Gene action and order effects in single, three-way and double cross hybrids of maize (*Zea mays* L.) for fodder yield across environments

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Abstract

In India maize is the third most important cereal crop after rice and wheat. Seven inbreds were involved in a crossing programme to obtain twenty one single crosses and 105 each of three-way and double crosses in half diallel fashion and further evaluated in *Kharif* 2015 at three locations. Diallel, triallel and quadriallel analyses were conducted to study general and specific combining abilities, gene action and order effects for forage yield. In diallel, good general combiners, BML 51 and BML 14 produced the highest fodder yielding single cross hybrid i.e. BML 51 × BML 14 and it was identified as good specific combiner. Triallel analysis also revealed the same inbreds to be good general combiners either as grand parent or parent. Among all the crosses, three-way cross *viz.*, (BML 14 × BML 6) × BML 51 had the highest mean yield of 9949 kg ha^{-1} where BML 14 was involved as grand parent and BML 51 as parent with the highest three-line specific effect. In quadriallel analysis the double cross combination (BML 51 × BML 10) × (BML 14 × BML 13) gave a fodder yield of 8333 kg ha^{-1} and also exhibited highly significant 3-line interaction effect (sijk) again indicating BML 51 as the best general combiner. Present study revealed that good general combiners and specific combiners identified through diallel analysis were involved in significant interaction effects of three-way and double crosses and resulted in higher fodder yields. Dominance interaction in single crosses and additive × additive and additive × dominance type of epistatic interactions in three-way crosses and additive × additive × additive interaction in double crosses were predominant, hence there exist a possibility of identifying promising hybrids through heterosis breeding and/or deriving potential inbreds through pedigree breeding. Information on parent order effects i.e. the order of lines in which they have to be crossed in three-way and double crosses for obtaining superior hybrids for fodder purpose is clearly elucidated.

Abbreviations

BML: All India Research Project on Maize (AICRP) indicated “B” code for the inbred lines developed at Maize Research Centre, Rajendranagar, Hyderabad. “ML” indicates maize line.

CD: Critical difference
gca: Genearal Combining Ability
sca: Specific Combining Ability

Introduction

Fodder crops are the plant species that are cultivated and harvested for feeding the animals in the form of forage (cut green and fed fresh), silage (preserved under anaerobic condition) and hay (dehydrated green fodder). In India, total cultivated area under fodders is 8.3 mha and fodder maize is cultivated in 0.9 mha with productivity ranging from 30-55 t ha^{-1}. As a fodder crop maize occupies fourth position after Sorghum, Berseem and Lucerne (Sunil *et al.*, 2012).

Maize stover is widely used as the major source of animal feed during the scarcity of green fodder. This fact assumes a lot of significance in view of the prevailing shortage of green fodder (61.1%), 21.9% dry crop residues and 64% concentrate feeds (Chaudhary *et al.*, 2012).

A broader genetic base is always aimed to pave the way for simultaneous improvement of desired traits in different selection procedures. In any plant breeding programme, choice of parents is the most important factor. It is more so in maize where different types of

Table 1A - ANOVA for combining ability of the Diallel for forage yield (kg ha^{-1}) across locations.

Source of variation	*df*	Mean square
Environments	2	36703396**
GCA	6	2942344**
SCA	21	7293290**
GCA × Environments	12	1674409**
SCA × Environments	42	1148254**
Error	81	599689

**Highly significant at p< 0.01 level

crosses and populations evolved from different component parent genotypes are put in the hybridization programme. In this background an attempt was made to estimate the combining ability, gene action and order effects of lines of normal maize already used as parents in diallel, triallel and quadriallel analysis for fodder yield (Sumalini *et al.*, 2016, 2018 & 2020).

Materials and methods

Genetic material and field trials

To study the 1-line general, 2-line, 3-line and 4-line interaction effects, gene action and order effects of double crosses, seven promising inbred lines of normal maize *viz.*, BML 51, BML 32, BML 14, BML 13, BML 10, BML 7 and BML 6 developed at Maize Research Centre, Rajendranagar, Hyderabad were crossed in

diallel fashion (Griffing, 1956 Method I Model II) and obtained twenty one crosses during *Kharif*, 2014 (Supplementary Table 1). Later these F1's were crossed to inbreds such that each inbred appear once in a cross and obtained 105 three-way crosses. Similarly, single crosses were involved in diallel set with restriction that only unrelated crosses were involved in crossing programme and obtained 105 double crosses. Single crosses were obtained during *Kharif* 2014 while three-way crosses and double crosses were obtained during rabi 2014-15 at ARS, Karimnagar.

During *Kharif*, 2015, the experimental material comprising of seven parents, twenty one single crosses and 105 each of three-way and double crosses and eighteen public /private checks were evaluated at three locations *viz.*, MRC, ARI, Rajendranagar (17°18′N latitude, 78°23′E longitude), ARS, Karimnagar (18°30′N latitude, 79°15'E longitude) and RARS, Palem (16°35′N latitude, 78°1′E longitude). All these 256 entries were evaluated in a balanced lattice (16 × 16) with two replications at each location. Each genotype was sown in two-row plots of 3 m length with a spacing of 60 cm between the rows and 20 cm within rows. All the intercultural operations were carried out in accordance with the recommended schedule (Vyavasaya panchangam, 2015).

Traits such as days to 50% pollen shed, days to 50% silk emergence, days to 75% dry husk, shelling percentage (%),100-kernel weight (g), grain yield (kg ha^{-1}) and fodder yield (kg plot^{-1}) were measured on plot basis whereas plant height (cm), ear height (cm), ear length (cm), ear diameter (cm), number of kernel rows ear^{-1}and number of kernels row^{-1} were recorded on ten randomly selected plants.

