

*Full Length Research Paper*

# Heterosis and combining ability of highland adapted maize (*Zea mays. L*) DH lines for desirable agronomic traits

**Zelege Keimeso<sup>1\*</sup>, Demissew Abakemal<sup>1</sup> and Wosene Gebreselassie<sup>2</sup>**

<sup>1</sup>EIAR- Ambo Agriculture Research Center, P. O. Box 37, Ambo, Ethiopia.

<sup>2</sup>College of Agriculture and Veterinary Medicine, Jimma University, P. O. Box 307, Jimma, Ethiopia.

Received 9 August, 2019; Accepted 10 October, 2019

Maize (*Zea mays L.*) is one of the cereals that provide calorie requirements in the majority of Ethiopians diet. The national average maize yield in Ethiopia is low and thus knowledge of combining ability and heterosis is a prerequisite to develop high yielding maize varieties. The objective of the present study is to estimate combining abilities of double haploid (DH) maize inbred lines for grain yield and related agronomic traits, and to identify crosses with higher standard heterosis. A total of 36 diallel crosses generated by crossing nine maize DH lines using half diallel mating scheme and four standard checks were studied for different desirable agronomic traits during 2017 cropping season at Ambo and Kulumsa Agricultural Research Centers. The genotypes were evaluated in alpha lattice design replicated twice in both locations. Analyses of variances showed significant mean squares due to crosses for most traits studied. The highest grain yields were obtained from crosses L1 x L3, L3 x L8, L4 x L8 and L8 x L9. GCA mean squares were significant for all studied traits, while SCA mean squares were significant only for grain yield, days to anthesis, ear per plant and ear diameter. Relatively larger GCA over SCA variances were observed in the current study for most studied traits revealing the predominance of additive gene action in controlling these traits. Of the DH inbred lines, L3 and L8 were the best general combiners for grain yield, and hence are promising parents for hybrid development. Inbred lines L2, L4, L6, L7 and L8 were good combiners for earliness whereas, L1, L2 and L6 showed negative and significant GCA effects for plant and ear height. In this study, none of the crosses showed positive and significant standard heterosis for grain yield.

**Key words:** Combining ability, general combining ability, highland maize, standard heterosis, specific combining ability.

## INTRODUCTION

Currently, maize is one of the most important field crops to fulfill food security in Ethiopia. It contributes the

greatest share of production and consumption along with other major cereal crops, such as tef, wheat and sorghum

\*Corresponding author. E-mail: zelege.keimiso@gmail.com.

**Table 1.** Description of testing sites.

Research center	Altitude (masl)	RF (mm)	Temp (°C)		Latitude	Longitude	Soil type
			Min	Max			
Ambo	2225	1050	10.4	26.3	8°57'N	38°7'E	Black vertisol
Kulumsa	2180	830	10	23.2	8°5'N	39°10'E	Luvisol/eutric nitosols

(CSA, 2017). It has a significant importance in the diets of rural Ethiopia and has gradually penetrated into urban centers. This is particularly evidenced by green maize cobs being sold at road sides throughout the country as a hunger-breaking food available during the months of May to August annually (Twumasi et al., 2012).

The high altitude sub-humid areas including the highland transition and true highland of Ethiopia is next to mid-altitude in maize production. It is estimated that the highland sub-humid agro-ecology covers 20% of the land devoted annually to maize cultivation and 30% of small-scale farmers in the area depend on maize production for their livelihood (Twumasi et al., 2001). In this agro-ecology, maize production is characterized by low yields owing to unimproved varieties coupled with biotic constraints such as turicum leaf blight, common leaf rust, stalk lodging, stalk borers, and storage pests and abiotic stresses such as frost, hailstorm and low soil fertility (Twumasi et al., 2001). Because of these constraints, the highland areas have been facing great challenges in maize production which occasionally lead to food insecurity, malnutrition, reduced income and widespread poverty (Demissew et al., 2014). Therefore, it remains important to develop high yielding, nutritionally enhanced and stress tolerant maize varieties which fit the diverse highland agro-ecology of the country.

Combining ability studies are of primary importance in maize hybrid development since it provides information for the selection of parents, identification of promising hybrids and on the nature and magnitude of gene actions. On the other hand, heterosis occurs when two inbred lines of out bred species are crossed, as much as when crosses are made between pure lines. It is practically exploited to develop hybrid varieties (George, 2007).

Several studies on combining ability and heterosis of maize inbred lines for grain yield and yield related traits were conducted for different sets of locally developed/introduced inbred lines in Ethiopia (Hadji, 2004; Dagne et al., 2010; Demissew et al., 2011; Yoseph et al., 2011; Shushay et al., 2013; Umar et al., 2014; Girma et al., 2015; Beyene, 2016; Tolera et al., 2017; Dufera et al., 2018). However, it is always mandatory for any breeding program to generate such information for any new batch of inbred lines generated locally or received outside of the program. Currently, at Ambo highland maize research program there are a number of new batches of inbred lines generated through different

methods of inbred line development. Little or no information is available on the particular sets of new inbred lines used for this study regarding the combining ability effects of the parental lines to be used for future hybrid development.

The focus of the current study was, therefore to generate information on nine elite maize inbred lines crossed using half diallel mating scheme following Griffing (1956) with the objectives of identifying best inbred lines having good general and specific combining ability effects, and determine the magnitude of standard heterosis for yield and yield related traits for further breeding and/or cultivar development.

## MATERIALS AND METHODS

### Descriptions of experimental sites

The experimental sites used for this experiment were two representative sites of highland sub-humid agro-ecology in Ethiopia, viz., Ambo Agricultural Research Centre (AARC) and Kulumsa Agricultural Research Centers (KARC) (Table 1).

### Experimental materials

Nine inbred lines obtained from Ambo highland maize breeding program were crossed using diallel mating design during the main cropping season of 2016 and thirty-six single cross hybrids were generated. The list of inbred lines and their origin is presented in Table 2. The DH lines used in the crosses were originally obtained from CIMMYT-Zimbabwe and were locally selected based on previous field performances in test-cross evaluations for adaptation, disease reaction and general combining ability by the highland maize breeding program at AARC. The thirty-six F<sub>1</sub> crosses together with four commercial hybrid checks: Arganne, Kolba, Jibat and Wenchi were used in the hybrid trial evaluations in 2017.

### Experimental design trial management and data collection

The 36 F<sub>1</sub> crosses plus the four hybrid commercial checks adapted to the highland agro-ecology of Ethiopia were planted using alpha lattice design (Patterson and Williams, 1976) with two replications each of which have eight blocks with five entries in each of the blocks. Design and randomization of the trials were generated using CIMMYT's Field book software (Bindiganavile et al., 2007).

The trials were hand planted with two seeds per hill, which later thinned to one plant per hill at the 2-4 leaf stage to get a total plant population of 53,333 per hectare. Reliable moisture level of the soil was assured before planting so as to insure good germination and seedling development. Pre-emergence herbicide, Premagram Gold660 at the rate of 5 lt ha<sup>-1</sup>, was applied three days after

**Table 2.** The list of inbred lines used to make the diallel crosses for the study.

Entry	Pedigree	Seed Source
1	(INTA-F2-192-2-1-1-1-B*9/CML505-B)DH-3060-B-B-#	AHMBP*
2	(LPSC7-C7-F64-2-6-2-1-B/CML488)DH-3033-B-B-#	AHMBP*
3	(CML444/CML539)DH-3091-B-B-#	AHMBP*
4	(CML144/CML159)DH-3049-B-B-#	AHMBP*
5	([LZ956441/LZ966205]-B-3-4-4-B-5-B*7-B/DTPWC9-F109-2-6-1-1-B)DH-3001-B-B-#	AHMBP*
6	(CML545/CML505)DH-10-B-#	AHMBP*
7	(CML545/CML505)DH-44-B-#	AHMBP*
8	([CML312/[TUXPSEQ]C1F2/P49-SR]F2-45-3-2-1-BB//INTA-F2-192-2-1-1-1-B*4]-1-5-1-2-1-B*6/CML505)DH-11-B-#	AHMBP*
9	(CML312/CML442)DH-3002-B-B-#	AHMBP*

\*AHMBP = Ambo Highland Maize Breeding Program.

planting of the seeds to control weeds followed by hand weeding at a later stage of crop emergence. Each entry was placed in a one-row plot of 5.25 m long and 0.75 m x 0.25 m apart between and within rows spacing, respectively. The recommended rate of inorganic fertilizers, that is, 150 and 200 kg ha<sup>-1</sup> of DAP and urea, respectively, were used. Urea was applied in two splits, viz., half of it was applied when plants had six to eight leaves, and the remaining half was applied at flag leaf emergence before flowering at both sites. Other standard cultural and agronomic practices were followed in trial management as per recommendations for the areas.

The procedure of data collection followed CIMMYT's manual for managing trials and reporting data (CIMMYT, 1985). Data on grain yield and other important agronomic traits were collected on a plot and sampled plants base. Data collected on a plot basis include: days to 50% anthesis (DA), days to 50% silking (DS), anthesis-silking interval (ASI), grain yield (GY) (t -ha<sup>-1</sup>), thousand kernel weight (TKW) (g). Data collected on plant base include: ear height (EH) (cm), plant height (PH) (cm), ear length (EL) (cm), ear diameter (ED) (cm), number of ears per plant (EPP), number of rows per ear (RPE), number of kernels per row (KPR).

