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HYBRID VIGOR AND ITS DETERIORATION IN INTRASPECIFIC POPULATIONS OF UPLAND COTTON

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SUMMARY

Seven lines (‘VH-292’, ‘VH-259’, ‘Bt-802’, ‘Sadori’, ‘Shahbaz’, ‘CRIS-342’, and ‘Bt.ZZ.NL-370’), and three testers (‘VH-291’, ‘FH-113’, and ‘IR-3701’) of upland cotton (*Gossypium hirsutum* L.) were crossed through line-by-tester mating to produce 21 F_1 hybrids. The lines, testers, and their F_1 and F_2 populations were grown in a randomized complete block design with three replications at Sindh Agriculture University, Tandojam, Pakistan, in consecutive cropping seasons. Analysis of variance revealed that the genotypes (including parental lines, testers, and their 21 F_1 and F_2 populations) and parent vs. hybrids differed significantly for all the studied traits, except for plant height in the F_2 population and sympodial branches plant^{-1} in the F_1 and F_2 populations. Lines ‘VH-292’ and ‘VH-259’ and testers ‘VH-291’ and ‘FH-113’ exhibited higher plant height, sympodial branches, bolls plant^{-1}, and boll weight than other genotypes and were identified as suitable parental genotypes for hybridization. The F_1 and F_2 populations of ‘VH-292’ × ‘VH-291’ and ‘VH-292’ × ‘FH-113’ produced more sympodial branches, bolls plant^{-1}, and seed cotton yield plant^{-1} than other crosses. The F_1 hybrid of ‘Bt-802’ × ‘VH-291’ and the F_2 population of the ‘Sadori’ × ‘VH-291’ cross produced higher boll weight than other genotypes. Overall, the mean performance of the F_1 hybrids for all the traits was better than that of their parents and the F_2 populations likely due to heterotic effects in the F_1 populations and inbreeding depression in the F_2 populations. The significant mean squares for parental genotypes, crosses, and parents vs. crosses indicated that the data obtained in this work are valuable for determining parental performance, hybrid evaluation, heterotic effects, and inbreeding depression. Significant mean squares due to parents vs. crosses revealed the good scope of heterotic effects in the F_1 populations for all the traits.

Keywords: Line-by-tester analysis, heterosis, heterobeltiosis, inbreeding depression, morphological and yield traits, upland cotton

Key findings: The F_1 hybrids showed better mean performance for the studied traits compared with their parental lines, the testers, and the F_2 populations likely due to heterotic effects. Lines VH-292 and VH-259 and the tester VH-291 were recognized as suitable parental genotypes for hybridization. Overall, the cross VH-292 × VH-291 showed the best performance in F_1 and F_2 generations. The best-performing hybrids with the highest heterosis must be trined up to F_2 and then combined with the hybrids with the highest heterotic effects but with lowest inbreeding depression for isolation and cultivar development.

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INTRODUCTION

In Pakistan, cotton is a cash crop and is mainly grown as a source of fiber, food, and feed. Moreover, cotton fibers play a vital role in uplifting the country's economy. It earns 65% of the foreign exchange and accounts for 8.2% of the value-added income in agriculture and for 2% of the GDP of Pakistan (USDA, 2021). Globally, Pakistan ranks fourth in cotton area and production. However, the yield per unit area in Pakistan is very low compared with that in other cotton-growing countries. Cotton provides the raw material for various agro-based industries, such as ginning factories, oil mills, textiles, and ghee industries, which also employ communities (Soomro, 2000).

The farmers of Pakistan are investigating and developing cotton with high fiber and lint yields. Cottonseed oil fulfills 18.8% of the demand for comestible oil. The information on seed cotton oil and its consumption is limited or nonexistent. The industry has an impregnable need to further improve cottonseed oil to enable its direct use as a vegetable cooking oil or its hydrogenation into solid ghee. In addition, cotton production is highly vulnerable to abiotic and biotic stresses (Khan, 2011; Shuli *et al.*, 2018).

Cotton breeders are trying to develop varieties that are well adapted to environmental conditions; produce high yields, high ginning outturn, and superior fiber quality; respond to high fertilizer applications; and exhibit increased tolerance to diseases and insect pests (Soomro *et al*., 2012). Parents for breeding programs must be genetically superior, physiologically efficient, and possess good general and specific combining abilities such that they could be utilized for varietal development and commercial heterosis exploitation for hybrid crop development. Improvement in quantitative characters is usually based on progeny performance (Khan *et al*., 2007; Soomro *et al*., 2008). In quantitative genetics, only additive genes determine progeny performance. By contrast, dominant genes are specific to only the genotypic value of an individual (Falconer, 1989) and thus do not contribute to the progeny from one generation to another.