Statistical analysis

Fodder yield was recorded plot-wise (kg plot^{-1}) and was corrected for standard variation using the methodolgy of covariance (Mendes, 2015). Using standard statistical procedures combining ability of single crosses (Griffing, 1956), three-way crosses (Rawlings and Cockerham, 1962a) and double crosses (Rawlings and Cockerham, 1962b) were carried out for each environment separately (data not shown) and combined over the environments using with INDOSTAT software. The general and specific line effects of various arrangements were estimated as per the formulae given by Singh and Chaudhary (1977). The criterion of *per se* performance was followed to compare the order effects in double crosses (Ganga Rao, 1997).

Supplementary Table 1 - Origin and descriptions of the maize inbred lines used in the study.

S.No.	Inbred	Pedigree	Days to 50% silking (days)	Maturity group	Grain type	Colour
1	BML-51	JCY 2-7-1-2	62.5	Late	Semi-flint	Orange with cap
2	BML-32	SRRL 68-B46-1-1-2- # - 1-2-1-Ä-1-1-Äb-Äb	61.5	Late	Semi-flint	Yellow with cap
3	BML-14	CO1B 96k-1-#-1-2-×b-1-2-×b-×b-2	64.2	Late	Flint	Dark orange
4	BML-13	[×2Y Pool × MMH 9607]-B 98k-2-1-3-1-Ä-Ä-Äb-Äb-Äb-Äb	57.5	Medium	Semi-dent	Yellow with cap
5	BML-10	[×2Y Pool × Suman 1 (T)]-B 98k-1-2-1-1-2-3-Ä-2-Ä-1-Äb-Äb-Äb	54.7	Medium	Flint	Pinkish orange
6	BML-7	[×2Y Pool × CML 226]-B 98 R-1-1-1-Äb-Äb-Äb-Äb-Äb-Äb	63.3	Late	Flint	Orange
7	BML-6	SRRL 65-B96-1-1-2- # - 2-2-1-Ä-1-1-Äb-Äb	62.7	Late	Semi-flint	Yellow

Supplementary Table 2 - ANOVA for forage yield (kg ha^{-1}) at individual locations.

Source of variation	*df*	Mean square		
		Hyderabad	Karimnagar	Palem
Replications	1	217318	57918	4450605
Genotypes	242	5396538**	4298411**	4960377**
Double crosses	104	2394268**	1466054**	2495115**
Three-way crosses	104	5563054**	6684774**	5936819**
Single crosses	20	4621920**	3157448**	7391243**
Parents	6	2684436*	5019370**	1750800
Checks	4	3270758*	8097525**	3482497*
Double crosses Vs Three-way crosses	1	269908704**	29664876**	126843288**
Double crosses Vs Single crosses	1	111392504**	331388	990754
Double crosses Vs Parents	1	42588976**	15752126**	16727829**
Double crosses Vs Checks	1	80662704**	35106376**	4036383
Three-way crosses Vs Single crosses	1	1142837	6599261**	30327326**
Three-way crosses Vs Parents	1	514850	4174869*	5297816*
Three-way crosses Vs Checks	1	16222709**	18342954**	29212276**
Single crosses Vs Parents	1	3163	10462533**	9690725**
Single crosses Vs Checks	1	10185264**	26767442**	5411387*
Parents Vs Checks	1	7130383*	3943819*	18466020**
Error	242	1074193	878843	1320183

* Significance at 5% level, ** Significance at 1% level

Results and Discussion

Combining ability and gene action in single crosses

The analysis of variance for fodder yield at individual locations showed highly significant differences among the genotypes in all the single, three-way and double crosses (Supplementary Table 2). ANOVA for combining ability effects was furnished in Table 1a, b and c for single, three-way and double crosses, respectively. Variance due to gca and sca was highly significant in single crosses and significant general and specific effects are furnished in Table 2A. Single cross hybrid i.e. BML 51 × BML 14 produced the highest fodder yield of 9161 kg ha^{-1} had highly significant sca effect (2650.75**) and could be the result of high × high general combiners with good *per se* performance. Other six crosses with highly significant sca effects are the combinations of either high × low or low × low general combiners. Estimates of genetic components of variance for diallel (Table 5) indicated that dominance (2231200) was more in magnitude than additive type of gene action (173530). On the contrary, Ertiro *et al.* (2013) and Guerrero *et al.* (2014) reported additive gene action for fodder yield.

2-line and 3-line interaction effects and gene action in three-way crosses

The results of triallel analysis across environments revealed that 1-line general effects of both first (hi) and second kind (gi), 1-line order effect and 2- line specific effects of second kind (sij) were found highly significant (Table 1B). Wright (1971) also reported significant 1-line general and 1-line order effects for the studied traits. The estimates of 1-line general and 2-line specific effects are given in Table 2B. Significant 1-line general effect of the first kind (hi) and second kind (gi) were highly significant in inbreds, BML 51 (364.3** and 1004.5**, respectively) and BML 14 (351.7** and 719.6**, respectively) indicating suitability of these inbreds either as grand parents or parents. 2-line specific effect of the first kind (dij) was highly significant in cross BML 32 × BML 13 (644.3**) while 2-line specific effect of the second kind (sij) was significant in crosses BML 32 × BML 13 (463.5*) and BML 10 × BML 6 (497.0*). From the same table it is seen that, of the five crosses with significant 3-line specific effects, four crosses had good general combiner parent either BML 51 or BML 14 as grandparent (hi) or parent (gi) or 2-line specific effects of the first kind (dij). Three-way cross (BML 14 × BML 6) × BML 51 had the highest mean yield of 9949 kg ha^{-1} with the highest 3-line specific effect (1106.9*) followed by (BML 32 × BML 13) × BML 14 with mean yield of 8994 kg ha^{-1} and 3-line specific effect (1036.8*) and other two crosses i.e. (BML 51 × BML 7) × BML 14 and (BML 51 × BML 14) × BML 7 had mean fodder yields of 8205 and 8102 kg ha^{-1}, respectively. One cross (BML 32 × BML 7) × BML 6 with poor general combiners had significant sca effect but exhibited poor *per se* performance (6006 kg ha^{-1}). Two crosses i.e. (BML 14

Table 2A - Significant general and specific effects in diallel analysis.

