggesting that average parental combining ability, specific cross combinations and cross direction were all important (Table 1). Figures 1, 2 and 3 show parental means and GCA effects, direct-cross SCA effects and cross means, and reciprocal effects and reciprocal-cross means, respectively. Standard errors are given for comparing these effects in Table 2.

The additive variance ($\sigma^2A = 19.20$) was smaller than the dominance related variance ($\sigma^2D = 65.05$) (Table 1). Naturally, if σ^2D is numerically larger, it does not necessarily indicate non-additive gene action. The highly significant GCA and SCA effects indicate the variations in boll number were due to both additive and non-additive genetic effect (Table 1). Parental mean of MNH-1026 was 16.5 while Cyto-608 and CIM-343 had means of 8.5 and 9.5, respectively (Figure 1). Favorable general combining ability (GCA) for boll number exists in the material evaluated, as evidenced by the positive GCA effect of MNH-1026, but note that parental mean and GCA are different measures and should be interpreted separately.

The Cyto-608 $\times$ CIM-343 showed the highest positive SCA effect (+0.85) in direct crosses while Cyto-608 $\times$ MNH-1026 and the CIM-343 $\times$ MNH-1026 showed negative effects of -1.25 and -0.60, respectively (Figure 2). The significant SCA effect (Table 1) suggests that there are differences in specific combining ability among the crosses tested. Therefore, Cyto-608 $\times$ CIM-343 could be worth of further testing on the basis of the positive SCA effect, but it should not be interpreted as a heterosis or hybrid superiority effect since heterosis has not been estimated directly. The reciprocal effect was also found to be significant and the

largest reported reciprocal effect (+2.20) was observed in the case of MNH-1026 × CIM-343 (Table 1 and Figure 3). This suggests that the cross direction has a statistically significant influence on boll number. But when differences are reciprocal, it is not definite that the inheritance is maternal or cytoplasmic, because differences caused by factors other than direction of inheritance may also account for the response.

The positive GCA of MNH-1026 indicated its potential as a parent for more boll number; Cyto-608 × CIM-343 may be considered for further studies due to its positive SCA effect (Figures 1 and 2). These interpretations only refer to boll number and do not reflect the overall parental superiority. There was also a strong bidirectional effect, suggesting that cross direction might be a factor when measuring this trait. The data are in agreement with earlier reports indicating that both additive and non-additive components play a part in boll number in cotton (28,29,30). Large GCA and SCA effects and significant reciprocal effects have also been reported for yield-related traits in cotton (7,11). Therefore, choosing favorable parents and assessing the particular cross combinations could help to improve boll number.

Boll Weight (g)

The boll weight differed significantly among the genotypes ($P \leq 0.05$) by analysis of variance, which means that there was some statistically detectable variation among the parents and F_1 hybrids. Replication effect was not significant. But none of these were significant: neither GCA, nor SCA nor reciprocal effects (Table 1). However, genotypic differences were observed but no statistically significant differences in average parental combining ability, specific cross performance or cross direction were found in the combining-ability analysis. Means and GCA effects are shown in Figure 1, direct-cross SCA effects and cross means in Figure 2, reciprocal effects and reciprocal-cross means in Figure 3, and standard errors are given in Table 2.

The additive variance ($\sigma^2A = 0.073$) was less than the dominance related variance ($\sigma^2D = 0.181$) (Table 1). The relative size of the variance components for GCA and SCA does not provide a conclusive indication of which form of gene action is most important since both variance components were not significant. Combining-ability is a more apt basis for interpretation of gene action, because the statistical significance of the combining-ability effects is determined. The most significant numerical increases in GCA effects were observed with MNH-1026 (+0.20), while the GCA effects for CIM-343 and Cyto-608 were negative, -0.05 and -0.15, respectively, (Figure 1). Among direct crosses, Cyto-608 × MNH-1026 showed the highest numerical SCA effect (+0.10), while CIM-343 × MNH-1026 showed the lowest (-0.15) (Figure 2). Since GCA and SCA were non-significant (Table 1), the numerical differences are considered descriptive observations that are not statistically proven differences in combining ability.

Similarly, the relationship between the use of the French newspaper and French language and the use of the German language was not significant (Table 1). There was no statistically supported difference between the numerical

reciprocal effects of MNH-1026 × Cyto-608 (+0.08). As such, there was no statistically significant difference found with regard to cross direction for boll weight. Similarly, the absence of a significant reciprocal effect does not mean that there are no maternal/cytoplasmic effects at all. There is no statistically significant difference in respect to GCA, SCA and reciprocal effects for boll weight (Table 1). Both the positive numerical GCA of MNH-1026 and the positive numerical SCA of Cyto-608 × MNH-1026 can only be taken as preliminary observations, and do not show statistically proven superiority (Figures 1 and 2). Hence, the interpretation of the predominant gene action and/or the relative importance of the environment on boll weight should be avoided since the experiment was performed in one location and one growing season.

