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Heterosis and mixing effects in Barley (*Hordeum vulgare* L.) for yield and drought related traits

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Abstract
The present investigation was carried out at Banaras Hindu University to study heterosis and mixing abilities for yield-determining traits in barley. The differences among the parents were highly significant for all the traits. The mean squares due to lines and testers were highly significant for all the characters studied. The expression of heterosis varied with the crosses as well yield attributing traits, was appreciable in both nature and magnitude over standard check. For grain yield, the maximum per cent heterosis over standard check was observed in Lakhan×K-551, Lakhan×Geetanjali and Lakhan×Harmal while the crosses RD-2552×K-551 followed by Lakhan×K-551 and Lakhan×Geetanjali showed positive significant heterosis over better parent. For proline content, the top auspicious crosses exhibiting heterobeltiosis were, HUB-113×Harmal, HUB-113×Moroc-9-75 and HUB-113×K-551. High heterosis was also reported for days to 50% flowering, days to maturity, plant height, number of effective tillers and stomatal conductance. High positive and significant gca estimates for grain yield per plant were observed for K-551 followed by Harmal and Azad. Considering specific combining abilities, Lakhan×Geetanjali, Jyoti×Moroc-9-75, Lakhan×K-551, HUB-113×Moroc-9-75 and Jyoti×Azad were some of the engrossing crosses for grain yield per plant.

Keywords: Barley, heterosis, combining abilities, gca and sca effects

Introduction
Barley is an annual cereal grain and fodder crop belonging to the family *Poaceae*, tribe triticeae and genus *Hordeum*, comprising nearly 350 species and it has been cultivated for more than 7000 years. Out of which *Hordeum* consists of about 32 species including the wild and cultivated one. Barley is a diploid with 2n= 14 chromosomes. The cultivated barley (*Hordeum vulgare* ssp. *vulgare*) is one of the oldest of the cultivated plants. Barley is cultivated in India since ancient times and is considered as a sacred grain. hind the demand. The major barley growing states in India are Rajasthan, Uttar Pradesh, Haryana, Punjab, Madhya Pradesh, Uttarakhand, Himachal Pradesh, Bihar, Jammu and Kashmir, West Bengal, Chhatishgarh and Sikkim. Overall India's barley production was estimated to be 1781.4 thousand tons spread over an area of 6.93 lakh ha for the year 2016-17. The average productivity was estimated to be 25.80 q/ha. The top three barley growing states with significant growth in production are Rajasthan (808 thousand tons), Uttar Pradesh (447 thousand tons) and Madhya Pradesh (261.6 thousand tons) (Anonymous, 2017) [3]. The choice of an efficient breeding program depends to a large extent on the knowledge of gene action involved in the expression of the character. The study of genetic conditions of different agricultural plants is one of the essential factors for the success of inbreeding plans. Therefore, it is required that precise and comprehensive information of the genetic parameters controlling the components of yield is collected and used for making decisions on the selection of an appropriate breeding method (Aghamiri *et al*., 2012) [2]. Analysis of combining abilities can provide useful information regarding the selection of capable parents in the hybridization programme, as well as the methods and strength of the effect of genes governing the expression of certain quantitative traits. Such findings on the traits determining crop productivity may be useful in the development of an efficient breeding program. Therefore, in this context, the present investigation was carried out to study heterosis and mixing abilities for yield-determining traits in barley.

Materials and Methods
The present investigation was carried out at the Agriculture Research Farm, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi during the *rabi* season 2015-16 and 2016-17. The experimental materials consisted of 10 parents and 24 F_1s. These F_1s were generated by crossing six lines (as males) and four testers (as females) in L×T fashion during

rabi 2015-16. Then during *rabi* 2016-17, parents and F_1s along with standard check (K-603) were raised by applying recommended management practices during the course of the crop. The data was recorded on various yield and its contributing traits along with drought tolerance related traits viz., days to 50% flowering, days to maturity, number of effective tillers, plant height, spike length, number of grains per spike, 100 grain weight, grain weight per spike, grain yield per plant, stomatal conductance, chlorophyll content and proline content. The statistical analysis comprised of ANOVA, heterosis studies, general and specific combining abilities.

Analysis of variance for Line×Tester was carried out according to procedure given by Kempthorne (1957) [9]. The generalized model to estimate the general and specific combining ability effects of ijkth observations is given below

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

Where,
μ = Population mean
g_i = gca effect of i th male parent
g_j = gca effect of j th female parent
s_{ij} = sca effect of ij th combinations
e_{ijk} = error associated with the observation X_{ijk}
i = number of male parents
j = number of female parents
k = number of replications

The heterosis is expressed as percentage increase or decreases of F_1s over better parent (heterobeltiosis) and check variety (standard heterosis) was also calculated according to the methods suggested by Kempthorne (1957) [9].