Diallel analysis	Effect
gca	
BML 51	554.14**
BML 14	282.80*
CD (g_i) at P=0.05%	273.20
CD (g_i) at P=0.01%	361.50
sca	
BML 51 × BML 14	2650.75**
BML 51 × BML 7	1029.50*
BML 32 × BML 7	1284.53**
BML 14 × BML 13	1350.20**
BML 13 × BML 10	933.61*
BML 13 × BML 6	1163.70**
BML 10 × BML 7	1116.74**
CD (s_{ij}) at P=0.05%	794.54
CD (s_{ij}) at P=0.01%	1051.36

*,**Significant at p< 0.05 and p< 0.01, respectively.

× BML 10) × BML 51 and (BML 32 × BML 6) × BML 51 had non significant 3-line effects, but produced fodder yield of 8750 and 8674 kg ha^{-1}, respectively and these two crosses showed good general combiners BML 51 and BML 14 either as grandparent (hi) or parent (gi) or both. This clearly indicated that significant 1-line general effects of first and second kind or significant 2-line specific effects of first kind resulted in highest significant 3-line specific effect and highest *per se* performance. Hence, the superiority of the triplets is mainly due to (1) two of three parents showing better 1-line general effects (2) one cross showing better 2-line specific effect and/or (3) the interaction might be due to additive × additive and additive × dominance among the three lines used in making the triplet (Joshi and Sharma, 1984). Estimates of genetic components of variance for triallel (Table 5) revealed that epistatic components of additive × additive (989254) and additive × dominance variances (681236) were higher in magnitude than additive variance (293802). Rajamani (2014) reported predominace of epistatic component of additive × dominance variance in cotton for fiber quality traits.

2-line, 3-line and 4-line interaction effects and gene action in double crosses

The ANOVA for quadriallel is presented in Table 1C. The analysis of variance showed that 1-line general effects were highly significant and 2 and 3-line specific and 2, 3 and 4-line arrangement effects were not significant. However, the variance due to 4-line specific effects was estimated as the number of parents were less than eight. When the parents are 7, only one variance as the total of 3 and 4-line specific sums with 14 degrees of freedom is possible (Rawlings and Cockerham, 1962b). Perusal of the data in Table 1C indicated that 1-line general effect accounts for the total additive effects and if the gene action is primarily of the additive type, the estimates of 1-line effect are sufficient to predict the hybrid performance (Chaudhary, 1984). Other estimates *viz.*, 2-line arrangement effects (tij, ti.j. and sij) and 3-line arrangement effects (tij.k) were not significant and helped to trace the 4-line arrangement effect (tij.kl) only to a limited extent. Hence, these estimates are discussed in the absence of significance. Since the inbreds are seven, 3-line and 4-line specific effects which are low in magnitude or often negative are not considered. Of the 1-line general, 2-line, 3-line and 4-line interaction effects, 2-line arrangement effect of t(ij) (- -) was found to be significant in six crosses (Table 2C). Highly significant 2-line arrangement t(ij) (- -) was shown by BML 14 × BML 13 (347.77**) followed by BML 51 × BML 32 (213.13**). Out of 7 inbreds, only BML 51 had the highest 1-line general effect (211.68) and with inbred BML 13 had maximum 2-line specific effect, sij (157.51). While, maximum 3-line arrangement effects t(ij) (k-) were high in (BML 51 × BML 10) × BML 32 (380.70) followed by (BML 32 × BML 14) × BML 51 (344.49) and 3-line specific effects sijk were high in (BML 51 × BML 13) × BML 10 (128.64) followed by (BML 51 × BML 14) × BML 10 (124.31), and (BML 32 × BML 14) × BML 7 (112.98) (Data not given).Two double crosses (BML 51 × BML 7) × (BML 13 × BML 10) and (BML 51 × BML 10) × (BML 14 × BML 13) had high *per se* performance of 8512 and 8333 kg ha^{-1}, respectively and didn't exhibit maximum 4-line arrangement effects

Table 5 - Estimates of genetic components of variance for forage yield (kg ha^{-1}) in diallel, triallel and quadriallel analysis.

Components	Estimate		
	Diallel	Triallel	Quadriallel
Additive	173530	293802	1924366
Dominance	2231200	-1302833	406681
Additive × additive	-	989254	-7206336
Additive × dominance	-	681236	-1571550
Dominance × dominance	-	187799	-47567
Additive × additive × additive	-	-	31387927

Table 1B - ANOVA for combining ability of the Triallel for forage yield (kg ha^{-1}) across locations.

