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HETEROTIC STUDIES AND INBREEDING DEPRESSION IN F_2 POPULATIONS OF UPLAND COTTON

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Abstract

To study the genetic potential, heterotic effects and inbreeding depression, 8 × 8 F_2 diallel populations with parental lines of upland cotton were grown during crop season 2010 in a randomized complete block design at Khyber Pakhtunkhwa Agricultural University Peshawar, Pakistan. Highly significant ($p \leq 0.01$) variations were noticed among parental lines and F_2 populations for all the traits. According to genotypes mean performance for various traits, plant height varied from 101.60 to 126.30 cm and 98.60 to 140.60 cm, bolls plant^{-1} (12.87 to 19.53; 12.13 to 22.60), boll weight (3.80 to 5.01 g; 3.04 to 5.38 g) and seed cotton yield plant^{-1} varied from 55.74 to 85.47 g and 45.57 to 96.05 g in parental cultivars and their F_2 populations, respectively. However, 12 and 7 F_2 populations manifested significant heterosis over mid and better parents for plant height, 7 and 3 for bolls plant^{-1}, 13 and 9 for boll weight and 13 and 5 F_2 populations for seed cotton yield plant^{-1}, respectively. F_2 populations i.e. CIM-554 × CIM-473, CIM-554 × CIM-499, CIM-496 × SLH-284, CIM-473 × CIM-446 and CIM-554 × SLH-284 with low mean values for plant height performed better and manifested highly significant heterotic values over mid and better parents for bolls per plant, boll weight and seed cotton yield. By comparing F_2 mean values with F_1s, inbreeding depression was observed for plant height (0.66 to 23.99%), bolls per plant (5.00 to 63.16%), boll weight (0.20 to 23.24%) and seed cotton yield (0.44 to 75.52%). However, 62% of F_2 populations revealed negative values for inbreeding depression, 14% for bolls per plant, 77% for boll weight and 21% for yield, revealed that these F_2 populations were more stable and performed better than F_1s even after segregation. Although, F_2 populations may display less heterosis as compared to F_1s, but still better than high parents and can be used as hybrid cotton to skip the expensive F_1 hybrid seed production.

Introduction

Gossypium hirsutum L. provides 90% of world fiber and is major cash and industrial crop. Cotton is grown on almost 32.4 million hectares in more than 90 countries of temperate, sub-tropical, and tropical regions of the world. The four main producing countries are China, India, USA and Pakistan and accounted for approximately three quarters of world output. If Uzbekistan and Brazil are added, six countries would account for 83% of world cotton production (Anon., 2011). Cotton is long day and often cross-pollinated crop, and usually requires little heavy soil, moderate rainfall and mostly sunshine.

Cotton is sixth largest source of vegetable oil in world, however, in Pakistan its share is 70% in local edible oil industry. Pakistan is the fourth largest cotton producer, and the crop occupying 12% of total cultivated area, 8.2% value added in agriculture sector and 2% of GDP and adds over $2.8 billion to national economy of Pakistan. On average, it earns 45 to 60% foreign exchange depending upon production and local consumption. During 2009-10, cotton was grown on 3.106 million hectares and seed cotton production was 12.70 million bales with average yield of 695 kg ha^{-1} (Anon., 2010). Pakistan cotton yields have been stagnant for last several years and very low as compared to other cotton growing countries. Factors responsible for low cotton production includes excessive rains at sowing time, high temperature and its fluctuations at flowering stage, late wheat harvesting resulting a decline in area planted to cotton, cotton leaf curl virus (CLCuV) incidence and lack of resistant varieties, pest attack and improper production technology in major cotton growing areas.

Heterosis works as a basic tool for improvement of crops in form of F_1 and F_2 populations, and economic heterosis (over standard cultivar). It also contributes to choose genotypes with desired genetic variance, vigor and maternal effects. Therefore, it is essential to have detailed information about desirable parental combiners in any breeding program, which can reflect a high degree heterotic response. In intra- and inter-specific heterosis, yield increase over better parent or greater than best commercial cultivar (useful heterosis) has been documented (Baloch *et al*., 1993b; Galanopoulou-Sendouca & Roupakias, 1999; Wei *et al*., 2002; Yuan *et al*., 2001 & 2002; Khan *et al*., 2007; Khan, 2011). Both positive and negative heterotic values have been detected, demonstrating potential of hybrid combinations for traits improvement in breeding programs (Hassan *et al*., 1999; Khan *et al*., 2009). F_1 hybrids with high heterosis were also associated with higher inbreeding depression; therefore, moderate type of heterosis has some stability in segregating populations (Tang *et al*., 1993; Soomro, 2000; Soomro & Kalhoro, 2000). Therefore, heterotic studies can provide basis for exploitation of valuable hybrid combinations in future breeding program.