Results and Discussion

The experimental materials (24 F_1s along with 6 lines and 4 testers including standard check i.e. K-603) were tested for variance. The data for all the quantitative traits were subjected to analysis of variance (ANOVA). Treatment variations showed highly significant differences for all the characters studied (Table 1). The differences among the parents were highly significant for all the traits. The variance due to parents was further partitioned into variance due to lines (male) and testers (female). The mean squares due to parents vs. crosses component showed significant differences for all the characters studied except for grain weight per spike, proline and grain yield per plant in irrigated condition while it was non-significant only for grain weight per spike under rainfed condition. The mean squares due to lines and testers and due to their interaction were highly significant for all most all the characters studied.

Heterosis

Heterosis was found in all crosses, for all measured barley traits and *per se* performances of F_1s along with lines and testers are represented in Figure 1. A wide range of variation in the heterosis over better parent and standard check was observed (Table 2). Numbers of desired and superior hybrids were found for most of the traits studied. In the present investigations, the expression of heterosis, though varied with the crosses as well yield attributing traits, was appreciable in both nature and magnitude over standard check. For grain yield, the maximum per cent heterosis over standard check was observed in Lakhan×K-551, Lakhan×Geetanjali and Lakhan×Harmal while the crosses RD-2552×K-551 followed by Lakhan×K-551 and Lakhan×Geetanjali showed positive significant heterosis over better parent. The superiority of hybrids particularly over best parent is more useful for commercial exploitation of heterosis and also indicated the parental combinations capable of producing the highest level of transgressive segregants. These observations were also substantiated by earlier reports of several workers, such as, Yin guang *et al*. (2009) [17], Fellahi *et al.* (2013) [5], Saad *et al*. (2013) [15], Potla *et al*. (2013) [14], Said (2014), Zhang *et al.* (2015) [18] and Pesaraklu *et al.* (2016) [13]. The results of present study exhibited that the crosses showing heterosis for grain yield per plant were not heterotic for all the characters (Table 2). The results of present investigation also supported the contentions of Grafius (1959) [6], who had suggested that there could be no separate gene system for yield per se as yield is an end product of the multiplicative interactions between its various component characters. This implied that heterosis in a complex character like yield can be registered by single or several characters. For proline content, the top auspicious crosses exhibiting heterobeltiosis in order of merit were, HUB-113×Harmal, HUB-113×Moroc-9-75 and HUB-113×K-551 whereas, for economic heterosis, the top three spectacular crosses were HUB-113×Harmal, Lakhan×Karan-16 and Lakhan×K-551. Similarly, high heterosis was reported for, days to 50% flowering, days to maturity, plant height, number of effective tillers and stomatal conductance. However, limited desirable heterosis over standard and better parent was found for grain weight per spike, 100-grain weight and chlorophyll content. For these traits, most of the crosses exhibited significant negative heterosis. The other most promising hybrids on the basis of consistent standard heterosis for short plant stature were HUB-113×Karan-16, Lakhan×Azad, Lakhan×Moroc-9-75; for earliness of flowering HUB-113×Harmal, HUB-113×Karan-16 and HUB-113×K-551; for early maturity HUB-113×Harmal, HUB-113×Karan-16 and RD-2552×Geetanjali; for number of effective tillers HUB-113×K-551 and HUB-113×Azad.

Other important characters contributing to yield heterosis over standard check (K-603) were grain weight per spike, 100-grain weight, chlorophyll content, stomatal conductance. For grain weight per spike, almost all the standard heterotic estimates were negative. Anyhow, two crosses *i.e*., RD-2552×Moroc-9-75 and Lakhan×Karan-16 were conspicuous. For 100-grain weight and chlorophyll content, only one cross each *i.e*., Lakhan×Geetanjal and Jyoti×Harmal respectively were significant for standard heterosis. Another important trait which affects grain yield significantly was stomatal conductivity. Low stomatal conductivity is desirable under moisture stress to retain plant water by minimizing transpirational loss while, reverse is true under irrigated condition which enable crops to accumulate more photosynthates. Considering this, RD-2552×Azad, Lakhan×Harmal, RD-2552×Moroc-9-75 were prominent for stomatal conductance. Significant positive heterosis and high *per se* performance for grain yield and its component traits were also reported by earlier workers such as Saini and Prakash (2005) [16], Said (2014), Zhang *et al.* (2015) [18] and Pesaraklu *et al.* (2016) [13].

General combining abilities

The high general combining ability (gca) effects indicates that their contribution in transferring these characters to their hybrids is high and vice versa. The estimates of general combining ability effects of ten divers parents (6 lines + 4 testers) for all the traits are presented in Table 3. For number of effective tillers, spike length, number of grains per spike, 100 grain weight, grain weight per spike, grain yield per plant, chlorophyll content, stomatal conductance and proline content, positive and significant gca effects were considered to be desirable. Whereas, in case of plant height, days to 50% flowering and days to maturity, negative and significant gca effects were considered to be desirable.

General combining abilities are needed to be studied to identify the best parents for deriving desirable transgressive segregants. Combining ability effects also aids in selecting desirable parents and crosses for exploitation in pedigree breeding. The *per se* performances do not necessarily reveal which parents are good or poor combiners. To surmount this difficulty, it is necessary to gather information on the nature of gene actions. General combining ability is attributed to additive type of gene effects, while specific combining ability is attributed to non-additive type of gene actions. Non-additive gene type of actions is not reliably fixable whereas additive type of gene actions or complementary type epistatic gene interactions are reliably fixable. For days to 50% flowering and maturity, plant height negative gca effects, while for other traits positive gca effects are desirable. General combining ability effects for most of the lines and testers were found significant for grain yield per plant.