Source of variation	*df*	Mean square
Locations	2	114045096**
1-line general effect of first kind (hi)	6	16965200**
1-line general effect of second kind (gi)	6	20203532**
2- line specific effect of the first kind (dij)	14	1968052ns
2- line specific effect of the second kind (sij)	29	2058112*
3-line specific effect (tij.k)	49	1405838^{ns}
Crosses	104	2756921**
1-line order	6	4800761**
2-line order	14	1728489^{ns}
Error	208	1214031

*,**Significant at p< 0.05 and p< 0.01, respectively; ^{ns}Not significant

(tij.kl). Cross (BML 51 × BML 32) × (BML 14 × BML 7) showed high *per se* performance (8173 kg ha^{-1}) had BML 51 with high 1-line general effect (211.68), (BML 51 × BML 32) with highly significant 2-line arrangement effect, tij (213.13**), high 3-line interaction effect irrespective of arrangement i.e. sijk (BML 32 × BML 14) × BML 7 (112.98) and high 4-line arrangement effect, tij.kl (594.71) (Data not given). 4-line arrangement effect didn't correspond to the highest phenotypic mean. Good *per se* performer was included as first parent in the maternal F1 hybrid in all the double cross combinations which showed the highest four-line arrangement effect as well as highest mean. Estimates of genetic components of variance indicated that non allelic additive × additive × additive variance (31387927) was high followed by additive (1924366) and dominant (406681) variance and derivation of diverse inbreds could be possible through pedigree breeding due to high magnitude of additive interactions (Table 5).

Order effects

Top five high yielding single, three-way and double crosses and their general and specific effects are given in Table 3 and it is clearly evident that highest yielding hybrid in all classes of hybrids had significant specific effects indicating combining ability and *per se* performance are related to each other. Order effect of the parents is very important in three-way and double crosses. For instance in double crosses, the specific combination (BML 14 × BML 13) (- -) which had the highly significant maximum 2-line arrangement effect t(ij) (- -) (347.77**), gave the negative effect, when used in another combination, i.e. t(i -) (j -) (BML 14 × -) (BML 13 × -) (-173.89). A change in the arrangement of the parents of the best combination of three parents (BML 51 × BML 10) × (BML 32 × -) which had highest desirable positive effect (380.7) into another combination, i.e. (BML 32 × BML 10) × (BML 51 × -) had negative effect (-217.19). Another combination in which the same three parents were involved, but in some other order, i.e. (BML 51 × BML 32) × (BML 10 × -) also had negative effect of (-163.51) and sum of all the three alternate forms is zero. The four parents say, BML 51, BML 32, BML14 and BML 6 in a specific order given above, i.e. (BML 51 × BML 14) × (BML 32 × BML 6) form the most effective combination (611.05) but not in other orders. For instance, the same parents in a cross (BML 51 × BML 6) × (BML 32 × BML 14) in this order, had in contrast the negative value (-264.0) and in other order (BML 51 × BML 32) × (BML 14 × BML 6) had the negative value (-347.05) and sum of all the three alternate forms is zero. These results confirm that the order in which the parents go into a double cross hybrid is a deciding factor for its high or low performance. Hence for each cross combination the particular arrangement should be given due importance (Chaudhary and Rai, 1982). This observation clearly shows the significance of the order in which the parents are involved in multiple crosses. Evidences of order effects in triallel were reported by Ponnuswamy *et al.* (1974) in maize, Chaud-

Table 2B - Significant general and specific effects in triallel analysis.

Triallel analysis	Effect
1-line general line effect of first kind (hi)-grand parent	
BML-51	364.30**
BML-14	351.70**
CD (P=0.05%)	241.40
CD (P=0.01%)	319.43
1-line general line effect of second kind (gi)-parent	
BML-51	1004.50**
BML-14	719.60**
CD (P=0.05%)	311.65
CD (P=0.01%)	412.39
2-line specific effect of first kind (dij: i and j as grandparents)	
(BML 32 × BML-13)	644.30**
CD (P=0.05%)	484.80
CD (P=0.01%)	641.51
2-line specific effect of second kind (sij: i as half parent and j as parent)	
(BML 32 -) × BML 13	463.50*
(BML 10 -) × BML 6	497.00*
CD (P=0.05%)	438.59
CD (P=0.01%)	580.36
3-line specific effects	
(BML 51 × BML 14) × BML 7	872.90*
(BML 32 × BML 7) × BML 6	907.90*
(BML 51 × BML 7) × BML 14	962.20*
(BML 32 × BML 13) × BML 14	1036.80*
(BML 14 × BML 6) × BML 51	1106.90*
CD (P=0.05%)	860.45
CD (P=0.01%)	1138.57

*,**Significant at p< 0.05 and p< 0.01, respectively.

Table 1C - ANOVA for combining ability of the Quadriallel analysis for forage yield (kg ha^{-1}) across locations.

Source of variation	*df*	Mean square
Locations	2	164240719**
Hybrids	104	1347097**
1 - line general	6	5720467**
2 - line specific	14	1210144^{ns}
3 - line specific	14	992982^{ns}
2 - line arrangement	14	858992^{ns}
3 - line arrangement	35	1066392^{ns}
4 - line arrangement	21	1218185^{ns}
Error	208	915311

*,**Significant at p< 0.05 and p< 0.01, respectively; ns Not significant.

Table 2C -Significant effects in quadriallel analysis.

Quadriallel analysis	Effect
2- line interaction effects of lines t(ij) (- -)	
(BML 14 × BML 13) × (- -)	347.77**
(BML 51 × BML 32) × (- -)	213.13**
(BML 13 × BML 10) × (- -)	135.02**
(BML 10 × BML 6) × (- -)	94.55**
(BML 51 × BML 7) × (- -)	86.04**
(BML 10 × BML 7) × (- -)	58.92*

*,**Significant at p< 0.05 and p< 0.01, respectively. .

hary *et al*. (1975) and Chaudhary (1978) in barley and Rajamani (2014) in cotton, while order effects in quadriallel was reported by Singh and Chaudhary (1977) in barley.

