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Estimation of Heterosis and Combining Ability in Barley (*Hordeum vulgare* L.) under Normal and Limited Moisture Condition of Rajasthan

Madhu Yadav, Ved Prakash

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ABSTRACT

Barley is arguably the widely adapted cereal crop with drought, cold and salt tolerance. Its grain is used as feed, food and for malting purpose while the straw provides an important source of roughage for animal, particularly in the dry areas. The estimates of heterosis and inbreeding depression jointly provide information about the type of gene action involved in the expression of several quantitative characteristics. Combining ability analysis is required for this method to identify the desirable parents for a hybridization program. The cross DWRUB 64 × RD 2508 in E_1 and DWRB 137 × RD 2052 in E_2 exhibited desirable heterosis for grain yield per plant and its attributing traits. On the basis of *per se* performance and GCA effects, the parents RD 2508, RD 2052 and PL 419 in both the generations and environments identified as good general combiners for grain yield per plant and some other associated characters. On the basis of *per se* performance and SCA effects, the crosses BH 946 × PL 419 and RD 103 × RD 2508 in F_1 of E_1, RD 2592 × PL 419 and DWRUB 64 × RD 2508 in F_1 of E_2, RD 2592 × PL 419 and DWRB 137 × RD 2052 in F_2 of E_2 were identified as good specific cross combinations for grain yield per plant and some associated traits.

Keywords Barley, Combining ability, Heterosis, GCA, SCA, Inbreeding depression.

INTRODUCTION

Barley (*Hordeum vulgare* L.) is a self-pollinated important cereal crop with the chromosomal number 2n=2x=14 and member of Poaceae family. Because of its extensive ecological adaption, low input demand, and improved resilience to adverse conditions, such as drought, salt, alkalinity and marginal areas, it is produced in tropical and temperate climates around the world. As a result, it has long been regarded as a poor man's crop around the world, particularly among those who depend on subsistence farming. It was one of the first cereals to be cultivated in the Near East's fertile crescent as early as 10000 years ago. Barley is a dominant crop that is regarded as the first cereal domesticated for human consumption as food and feed. *Hordeum vulgare* subsp. Spontaneum (the wild ancestor of domesticated barley) is common in grasslands and forests in the fertile crescent region of N-E Africa and Western Asia. In some regions, barley is grown for human consumption where, other cereal grains do not grow well. These days, barley

Madhu Yadav[1]*, Ved Prakash[2]

[1]PhD Research Scholar, [2]Professor
[1,2]Division of Plant Breeding and Genetics, Rajasthan Agricultural Research Institute, Sri Karan Narendra Agriculture University, Jobner, Durgapura, Jaipur 302018, Rajasthan, India

Email : ymadhu147@gmail.com
*Corresponding author

has countless advantages in food industry because of high content of bioactive compounds such as β-glucan and phenolics like cinnamic benzoic acid derivatives, chalcones and flavones. It is graining importance in neutraceutical diets and has potential health benefits due to soluble fiber β-glucan which helps in lowering cholesterol level, improving lipid metabolism (Koulagi *et al*. 2018). In India, it is grown over an area of 5.40 lakh hectares and total production of 15.90 lakh tonns with an average grain productivity of 2930 kg per hectare (Anonymous 2022). Whereas in Rajasthan, it is an important *rabi* cereal crop after wheat in both area and production. It is grown over an area of 3.30 lakh hectares and a total production of 11.25 lakh tonns with an average grain productivity of 3403 kg per hectare (Anonymous 2022-23). The estimates of heterosis and inbreeding depression jointly provide information about the type of gene action involved in the expression of several quantitative characteristics. Study of heterosis assists the breeder in selecting the most productive crosses in the early generations. Heterosis is a useful technique in evaluating genetic parameters in most crops, including barley. Plant breeders may need to consider the nature and magnitude of heterosis while developing breeding procedures. Many biometrical approaches have been devised to gain knowledge on combining ability and diallel analysis is one of them that is commonly used to analyze the combining ability of the parents chosen for heterosis breeding. It provides a one-of-a-kind opportunity to evaluate a variety of lines in all possible combinations (Mather and Jinks 1971). Combining ability analysis is required for this method to identify the desirable parents for a hybridization program. General and specific combining abilities are very effective in the designing and execution of a breeding program and are used to test the performance of parents in different cross combinations as well as characterize the nature and magnitude of gene effects for yield expression.