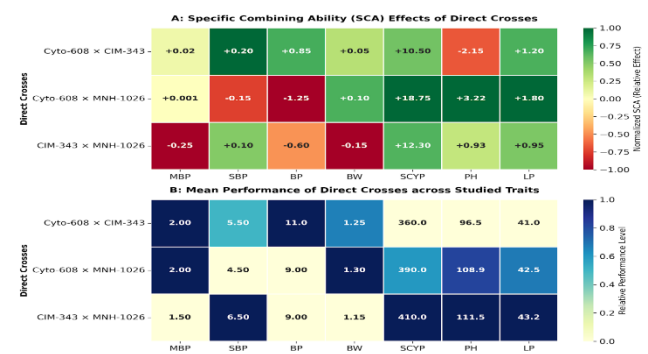


Figure 2: Specific Combining Ability (SCA) effects (A) and mean performance (B) of direct cross combinations across seven yield and agronomic traits in *Gossypium hirsutum* L.

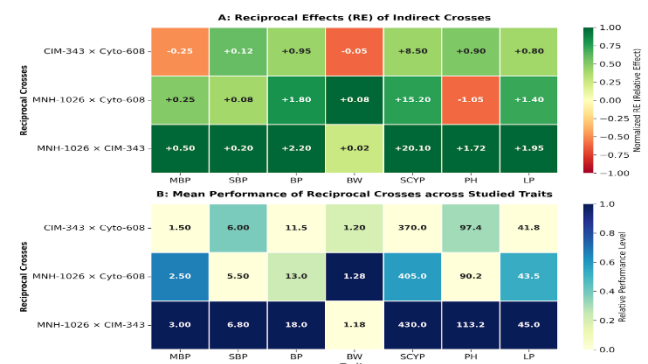


Figure 3: Reciprocal Effects (A) and mean performance (B) of indirect cross combinations across seven yield and agronomic traits in *Gossypium hirsutum* L.

This result is in general agreement with previous reports concerning the variability of genetic control and combining-ability of boll weight in cotton (31,32,33). Considering the breeding value from the present results, it would be necessary to use more parents, replications and multi-environment testing to establish whether the numerical differences observed have consistent breeding value.

Seed Cotton Yield per Plant (g)

The differences in seed cotton yield per plant were highly significant ($P \leq 0.01$) among genotype, which suggested there was ample phenotypic variation between the parents

and F_1 hybrids. The replication effect was not significant. All the three effects, namely average parental combining ability, specific cross performance and cross direction were highly significant (Table 1), indicating the role of average parental combining ability, specific cross performance and cross direction, respectively. The means and GCA effects are shown in Figure 1 while the means and SCA effects are shown in Figure 2 and the means and the cross means in Figure 3. The standard errors are shown in Table 2. The variance due to dominance ($\sigma^2D = 346.95$) was more than the variance due to additive genetic effects ($\sigma^2A = 100.97$) (Table 1). But the higher value of σ^2D is not enough to indicate dominant non-additive gene action. The additive and non-additive genetic effects are highly significant indicating that both effects played a role in seed cotton yield (Table 1).

The mean of seed cotton yield of parents of MNH-1026 (420 g) was highest with positive GCA effect (+55.75), while CIM-343 and Cyto-608 with mean of 350 and 320 g respectively showed negative GCA effect of (-20.25) and (-35.50) respectively (Figure 1). Therefore, MNH-1026 exhibited good general combining ability for seed cotton production in the test material. This good GCA is only for seed cotton yield and is not a reflection of overall parental superiority for all traits. The mean performance of parents and GCA effects should also be distinguished. Among direct crosses, Cyto-608 $\times$ MNH-1026 showed the highest positive SCA effect (+18.75), followed by CIM-343 $\times$ MNH-1026 (+12.30) and Cyto-608 $\times$ CIM-343 (+10.50) (Figure 2). As SCA was very important (Table 1), the results suggest that there were statistically significant differences between certain cross combinations. The favorable SCA effects do not represent a direct estimation of heterosis or hybrid superiority because heterosis was not assessed in the present study and such effects should not be interpreted as such.