Per se performance and order effects

Criterion of *per se* performance was followed to compare the order effects in three-way and double crosses (Table 4A and B, respectively). 105 each of three way and double crosses were classified in to thirty five groups of three crosses each. Crosses of each group involved three parents in triallel and four parents in quadriallel in different parental line order arrangements. Of the thirty five groups in triallel, twenty eight groups had superior *per se* performance with particular parental line order arrangement in that particular group and in quadriallel also, twenty five groups exhibited superior *per se* performance in a particular parental line order arrangement in that particular group. For example in the group 9 of three-way crosses, (BML 14 × BML 6) × BML-51 had superior *per se* performance with fodder yield of 9949 kg ha^{-1} than other arrangements *viz.*, (BML 51 × BML 14) × BML 6 with 7930 kg ha^{-1} and (BML 51 × BML 6) × BML 14 with 6710 kg ha^{-1}. Similarly in group 17 of double crosses, (BML 51 × BML 7) × (BML 13 × BML 10) had superior *per se* performance with fodder yield of 8512 kg ha^{-1} than other arrangements *viz.*, (BML 51 × BML 10) × (BML 13 × BML 7) (6590 kg ha^{-1}) and (BML 51 × BML 13) × (BML 10 × BML 7) (6608 kg ha^{-1}). However, seven groups in triallel *viz.*, 1,14,15,24,28,28,34 and ten groups in quadriallel *viz.*, 1,7,10,15,16,20,23,27,30,35 had shown comparable performance for all the three types of parental line order arrangements in that specific group. Out of 105 three-way crosses, fifteen crosses belong to thirteen groups and of the 105 double crosses fourteen crosses belong to eleven groups that expressed superior performance over the mean. Three-way cross (BML 14 × BML 6) × BML 51 had the highest fodder yield of 9949 kg ha^{-1} followed by (BML 32 × BML 13) × BML 14 with fodder yield of 8994 kg ha^{-1} and in double crosses, (BML 51 × BML 7) × (BML 13 × BML 10) had the highest fodder yield of 8512 kg ha^{-1}. Among these two three-way crosses, either BML 51 or BML 14 were involved either as grand parent or immediate parent which had significant hi and gi effects. (BML 14 × BML 6) × BML 51 had significant 3-line effect (tijk) and (BML 32 × BML 13) × BML 14 had significant 2-line specific effect of first kind (dij). Double cross, (BML 51 × BML 7) × (BML 13 × BML 10) had BML-51 with high 1-line general effect and highly significant 2-line interaction effect t(ij) (- -).

Table 3 - *Per se* performance of top five single, three-way and double crosses at pooled locations for yield and yield contributing traits.

Trait	Single crosses	Three-way crosses	Double crosses
Fodder yield (kg plot^{-1})	BML- 51 × BML-14 (9161)**	(BML- 14 × BML-6) × BML-51 (9949)^{c}	(BML- 51 × BML-7) × (BML-13 × BML-10) (8512)^{1}
	BML- 51 × BML-7 (7199)**	(BML- 32 × BML-13) × BML-14 (8994)^{a,c}	(BML- 51 × BML-10) × (BML-14 × BML-13) (8333)
	BML- 51 × BML-6 (7062)	(BML- 14 × BML-10) × BML-51 (8750)	(BML- 51 × BML-14) × (BML-10 × BML-7) (8316)
	BML- 14 × BML-13 (7038)**	(BML- 32 × BML-6) × BML-51 (8674)	(BML- 51 × BML-32) × (BML-14 × BML-7) (8173)^{1}
	BML- 13 × BML-6 (6658)**	(BML- 14 × BML-13) × BML-51 (8300)	(BML- 51 × BML-14) × (BML-13 × BML-10) (8120)

Note: *- signifcant *sca* effects in single crosses
[a]-highly significant 2-line specific effects of first kind, dij *i.e.* i and j as grandparents in three-way crosses
[b]-significant 2-line specific effects of second kind, sij *i.e.* i as grandparent and j as immediate parent in three-way crosses
[c]-significant 3-line specific effects, tijk in three-way crosses
[1]-significant 2-line interaction effect of lines i and j due to the particular arrangement, t(ij) (- -)

Table 4 A - Order effects with respect to *per se* performance for fodder yield (kg ha^{-1}) pooled over locations in three-way crosses.