Among the lines, K-551 was found to be superior general combiner for days to 50% flowering, number of effective tillers, spike length, 100-grain weight, grain weight per spike, stomatal conductance and chlorophyll content and grain yield per plant; Harmal for days to 50% flowering, days to maturity, plant height, chlorophyll content, stomatal conductance, proline content and grain yield per plant; Azad for number of grains per spike, number of effective tillers, stomatal conductance and grain yield per plant (Table 3). Therefore, these genotypes can be potential parents which can contribute in subsequent development of hybrids with increased yield and other concerned characters.

Similarly, among testers, HUB-113 was proved to be a good general combiner for days to maturity, plant height, 100-grain weight, proline content and grain yield per plant; RD-2552 for number of grains per spike, grain weight per spike, 100-grain weight, stomatal conductance and grain yield per plant; Lakhan for for plant height, grain weight per spike, 100-grain weight, chlorophyll content, stomatal conductance, proline content and grain yield per plant.

The parents Azad, K-551, Harmal, HUB-113, RD-2552 and Lakhan might have exhibited some genetic mechanism to thrive well on larger areas through manipulations of various yield components. To synthesize a dynamic population with most of the favorable genes accumulated, it will be pertinent to make use of the aforesaid parents which were good general combiners for several characters, in multiple crossing programmes.

Therefore, in barley breeding programme, aiming to improve the yield and drought tolerance, it might be suggested that, crosses involving Azad, K-551, Harmal, HUB-113, RD-2552 and Lakhan may be expected to yield transgressive segregants in segregating generations. Apart from conventional breeding methods relying solely upon additive or additive x additive type of gene action, population improvement appears to be a promising alternative. The diallel selective mating (Jensen, 1970) [7] is a good technique to delay quick fixation of gene complexes, break linkages, foster recombination, and concentrate favorable genes/gene complexes into the central gene pool by a series of multiple crosses.

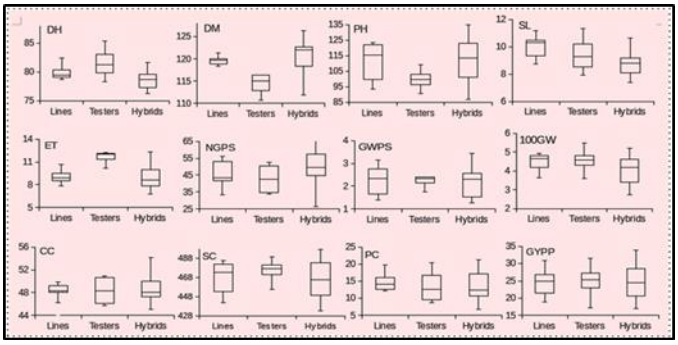

Fig 1: Box plots for performances of parents and crosses for twelve measured traits. The upper and lower lines outside the box stand for max and min value, respectively. The line inside the box stands for median value. The upper and lower hinge of the boxes stand for 75% and 25% percentile, respectively

Specific combining abilities

Specific combining ability (sca) effect is an index to determine the usefulness of a particular cross combination in the exploitation of heterosis. Since yield is a complex trait having low heritability, *per se*, selection for it is generally ambiguous and leads to unpredictable results. Indirect selection by making use of simple inherited traits have been advocated and used for the improvement of yield since time immemorial (Borojevic, 1990) [4]. While selecting the best specific combination for yield, it would be important to give due weightage to yield related traits.

Based on sca effects, the crosses RD-2552×Geetanjali, HUB-113×Karan-16, HUB-113×Harmal and Jyoti×K-551 were outstanding in reaching maturity early (Table 4). Therefore, these crosses possess features which enable them to avoid terminal drought stress during grain filling. For proline content, the trait which is directly correlated to drought tolerance, HUB-113×Moroc-9-75 followed by HUB-113×Harmal and Lakhan×K-551 were promising. As far as the yield is concerned, Lakhan×Geetanjali, Jyoti×Moroc-9-75, Lakhan×K-551, HUB-113×Moroc-9-75 and Jyoti×Azad were proven to be some of the engrossing crosses.

The combining ability effects revealed that the estimates of gca effects were correlated with *per se* performance of parents for most of the traits studied. Breeding potential of a genotype/line to be used as parent in hybridization or of a cross used for a commercial hybrid may be determined by comparing the *per se* performance of the parent, the F_1 value, F_2 performance and combining ability effects. Top three parents, F_1s and best general and specific combiners for 12 quantitative traits under rainfed and irrigated condition are presented in Table 5. It's evident from the table that *per se* performance of the parents may provide a reasonable indication of their gca effects. These outcomes were corroborated by similar reports of Potla *et al*. (2013) [14], Pawar and Singh (2013) [12], Adriana *et al*. (2015) [1], Zhang *et al.* (2015) [18], Mansour and Moustafa (2016) [10], Patial *et al.* (2016) [11] and Pesaraklu *et al.* (2016) [13].