In countries like India and China, where labor is cheaper, successful hybrid cotton is produced on large scale since 1960's (Khan *et al*., 2007). Cook (1909) was the first to utilize hybrid vigor in inter-specific hybrids (*G. barbadense* L. × *G. hirsutum* L.) and later a number of workers all over the world supported his conclusions. Hybrid cotton is a good approach for significant improvement in genetic potential for morpho-yield and fiber quality traits and has attracted attention of cotton breeders for commercial growing of hybrid generations (Meredith, 1990; Baloch *et al*., 1993a & b; Meredith & Brown, 1998; Khan *et al*., 2000 & 2009). However, efforts have not delivered the expected results due to self pollination which has some different implications on hybrid seed production in comparison to cross pollinated crops. Cotton producing countries are trying to increase yield through commercial growing of hybrid generations, but India and China are the only leading countries having significant acreage under hybrid cotton (Wu *et al*., 2004; Khan, 2011).

Apart from F_1s, the F_2s have larger heterogenity and genetic variation, which result in greater range of adaptation relative to their parents and F_1 hybrids (Meredith & Brown, 1998; Wu *et al*., 2004). F_2s manifested superiority over their better parents when grown under stress conditions and can produce better combinations of yield and fiber quality (Meredith, 1990). F_2s yield performance was highly correlated with F_1s and parents. It is expected that F_2 populations may express only 50% of economic heterosis shown by F_1 hybrids and even less when heterosis is defined in terms of higher yielding parent. Nonetheless, F_2 populations with lower inbreeding depression in yield and superior performance than adapted cultivars have been found (Meredith, 1990). The existence of such populations lends credibility to use F_2s as hybrid cotton. Previous findings are also of view about F_2 populations heterosis in cotton (Tang *et al*., 1993; Meredith & Brown, 1998; Wu *et al*, 2004; Khan *et al*, 2007). Therefore, the present research was planned to study the genetic potential, heterosis over mid and better parents and inbreeding depression in 8 × 8 F_2 diallel populations.

Materials and Methods

Breeding material, design and procedure: The heterotic studies and inbreeding depression of polygenic traits in F_2 population of upland cotton were conducted at Khyber Pakhtunkhwa Agricultural University, Peshawar, Pakistan. The experimental material consists of eight upland cotton genotypes i.e. SLH-284, CIM-446, CIM-473, CIM-496, CIM-499, CIM-506, CIM-544 and CIM-707 and their 56 F_2 populations. The parental genotypes and F_2s were hand sown during crop season 2010 in a randomized complete block (RCB) design with three replications. Each treatment consists of two rows having five meters length with 30 and 75 cm plants and rows spacing, respectively. Cultural practices were carried out as per recommended package for cotton production and all the entries were grown under uniform conditions to minimize environmental variations to the maximum possible coverage. Picking was made on single plant basis during November, 2010 and data were recorded on plant height, bolls per plant, boll weight and seed cotton yield per plant.

Statistical analysis: Data of various F_2 populations and their parental lines were analyzed according to Steel & Torrie (1980) and Least significant difference (LSD) test was used for means separation and comparison. Heterosis was calculated in terms of percent increase/decrease of F_2 populations over its mid and better parent values (Fehr, 1987). The "t" test was used to see whether F_2 hybrid means were significantly different from mid and better parental values (Wynne *et al.*, 1970). Inbreeding depression was formulated as percent decrease of F_2 populations by comparing with F_1 hybrid means (Hallauer & Miranda, 1988).

Results and Discussion

Highly significant ($p \leq 0.01$) differences were observed in F_2 populations and parental means for plant height, bolls per plant, boll weight and seed cotton yield per plant (Table 1). The traits-wise results about genetic potential, heterosis over mid and better parents and inbreeding depression in F_2 populations in light of previous review are discussed as follows.

Table 1. Mean squares and CV% for various morpho-yield traits of upland cotton.

Parameters	Mean Squares	C.V (%)
Plant height	203.90**	8.70
Bolls plant^{-1}	14.77**	13.30
Boll weight	0.85**	7.95
Seed cotton yield plant^{-1}	352.52**	8.83

**, Significant at $p \leq 0.01$

Plant height: Plant height ranged from 101.60 to 126.30 cm among parental cultivars and 98.60 to 140.60 cm among F_2 genotypes (Table 2). Minimum plant height (98.60 cm) was observed in F_2 hybrid CIM-499 × SLH-284 and was found at par with 15 F_2 populations and four parental cultivars. Highest plant height (140.60 cm) was observed in CIM-554 × CIM-446, however, it was found at par with 20 other F_2 populations and two parents with range of 123.90 to 133.10 cm. All other genotypes showed medium plant height. Khan *et al*., (1999) and Khan *et al*., (2009) indicated significant variability among various F_1 and F_2 populations for plant height.

Mostly breeders are interested in short stature cotton plants for easy manual and machine picking and to skip the lodging threat. Therefore, negative heterosis is desirable to discourage the maximum plant height. According to mid parent heterosis (Table 3), negative heterosis was observed in 17 F_2 populations ranged from -0.04 (CIM-554 × CIM-473) to -11.96% (CIM-499 × SLH-284). The later hybrid was followed by four other F_2 populations i.e. CIM-496 × CIM-446, CIM-473 × CIM-499, CIM-496 × CIM-499 and CIM-707 × CIM-446 ranged from -8.11 to -11.46%. In case of positive heterosis over mid parent, 39 F_2 populations exhibited positive heterosis, and lowest heterotic effects were recorded in hybrid CIM-446 × CIM-506 (0.22%) while highest in CIM-473 × CIM-506 (19.03%). However, three other F_2 populations (CIM-473 × CIM-554, CIM-473 × SLH-284 and CIM-554 × CIM-446) also showed increased heterosis of 17.69, 16.66 and 16.20%, respectively, Overall, 12 F_2 populations showed significant heterosis over mid parent values.