	Crosses	Fodder yield (kg ha^{-1})	Crosses	Fodder yield (kg ha^{-1})	Crosses	Fodder yield (kg ha^{-1})
	Group-1		Group-13		Group-25	
1	(BML-51×BML-32)×BML-14	7457	(BML-51×BML-10)×BML-7	6448	(BML-32×BML-7)×BML-6	6006
2	(BML-51×BML-14)×BML-32	7172	(BML-51×BML-7)×BML-10	6725	(BML-32×BML-6)×BML-7	6922
3	(BML-32×BML-14)×BML-51	7872	(BML-10×BML-7)×BML-51	7007	(BML-7×BML-6)×BML-32	7402
	Group-2		Group-14		Group-26	
1	(BML-51×BML-32)×BML-13	7030	(BML-51×BML-10)×BML-6	8092	(BML-14×BML-13)×BML-10	4341
2	(BML-51×BML-13)×BML-32	6247	(BML-51×BML-6)×BML-10	6468	(BML-14×BML-10)×BML-13	6633
3	(BML-32×BML-13)×BML-51	7557	(BML-10×BML-6)×BML-51	5415	(BML-13×BML-10)×BML-14	7605
	Group-3		Group-15		Group-27	
1	(BML-51×BML-32)×BML-10	6054	(BML-51×BML-7)×BML-6	6894	(BML-14×BML-13)×BML-7	6910
2	(BML-51×BML-10)×BML-32	6505	(BML-51×BML-6)×BML-7	6922	(BML-14×BML-7)×BML-13	6075
3	(BML-32×BML-10)×BML-51	6992	(BML-7×BML-6)×BML-51	7718	(BML-13×BML-7)×BML-14	6677
	Group-4		Group-16		Group-28	
1	(BML-51×BML-32)×BML-7	5687	(BML-32×BML-14)×BML-13	6350	(BML-14×BML-13)×BML-6	6513
2	(BML-51×BML-7)×BML-32	6809	(BML-32×BML-13)×BML-14	8994	(BML-14×BML-6)×BML-13	5652
3	(BML-32×BML-7)×BML-51	7357	(BML-14×BML-13)×BML-32	6751	(BML-13×BML-6)×BML-14	6274
	Group-5		Group-17		Group-29	
1	(BML-51×BML-32)×BML-6	5485	(BML-32×BML-14)×BML-10	6031	(BML-14×BML-10)×BML-7	5528
2	(BML-51×BML-6)×BML-32	7036	(BML-32×BML-10)×BML-14	6598	(BML-14×BML-7)×BML-10	5416
3	(BML-32×BML-6)×BML-51	8674	(BML-14×BML-10)×BML-32	7129	(BML-10×BML-7)×BML-14	7348
	Group-6		Group-18		Group-30	
1	(BML-51×BML-14)×BML-13	6645	(BML-32×BML-14)×BML-7	7064	(BML-14×BML-10)×BML-6	8061
2	(BML-51×BML-13)×BML-14	6804	(BML-32×BML-7)×BML-14	5836	(BML-14×BML-6)×BML-10	5879
3	(BML-14×BML-13)×BML-51	8300	(BML-14×BML-7)×BML-32	7524	(BML-10×BML-6)×BML-14	7291
	Group-7		Group-19		Group-31	
1	(BML-51×BML-14)×BML-10	6267	(BML-32×BML-14)×BML-6	5779	(BML-14×BML-7)×BML-6	5522
2	(BML-51×BML-10)×BML-14	7447	(BML-32×BML-6)×BML-14	7403	(BML-14×BML-6)×BML-7	6303
3	(BML-14×BML-10)×BML-51	8750	(BML-14×BML-6)×BML-32	5712	(BML-7×BML-6)×BML-14	7506
	Group-8		Group-20		Group-32	
1	(BML-51×BML-14)×BML-7	8102	(BML-32×BML-13)×BML-10	4905	(BML-13×BML-10)×BML-7	5819
2	(BML-51×BML-7)×BML-14	8205	(BML-32×BML-10)×BML-13	5650	(BML-13×BML-7)×BML-10	4855
3	(BML-14×BML-7)×BML-51	7273	(BML-13×BML-10)×BML-32	6136	(BML-10×BML-7)×BML-13	5851
	Group-9		Group-21		Group-33	
1	(BML-51×BML-14)×BML-6	7930	(BML-32×BML-13)×BML-7	6743	(BML-13×BML-10)×BML-6	6619
2	(BML-51×BML-6)×BML-14	6710	(BML-32×BML-7)×BML-13	5633	(BML-13×BML-6)×BML-10	5357
3	(BML-14×BML-6)×BML-51	9949	(BML-13×BML-7)×BML-32	7276	(BML-10×BML-6)×BML-13	5220
	Group-10		Group-22		Group-34	
1	(BML-51×BML-13)×BML-10	5555	(BML-32×BML-13)×BML-6	6131	(BML-13×BML-7)×BML-6	6277
2	(BML-51×BML-10)×BML-13	6716	(BML-32×BML-6)×BML-13	6254	(BML-13×BML-6)×BML-7	6196
3	(BML-13×BML-10)×BML-51	5805	(BML-13×BML-6)×BML-32	5341	(BML-7×BML-6)×BML-13	5456
	Group-11		Group-23		Group-35	
1	(BML-51×BML-13)×BML-7	6395	(BML-32×BML-10)×BML-7	7001	(BML-10×BML-7)×BML-6	5802
2	(BML-51×BML-7)×BML-13	5471	(BML-32×BML-7)×BML-10	5846	(BML-10×BML-6)×BML-7	6985
3	(BML-13×BML-7)×BML-51	7266	(BML-10×BML-7)×BML-32	7016	(BML-7×BML-6)×BML-10	6560
	Group-12		Group-24		**Mean**	**6608**
1	(BML-51×BML-13)×BML-6	7134	(BML-32×BML-10)×BML-6	5541		
2	(BML-51×BML-6)×BML-13	5910	(BML-32×BML-6)×BML-10	5607	**SEm ±**	**899.64**
3	(BML-13×BML-6)×BML-51	6431	(BML-10×BML-6)×BML-32	6034		

Table 4 B - Order effects with respect to *per se* performance for fodder yield (kg ha^{-1}) pooled over locations in double crosses.