MATERIALS AND METHODS

The present investigation was carried out during *rabi* 2018-19 and 2019-20 at Research Farm, Rajasthan Agricultural Research Institute (Sri Karan Narendra Agriculture University, Jobner), Durgapura, Jaipur (Rajasthan). Ten diverse parents namely: BH 946, RD 2592, DWRUB 64, DWRB 137, PL 426, PL 419, RD 103, RD 2035, RD 2052 and RD 2508 were selected and crossed in diallel fashion (excluding reciprocals) in all possible combinations during *rabi* 2018-19. In summer 2019, half of the F_1's seed was multiplied during off-season at IARI regional station, Wellington (Tamil Nadu) to advance the generation. In *rabi* 2019-20 ten varieties together with their 45 F_1's and 45 F_2's progenies were evaluated under the limited moisture condition created by giving only three irrigations at the crop stage of 30, 60 and 90 days with three replications in Randomized Block Design. Each replication contained two parts. The parents and F_1s sown in two rows with 3 m row length and F_2's were sown in 4 rows of 3 m in each replication. Row to row and plant to plant distance was kept 30 cm and 10 cm, respectively. Non-experimental rows were planted all around the experiment to eliminate the border effects, if any. All recommended agronomical package of practices were adopted to raise good crop. Observations were recorded days to maturity, plant height, number of effective tillers per plant, flag leaf area, 1000-grain weight, grain yield per plant and harvest index.

Heterosis over mid parent was calculated by = $((F_1\text{-MP})/\text{MP}) \times 100$ and heterobeltiosis were calculated by formula proposed by Fonseca and Patterson (1968) i.e. $((F_1\text{-BP})/\text{BP}) \times 100$. Where F_1= mean values of hybrid, MP = Mean values of mid parents and BP= Mean values of batter parents.

Analysis of variance for combining ability was done for individual environment following Griffing (1956) method 2 model I. The general mathematical model for analysis as given by Griffing (1956).

$$X_{ijk} = \mu + g_i + g_j + s_{ij} + e_{ijk}/b$$

Where,

X_{ij} =An observation of the phenotype of a cross between i^{th} and j^{th} parents in k^{th} block k,

μ = General mean,

g_i = General combining ability (GCA) effect of j^{th} parent,

s_{ij} = Specific combining ability (SCA) effect for cross between i^{th} and j^{th} parent such that $s_i = s_j$,

e_{ijk} = Environmental effects associated with ijk^{th} observation,

B = Number of blocks.

RESULTS AND DISCUSSION

The superiority of hybrids over better parents is more relevant and beneficial in establishing the feasibility of commercial exploitation of heterosis as well as indicating the parental combinations have the potential to producing the highest level of transgressive segregants. In the present study, the maximum range of heterosis has been estimated for all studied characters. An overall appraisal of the investigation shown that heterosis ranged from -10.74 to 4.97 in E_1 and -12.29 to 13.41 in E_2 for days to maturity, -16.44 to 21.70 in E_1 and -24.88 to 23.77 in E_2 for plant height, -28.40 to 42.35 in E_1 and -14.38 to 36.60 in E_2 for number of effective tillers per plant, -22.97 to 38.97 in E_1 and -24.49 to 47.78 in E_2 for flag leaf area, -18.65 to 25.49 in E_1 and -9.86 to 24.65 in E_2 for 1000-grain weight; -16.70 to 67.16 in E_1 and 3.51 to 81.75 in E_2 for grain yield per plant, -24.84 to 56.39 in E_1 and -8.35 to 45.35 in E_2 for harvest index. The result in both the environments for different characters are in conformity with the findings of several researchers such as Mansour (2016), Ram and Shekhawat (2017), Lal *et al.* (2018b), Parashar *et al.* (2019) and Bouchetat *et al.* (2020). Three best heterotic and heterobeltiotic crosses for grain yield per plant are given in Table 1. The cross DWRUB 64 × RD 2508 in E_1 exhibited desirable heterosis at least for five or more yield attributing characters. Whereas, cross DWRB 137 × RD 2052 in E_2 exhibited desirable heterosis at least for five or more yield attributing characters. The cross PL 419 × RD 2052 in E_1 exhibited desirable

Table 1. Top three crosses for their heterosis, heterobeltiosis and inbreeding depression estimates under normal irrigated (E_1) and limited moisture (E_2) conditions for yield and associated traits.

