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Full Length Article

Genotype by Environment Interactions Affecting Heterotic Effects in Maize for Earliness traits and Grain Yield

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Abstract

Heterosis refers to the phenomenon that F_1 hybrids perform better than their parental genotypes and standard cultivars relating to phenotypic traits including, growth, yield, quality, fertility and disease resistance. Heterosis over mid- and better parent, economic and commercial heterosis (over two commercial checks 'OPV-Jalal' and 'Pioneer hybrid 30K08') were studied in 20 maize F_1 hybrids evaluated through genotype × environment interactions (GEI) for earliness traits and grain yield across four environments. Significant ($P \leq 0.01$) variations were recorded among maize genotypes (G), environments (E) and G × E interactions for all the traits. According to heterosis analysis, the promising F_1 hybrids FRHW-2 × FRHW-3, FRHW-1 × SWAJK-1, and FRHW-3 × FRHW-2 showed significant ($P \leq 0.01$) negative mid- and better parent, economic and commercial heterosis for earliness traits and took fewer days to flowering and maturity across four locations. However, for grain yield, the F_1 hybrids PSEV3 × FRHW-1, PSEV3 × FRHW-3, FRHW-1 × SWAJK-1, FRHW-2 × FRHW-3, and FRHW-3 × PSEV3 showed significant positive heterotic effects with best performance for grain yield at four environments. As an area-specific, F_1 hybrids PSEV3 × FRHW-1 and PSEV3 × FRHW-3 at CCRI, Pirsabak - Nowshera, and the University of Haripur, were found more productive. However, hybrids PSEV3 × FRHW-1, FRHW-1 × SWAJK-1, and FRHW-3 × PSEV3 produced more grain yield and can be recommended for ARS, Baffa – Mansehra, and ARI, Mingora - Swat, Pakistan. Overall, F_1 hybrids matured earlier than parental and check genotypes, and proved significant ($P \leq 0.01$) negative heterotic effects. On average, hybrids excelled parental cultivars by achieving more grain yield with significant ($P \leq 0.01$) positive heterotic values. In general, F_1 hybrids matured earlier than their parental genotypes in plains as compared to hilly areas which might be due to warmer climate. Genotype-environment testing was found helpful in identifying the genotypes for a specific area. These promising F_1 hybrids could be used in the development of early maturing and high yielding maize hybrids/cultivars.

Keywords: F_1 diallel hybrids; Mid and better parent hybrid vigor; Economic and commercial hybrid vigor; Flowering; maturity and production variables; *Zea mays* L.

Introduction

In Pakistan, maize is mostly grown in the provinces of Punjab and Khyber Pakhtunkhwa, and very little (2-3%) maize grains are produced by two other provinces. In Punjab and Khyber Pakhtunkhwa, during spring season the progressive farmers are getting good yield by planting maize hybrids for grains with improved production technology (Ali 2015; Ali *et al.* 2019; Hassan *et al.* 2019). However, hybrid seed supplied by the seed companies is very costly as they mainly rely on the imported seed and a very small amount of locally produced hybrid seed is available in the market. In Pakistan, hybrid seed production offers the most effective strategy for improving maize yield. Thus, there is enormous scope for establishing the local maize hybrids, and to study them at different ecological zones to get a good yield.

Maize (*Zea mays* L.) is ranked as the third essential cereal crop after wheat and rice globally and in Pakistan, and grown in irrigated and in rain-fed regions (Kumar *et al.* 2019; Ullah *et al.* 2019). Usually, maize is cultivated up to

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3300 meters above sea level, 500 N to 400 S latitude in the majority of the areas of the world (Sajjad 2018; Cherchali *et al.* 2019). Maize is adapted to a variety of soils; however, the soils with a pH range of 6.5 to 7.5 are most favorable. In Pakistan, maize used as green and dry fodder, and maize grains are used as the main staple food by the farming community (Sajjad *et al.* 2016; Khan *et al.* 2018). However, its usage as human food is decreasing, whereas its industrial use is rising rapidly. In current maize production, about 60% is being utilized in poultry feed, 28% in wet milling, and 6% in food. Food utilization is reducing but poultry feed and silage demand are increasing. During 2018-19, maize was grown on an area of 1.318 million hectares and total production was 6.309 million tones with average grain yield of 4787 kg ha^{-1} in Pakistan (PBS 2018-19).

Until the mid-twentieth century, the mechanism of heterosis was mainly explained by the hypotheses of dominance and over-dominance (Ige *et al.* 2018; Govindaraju 2019; Yi *et al.* 2019). However, it is difficult to find out whether that dominance is partial to complete or in the over-dominance range (Barata *et al.* 2019; Ullah *et al.* 2019). Despite its importance, little is known about the genetic and molecular basis of heterosis. Even though globally the breeders had been working for more than a century on heterosis/hybrid vigor; however, the elementary reasons that contribute heterosis are still vague (Ding *et al.* 2014; Liu *et al.* 2019; Shi *et al.* 2019). However, in the recent era, it has become more apparent that the mechanism of heterosis requires a revisit for detailed genetic analysis of various characters (Ali *et al.* 2013a, b; Li *et al.* 2018; Hablak 2019). The emergence of heterosis based on allelic and non-allelic gene interactions which creates a favorable combination of genes during hybridization.

In the early 20th century, heterosis was first established in maize, however, at that time the hybrids could not be economically made available on a large scale for commercial use (Li *et al.* 2018; Ali *et al.* 2019). Later on, the breeders produced inbred lines with sufficient vigor for practical production of double-cross and single-cross maize hybrids. Development of F_1 hybrids not only revolutionized maize breeding schemes but also constituted the foundation of the maize seed industry (Kiani *et al.* 2015; Ullah *et al.* 2017; Khan *et al.* 2018). In maize hybrids, the persistence of heterosis is necessary for their commercial exploitation, and the hybrids with significant heterosis could be recommended for commercial cultivation (Ali *et al.* 2018; Kumar *et al.* 2014, 2019). Usually, heterosis has been gauged in genetically diverse populations which combine the associations. Neither heterozygosity nor genetic diversity is a suitable indicator for predicting the desirable heterosis (Govindaraju, 2019; Liu *et al.* 2019).

Estimation of heterosis is beneficial in the valuation of parent's performance for hybrid combinations, and past studies revealed substantial standard heterosis in F1 populations for leaf area, anthesis silking interval, and grain yield in maize (Venkatesha *et al.* 2013; Sharma *et al.* 2019). In maize hybrids, the standard heterosis was reported for earliness, grains per ear, ear length, ear diameter, and grain yield and some desirable crosses were recommended for the development of commercial hybrids (Barata *et al.* 2019; Yi *et al.* 2019). Therefore, keeping in view these considerations, the present study was planned with the objectives to a) study the performance of 5 × 5 F_1 complete diallel hybrids along with parental genotypes for earliness, morphological and yield traits across four environments, b) quantify the mid, better, economic and commercial parent heterosis, and c) identify the promising F_1 hybrid based on their genetic potential for commercial cultivation in Khyber Pakhtunkhwa, Pakistan.

Materials and Methods

Plant material, environments, and procedure

Five white kernel maize inbred lines i.e., FRHW-22(F2)-5 (FRHW-1), FRHW-22(F2)-4-7 (FRHW-2), FRHW-20-4 (FRHW-3), PSEV3-120-2-2-2 (PSEV3) and SWAJK-6-6-3-6 (SWAJK-1) with distinct genetic makeup were crossed in a complete diallel fashion during spring season 2011 at Cereal Crops Research Institute (CCRI), Pirsabak, Nowshera, Pakistan (Table 1). The resulting 20 F_1 hybrids, five parental inbred lines and two check genotypes (OPV 'Jalal' and 'Pioneer hybrid 30K08') were evaluated during subsequent summer crop season 2011 through field experiments at four different locations in the province of Khyber Pakhtunkhwa, Pakistan. The study four sites were a) Cereal Crops Research Institute (CCRI), Pirsabak – Nowshera (situated between 34° N latitude and 72° E longitude with an altitude of 288 m), b) University of Haripur (UOH), Haripur (lies between 34° North latitude and 72° East longitude with an altitude of 520 m), c) Agricultural Research Station (ARS), Baffa – Mansehra (located between 33° North latitude and 71° East longitude with an altitude of 1067 m), and d) Agricultural Research Institute (ARI) Mingora – Swat (lies between 34.79° North latitude and 72.29° East longitude with an altitude of 984 m). The maximum and minimum temperatures, and rainfall data of maize summer crop season during 2011 for the above four locations are provided in Fig. 1 and 2, respectively.

The experiments at all the four locations were laid out in a randomized complete block design (RCBD) with three replications. Experimental sub-plots for all the maize genotypes comprising four rows with 10 m length. Rows and plants spacing was kept 75 and 25 cm, respectively. Recommended cultural practices and inputs were uniformly applied to all the genotypes at all the locations to minimize the field variations.

Characters investigation and data collection

Data for all the parameters were recorded on 10 randomly selected plants in each genotype/replication/location.