	Group-1		Group-13		Group-25	
1	(BML-51×BML-32)×(BML-14×BML-13)	7313	(BML-51×BML-14)×(BML-13×BML-6)	6912	(BML-32×BML-14)×(BML-10×BML-6)	5485
2	(BML-51×BML-14)×(BML-32×BML-13)	6719	(BML-51×BML-13)×(BML-14×BML-6)	7836	(BML-32×BML-10)×(BML-14×BML-6)	5979
3	(BML-51×BML-13)×(BML-32×BML-14)	7064	(BML-51×BML-6)×(BML-14×BML-13)	7631	(BML-32×BML-6)×(BML-14×BML-10)	6387
	Group-2		Group-14		Group-26	
1	(BML-51×BML-32)×(BML-14×BML-10)	6668	(BML-51×BML-14)×(BML-10×BML-7)	8316	(BML-32×BML-14)×(BML-7×BML-6)	7038
2	(BML-51×BML-14)×(BML-32×BML-10)	6158	(BML-51×BML-10)×(BML-14×BML-7)	6393	(BML-32×BML-7)×(BML-14×BML-6)	7275
3	(BML-51×BML-10)×(BML-32×BML-14)	7281	(BML-51×BML-7)×(BML-14×BML-10)	7233	(BML-32×BML-6)×(BML-14×BML-7)	6465
	Group-3		Group-15		Group-27	
1	(BML-51×BML-32)×(BML-14×BML-7)	8173	(BML-51×BML-14)×(BML-10×BML-6)	7663	(BML-32×BML-13)×(BML-10×BML-7)	6345
2	(BML-51×BML-14)×(BML-32×BML-7)	6095	(BML-51×BML-10)×(BML-14×BML-6)	7296	(BML-32×BML-10)×(BML-13×BML-7)	5999
3	(BML-51×BML-7)×(BML-32×BML-14)	7218	(BML-51×BML-6)×(BML-14×BML-10)	7722	(BML-32×BML-7)×(BML-13×BML-10)	6185
	Group-4		Group-16		Group-28	
1	(BML-51×BML-32)×(BML-14×BML-6)	6662	(BML-51×BML-14)×(BML-7×BML-6)	6739	(BML-32×BML-13)×(BML-10×BML-6)	5701
2	(BML-51×BML-14)×(BML-32×BML-6)	6908	(BML-51×BML-7)×(BML-14×BML-6)	6997	(BML-32×BML-10)×(BML-13×BML-6)	5998
3	(BML-51×BML-6)×(BML-32×BML-14)	7526	(BML-51×BML-6)×(BML-14×BML-7)	6823	(BML-32×BML-6)×(BML-13×BML-10)	7422
	Group-5		Group-17		Group-29	
1	(BML-51×BML-32)×(BML-13×BML-10)	7554	(BML-51×BML-13)×(BML-10×BML-7)	6608	(BML-32×BML-13)×(BML-7×BML-6)	6682
2	(BML-51×BML-13)×(BML-32×BML-10)	6705	(BML-51×BML-10)×(BML-13×BML-7)	6590	(BML-32×BML-7)×(BML-13×BML-6)	5597
3	(BML-51×BML-10)×(BML-32×BML-13)	6064	(BML-51×BML-7)×(BML-13×BML-10)	8512	(BML-32×BML-6)×(BML-13×BML-7)	6089
	Group-6		Group-18		Group-30	
1	(BML-51×BML-32)×(BML-13×BML-7)	7275	(BML-51×BML-13)×(BML-10×BML-6)	7846	(BML-32×BML-10)×(BML-7×BML-6)	6637
2	(BML-51×BML-13)×(BML-32×BML-7)	7621	(BML-51×BML-10)×(BML-13×BML-6)	6579	(BML-32×BML-7)×(BML-10×BML-6)	6497
3	(BML-51×BML-7)×(BML-32×BML-13)	6381	(BML-51×BML-6)×(BML-13×BML-10)	7162	(BML-32×BML-6)×(BML-10×BML-7)	6664
	Group-7		Group-19		Group-31	
1	(BML-51×BML-32)×(BML-13×BML-6)	7254	(BML-51×BML-13)×(BML-7×BML-6)	7120	(BML-14×BML-13)×(BML-10×BML-7)	7188
2	(BML-51×BML-13)×(BML-32×BML-6)	7125	(BML-51×BML-7)×(BML-13×BML-6)	6920	(BML-14×BML-10)×(BML-13×BML-7)	6383
3	BML-51×BML-6)×(BML-32×BML-13)	6515	(BML-51×BML-6)×(BML-13×BML-7)	6120	(BML-14×BML-7)×(BML-13×BML-10)	6149
	Group-8		Group-20		Group-32	
1	(BML-51×BML-32)×(BML-10×BML-7)	6407	(BML-51×BML-10)×(BML-7×BML-6)	6356	(BML-14×BML-13)×(BML-10×BML-6)	6326
2	(BML-51×BML-10)×(BML-32×BML-7)	7290	(BML-51×BML-7)×(BML-10×BML-6)	6839	(BML-14×BML-10)×(BML-13×BML-6)	6716
3	(BML-51×BML-7)×(BML-32×BML-10)	5809	(BML-51×BML-6)×(BML-10×BML-7)	6629	(BML-14×BML-6)×(BML-13×BML-10)	5817
	Group-9		Group-21		Group-33	
1	(BML-51×BML-32)×(BML-10×BML-6)	6779	(BML-32×BML-14)×(BML-13×BML-10)	5359	(BML-14×BML-13)×(BML-7×BML-6)	7351
2	(BML-51×BML-10)×(BML-32×BML-6)	6296	(BML-32×BML-13)×(BML-14×BML-10)	6088	(BML-14×BML-7)×(BML-13×BML-6)	6598
3	(BML-51×BML-6)×(BML-32×BML-10)	7550	(BML-32×BML-10)×(BML-14×BML-13)	7243	(BML-14×BML-6)×(BML-13×BML-7)	7524
	Group-10		Group-22		Group-34	
1	(BML-51×BML-32)×(BML-7×BML-6)	6585	(BML-32×BML-14)×(BML-13×BML-7)	6120	(BML-14×BML-10)×(BML-7×BML-6)	6369
2	(BML-51×BML-7)×(BML-32×BML-6)	6359	(BML-32×BML-13)×(BML-14×BML-7)	6012	(BML-14×BML-7)×(BML-10×BML-6)	8002
3	(BML-51×BML-6)×(BML-32×BML-7)	6264	(BML-32×BML-7)×(BML-14×BML-13)	7203	(BML-14×BML-6)×(BML-10×BML-7)	6568
	Group-11		Group-23		Group-35	
1	(BML-51×BML-14)×(BML-13×BML-10)	8120	(BML-32×BML-14)×(BML-13×BML-6)	7020	(BML-13×BML-10)×(BML-7×BML-6)	6252
2	(BML-51×BML-13)×(BML-14×BML-10)	7551	(BML-32×BML-13)×(BML-14×BML-6)	6927	(BML-13×BML-7)×(BML-10×BML-6)	6570
3	(BML-51×BML-10)×(BML-14×BML-13)	8333	(BML-32×BML-6)×(BML-14×BML-13)	6361	(BML-13×BML-6)×(BML-10×BML-7)	6183
	Group-12		Group-24		**Mean**	**6831**
1	(BML-51×BML-14)×(BML-13×BML-7)	7555	(BML-32×BML-14)×(BML-10×BML-7)	7320		
2	(BML-51×BML-13)×(BML-14×BML-7)	6716	(BML-32×BML-10)×(BML-14×BML-7)	7933	**S.E.±**	**781.16**
3	(BML-51×BML-7)×(BML-14×BML-13)	7860	(BML-32×BML-7)×(BML-14×BML-10)	6691		