From the results of the general combining ability and per se performance, the parental lines K-551, Harmal, Lakhan, Azad and HUB-113 showed significant gca effects for grain yield and relatively high gca and per se values for other yield components also. It is also observed from the study that the crosses showing high sca for grain yield also manifested high or average sca for other yield components. It is noteworthy that crosses which exhibited high sca effects along with high *per se* performances, also exhibited positive significant heterosis over check. Thus, the results of the present study indicated some relationship between sca effects, *per se* performances and heterosis. It is therefore suggested that sca effects and *per se* performance should be considered as a criterion for selecting the best crosses in barley. The study establish that both the additive (fixable) and non-additive (non-fixable) components of genetic variance were involved in governing the inheritance of almost all the quantitative traits, although predominated by non-additive variance. Therefore, bi-parental mating and/or diallel selective mating, which allows the inter-mating of selected lines in different cycles and exploits both additive and non-additive gene effects could be useful in the genetic improvement of the characters of barley.

Table 1: Analysis of variance for line × tester analysis of yield and drought related traits of barley

Source of Variance	df	Mean Sum of Squares											
		DH	DM	PH	ET	SL	NGPS	GWPS	100 GW	CC	SC	PC	GYPP
Replication	2	2.537	0.07	4.858	0.097	0.078	2.585**	0.039	0.016	0.917	88.642	2.164	1.082
Treatments	33	13.323**	70.025**	486.127**	7.949**	3.585**	335.683**	1.332**	1.535**	17.7**	1015.947**	48.111**	69.399**
Parents	9	20.3**	32.237**	462.891**	7.687**	3.879**	228.521**	1.016**	1.03**	14.816**	857.761**	44.35**	67.01**
Parents vs Crosses	1	112.291**	122.825**	595.057**	20.659**	21.947**	689.091**	-0.002	3.783**	4.35**	228.912**	3.564	0.008
Crosses	23	6.289**	82.516**	490.483**	7.499**	2.672**	362.25**	1.513**	1.635**	19.409**	1112.064**	51.52**	73.35**
Lines	5	2.714**	35.792**	147.761**	9.624**	1.012**	307.865**	1.311**	1.655**	3.973**	1118.841**	38.153**	63.155**
Testers	3	6.681**	120.977**	602.31**	16.017**	2.831**	176.742**	0.948**	2.013**	23.665**	2494.199**	115.03**	101.057**
Line x tester	15	7.403**	90.399**	582.358**	5.087**	3.193**	417.481**	1.694**	1.553**	23.703**	833.378**	43.273**	71.207**
Error	66	0.812	0.685	1.776	0.357	0.211	0.465	0.023	0.012	0.469	29.448	2.446	0.652

* Significant at p= 0.05, ** Significant at p= 0.01

DH = Days to 50% flowering DM = Days to maturity PH = Plant height (cm) ET= Number of effective tillers
SL = Spike length (cm) NGPS = Number of grains per spike GWPS = Grain weight per spike (g) 100GW = 100-grain weight (g)
CC = Chlorophyll content SC = Stomatal conductance (m mol/m^2/s) PC = Proline content (mg/g) GYPP = Grain yield per plant (g)

Table 2a: Estimates of standard heterosis and better parent heterosis for yield and drought related traits of barley