Characters	Env	Heterosis	Heterobeltiosis	Inbreeding depression
Days to maturity	E_1	PL 419 × RD 2508	PL 419 × RD 2508	RD 2592 × PL 426
		RD 2052 × RD 2508	RD 2052 ×RD 2508	BH 946 × RD 103
		PL 419 × RD 2052	PL 419 × RD 2052	RD 2592 × DWRUB 64
	E_2	BH 946 × RD 2592	BH 946 × RD 2592	BH 946 × RD 2035
		BH 946 × RD 2052	BH 946 × RD 2052	DWRUB 64 × DWRB 137
		RD 2592 ×RD 2508	RD 2592 × RD 2508	DWRUB 64 × RD 2035
Plant height	E_1	PL 419 × RD 2508	RD 2592 × RD 2508	RD 2592 × RD 2508
		DWRB 137 × RD 2035	RD 2592 × RD 2035	RD 2592 × RD 2035
		RD 2592 × RD 2508	PL 419 × RD 2508	PL 419 × RD 2508
	E2	PL 419 × RD 2508	PL 419 × RD 2508	DWRUB 64 × RD 2035
		RD 2592 × DWRB 137	RD 2052 × RD 2508	DWRB 137 × PL 419
		RD 2052 ×RD 2508	PL 419 × RD 103	DWRUB 64 × PL 419
Number of effective tillers per plant	E_1	PL 419 × RD 2508	PL 419 ×RD 2508	DWRUB 64 × DWRB 137
		DWRB 137 × RD 2035	BH 946 × RD 2508	BH 946 × RD 2035
		BH 946 × RD 2508	DWRB 137 × RD 2035	PL 426 × RD 103
	E_2	PL 419 × RD 2508	RD 2592 × RD 2052	BH 946 × PL 419
		RD 2592 × RD 2052	BH 946 × RD 2052	RD 2035 × RD 2052
		BH 946 × RD 2052	PL 419 × RD 103	RD 2052 × RD 2508
Flag leaf area	E_1	RD 103 × RD 2035	RD 2592 × PL 419	PL 419 × RD 2035
		RD 2592 × PL 426	PL 419 × RD 2508	DWRB 137 × RD 2035
		RD 2035 ×RD 2508	DWRUB 64 × RD 2035	PL 426 × PL 419
	E_2	RD 2052 × RD 2508	RD 2592 × RD 2508	BH 946 × RD 2035
		RD 2592 × RD 2052	RD 2052 × RD 2508	RD 2035 × RD 2052
1000-grain weight	E_1	RD 2592 × RD 2508	RD 2592 × RD 2508	BH 946 × PL 426
		RD 2592 × PL 419	RD 2592 × RD 2052	RD 2035 × RD 2052
		RD 2592 ×RD 2052	RD 2052 × RD 2508	DWRB 137 × RD 103
	E_2	DWRUB 64 × RD 2508	RD 2592 × RD 2052	RD 103 × RD 2052
		BH 946 × RD 2508	RD 2592 × RD 2508	DWRUB 64 × RD 2035
		PL 426 × RD 2508	BH 946 × RD 2052	RD 2052 × RD 2508

Table 1. Continued.

Characters	Env	Heterosis	Heterobeltiosis	Inbreeding depression
Grain yield per plant	E_1	RD 103 × RD 2508	PL 419 × RD 2052	DWRUB 64 × RD 2052
		RD 2592 × RD 2035	BH 946 × PL 419	DWRB 137 × RD 2508
		DWRUB 64 × RD 2508	DWRUB 64 × RD 2035	RD 2035 × RD 2508
	E_2	DWRB 137 × RD 2508	PL 419 × RD 2052	RD 2052 × RD 2508
		DWRB 137 × RD 2052	PL 419 × RD 2508	PL 419 × RD 2508
		PL 426 × RD 2052	PL 426 × RD 2035	BH 946 × DWRB 137
Harvest index	E_1	RD 2592 × DWRUB 64	RD 2592 × DWRUB 64	BH 946 × PL 426
		DWRB 137 × PL 419	DWRB 137 × PL 419	DWRUB 64 × RD 2052
		RD 2592 × DWRB 137	RD 2592 × DWRB 137	DWRUB 64 × RD 2508
	E_2	DWRB 137 × RD 2508	PL 426 × RD 103	RD 2035 × RD 2508
		DWRB 137 × RD 2052	DWRUB 64 × RD 2508	RD 2592 × PL 419
		DWRB 137 × PL 419	PL 426 × RD 2035	PL 419 × RD 2508
		DWRB 137 × RD 2052	DWRB 137 × RD 2052	PL 419 × RD 2035

heterobeltiosis at least for six or more yield attributing characters. Whereas, cross PL 419 × RD 2508 in E_2 exhibited desirable heterobeltiosis at least for six or more yield attributing characters.