Table 1: Parental inbred lines and their 5 × 5 F_1 diallel hybrids of maize used in the studies

S. No.	Inbred line	Code	Pedigree
1	FRHW-22(F2)-5	FRHW-1	Male parental single cross of maize hybrid 'Babar'
2	FRHW-22(F2)-4-7	FRHW-2	Male parental single cross of maize hybrid 'Babar'
3	FRHW-20-4	FRHW-3	Female parental single cross of maize hybrid 'Babar'
4	PSEV3-120-2-2-2	PSEV3	Derived from white maize population 'PSEV3'
5	SWAJK-6-6-3-6	SWAJK-1	Derived from open pollinated long duration maize variety 'Sarhad White'
Check genotypes			
6	OPV 'Jalal'		
7	Pioneer hybrid 30K08		

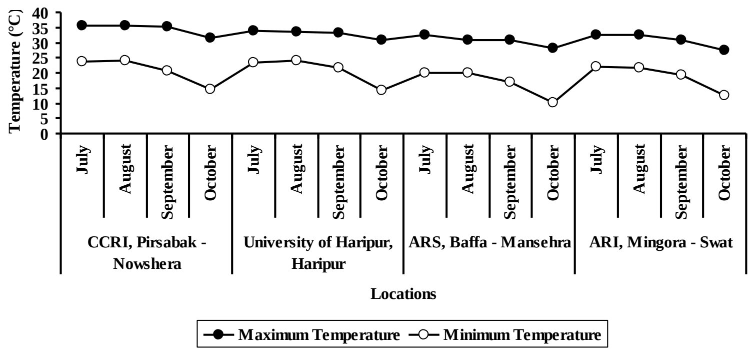

Fig. 1: Maximum and minimum temperatures during maize summer crop season 2011 at four locations

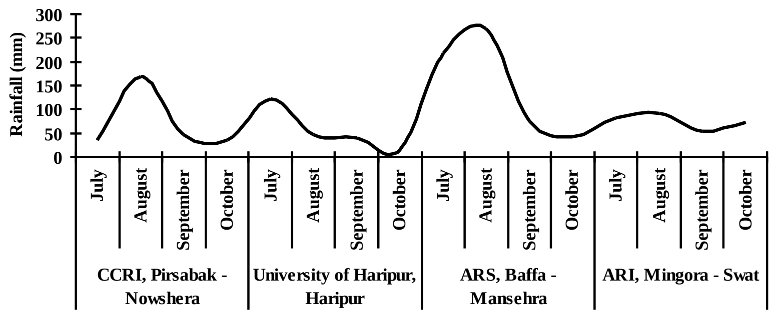

Fig. 2: Rainfall during maize summer crop season 2011 at four locations

Data regarding days to 50% tasseling, days to 50% pollen shedding and days to 50% silking were recorded by regular visits to the field and days were counted from sowing to the day when 50% of the plants produced tassels, silks and when pollen shedding was started after dehiscence of anthers on central branch of the tassel in a genotype in each subplot. Data regarding days to physiological maturity was recorded when a black layer was observed in the grains on the mid-portion of ear and numbers of days were then counted from the date of sowing to physiological maturity. Grain yield (kg ha^{-1}) of each genotype was calculated in kg after harvesting and adjusting the fresh ear weight to 150 g kg^{-1} grain moisture by using the relationship of Carangal *et al.* (1971).

Statistical analyses

All the data were subjected to G × E interaction analysis to partition the variances due to genotypes, environments, and genotype by environment interactions (Gomez and Gomez 1984). Genotypes, environments, and genotype × environment interactions with significant means differences for various traits were further compared and separated by using the least significant difference ($LSD_{0.05}$). After G × E interaction analysis, heterotic effects over mid-parent (MP), better-parent (BP), economic (EH) and commercial heterosis (CH) were calculated by comparing the F_1 hybrid means with existing parental genotypes, commercial open-pollinated variety (OPV 'Jalal') and commercial hybrid (Pioneer hybrid 30K08), respectively for various traits (Fonseca 1965; Fehr 1987). In F_1 hybrids, the heterotic effects were subjected to 't-test' to determine whether F_1 hybrid means were statistically different from their mid and better-parents, and OPV and hybrid or not (Wynne *et al.* 1970; Falconer and Mackay 1996).

Results

Significant ($P \leq 0.01$) differences were observed among the genotypes, environments (locations) and genotype by environment interactions (GEI) for earliness traits and grain yield (Table 2). Results revealed greater genetic variability among the genotypes which might be due to their diverse genetic makeup as well as environments. In proportional contribution to total sum of squares, environments and genotypes played a major role in managing the earliness traits and grain yield. However, shares of G × E interaction and experimental error (replications) were negligible. Larger effects of environment and genotypes to total variation (G + E + GEI) persuade the earliness traits and grain yield. For earliness traits, the negative heterotic effects are considered desirable for identification of F_1 hybrids with lesser days to tasseling, pollen shedding, silking and physiological maturity. The trait-wise results are presented as follows.

Days to 50% tasseling

For days to 50% tasseling, in F_1 hybrids the negative mid-, better parent, economic and commercial heterotic effects ranged from -1.35 to -10.32%, -1.99 to -8.55%, 0.69 to -3.47%, and -0.71 to -1.42%, respectively at CCRI, Pirsabak - Nowshera (Table 3). Overall, 18, 12, 6, and 3 hybrids showed significant heterotic effects for above four types of heterosis. However, maximum negative mid- and better-parent heterosis were recorded in F_1 hybrids FRHW-2 × FRHW-3, FRHW-3 × FRHW-1, FRHW-1 × SWAJK-1, and its reciprocal, respectively for days to 50% tasseling. By comparing the F_1 hybrids with OPV - Jalal and commercial hybrid (Pioneer hybrid 30K08), three F_1 hybrids FRHW-2 × PSEV3, FRHW-2 × FRHW-3, and FRHW-2 × PSEV3 showed maximum negative economic and commercial heterosis for days to 50% tasseling.

At the University of Haripur, 10, 6, 8 and 2 F_1 hybrids out of 20 showed negative mid-, better-parent, economic and commercial heterosis ranged from -0.33 to -4.58%, -1.30 to -3.95%, -0.66 to -3.31%, and zero to -1.35%, respectively for days to 50% tasseling (Table 3). Overall, 6, 4, 4, and zero hybrids showed significant heterotic effects for above four types of heterosis. F_1 hybrids FRHW-1 × PSEV3 and its reciprocal, and SWAJK-1 × FRHW-3 showed highest negative mid- and better parent heterosis. For economic and commercial heterosis, the F_1 hybrids FRHW-1 × PSEV3 and SWAJK-1 × FRHW-2 performed well for having maximum negative effects for days to 50% tasseling.

At Agriculture Research Station (ARS), Baffa – Mansehra, 15, 11, 15, 20 F_1 hybrids enunciated negative mid-, better-parent, economic and commercial heterosis in which 14, 10, 13, and 20 out of 20 hybrids showed significant heterosis (Table 3). For above four categories of negatives heterosis, the ranges were -0.91 to -8.88%, -0.62 to -4.97%, -0.54 to -7.17%, and -1.79 to -11.61%, respectively. Highest negative mid-, better-parent, economic and commercial heterosis were recorded in F_1 hybrids FRHW-3 × PSEV3, FRHW-1 × FRHW-3, and it's reciprocal, FRHW-2 × FRHW-3 and its reciprocal and PSEV3 × FRHW-1.

At Agricultural Research Institute (ARI), Mingora – Swat, out of 20 the 14, 11, 17 and 18 F_1 hybrids revealed negative mid-, better-parent, economic and commercial heterosis ranged from -0.30 to -10.85% and -0.62 to -8.98%, -0.66 to -9.04% and -1.72 to -10.01%, respectively for days to 50% tasseling (Table 3). However, 13, 10, 16 and 17 F_1 hybrids exhibited significant negative mid-, better-parent, economic, and commercial heterosis. By comparing with mid-, better-parent, commercial OPV and hybrid cultivar, the F_1 hybrids FRHW-2 × FRHW-3, and PSEV3 × FRHW-3 showed maximum negative heterotic effects.