Cross	Days to 50% flowering		Days to maturity		Plant Height (cm)		Spike Length (cm)		No. of grains per spike		No. of effective tillers	
	BPH	SH	BPH	SH	LPH	SH	BPH	SH	BPH	SH	BPH	SH
HUB-113×Azad	0.415	3.863**	7.038**	0.275	11.873**	-17.435**	-34.902**	-25.81**	-14.676**	-8.249**	-3.673	9.271**
HUB-113×K-551	-2.954**	-1.288**	10.264**	3.297**	35.251**	-0.181	-20.132**	-8.978**	14.336**	10.034**	2.112	15.833**
HUB-113×Moroc-9-75	-0.84	1.288**	2.639**	-3.846**	27.05**	-6.233**	-9.706**	2.905	7.713**	3.66**	-8.264**	4.063
HUB-113×Harmal	-4.979**	-1.717**	-6.452**	12.363**	11.873**	-17.435**	-32.814**	-23.43**	-57.688**	-54.173**	-20.202**	-9.479**
HUB-113×Geetanjali	1.674**	4.292**	4.399**	-2.198**	19.094**	-12.105**	-14.608**	-2.682	-8.853**	-12.283**	-32.966**	-23.958**
HUB-113×Karan-16	-2.542**	-1.288**	-4.985**	10.989**	-4.284**	-29.359**	-32.745**	-23.352**	33.199**	28.187**	-31.221**	-21.979**
Jyoti×Azad	-0.851	0.014	10.843**	1.099**	15.275**	2.258**	21.574**	7.039**	-10.969**	-4.263**	-7.563**	3.125
Jyoti×K-551	-1.702**	-0.858	5.422**	-3.846**	-7.739**	-18.157**	0.745	5.810**	7.335**	-12.638**	-36.508**	-29.167**
Jyoti×Moroc-9-75	0.426	1.288**	10.241**	0.549	16.191**	3.071**	-19.147**	-8.939**	-8.174**	-19.512**	-43.137**	-36.563**
Jyoti×Harmal	0.426	1.288**	6.928**	-2.473**	-7.23**	-17.706**	-12.951**	-8.38**	2.98**	11.534**	-30.345**	-22.292**
Jyoti×Geetanjali	-1.277**	-0.429	10.843**	1.099**	28.656**	-2.258**	-17.705**	-15.866**	19.71**	-3.957**	-39.309**	-32.292**
Jyoti×Karan-16	1.702**	2.575**	14.157**	4.121**	27.021**	-0.632	-6.258*	-14.637**	35.57**	-7.829**	-32.866**	-25.104**
RD-2552×Azad	-9.375**	-0.429	4.871**	0.549	33.333**	9.485**	-14.253**	-15.307**	21.789**	30.962**	13.777**	3.229
RD-2552×K-551	0.422	2.146**	6.017**	1.648**	15.732**	-4.968**	-15.426**	-11.173**	-1.266*	0.691	2.067	-7.396**
RD-2552×Moroc-9-75	-2.521**	-0.429	5.444**	1.099**	23.542**	1.445**	-32.738**	-24.246**	8.608**	10.76**	-28.932**	-35.521**
RD-2552×Harmal	-4.132**	-0.429	6.304**	1.923**	22.332**	0.452	-13.694**	-9.162**	-11.681**	-4.344**	2.181	-7.292**
RD-2552×Geetanjali	-0.418	2.146**	-6.017**	-9.89**	8.205**	-17.796**	-22.951**	-21.229**	11.519**	13.729**	4.248	-5.417
RD-2552×Karan-16	1.271**	2.575**	3.438**	-0.824**	7.275**	-16.079**	0.147	-1.084	-15.633**	-13.961**	-19.147**	-19.063**
Lakhan×Azad	-4.858**	0.858	4.871**	0.549	-7.588**	-26.287**	-6.091*	-17.318**	-19.868**	-13.832**	-29.053**	-18.854**
Lakhan×K-551	0.422	2.146**	1.719**	-2.473**	14.156**	-8.943**	-18.298**	-14.19**	-39.889**	-51.075**	-29.781**	-19.688**
Lakhan×Moroc-9-75	2.941**	5.15**	4.585**	0.275	1.699*	-18.88**	-21.131**	-11.173**	31.664**	15.407**	-19.854**	-8.333**
Lakhan×Harmal	-1.24**	2.575**	4.871**	0.549	2.605**	-18.157**	-10.934**	-6.257**	-27.473**	-21.448**	-40.073**	-31.458**
Lakhan×Geetanjali	-1.674**	0.858	4.871**	0.549	28.062**	-2.710**	-25.464**	-23.799**	57.924**	26.702**	-29.053**	-18.854**
Lakhan×Karan-16	1.271**	2.575**	6.877**	2.473**	27.945**	0.090	-3.313	-11.955**	65.979**	9.017**	-37.978**	-29.063**

Table 2b

Cross	Grain weight per spike (g)		100-grain weight (g)		Chlorophyll content		Stomatal Conductance (m mol/m^2/s)		Proline content (mg/g)		Grain yield per plant (g)	
	BPH	SH	BPH	SH	BPH	SH	BPH	SH	BPH	SH	BPH	SH
HUB-113×Azad	-60.007**	-60.589**	-36.357**	-38.762**	5.38**	-5.537**	0.347	3.832**	-28.904**	-38.948**	-14.959**	-6.824**
HUB-113×K-551	37.384**	2.288	-5.108**	-11.661**	0.401	-14.362**	-6.127**	-2.867**	19.942**	-15.32**	-9.049**	-0.349
HUB-113×Moroc-9-75	3.184	-22.496**	-0.578	-10.423**	-9.054**	-16.04**	-9.442**	-6.297**	61.918**	9.489**	-9.651**	-1.008
HUB-113×Harmal	-54.493**	-58.925**	-0.824	-5.928**	-0.912	-10.217**	-11.511**	-8.438**	68.07**	18.181**	-19.206**	-11.477**
HUB-113×Geetanjali	1.676	-24.298**	5.423**	-5.016**	-2.85**	-9.558**	-9.292**	-6.142**	-36.495**	-30.226**	-34.105**	-27.801**
HUB-113×Karan-16	-29.842**	-47.764**	-36.37**	-42.671**	3.979**	-6.78**	-7.876**	-4.677**	-15.051**	-23.439**	-25.788**	-18.689**