### Statistical analyses

Before data analyses, anthesis-silking interval (ASI) was normalized using  $\ln\sqrt{ASI + 10}$  as suggested by Bolanos and Edmeades (1996). Analysis of variance (ANOVA) per individual and across locations was carried out using PROC MIXED method = type3 procedure in SAS (2003) by considering genotypes as fixed effects and replications and blocks within replications as random effects for individual site analyses. In the combined analyses, environments, replications within environments and blocks within replications and environments were considered as random while genotypes remained as fixed effects following same procedure of Moore and Dixon (2015). Combined analyses were performed for traits that showed significant genotypic differences in the individual location analyses, and after testing homogeneity of error variance using Bartlett's test (Gomez and Gomez, 1984). In the combined analyses, entry and location main effects were tested using entry x location interaction mean squares as error term, while entry x location interaction mean squares were tested against pooled error.

### Combining ability analyses

Combining ability analyses were done for traits that showed

significant differences among genotypes and thus Griffing's Method IV (crosses only) and Model I (fixed) of diallel analyses (Griffing, 1956) was used to estimate combining ability effects and associated standard errors using a modification of the DIALLEL-SAS program (Zhang et al., 2005). The significance of GCA and SCA effects were tested against the respective standard errors of GCA and SCA effects, respectively, using t-test (Griffing, 1956; Singh and Chaudhary, 1985). In the across locations combining ability analyses, the significance of GCA and SCA mean squares were tested using the corresponding interactions with location as error term. The mean squares attributable to all the interactions with locations were tested against pooled error.

The linear mathematical model developed by Griffing (1956) for an observation made on the genotype for Method IV and model I was used as follows:

$$X_{ij} = \mu + g_i + g_j + s_{ij} + \frac{1}{bc} \sum_k \sum_l e_{ijkl}$$

$$\begin{cases} i, j = 1, \dots, p, \\ k = 1, \dots, b, \\ l = 1, \dots, c. \end{cases}$$

Where,  $X_{ij}$  = the value of a character measured on cross of  $i^{\text{th}}$  and  $j^{\text{th}}$  parents;  $\mu$  = Population mean;  $g_i$  ( $g_j$ ) = the general combining ability effects of the  $i^{\text{th}}$  and  $j^{\text{th}}$  parents,  $s_{ij}$  = the specific combining ability effects of the crosses,  $e_{ijkl}$  = is the error effect, p, b and c = number of parents, blocks and sampled plants, respectively.

### Estimation of standard heterosis

Standard heterosis or economic heterosis was calculated for the characters that showed significant differences for genotypes following the method suggested by Falconer and Mackay (1996). This was computed as percentage increase or decrease of the cross performances over the best standard check. Kolba was used as the best standard check.

$$SH (\%) = \frac{(F1 - SV)}{SV} \times 100$$

Where, F1 = Mean value of a cross, SV = Mean value of standard

**Table 3.** Combined analyses of variance for grain yield and yield related traits of 36 diallel crosses and four hybrid checks evaluated at Ambo and Kulumsa.

Trait	Sources of variation						Grand mean	SE(m)	CV(%)
	Loc (DF = 1)	Rep(Loc) (DF = 2)	Blk(Loc,rep) (DF = 28)	Genotype (DF = 39)	Genotype*Loc (DF = 39)	Error (DF =50)			
GY	228.90**	0.57 <sup>ns</sup>	1.20*	4.81**	1.89**	0.62	8.34	±0.56	9.48
DA	739.60**	3.70 <sup>ns</sup>	3.13 <sup>ns</sup>	41.56**	3.40 <sup>ns</sup>	2.62	90.32	±1.14	1.79
DS	288.90**	6.23 <sup>ns</sup>	4.59*	47.64**	3.79 <sup>ns</sup>	2.71	92.25	±1.16	1.78
ASI	0.20**	0.0005 <sup>ns</sup>	0.001 <sup>ns</sup>	0.004**	0.003**	0.0015	1.23	±0.03	3.15
PH	48546.05**	694.08*	226.27 <sup>ns</sup>	951.19**	196.36 <sup>ns</sup>	183.59	214.36	±9.58	6.32
EPP	0.48**	0.008 <sup>ns</sup>	0.03 <sup>ns</sup>	0.08**	0.05 <sup>ns</sup>	0.02	1.42	±0.1	10.85
ED	1.64**	0.17 <sup>ns</sup>	0.03 <sup>ns</sup>	0.11**	0.03**	0.03	4.53	±0.12	3.54
TKW	217378.16 <sup>ns</sup>	828.46 <sup>ns</sup>	1143.64 <sup>ns</sup>	4907.65**	1207.44 <sup>ns</sup>	1436.51	343.41	±26.8	11.04

\*\*Significant at 0.01 level of probability; \* = significant at 0.05 level of probability; ns = non-significant; Loc= location; Rep= replication; Blk= block; DF= degrees of freedom; SE(m)= standard error of mean; GY= grain yield; DA= number of days to anthesis; DS= number of days to silking; ASI= anthesis silking interval; PH= plant height; EPP= number of ears per plant; ED= ear diameter and TKWT =1000-kernel weight.

check, SH= Standard heterosis expressed as percentage. Variety test of significance for percent heterosis was made using the t-test. The standard errors of the difference for heterosis and t-value were computed as follows (Singh, 1985).

$$t \text{ (standard cross)} = \frac{F1-SV}{SE(d)}$$

$$SE(d) \text{ for SH} = \sqrt{2MSe/r}$$

Where, SE (d) = standard error of the difference, SH= standard heterosis, Me = error mean square, r = number of replications. The computed t value was tested against the t tabular-value at error degree of freedom .

## RESULTS AND DISCUSSION

### Analyses of variance (ANOVA)

Combined analyses of variances revealed highly significant ( $P < 0.01$ ) differences among the 40 genotypes including checks for all traits studied under combined analyses (Table 3). This indicates the presence of inherent variation among the materials, which makes selection possible. Desirable genes from these genotypes can effectively be utilized to develop high performing hybrids. Similarly, several previous studies reported significant differences among genotypes for grain yield and yield related traits in different sets of maize genotypes (Dagne et al., 2007; Demissew, 2014; Habtamu et al., 2015; Amare et al., 2016; Tolera et al., and Dufera et al., 2018).

The interaction between genotypes and locations (G x LOC) was significant for grain yield, Anthesis-silking interval and ear diameter, indicating that genotypes

performed differently across locations, which means that the relative performances of the genotypes were influenced by the varying environmental conditions for these traits. On the other hand, days to anthesis, days to silking, plant height, number of ears per plant and thousand kernel weight showed non-significant difference for genotype by location interaction (Table 2), indicating that the relative performance of the genotypes for these traits was not influenced by the varying environmental conditions. Consistent with the present finding, Gudeta (2007) reported significant G x LOC interaction for grain yield, number of rows per ear and ear diameter and non-significant G x LOC interaction for number of ears per plant.

### Genotypes performances

The combined means from across locations' analyses are given in Table 3. Overall mean grain yield of the genotypes was 8.34 t/ha with a range of 6.16 t/ha to 11.07 t/ha. Kolba (11.07 t/ha) followed by Jibat (10.91 t/ha), Wenchi (10.43 t/ha) and Argane (10.15t/ha) had higher grain yield, while crosses L5 x L9 (6.16 t/ha) and L2 x L9 (6.74 t/ha) showed lower grain yield. The high heritability value (0.64) for this trait indicated more contributions of genetic factors rather than environmental effects on this trait, implying selection for this character could be more effective. In line with this, Dagne et al. (2010), Amare et al. (2016); Beyene (2016), Dufera et al. (2018) also identified genotypes that performed better than the checks used in their studies for grain yield.

Days to anthesis ranged from 84.25 days (L4 x L6) to 102 days (L5 x L9) with overall mean of 90.33 days. Mean number of days to silking was 92.26 with a range of 85.5 (L4 x L6) to 103.5 (L5 x L9). Most of the crosses

showed longest number of days to anthesis and silking. This shows that those crosses could be grouped as late maturing types. Late maturing crosses are important in the breeding programs for development of high yielding hybrids in areas that receive sufficient rain fall (Girma et al., 2015). The heritability values for both days to anthesis and silking were very high (0.92 and 0.93 respectively) indicating the traits were not greatly influenced by environment. Thus, it shows selection for these traits could be more effective and easy since the genetic variability was detected clearly because of low environmental influence (Table 4). Anthesis-silking interval ranged from 1.14 days (L2 x L8) to 1.29 days (L4 x L5) with a mean of 1.23 days (Table 4). In general, all crosses exhibited short ASI or short gaps between anthesis and silking days which is a desired character for good seed setting. The positive ASI observed for all of the genotypes studied is an expected result as maize is a protoandrous plant in which anthesis normally begins 1-3 days before silk emergence (Rahman et al., 2013).

Plant height ranged from 185.25 cm (L2 x L6) to 251.25 cm (Kolba) with a mean of 214.37 cm. Genotypes with shorter plant height could be used as sources of genes for the development of shorter statured varieties for highland agro-ecology of Ethiopia. In agreement with this result, Beyene (2016), Abiy (2017) and Tolera et al. (2017) also identified genotypes with short and long plant and ear heights. Mean number of ears per plant of genotypes was 1.42 ranged from 1.18 (L1 x L7) to 1.74 (L1 x L3). Seven crosses exhibited higher number of ears per plant than the best check, Kolba (Table 4). Desirability of higher number of ears for grain yield improvement was suggested by various authors such as Dagne et al. (2010), Demissew et al. (2011), Girma et al. (2015), Ram et al. (2015), Amare et al. (2016).

The mean for ear diameter ranged from 4.05 to 5.05 cm with overall mean of 4.53 cm. The cross L3 x L9 (4.05 cm) had the smallest diameter as compared to other hybrids, while cross L4 x L8 (5.05 cm) displayed the largest ear diameter. The crosses with wider ear diameter could be used for grain yield improvement since increasing ear diameter could lead to increase in number of rows per ear. Thousand kernel weight ranged from 214.18 g for (L3 x L9) to 410.9 g for (Jibat) with overall mean of 343.41 g.