Table 2: Mean squares and proportional contribution of G, E, and G × E interaction for earliness traits and grain yield in 5 × 5 maize F_1 diallel hybrids at four locations

Variables	S.O.V.	M.S.	C.V. (%)
Days to 50% tasseling	G	18.205**	1.32
	E (locations)	693.765**	
	G × E	7.289**	
	Replications	1.475**	
	Error	0.469	
Days to 50% pollen shedding	G	18.102**	1.26
	E (locations)	619.312**	
	G × E	6.724**	
	Replications	2.966**	
	Error	0.479	
Days to 50% silking	G	17.983**	1.19
	E (locations)	621.789**	
	G × E	7.806**	
	Replications	2.917**	
	Error	0.458	
Days to physiological Maturity	G	237.18**	0.71
	E (locations)	7988.90**	
	G × E	3.63**	
	Replications	0.13 N.S.	
	Error	0.44	
Grain yield	G	5.750E+07**	4.68
	E (locations)	2.303E+08**	
	G × E	3591133**	
	Replications	329509 N.S.	
	Error	179730	

Days to 50% pollen shedding

At CCRI, Pirsabak, 19, 12, 17, and 7 F_1 hybrids exhibited negative mid-, better-parent, economic and commercial heterosis in which 16, 12, 8, and 4 hybrids showed significant heterosis, respectively days to 50% pollen shedding (Table 4). However, in F_1 hybrids the above four types of negatives heterotic effects ranged from -0.32 to -10.51%, -2.50 to -8.02%, -0.64 to -4.49%, and -0.65 to -2.61%, respectively. The maximum negative mid- and better-parent heterotic values were observed in F_1 hybrids FRHW-2 × FRHW-3, FRHW-1 × SWAJK-1. For economic

Table 3: Mid- and better-parents, economic and commercial heterosis in 5 × 5 maize F_1 diallel hybrids for days to 50% tasseling across four locations

F_1 hybrids	Days to 50% tasseling															
	CCRI, Pirsabak - Nowshera				University of Haripur, Haripur				ARS, Baffa - Mansehra				ARI, Mingora - Swat			
	MP heterosis (%)	BP heterosis (%)	Economic heterosis (%)	Commercial Heterosis (%)	MP heterosis (%)	BP heterosis (%)	Economic heterosis (%)	Commercial heterosis (%)	MP heterosis (%)	BP heterosis (%)	Economic heterosis (%)	Commercial heterosis (%)	MP heterosis (%)	BP heterosis (%)	Economic heterosis (%)	Commercial heterosis (%)
FRHW-1 × FRHW-2	-5.92**	-5.98**	-0.69	1.42*	3.05**	7.80**	0.66	2.70**	-0.91	0.62	-1.75*	-5.83**	-3.95**	-2.47**	-5.45**	-6.45**
FRHW-1 × FRHW-3	-6.45**	-4.61**	0.69	2.84**	-2.88**	-1.30	0.66	2.70**	-7.56**	-4.79**	-4.16**	-8.15**	-4.17**	-0.62	-3.65**	-4.68**
FRHW-1 × PSEV3	-4.14**	0.72	-3.47**	-1.42*	-4.58**	-3.95**	-3.31**	-1.35	-3.66**	-1.86*	-4.76**	-8.72**	1.56*	2.52**	-2.45**	-3.49**
FRHW-1 × SWAJK-1	-7.59**	-7.28**	-2.78**	-0.71	-2.93**	-2.61**	-1.32	0.68	1.49*	1.80*	2.47**	-1.79*	1.20	3.70**	0.54	-0.53
FRHW-2 × FRHW-1	-3.95**	-4.01**	1.39	3.55**	4.41**	9.22**	1.99*	4.05**	0.91	2.47**	0.06	-4.10**	-3.95**	-2.47**	-5.45**	-6.45**
FRHW-2 × FRHW-3	-10.32**	-8.55**	-3.47**	-1.42*	0.00	6.38**	-0.66	1.35	-6.78**	-2.47**	-4.76**	-8.72**	-10.85**	-8.98**	-9.04**	-10.01**
FRHW-2 × PSEV3	-4.14**	0.72	-3.47**	-1.42*	1.71*	5.67**	-1.32	0.68	0.31	0.62	-2.35**	-6.41**	0.61	3.14**	-1.86*	-2.90**
FRHW-2 × SWAJK-1	-5.61**	-5.30**	-0.69	1.42*	2.72**	7.09**	0.00	2.03*	-1.82*	0.00	-2.35**	-6.41**	0.30	1.20	1.14	0.06
FRHW-3 × FRHW-1	-8.39**	-6.58**	-1.39	0.71	-2.88**	-1.30	0.66	2.70**	-5.81**	-2.99**	-2.35*	-6.41**	-7.74**	-4.32**	-7.24**	-8.23**
FRHW-3 × FRHW-2	-6.45**	-4.61**	0.69	2.84**	6.00**	12.77**	5.30**	7.43**	-6.78**	-2.47**	-4.76**	-8.72**	-7.33**	-5.39**	-5.45**	-6.45**
FRHW-3 × PSEV3	-1.35	5.80**	1.39	3.55**	-0.96	1.32	1.99*	4.05**	-8.88**	-4.35**	-7.17**	-11.03**	-3.90**	0.63	-4.25**	-5.27**
FRHW-3 × SWAJK-1	-4.21**	-1.99*	2.78**	4.96**	-1.28	0.65	1.99*	4.05**	-4.35**	-1.79*	-0.54	-4.68**	-4.65**	-3.53**	-1.86*	-2.90**
PSEV3 × FRHW-1	-2.07*	2.90**	-1.39	0.71	-3.27**	-2.63**	-1.99*	0.00	-6.71**	-4.97**	-7.78**	-11.61**	2.18**	3.14**	-1.86*	-2.90**
PSEV3 × FRHW-2	-2.07*	2.90**	-1.39	0.71	2.39**	6.38**	-0.66	1.35	-0.93	-0.62	-3.56**	-7.57**	-2.45**	0.00	-4.85**	-5.86**
PSEV3 × FRHW-3	10.14**	18.12**	13.19**	15.60**	6.75**	9.21**	9.93**	12.16**	-2.96**	1.86*	-1.15	-5.26**	-8.71**	-4.40**	-9.04**	-10.01**
PSEV3 × SWAJK-1	0.35	5.07**	0.69	2.84**	2.30**	2.63**	3.31**	5.41**	0.91	3.11**	0.06	-4.10**	-0.30	3.14**	-1.86*	-2.90**
SWAJK-1 × FRHW-1	-7.59**	-7.28**	-2.78**	-0.71	-0.33	0.00	1.32	3.38**	-2.69**	-2.40**	-1.75*	-5.83**	-4.82**	-2.47**	-5.45**	-6.45**
SWAJK-1 × FRHW-2	-5.61**	-5.30**	-0.69	1.42*	-0.68	3.55**	-3.31**	-1.35	-3.64**	-1.85*	-4.16**	-8.15**	-5.04**	-4.19**	-4.25**	-5.27**
SWAJK-1 × FRHW-3	-4.21**	-1.99*	2.78**	4.96**	-3.85**	-1.96*	-0.66	1.35	-2.61**	0.00	1.27	-2.95**	-3.49**	-2.35**	-0.66	-1.72**
SWAJK-1 × PSEV3	-1.73*	2.90**	-1.39*	0.71	4.26**	4.61**	5.30**	7.43**	0.91	3.11**	0.06	-4.10**	3.34**	6.92**	1.74*	0.65

**, * = Significant at 1% and 5% level of probability, MP = Mid-parent, BP = Better-parent

Table 4: Mid- and better-parents, economic and commercial heterosis in 5 × 5 maize F_1 diallel hybrids for days to 50% pollen shedding across four locations