Jyoti×Azad	-46.746**	-47.522**	-42.892**	-38.762**	-0.222	-10.559**	-0.44	1.909**	-33.112**	-42.562**	-15.965**	-9.383**
Jyoti×K-551	-34.304**	-53.865**	-37.728**	-33.225**	10.253**	-5.102**	-2.85**	-1.81**	-12.373	-38.135**	-23.25**	-33.695**
Jyoti×Moroc-9-75	1.015	-24.125**	-17.072**	-11.075**	-3.433**	-10.851**	-3.94**	-1.423**	-44.152**	-62.235**	-5.846**	-11.943**
Jyoti×Harmal	-10.33**	-19.064**	-31.713**	-26.775**	14.849**	4.064**	-3.101**	-2.064**	-11.581	-37.826**	-29.149**	-33.463**
Jyoti×Geetanjali	-3.306	-51.334**	-50.425**	-46.84**	-8.378**	-14.704**	-6.746**	-5.748**	-40.606**	-34.743**	-28.636**	-38.348**
Jyoti×Karan-16	35.399**	-31.854**	-25.638**	-20.261**	0.79	-9.639**	-6.683**	-5.684**	-23.831**	-31.352**	-19.614**	-30.554**
RD-2552×Azad	-1.442	-2.877	-1.963*	-5.668**	-8.945**	-14.157**	2.67**	5.093**	-35.012**	-44.194**	-1.906	5.777**
RD-2552×K-551	-12.175**	-34.489**	-2.239*	-8.99**	-5.834**	-11.224**	4.477**	0.099	-30.889**	-40.909**	51.542**	-0.349
RD-2552×Moroc-9-75	42.501**	7.036**	13.836**	1.303	-6.658**	-12.00*	1.489**	4.149**	-35.69**	-45.014**	-22.264**	-27.297**
RD-2552×Harmal	-23.003**	-30.503**	-12.225**	-16.743**	-10.811**	-15.916**	8.352**	3.811**	11.435*	-4.721	14.699**	7.716**
RD-2552×Geetanjali	0.651	-24.922**	-8.609**	-19.088**	-0.956	-6.625**	-4.05**	-4.05**	-24.425**	-16.965**	6.968**	-22.024**
RD-2552×Karan-16	-40.799**	-55.841**	-26.858**	-35.244**	-5.339**	-10.758**	-0.253	-0.085	9.578	-1.241	-8.475**	-26.716**
Lakhan×Azad	-57.263**	-57.886**	-34.123**	-36.612**	-6.246**	-10.913**	-5.45**	-3.219**	-20.287**	-9.67**	-33.981**	-28.81**
Lakhan×K-551	6.157	-23.501**	-10.007**	-16.221**	3.466**	-1.684**	2.188**	2.965**	1.845	15.409**	31.622**	18.302**
Lakhan×Moroc-9-75	5.353	-20.867**	-10.029**	-19.935**	1.635*	-3.424**	-8.12**	-5.712**	-47.673**	-40.704**	-36.866**	-40.954**
Lakhan×Harmal	-50.845**	-55.633**	-25.412**	-29.251**	-7.26**	-11.876**	3.915**	4.705**	-48.217**	-41.32**	16.35**	9.267**
Lakhan×Geetanjali	40.693**	1.386	42.831**	1.889**	-4.12**	-8.893**	-0.259	0.5	-14.349**	-2.941	22.347**	9.965**
Lakhan×Karan-16	45.647**	4.957**	13.201**	-10.619**	-2.041**	-6.917**	-0.426	0.331	4.01	17.863**	-7.248**	-16.634**

Where, SH = Standard Heterosis, BPH= Better Parent Heterosis (Heterobeltiosis), * Significant at p= 0.05, ** Significant at p= 0.01

Table 3: Estimates of general combining ability effects for yield and drought related traits in barley

Trait Parent	Days to 50% flowering	Days to maturity	Plant height (cm)	Spike length (cm)	No. of grains per spike	No. of effective tillers	Grain weight per spike (g)	100 grain weight (g)	Chlorophyll content	Stomatal conductance (m mol/m²/s)	Proline content (mg/g)	Grain yield per plant (g)
Lines												
Azad	-0.097	2.208**	1.366**	-0.104	2.035**	1.542**	-0.375**	-0.495**	-0.521*	15.086**	-2.033**	1.192**
K-551	-0.514*	1.042**	1.282**	0.464**	-5.402**	0.55**	0.101*	0.141**	0.658**	4.169**	0.509	2.851**
Moroc-9-75	0.486*	0.875**	4.866**	0.143	2.771**	-0.408*	0.494**	0.524**	-0.675**	-4.906**	-2.172**	-1.814**
Harmal	-0.597**	-2.292**	-5.051**	-0.001	-7.396**	-0.253	-0.337**	0.031	0.447*	3.728*	1.107*	2.001**
Geetanjali	0.403	-1.708**	0.477	-0.407**	4.563**	-0.519**	0.184**	0.154**	-0.335	-12.189**	0.242	-1.599**
Karan-16	0.319	-0.125	-2.94**	-0.095	3.429**	-0.911**	-0.067	-0.354**	0.427*	-5.889**	2.346**	-2.63**
Std error	±0.217	±0.244	±0.402	±0.138	±0.185	±0.189	±0.047	±0.027	±0.202	±1.433	±0.498	±0.226
Testers												
HUB-113	-0.264	-3.764**	-5.764**	-0.175	-1.386**	1.161**	-0.153**	0.061**	-0.588**	-13.317**	1.655**	0.844**
Jyoti	-0.431	1.569**	4.347**	0.594**	-1.717**	-0.902**	-0.238**	-0.472**	0.816**	-5.611**	-3.348**	-3.513**
RD-2552	-0.208	0.347	5.569**	-0.189	4.696**	0.357	0.222**	0.317**	-1.32**	13.189**	-0.53	1**
Lakhan	0.903**	1.847**	-4.153**	-0.23	-1.593**	-0.617**	0.169**	0.093**	1.092**	5.739**	2.223**	1.67**
Std error	±0.177	±0.200	±0.328	±0.113	±0.151	±0.154	±0.038	±0.022	±0.165	±1.170	±0.407	±0.185