### Standard heterosis

The estimate of standard heterosis over the best standard check (Kolba) was computed for grain yield and yield related traits that showed significant differences among genotypes and the result is presented in Table 5. Standard heterosis for grain yield over the best check Kolba ranged from -44.35% (L5 x L9) to -8.31% (L1 x L3). Out of the 36 hybrids studied, none of the hybrids had positive and significant as well as negative and significant

heterosis over the standard check Kolba (Table 5). All hybrids exhibited non-significant and negative standard heterosis over the best standard check Kolba. This indicates that the check hybrid Kolba was more prolific than all the F1 hybrids and indicating lack of significant heterosis among the crosses used in the current study. The highest negative standard heterosis was manifested by L5 x L9 (-44.35 %) followed by L2 x L9 (-39.11 %) and L1 x L7 (-36.49 %) over Kolba for grain yield. Positive standard heterosis was considered to be desirable for grain yield as it indicates increased yield over the existing standard check. In contrast to this finding, several other authors reported positive and significant heterosis for grain yield over best standard check indicating the possibility of increasing yield by exploiting heterotic potential of maize genotypes (Tiwari, 2003; Twumasi et al., 2003; Amiruzzaman et al., 2010; Wali et al., 2010; Habtamu et al., 2015; Ziggiju and Legesse, 2016; Dufera et al., 2018).

Negative standard heterosis was considered as desirable for days to anthesis and silking as it indicates earliness of a genotype and the reverse is true for the crosses with positive and significant standard heterosis. Standard heterosis over best check Kolba ranged from -3.71 to 16.57% and -5.00 to 15.00%, respectively, for days to anthesis and silking which was revealed by crosses (L4 x L6) and (L5 x L9), respectively, for both traits. Out of the 36 hybrids studied, ten crosses exhibited negative and non-significant standard heterosis for days to anthesis, while twenty of the hybrids showed significant heterosis and the rest six hybrids exhibited positive and non-significant heterosis for days to anthesis in undesired direction. For days to silking, out of 36 hybrids, twelve crosses revealed negative heterosis, while only two crosses (L4 x L6) and (L6 x L8) revealed significant heterosis in desired direction over best standard check. Twenty four crosses showed positive heterosis over best standard check. Among them, seventeen of the crosses revealed significant heterosis in undesired direction. Negative heterosis for these traits indicated earliness as compared to the standard check (Kolba). Similar to this study, Natol et al. (2017) also reported negative and non-significant, and positive and significant heterosis for days to anthesis and silking in their study on standard heterosis of maize inbred lines for grain yield and yield related traits at southern Ethiopia. In addition, previous investigators reported significant negative and positive standard heterosis for days to anthesis and silking over standard check (Bayisa, 2004; Mahantesh, 2006; Shushay, 2014; Ziggiju and Legesse, 2016; Abiy, 2017).

For anthesis silking interval, standard heterosis ranged from -9.52 % (L2 x L8) to 2.38 % (L4 x L5) over Kolba. Almost all crosses showed negative standard heterosis over the best check for anthesis silking interval, indicating the tendency of the crosses to have short interval between anthesis and silking dates than Kolba, which is

**Table 4.** Mean values of yield and yield related traits of 36 diallel crosses and four commercial checks evaluated at Ambo and Kulumsa in 2017.

Genotype	Traits							
	GY	DA	DS	ASI	PH	EPP	ED	TKW
L1*L2	8.80	87.25	88.50	1.21	199.75	1.37	4.53	379.10
L1*L3	10.05	91.75	94.50	1.27	210.75	1.74	4.50	306.48
L1*L4	7.87	88.00	90.25	1.25	198.00	1.22	4.88	363.33
L1*L5	9.03	92.75	95.25	1.26	228.75	1.38	4.58	335.78
L1*L6	7.09	87.00	89.50	1.26	187.50	1.20	4.53	377.33
L1*L7	7.03	88.50	90.50	1.24	192.00	1.18	4.43	358.48
L1*L8	8.25	88.00	89.50	1.21	207.75	1.29	4.83	370.28
L1*L9	7.49	92.75	95.50	1.27	218.75	1.31	4.70	326.03
L2*L3	8.96	91.00	93.25	1.25	219.25	1.62	4.35	329.10
L2*L4	8.85	86.75	88.50	1.23	205.50	1.44	4.60	343.85
L2*L5	7.48	92.75	94.75	1.24	216.75	1.23	4.45	357.15
L2*L6	7.44	86.25	87.25	1.19	185.25	1.48	4.35	350.35
L2*L7	9.06	88.50	90.00	1.22	209.00	1.54	4.40	378.85
L2*L8	8.07	88.50	88.50	1.14	202.25	1.27	4.65	381.90
L2*L9	6.74	94.75	96.00	1.21	212.75	1.41	4.40	276.68
L3*L4	8.55	91.75	94.25	1.26	232.50	1.39	4.48	313.25
L3*L5	8.00	96.00	98.25	1.25	237.50	1.44	4.40	290.83
L3*L6	8.75	91.25	92.75	1.22	199.00	1.66	4.33	330.23
L3*L7	7.41	92.00	94.75	1.27	219.50	1.47	4.25	306.90
L3*L8	9.68	92.50	95.50	1.28	224.25	1.71	4.43	328.65
L3*L9	7.34	98.75	100.50	1.23	226.00	1.63	4.05	214.18
L4*L5	8.03	90.50	93.75	1.29	204.50	1.37	4.43	316.20
L4*L6	7.54	84.25	85.50	1.21	194.50	1.23	4.58	312.90
L4*L7	8.78	86.75	89.50	1.27	207.00	1.36	4.75	384.00
L4*L8	9.41	86.50	87.00	1.17	228.50	1.30	5.05	378.73
L4*L9	7.59	91.25	93.50	1.25	213.25	1.41	4.58	312.10
L5*L6	7.29	91.00	92.25	1.21	208.75	1.36	4.48	359.75
L5*L7	7.54	93.50	96.00	1.26	232.25	1.29	4.63	334.38
L5*L8	8.13	93.00	95.00	1.24	240.25	1.49	4.73	308.53
L5*L9	6.16	102.00	103.50	1.22	224.00	1.30	4.58	274.20
L6*L7	7.18	86.25	87.50	1.21	188.25	1.25	4.45	405.68
L6*L8	8.01	85.75	86.25	1.17	191.75	1.42	4.63	399.95
L6*L9	7.62	92.50	94.75	1.25	200.75	1.59	4.43	327.28
L7*L8	8.23	86.50	89.00	1.26	198.25	1.26	4.65	389.18
L7*L9	8.42	92.25	94.75	1.26	226.00	1.55	4.40	327.98
L8*L9	9.26	91.75	93.25	1.22	235.50	1.63	4.70	301.28
Argane	10.15	87.75	89.50	1.23	222.50	1.48	4.50	383.55
Kolba	11.07	87.50	90.00	1.26	251.25	1.57	4.55	408.03
Jibat	10.91	88.75	90.00	1.19	239.75	1.55	4.55	410.90
Wenchi	10.43	88.50	91.50	1.28	235.00	1.54	4.50	383.18
Mean	8.34	90.33	92.26	1.23	214.37	1.42	4.53	343.41
LSD <sub>(0.05)</sub>	1.12	2.30	2.34	0.055	19.24	0.22	0.23	53.83
CV (%)	9.48	1.79	1.78	3.15	6.32	10.9	3.54	11.04
R <sup>2</sup>	0.95	0.96	0.96	0.88	0.92	0.86	0.88	0.89
H <sup>2</sup>	0.64	0.92	0.93	0.12	0.81	0.37	0.76	0.81
Min	6.16	84.25	85.5	1.14	185.25	1.18	4.05	214.18
Max	11.07	102	103.5	1.29	251.25	1.74	5.05	410.9

GY= grain yield; DA= number of days to anthesis; DS= number of days to silking; ASI= anthesis silking interval; PH= plant height; EH= ear height; EPP= number of ears per plant; EL= ear length; ED= ear diameter; RPE= number of kernel rows per ear; KPR= number of kernels per row; and TKWT =1000-kernel weight; R<sup>2</sup> = Coefficient of determination; H<sup>2</sup>= heritability in broad sense; Min= minimum; Max= maximum.

desirable for synchronization of anthesis and silking, and for seed setting. In line with this study, Dufera et al. (2018) reported negative standard heterosis over best checks in their study on combining ability, heterosis and heterotic grouping of quality protein maize inbred lines at bako, western Ethiopia. The magnitude of standard heterosis for plant height ranged from -26.27 % (L2 x L6) to -4.38 (L5 x L8) (Table 4). For this trait, all of the crosses showed negative and non-significant heterosis over the best check. This implies that all crosses were shorter in plant height than kolba, which is favorable trait for lodging resistance. This result is in agreement with the findings of Shushay (2014).

For number of ears per plant, standard heterosis among hybrids varied from -24.84 (L1 x L7) to 10.83 % (L1 x L3). Seven hybrids showed positive standard heterosis over the check kolba. This result indicated the prolificacy of the new hybrids over the standard check, Kolba. The rest 29 crosses showed negative standard heterosis over best check and are undesirable for high number of ear per plant. Similarly significant positive and negative standard heterosis was observed by Koppad (2007), Shushay (2014) and Ziggiju and Legesse, 2016 for number of ears per plant.