The Table 2 shows a significant relation between heterosis and heterobeltiosis for grain yield and its contributing characters i.e., crosses which have exhibited desirable heterosis and heterobeltiosis for

Table 2. Best crosses exhibiting high heterosis and heterobeltiosis for grain yield per plant along with desirable (+) heterotic expression for other characters under normal irrigated (E_1) and limited moisture (E_2) conditions.

Particulars	Heterosis					
Environment		E_1			E_2	
Crosses possessing high heterosis and heterobeltiosis for grain yield per plant	RD 103 × RD 2508	RD 2592 × RD 2035	DWRUB 64 × RD 2508	DWRB 137 × RD 2508	DWRB 137 × RD 2052	PL 426 × RD 2052
Days to maturity	+	+	+	-	-	-
Plant height	+	+	-	+	+	-
Number of effective tillers per plant	+	+	-	-	-	-
Flag leaf area	+	+	+	+	+	+
1000-grain weight	+	-	+	+	+	+
Harvest index	+	+	+	+	+	+

Table 2. Continued.

Particulars	Heterobeltiosis					
Environment		E_1			E_2	
Crosses possessing high heterosis and heterobeltiosis for grain yield per plant	PL 419 × RD 2052	BH 946× PL 419	DWRUB 64× RD 2035	PL 419 × RD 2052	PL 419 × RD 2508	PL 426 × RD 2035
Days to maturity	+	+	-	+	+	-
Plant height	+	-	+	+	+	+
Number of effective tillers per plant	-	+	-	+	+	-
Flag leaf area	+	-	+	+	+	-
1000-grain weight	+	-	-	+	+	-
Harvest index	+	-	+	+	+	+

Table 3. Analysis of variance for general and specific combining ability under normal irrigated and limited moisture conditions for yield and its contributing traits.

Characters	Env	Source of variation							
		GCA (df = 9)		SCA (df = 45)		Error (df =108)		GCA/SCA ratio	
		F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2
Days to maturity	E_1	50.44**	25.72**	26.09**	15.57**	0.79	0.87	0.16	0.14
	E_2	98.01**	94.52**	31.88**	26.23**	1.05	0.83	0.26	0.31
Plant height	E_1	183.24**	89.74**	46.24**	38.53**	2.18	17.13	0.34	0.28
	E_2	167.44**	38.26**	62.40**	32.92**	2.09	13.07	0.23	0.11
Effective tillers per plant	E_1	3.40**	4.05**	1.77**	1.90**	0.09	0.16	0.16	0.19
	E_2	2.86**	2.79**	0.67**	0.83**	0.09	0.09	0.40	0.30
Flag leaf area	E_1	25.17**	31.77**	9.96**	14.65**	1.28	1.18	0.23	0.19
	E_2	15.23**	19.80**	5.84**	5.57**	0.90	0.83	0.24	0.33
1000- grain weight	E_1	18.91**	12.94**	8.24**	8.81**	0.44	0.6	0.20	0.13
	E_2	16.00**	13.71**	5.93**	8.29**	0.42	0.51	0.24	0.14
Grain yield per plant	E_1	54.33**	65.11**	4.94**	5.75**	0.35	0.31	0.98	0.99
	E_2	20.48**	25.53**	1.67**	2.37**	0.10	0.14	1.08	0.95
Harvest index	E_1	108.36**	132.86**	18.77**	18.95**	0.89	0.83	0.50	0.61
	E_2	75.76**	87.84**	7.61**	9.70**	0.49	0.79	0.88	0.81

grain yield, also showed desirable heterosis and heterobeltiosis for at least three or more yield attributes. For instance, plant height, flag leaf area, 1000-grain weight and harvest index in both the environments. Hence, heterobeltiosis for various yield component characters might be the result of expression of heterobeltiosis for grain yield. Though, the crosses exhibiting heterotic expressions for grain yield were not heterotic for all the traits. It was also perceived that expression of heterosis and heterobeltiosis was influenced by the environments for most of the characters due to significant G × E interactions. These results are in accordance with earlier reports of Mansour (2016), Ram and Shekhawat (2017), Lal *et al.* (2018b), Parashar *et al.* (2019) and Bouchetat *et al.* (2020) who also reported maximum heterosis for grain yield per plant. Higher grain yield per plant is a desirable character in barley associated with negative magnitude of inbreeding depression. Thirty crosses in E_1 and thirty five crosses in E_2 were inclined towards negative magnitudes, of which four crosses in E_1 and five crosses in E_2 showed negative significant inbreeding depression, which indicated that grain yield per plant in F_2 generation was higher than F_1 generation.