* Significant at P = 0.05, ** Significant at P= 0.01

Table 4: Estimates of specific combining ability effects for yield and drought related traits in barley

Character Cross	Days to 50% flowering	Days to maturity	Plant height (cm)	Spike length (cm)	No. of grains per spike	No. of effective tillers	Grain weight per spike (g)	100 grain weight (g)	Chlorophyll content	Stomatal conductance (m mol/m²/s)	Proline content (mg/g)	Grain yield per plant (g)
HUB-113×Azad	2.431**	3.347**	-5.847**	-1.114**	-3.47**	-0.086	-0.436**	-0.512**	3.138**	22.442**	-2.575**	0.011
HUB-113×K-551	-1.153**	8.181**	15.458**	-0.009	13.409**	1.606**	1.104**	0.239**	-2.775**	1.658	-0.859*	0.209
HUB-113×Moroc-9-75	-0.153	-0.319	4.431**	1.494**	1.944**	1.308**	-0.084*	-0.081**	-2.341**	-5.5**	6.292**	4.684**
HUB-113×Harmal	-1.403**	-7.486**	0.569	-0.981**	-17.756**	-0.292	-0.421**	0.642**	-0.34*	-24.267**	4.58**	-2.13**
HUB-113×Geetanjali	2.264**	4.264**	1.597	1.489**	-8.081**	-1.569**	0.169	0.565**	0.795	2.517	-3.278**	-3.208**
HUB-113×Karan-16	-1.986**	-7.986**	-16.208**	-0.879**	13.953**	-0.967*	-0.332**	-0.853**	1.523**	3.15	-4.16**	0.434
Jyoti×Azad	-0.403	-0.986*	8.264**	1.384**	-1.081**	1.321**	0.068	0.021	-0.959*	5.636	1.777	3.636**
Jyoti×K-551	-0.653	-5.819**	-16.764**	0.693*	2.031**	-1.131**	-0.61**	-0.332**	0.788	-1.047	0.033	-4.989**
Jyoti×Moroc-9-75	0.014	-0.319	5.764**	-0.452	-9.692**	-0.962*	-0.051	0.418**	-0.962*	9.861**	-1.629	5.908**
Jyoti×Harmal	1.097*	-0.819	-9.875**	-0.253	16.508**	0.405	0.942**	0.108	5.916**	-1.806	-0.509	-4.073**
Jyoti×Geetanjali	-1.236**	2.931**	3.597**	-0.591*	-3.45**	-0.395	-0.613**	-1.042**	-3.368**	-3.322	0.911	-1.873**
Jyoti×Karan-16	1.181**	5.014**	9.014**	-0.781**	-4.317**	0.763*	0.263**	0.827**	-1.414**	-9.322**	-0.582	1.391**
RD–2552×Azad	-0.958*	-0.431	15.931**	-0.056	10.698**	0.073	1.039**	0.925**	-0.754	1.903	-1.335	3.467**
RD–2552×K-551	1.458**	2.069**	-1.764*	-0.213	2.502**	-0.069	-0.45**	0.119*	-0.36	-10.814**	-3.284**	0.053
RD–2552×Moroc-9-75	-1.542**	1.569**	2.542**	-1.192**	-0.471	-2.11**	0.488**	0.263**	0.557	17.428**	-1.343	-3.005**

RD–2552×Harmal	-0.458	5.736**	11.236**	0.452	1.896**	0.745	0.115	-0.167**	-2.665**	7.194*	2.639*	3.214**
RD–2552×Geetanjali	0.542	-9.181**	-16.736**	-0.342	-0.729	1.212**	-0.226*	-0.411**	3.1**	-14.089**	1.297	-1.708**
RD–2552×Karan-16	0.958*	0.236	-11.208**	1.35**	-13.896**	0.148	-0.966**	-0.729**	0.121	-1.622	2.026*	-2.022**
Lakhan×Azad	-1.069*	-1.931**	-18.347**	-0.214	-6.147**	-1.308**	-0.671**	-0.434**	-1.425**	-29.981**	2.133*	-7.114**
Lakhan×K-551	0.347	-4.431**	3.069**	-0.472	-17.942**	-0.406	-0.044	-0.026	2.346**	10.203**	4.111**	4.728**
Lakhan×Moroc-9-75	1.681**	-0.931	-12.736**	0.15	8.218**	1.764**	-0.353**	-0.6**	2.746**	-21.789**	-3.32**	-7.588**
Lakhan×Harmal	0.764	2.569**	-1.931*	0.782**	-0.649	-0.858*	-0.637**	-0.583**	-2.91**	18.878**	-6.71**	2.989**
Lakhan×Geetanjali	-1.569**	1.986**	11.542**	-0.556*	12.26**	0.753	0.67**	0.887**	-0.527	14.894**	1.071	6.789**
Lakhan×Karan-16	-0.153	2.736**	18.403**	0.31	4.26**	0.056	1.036**	0.755**	-0.23	7.794**	2.715**	0.197
Std error	±0.433	±0.489	±0.804	±0.276	±0.370	±0.378	±0.093	±0.055	±0.405	±2.867	±0.996	±0.452