Heterosis refers to the superiority of F_1 hybrid performance over parental performance (Wu *et al.,* 2004). Generally, positive heterosis is considered desirable. However, in cotton, negative heterosis is useful for some traits, such as plant height, days to first flowering and maturity, node to first sympodial branch, micronaire, and gossypol content, because hybrids with these traits are superior to their parental lines (Singh *et al.,* 2012). The magnitude of heterosis should be at an acceptable level for the successful development of hybrid cotton. In cotton, heteroses of 50% over the popular variety and of 20% over the popular hybrid are considered useful for hybrid development (Batool and Khan, 2012). The present study aims to a) generate genetic variability among upland cotton genotypes for increased seed cotton yield and b) study heterotic effects and inbreeding depression in F_1 and F_2 populations.

MATERIALS AND METHODS

The experimental material consisted of seven parental lines, i.e., 'VH-292', 'VH-259', 'Bt-802', 'Sadori', 'Shahbaz', 'CRIS-342', and 'Bt.ZZ.NL-370'; three testers, i.e., 'VH-291', 'FH-113', and 'IR-3701'; and 21 hybrids that were developed through the line × tester mating of upland cotton. The lines, testers, and their F_1 and F_2 populations were grown during 2012–2013 and 2013–2014 in a randomized complete block design with three replications at Sindh Agriculture University, Tandojam, Pakistan. The spaces between rows and plants were maintained at 75 and 30 cm, respectively. Ten plants were tagged at random from the central row per entry and per replication. Data on plant height, sympodial branches plant^{-1}, boll weight (g), bolls plant^{-1}, and seed cotton yield (g) plant^{-1} were recorded.

Statistical analyses

Analysis of variance was carried out in accordance with Gomez and Gomez (1984) to determine differences among genotypes, and heterosis and heterobeltiosis effects were determined in accordance with Fehr (1987). The population means were further compared and separated by using Duncan's new multiple range test (Duncan, 1955). Inbreeding depression in F_2 populations was calculated as the percent decrease in the means of F_2s compared with that of F_1 hybrids as outlined by Baloch *et al*. (1993).

RESULTS AND DISCUSSION

Analysis of variance revealed that the genotypes and their F_1 and F_2 populations showed significant differences in boll weight, bolls plant^{-1}, and seed cotton yield plant^{-1} (Table 1). The present results reflected the differences between parents vs. hybrids and further suggested the scope of heterosis breeding. However, differences among the genotypes were nonsignificant for sympodial branches in F_1 and F_2 populations and for plant height in F_1 populations. Significant differences were also recorded among the upland cotton genotypes for various morphological and yield-related traits (Panni *et al*., 2010; Soomro *et al*., 2010, 2012; Khan, 2011; Komal *et al*., 2014; Muhammad *et al*., 2014).

Table 1. Mean squares for various traits of F_1 and F_2 populations of upland cotton.

Source of variation	d.f.	Plant height		Sympodial branches plant^{-1}		Boll weight		Boll plant^{-1}		Seed cotton yield plant^{-1}	
		F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2
Replications	2	27.01	86.91	12.21	4.2	0.01	0.01	14.94	15.22	15.13	21.02
Genotypes	30	346.82**	22.62^{NS}	7.64^{NS}	2.07^{NS}	0.05**	0.06**	55.06**	25.73**	910.37**	487.46**
Parents (P)	9	848.43**	36.52^{NS}	5.27^{NS}	4.71^{NS}	0.09**	0.09**	43.48**	32.85**	672.28**	607.68**
P vs. C	1	7635.85**	63.27^{NS}	47.43**	2.97^{NS}	0.78**	0.02^{NS}	391.33**	9.61^{NS}	6050.5**	0.46^{NS}
Crosses (C)	20	25.42**	14.33^{NS}	7.76^{NS}	0.84^{NS}	0.04**	0.05**	44.70**	23.34**	856.45**	457.72**
Lines	6	37.41^{NS}	30.15^{NS}	13.68 ^{NS}	0.81^{NS}	0.01**	0.03*	45.18**	37.20**	667.50**	485.52**
Testers	2	61.39**	9.91^{NS}	22.04**	3.29^{NS}	0.33**	0.29**	251.12**	106.08**	5751.35**	2811.93**
Line × Tester	12	13.43*	7.16 ^{NS}	2.42 ^{NS}	0.44^{NS}	0.001^{NS}	0.01**	10.06**	2.62^{NS}	135.1**	51.44*
Error	60	5.76	20.94	6.53	7.3	0.001	0.01	0.72	3.91	0.76	25.61

*, ** = Significant at the 5% and 1% levels of probability, respectively. NS = Nonsignificant.