In case of better parents, negative heterobeltiosis was observed in 27 F_2 populations ranged from -0.09 (SLH-284 × CIM-506) to -12.97% (CIM-499 × SLH-284) (Table 3). The later hybrid was followed by three other F_2 populations viz; CIM-446 × CIM-473, CIM-496 × CIM-499 and CIM-496 × CIM-446 with values of -12.93, -12.91 and -11.60%, respectively. Positive heterobeltiosis was observed in 29 F_2 populations ranged from 0.32 (CIM-496 × CIM-707) to 16.08% (CIM-473 × SLH-284). The later hybrid was followed by three other F_2 populations of CIM-473 as paternal and maternal parent i.e., CIM-473 × CIM-506 (14.69%), CIM-473 × CIM-554 (14.50%) and SLH-284 × CIM-473 (12.38%). However seven F_2 populations showed significant heterosis over better parents. Plant height was mostly found positively correlated with seed cotton yield, if lodging didn't occur. Results were in agreement with findings of Baloch *et al*., (1993a & b), Khan *et al*., (2000) Mukhtar & Khan (2000), Babar *et al*., (2001), Khan *et al*., (2007) and Abro *et al*., (2009) as observed significant variations among F_1 and F_2 genotypes mean performance and significant heterosis over mid and betters parents.

Table 2. Mean performance of parental cultivars and F_2s for morpho-yield traits of upland cotton.

Parents and F_2 Populations	Plant height (cm)	Bolls plant^{-1}	Boll weight (g)	Seed cotton yield plant^{-1} (g)
SLH-284	110.70	16.07	4.13	67.51
CIM-446	126.10	13.67	4.17	62.87
CIM-473	109.60	18.67	3.80	76.72
CIM-496	126.30	16.43	5.01	85.47
CIM-499	113.30	19.53	4.09	75.86
CIM-506	101.60	18.33	4.22	84.26
CIM-554	115.90	12.87	4.06	55.74
CIM-707	120.50	15.77	4.63	73.09
SLH-284 × CIM-446	115.70	14.68	4.21	68.83
SLH-284 × CIM-473	124.40	19.27	4.40	91.37
SLH-284 × CIM-496	121.50	17.47	4.05	69.68
SLH-284 × CIM-499	110.10	16.80	4.04	72.08
SLH-284 × CIM-506	110.60	15.87	4.37	72.74
SLH-284 × CIM-554	117.90	15.33	4.53	72.68
SLH-284 × CIM-707	127.30	17.87	3.83	74.46
CIM-446 × SLH-284	119.00	14.93	4.20	64.63
CIM-446 × CIM-473	109.80	17.33	4.47	83.83
CIM-446 × CIM-496	128.10	14.80	4.81	74.56
CIM-446 × CIM-499	117.20	13.67	3.58	45.94
CIM-446 × CIM-506	114.10	14.20	4.86	70.11
CIM-446 × CIM-554	130.60	13.53	5.04	72.56
CIM-446 × CIM-707	121.80	17.58	3.91	72.95
CIM-473 × SLH-284	128.50	12.13	3.58	45.57
CIM-473 × CIM-446	130.10	18.20	4.99	88.21
CIM-473 × CIM-496	127.70	14.47	4.70	68.49
CIM-473 × CIM-499	101.40	14.93	4.18	64.04
CIM-473 × CIM-506	125.70	18.40	4.69	89.03
CIM-473 × CIM-554	132.70	14.13	3.65	58.06
CIM-473 × CIM-707	121.40	19.67	4.17	74.08
CIM-496 × SLH-284	120.80	19.20	5.27	96.05
CIM-496 × CIM-446	112.00	18.00	4.06	80.99
CIM-496 × CIM-473	113.60	16.60	3.67	54.29
CIM-496 × CIM-499	110.00	19.20	3.45	70.90
CIM-496 × CIM-506	131.00	14.07	3.34	61.57
CIM-496 × CIM-554	120.50	19.00	4.07	76.89
CIM-496 × CIM-707	126.70	14.40	3.61	52.97
CIM-499 × SLH-284	98.60	21.47	3.57	74.91
CIM-499 × CIM-446	115.90	18.67	3.04	60.32
CIM-499 × CIM-473	104.60	17.60	4.32	76.35
CIM-499 × CIM-496	114.60	16.73	3.63	59.89
CIM-499 × CIM-506	122.10	16.80	3.83	70.29
CIM-499 × CIM-554	125.10	18.07	3.79	73.79
CIM-499 × CIM-707	114.50	16.67	5.12	73.75
CIM-506 × SLH-284	123.30	15.40	4.82	73.22
CIM-506 × CIM-446	119.30	15.73	3.71	61.76
CIM-506 × CIM-473	116.00	19.13	3.77	77.06
CIM-506 × CIM-496	123.90	18.73	4.26	92.04
CIM-506 × CIM-499	120.50	15.20	4.56	73.13
CIM-506 × CIM-554	123.20	14.47	4.01	59.50
CIM-506 × CIM-707	122.70	17.60	4.24	75.25
CIM-554 × SLH-284	119.30	14.80	5.07	73.93
CIM-554 × CIM-446	140.60	15.87	3.18	53.77
CIM-554 × CIM-473	112.30	22.47	3.74	82.00
CIM-554 × CIM-496	124.50	15.67	3.65	60.91
CIM-554 × CIM-499	120.50	22.60	5.38	86.01
CIM-554 × CIM-506	123.90	16.80	4.42	74.17
CIM-554 × CIM-707	127.10	16.63	3.71	77.27
CIM-707 × SLH-284	133.10	16.40	4.57	80.15
CIM-707 × CIM-446	113.30	13.70	3.37	59.89
CIM-707 × CIM-473	119.70	14.80	4.08	67.66
CIM-707 × CIM-496	129.10	17.00	3.63	67.94
CIM-707 × CIM-499	124.70	17.73	4.36	77.55
CIM-707 × CIM-506	115.20	16.13	4.26	70.81
CIM-707 × CIM-554	128.40	14.93	3.49	53.55
$LSD_{0.05}$	16.84	3.576	0.46	7.437