F_1 hybrids	Days to 50% pollen shedding															
	CCRI, Pirsabak - Nowshera				University of Haripur, Haripur				ARS, Baffa - Mansehra				ARI, Mingora - Swat			
	MP heterosis (%)	BP heterosis (%)	Economic heterosis (%)	Commercial Heterosis (%)	MP heterosis (%)	BP heterosis (%)	Economic heterosis (%)	Commercial heterosis (%)	MP heterosis (%)	BP heterosis (%)	Economic heterosis (%)	Commercial heterosis (%)	MP heterosis (%)	BP heterosis (%)	Economic heterosis (%)	Commercial heterosis (%)
FRHW-1 × FRHW-2	-5.88**	-5.65**	-2.56**	-0.65	3.16**	6.54**	0.62	3.16**	-3.45**	-2.33**	-5.08**	-6.20**	-1.44*	0.00	-0.52	-4.52**
FRHW-1 × FRHW-3	-6.63**	-3.73**	-0.64	1.31	-3.01**	-1.23	-0.62	1.90*	-3.66**	-0.58	-3.39**	-4.52**	-6.96**	-5.11**	-2.85**	-6.76**
FRHW-1 × PSEV3	-3.90**	0.68	-5.13**	-3.27**	-5.23**	-4.94**	-4.94**	-2.53**	1.47*	2.37**	-2.26**	-3.41**	-2.62**	0.00	-2.85**	-6.76**
FRHW-1 × SWAJK-1	-7.17**	-6.88**	-4.49**	-2.61*	-3.66**	-3.07**	-2.47**	0.00	1.42*	3.49**	0.56	-0.61	0.57	0.51	2.97**	-1.17
FRHW-2 × FRHW-1	-3.41**	-3.17**	0.00	1.96*	4.43**	7.84**	1.85*	4.43**	-3.45**	-2.33**	-5.08**	-6.20**	-0.86	0.58	0.06	-3.96**
FRHW-2 × FRHW-3	-10.51**	-8.02**	-4.49**	-2.61*	-1.24	3.92**	-1.85	0.63	-9.75**	-7.95**	-8.47**	-9.55**	-5.65**	-2.34**	-2.85**	-6.76**
FRHW-2 × PSEV3	-3.56**	1.36	-4.49**	-2.61*	0.95	3.92**	-1.85*	0.63	0.87	2.96**	-1.69*	-2.85**	1.18	2.40**	-0.52	-4.52**
FRHW-2 × SWAJK-1	-4.97**	-4.38**	-1.92*	0.00	1.26	5.23**	-0.62	1.90*	0.85	1.70**	1.13	-0.06	-1.44*	0.00	-0.52	-4.52**
FRHW-3 × FRHW-1	-7.23**	-4.35**	-1.28	0.65	-1.81*	0.00	0.62	3.16**	-7.04**	-4.07**	-6.78**	-7.87**	-6.41**	-4.55**	-2.27*	-6.20**
FRHW-3 × FRHW-2	-7.51**	-4.94**	-1.28	0.65	3.11**	8.50**	2.47**	5.06**	-6.41**	-4.55**	-5.08**	-6.20**	-6.21**	-2.92**	-3.43**	-7.31**
FRHW-3 × PSEV3	-3.14**	4.76**	-1.28	0.65	-0.91	1.23	1.23	3.80**	-3.41**	0.59	-3.95**	-5.08**	-7.43**	-2.99**	-5.76**	-9.55**
FRHW-3 × SWAJK-1	-6.34**	-3.13**	-0.64	1.31	-2.99**	-1.82*	0.00	2.53**	-3.87**	-2.79**	-1.69*	-2.85**	-3.62**	-1.70*	0.64	-3.41**
PSEV3 × FRHW-1	-1.95*	2.72**	-3.21**	-1.31	-2.15**	-1.85*	-1.85*	0.63	2.05**	2.96**	-1.69**	-2.85**	-5.54**	-2.99**	-5.76**	-9.55**
PSEV3 × FRHW-2	-0.32	4.76**	-1.28	0.65	2.22**	5.23**	-0.62	1.90*	-2.03**	0.00	-4.52**	-5.64**	0.00	1.20	-1.69	-5.64**
PSEV3 × FRHW-3	8.18**	17.01**	10.26**	12.42**	7.55**	9.88**	9.88**	12.66**	-7.95**	-4.14**	-8.47**	-9.55**	-1.14	3.59**	0.64	-3.41**
PSEV3 × SWAJK-1	-0.33	4.08**	-1.92	0.00	2.14**	3.09**	3.09**	5.70**	0.00	2.96**	-1.69**	-2.85**	0.87	3.59**	0.64	-3.41**
SWAJK-1 × FRHW-1	-4.05**	-3.75**	-1.28	0.65	-0.61	0.00	0.62	3.16**	-4.27**	-2.33**	-5.08**	-6.20**	-2.27**	-2.33**	0.06	-3.96**
SWAJK-1 × FRHW-2	-4.97**	-4.38**	-1.92	0.00	-0.63	3.27**	-2.47**	0.00	-4.23**	-3.41**	-3.95**	-5.08**	-3.17**	-1.75*	-2.27*	-6.20**
SWAJK-1 × FRHW-3	-5.74**	-2.50**	0.00	1.96*	-3.59**	-2.42**	-0.62	1.90*	-1.66*	-0.56	0.56	-0.61	-1.95**	0.00	2.39**	-1.73*
SWAJK-1 × PSEV3	-0.98	3.40**	-2.56**	-0.65	3.36**	4.32**	4.32**	6.96**	3.45**	6.51**	1.69*	0.50	2.04**	4.79**	1.80**	-2.29**

**, * = Significant at 1% and 5% level of probability, MP = Mid-parent, BP = Better-parent

and commercial heterosis, the F_1 hybrids FRHW-1 × SWAJK-1, FRHW-2 × FRHW-3, and FRHW-2 × PSEV3 performed better over standard OPV - Jalal and hybrid cultivar for taking fewer days to 50% pollen shedding.

At the University of Haripur, 10, 6, 10, and one out of 20 F_1 hybrids exhibited negative mid-, better-parent, economic and commercial heterosis ranged from -0.61 to -5.23%, -1.23 to -4.94%, -0.62 to -4.94%, and zero to -2.53%, respectively for days to 50% pollen shedding (Table 4). However, 7, 5, 5, and one F_1 hybrid attained significant negative level for mid-, better-parent, economic, and commercial heterosis. The promising F_1 hybrids FRHW-1 × PSEV3, FRHW-1 × SWAJK-1, and FRHW-1 × FRHW-3 recorded with the highest values for all the four types heterosis for days to 50% pollen shedding.

For days to 50% pollen shedding at ARS, Baffa, 13, 11, 16, and 19 F_1 hybrids revealed negative mid-, better-parent economic and commercial heterosis ranged from -1.14 to -7.43%, -0.56 to -7.95%, -1.69 to -8.47%, and -0.06 to -9.55%, respectively (Table 4). As compared to concerned parents, commercial OPV and hybrid cultivar, 13, 9, 16, and 16 F_1 hybrids showed significant negative effects for the said trait. Promising F_1 hybrids FRHW-2 × FRHW-3 and its reciprocal, and PSEV3 × FRHW-3, FRHW-3 × FRHW-1, FRHW-2 × FRHW-1 performed better than both parents, OPV-Jalal and commercial hybrid to took fewer days to 50% pollen shedding.

At ARI, Mingora, for mid-, better-parent, economic and commercial heterosis, 15, 9, 12, and 20 F_1 hybrids exhibited negative effects for days to 50% pollen shedding ranged from -0.86 to -7.43%, -1.70 to -5.11%, -0.52 to -5.76%, and -1.17 to -9.55%, respectively (Table 4). However, 13, 9, 8, and 19 F_1 hybrids showed significant negative heterotic effects for above four types of heterosis.

Table 5: Mid- and better-parents, economic and commercial heterosis in 5 × 5 maize F_1 diallel hybrids for days to 50% silking across four locations

F_1 hybrids	Days to 50% silking															
	CCRI, Pirsabak - Nowshera				University of Haripur, Haripur				ARS, Baffa - Mansehra				ARI, Mingora - Swat			
	MP heterosis (%)	BP heterosis (%)	Economic heterosis (%)	Commercial Heterosis (%)	MP heterosis (%)	BP heterosis (%)	Economic heterosis (%)	Commercial heterosis (%)	MP heterosis (%)	BP heterosis (%)	Economic heterosis (%)	Commercial heterosis (%)	MP heterosis (%)	BP heterosis (%)	Economic heterosis (%)	Commercial heterosis (%)
FRHW-1 × FRHW-2	-4.82**	-4.24**	-1.87*	-0.01	3.05**	6.29****	0.00	2.42**	-2.52**	-2.25**	-4.92**	-6.00**	-1.10	1.13	0.57	-3.25**
FRHW-1 × FRHW-3	-6.40**	-3.59**	-0.01	1.89*	-4.65**	-2.96**	-2.96**	-0.61	-3.54**	-0.56	-3.28**	-4.38**	-7.49**	-6.49**	-2.80**	-6.49**
FRHW-1 × PSEV3	-4.05**	0.00	-4.35**	-2.54**	-5.04**	-4.76**	-5.33**	-3.03**	3.12**	4.00**	-0.55	-1.67*	-3.35**	0.00	-2.80**	-6.49**
FRHW-1 × SWAJK-1	-5.11**	-4.82**	-1.87*	-0.01	-4.73**	-4.73**	-4.73**	-2.42**	1.10	3.37**	0.55	-0.59	-0.27	0.55	2.81**	-1.09
FRHW-2 × FRHW-1	-2.41**	-1.82*	0.61	2.53**	4.27**	7.55**	1.18	3.64**	-2.52**	-2.25**	-4.92**	-6.00**	-0.55	1.69*	1.13	-2.71**
FRHW-2 × FRHW-3	-9.36**	-6.06**	-3.73**	-1.90*	-1.20	3.77**	-2.37**	0.00	-9.78**	-7.26**	-9.29**	-10.32**	-5.46**	-2.26**	-2.80**	-6.49**
FRHW-2 × PSEV3	-2.82**	0.65	-3.73**	-1.90*	-0.92	1.89*	-4.14**	-1.82*	1.69*	2.86**	-1.64*	-2.76**	0.00	1.16	-1.68*	-5.41**
FRHW-2 × SWAJK-1	-5.14**	-4.85**	-2.49**	-0.64	1.83*	5.03**	-1.18	1.21	-0.27	1.68*	-0.55	-1.67*	-1.39*	0.00	-0.56	-4.33**
FRHW-3 × FRHW-1	-6.98**	-4.19**	-0.63	1.26	-1.74*	0.00	0.00	2.42**	-6.81**	-3.93**	-6.56**	-7.62**	-5.35**	-4.32**	-0.56	-4.33**
FRHW-3 × FRHW-2	-8.19**	-4.85**	-2.49**	-0.64	2.99**	8.18**	1.78*	4.24**	-7.07**	-4.47**	-6.56**	-7.62**	-6.01**	-2.82**	-3.37**	-7.03**
FRHW-3 × PSEV3	-3.32**	3.90**	-0.63	1.26	0.87	2.98**	2.37**	4.85**	-3.30**	0.57	-3.83**	-4.92**	-7.18**	-2.89**	-5.61**	-9.19**
FRHW-3 × SWAJK-1	-4.37**	-1.20	1.86*	3.79**	-2.33**	-0.59	-0.59	1.82*	-2.40**	-1.61*	0.00	-1.13	-4.58**	-2.75**	-0.56	-4.33**
PSEV3 × FRHW-1	-4.05**	0.00	-4.35**	-2.54**	-2.08**	-1.79*	-2.37**	0.00	1.98**	2.86**	-1.64*	-2.76**	-6.15**	-2.89**	-5.61**	-9.19**
PSEV3 × FRHW-2	0.31	3.90**	-0.63	1.26	2.14**	5.03**	-1.18	1.21	-1.13	0.00	-4.37**	-5.46**	0.00	1.16	-1.68*	-5.41**
PSEV3 × FRHW-3	7.55**	15.58**	10.55**	12.65**	7.29**	9.52**	8.88**	11.52**	-9.34**	-5.71**	-9.84**	-10.86**	-2.76**	1.73*	-1.12	-4.87**
PSEV3 × SWAJK-1	1.25	5.19**	0.61	2.53**	0.89	1.19	0.59	3.03**	-1.39*	1.71**	-2.73**	-3.84**	2.54**	5.20**	2.25**	-1.63*
SWAJK-1 × FRHW-1	-3.90**	-3.61**	-0.63	1.26	0.00	0.01	0.00	2.42**	-3.30**	-1.12	-3.83**	-4.92**	-3.00**	-2.20**	0.01	-3.79**
SWAJK-1 × FRHW-2	-3.93**	-3.64**	-1.25	0.63	0.00	3.14**	-2.96**	-0.61	-3.56**	-1.68	-3.83**	-4.92**	-3.06**	-1.69*	-2.24**	-5.95**
SWAJK-1 × FRHW-3	-5.54**	-2.41**	0.61	2.53**	-2.91**	-1.18	-1.18	1.21	-1.87**	-1.08	0.55	-0.59	-1.89**	0.00	2.25**	-1.63*
SWAJK-1 × PSEV3	-1.25	2.60**	-1.87*	-0.01	3.86**	4.17**	3.55**	6.06**	3.05**	6.29**	1.64*	0.49	0.28	2.89**	0.01	-3.79**