Mean performance of the cotton populations

Plant height

The average performance of the hybrids indicated that the F_1 hybrids of 'VH-292' × 'IR-3701', 'VH-259' × 'IR-3701', 'Shahbaz' × 'IR-3701', and 'CRIS-342' × 'VH-291' produced medium-tall plants (Table 2). The average performance of the hybrids indicated that 'VH-292' × 'VH-291', 'VH-259' × 'IR-3701', and 'VH-259' × 'FH-113' produced medium-tall plants in their F_2 populations (Table 3). The present results were in agreement with the findings of past studies, which also recorded similar heterosis in the F_1 and F_2 populations of upland cotton (Sohu *et al.,* 2010; Soomro *et al.*, 2010; Basal *et al.,* 2011; Saravanan and Koodaligam, 2011; Iqbal *et al.,* 2013; Vineela *et al.,* 2013; Liu *et al.*, 2014). Heterosis may be considered desirable for medium-tall plants. The desirable crosses were 'VH-292' × 'FH-113', 'VH-292' × 'IR-3701', and 'CRIS-342' × VH291. The F_2 populations 'VH-292' × 'FH-113', 'Bt.ZZ.NL-370' × 'VH-291', and 'Bt-802' × 'VH-291' expressed the highest inbreeding depression. The present findings confirmed the results of Abro *et al.* (2014) and Muhammad *et al.* (2014), who also observed desirable heterosis in F_1 hybrids and inbreeding depression in F_2 populations for plant height. The present results are also in agreement with the results of past studies, which also described that medium-tall plants can produce a fair number of sympodial branches and hence produce additional fruiting branches and exhibit resistance to lodging (Basal *et al.*, 2011; Saravanan and Koodalingam, 2011; Iqbal *et al.*, 2013; Liu *et al.*, 2014).

For plant height, 18 F_1 hybrids revealed relative positive heterosis, whereas 14 expressed positive heterobeltiosis (Table 4). The relative positive heterosis ranged from 1.64% to 23.31%, and heterobeltiosis ranged from 0.43% to 11.35%. The highest relative heterosis (23.31%) was calculated for the 'Sadori' × 'IR-3701' cross. The hybrid 'Bt-802' × 'IR-3701' produced higher heterobeltiosis (11.35%) than other crosses. Three hybrids expressed negative heterosis as reflected by their lower mean values than those of their respective mid-parents.

The heterotic effects and inbreeding depression in F_2 populations for plant height are presented in Table 5. The hybrids 'VH-292' × 'IR-3701' and 'Shahbaz' × 'VH-291' showed desirable heterotic and heterobeltiotic effects that ranged from −4.22% to −2.70%. The maximum inbreeding depression was exhibited

Table 2. Mean performance of lines, testers, and their F_1 populations involved in the L × T mating design for various traits of upland cotton.

Lines, testers, and their F_1 populations	Plant height (cm)	Sympodia plant^{-1}	Boll weight (g)	Bolls plant^{-1}	Seed cotton yield plant^{-1} (g)
Lines					
VH-292	149.86a	23.67a–c	3.38h–j	38.40d–g	125.18d–j
VH-259	121.53h–i	22.40a–e	3.44c–g	37.40e–i	122.60d–j
Bt-802	106.9n	20.30a–g	3.47a–e	37.00f–j	123.50d–f
Sadori	85.00o	21.60g	3.34j–l	35.1f–j	115.60e–i
Shahbaz	106.2n	20.30e–g	3.25n–r	32.40i–k	101.11h–j
CRIS-342	107.13mn	19.70d–g	3.26m–p	29.7k	100.73h–j
Bt.ZZ.NL-370	111.00lm	21.40e–g	3.30k–n	28.80k	90.73j
Testers					
VH-291	127.33b–f	22.50a–g	3.45b–f	38.00e–h	126.39d–f
FH-113	116.87jk	19.60c–g	3.29l–o	39.5c–f	125.31d–f
IR-3701	113.53kl	21.40fg	2.88t	32.40i–k	89.57j
F_1 Populations					
VH-292 × VH-291	129.66bc	24.80a	3.48a–d	45.7a	155.32a
VH-292 × FH-113	131.45b	24.20ab	3.39g–j	43.30b–d	142.25a–d
VH-292 × IR-3701	125.16c–h	24.10a–c	3.21p–s	37.20e–j	117.66e–i
VH-259 × VH-291	126.65c–g	23.40a–c	3.49ab	42.3b–f	142.74a–b
VH-259 × FH-113	127.33b–f	21.90a–e	3.39g–j	40.20b–f	131.30b–f
VH-259 × IR-3701	124.46d–i	21.50a–e	3.28m–o	36.6f–j	113.92f–i
Bt.802 × VH-291	128.25b–e	22.90a–d	3.51a	44.60b	149.80a–c
Bt.802 × FH-113	122.55g–i	20.40a–f	3.43d–h	39.20c–f	128.72d–f
Bt.802 × IR-3701	126.38c–g	18.20d–g	3.24o–r	36.70f–j	113.88f–i
Sadori × VH-291	127.62b–f	23.30a–d	3.49a–c	44.80b	150.34ab
Sadori × FH-113	123.44f–i	20.20a–f	3.36i–k	39.00c–f	127.20d–f
Sadori × IR-3701	122.39g–i	20.80a–e	3.25n–q	38.80c–f	117.40e–i
Shahbaz × VH-291	123.4f–i	23.30a–d	3.46a–f	43.70bc	136.26a–e
Shahbaz × FH-113	122.52g–i	22.90a–d	3.34j–l	37.40e–i	118.92e–h
Shahbaz × IR-3701	124.36d–i	23.10a–d	3.19rs	33.60g–k	98.83h–i
CRIS-342 × VH-291	125.65c–h	24.20ab	3.41f–i	39.70c–f	130.19c–f
CRIS-342 × FH-113	120.35i–j	21.80ab	3.32k–m	39.20c–f	126.03d–f
CRIS-342 × IR-3701	121.46h–i	21.60a–f	3.19q–s	33.20h–k	102.43g–j
Bt.ZZ.NL-370 × VH-291	128.39b–d	23.40a–c	3.42e–h	35.80f–j	116.92e–i
Bt.ZZ.NL-370 × FH-113	122.48g–i	21.9a–c	3.34 j–l	38.40d–g	125.50d–f
Bt.ZZ.NL-370 × IR-3701	123.64e–i	23.20a–d	3.16s	32.30 jk	97.34u
$LSD_{0.05}$	6.435	4.62	0.057	1.15	19.98