By comparing F_2 mean values with F_1s plant height, the inbreeding depression was observed in 38% of F_2 populations ranged form 0.66 (CIM-554 × CIM-499) to 23.99% (SLH-284 × CIM-506). The 62% of F_2 populations revealed negative values for inbreeding depression, means that these F_2s were stable and performed better than F_1 populations even after segregation. However, negative inbreeding depression values ranged from -0.90 (CIM-554 × CIM-506) to -46.88% (CIM-473 × CIM-506) and later F_2 hybrid was followed by ten other F_2 populations ranged from -29.10 (CIM-707 × SLH-284) to -46.23% (CIM-499 × CIM-506). Results were in line with findings of Khan *et al*., (1999, 2000, 2011) as elaborated that F_2 populations can be used as hybrid cotton if have better performance over their superior parents because F_2 crop can easily be managed with increased amount of seed produced by F_1 plants. Therefore, in cotton the F_2 populations could be used for hybrid cotton production.

Bolls per plant: Bolls per plant varied from 12.87 to 19.53 and 12.13 to 22.60 among parental cultivars and their F_2 populations, respectively (Table 2). Maximum bolls per plant were observed in F_2 hybrid CIM-554 × CIM-499 (22.60) and was found at par with seven other F_2 populations and one parent ranged from 19.13 to 22.47. Minimum bolls per plant were exhibited by F_2 hybrid CIM-473 × SLH-284 (12.13) and was found at par with 20 other F_2 populations and two parental cultivars CIM-554 (12.87) and CIM-446 (13.67). The remaining genotypes showed medium number of bolls per plant. Khan *et al*., (2009 & 2011) and Soomro *et al*., (2010) reported similar results and indicated significant variability for bolls per plant among different cotton cultivars and their F_1 and F_2 populations.

Overall, 31 and 17 F_2 populations showed positive heterosis over mid and better parent, respectively for bolls per plant (Table 3). However, mid parent heterosis ranged from 0.40 (CIM-446 × SLH-284) to 42.49% (CIM-554 × CIM-473). The later hybrid was followed by three other F_2 populations CIM-554 × CIM-499 (39.51%), CIM-496 × CIM-554 (29.69%) and CIM-499 × SLH-284 (20.62%) by having maximum heterosis. Positive heterosis over better parents for bolls per plant ranged from 2.05 (CIM-707 × SLH-284) to 20.35% (CIM-554 × CIM-473). The later hybrid was followed by three other F_2 populations (CIM-496 × SLH-284, CIM-554 × CIM-446 and CIM-554 × CIM-499) with range of 15.72 to 16.86% heterobeltiosis. Overall, seven and three F_2 populations revealed significant mid and better parent heterosis, respectively, Remaining F_2 populations exhibited negative heterosis in both categories. Results were in accordance with findings of Galanopoulou-Sendouca & Roupakias (1999), Hassan *et al*., (1999), Soomro (2000), Babar *et al*., (2001), Basal and Turgut (2003), Gbri *et al*., (2006), Ye & Zhu (2006) and Abro *et al*., (2009) as they noticed positive and significant heterosis and heterobeltiosis for bolls per plant and seed cotton yield.

In comparison of F_2s bolls per plant with F_1s mean values, 86% of F_2 populations showed inbreeding depression ranged from 5.00 (CIM-554 × CIM-499) to 63.16% (CIM-446 × CIM-554). However, 14% of F_2 populations revealed negative values for inbreeding depression, means that these F_2s performed better than F_1 hybrids after segregation. In F_2 populations, the negative inbreeding depression ranged from -0.78 (SLH-284 × CIM-499) to -29.03% (CIM-496 × CIM-499) and later F_2 hybrid was followed by three F_2 populations ranged from -15.84 (CIM-499 × CIM-707) to -19.08% (CIM-499 × SLH-284). Results supported the idea that F_2 populations could work as a hybrid crop if properly managed and if parents selected on basis of F_2 performance, because F_1 hybrids cannot clarify the stability of F_2 populations (Galanopoulou & Roupakias, 1999; Khan, 2011). Therefore, such F_2 populations would be desirable to use as hybrid cotton to enhance the boll number and eventually seed cotton yield.