**, * = Significant at 1% and 5% level of probability, MP = Mid-parent, BP = Better-parent

Table 6: Mid- and better-parents, economic and commercial heterosis in 5 × 5 maize F_1 diallel hybrids for days to physiological maturity across four locations

F_1 hybrids	Days to physiological maturity															
	CCRI, Pirsabak - Nowshera				University of Haripur, Haripur				ARS, Baffa - Mansehra				ARI, Mingora - Swat			
	MP heterosis (%)	BP heterosis (%)	Economic heterosis (%)	Commercial heterosis (%)	MP heterosis (%)	BP heterosis (%)	Economic heterosis (%)	Commercial heterosis (%)	MP heterosis (%)	BP heterosis (%)	Economic heterosis (%)	Commercial heterosis (%)	MP heterosis (%)	BP heterosis (%)	Economic heterosis (%)	Commercial heterosis (%)
FRHW-1 × FRHW-2	0.00	2.95**	-8.92**	-13.75**	3.31**	7.76**	-8.12**	-13.46**	0.65	3.69**	-6.93**	-9.91**	-2.50**	0.00	-10.28**	-14.81**
FRHW-1 × FRHW-3	-0.38	5.58**	-1.08*	-6.33**	0.00	6.75**	-1.14**	-6.89**	0.76*	4.75**	-0.30	-3.50**	0.35	6.39**	0.35	-4.71**
FRHW-1 × PSEV3	-0.79	-0.40	-6.68**	-11.63**	2.91**	5.16**	-2.61**	-8.27**	1.25**	2.22**	-2.71**	-5.83**	-0.93*	-0.38	-6.03**	-10.77**
FRHW-1 × SWAJK-1	-2.06**	3.98**	-2.58**	-7.74**	1.29**	8.73**	0.70	-5.16**	0.30	4.11**	-0.90*	-4.08**	-0.71	4.89**	-1.06*	-6.06**
FRHW-2 × FRHW-1	-1.23*	1.69**	-10.04**	-14.81**	2.48**	6.90**	-8.86**	-14.16**	0.65	3.69**	-6.93**	-9.91**	-1.35**	1.19*	-9.22**	-13.80**
FRHW-2 × FRHW-3	-1.93**	7.17**	-5.19**	-10.22**	-1.93**	9.48**	-6.65**	-12.08**	-0.78*	6.38**	-4.52**	-7.58**	-3.45**	5.14**	-5.67**	-10.44**
FRHW-2 × PSEV3	-0.82	2.53**	-9.29**	-14.10**	0.61	7.33**	-8.49**	-13.81**	-0.97*	3.02**	-7.53**	-10.50**	-1.92**	1.19*	-9.22**	-13.80**
FRHW-2 × SWAJK-1	-2.50**	6.75**	-5.56**	-10.57**	-1.34**	10.78**	-5.55**	-11.04**	-0.31	6.71**	-4.22**	-7.29**	-4.92**	3.16**	-7.45**	-12.12**
FRHW-3 × FRHW-1	0.75	6.77**	0.04	-5.27**	-0.37	6.35**	-1.51**	-7.23**	1.07**	5.06**	0.00	-3.21**	-1.42**	4.51**	-1.42**	-6.40**
FRHW-3 × FRHW-2	-0.77*	8.44**	-4.07**	-9.16**	-0.77	10.78**	-5.55**	-11.04**	1.10**	8.39**	-2.71**	-5.83**	-1.63**	7.11**	-3.90**	-8.75**
FRHW-3 × PSEV3	1.12*	6.72**	0.78	-4.56**	-1.28**	3.04**	-0.40	-6.20**	-1.06**	1.86**	-1.20**	-4.37**	-2.65**	2.60**	-2.13**	-7.07**
FRHW-3 × SWAJK-1	0.53	0.71	5.64**	0.04	-0.52	0.00	5.11**	-1.00*	1.03**	1.18**	3.61**	0.29	-1.35**	-1.01*	3.90**	-1.35**
PSEV3 × FRHW-1	-1.98**	-1.59**	-7.80**	-12.69**	2.91**	5.16**	-2.61**	-8.27**	1.88**	2.85**	-2.11**	-5.25**	-1.68**	-1.13*	-6.74**	-11.45**
PSEV3 × FRHW-2	1.22*	4.64**	-7.43**	-12.34**	2.63**	9.48**	-6.65**	-12.08**	-0.32	3.69**	-6.93**	-9.91**	-3.07**	0.00	-10.28**	-14.81**
PSEV3 × FRHW-3	-3.00**	2.37**	-3.32**	-8.45**	-2.00**	2.28**	-1.14**	-6.89**	-1.36	1.55**	-1.51**	-4.66**	-3.35**	1.86**	-2.84**	-7.74**
PSEV3 × SWAJK-1	-2.80**	2.77**	-2.95**	-8.09**	-0.72	4.18**	0.70	-5.16**	0.30	3.11**	0.00	-3.21**	-1.24**	3.72**	-1.06*	-6.06**
SWAJK-1 × FRHW-1	-1.31**	4.78**	-1.83**	-7.03**	0.18	7.54**	-0.40	-6.20**	1.22**	5.06**	0.00	-3.21**	0.00	5.64**	-0.35	-5.39**
SWAJK-1 × FRHW-2	-1.73**	7.59**	-4.82**	-9.86**	0.58	12.93**	-3.71**	-9.31**	0.31	7.38**	-3.61**	-6.71**	-3.46**	4.74**	-6.03**	-10.77**
SWAJK-1 × FRHW-3	0.18	0.36	5.26**	-0.32	0.52	1.05**	6.21**	0.03	-0.44	-0.29	2.11**	-1.17**	0.00	0.34	5.32**	0.00
SWAJK-1 × PSEV3	-2.06**	3.56**	-2.20**	-7.39**	-0.72	4.18**	0.70	-5.16**	0.91**	3.73**	0.60	-2.62**	-0.53	4.46**	-0.35	-5.39**

**, * = Significant at 1% and 5% level of probability, MP = Mid-parent, BP = Better-parent

The F_1 hybrids FRHW-3 × PSEV3, FRHW-1 × FRHW-3 and its reciprocal, and FRHW-3 × FRHW-2 performed better than both the parents. While the highest and at par negative economic and commercial heterotic effects were observed in F_1 hybrids FRHW-3 × PSEV3 and PSEV3 × FRHW-1, respectively days to 50% pollen shedding.