by the populations of 'VH-292' × 'FH-113' (10.05%), 'Bt.ZZ.NL-370' × 'VH-291' (8.69%), and 'Bt-802' × 'VH-291' (8.57%). The minimum inbreeding depression (2.48) was shown by 'VH-259' × 'IR-3701'.

Two crosses can be regarded as desirable: 'VH-292' × 'VH-291' and 'VH-292' × 'IR-3701'. 'VH-292' × 'IR-3701' could present better performance than other genotypes because it has shown desirable heterotic effects for plant height. The present findings are also validated by past findings that obtained desirable heterosis for plant stature (Campbell and Bowman, 2010; Senthil *et al.*, 2010; Patel *et al.*, 2011).

Sympodial branches plant^{-1}

The F_1 and F_2 populations of 'VH-292' × 'VH-291' showed the highest sympodial branches plant^{-1} of 24.8 and 21.65 in, respectively, followed by the F_1 population of 'VH-292' × 'FH-113' and the F_2 population of 'Sadori' × 'VH-291' (Table 2). The heterotic effects revealed that 17 hybrids showed relative positive heterosis and 16 expressed heterobeltiosis (Table 4). The relative desirable heterosis varied from 2.25% to 14.79%, whereas heterobeltiosis ranged from 0.49% to 12.80%. For sympodial branches plant^{-1}, the highest relative heterosis (14.79%) and

Table 3. Mean performance of lines, testers, and their F_2 populations involved in the L × T mating design for various traits of upland cotton.

Lines, testers, and their F_2 populations	Plant height (cm)	Sympodial branches plant^{-1}	Boll weight (g)	Bolls plant^{-1}	Seed cotton yield plant^{-1} (g)
Lines					
VH-292	125.85	23.40	3.37a–e	34.70a–d	113.23a–f
VH-259	122.67	21.30	3.44ab	35.21a–c	116.99a–c
Bt-802	117.25	20.20	3.46a	34.42a–e	115.36a–d
Sadori	118.42	20.90	3.32b–e	33.36b–e	106.79d–h
Shahbaz	116.52	20.30	3.26e–g	30.63e–h	96.30ij
CRIS-342	114.36	19.50	3.27d–g	28.52g–i	94.13j
Bt.ZZ.NL-370	118.45	21.30	3.28b–f	26.43i	83.41k
Testers					
VH-291	120.72	22.60	3.43ab	36.31ab	120.76ab
FH-113	115.35	19.50	3.29b–f	33.62b–e	106.99g–h
IR-3701	117.46	21.00	2.85i	29.24f–i	80.20k
F_2 populations					
VH-292 × VH-291	121.39	21.65	3.37a–e	37.61a	121.91a
VH-292 × FH-113	118.24	20.62	3.31b–e	35.92a–c	114.29a–e
VH-292 × IR-3701	116.52	21.48	3.14gh	32.23c–g	96.81ij
VH-259 × VH-291	118.45	20.59	3.40a–e	36.75ab	120.12ab
VH-259 × FH-113	119.62	20.35	3.32b–e	35.08a–c	111.78b–g
VH-259 × IR-3701	121.37	20.56	3.16f–h	33.00d–f	99.84h–j
Bt.802 × VH-291	117.26	20.92	3.41a–d	36.35ab	119.13ab
Bt.802 × FH-113	115.15	20.20	3.34a–e	32.12c–g	102.13g–j
Bt.802 × IR-3701	118.64	20.70	3.14gh	32.07c–g	96.32ij
Sadori × VH-291	118.25	21.58	3.42a–c	36.32ab	119.38ab
Sadori × FH-113	115.36	19.94	3.30b–e	32.95b–f	104.16f–i
Sadori × IR-3701	115.29	20.52	3.14gh	32.32c–g	97.09ij
Shahbaz × VH-291	115.41	20.95	3.35a–e	34.71a–d	111.58b–g
Shahbaz × FH-113	116.73	20.10	3.26e–g	32.05c–g	99.98h–j
Shahbaz × IR-3701	117.46	20.46	3.03h	29.23f–i	84.69k
CRIS-342 × VH-291	115.31	20.72	3.31b–e	33.12b–e	105.03e–i
CRIS-342 × FH-113	113.26	20.81	3.28c–f	32.42c–f	108.12c–h
CRIS-342 × IR-3701	114.27	19.86	3.04h	28.22hi	81.66k
Bt.ZZ.NL-370 × VH-291	117.23	20.78	3.33a–e	30.94d–h	98.50h–j
Bt.ZZ.NL-370 × FH-113	115.33	19.64	3.26e–g	30.85d–h	96.12ij
Bt.ZZ.NL-370 × IR-3701	115.21	20.55	3.05h	27.30hi	79.16k
$LSD_{0.05}$	-	-	0.138	3.272	8.726