The combining ability analysis in the individual environment showed that the GCA and SCA variances were highly significant for all the studied characters in both the generations (Table 3). The significant differences of both GCA and SCA indicated that both additive and non-additive gene action played vital role in the genetic control of characters under this study. The GCA/SCA variance ratio (predictability ratio) was less than unity in both the environments for most of the traits (except grain yield per plant in F_1 generation of E_2 environment) which clearly showed the preponderance of non-additive gene action for all the traits under investigation while, the characters having predictability ratio more than unity, which indicated the preponderance of additive gene action (Table 3).

The GCA/SCA variance ratio (predictability ratio) was less than unity in both environments for most of the characters (except grain yield per plant in F_1 of E_2) which clearly showed the predominance of non-additive gene action for all the traits under investigation. The results are in accordance with earlier findings of Parashar *et al.* (2019), Lal *et al.* (2018a), Bouchetat and Aissat (2019) and Kumari *et al.* (2020). The GCA/SCA variance ratio (predictability ratio) was more than unity for grain yield per plant in F_1 of E_2 which indicated the preponderance of additive gene action. The results are in accordance with earlier findings of Shendy (2015) and Rathore and Chauhan (2017).

Best three parents and crosses on the basis of *per se* performance, GCA and SCA effects (Table 4). In

Table 4. Best three parents, F_1's and F_2's for their mean values, GCA and SCA effects under normal irrigated (E_1) and limited moisture (E_2) conditions for yield and associated traits.

Characters	Env	High mean		
		Parents	F_1	F_2
Days to maturity	E_1	BH 946	BH 946 × PL 419	PL 419 × RD 103
		RD 2035	PL 419 × RD 2508	BH 946 × RD 2035
		RD 2592	BH 946 × RD 2592	DWRB 137 × RD 2035
	E_2	DWRUB 64	BH 946 × RD 2052	BH 946 × DWRUB 64
		PL 419	RD 2592 × DWRUB 64	RD 2592 × PL 419
		DWRB 137	PL 419 × RD 2052	PL 419 × RD 2052
Plant height	E_1	BH 946	RD 2592 × RD 2508	RD 2592 × RD 2508
		RD 2592	BH 946 × RD 2592	RD 103 × RD 2035
		RD 2052	BH 946 × RD 2052	RD 2035 × RD 2052
	E_2	RD 2035	PL 419 × RD 2508	RD 2052 × RD 2508
		BH 946	RD 2592 × DWRB 137	RD 2592 × DWRB 137
		PL 419	PL 419 × RD 2035	PL 419 × RD 103
Number of effective tillers per plant	E_1	RD 2052	PL 419 × RD 2508	BH 946 × RD 2508
		DWRUB 64	BH 946 × RD 2508	PL 419 × RD 2508
		RD 103	RD 2592 × RD 2508	RD 2052 × RD 2508
	E_2	DWRUB 64	PL 419 × RD 2508	RD 2035 × RD 2508
		RD 2508	RD 2052 × RD 2508	RD 2035 × RD 2052
		DWRB 137	RD 2035 × RD 2508	PL 419 × RD 2508
Flag leaf area	E_1	BH 946	BH 946 × RD 2052	RD 2592 × PL 419
		RD 2052	RD 2592 × PL 419	RD 2052 × RD 2508
		RD 2592	RD 2592 × PL 426	BH 946 × DWRUB 64
	E_2	BH 946	RD 2592 × RD 2508	RD 2592 × RD 2508
		PL 426	BH 946 × RD 2508	BH 946 × RD 2508
		RD 2592	BH 946 × RD 2592	PL 419 × RD 2052
1000-grain weight	E_1	BH 946	RD 2592 × PL 419	DWRUB 64 × RD 2035
		PL 426	BH 946 × RD 2035	RD 2592 × RD 2052
		DWRUB 64	BH 946 × RD 2508	BH 946 × RD 2052
	E_2	DWRUB 64	DWRUB 64 × RD 2508	DWRUB 64 × RD 2035
		PL 426	DWRUB 64 × RD 2035	DWRUB 64 × RD 2052
		RD 2035	PL 426 × RD 2508	DWRUB 64 × RD 2508
Grain yield per plant	E_1	RD 2508	PL 419 × RD 2508	RD 2052 ×RD 2508
		RD 2052	BH 946 × PL 419	RD 2592 × PL 419
		PL 419	RD 103 × RD 2508	DWRUB 64 × RD 2508
	E_2	BH 946	PL 419 × RD 2052	PL 419 × RD 2052
		RD 2052	BH 946 × RD 2052	RD 2592 × PL 419
		PL 419	BH 946 × PL 419	DWRB 137 × RD 2052
Harvest index	E_1	BH 946	RD 2592 × DWRUB 64	RD 2592 × DWRUB 64
		RD 2508	RD 2592 × DWRB 137	DWRB 137 × PL 419
		RD 2592	DWRB 137 × PL 419	DWRUB 64 × RD 2508
	E_2	BH 946	DWRUB 64 × RD 2508	RD 2592 × PL 419
		RD 2052	BH 946 × PL 419	PL 419 × RD 2508
		RD 2508	BH 946 × RD 2052	DWRUB 64 × RD 2508