In case of reciprocal effect, the largest mean was observed between MNH-1026 $\times$ CIM-343 (+20.10) which was found highly significant (Table 1; Figure 3). This indicates that cross direction was significantly associated with seed cotton yield. Reciprocal differences could be due to maternal or cytoplasmic differences but cannot prove the maternal or cytoplasmic origin of the differences because other direction-specific genetic or experimental factors might cause the difference. The positive GCA effect for MNH-1026 suggests that it might be a good parent to improve seed cotton yield, and Cyto-608 $\times$ MNH-1026 may deserve additional testing as a potential parent due to the positive SCA effect (Figures 1 and 2). The large reciprocal effect also implies that the crossing direction needs to be taken into account when assessing these parental combinations. Such results are specific to the traits and should not be extrapolated to overall breeding superiority.

The results of the present study confirm the results of earlier studies which found GCA and SCA effects, as well as additive and non-additive genetic effects, to be important in seed cotton yield (34,35,36,37). The results from a breeding point of view confirm the need to select material for yield improvement based on a combination of parental GCA and cross-specific SCA. The results are based on three parents and two replications with one experimental environment,

and therefore multi-season and multi-environment testing with a wider breeding base is required to assess the stability and wider breeding value of the parents and crosses identified.

Plant Height (cm)

The differences among the genotypes in plant height were highly significant indicating a high degree of plant height diversity among the parents and the F_1 hybrids. Replication effect was not significant. The GCA was highly significant, the SCA was significant and the reciprocal effect was not significant (Table 1). Therefore, there were significant effects of average parentals combining ability and cross performance on plant height, while there was no statistically significant effect from cross direction. The parental means and the GCA effects are displayed in Figure 1, the direct-cross SCA effects and cross means in Figure 2, the reciprocal effects and the reciprocal-cross means in Figure 3, and the standard error of the differences in Table 2. Dominance related variance ($\sigma^2D = 15.67$) numerically exceeded the additive variance ($\sigma^2A = 13.69$) (Table 1).

This is a numeric difference only, however, and is not sufficient to prove predominant dominance or non-additive gene action. The highly significant GCA effect along with the significant SCA effect suggest that additive and non-additive genetic effects are involved (Table 1). The non-significant reciprocal effect suggests that there is no statistical evidence of a cross-direction effect. MNH-1026 showed the maximum mean plant height (117.8 cm) and positive GCA effect (+18.54) while CIM-343 had the lowest mean plant height (90.4 cm) and negative GCA effect (-13.42). The negative GCA effect (-5.12) was also observed with Cyto-608 (Figure 1). The positive GCA of MNH-1026 suggests that it has good average combining ability with the test material. The following interpretation is only for height of the plant and is not necessarily a reflection of overall parental superiority.

Among direct crosses, Cyto-608 $\times$ MNH-1026 showed the highest positive SCA effect (+3.22), followed by CIM-343 $\times$ MNH-1026 (+0.93), whereas Cyto-608 $\times$ CIM-343 showed a negative effect (-2.15) (Figure 2). The differences in specific combining ability among crosses are suggested by the result of the SCA that was significant (Table 1). Cyto-608 $\times$ MNH-1026, however, might be worth further testing for plant height, but should not be considered as heterosis nor hybrid superiority as heterosis was not estimated. The large GCA effects are substantiated by the large SCA effects, and both should be considered in the case of plant height (Table 1). Cyto-608 $\times$ MNH-1026's positive SCA makes it a candidate for additional studies and MNH-1026 is recommended for use in situations where tall stature is desired due to its positive GCA (Figures 1 and 2). The effects listed should be seen as trait-specific responses to the genetic material tested and not as proof of superiority of the parent or cross. The results are similar to those of previous studies showing both additive and non-additive genetic influences on plant height in upland cotton (38, 39, 40). Therefore, in breeding for plant height both GCA and SCA should be taken into consideration. However, the three parent, two replications, single environment design results in limited

applicability and further testing of the effects over seasons and environments would be needed to verify the uniformity of the cause.

Lint Percentage (%)

The analysis of variance showed highly significant differences in the lint percentage ($P \leq 0.01$) among the genotypes, which would suggest that there is a statistically significant difference between the parents and F_1 hybrids. Replication effect was not significant. The GCA effects were highly significant, while the reciprocal effects were significant (Table 1), SCA effects were not significant. The present results show the effect of the average combining ability of parents, the specific cross and the cross direction. Parental, direct-cross SCA, cross means, and reciprocal and reciprocal-cross means are shown in Figure 1 and 2, respectively. Table 2 shows the standard errors for comparing the various means. There was a higher dominance-related variance ($\sigma^2D = 18.29$) than there was additive variance ($\sigma^2A = 5.61$) (Table 1). The difference in numbers of these components is not, however, a sufficient criterion for predominant non-additive gene action. The highly significant GCA and SCA effects indicate that both additive and non-additive genetic effects were involved in lint percentage. The large cross direction effect also suggests that there was a significant cross direction effect (Table 1).