heterobeltiosis (12.80%) were observed for the F_1 and F_2 populations of the cross ‘Shahbaz’ × ‘FH-113’.

The heterotic effects of F_2 populations revealed that positive heterosis and heterobeltiosis values were recorded for the cross ‘CRIS-342’ × ‘FH-113’ (6.71% and 6.72%) for sympodial branches plant^{-1} (Table 5). The maximum inbreeding depression was observed in the F_2 populations of the crosses ‘VH-292’ × ‘FH-113’(14.79) and ‘CRIS-342’ × ‘VH-291’ (14.38), and the minimum depression (0.98) was displayed by the cross ‘Bt-802’ × ‘FH-113’. These findings were in agreement with the results of Ahmad *et al.* (2013), Abro *et al.* (2014). Kumar *et al.* (2014) and Latif *et al.* (2014) also reported similar heterotic effects and inbreeding depression in the F_1 and F_2 populations of upland cotton. The maximum positive heterotic effects were recorded for the crosses ‘Shahbaz’ × ‘FH-113’ and ‘CRIS-342’ × ‘VH-291’ then in cross ‘Shahbaz’ × ‘IR-3701’, and the positive heterosis for the said trait was also reported in the F_1 and F_2 populations of upland cotton (Dhivya *et al.*, 2014; Patel and Kumar, 2014; Baloch *et al.*, 2015) (Table 5).

Table 4. Heterotic effects in F_1 populations (over mid- and better-parents) for various traits of upland cotton.

F_1 Populations	Plant height		Sympodial branches plant^{-1}		Boll weight		Bolls plant^{-1}		Seed cotton yield plant^{-1}	
	Ht (%)	Htb (%)	Ht (%)	Htb (%)	Ht (%)	Htb (%)	Ht (%)	Htb (%)	Ht (%)	Htb (%)
VH-292 × VH-291	−6.46	−13.50	7.36	4.64	1.75	0.87	19.63	19.01	23.47	22.87
VH-292 × FH-113	−0.46	−12.30	11.78	2.10	1.50	0.30	11.31	9.62	15.92	13.53
VH-292 × IR-3701	−4.96	−16.50	6.87	1.69	2.56	−5.03	5.08	−3.12	9.55	−6.02
VH-259 × VH-291	1.64	−0.82	4.23	4.00	1.15	1.16	12.20	11.32	14.65	12.93
VH-259 × FH-113	6.82	4.79	4.28	−2.23	0.59	−1.45	4.42	1.77	5.97	4.79
VH-259 × IR-3701	5.92	2.44	−1.83	−4.02	3.80	−4.65	4.87	−2.14	7.37	−7.08
Bt-802 × VH-291	9.33	0.43	7.00	1.78	1.45	1,15	18.93	17.37	19.94	18.51
Bt-802 × FH-113	9.52	4.83	2.25	0.49	1.48	−1.15	2.35	−0.76	3.47	2.73
Bt-802 × IR-3701	14.68	11.35	−12.70	−14.95	1.89	−6.63	5.76	−0.81	6.83	−7.79
Sadori × VH-291	20.21	0.23	5.67	3.55	2.65	1.16	22.40	17.89	24.25	18.94
Sadori × FH-113	22.27	5.59	−1.94	−6.48	1.20	0.60	4.56	−1.27	5.56	1.52
Sadori × IR-3701	23.31	7.83	−3.25	−3.70	4.50	−2.70	14.79	10.54	14.43	1.56
Shahbaz × VH-291	5.69	−3.09	8.88	3.55	3.28	0.29	24.15	15.00	28.52	15.71
Shahbaz × FH-113	9.83	4.80	14.79	12.80	2.14	1.52	4.18	−5.32	5.05	−5.09
Shahbaz × IR-3701	13.20	9.57	10.79	7.94	3.91	−1.85	3.70	3.71	3.60	−2.25
CRIS-342 × VH-291	7.18	−1.32	14.69	7.55	1.49	−1.16	17.11	4.48	14.60	2.99
CRIS-342 × FH-113	7.44	2.95	10.94	10.66	1.22	0.91	13.30	−0.76	11.53	0.58
CRIS-342 × IR-3701	10.10	7.01	5.10	0.93	3.9	−2.15	5.40	2.47	7.56	1.69
Bt.ZZ.NL.370 × VH-291	7.75	0.83	6.60	4.00	1.18	−0.87	4.68	−5.79	7.66	−7.5
Bt.ZZ.NL.370 × FH-113	7.48	4.77	6.83	2.34	1.52	1.21	12.28	−2.78	16.20	0.16
Bt.ZZ.NL.370 × IR-3701	10.15	8.93	8.4	8.41	2.27	−4.24	5.56	−9.30	7.92	7.32