Boll weight: Boll weight varied from 3.80 to 5.01 g among parental cultivars and 3.04 to 5.38 g among F_2 populations (Table 2). Bigger bolls were noticed in F_2 hybrid CIM-554 × CIM-499 (5.38 g) and were found at par with six F_2 populations and one parent ranged from 4.86 to 5.27 g. Lowest boll weight was recorded in F_2 population CIM-499 × CIM-446 (3.04 g) and was found at par with five F_2 populations ranged from 3.18 to 3.57 g. Other F_2 populations revealed moderate boll weight. Meredith (1990), Tang *et al*., (1993), Meredith & Brown (1998) and Khan *et al*., (2009) manifested similar proportion and variation among segregating populations for boll weight. Boll weight is an important yield contributing trait and has direct impact on seed cotton yield. Therefore, during selection due attention should be paid to boll weight.

Overall, 22 F_2 populations showed positive mid parent heterosis for boll weight and ranged from 1.20 (CIM-446 × SLH-284) to 40.08% (CIM-499 × CIM-707) (Table 4). The later hybrid was followed by three F_2 populations viz; CIM-554 × CIM-499, CIM-473 × CIM-446 and CIM-554 × SLH-284 with heterotic effects of 32.02, 25.22 and 23.81%, respectively. However, 13 F_2 populations revealed significant mid parent heterosis. For better parent heterosis, 19 F_2 populations showed positive values for said trait and varied from 0.72 (CIM-446 × SLH-284) to 31.54% (CIM-554 × CIM-499). The four F_2 populations (CIM-499 × CIM-707, CIM-554 × SLH-284, CIM-446 × CIM-554 and CIM-473 × CIM-446) also showed remarkable heterobeltiosis ranged from 19.66 to 25.18%. However, nine F_2 populations revealed significant better parent heterosis. Remaining F_2 populations exhibited negative heterosis in both categories. Results were in accordance with findings of Meredith & Brown (1998), Mukhtar & Khan (2000), Babar *et al*., (2001), Yuan *et al*., (2002), Basal & Turgut (2003), Junpei *et al*., (2004) Wu *et al*., (2004), Xing *et al*. (2007), Natera *et al*., (2007) Campbell *et al*., (2008) and Soomro *et al*., (2010) as reported positive and significant heterosis over mid and better parents for boll weight.

By comparing F_2s boll weight with F_1s mean values, inbreeding depression was observed in 23% of F_2 populations ranged from 0.20 (CIM-499 × SLH-284) to 23.24% (CIM-554 × CIM-446). The 77% of F_2 populations revealed negative values for inbreeding depression, means that these F_2 populations were having increased boll weight and performed better as compared to F_1 hybrids even after segregation, and plant breeder interested in this type of depression. However, negative inbreeding depression ranged from -0.19 (CIM-496 × CIM-473) to -57.06% (CIM-499 × CIM-707) and later F_2 hybrid was followed by 11 F_2 populations ranged from -29.41 (CIM-446 × CIM-496) to -52.41% (CIM-554 × CIM-499). Meredith (1990) reported that F_2 hybrid had superior performance than well adapted existing cultivars by having low inbreeding depression. Khan *et al*., (2000, 2007) and Basal & Turgut (2003) also mentioned that F_1 hybrids with high heterosis were also associated with higher inbreeding depression. Average heterosis of F_2 over mid parents suggested that little inbreeding depression exists for F_2 and F_3 generations and it is possible to select high yielding F_2 populations for further use (Yuan *et al*., 2002). Therefore, such promising F_2 populations which showed stability and even better performance than F_1s can be used for increased seed cotton yield.

Table 3. Heterosis and heterobeltiosis for plant height and bolls plant^{-1} in F_2s of upland cotton.