Days to 50% silking

At CCRI, Pirsabak for days to 50% silking, the negative mid-, better-parent, economic and commercial heterotic were recorded in 17, 12, 15, and 8 F_1 hybrids ranged from -1.25 to -9.36%, -1.20 to -6.06%, -0.01 to 4.35%, and -0.01 to 2.54%, respectively (Table 5). However, 16, 11, 11, and 4 F_1 hybrids attained the significance level for the said trait. Maximum negative mid- and better-parent heterosis was recorded in F_1 hybrids FRHW-2 × FRHW-3 and its reciprocal, FRHW-3 × FRHW-1. The highest negative economic and commercial heterosis were recorded in F_1 hybrids FRHW-1 × PSEV3 and its reciprocal, FRHW-2 × FRHW-3, and FRHW-2 × PSEV3 for days to 50% silking.

At the University of Haripur, 9, 6, 11, and 5 F_1 hybrids exhibited negative mid-, better-parent, economic and commercial heterosis, in which 7, 4, 7, and 3 hybrids revealed significant heterotic values for days to 50% silking (Table 5). However, the ranges for various heterosis were -0.92 to -5.04%, -1.18 to -4.76%, -0.59 to -5.33%, and -0.61 to -3.03%, respectively. The F_1 hybrids FRHW-1 × PSEV3, and FRHW-1 × SWAJK-1 showed maximum negative heterotic effects over mid-, better-parent, economic and commercial heterosis for days to 50% silking.

For days to 50% silking at ARS, Baffa, Mansehra, 15, 11, 16, and 19 F_1 hybrids revealed negative heterosis after comparing with both mid- and better-parents,

Table 7: Mid- and better-parents, economic and commercial heterosis in 5 × 5 maize F_1 diallel hybrids for grain yield across four locations

F_1 hybrids	Grain yield															
	CCRI, Pirsabak - Nowshera				University of Haripur, Haripur				ARS, Baffa - Mansehra				ARI, Mingora - Swat			
	MP heterosis (%)	BP heterosis (%)	Economic heterosis (%)	Commercial heterosis (%)	MP heterosis (%)	BP heterosis (%)	Economic heterosis (%)	Commercial heterosis (%)	MP heterosis (%)	BP heterosis (%)	Economic heterosis (%)	Commercial heterosis (%)	MP heterosis (%)	BP heterosis (%)	Economic heterosis (%)	Commercial heterosis (%)
FRHW-1 × FRHW-2	56.85**	36.25**	-14.34**	-41.81**	147.51**	127.93**	-34.47**	-43.18**	55.93**	41.55**	-23.58**	-21.90**	84.59**	71.90**	-13.01**	-20.95**
FRHW-1 × FRHW-3	100.35**	90.89**	-2.27	-33.61**	109.67**	69.79**	-21.22**	-31.69**	116.08**	113.58**	-3.72	-1.61	123.56**	94.82**	-1.41	-10.40**
FRHW-1 × PSEV3	66.13**	51.21**	-14.56**	-41.96**	88.30**	43.01**	-20.77**	-31.31**	121.72**	91.83**	-15.53**	-13.68**	54.10**	39.88**	-13.19**	-21.11**
FRHW-1 × SWAJK-1	64.20**	38.69**	-6.73	-36.64**	106.60**	54.90**	-10.84**	-22.70**	175.02**	150.79**	34.05**	36.99**	114.03**	89.61**	24.33**	12.98**
FRHW-2 × FRHW-1	57.48**	36.80**	-13.99**	-41.57**	197.40**	173.87**	-21.26**	-31.73**	86.56**	69.36**	-8.56**	-6.56*	98.57**	84.92**	-6.41*	-14.96**
FRHW-2 × FRHW-3	88.94**	71.40**	7.76	-26.79**	162.19**	99.47**	-7.45*	-19.75**	103.19**	86.42**	0.65	2.85	151.25**	133.82**	2.06	-7.25**
FRHW-2 × PSEV3	103.32**	93.03**	21.36**	-17.56**	147.41**	77.74**	-1.53	-14.62**	125.38**	79.81**	-2.92	-0.79	97.10**	67.86**	4.18	-5.33*
FRHW-2 × SWAJK-1	71.68**	66.08**	11.70**	-24.12**	123.74**	58.90**	-8.53**	-20.70**	79.99**	79.09**	-3.31	-1.19	78.91**	49.01**	-2.29	-11.21**
FRHW-3 × FRHW-1	91.64**	82.58**	-6.52	-36.50**	131.52**	87.49**	-13.01**	-24.57**	101.44**	99.10**	-10.25**	-8.28**	103.66**	77.48**	-10.18**	-18.38**
FRHW-3 × FRHW-2	88.13**	70.66**	7.30	-27.11**	137.60**	80.76**	-16.13**	-27.28**	68.71**	54.79**	-16.43**	-14.60**	112.14**	97.42**	-13.82**	-21.69**
FRHW-3 × PSEV3	118.60**	108.32**	17.72**	-20.03**	78.45**	63.95**	-9.17**	-21.25**	141.28**	106.70**	-6.82*	-4.78	116.27**	73.64**	7.77**	-2.07
FRHW-3 × SWAJK-1	90.24**	67.53**	12.67**	-23.46**	91.32**	72.77**	-0.55	-13.78**	105.95**	89.82**	1.46	3.68	72.06**	35.36**	-11.25**	-19.35**
PSEV3 × FRHW-1	144.25**	122.32**	25.63**	-14.66**	159.46**	97.05**	9.17**	-5.34*	175.56**	138.40**	4.98*	7.28*	80.74**	64.06**	1.82	-7.47**
PSEV3 × FRHW-2	77.16**	68.19**	5.74	-28.17**	103.86**	46.46**	-18.86**	-29.65**	89.78**	51.41**	-18.25**	-16.46**	83.78**	56.52**	-2.86	-11.73**
PSEV3 × FRHW-3	131.78**	120.89**	24.82**	-15.21**	84.65**	69.65**	-6.01*	-18.51**	140.55**	106.08**	-7.10*	-5.07	83.47**	47.31**	-8.58**	-16.93**
PSEV3 × SWAJK-1	37.95**	26.93**	-14.64**	-42.01**	66.07**	62.96**	-6.20*	-18.67**	197.66**	138.38**	27.42**	30.21**	81.93**	77.06**	16.10**	5.50*
SWAJK-1 × FRHW-1	68.05**	41.94**	-4.54	-35.15**	160.08**	94.99**	12.24**	-2.69	132.68**	112.18**	13.41**	15.90**	88.32**	66.84**	9.40**	-0.59
SWAJK-1 × FRHW-2	84.35**	78.34**	19.94**	-18.52**	138.78**	69.59**	-2.38	-15.36**	84.37**	83.45**	-0.96	1.21	70.17**	41.73**	-7.07**	-15.55**
SWAJK-1 × FRHW-3	86.54**	64.27**	10.48**	-24.95**	42.29**	28.49**	-26.04**	-35.87**	139.67**	120.90**	18.07**	20.66**	98.12**	55.86**	2.20	-7.13**
SWAJK-1 × PSEV3	77.66**	63.47**	9.94*	-25.32**	69.23**	66.06**	-4.41	-17.12**	145.82**	96.86**	5.23*	7.53*	56.08**	51.91**	-0.39	-9.49**

**, * = Significant at 1% and 5% level of probability, MP = Mid-parent, BP = Better-parent

commercial OPV and hybrid, ranged from -0.27 to -9.78%, -0.56 to -7.26%, -0.55 to -9.84%, and -0.59 to -10.86%, respectively (Table 5). However, 13, 7, 14, and 16 F_1 hybrids authenticated their significance for the said trait. The F_1 hybrids FRHW-2 × FRHW-3, and its reciprocal, and PSEV3 × FRHW-3 showed the highest heterosis after comparing with mid-, better-parent, commercial OPV-Jalal and hybrid for days to 50% silking.

Regarding days to 50% silking at ARI, Mingora - Swat, 16, 9, 13, and 20 F_1 hybrids manifested negative mid-, better-parent, economic and commercial heterosis ranged from -0.55 to -7.49%, -1.69 to -6.49%, -0.56 to -5.61%, and -1.69 to -9.19%, respectively (Table 5). However, 13, 9, 9, and 19 F_1 hybrids confirmed their significance for above four types of heterosis, respectively. Overall, the F_1 hybrids FRHW-1 × FRHW-3, FRHW-3 × PSEV3, PSEV3 × FRHW1, and FRHW-3 × FRHW-2 performed better and revealed maximum negative effects for mid-, better-parent economic and commercial heterosis for days to 50% silking.

Days to physiological maturity

At CCRI, Pirsabak for days to physiological maturity, 14, 2, 16, and 19 F_1 hybrids revealed negative mid-, better-parent, economic and commercial heterosis, ranged from -0.38 to -3.00%, -0.40% to -1.59%, -1.08 to -10.04%, and -0.32 to -14.81%, respectively (Table 6). However, for the said trait the significance level achieved by 11, 1, 16, and 18 hybrids. As compared to mid-parent values, F_1 hybrids PSEV3 × FRHW-3, PSEV3 × SWAJK-1 and its reciprocal, and for better parent the hybrid FRHW-1 × PSEV3 enunciated maximum negative heterotic effects. However, by comparing with commercial OPV - Jalal and hybrid, the promising F_1 hybrids FRHW-2 × FRHW-1, and its reciprocal, and FRHW-2 × PSEV3 showed maximum negative heterotic effects.