Table 5. Heterotic effects in F_2 populations (over mid and better-parents) and inbreeding depression for various traits of upland cotton.

F_2 Populations	Plant height			Sympodial branches plant^{-1}			Boll weight			Bolls plant^{-1}			Seed cotton yield plant^{-1}		
	Ht (%)	Htb (%)	Ibd (%)	Ht (%)	Htb (%)	Ibd (%)	Ht (%)	Htb (%)	Ibd (%)	Ht (%)	Htb (%)	Ibd (%)	Ht (%)	Htb (%)	Ibd (%)
VH-292 × VH-291	−1.53	−3.54	6.38	−5.87	−7.48	12.70	−0.88	−1.75	3.16	5.94	3.58	17.70	4.19	0.36	21.51
VH-292 × FH-113	−1.96	−6.05	10.05	−3.87	−11.88	14.79	−0.60	−1.78	2.36	5.18	3.51	17.04	3.70	0.85	19.72
VH-292 × IR-3701	−4.22	−7.41	6.9	−3.24	−8.20	10.87	0.96	−6.82	2.18	0.88	−7.12	13.36	0.09	−14.50	17.72
VH-259 × VH-291	−2.66	−3.44	6.47	−6.19	−8.89	12.00	−0.87	−1.16	2.86	2.79	1.21	13.12	1.04	−0.53	15.85
VH-259 × FH-113	0.51	−2.49	6.05	−0.24	−4.46	7.08	−1.19	−3.20	2.06	1.98	−0.37	12.74	−0.16	−4.45	14.87
VH-259 × IR-3701	1.09	−1.06	2.48	−2.79	−3.57	4.37	0.64	−7.87	3.66	2.48	−6.28	9.84	1.26	−14.66	12.36
Bt-802 × VH-291	−1.44	−2.87	8.57	−2.24	−7.43	8.65	−1.16	−1.44	2.85	2.83	0.11	18.49	0.93	−1.35	20.47
Bt-802 × FH-113	−0.99	−1.79	6.05	1.76	0.00	0.98	−1.18	−3.43	2.62	−5.53	−6.68	18.06	−7.60	−10.93	20.21
Bt-802 × IR-3701	1.09	1.00	6.12	0.48	−1.43	−12.08	−0.63	−9.25	3.09	0.82	−6.83	12.61	−1.46	−16.46	15.42
Sadori × VH-291	−1.1	−2.05	7.34	−0.78	−4.51	7.38	1.18	−0.29	2.00	4.37	0.03	18.93	4.92	−1.14	20.59
Sadori × FH-113	−1.47	−2.58	6.54	−1.29	−4.59	1.29	−0.30	−0.60	1.78	−1.49	−1.99	15.51	−2.55	−2.64	18.11
Sadori × IR-3701	−2.25	−2.64	5.8	−0.21	−2.28	1.36	1.62	−5.42	3.38	3.42	−3.12	16.70	3.84	−9.08	17.29
Shahbaz × VH-291	−2.70	−4.39	6.47	−2.33	−7.30	10.08	−0.10	−2.33	3.18	3.77	−4.40	20.57	2.81	−7.60	23.71
Shahbaz × FH-113	0.69	0.18	4.72	1.00	−0.98	12.23	−0.60	−0.91	2.39	−0.15	−4.67	14.30	−1.64	−6.55	15.93
Shahbaz × IR-3701	0.40	0.00	5.55	−0.92	−2.57	11.43	−0.98	−7.05	5.01	−2.24	−4.57	12.70	−4.03	−12.06	14.30
CRIS-342 × VH-291	−1.89	−4.48	8.23	−1.57	−8.32	14.38	−1.19	−3.49	2.93	2.22	−8.78	16.57	−2.24	−13.02	19.32
CRIS-342 × FH-113	−1.38	−1.81	5.89	6.71	6.72	4.54	0.00	−0.30	1.22	4.41	−3.57	17.08	1.55	−4.55	18.97
CRIS-342 × IR-3701	−1.41	−2.71	5.87	−1.97	−5.48	8.10	−0.65	−7.03	5.00	−2.18	−3.49	15.00	−6.31	−13.24	20.25
Bt.ZZ.NL-370 × VH-291	−1.86	−2.89	8.69	−5.33	−8.05	11.19	−0.89	−2.91	2.63	−1.30	−14.79	13.57	−3.52	−18.43	15.75
Bt.ZZ.NL-370 × FH-113	−1.34	−2.63	5.84	−3.72	−7.79	10.32	−0.60	−0.91	2.39	2.83	−8.24	19.66	0.97	−10.16	23.41
Bt.ZZ.NL-370 × IR-3701	−2.32	−2.73	6.82	−2.84	−3.52	11.42	−7.01	−7.29	3.48	−1.79	−6.63	15.48	−3.24	−5.09	18.68