F_2 populations	Plant height			Bolls plant^{-1}		
	MP (%)	BP (%)	Inb. Dep. (%)	MP (%)	BP (%)	Inb. Dep. (%)
SLH-284 × CIM-446	-2.28	-8.25	20.15	-1.28	-8.65	59.40
SLH-284 × CIM-473	12.94*	12.38*	9.59	10.94	3.21	43.14
SLH-284 × CIM-496	2.53	-3.80	2.25	7.51	6.33	46.10
SLH-284 × CIM-499	-1.70	-2.82	-2.13	-5.62	-13.98	-0.78
SLH-284 × CIM-506	4.19	-0.09	23.99	-7.73	-13.42	43.08
SLH-284 × CIM-554	4.06	1.73	12.67	5.94	-4.60	62.44
SLH-284 × CIM-707	10.12	5.64	-4.43	12.25	11.20	32.28
CIM-446 × SLH-284	0.51	-5.63	11.26	0.40	-7.09	57.31
CIM-446 × CIM-473	-6.83	-12.93	4.69	7.17	-7.18	41.55
CIM-446 × CIM-496	1.51	1.59	-8.19	-1.66	-9.92	60.19
CIM-446 × CIM-499	-2.09	-7.06	-13.02	-17.65	-30.01	32.56
CIM-446 × CIM-506	0.22	-9.52	4.60	-11.25	-22.53	50.42
CIM-446 × CIM-554	7.93	3.57	6.51	1.96	-1.02	63.16
CIM-446 × CIM-707	-1.22	-3.41	0.57	19.43*	11.48	42.42
CIM-473 × SLH-284	16.66**	16.08**	-8.07	-30.17	-35.03	60.71
CIM-473 × CIM-446	10.39	3.17	-20.91	12.55	-2.52	18.02
CIM-473 × CIM-496	8.27	1.11	-12.41	-17.55	-22.50	46.76
CIM-473 × CIM-499	-9.02	-10.50	-14.02	-21.83	-23.55	9.24
CIM-473 × CIM-506	19.03**	14.69*	-46.88	-0.54	-1.45	28.10
CIM-473 × CIM-554	17.69**	14.50**	7.78	-10.40	-24.32	70.15
CIM-473 × CIM-707	5.52	0.75	-13.46	14.23	5.36	-18.00
CIM-496 × SLH-284	1.94	-4.35	8.07	18.15*	16.86*	45.08
CIM-496 × CIM-446	-11.25	-11.60	14.11	19.60*	9.56	43.75
CIM-496 × CIM-473	-3.69	-10.06	-14.74	-5.41	-11.09	11.28
CIM-496 × CIM-499	-8.18	-12.91	-18.10	6.79	-1.69	-29.03
CIM-496 × CIM-506	14.96**	3.72	-39.90	-19.04	-23.24	24.96
CIM-496 × CIM-554	-0.50	-4.59	-6.35	29.69**	15.64	22.23
CIM-496 × CIM-707	2.67	0.32	-30.48	-10.56	-12.36	8.63
CIM-499 × SLH-284	-11.96	-12.97	-2.17	20.62**	9.93	-19.08
CIM-499 × CIM-446	-3.17	-8.09	-32.85	12.47	-4.40	14.79
CIM-499 × CIM-473	-6.15	-7.68	-9.60	-7.85	-9.88	36.39
CIM-499 × CIM-496	-4.34	-9.26	-11.59	-6.95	-14.34	38.72
CIM-499 × CIM-506	13.63*	7.77	-46.23	-11.25	-13.98	32.56
CIM-499 × CIM-554	9.16	7.94	-14.88	11.54	-7.48	26.99
CIM-499 × CIM-707	-2.05	-4.98	-20.98	-5.55	-14.64	-15.84
CIM-506 × SLH-284	16.16**	11.38*	4.79	-10.47	-15.98	55.22
CIM-506 × CIM-446	4.79	-5.39	-8.16	-1.69	-14.18	52.56
CIM-506 × CIM-473	9.85	5.84	-42.00	3.41	2.46	5.81
CIM-506 × CIM-496	8.73	-1.90	-32.80	7.77	2.18	33.93
CIM-506 × CIM-499	12.15*	6.35	-11.37	-19.70	-22.17	54.55
CIM-506 × CIM-554	13.29*	6.30	9.94	-7.24	-21.06	59.82
CIM-506 × CIM-707	10.49	1.83	-30.64	3.23	-3.98	-5.96
CIM-554 × SLH-284	5.30	2.93	9.21	2.28	-7.90	31.48
CIM-554 × CIM-446	16.20**	11.50*	5.19	19.59	16.09	50.44
CIM-554 × CIM-473	-0.40	-3.11	3.11	42.49**	20.35**	11.95
CIM-554 × CIM-496	2.81	-1.43	-15.17	6.96	-4.63	20.17
CIM-554 × CIM-499	5.15	3.97	0.66	39.51**	15.72*	5.00
CIM-554 × CIM-506	13.93*	6.90	-0.90	7.69	-8.35	41.09
CIM-554 × CIM-707	7.53	5.48	-1.11	16.13	5.45	50.49
CIM-707 × SLH-284	15.14**	10.46*	-29.10	3.02	2.05	-1.99
CIM-707 × CIM-446	-8.11	-10.15	6.52	-6.93	-13.13	-3.01
CIM-707 × CIM-473	4.04	-0.66	-20.12	-14.05	-20.73	12.84
CIM-707 × CIM-496	4.62	2.22	-18.99	5.59	3.47	43.43
CIM-707 × CIM-499	6.67	3.49	-33.18	0.45	-9.22	6.19
CIM-707 × CIM-506	3.74	-4.40	-28.46	-5.40	-12.00	25.43
CIM-707 × CIM-554	8.63	6.56	-29.46	4.26	-5.33	15.79

MP = Mid Parent, HP = High Parent, Inb. Dep.: Inbreeding depression

Table 4. Heterosis and heterobeltiosis for boll weight and seed cotton yield plant^{-1} in F_2s of upland cotton.