Conclusions

The high fodder yielding hybrids in each category *viz.*, BML 51 × BML 14 (9161 kg ha^{-1}), (BML 14 × BML 6) × BML 51 (9949 kg ha^{-1}) and (BML 51 × BML 7) × (BML 13 × BML 10) (8512 kg ha^{-1}) also showed superior grain yields 8733, 8395 and 7844 kg ha^{-1}, respectively. It clearly indicated that single and three-way crosses would give better fodder yields than double crosses but, in fodder scarcity areas under drought prone environments where majority of the farmers are resource poor, three-way crosses are a better option than single crosses. The high fodder and grain yields could be attributed to the involvement of good general combiners in single crosses and good general and specific combiners in three-way crosses.

References

Chaudhary BD, 1978. Triallel analysis for seed weight in barley. Indian J Hered 10: 59-67.

Chaudhary BD, 1984. Double-cross hybrid analysis for spikes per plant in barley. Andhra Agric J 31: 201-206.

Chaudhary BD, Rai L, 1982. Estimation of epistatic components for seed size [barley]. Genetica Iberica (Spain).

Chaudhary BD, Singh RK, Kakar SN, 1975. Estimation of genetic parameters in barley (Hordeum vulgare L.). III. Triallel analysis. J Cytol Genet Congr Supply 58-60.

Chaudhary DP, Kumar A, Mandhania SS, Srivastava P, Kumar RS, 2012.Maize As Fodder? An alternative approach, Directorate of Maize Research, Pusa Campus, New Delhi -110 012, Technical Bulletin 2012/04: 32.

Ertiro BT, Zeleke H, Friesen D, Blummel M, Twumasi-Afriyie S, 2013. Relationship between the performance of parental inbred lines and hybrids for food-feed traits in maize (*Zea mays* L.) in Ethiopia. Field Crops Res 153: 86-93.

Ganga Rao NVPR, 1997. Genetics of seed yield and oil content in single, three-way and double crosses of Indian mustard. Ph.D. Thesis, Indian Agricultural Research Institute, New Delhi.

Griffing B, 1956. Concept of general and specific combining ability in relation to diallel crossing systems. Aust J Biol Sci 9: 463-493.

Guerrero CG, Robles MAG, Ortega JGL, Castillo IO, Vázquez CV, Carrillo MG, Resendez AM, Torres AG, 2014. Combining ability and heterosis in corn breeding lines to forage and grain. American J Plant Sci 5: 845.

Joshi AK, Sharma GS, 1984. Genetics of flag leaf area in wheat triallel analysis. Indian J Genet & Pl br 44: 399-405.

Mendes UC, Oliveira AS, Reis EFD, 2015. Heterosis and combining ability in crosses between two groups of open-pollinated maize populations. Crop Breed & Appl Biotech 15: 235-243.

Ponnuswamy KN, Das MN, Handoo MI, 1974. Combining ability type of analysis for triallel crosses in maize (*Zea mays* L.). Theor & Appl Genet 45: 170-175.

Rajamani S, 2014. Triallel Analysis for Fibre Characters in Cotton (Gossipium hirsutum L.). J of Plant & Pest Sci 1: 22-28.

Rawlings JO, Cockerham CC, 1962a. Triallel analysis. Crop Sci 2: 228-231.

Rawlings JO, Cockerham CC, 1962b. Analysis of double cross hybrid population. Biometrics 18: 229-244.

Singh RK, Chaudhary BD, 1977. The order effects in double-cross hybrids. Crop Improv 4: 213-220.

Sumalini K, Pradeep T, Sravani D, 2016. Combining ability analysis over environments in Diallel crosses of Maize (*Zea mays*). Madras Agric J 103(10-12): 297-303.

Sumalini K, Pradeep T, Sravani D, Rajanikanth E, Reddy SN, 2018. Gene action and order effects in double cross hybrids of maize (*Zea mays* L.) for grain yield under diverse agroclimatic zones of telangana. The Bioscan 13(3): 761-768.

Sumalini K, Pradeep T, Sravani D, 2020. Triallel analysis for grain yield and its components over pooled environments in maize (*Zea mays* L.). Maydica 64(2): 1-10.

Sunil K, Agrawal RK, Dixit AK, Rai AK, Singh JB, Rai SK, 2012.Forage Production Technology for Arable Lands. Technology Bulletin 39: 255-260.

Vyavasaya Panchangam, 2015. Maize Package of practices. A Professor Jayashankar Telangana State Agricultural University publication.pp 30-41.

Wright JA, Hallauer AR, Penny LH, Eberhart SA, 1971. Estimating genetic variance in maize by use of single and three-way crosses among unselected inbred lines. Crop Sci 11: 690-695.