Table 4. Continued.

Characters	Env	GCA		SCA	
		F_1	F_2	F_1	F_2
Days to maturity	E_1	RD 2052	RD 2592	DWRB 137 × RD 2035	PL 419 × RD 103
		BH 946	BH 946	BH 946 × RD 2592	DWRB 137 × RD 2035
		PL 419	PL 419	PL 426 × RD 103	BH 946 × RD 2035
	E_2	DWRUB 64	BH 946	DWRB 137 × PL 426	DWRB 137 × RD 103
		PL 419	DWRUB 64	RD 2035 × RD 2508	RD 2592 × PL 419
		RD 2592	PL 419	BH 946 × RD 2052	BH 946 × RD 2035

Table 4. Continued.

Characters	Env	GCA F$_1$	GCA F$_2$	SCA F$_1$	SCA F$_2$
Plant height	E$_1$	RD 2592	RD 2592	DWRB 137 × RD 2035	RD 103 × RD 2035
		RD 2052	BH 946	BH 946 × RD 2052	DWRUB 64 × DWRB 137
		BH 946	-	PL 419 × RD 2508	RD 2592 × RD 2508
	E$_2$	PL 419	-	DWRUB 64 × RD 103	RD 2052 × RD 2508
		RD 2592	-	RD 2592 ×DWRB 137	PL 419 × RD 103
		RD 2035	-	RD 2052 × RD 2508	DWRB 137 × PL 426
Number of effective tillers per plant	E$_1$	RD 2508	RD 2508	DWRUB 64 × PL 426	DWRUB 64 × PL 426
		PL 419	DWRUB 64	PL 419 × RD 2508	BH 946 × RD 2508
		RD 2052	RD 2052	DWRB 137 × RD 2035	DWRB 137 × RD 2035
	E$_2$	RD 2508	RD 2508	RD 2592 × RD 2052	RD 2052 × RD 2508
		BH 946	RD 2052	DWRUB 64 × RD 2035	RD 2035 × RD 2508
		RD 2052	DWRUB 64	DWRB 137 × PL 426	RD 2592 × RD 2508
Flag leaf area	E$_1$	BH 946	BH 946	RD 103 × RD 2035	RD 2592 × PL 419
		RD 2052	RD 2052	RD 2592 × PL 426	BH 946 × DWRUB 64
		RD 2592	PL 419	RD 2592 × PL 419	RD 103 × RD 2035
	E$_2$	RD 2508	BH 946	RD 103 × RD 2035	RD 103 × RD 2035
		BH 946	RD 2508	DWRB 137 × RD 2052	DWRB 137 × RD 2052
		RD 2592	RD 2592	RD 2592 × RD 2052	PL 419 × RD 2052
1000-grain weight	E$_1$	BH 946	PL 419	RD 2592 × PL 419	DWRB 137 × PL 426
		PL 419	BH 946	BH 946 × RD 2035	RD 2592 × RD 2052
		DWRUB 64	RD 2052	PL 426 × RD 2035	DWRUB 64 × RD 2035
	E$_2$	DWRUB 64	DWRUB 64	DWRUB 64 × RD 2508	DWRUB 64 × RD 2035
		PL 426	BH 946	DWRUB 64 × RD 2052	DWRB 137 × PL 426
		BH 946	PL 419	PL 426 × RD 2508	DWRUB 64 × RD 2508
Grain yield per plant	E$_1$	RD 2508	RD 2508	RD 103 × RD 2508	DWRUB 64 × RD 2052
		PL 419	RD 2052	RD 2592 × RD 2035	DWRUB 64 × RD 2508
		RD 2052	PL 419	BH 946 × PL 419	RD 2592 × PL 419
	E$_2$	RD 2052	RD 2052	DWRB 137 × RD 2508	DWRB 137 × RD 2508
		PL 419	RD 2508	DWRB 137 × RD 2052	DWRB 137 × RD 2052
		RD 2508	PL 419	DWRUB 64 × RD 2508	RD 2592 × PL 419
Harvest index	E$_1$	RD 2592	RD 2508	RD 2592 × DWRUB 64	DWRB 137 × PL 419
		RD 2508	RD 2592	DWRB 137 × PL 419	RD 2592 × DWRUB 64
		PL 419	PL 419	RD 2592 × DWRB 137	RD 2592 ×RD 103
	E$_2$	RD 2508	RD 2508	DWRB 137 × RD 2508	RD 2035 × RD 2508
		BH 946	RD 2052	BH 946 × RD 103	DWRB 137 × RD 2508
		RD 2052	BH 946	DWRUB 64 × RD 2508	RD 2592 × PL 419