For inbreeding depression, the 21 crosses displayed positive values, whereas one cross, namely, 'Bt-802' × 'IR-3701', exhibited negative effects for the said character. These results were in agreement with those of Panni *et al.* (2010) and Muhammad *et al.* (2014), who also reported that F_2 populations with positive values of inbreeding depression exhibit better gene recombination.

Boll weight

The F_1 population of the cross 'Bt-802' × 'VH-291' displayed the highest boll weight (3.51 g), whereas the F_2 population of the cross 'Sadori' × 'VH-291' ranked at the top. Boll weight is assumed to increase yield if the bolls plant^{-1} remain constant. The present results are also supported by previous findings indicating that the significant heterotic effects for boll weight may be due to additive and nonadditive gene effects (Ashok *et al.,* 2010; Panni *et al.*, 2010; Khan and Qasim, 2012). The results suggested that the parental lines 'VH-259' and 'Bt-802' and the tester 'VH-291' were the best general combiners and hence may be used in hybridization and selection programs.

The heterotic and heterobeltiotic effects for boll weight are presented in Table 4, wherein 21 F_1 hybrids expressed positive heterosis that ranged from 0.59% to 4.50% and 10 hybrids demonstrated positive heterobeltiosis that ranged from 0.30% to 1.52%. The highest relative heterosis (4.5%) was presented by the F_1 hybrid 'Sadori' × 'IR-3701', and the highest heterobeltiosis (1.52%) was exhibited by the F_2 hybrid 'Shahbaz' × 'FH-113'. Four out of 21 F_2 populations showed positive heterosis (Table 5). The hybrids 'Sadori' × 'VH-291' (1.18%) and 'Sadori' × 'IR-3701' (1.62%) presented the maximum positive heterotic effects. However, all the crosses showed negative heterobeltiosis for the said trait. Maximum inbreeding depression was recorded for 'Shahbaz' × 'IR-3701' (5.01%) and 'CRIS-342' × 'IR-3701' (5.00%), whereas the minimum depression (1.22) was shown by 'CRIS-342' × 'FH-113'. Therefore, F_2 populations should be exploited as hybrids for the enhancement of boll weight and eventually seed cotton yield. Past investigations have revealed that F_2 populations have higher boll weight and better performance than F_1 hybrids even after segregation, and plant breeders are mostly interested in such types of F_2 populations (Panni *et al.*, 2010; Ranganath *et al.,* 2013; Vineela *et al.,* 2013; Kumar *et al.,* 2014; Muhammad *et al.,* 2014).

Bolls plant^{-1}

The F_1 and F_2 populations of 'VH-292' × 'VH-291' produced the highest number of bolls plant^{-1} (45.7 and 37.61), followed by those of 'Bt-802' × 'VH-291' and 'VH-259' × 'VH-291'. All of the 21 hybrids expressed positive relative heterotic effects for bolls plant^{-1} (Table 4). The highest heterosis (24.15%) was exhibited by the hybrid 'Shahbaz' × 'VH-291'. For the said character, the relative heterosis ranged between 2.35% to 24.15%, and positive heterobeltiosis varied from 1.77% to 19.01%. Among the 21 F_2 populations, 15 expressed relative positive heterosis, and the cross 'VH-292' × 'VH-291' presented the highest values of heterosis (5.94%). However, 16 F_2 populations showed negative heterobeltiosis for bolls plant^{-1}. The crosses 'Shahbaz' × 'VH-291' (20.57%) and 'Bt.ZZ.NL-370' × 'FH-113' (19.66%) presented the maximum inbreeding depression, whereas the cross 'VH-259' × 'IR-3701' showed the minimum depression (9.84) (Table 5).