Standard heterosis for ear diameter varied between -10.99 (L3 x L9) and 10.99 % (L4 x L8) over kolba (Table 5). Sixteen crosses showed positive heterosis over best standard check. Among them only one cross (L4 x L8) showed significant and positive standard heterosis over kolba. Among twenty crosses those showed negative standard heterosis, only one hybrid (L3 x L9) had negative and significant standard heterosis over Kolba for ear diameter. Positive standard heterosis shows that the F1 crosses had larger ear diameter than the standard check which is important to increase number of kernel rows per ear and thus important to increase grain yield while negative heterosis depicts that the check hybrids had larger ear diameter than the F1 hybrids. Similar result was previously reported by Beyene (2016). Standard heterosis for thousand kernel weight varied from -47.51 (L3 x L9) to -0.58 % (L6 x L7). All of the crosses showed negative and non-significant standard heterosis over the standard check Kolba (Table 5). Similar to the current study, both desirable and undesirable heterosis for thousand kernel weight in maize has been reported by previous investigators (Amiruzzaman et al., 2010; Shushay, 2014).

### Combining ability analyses

Combining ability analysis across the two locations is presented in Table 6. The results showed that mean squares due to GCA and SCA were significant for grain yield, days to anthesis, number of ears per plant and ear diameter. This indicates that both additive and non-additive gene actions are important in the inheritance of

these traits. Reports on similar studies by Dagne et al. (2007) showed that both GCA and SCA mean squares were significant for ear height, plant height and days to maturity. Similarly, Yoseph et al. (2011) observed significant GCA and SCA for anthesis date, anthesis silking interval, ear height and plant height in elite maize inbred lines developed by CIMMYT for insect resistance. The contribution of GCA variances was much greater than that of SCA variances for most of the traits except for grain yield at Kulumsa and across locations, number of ears per plant at Ambo and anthesis silking interval at both Ambo and Kulumsa, which showed higher contribution of SCA variance for these traits at these particular locations. The higher percentage relative contribution of GCA sum of squares over SCA sum of squares showed the predominant role of additive gene action over non-additive gene action in the inheritance of the traits studied. The breeding implication of this predominance of additive gene action is that the genotypes having this character can be used to develop hybrid and/or synthetic varieties. Similar results were reported by other authors in their study on combining ability for yield and yield related traits in maize (Chandel and Mankotia, 2014; Amare et al., 2016; Beyene, 2016; Bitew et al., 2017 and Tolera et al., 2017). They reported predominance of additive gene action over non-additive for most of the traits they studied.

GCA and SCA mean squares were significant for grain yield across the two locations. This significant GCA and SCA mean squares indicated the importance of both additive and non-additive gene actions in governing grain yield. This has breeding implications, since hybridization methods such as reciprocal recurrent selection which utilizes both additive and non-additive gene effects simultaneously, could be useful in genetic improvement of the population characters under consideration. Similar to the present study Hadji (2004) found highly significant mean squares due to GCA and SCA for grain yield in diallel study of quality protein maize inbred lines. In addition, Dagne et al., 2011; Demissew et al., 2011; Shushay et al., 2013 and Bitew et al., 2017 also reported the importance of both additive and non-additive gene actions in governing grain yield in maize.

For number of days to anthesis and silking, mean squares due to GCA were significant at across the two locations. Mean square due to SCA was significant for days to anthesis but for days to silking, mean square due to SCA was non-significant. In agreement with this study, Tolera et al. (2017) found the importance of both additive and non-additive gene effects for days to anthesis. GCA sum of squares were larger than SCA sum of squares for anthesis and silking dates. In line with this study, Ahmad and Saleem (2003) reported the preponderance of additive gene action in the inheritance of days to anthesis and silking.

For plant height, mean squares due to GCA were highly significant ( $p < 0.01$ ). While it showed non-significant



**Table 5.** Standard heterosis of F1 hybrids over Kolba for grain yield and related traits evaluated at Kulumsa and Ambo in 2017.

Crosses	GY	DA	DS	ASI	PH	EPP	ED	TKW
L1*L2	-20.51 <sup>ns</sup>	-0.29 <sup>ns</sup>	-1.67 <sup>ns</sup>	-3.97 <sup>ns</sup>	-20.5 <sup>ns</sup>	-12.74 <sup>ns</sup>	-0.44 <sup>ns</sup>	-7.09 <sup>ns</sup>
L1*L3	-8.31 <sup>ns</sup>	4.86*	5.00**	0.79 <sup>ns</sup>	-16.12 <sup>ns</sup>	10.83 <sup>ns</sup>	-1.10 <sup>ns</sup>	-24.89 <sup>ns</sup>
L1*L4	-28.91 <sup>ns</sup>	0.57 <sup>ns</sup>	0.28 <sup>ns</sup>	-0.79 <sup>ns</sup>	-21.19 <sup>ns</sup>	-22.29 <sup>ns</sup>	7.25 <sup>ns</sup>	-10.96 <sup>ns</sup>
L1*L5	-18.43 <sup>ns</sup>	6.00**	5.83**	0.00 <sup>ns</sup>	-8.96 <sup>ns</sup>	-12.10 <sup>ns</sup>	0.66 <sup>ns</sup>	-17.71 <sup>ns</sup>
L1*L6	-35.95 <sup>ns</sup>	-0.57 <sup>ns</sup>	-0.56 <sup>ns</sup>	0.00 <sup>ns</sup>	-25.37 <sup>ns</sup>	-23.57 <sup>ns</sup>	-0.44 <sup>ns</sup>	-7.52 <sup>ns</sup>
L1*L7	-36.49 <sup>ns</sup>	1.14 <sup>ns</sup>	0.56 <sup>ns</sup>	-1.59 <sup>ns</sup>	-23.58 <sup>ns</sup>	-24.84 <sup>ns</sup>	-2.64 <sup>ns</sup>	-12.14 <sup>ns</sup>
L1*L8	-25.47 <sup>ns</sup>	0.57 <sup>ns</sup>	-0.56 <sup>ns</sup>	-3.97 <sup>ns</sup>	-17.31 <sup>ns</sup>	-17.83 <sup>ns</sup>	6.15 <sup>ns</sup>	-9.25 <sup>ns</sup>
L1*L9	-32.34 <sup>ns</sup>	6.00**	6.11**	0.79 <sup>ns</sup>	-12.94 <sup>ns</sup>	-16.56 <sup>ns</sup>	3.30 <sup>ns</sup>	-20.10 <sup>ns</sup>
L2*L3	-19.06 <sup>ns</sup>	4.00*	3.61 <sup>ns</sup>	-0.79 <sup>ns</sup>	-12.74 <sup>ns</sup>	3.18 <sup>ns</sup>	-4.40 <sup>ns</sup>	-19.34 <sup>ns</sup>
L2*L4	-20.05 <sup>ns</sup>	-0.86 <sup>ns</sup>	-1.67 <sup>ns</sup>	-2.38 <sup>ns</sup>	-18.21 <sup>ns</sup>	-8.28 <sup>ns</sup>	1.10 <sup>ns</sup>	-15.73 <sup>ns</sup>
L2*L5	-32.43 <sup>ns</sup>	6.00**	5.28**	-1.59 <sup>ns</sup>	-13.73 <sup>ns</sup>	-21.66 <sup>ns</sup>	-2.20 <sup>ns</sup>	-12.47 <sup>ns</sup>
L2*L6	-32.79 <sup>ns</sup>	-1.43 <sup>ns</sup>	-3.06 <sup>ns</sup>	-5.56 <sup>ns</sup>	-26.27 <sup>ns</sup>	-5.73 <sup>ns</sup>	-4.40 <sup>ns</sup>	-14.14 <sup>ns</sup>
L2*L7	-18.16 <sup>ns</sup>	1.14 <sup>ns</sup>	0.00 <sup>ns</sup>	-3.17 <sup>ns</sup>	-16.82 <sup>ns</sup>	-1.91 <sup>ns</sup>	-3.30 <sup>ns</sup>	-7.15 <sup>ns</sup>
L2*L8	-27.10 <sup>ns</sup>	1.14 <sup>ns</sup>	-1.67 <sup>ns</sup>	-9.52 <sup>ns</sup>	-19.50 <sup>ns</sup>	-19.11 <sup>ns</sup>	2.20 <sup>ns</sup>	-6.40 <sup>ns</sup>
L2*L9	-39.11 <sup>ns</sup>	8.29**	6.67**	-3.97 <sup>ns</sup>	-15.32 <sup>ns</sup>	-10.19 <sup>ns</sup>	-3.30 <sup>ns</sup>	-32.19 <sup>ns</sup>
L3*L4	-22.76 <sup>ns</sup>	4.86*	4.72*	0.00 <sup>ns</sup>	-7.46 <sup>ns</sup>	-11.46 <sup>ns</sup>	-1.54 <sup>ns</sup>	-23.23 <sup>ns</sup>
L3*L5	-27.73 <sup>ns</sup>	9.71**	9.17**	-0.79 <sup>ns</sup>	-5.47 <sup>ns</sup>	-8.28 <sup>ns</sup>	-3.30 <sup>ns</sup>	-28.72 <sup>ns</sup>
L3*L6	-20.96 <sup>ns</sup>	4.29*	3.06 <sup>ns</sup>	-3.17 <sup>ns</sup>	-20.80 <sup>ns</sup>	5.73 <sup>ns</sup>	-4.84 <sup>ns</sup>	-19.07 <sup>ns</sup>
L3*L7	-33.06 <sup>ns</sup>	5.14**	5.28**	0.79 <sup>ns</sup>	-12.64 <sup>ns</sup>	-6.37 <sup>ns</sup>	-6.59 <sup>ns</sup>	-24.78 <sup>ns</sup>
L3*L8	-12.56 <sup>ns</sup>	5.71**	6.11**	1.59 <sup>ns</sup>	-10.75 <sup>ns</sup>	8.92 <sup>ns</sup>	-2.64 <sup>ns</sup>	-19.45 <sup>ns</sup>
L3*L9	-33.69 <sup>ns</sup>	12.86**	11.67**	-2.38 <sup>ns</sup>	-10.05 <sup>ns</sup>	3.82 <sup>ns</sup>	-10.99**	-47.51 <sup>ns</sup>
L4*L5	-27.46 <sup>ns</sup>	3.43 <sup>ns</sup>	4.17*	2.38 <sup>ns</sup>	-18.61 <sup>ns</sup>	-12.74 <sup>ns</sup>	-2.64 <sup>ns</sup>	-22.51 <sup>ns</sup>
L4*L6	-31.89 <sup>ns</sup>	-3.71 <sup>ns</sup>	-5.00**	-3.97 <sup>ns</sup>	-22.59 <sup>ns</sup>	-21.66 <sup>ns</sup>	0.66 <sup>ns</sup>	-23.31 <sup>ns</sup>
L4*L7	-20.69 <sup>ns</sup>	-0.86 <sup>ns</sup>	-0.56 <sup>ns</sup>	0.79 <sup>ns</sup>	-17.61 <sup>ns</sup>	-13.38 <sup>ns</sup>	4.40 <sup>ns</sup>	-5.89 <sup>ns</sup>
L4*L8	-15.00 <sup>ns</sup>	-1.14 <sup>ns</sup>	-3.33 <sup>ns</sup>	-7.14 <sup>ns</sup>	-9.05 <sup>ns</sup>	-17.20 <sup>ns</sup>	10.99**	-7.18 <sup>ns</sup>
L4*L9	-31.44 <sup>ns</sup>	4.29*	3.89*	-0.79 <sup>ns</sup>	-15.12 <sup>ns</sup>	-10.19 <sup>ns</sup>	0.66 <sup>ns</sup>	-23.51 <sup>ns</sup>
L5*L6	-34.15 <sup>ns</sup>	4.00*	2.50 <sup>ns</sup>	-3.97 <sup>ns</sup>	-16.92 <sup>ns</sup>	-13.38 <sup>ns</sup>	-1.54 <sup>ns</sup>	-11.83 <sup>ns</sup>
L5*L7	-31.89 <sup>ns</sup>	6.86**	6.67**	0.00 <sup>ns</sup>	-7.56 <sup>ns</sup>	-17.83 <sup>ns</sup>	1.76 <sup>ns</sup>	-18.05 <sup>ns</sup>
L5*L8	-26.56 <sup>ns</sup>	6.29**	5.56**	-1.59 <sup>ns</sup>	-4.38 <sup>ns</sup>	-5.10 <sup>ns</sup>	3.96 <sup>ns</sup>	-24.39 <sup>ns</sup>
L5*L9	-44.35 <sup>ns</sup>	16.57**	15.00**	-3.17 <sup>ns</sup>	-10.85 <sup>ns</sup>	-17.20 <sup>ns</sup>	0.66 <sup>ns</sup>	-32.80 <sup>ns</sup>
L6*L7	-35.14 <sup>ns</sup>	-1.43 <sup>ns</sup>	-2.78 <sup>ns</sup>	-3.97 <sup>ns</sup>	-25.07 <sup>ns</sup>	-20.38 <sup>ns</sup>	-2.20 <sup>ns</sup>	-0.58 <sup>ns</sup>
L6*L8	-27.64 <sup>ns</sup>	-2.00 <sup>ns</sup>	-4.17*	-7.14 <sup>ns</sup>	-23.68 <sup>ns</sup>	-9.55 <sup>ns</sup>	1.76 <sup>ns</sup>	-1.98 <sup>ns</sup>
L6*L9	-31.17 <sup>ns</sup>	5.71**	5.28**	-0.79 <sup>ns</sup>	-20.10 <sup>ns</sup>	1.27 <sup>ns</sup>	-2.64 <sup>ns</sup>	-19.79 <sup>ns</sup>
L7*L8	-25.65 <sup>ns</sup>	-1.14 <sup>ns</sup>	-1.11 <sup>ns</sup>	0.00 <sup>ns</sup>	-21.09 <sup>ns</sup>	-19.75 <sup>ns</sup>	2.20 <sup>ns</sup>	-4.62 <sup>ns</sup>
L7*L9	-23.94 <sup>ns</sup>	5.43**	5.28**	0.00 <sup>ns</sup>	-10.05 <sup>ns</sup>	-1.27 <sup>ns</sup>	-3.30 <sup>ns</sup>	-19.62 <sup>ns</sup>
L8*L9	-16.35 <sup>ns</sup>	4.86*	3.61 <sup>ns</sup>	-3.17 <sup>ns</sup>	-6.27 <sup>ns</sup>	3.82 <sup>ns</sup>	3.30 <sup>ns</sup>	-26.16 <sup>ns</sup>
Kolba (mean)	11.07	87.50	90.00	2.50	251.25	1.57	4.55	408.03
SE(d)	0.79	1.62	1.65	0.04	13.55	0.14	0.17	37.90