general it was observed that best three parents on the basis of high *per se* performance, have also appeared as a good general combiner in individual environment for various characters. This indicated that GCA effects of parents could reasonably be expected from their *per se* performance. However, good general combiner parents did not have certainly good *per se* performance e.g. RD 2052 in E_1 for days to maturity, PL 419 in E_1 and BH 946 in E_2 for number of effective tillers per plant, PL 419 in E_1 and RD 2508 in E_2 for flag leaf area, RD 2052 in E_1 and PL 419 in both the environments for 1000-grain weight and PL 419 in E_1 for harvest index.

The cross combinations that were significant and good for two or more characters in F_1 of E_1 only (Table 4) were DWRB 137 × RD 2035 for days to maturity, plant height and number of effective tillers per plant; PL 419 × RD 2508 for plant height and number of effective tillers per plant; RD 2592 × PL 419 for flag leaf area and 1000-grain weight, RD 2592 × DWRB 137 for peduncle length and harvest index.

The cross combinations that were significant and good for two or more characters in F_1 of E_2 only (Table 4) were DWRB 137 × PL 426 for days to maturity and number of effective tillers per plant,

Table 5. Best parents possessing high GCA effects along with their *per se* performance for grain yield per plant and significant desirable (+) GCA effects for other characters under normal irrigated (E_1) and limited moisture (E_2) conditions in F_1 and F_2 generation.

Environment	E_1						E_2			
Generation in which exhibited high GCA effects and *per se* performance	F_1			F_2			F_1		F_2	
Best parents based on desirable GCA effects and *per se* performance for grain yield per plant	RD 2508	RD 2052	PL 419	RD 2508	RD 2052	PL 419	RD 2052	PL 419	RD 2052	PL 419
Days to maturity	+	+	+	-	-	+	+	+	+	+
Plant height	+	+	+	-	-	-	+	+	-	-
Number of effective tillers per plant	+	+	+	+	+	+	+	-	+	-
Flag leaf area	+	+	+	+	+	+	-	+	-	-
1000-grain weight	-	-	+	+	+	+	-	+	-	+
Harvest index	+	+	+	+	+	+	+	+	+	+

RD 2592 × RD 2052 for number of effective tillers per plant and flag leaf area, DWRB 137 × RD 2052 for flag leaf area and grain yield per plant, DWRUB 64 × RD 2508 for 1000-grain weight, grain yield per plant and harvest index; DWRB 137 × RD 2508 for grain yield per plant and harvest index.

The cross combinations that were significant and good for two or more characters in F_2 of E_1 only (Table 4) were RD 2592 × PL 419 for flag leaf area and grain yield per plant, PL 419 × RD 103 for days to maturity and biomass per plant, DWRB 137 × RD 2035 for days to maturity and number of effective tillers per plant, RD 103 × RD 2035 for plant height and flag leaf area.