Table 5: Top three parents, F_1s, general and specific combiners for yield and drought related traits

Character	**Top 3 parents (*per se*)**	**Top 3 general combiners**	**Top three F_1s (*per se*)**	**Top 3 specific combiners**	**Top 3 F_1s (over standard check)**
Days to 50% flowering	Jyoti Karan-16 K-551	Harmal K-551	HUB-113×Harmal HUB-113×Karan-16 HUB-113×K-551	HUB-113×Karan-16 Lakhan×Geetanjali RD-2552×Moroc-9-75	HUB-113×Harmal HUB-113×Karan-16 HUB-113×K-551
Days to maturity	Jyoti HUB-113 Lakhan	HUB-113 Harmal Geetanjali	HUB-113×Harmal HUB-113×Karan-16 RD–2552×Geetanjali	RD-2552×Geetanjali HUB-113×Karan-16 HUB-113×Harmal	HUB-113×Harmal HUB-113×Karan-16 RD-2552×Geetanjali
Plant height (cm)	HUB-113 Geetanjali Karan-16	HUB-113 Harmal Lakhan	HUB-113×Karan-16 Lakhan×Azad Lakhan×Moroc-9-75	Lakhan×Azad Jyoti×K-551 RD-2552×Geetanjali	HUB-113×Karan-16 Lakhan×Azad Lakhan×Moroc-9-75
Spike length (cm)	HUB-113 Moroc-9-75 Harmal	Jyoti K-551	Jyoti×Azad Jyoti×K-551 HUB-113×Moroc-9-75	HUB-113×Moroc-9-75 HUB-113×Geetanjali Jyoti×Azad	Jyoti×Azad Jyoti×K-551
No. of grains per spike	Harmal Azad RD-2552	RD-2552 Geetanjali Karan-16	RD-2552×Azad HUB-113×Karan-16 Lakhan×Geetanjali	Jyoti×Harmal HUB-113×Karan-16 HUB-113×K-551	RD-2552×Azad HUB-113×Karan-16 Lakhan×Geetanjali
No. of effective tillers	Lakhan HUB-113 Jyoti	Azad HUB-113 K-551	HUB-113×K-551 HUB-113×Azad HUB-113×Moroc-9-75	Lakhan×Moroc-9-75 HUB-113×K-551 Jyoti×Azad	HUB-113×K-551 HUB-113×Azad
Grain weight per spike (g)	Azad Harmal Moroc-9-75	Moroc-9-75 RD-2552 Geetanjali	RD–2552×Moroc-9-75 Lakhan×Karan-16 HUB-113×K-551	HUB-113×K-551 RD-2552×Azad Lakhan×Karan-16	RD-2552×Moroc-9-75 Lakhan×Karan-16
100 grain weight (g)	Jyoti Azad Harmal	Moroc-9-75 RD-2552 Geetanjali	Lakhan×Geetanjali RD-2552×Moroc-9-75 HUB-113×Geetanjali	RD-2552×Azad Lakhan×Geetanjali Jyoti×Karan-16	Lakhan×Geetanjali
Chlorophyll content	Lakhan RD-2552 Geetanjali	Lakhan Jyoti K-551	Jyoti×Harmal Lakhan×K-551 Lakhan×Moroc-9-75	Jyoti×Harmal HUB-113×Azad RD-2552×Geetanjali	Jyoti×Harmal
Stomatal conductance (m mol/m^2/s)	HUB-113 Moroc-9-75 Azad	Azad RD-2552 Lakhan	RD-2552×Azad Lakhan×Harmal RD-2552×Moroc-9-75	HUB-113×Azad Lakhan×Harmal RD-2552×Moroc-9-75	RD-2552×Azad Lakhan×Harmal RD-2552×Moroc-9-75
Proline content (mg/g)	Lakhan Geetanjali Karan-16	Karan-16 Lakhan HUB-113	HUB-113×Harmal Lakhan×Karan-16 Lakhan×K-551	HUB-113×Moroc-9-75 HUB-113×Harmal Lakhan×K-551	HUB-113×Harmal Lakhan×Karan-16 Lakhan×K-551
Grain yield per plant (g)	HUB-113 Azad Harmal	K-551 Harmal Lakhan	Lakhan×K-551 Lakhan×Geetanjali Lakhan×Harmal	Lakhan×Geetanjali Jyoti×Moroc-9-75 Lakhan×K-551	Lakhan×K-551 Lakhan×Geetanjali Lakhan×Harmal

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