For days to physiological maturity at the University of Haripur, 9, zero, 13, and 19 F_1 hybrids exhibited negative mid-, better-parent, economic and commercial heterosis, ranged from -0.37 to -2.00%, 0 to 0, -0.40 to -8.86%, and -1.00 to -14.16%, respectively (Table 6). However, 4, zero, 13, and 19 hybrids attained the level of significance for the said trait. Highest mid-parent negative heterosis was recorded in F_1 hybrids PSEV3 × FRHW-3 and FRHW-2 × FRHW-3. while three F_1 hybrids FRHW-2 × FRHW-1 and its reciprocal, and FRHW-2 × PSEV3 were considered as promising for economic and commercial heterosis for days to physiological maturity.

At ARS, Baffa - Mansehra for days to physiological maturity, 7, one, 14, and 19 F_1 hybrids exhibited negative mid-, better-parent, economic and commercial heterosis, in which 3, zero, 11, and 19 attained the level of significance, respectively (Table 6). However, the ranges for above four types of heterosis were -0.31 to -1.36%, 0 to -0.29%, -0.30 to -7.53%, and -1.17 to -10.50%, respectively. Maximum heterosis over mid-parents was observed in F_1 hybrids PSEV3 × FRHW-3 and its reciprocal, and FRHW-3 × SWAJK-1. Promising F_1 hybrids FRHW-2 × PSEV3 and FRHW-2 × FRHW-1 and their reciprocals showed maximum negative economic and commercial heterotic effects for days to physiological maturity.

For days to physiological maturity at ARI, Mingora - Swat, 17, 3, 17, and 19 F_1 hybrids showed negative heterosis by comparing with mid, better-parent, and commercial OPV - Jalal and hybrid, ranged from -0.53 to -4.92%, -0.38 to -1.13%, -0.35 to -10.28%, and -1.35 to -14.81%, respectively (Table 6). The above four types of significant heterosis was seen in 15, 2, 15, and 19 hybrids, respectively. Promising F_1 hybrids FRHW-2 × SWAJK-1 and its reciprocal, FRHW-2 × FRHW-3 and PSEV3 × FRHW-3 showed the highest negative mid-parent heterosis. Two F_1 hybrids PSEV3 × FRHW-1 and FRHW-1 × SWAJK-1 showed highest negative better-parent heterosis. The promising F_1 hybrids FRHW-1 × FRHW-2 and PSEV3 × FRHW-2 and their reciprocals exhibited the highest negative economic and commercial heterosis for days to physiological maturity.

Grain yield

All the F_1 hybrids manifested significant positive mid- and better-parent heterosis ranged from 37.95 to 144.25% and 26.93 to 122.32%, respectively for grain yield at CCRI, Pirsabak (Table 7). Promising F_1 hybrids PSEV3 × FRHW-1, PSEV3 × FRHW-3 and their reciprocals, and FRHW-2 × PSEV3 showed highest positive heterosis by comparing with mid- and better-parents. For economic heterosis, 12 F_1 hybrids revealed positive effects ranged from 5.74 to 25.63%, in which 11 hybrids achieved significance for grain yield. By comparing with commercial OPV-Jalal, maximum economic heterotic effects were recorded in F_1 hybrids PSEV3 × FRHW-1, PSEV3 × FRHW-3, FRHW-2 × PSEV3, and SWAJK-1 × FRHW-2 for grain yield. For commercial heterosis, none of the F_1 hybrids out-yielded the commercial hybrid for grain yield.

For grain yield at the University of Haripur, all the F_1 hybrids revealed significant positive heterosis over mid- and better-parents ranged from 42.29 to 197.40% and 28.49 to 173.87%, respectively (Table 7). However, the highest mid- and better parent positive heterotic effects were observed in F_1 hybrids FRHW-2 × FRHW-1 and its reciprocal, FRHW-2 × FRHW-3, SWAJK-1 × FRHW-1, PSEV3 × FRHW-1, and FRHW-2 × PSEV3 for grain yield. Two F_1 hybrids SWAJK-1 × FRHW-1 and PSEV3 × FRHW-1 exhibited significant positive economic heterosis and proved to be the high yielding hybrids than check OPV-Jalal for grain yield. For commercial heterosis, none of the F_1 hybrids excelled the commercial hybrid to exhibit positive heterotic effects.

At ARS, Baffa - Mansehra for grain yield, all the F_1 hybrids revealed significant positive mid- and better-parent heterotic effects ranged from 55.93 to 197.66% and 41.55 to 150.79%, respectively (Table 7). Maximum mid- and better-parents heterotic effects were recorded in F_1 hybrids PSEV3 × SWAJK-1, FRHW-1 × FRHW-2, and FRHW-1 × SWAJK-1 for grain yield. For economic and commercial heterosis, 8 and 9 F_1 hybrids revealed positive heterotic values ranged from 0.65 to 34.05%, and 1.21 to 36.99%, respectively in which six each hybrids attained the significance. By comparing the F_1 hybrids with commercial OPV and hybrid, the F_1 hybrids FRHW-1 × SWAJK-1, PSEV3 × SWAJK-1, and SWAJK-1 × FRHW-3 revealed highest economic and commercial heterosis for grain yield.

For grain yield at ARI, Mingora - Swat, all the F_1 hybrids exhibited significant positive mid- and better-parents heterosis ranged from 54.10 to 151.25% and 35.36 to 133.82%, respectively (Table 7). Maximum mid- and better-parent heterotic effects were observed in F_1 hybrids FRHW-2 × FRHW-3, FRHW-1 × FRHW-3, FRHW-3 × PSEV3, and FRHW-1 × SWAJK-1. For economic heterosis, eight F_1 hybrids showed positive values ranged from 1.82 to 24.33%, in which five hybrids attained the level of significance for grain yield. Maximum economic heterosis was recorded in F_1 hybrids FRHW-1 × SWAJK-1 and its reciprocal, and PSEV3 × SWAJK-1. Significant positive commercial heterosis was recorded in two F_1 hybrids FRHW-1 × SWAJK-1 and PSEV3 × SWAJK-1 for grain yield.

For earliness trait i.e., days to tasseling, pollen shedding and silking, the negative heterotic effects are desirable and favored because of their positive association with early maturity. The environmental data including temperature, rainfall, and humidity also confirmed that the hilly areas i.e., ARS, Baffa - Mansehra followed by ARI, Mingora - Swat were found cooler than plain areas i.e., CCRI, Pirsabak – Nowshera, and University of Haripur, Khyber Pakhtunkhwa, Pakistan (Fig. 1, 2). Results further enunciated that due to interaction of genotypes with existing environmental factors, the F_1 hybrids revealed significantly varying heterotic effects for earliness traits and grain yield at different locations. Overall, F_1 hybrids matured earlier than parental inbred lines and commercial 'OPV - Jalal' and 'Pioneer hybrid 30K08' in plain areas as compared to hilly areas. On average, the highest negative heterotic effects were observed in F_1 hybrids at CCRI, Pirsabak - Nowshera and took fewer days to tasseling, pollen shedding, silking, and physiological maturity because of high temperature, less rainfall and a warmer climate, followed by University of Haripur, and ARI, Mingora, Swat. At ARS, Baffa - Mansehra, the F_1 hybrids showed less negative heterotic effects for earliness traits and took more days to tasseling, pollen shedding, silking, and physiological maturity due to low temperature, more rainfall and humidity, and high altitude which make the environment cooler and delayed the flower initiation and maturity. Overall for earliness traits, majority of the F_1 hybrids performed better by showing highly significant negative heterotic effects and taking less days to tasseling, pollen shedding, silking and physiological maturity as compared to parental inbred lines and commercial OPV and hybrid at all the locations. For grain yield, the F_1 hybrids surpassed parental inbred lines by showing significant ($P \leq 0.01$) positive mid- and better-parent heterosis but not able to perform better than commercial OPV and hybrid at all the locations.

Discussion

Heterosis refers to the superior performance of F_1 hybrids than their parental inbred lines, standard cultivars, and commercial hybrids concerning growth and yield traits (Ali *et al.* 2019). Although little known about the genetic and molecular basis of heterosis, however, it has been reported that heterosis managed by both dominant and epistatic gene actions (Khan *et al.* 2018; Govindaraju 2019). The main target of hybrid crop breeding is to identify parental genotypes with high genetic diversity that have a high proportion of strong heterosis in F_1 hybrids (Kumar *et al.* 2014, 2019; Liu *et al.* 2019).