The cross combination that were significant and good for two or more characters in F_2 of E_2 only (Table 4) were RD 2592 × PL 419 for days to maturity, grain yield per plant and harvest index; RD 2052 × RD 2508 for plant height and number of effective tillers per plant, DWRB 137 × PL 426 for plant height and

Table 6. Best crosses possessing high SCA effects along with their *per se* performance for grain yield per plant and significant desirable (+) SCA effects for other characters under normal irrigated (E_1) and limited moisture (E_2) conditions in F_1 and F_2 generation.

Environment	E_1		E_2			
Generation in which exhibited high SCA effects and *per se* performance	F_1		F_1		F_2	
Best crosses based on desirable SCA effects and *per se* performance for grain yield per plant	BH 946× PL 419	RD103 × RD 2508	RD 2592 × PL 419	DWRUB 64 × RD 2508	RD 2592 × PL 419	DWRB 137 × RD 2052
Days to maturity	+	+	+	-	+	-
Plant height	-	-	+	+	-	-
Number of effective tillers per plant	-	+	+	-	-	-
Flag leaf area	-	+	-	-	-	+
Biomass per plant	+	+	+	-	+	+
1000-grain weight	-	-	+	+	+	-
Harvest index	-	+	-	+	+	+

1000-grain weight, RD 2035 × RD 2508 for number of effective tillers per plant and harvest index, DWRB 137 × RD 2052 for flag leaf area and grain yield per plant; DWRB 137 × RD 2508 for grain yield per plant and harvest index.

Appraisal of Table 5 recognized an interesting relation between GCA effects of grain yield per plant and other yield contributing characters. Parents, which exhibit desirable GCA effects for grain yield per plant, also slowed desirable GCA effects for one or more yield attributing characters. The parents RD 2508, RD 2052 and PL 419 in both the generations of both the environments performed as good general combiners for grain yield per plant and some other associated characters. The parents possessing good general combining ability in barley were reported by several researchers such as Madakemohekar *et al.* (2015), Sultan *et al.* (2016) and Parashar *et al.* (2019).

The evaluation of Table 6 established a significant relation between the SCA effect of grain yield per plant and other component characters. The crosses, which exhibited high *per se* performance with desirable SCA effects for grain yield per plant and one or more yield attributing characters and exhibited as good specific cross combinations are as follows: BH 946 × PL 419 and RD 103 × RD 2508 in F_1 of E_1, RD 2592 × PL 419 and DWRUB 64 × RD 2508 in F_1 of E_2, RD 2592 × PL 419 and DWRB 137 × RD 2052 in F_2 of E_2. The parents BH 946, PL 419, RD 2508, RD 2592 and RD 2052 involved in these cross combinations appeared as good general combiners for grain yield per plant and one or more yield associated characters, while the other appeared as poor general combiners. An overall appraisal showed that the crosses DWRUB 64 × RD 2508 and RD 2592 × PL 419 appeared as good cross combinations for grain yield in both the environment.

Conclusively, the extent of heterosis and heterobeltiosis were sufficient for all the characters. The cross DWRUB 64 × RD 2508 in E_1 and DWRB 137 × RD 2052 in E_2 exhibited desirable heterosis for grain yield per plant and its attributing characters. The cross PL 419 × RD 2052 in E_1 and PL 419 × RD 2508 in E_2 environment exhibited desirable heterobeltiosis for grain yield per plant and its attributing characters. Therefore, these crosses may be considered as promising type for material advancement of barley crop under normal and limited moisture condition. Hence, progeny of these crosses may have potential for high grain yield and progeny of heterotic crosses may provide transgressive segregants. Likewise, the degree of heterosis is essential for deciding the direction of future breeding program. On the basis of *per se* performance, SCA effects and heterosis, the cross RD 103 × RD 2508 in E_1 and DWRB 137 × RD 2052 in E_2 environment emerged as good crosses for grain yield per plant and its attributing characters. On the basis of *per se* performance and GCA effects, the parents RD 2508, RD 2052 and PL 419 in both the generations and environments identified as good general combiners for grain yield per plant and some other associated characters. Therefore, these parents may be used in hybridization program for further material advancement in barley yield by developing superior lines. On the basis of *per se* performance and SCA effects, the crosses BH 946 × PL 419 and RD 103 × RD 2508 in F_1 of E_1, RD 2592 × PL 419 and DWRUB 64 × RD 2508 in F_1 of E_2, RD 2592 × PL 419 and DWRB 137 × RD 2052 in F_2 of E_2 were identified as good specific cross combinations for grain yield per plant and some associated traits. These crosses have potential to utilize in multiple crossing program for further improvement in barley genotypes.

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