\*\*Significant at 0.01 level of probability; \* = significant at 0.05 level of probability; ns = non-significant; SE(d)= standard error of difference; GY= grain yield; DA= number of days to anthesis; DS= number of days to silking; ASI= anthesis silking interval; PH= plant height; EPP= number of ears per plant; ED= ear diameter and TKWT =1000-kernel weight.

SCA mean square across locations (Table 6). In this study, additive gene action than non-additive gene action was important for plant height. In consistent with this finding, Dagne (2002), Hadji (2004) and Demissew et al. (2011) reported the importance of additive and non-additive gene action in the inheritance of plant height. Combining ability analyses revealed highly significant

GCA and SCA effects for ear per plant. Similar to the present study, Malik et al. (2004) reported significant GCA and SCA mean squares for number of ears per plant in a diallel study of nine quality protein maize (QPM) inbred lines.

Both GCA and SCA mean squares for ear diameter were significantly different ( $p < 0.05$ ) across the two



**Table 6.** Across locations combining ability analyses of variance for grain yield and other agronomic traits of 36 diallel crosses evaluated at Ambo and Kulumsa (2017).

Source of variation	Mean squares							
	DF	GY	DA	DS	PH	EPP	ED	TKW
Location (LOC)	1	201.17**	720.03**	315.06**	43646.17**	0.29**	1.65**	189667.5**
Replication (LOC)	2	0.71 <sup>ns</sup>	5.14 <sup>ns</sup>	8.26 <sup>ns</sup>	730.03*	0.0042 <sup>ns</sup>	0.17**	1393.92 <sup>ns</sup>
Crosses	35	3.12**	57.57**	66.16**	952.29**	0.09**	0.14**	6551.29**
GCA	8	5.89*	235.78**	274.24**	3189.48**	0.23**	0.47**	22818.03**
SCA	27	2.30*	4.76*	4.51 <sup>ns</sup>	289.42 <sup>ns</sup>	0.05**	0.04*	1731.52 <sup>ns</sup>
GCA*LOC	8	3.22**	7.40*	3.87 <sup>ns</sup>	263.14 <sup>ns</sup>	0.09**	0.03 <sup>ns</sup>	953.31 <sup>ns</sup>
SCA*LOC	27	1.50*	4.45 <sup>ns</sup>	3.14 <sup>ns</sup>	239.98 <sup>ns</sup>	0.04*	0.03 <sup>ns</sup>	1725.43 <sup>ns</sup>
Error	70	0.81	2.87	3.33	189.83	0.02	0.03	1331.38
% GCA		43.18	93.62	94.74	76.55	55.91	76.54	79.61
% SCA		56.82	6.38	5.26	23.45	44.09	23.46	20.39

\*\*Significant at 0.01 level of probability, \* = significant at 0.05 level of probability, ns = non-significant, GY= grain yield, DA= number of days to anthesis, DS= number of days to silking, PH= plant height, EPP= number of ears per plant, ED= ear diameter and TKW=1000-kernel weight.

locations indicating that both additive and non-additive gene effects were important in agreement with the study of Dagne (2002), Hadji (2004) and Gudeta (2007). Mean squares due to GCA for thousand kernel weight were highly significant ( $p < 0.01$ ) across locations (Table 6) but mean squares due to SCA were not significant. This study showed additive than non-additive gene actions were important in governing this trait. In contrast to this finding, Dagne (2002), Dagne et al. (2007), Gudeta (2007) and Beyene (2016) reported the importance of both additive and non-additive gene actions for this trait.

GCA  $\times$  Loc mean squares were significant for grain yield, days to anthesis and ears per plant indicating that GCA effects associated with parents were not consistent for these traits over the two environments (Table 6). But the interaction was not significant for days to silking, plant height, ear diameter and thousand kernel weight, indicating that GCA effects associated with parents were consistent over the two environments. SCA  $\times$  Loc mean squares were significant for grain yield and ear per plant showing that SCA effects of these traits associated with crosses were not consistent over the two environments, while, SCA  $\times$  Loc showed non-significant mean squares for the rest of traits, indicating that SCA effects associated with crosses were consistent over the two environments. Similar findings were reported by Dagne et al. (2007) in their study on heterosis and combining ability for grain yield and its component in selected maize inbred lines.

### General combining ability effects

The general combining ability effects of parental inbred lines were computed for the traits exhibited significant general combining ability (GCA) mean squares in

combining ability analyses of variance (Table 6). The Estimates of GCA effects for parental lines showed significant differences for various traits. General combining ability effects of grain yield and related agronomic traits for across locations analyses are presented in Table 7.