Genotypes, environments (locations) and genotype by environment interactions revealed significant ($P \leq 0.01$) differences for earliness traits and grain yield. Significance of these three major components authenticated that differences might be due to varied genetic makeup of the maize genotypes and their interaction with varying environmental factors at different locations. Present study also enunciated that in proportional contribution to the total sum of squares, larger effects of environment and genotypes to total variation (G + E + GEI) persuade the studied traits. Significant differences in genotypes and environments preceded to various types of desirable negative and positive heterotic effects under four environments. Significant differences among inbred lines and F_1 populations manifested the choice for exploitation of heterosis for earliness traits and grain yield in maize across environments (El-Hosary *et al.* 2014; Panda *et al.* 2017; Sajjad *et al.* 2020). Past findings revealed significant variations among the maize populations and environments, and their greater role in proportional contribution total sum of square studied for earliness and grain yield in distinct environments (Kiani *et al.* 2015; Ullah *et al.* 2019). Significant diversity was observed among maize F_1 hybrids for earliness and grain yield which might be due to their varied genetic background and their interaction with environment (Nzuve *et al.* 2014; Kumar *et al.* 2019).

For earliness traits, the negative heterosis is desirable because it could be used for the development and production of early maturing maize hybrids. Overall, the F_1 hybrids performed better by showing significant ($P \leq 0.01$) negative heterotic effects by taking less days to tasseling, pollen shedding, silking and physiological maturity as compared to parental inbred lines and commercial OPV and hybrid at almost all the locations. However, at the University of Haripur, minimum number of F_1 hybrids showed negative economic and commercial heterotic effects, and that varied performance of the maize genotype might be due to diverse environmental conditions. Greater genetic variability and desirable negative and positive mid- and better parents heterotic effects were reported in F_1 populations for earliness and yield traits, respectively in maize under different environments (Ali *et al.* 2019; Yi *et al.* 2019). By comparing with mid- and better-parents, and standard cultivar, F_1 maize hybrids exhibited negative heterotic effects of varying magnitudes for earliness traits and grain yield in varied environmental conditions (Kumar *et al.* 2014; Rajesh *et al.* 2014). Negative economic and commercial heterotic effects were determined in F_1 maize hybrids by comparing with check genotypes (commercial cultivar and hybrid) under diverse climatic conditions for days to tasseling, pollen shedding, silking and physiological maturity (Singh 2015; Khan *et al.* 2018). Therefore, in genotype by environment interaction studies, the role of the environment cannot be ignored during the recommendation of maize genotypes for specific and different localities. Present results about different types of heterosis were in line with past findings as reported significant negative heterotic effects in F_1 maize populations for days to tasseling, pollen shedding, silking and physiological maturity (Ali *et al.* 2013a, b; Ding *et al.* 2014; Li *et al.* 2018). Significant negative standard heterosis was reported in the majority of the maize test crosses for tasseling, pollen shedding, silking and other earliness traits (Izhar and Chakraborty 2013; Abrha 2014: Kumar *et al.* 2019).

Overall, a large number of F_1 hybrids revealed significant negative mid- and better parent, economic and commercial heterosis for earliness traits at most of the locations except the University of Haripur, Haripur where a small number of F_1 hybrids revealed negative heterosis. Present also results revealed that parental inbred lines and F_1 hybrids showed a similar tendency in response to environmental factors and both are donating to the observed genotype by environment interactions for heterosis (Li *et al.* 2018). Varying magnitudes of negative mid- and better parents, and standard heterosis were reported in F_1 populations for various earliness traits (Singh 2015; Kumar *et al.* 2014). Some other past findings also summarized that varying degrees of negative mid- and better parents heterotic effects were recorded in maize F_1 hybrids for earliness traits (Nethra *et al.* 2013).

The identified promising F_1 hybrids with significant earliness in flowering and maturity traits (FRHW-2 × FRHW-3, FRHW-1 × SWAJK-1, and FRHW-3 × FRHW-2), and grain yield (PSEV3 × FRHW-1, PSEV3 × FRHW-3, FRHW-1 × SWAJK-1, FRHW-2 × FRHW-3, and FRHW-3 × PSEV3) have greater potential for developing early maturing and high yielding hybrids for multiple cropping systems. Past studies revealed varying degrees of heterosis and heterobeltiosis among in F_1 maize populations for days to male and female flowering and physiological maturity under different environmental conditions (Ali *et al.* 2019; Cherchali *et al.* 2019). Significant negative better parent, economic and commercial heterosis were observed in F_1 maize hybrids for earliness traits and physiological maturity in diverse environments (Nethra *et al.* 2013; Rajesh *et al.* 2014). Previous findings revealed that experimental hybrids were developed with a determined extent of heterosis in respect of maturity and grain yield in maize (Sharma *et al.* 2019; Ullah *et al.* 2017; 2019).

For grain yield, all the F_1 hybrids surpassed parental inbred lines by showing significant ($P \leq 0.01$) positive mid- and better-parent heterosis, however, majority of the hybrids were not able to perform better than commercial OPV and hybrid for economic and commercial heterosis at all the locations. For commercial heterosis, nine and two F_1 hybrids showed positive heterotic effects at ARS, Baffa - Mansehra, and ARI, Mingora - Swat, respectively by comparing with the commercial hybrid. However, at CCRI, Pirsabak and the University of Haripur, the F_1 hybrids cannot compete with commercial hybrid and showed negative heterotic effects for grain yield. Results further authenticated that environment has greater contribution in phenotypic performance of the same genotypes at different locations result in due to interaction of maize genotypes with existing environmental factors. Significant mid- and better-parent heterotic effects have been reported in F_1 hybrids by comparing with their inbred lines for yield related traits in maize in different environments (Khan *et al.* 2018). In F_1 maize populations, varied values of economic and commercial heterosis have been reported for grain yield and its attributes in different environments (Ali 2015, Ali *et al.* 2018; Shrestha *et al.* 2018). However, in some other studies, significant mid- and better parents heterotic effects were reported in F_1 maize hybrids for yield related traits (Ali *et al.* 2013a, b; Singh 2015; Ige *et al.* 2018). Standard positive heterosis was reported in various studies of F_1 maize cross combinations for grain yield and its components in diverse environments (Izhar and Chakraborty 2013; Nethra *et al.* 2013). Similarly, various levels of mid- and better parents and standard heterosis was reported in F_1 maize hybrids for grain yield under different growing seasons (Kumar *et al.* 2014, 2019).

Heterosis is considerably influenced by the genetic background of the genotypes and environmental conditions. Results further revealed that due to varying levels of soil, temperature, rainfall, humidity and altitude at four locations, the inbred lines and their F_1 hybrids revealed significant differences in performance through heterotic effects for earliness and grain yield. Because of high temperature, less rainfall and warmer climate at CCRI, Pirsabak - Nowshera, the F_1 hybrids showed the highest negative heterotic effects and took fewer days to tasseling, pollen shedding, silking, and physiological maturity followed by University of Haripur, and ARI, Mingora, Swat. However, due to low temperature, more rainfall and humidity, and high altitude at ARS, Baffa located in a hilly area, make the environment cooler and the same maize genotypes took more time to flower and maturity, resulting in less magnitude of negative heterotic effects.

Present results also authenticated that extent of heterosis is not an inherent trait of a specific hybrid, but its appearance depends on the trait measured and the environment where the study was carried out. Promising F_1 hybrids FRHW-2 × FRHW-3, FRHW-$_1$ × SWAJK-1, and FRHW-3 × FRHW-2 showed significant negative heterotic effects for earliness traits. For grain yield across the four environments, F_1 hybrids PSEV3 × FRHW-1, PSEV3 × FRHW-3, FRHW-1 × SWAJK-1, FRHW-2 × FRHW-3, and FRHW-3 × PSEV3 showed best performance with significant positive heterotic effects. On average, F_1 hybrids took less days to flowering and maturity than their parental genotypes in plains as compared to hilly areas which might be due to high temperature (Fig. 1 and 2). Maturity duration of maize increased in hilly area than that in plains, and substantially increased the grain yield which might be due low temperature and cooler climate (Singode *et al.* 2014). Early maturing and high yielding genotypes could help in adapting maize to diverse climatic conditions, and to escape the crop from drought stress due to warmer climate that occurs during the grain-filling stage in late season maize crop (Ali *et al.* 2019; Fromme *et al.* 2019; Yi *et al.* 2019). These promising F_1 populations could be used in future breeding programs for the development of early maturing and high yielding maize hybrids/cultivars.

Conclusion

Overall, maize F_1 hybrids excelled the parental inbred lines and check genotypes ('OPV - Jalal' and 'Pioneer hybrid 30K08') by showing significant negative heterotic effects for earliness traits while positive values for grain yield across environments. Promising F_1 hybrids FRHW-2 × FRHW-3, FRHW-1 × SWAJK-1, and FRHW-3 × FRHW-2 showed significant negative heterotic effects by comparing with parental inbred lines and check genotypes across locations. However, F_1 hybrids PSEV3 × FRHW-1, PSEV3 × FRHW-3, FRHW-1 × SWAJK-1, FRHW-2 × FRHW-3, and FRHW-3 × PSEV3 showed significant positive heterotic effects and best mean performance for grain yield across environments. Therefore, these promising F_1 hybrids could be used in the development of early maturing and high yielding maize hybrids/cultivars. Based on present finding, the hybrid crop production is recommended for hilly as well as plain areas in Pakistan.

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