F_2 populations	Boll weight			Seed cotton yield plant^{-1}		
	MP (%)	BP (%)	Inb. Dep. (%)	MP (%)	BP (%)	Inb. Dep. (%)
SLH-284 × CIM-446	1.45	0.96	-14.18	5.58	1.96	45.11
SLH-284 × CIM-473	10.97*	6.54	-12.53	26.70**	19.10**	29.23
SLH-284 × CIM-496	-11.38	-19.16	-16.65	-8.90	-18.47	39.57
SLH-284 × CIM-499	-1.70	-2.18	-8.11	0.55	-4.98	-21.22
SLH-284 × CIM-506	4.67	3.55	-15.30	-4.14	-13.67	45.39
SLH-284 × CIM-554	10.62*	9.69*	-27.14	17.94**	7.66	47.97
SLH-284 × CIM-707	-12.56	-17.28	-16.17	5.92	1.87	20.25
CIM-446 × SLH-284	1.20	0.72	-9.38	-0.86	-4.27	52.76
CIM-446 × CIM-473	12.17*	7.19	-26.27	20.11**	9.27	25.75
CIM-446 × CIM-496	4.79	-3.99	-29.41	0.53	-12.76	52.11
CIM-446 × CIM-499	-13.32	-14.15	13.11	-33.77	-39.44	39.14
CIM-446 × CIM-506	15.85**	15.17**	-29.95	-4.70	-16.79	34.96
CIM-446 × CIM-554	22.48**	20.86**	-27.18	22.35**	15.41*	52.76
CIM-446 × CIM-707	-11.14	-15.55	-12.58	7.31	-0.19	35.33
CIM-473 × SLH-284	-9.71	-13.32	1.65	-36.81	-40.60	60.13
CIM-473 × CIM-446	25.22**	19.66**	-35.86	26.38**	14.98**	-6.23
CIM-473 × CIM-496	6.70	-6.19	-25.90	-15.54	-19.87	36.88
CIM-473 × CIM-499	5.96	2.20	-29.81	-16.06	-16.53	-16.27
CIM-473 × CIM-506	16.96**	11.14*	-38.63	10.61*	5.66	0.44
CIM-473 × CIM-554	-7.12	-10.10	6.00	-12.34	-24.32	66.01
CIM-473 × CIM-707	-1.07	-9.94	-18.80	-1.10	-3.44	-18.47
CIM-496 × SLH-284	15.32**	5.19	-40.42	25.57**	12.38**	28.96
CIM-496 × CIM-446	-11.55	-18.96	-2.53	9.20	-5.24	39.15
CIM-496 × CIM-473	-16.69	-26.75	-0.19	-33.05	-36.48	21.43
CIM-496 × CIM-499	-24.18	-31.14	3.63	-12.11	-17.05	-28.51
CIM-496 × CIM-506	-27.63	-33.33	5.92	-27.45	-27.96	9.93
CIM-496 × CIM-554	-10.25	-18.76	-12.74	8.90	-10.04	18.57
CIM-496 × CIM-707	-25.10	-27.94	5.92	-33.19	-38.03	19.06
CIM-499 × SLH-284	-13.14	-13.56	0.20	4.50	-1.25	-7.74
CIM-499 × CIM-446	-26.39	-27.10	13.81	-13.04	-20.49	4.90
CIM-499 × CIM-473	9.51	5.62	-34.45	0.08	-0.48	15.28
CIM-499 × CIM-496	-20.22	-27.54	-3.71	-25.75	-29.93	13.85
CIM-499 × CIM-506	-7.22	-9.24	-9.12	-12.20	-16.58	17.61
CIM-499 × CIM-554	-6.99	-7.33	1.04	12.14*	-2.73	14.64
CIM-499 × CIM-707	17.43**	10.58	-57.06	-0.97	-2.78	-75.14
CIM-506 × SLH-284	15.45**	14.22**	-35.77	-3.51	-13.10	46.28
CIM-506 × CIM-446	-11.56	-12.09	-0.46	-16.05	-26.70	54.72
CIM-506 × CIM-473	-5.99	-10.66	-12.20	-4.26	-8.54	-15.72
CIM-506 × CIM-496	-7.69	-14.97	-22.31	8.45	7.69	8.96
CIM-506 × CIM-499	9.75*	8.06	-35.19	-8.66	-13.21	29.48
CIM-506 × CIM-554	-3.14	-4.98	-10.87	-15.00	-29.39	75.52
CIM-506 × CIM-707	-4.18	-8.42	-28.37	-4.35	-10.69	-7.24
CIM-554 × SLH-284	23.81**	22.76**	-28.58	19.97**	9.51	23.74
CIM-554 × CIM-446	-22.72	-23.74	23.24	-9.33	-14.47	61.34
CIM-554 × CIM-473	-4.83	-7.88	-3.52	23.81**	6.88	21.23
CIM-554 × CIM-496	-19.51	-27.15	2.33	-13.73	-28.74	20.23
CIM-554 × CIM-499	32.02**	31.54**	-52.41	30.71**	13.38**	11.78
CIM-554 × CIM-506	6.76	4.74	-19.36	5.96	-11.97	34.36
CIM-554 × CIM-707	-14.61	-19.87	-6.82	19.96**	5.72	31.13
CIM-707 × SLH-284	4.34	-1.30	-33.24	14.01*	9.66	-25.57
CIM-707 × CIM-446	-23.41	-27.21	3.52	-11.90	-18.06	39.91
CIM-707 × CIM-473	-3.20	-11.88	-16.01	-9.67	-11.81	38.27
CIM-707 × CIM-496	-24.69	-27.54	-6.55	-14.30	-20.51	47.82
CIM-707 × CIM-499	0.00	-5.83	-18.25	4.13	2.23	-22.03
CIM-707 × CIM-506	-3.73	-7.99	-27.28	-10.00	-15.96	-10.49
CIM-707 × CIM-554	-19.68	-24.62	4.90	-16.87	-26.73	47.50