GCA effects of lines for grain yield ranged between - 0.59 t/ha (L9) to 0.61 t/ha (L3) (Table 7). Five inbred lines showed positive GCA effects for grain yield. Two inbred lines L3 (0.61 t/ha) and L8 (0.62 t/ha) showed positive and significant GCA effects. This indicates the potential advantage of these inbred lines for the development of high-yielding hybrids and/or synthetic varieties, as the lines can contribute desirable alleles in the synthesis of new varieties. Four inbred lines (L5, L6, L7 and L9) showed negative and non-significant GCA (Table 7), indicating these lines were poor combiners for grain yield. Results of the current study are similar to the findings of several authors (Kanagarasu et al., 2010; Yoseph et al., 2011; Girma et al., 2015; Amare et al., 2016; Beyene, 2016; Dufera et al., 2018) who reported significant positive and negative GCA effects for grain yield in maize germplasm.

GCA effects of lines for days to anthesis ranged between -2.90 (L6) to 4.49 (L9), while for days to silking it ranged from -3.44 (L6) to 4.56 (L9) (Table 7). Six inbred lines (L1, L2, L4, L6, L7 and L8) showed negative and significant GCA effects for days to anthesis. This indicates that these lines were good general combiners for early maturity while three inbred lines (L3, L5 and L9) exhibited significant and positive GCA effects for days to anthesis and that these lines have tendency to increase late maturity. L9 had higher and positive GCA effect for days to silking (4.45) whereas L6 had lower and negative GCA effect (-3.44). All the three inbred lines which showed positive GCA effects had significant GCA effects

**Table 7.** Estimates of general combining ability effects (GCA) of nine inbred lines across the two locations (2017).

Line	GY	DA	DS	PH	EPP	ED	TKW
L1	0.14 <sup>ns</sup>	-1.22*	-0.90*	-7.35 <sup>ns</sup>	-0.09**	0.10**	16.66 <sup>ns</sup>
L2	0.09 <sup>ns</sup>	-1.26*	-1.87**	-6.32 <sup>ns</sup>	0.01 <sup>ns</sup>	-0.07*	13.82 <sup>ns</sup>
L3	0.61*	2.92**	3.42**	10.58**	0.19**	-0.21**	-40.08**
L4	0.26 <sup>ns</sup>	-2.69**	-2.51**	-1.57 <sup>ns</sup>	-0.08*	0.15**	3.45 <sup>ns</sup>
L5	-0.44 <sup>ns</sup>	3.85**	4.14**	14.00**	-0.06 <sup>ns</sup>	0.0008 <sup>ns</sup>	-17.62 <sup>ns</sup>
L6	-0.54 <sup>ns</sup>	-2.90**	-3.44**	-19.85**	-0.02 <sup>ns</sup>	-0.07*	23.33*
L7	-0.15 <sup>ns</sup>	-1.47**	-1.12**	-3.21 <sup>ns</sup>	-0.06 <sup>ns</sup>	-0.04 <sup>ns</sup>	26.46**
L8	0.62*	-1.72**	-2.26**	4.83 <sup>ns</sup>	0.01 <sup>ns</sup>	0.20**	22.61*
L9	-0.59 <sup>ns</sup>	4.49**	4.56**	8.89*	0.08*	-0.06 <sup>ns</sup>	-48.64**
SE(g)	0.31	0.57	0.44	4.45	0.034	0.037	10.01

\*\*Significant at 0.01 level of probability, \* = significant at 0.05 level of probability, ns = non-significant, GY= grain yield, DA= number of days to anthesis, DS= number of days to silking, PH= plant height, EPP= number of ears per plant, ED= ear diameter and TKW=1000-kernel weight.

for days to silking while six inbred lines exhibited significant and negative GCA effects for this trait. L1 (-0.90), L2 (-1.87), L4 (-2.51), L6 (-3.44), L7 (-1.12) and L8 (-2.26) were the best general combiners for early maturity (Table 7). Lines with negative and significant GCA effects for days to anthesis and silking are desirable when the objective is to develop early maturing hybrids, as hybrids generated using these lines tend to flower earlier. Similarly, lines with positive and significant GCA effects for days to flowering are desirable when the objective is to develop late maturing hybrids. Thus, there is possibility of making effective selection for these traits, which could lead to considerable genetic improvement for earliness and lateness. Desirability of negative GCA for days to anthesis and silking for earliness and desirability of positive GCA for these traits for lateness was suggested by various authors such as Shushay et al. (2013), Umar et al. (2014), Girma et al. (2015), Beyene, (2016) and Abiy (2017).

Even though five inbred lines showed negative GCA effects for plant height in combined analyses across locations (Table 7), only one inbred line L6 (-19.85) showed significant GCA effect, implying the tendency of this line to reduce plant height, which is very important for development of genotypes resistant to lodging. All the four inbred lines that showed positive GCA (L3, L5, L8 and L19) were poor general combiners for short plant height as they showed positive and significant GCA effects. In line with the present study, Dagne et al. (2010), Demissew et al. (2011) and Dufera et al. (2018) found significant positive and negative GCA effects for plant height.

For number of ears per plant, four inbred lines showed positive GCA effects among them two inbred lines L3 (0.19) and L9 (0.08) had significant GCA effects. L3 had positive and highly significant GCA effect for number of ears per plant, hence, it was the best general combiner

for prolificacy. Two inbred lines L1 (-0.09) and L4 (-0.08) showed significantly negative GCA effects for ears per plant, hence are considered as poor combiners for number of ears per plant. L1 had the smallest GCA effect of -0.09 for ears per plant. Similar to the present findings, Dagne et al. (2007) reported significant positive and negative GCA effects for number of ears per plant.

In combined analyses across the two locations, four inbred lines showed positive GCA effects for ear diameter among them three inbred lines had significant GCA effects. L1 (0.1), L4 (0.15) and L8 (0.20) were the best general combiners for ear diameter, that is these lines have the tendency to increase ear diameter as they had highly significant and positive GCA effect (Table 7). On the other hand, three inbred lines had significantly negative GCA effects. The present study is in agreement with Melkamu (2013), Rahman et al. (2013) and Habtamu (2015) who reported significant positive and negative GCA effects for ear diameter.

Significantly positive and negative GCA effects were obtained for thousand kernel weight across the two locations. From a total of six inbred lines which showed positive GCA effects for thousand-kernel weight, three of the inbred lines L6 (23.33), L7 (26.46) and L8 (22.61) showed significant and positive GCA effects, indicating that the inbred lines were the best general combiners for thousand-kernel weight. On the other hand, L3 (-40.08) and L9 (-48.64) showed negative and significant GCA effects, which are undesirable. In support of this findings, Amiruzzaman et al. (2010) and Demissew et al. (2011) recorded significant positive and negative GCA effects for thousand kernel weights.

### Specific combining ability effects

Specific combining ability effects for grain yield and

**Table 8.** Estimates of specific combining ability effects (SCA) of 36 diallel crosses evaluated at Ambo and Kulumsa in 2017.