In cotton plants, as the number of bolls plant^{-1} increases, the yield also increases. Thus, a significant positive association exists between bolls plant^{-1} and seed cotton yield. In terms of heterotic performance, the hybrids of 'Sadori' × 'VH-291' and 'VH-292' × 'VH-291' displayed higher relative heterosis and heterobeltiosis than other genotypes (Table 4). These hybrids thus expressed more hybrid vigor for the number of bolls plant^{-1} than other genotypes and hence may be exploited for hybrid crop development. Past studies have also reported the high heterosis over better parent and standard check cultivars in boll formation, and the said trait has been found to be positively associated with seed cotton yield (Kaushik and Satary, 2011; Khan, 2011; Patel and Kumar, 2012). In general, the heterotic and inbreeding depression effects for bolls plant^{-1} were moderate to high. The F_2 populations of 'VH-292' × 'VH-291' and 'VH-292' × 'FH-113' demonstrated the highest positive heterosis and heterobeltiosis. The hybrid 'Shahbaz' × 'VH-291' presented the maximum inbreeding depression, followed by 'Bt.ZZ.NL-370' × 'FH-113'. However, the maximum inbreeding depression in the F_2 populations of upland cotton may be exploited (Ranganatha *et al.*, 2013; Soomro *et al.*, 2012; Kumar *et al.,* 2014; Tyagi *et al.*, 2014).

Seed cotton yield plant^{-1}

The F_1 and F_2 populations of the cross 'VH-292' × 'VH-291' displayed the highest seed cotton yield (155.32 and 121.91 g), followed by the F_1 of 'Sadori' × 'VH291' and the F_2 populations of 'VH-259' × 'VH-291'. All the F_1 hybrids showed positive heterosis for seed cotton yield plant^{-1} that varied from 3.47 to 28.52% (Table 4), whereas heterobeltiosis ranged from 0.16% to 22.87%. The top-scoring F_1 hybrid originated from 'Shahbaz' × 'VH-291' and presented an increase of 28.52%. The heterotic effects presented in Table 5 indicate that all the F_2 populations exhibited negative heterosis. However, two populations showed positive heterobeltiosis. The maximum heterosis was expressed by 'Sadori' × 'VH-291' (4.92%) and 'VH-292' × 'VH-291' (4.19%), and positive heterobeltiotic effects were recorded only for 'VH-292' × 'FH-113' (0.85%) and 'VH-292' × 'VH-291' (0.36%). The maximum inbreeding depression was observed in 'Shahbaz' × 'VH-291' (23.71%), 'Bt.ZZ.NL-370' × 'FH-113' (23.41%), and 'VH-292' × 'VH-291' (21.51%), whereas the minimum inbreeding depression was displayed by 'VH-259' × 'IR-3701' (12.36%).

Seed cotton yield plant^{-1} has unique importance compared with other yield-contributing characters because it plays an important role in the production and strengthening of the economy of the growers and the country. Analysis of variance revealed that the genotypes displayed highly significant differences for seed cotton yield. 'VH-292' followed by 'VH-259' produced the maximum seed cotton yield plant^{-1}. Among the testers, 'VH-291', followed by 'FH-113' produced the highest seed cotton yield plant^{-1} (Table 2).

The present results conformed with the findings of Kumar *et al.* (2014) and Patel and Kumar (2014), who also reported significant heterosis in F_1 and F_2 populations for seed cotton yield plant^{-1}. For seed cotton yield plant^{-1}, the hybrid of 'Sadori' × 'VH-291'exhibited the maximum relative heterosis and heterobeltiosis, followed by the hybrid of 'VH-292' × 'VH-291'. However, the hybrid of 'Bt-802' × 'VH-291' also showed a fair amount of heterosis and heterobeltiosis for seed cotton yield plant^{-1} (Table 5). Previous studies also reported significant heterosis over the mid- and better-parent for seed cotton yield and its contributing characters (Soomro *et al*., 2010, 2012; Patel *et al.,* 2011; Komal *et al.,* 2014; Baloch *et al.,* 2015).

Among the F_2 populations, 'VH-292' × 'VH-291' and 'VH-292' × 'FH-113' showed positive heterobeltiosis (Table 5). The hybrids of 'Shahbaz' × 'VH-291' and 'VH-292' × 'VH-291' recorded the highest inbreeding depression, whereas 'VH-259' × 'IR-3701' showed the minimum inbreeding depression for seed cotton yield plant^{-1}. The high heterotic effects for seed cotton yield perfectly favor the exploitation of heterosis breeding in cotton, and the hybrid with a high number of favorable dominant and overdominant genes at many loci is the most reliable breeding material for hybrid cotton development (Ahmad *et al.,* 2013; Alkuddsi *et al.*, 2013; El-Hashah, 2013; Kaushik and Kapoor, 2013).

CONCLUSIONS

Genotypes, parents, and crosses were highly significant for all the traits studied, except for sympodial branches plant^{-1} in F_1 and F_2 populations. Both populations of 'VH-292' × 'VH-291' produced higher sympodial branches plant^{-1}, bolls plant^{-1}, and seed cotton yield plant^{-1} and expressed higher heterobeltiosis for bolls plant^{-1} and seed cotton yield plant^{-1} than other populations, whereas 'VH-259' × 'IR-3701' showed the minimum depression for plant height, bolls plant^{-1}, and seed cotton yield plant^{-1}. 'VH-292' × 'VH-291' and 'VH-259' × 'IR-3701' could be utilized to increase the seed cotton yield of segregating populations, such as F_2.

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