MP = Mid Parent, HP = High Parent, Inb. Dep.: Inbreeding depression

Seed cotton yield: Seed cotton yield per plant varied from 55.74 to 85.47 g and 45.57 to 96.05 g among parental cultivars and F_2 populations, respectively (Table 2). Maximum seed cotton yield was obtained in F_2 hybrid CIM-496 × SLH-284 (96.05 g) and it was at par with five F_2 populations ranged from 86.01 to 92.04 g. Lowest seed cotton yield was observed in F_2 hybrid CIM-473 × SLH-284 (45.57 g) and was found at par with five other F_2 populations ranged from 45.945 to 54.29 g. Other genotypes showed medium values for seed cotton yield per plant. Results were in corroboration with findings of Baloch *et al*., (1993a & b), Babar *et al*., (2001), Basal & Turgut (2003), Khan *et al*., (2007) and Soomro *et al*., (2010) as observed significant variations among genotypes and their F_1 and F_2 hybrids for seed cotton yield.

In case of heterosis for yield (Table 4), 25 F_2 populations showed positive mid parent heterosis ranged from 0.08 (CIM-499 × CIM-473) to 30.71% (CIM-554 × CIM-499). The three F_2 populations SLH-284 × CIM-473 (26.70%) CIM-473 × CIM-446 (26.38%) and CIM-496 × SLH-284 (25.57%) also followed the above top promising hybrid and showed maximum heterosis for said trait. However, 13 F_2 populations significantly surpassed the mid parent values. The 16 F_2 populations were superior to best parent utilized in the crosses by having positive heterobeltiosis. However, heterobeltiosis for yield ranged from 1.35 (CIM-473 × CIM-707) to 28.82% (CIM-496 × CIM-446). The later promising F_2 hybrid was followed by three F_2 populations (SLH-284 × CIM-473, CIM-473 × CIM-446 and CIM-554 × CIM-499) with range of 13.38 to 19.10%. Overall, five F_2 populations significantly exceeded better parent values. Results were in accordance with findings of Tang *et al*., (1993), Galanopoulou & Roupakias (1999) and Khan *et al*., (2010) as reported maximum increase in yield and yield components in segregating populations through transgressive segregation against standard cultivars and F_1 hybrids. Khan *et al*., (2000), Soomro (2000), Yuan *et al*., (2002) Wu *et al*., (2004), Gbri *et al*., (2006) Basbag *et al*., (2007), Xing *et al*., (2007) and Campbell *et al*., (2008) also reported significant heterotic effects for seed cotton yield over mid and better parents in F_1 and F_2 hybrids.

By comparing F_2s yield with F_1s mean values, 79% of F_2 populations showed inbreeding depression ranged from 0.44 (CIM-473 × CIM-506) to 75.52% (CIM-506 × CIM-554). However, 21% of F_2 populations revealed negatives values for inbreeding depression means that these F_2 populations performed better and produced more seed cotton yield as compared to F_1 hybrids. The negative inbreeding depression ranged from -6.23 (CIM-473 × CIM-446) to -75.14% (CIM-499 × CIM-707) and later F_2 hybrid was followed by five other F_2 populations ranged from -16.27 (CIM-473 × CIM-499) to -28.51% (CIM-496 × CIM-499). The involvement of cultivar CIM-499 in above F_2 populations exhibited best performance even as paternal/maternal parent. Although, F_2 populations may display less heterosis as compared to F_1s, but still better than high parents and can be used for hybrid cotton to skip expensive manual method of F_1 hybrid seed production through hand emasculation and pollination (Wu, *et al*., 2004; Khan *et al*., 2007, 2009, 2011). F_1 hybrids having extra ordinary performance could also be used as F_2 crop seed to increase seed cotton yield per unit area (Baloch *et al*., 1993a; Khan *et al*, 2000, 2009). F_2 populations have more genetic variation and might result in a greater range of adaptation relative to their parents and F_1 hybrids (Meredith & Brown, 1998; Wang & Li, 2000; Wei *et al*., 2002; Wu *et al*., 2004). The F_2 populations heterosis in cotton has been reported and can express at least 50% of economic heterosis shown by F_1 hybrids that can increase the yield (Wang & Pan, 1991; Tang *et al*., 1993; Li *et al*., 2000; Xing *et al*., 2000; Khan *et al*, 2010). Therefore, F_2 populations with negative inbreeding depression are desirable in cotton and can be used for yield enhancement.

Conclusion

F_2 populations i.e. CIM-554 × CIM-473, CIM-554 × CIM-499, CIM-496 × SLH-284, CIM-473 × CIM-446 and CIM-554 × SLH-284 performed better with significant heterosis for yield and yield contributing traits. Inbreeding depression was observed with varied values among F_2 populations for all the traits. However, significant percentage of F_2 populations revealed negative values for inbreeding depression for all the traits revealed that these F_2s excelled F_1s even after segregation, and could be used as hybrid cotton.

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