Crosses	GY	DA	EPP	ED
L1*L2	0.47 <sup>ns</sup>	-0.84 <sup>ns</sup>	0.04 <sup>ns</sup>	-0.032 <sup>ns</sup>
L1*L3	1.47*	-0.52 <sup>ns</sup>	0.22**	0.08 <sup>ns</sup>
L1*L4	-0.64 <sup>ns</sup>	1.34 <sup>ns</sup>	-0.03 <sup>ns</sup>	0.09 <sup>ns</sup>
L1*L5	1.23 <sup>ns</sup>	-0.45 <sup>ns</sup>	0.12 <sup>ns</sup>	-0.06 <sup>ns</sup>
L1*L6	-0.59 <sup>ns</sup>	0.55 <sup>ns</sup>	-0.11 <sup>ns</sup>	-0.036 <sup>ns</sup>
L1*L7	-1.27 <sup>ns</sup>	0.63 <sup>ns</sup>	-0.09 <sup>ns</sup>	-0.16 <sup>ns</sup>
L1*L8	-0.60 <sup>ns</sup>	0.38 <sup>ns</sup>	-0.05 <sup>ns</sup>	-0.0071 <sup>ns</sup>
L1*L9	-0.15 <sup>ns</sup>	-1.09 <sup>ns</sup>	-0.09 <sup>ns</sup>	0.13 <sup>ns</sup>
L2*L3	0.18 <sup>ns</sup>	-1.23 <sup>ns</sup>	0.0012 <sup>ns</sup>	0.10 <sup>ns</sup>
L2*L4	0.39 <sup>ns</sup>	0.13 <sup>ns</sup>	0.101 <sup>ns</sup>	-0.01 <sup>ns</sup>
L2*L5	-0.27 <sup>ns</sup>	-0.41 <sup>ns</sup>	-0.13 <sup>ns</sup>	-0.007 <sup>ns</sup>
L2*L6	-0.21 <sup>ns</sup>	-0.16 <sup>ns</sup>	0.07 <sup>ns</sup>	-0.035 <sup>ns</sup>
L2*L7	1.02 <sup>ns</sup>	0.66 <sup>ns</sup>	0.17*	-0.014 <sup>ns</sup>
L2*L8	-0.73 <sup>ns</sup>	0.91 <sup>ns</sup>	-0.16*	-0.007 <sup>ns</sup>
L2*L9	-0.86 <sup>ns</sup>	0.95 <sup>ns</sup>	-0.09 <sup>ns</sup>	0.0036 <sup>ns</sup>
L3*L4	-0.39 <sup>ns</sup>	0.95 <sup>ns</sup>	-0.13 <sup>ns</sup>	0.00 <sup>ns</sup>
L3*L5	-0.24 <sup>ns</sup>	-1.34 <sup>ns</sup>	-0.11 <sup>ns</sup>	0.08 <sup>ns</sup>
L3*L6	0.61 <sup>ns</sup>	0.66 <sup>ns</sup>	0.07 <sup>ns</sup>	0.08 <sup>ns</sup>
L3*L7	-1.33 <sup>ns</sup>	-0.02 <sup>ns</sup>	-0.09 <sup>ns</sup>	-0.03 <sup>ns</sup>
L3*L8	0.38 <sup>ns</sup>	0.73 <sup>ns</sup>	0.09 <sup>ns</sup>	-0.096 <sup>ns</sup>
L3*L9	-0.76 <sup>ns</sup>	0.77 <sup>ns</sup>	-0.05 <sup>ns</sup>	-0.21*
L4*L5	0.11 <sup>ns</sup>	-1.23 <sup>ns</sup>	0.102 <sup>ns</sup>	-0.26**
L4*L6	-0.28 <sup>ns</sup>	-0.73 <sup>ns</sup>	-0.09 <sup>ns</sup>	-0.04 <sup>ns</sup>
L4*L7	0.57 <sup>ns</sup>	0.34 <sup>ns</sup>	0.08 <sup>ns</sup>	0.11 <sup>ns</sup>
L4*L8	0.43 <sup>ns</sup>	0.34 <sup>ns</sup>	-0.04 <sup>ns</sup>	0.16 <sup>ns</sup>
L4*L9	-0.19 <sup>ns</sup>	-1.13 <sup>ns</sup>	0.00053 <sup>ns</sup>	-0.05 <sup>ns</sup>
L5*L6	0.18 <sup>ns</sup>	-0.52 <sup>ns</sup>	0.03 <sup>ns</sup>	0.014 <sup>ns</sup>
L5*L7	0.04 <sup>ns</sup>	0.55 <sup>ns</sup>	-0.0063 <sup>ns</sup>	0.14 <sup>ns</sup>
L5*L8	-0.14 <sup>ns</sup>	0.30 <sup>ns</sup>	0.125 <sup>ns</sup>	-0.007 <sup>ns</sup>
L5*L9	-0.91 <sup>ns</sup>	3.09*	-0.128 <sup>ns</sup>	0.104 <sup>ns</sup>
L6*L7	-0.21 <sup>ns</sup>	0.05 <sup>ns</sup>	-0.09 <sup>ns</sup>	0.032 <sup>ns</sup>
L6*L8	0.15 <sup>ns</sup>	-0.19 <sup>ns</sup>	0.0087 <sup>ns</sup>	-0.04 <sup>ns</sup>
L6*L9	0.66 <sup>ns</sup>	0.34 <sup>ns</sup>	0.12 <sup>ns</sup>	0.025 <sup>ns</sup>
L7*L8	-0.33 <sup>ns</sup>	-0.88 <sup>ns</sup>	-0.10 <sup>ns</sup>	-0.04 <sup>ns</sup>
L7*L9	1.07 <sup>ns</sup>	-1.34 <sup>ns</sup>	0.12 <sup>ns</sup>	-0.03 <sup>ns</sup>
L8*L9	1.14 <sup>ns</sup>	-1.58 <sup>ns</sup>	0.13 <sup>ns</sup>	0.03 <sup>ns</sup>
SE(s <sub>ij</sub> )	0.75	1.39	0.083	0.09

\*\*Significant at 0.01 level of probability, \* = significant at 0.05 level of probability, ns = non-significant, GY= grain yield, DA= number of days to anthesis, DS= number of days to silking, PH= plant height, EPP= number of ears per plant, ED= ear diameter and TKW=1000-kernel weight.

related agronomic traits for across location is presented in Table 8. The crosses showed considerable variation in their SCA effects for the different traits.

In combined analyses across the two locations, positive SCA effects were found in seventeen of the crosses for grain yield. The cross L1 x L3 was the only best positive and significant ( $p < 0.05$ ) cross combination with SCA value of 1.47. Thus, this cross could be selected for its

specific combining ability to improve grain yield. Crosses with higher value of SCA effects also showed higher values of mean grain yield, indicating good correspondence between SCA effects and mean grain yield. Hence such cross combinations could effectively be exploited in hybrid breeding program in maize research. Nineteen crosses showed negative SCA effects for grain yield (Table 8) which are undesirable as these crosses

showed a tendency to reduce grain yield performance. In line with the current finding, Kamara et al. (2014), Girma al. (2015), Ram et al. (2015), Bullo and Dagne (2016) reported significant positive and negative SCA for grain yield. They suggested that, when high yielding specific combinations are desired, especially in hybrid maize development, SCA effects could help in the selection of parental material for hybridization.

For days to anthesis, only one cross L5 x L9 (3.09) showed positive and significant SCA effect (Table 8). Thus, this cross could be used for late maturity for the locations with sufficient rainfall. In agreement with this finding several researchers reported significant positive and negative SCA effects for days to anthesis (Kanagarasu et al., 2010, Dagne et al., 2011, Aminu and Izge, 2013; Aminu et al., 2014).

Positive SCA effects were found in eighteen of the crosses for ear per plant. The crosses L1 x L3 and L2 x L7 were the two best positive and significant cross combinations with SCA values of 0.22 and 0.17, respectively. Thus, these crosses could be selected for their specific combining ability to improve number of ears per plant. Eighteen crosses showed negative SCA effects in undesired direction for ear per plant with only one significant and negative SCA, L2 x L8 (-0.16) (Table 8). This indicates that this hybrid combination is poor for number of ears per plant. Similar results were reported by Berhanu (2009) and Bello and Olawuyi (2015). They indicated the capacity of the crosses to produce hybrids having increased number of ears per plant.

Sixteen of the crosses showed positive SCA effects for ear diameter but none of them were significant (Table 8). On other hand, twenty of the crosses showed negative SCA effects, but only two of the crosses L3 x L9 (-0.21) and L4 x L5 (-0.26) showed significant and negative SCA effects for this trait. This indicates that none of these crosses were significantly good specific combinations for ear diameter. Amiruzzaman et al. (2010) found significant positive and negative SCA effects for ear diameter.

## Conclusion

From the study, it can be concluded that better performing inbred lines with desirable GCA, cross combinations with desirable SCA effects and crosses with noticeable level of heterosis above the standard check for grain yield and other grain yield related traits were successfully identified. These genotypes constitute a source of valuable genetic materials that could be successively used for future breeding work in the development of maize cultivars with desirable traits' composition for highland sub-humid agro-ecology of Ethiopia.

## CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

## ACKNOWLEDGEMENTS

The authors express their sincere appreciation to the maize research staff at Ambo, Hollata and Kulumsa Agricultural Research Centers for hosting the trials and collecting data. Also, the Ethiopian Institute of Agricultural Research (EIAR) are appreciated for the financial support.

## REFERENCES

- Abiy B (2017). Combining ability of highland maize (*Zea mays* L.) inbred lines using line x tester analysis (doctoral dissertation, Hawassa University) 134 p.
- Ahmad A, Saleem M (2003). Combining ability analyses in *Zea mays* L. International Journal of Agriculture and Biology 5:239-244.
- Amare S, Dagne W, Sentayehu A (2016). Combining ability of elite highland maize (*Zea mays* L.) inbred lines at Jimma Dedo, South West Ethiopia. Advances in Crop Science and Technology, pp. 1-9.
- Aminu D, Izge A (2013). Gene action and heterosis for yield and yield traits in maize (*Zea mays* L.), under drought conditions in Northern Guinea and Sudan Savannas of Borno State. Peak Journal of Agricultural Sciences 1(1):17-23.
- Aminu D, Mohammed S, Kabir B (2014). Estimates of combining ability and heterosis for yield and yield traits in maize population (*Zea mays* L.), under drought conditions in the northern Guinea and Sudan savanna zones of Borno State, Nigeria. International Journal of Agriculture Innovations and Research 2:824-830.
- Amiruzzaman M, Islam M, Hassan L, Rohman M (2010). Combining ability and heterosis for yield and component characters in maize. Academic Journal of plant Sciences 3(2):79-84.
- Bayisa A (2004). Heterosis and Combining Ability of Transitional highland maize (*Zea mays* L.). M.Sc. Thesis. School of Graduate Studies, Alemaya University, Ethiopia. 72pp.
- Bello O, Olawuyi O (2015). Gene action, heterosis, correlation and regression estimates in developing hybrid cultivars in maize. Tropical Agriculture 92(2):102-117.
- Berhanu T (2009). Heterosis and combining ability for yield related parameters and stover quality traits for food-feed in maize (*Zea mays* L.) Adapted to the mid-altitude agro-ecology of Ethiopia. MSc. Thesis, Haramaya University, Haramaya, Ethiopia 216p.
- Beyene A (2016). Heterosis and Combining Ability of Mid Altitude Quality Protein Maize (*Zea mays* L.) Inbred Lines at Bako, Western Ethiopia. Doctoral dissertation, Haramaya University, 172p.
- Bindiganavile S, Joseph K, Simbarashe C, Cosmos M (2007). Fieldbook: Software For Managing A Maize Breeding Program: A Cookbook For Handling Field Experiments, Data, Stocks and Pedigree Information. CIMMYT.
- Bitew T, Midekisa D, Temesgen D, Belay G, Girma D, Dejene K, Dagne W, Adefiris T (2017). Combining ability analyses of quality protein maize (QPM) inbred lines for grain yield, agronomic traits and reaction to grey leaf spot in mid-altitude areas of Ethiopia. African Journal of Agricultural Research 12(20):1727-1737.
- Bolanos J, Edmeades G (1996). The importance of the anthesis-silking interval in breeding for drought tolerance in tropical maize. Field Crops Research 48(1):65-80.
- Bullo T, Dagne W (2016). Combining ability of inbred lines in quality protein maize (QPM) for varietal improvement. International journal of plant breeding and crop Science 3(1):79-89.
- Chandel U, Mankotia B (2014). Combining ability in local and cimmyt inbred lines of maize (*Zea mays* L.) for grain yield and yield components using line x tester analyses. SABRAO Journal of Breeding and Genetics 46(2):256-264.
- CIMMYT (1985). Managing Trials and Reporting Data for CIMMYT's International Maize Testing Program. Mexico, D.F.
- Central Statistical Agency (CSA) (2017). Agricultural sample survey report on area and production of major crops. Private peasant holdings, Meherseason. Statistical Bulletin. Addis Ababa, Ethiopia.
- Dagne W (2002). Combining ability analyses for traits of agronomic