MNH-1026 had the highest parental lint percentage (44.8%) and a positive GCA effect (+2.95), whereas CIM-343 (40.2%) and Cyto-608 (38.5%) had negative GCA effects of -0.85 and -2.10, respectively (Figure 1). Hence, MNH-1026 exhibited good general combining ability for lint percentage in the material evaluated. Table 2 shows the standard error of comparing the GCA effects was 0.70. Parental mean performance, however, is not a measure of GCA and should not be used interchangeably. The positive GCA for MNH-1026 is only for lint percentage and is not indicative of the overall parental superiority. Among direct crosses, Cyto-608 $\times$ MNH-1026 showed the highest positive SCA effect (+1.80), followed by Cyto-608 $\times$ CIM-343 (+1.20) and CIM-343 $\times$ MNH-1026 (+0.95) (Figure 2). Since SCA was highly significant (Table 1), the results suggest that there are statistically significant differences in specific combining ability. The standard error of comparing SCA-effects was 0.90 (Table 2). Such positive SCA effects can be used to help select combinations for further breeding testing, but cannot be assumed to mean heterosis or hybrid superiority was achieved since heterosis was not directly estimated.

The reciprocal effect was also highly significant with the highest reported effect (+1.95) being for MNH-1026 $\times$ CIM-343 (Table 1; Figure 3). This shows that there is a measurable effect on the lint percentage due to cross direction. Reciprocal differences can be explained by maternal effects but do not unequivocally indicate maternal or cytoplasmic inheritance since other genetic or experimental considerations could account for the discrepancies. The standard error for the reciprocal effects was 1.21 (Table 2). Both the significant GCA and SCA

effects suggest that parental combining ability and specific combinations were important in influencing lint percentage, and the significant reciprocal effect suggests that cross direction was also important (Table 1). Therefore, MNH-1026 would be useful for trait specific improvement due to positive GCA and Cyto-608 $\times$ MNH-1026 may be further evaluated due to favorable SCA (Figures 1 and 2). The results should be interpreted in the context of the genetic resources tested and should not be interpreted as evidence of general parental or hybrid superiority.

These results agree with the results of earlier research which reported additive and non-additive genetic effects on lint percentage in cotton (41,42,43,44). The GCA and SCA effects for lint-related traits were also significant as reported by Chakholoma et al. (2022) and Shahzad et al. (2019) and this result concluded that combining-ability analysis is an important tool to select useful parents and cross combinations (42, 34). Thus, to improve the lint percentage, it may be helpful to consider favourable GCA in combination with SCA and reciprocally with performance and then validate under other environmental conditions.

All results have shown that the effect of combination of ability is different for various traits and parental combinations. Overall, MNH-1026 demonstrated good GCA for a number of traits, especially boll number, seed cotton yield, plant height, and lint percentage, but the value of this cultivar should be evaluated individually. Specific crosses like MNH-1026 $\times$ Cyto-608 and Cyto-608 $\times$ CIM-343 exhibited good SCA for certain traits (Figures 1 and 2). The highly significant interaction for boll number, seed cotton produced, and lint percentage also suggest that there may be cross-directional effects on these traits (Figure 3; Table 1). The results of this study, however, should be considered preliminary as it was conducted with only three parental genotypes, two replications and a single environment. Additional testing of these parents and cross combinations under various seasons and environments with a more diverse genetic background is needed to confirm the stability and breeding value.

Conclusion

The present study showed the statistically detectable difference between the evaluated parental genotypes and the crosses of F_1 generation for all yield and yield-related traits studied. The relative contribution of GCA and SCA was found to be different among different traits, indicating involvement of both additive and non-additive genetic effects. The overall performance of MNH-1026 was good for several desirable traits, but not all, such as boll number, seed cotton yield, plant height and lint percentage and was not necessarily best for all breeding needs. A number of other crosses were also found to have positive SCA activity and might be suitable for further testing. Significant reciprocal effects for boll number, seed cotton yield and lint percentage suggested that the direction of crossing had some bearing on the expression of these traits, but this could not be conclusively attributed to either maternal or cytoplasmic inheritance. Results should also be considered

as not evidence of heterosis since heterosis was not directly estimated. The results are preliminary and may only be valid for the genetic materials and experimental conditions evaluated, because of the use of only three parents and two replications, and one location and growing season. To establish the stability and breeding value of the identified parents and cross combinations more extensive evaluation with more parents, more replications and more environments and seasons is needed. This study offers valuable preliminary data for the selection of parents and cross combinations for possible further improvement in yield and yield related characters of upland cotton.

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