- importance in maize (*Zea mays* L.) inbred lines with different levels of resistance to grey leaf spot (*Cercosporazea maydis*). School of Graduate Studies of Haramaya University, Ethiopia, 97p.
- Dagne W, Habtamu Z, Labuschagne M, Hussien T, Singh H (2007). Heterosis and combining ability for grain yield and its component in selected maize inbred lines. *South African Journal of Plant and Soil* 24:133-137.
- Dagne W, Vivek B, Birhanu T, Koste A, Mosisa W, Legesse W (2010). Combining ability and heterotic relationships between CIMMYT and Ethiopian inbred lines. *Ethiopian Journal of Agricultural Sciences* 20:82-93.
- Dagne W, Vivek B, Berhanu T, Koste A, Mosisa W, Legesse W (2011). Combining ability and heterotic relationships between CIMMYT and Ethiopian maize inbred lines. *Ethiopian Journal of Agricultural Sciences* 21:82-93.
- Demissew A, Habtamu Z, Kanuajia K, Dagne W (2011). Combining ability in maize lines for agronomic traits and resistance to weevil. *Ethiopian Journal of Agricultural Sciences* 2(1):40-47.
- Demissew A (2014). Genetic Diversity and Combining Ability of Selected Quality Protein Maize (QPM) Inbred Lines Adapted to the Highland Agro-ecology of Ethiopia. Doctoral dissertation, University of KwaZulu-Natal, Pietermaritzburg.
- Dufera T, Bulti T, Grum A (2018). Heterosis and combining ability analyses of quality protein maize (*Zea mays* L.) inbred lines adapted to mid-altitude sub-humid agro-ecology of Ethiopia. *African Journal of Plant Science* 12(3):47-57.
- Falconer D, Mackay L (1996). *Introduction To Quantitative Genetics*. 4th edition. Longman, Essex, England.
- George A (2007). *Principles of plant genetics and breeding*, 1st edition. Blackwell Publishing Ltd., P. 485.
- Girma C, Sentayehu A, Berhanu T, Temesgen M (2015). Test cross performance and combining ability of maize (*Zea mays* L.) inbred lines at Bako, Western Ethiopia. *Global Journal of Science Frontier Research* 15(4):1-24.
- Gomez K, Gomez A (1984). *Statistical procedures for agricultural research*. John Wiley & Sons, Unites States of America, 277p.
- Griffing B (1956). Concept of general and specific combining ability in relation to diallel crossing system. *Australian Journal of Biological Sciences* 9:463-493.
- Gudeta N (2007). Heterosis and combining abilities in QPM versions of early generation highland maize (*Zea mays* L.) inbred lines. M. Sc. Thesis. School of Graduate studies, Alemaya University, Ethiopia. 243p.
- Hadiji T (2004). Combining Ability Analyses for yield and yield related traits in quality Protein maize (QPM) inbred lines. M.Sc. Thesis. School of Graduate studies, Alemaya University.
- Habtamu Z (2015). Heterosis and combining ability for grain yield and yield component traits of maize in Eastern Ethiopia. *Science, Technology and Arts Research Journal* 4(3):32-37.
- Kamara M, El-Degwy I, Koyama H (2014). Estimation of combining ability of some maize inbred lines using line x tester mating design under two nitrogen levels. *Australian Journal of Crop Science* 8(9):1336.
- Kanagarasu S, Nallathambi G, Ganesan K (2010). Combining ability analysis for yield and its component traits in maize (*Zea mays* L.). *Electronic Journal of Plant Breeding* 1:915-920.
- Koppad N (2007). Identification of superior parental combinations *mays* L.). MSc. Thesis. University of Agricultural Sciences, Dharwad 91p.
- Mahantesh (2006). Combining ability of and heterosis analysis for based on three way cross hybrid performance in maize (*Zea* grain yield components in single cross hybrids of maize (*Zea mays* L.). M.Sc. Thesis. College of agriculture, Dharwad University of agricultural sciences 103 p.
- Malik S, Malik H, Minhas N, Munir M (2004). General and Specific Combining Ability Studies in Maize Diallel Crosses. *International Journal of Agriculture and Biology* 8:56-59.
- Melkamu E (2013). Estimation of Combining Ability and Heterosis of Quality Protein Maize Inbred Lines. *African Journal of Agricultural Research* 8(48):6309-17.
- Moore KJ, Dixon PM (2015). Analysis of combined experiments revisited. *Agronomy Journal* 107(2):763-771.
- Natol B, Birahanu A, Mandefro N (2017). Standard Heterosis of Maize (*Zea mays* L.) Inbred Lines for Grain Yield and Yield Related Traits at Southern Ethiopia, Hawassa. *American-Eurasian Journal of Agricultural and Environmental Sciences* 17(3):257-264.
- Patterson H, Williams E (1976). A new class of resolvable incomplete block designs. *Biometrika* 63(1):83-92.
- Rahman H, Ali A, Shah Z, Iqbal M, Noor M, Amanullah J (2013). Line x analyses for grain yield and yield related traits in maize variety sarhad-white. *Pakistan Journal of Botany* 45:383-387.
- Ram L, Singh R, Singh S, Srivastava R (2015). Heterosis and combining ability studies for quality protein maize. *Journal of Crop Breeding and Genetics* 1-2:8-25.
- SAS Institute Inc (2003). SAS proprietary Software. SAS Institute, Inc, CARY, NC, Canada.
- Shushay W, Habtamu Z, Dagne W (2013). Line x tester analyses of maize inbred lines for grain yield and yield related traits. *Asian Plant Science Research* 3(5): 12-19.
- Shushay W (2014). Standard Heterosis of Maize (*Zea mays* L.) Inbred Lines for Grain Yield and Yield Related Traits in Central Rift Valley of Ethiopia. *Journal of Biology, Agriculture and Healthcare* 4(23):31-37.
- Singh R (1985). *Biometrical methods in Quantitative Genetic Analyses*. Kalyani Pub. Ludhiana. New Delhi, 318p.
- Tiwari V (2003). Studies on heterosis, combining ability, inbreeding tolerance and phenotypic stability in intra and inter-group single cross hybrids of maize (*Zea mays* L.). Ph.D. Thesis. GBPUA and T, Pantnagar, India, pp. 173-197.
- Tolera K, Mosisa W, Zeleke H (2017). Combining ability and heterotic orientation of mid-altitude sub-humid tropical maize inbred lines for grain yield and related traits. *African Journal of Plant Science* 11(6):229-239.
- Twumasi S, Habatmu Z, Kass Y, Bayisa Y, Sewagegn T (2001). Development and improvement of highland maize in Ethiopia. Proceedings of the Second National Maize Workshop of Ethiopia, 12-16 November 2001, Addis Ababa, Ethiopia.
- Twumasi A, Kassa Y, Gudeta N (2003). Exploitation of Combining Ability and Heterotic Responses in Maize Germplasm to Develop Cultivars for the Eastern Africa Highlands. pp. 282-283. CIMMYT, 2003. Book of Abstracts: A. R. Hallauer International symposium on Plant Breeding, 17-22 August 2003, Mexico City, Mexico, D. F.
- Twumasi A, Demissew A, Gezahegn B, Wende A, Gudeta N, Demoz N, Friesen D, Kassa Y, Bayisa A, Girum A, Wondimu F (2012). A Decade of Quality Protein Maize Research Progress in Ethiopia (2001–2011). pp. 47-57. In: Mosisa W, Twumasi AS, Legesse W, Berhanu T, Girma D, Gezahegn B, Dagne W, Prasanna BM (eds.), Proceedings of the Third National Maize Workshop of Ethiopia. Addis Ababa, Ethiopia. 18-20 April 2011.
- Umar U, Ado S, Aba D, Bugaje S (2014). Estimates of combining ability and gene action in maize (*Zea mays* L.) under water stress and non-stress conditions. *Journal of Biology, Agriculture and Healthcare* 4(25):247-253.
- Wali M, Kachapur R, Chandrashekhar C, Kulkarni V, Devaranavadagi S (2010). Gene action and combining ability studies in single cross hybrids of maize (*Zea mays* L.). *Karnataka, Journal of Agricultural Sciences* 23(4):557-562.
- Yoseph B, Stephen M, John G, Haron K, Charles M, Stephen N, Dorcas C, Jackson M, Regina T (2011). Combining ability of Maize (*Zea mays* L.) inbred lines resistant to Stem Borers. *African Journal of Biotechnology* 10(23):4759-66.
- Zhang Y, Kang MS, Lamkey K (2005). DIALLEL-SAS05: A comprehensive program for Griffing's and Gardner-Eberhart analyses. *Agronomy Journal* 97(4):1097-1106.
- Ziggiju M, Legesse W (2016). Standard Heterosis, Path Coefficient Analyses and Association of Yield and Yield Related Traits of Pipeline Maize (*Zea mays* L.) Hybrids at Pawe, Northwestern Ethiopia (Doctoral dissertation, Haramaya University).