Identification of potential parental lines for single, three-way and double crosses in maize (*Zea mays* L.)

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Abstract

A series of single, three way and double cross hybrids in maize were developed by involving seven inbred lines through half diallel and were evaluated along with private/public hybrids for yield and yield contributing traits in a balanced lattice design at three environments during *kharif* 2015. Combining ability studies revealed that good general combiners identified through diallel had significant and desirable 1-line general effects of first kind and second kind for majority of the yield and yield contributing traits in triallel and 1-line general effects in desirable direction for all the studied traits in quadriallel. Good specific combiners that were involved as grandparents / half parents had significant 2-line and 3-line interaction effects in triallel and 2-line, 3-line and 4-line interaction effects in quadriallel for majority of the yield and yield contributing traits. Good specific combiners from diallel *viz.*, BML-51 × BML-6 as half parents in three-way crosses along with, BML-51 × BML-7 as half parents in double crosses, BML-51 × BML-14, BML-32 × BML-13 and BML-32 × BML-6 as half or grandparents in three way and double crosses produced high yielding three way and double cross hybrids. From the present investigation it is deduced that the good general and specific combiners identified through diallel analysis would certainly contribute to the development of potential climate resilient multiple cross hybrids and save valuable resources and precious time.

Introduction

In crop improvement programs, two or more inbred lines are generally utilized to create variability for improvement of a character. In this process decision on choice of the parents to be involved in hybridization and choice of crosses to be advanced from among several effected crosses are equally important. For quantitative traits like grain yield, choice of parents is difficult because in several cases it is observed that certain parents nick well when crossed and produce a large number of superior segregates while certain crosses obtained between desirable parents may produce an array of disappointing progeny.

Combining ability analysis is targeted to identify the better combiners which can be hybridized to exploit heterosis and to select better crosses for direct use or for further breeding work. According to Allard (1960), the 'expected' value of any particular cross is the sum of the GCA's (General Combining Ability) of its two parental lines, while the deviation from this expected value is called SCA (Specific Combining Ability). GCA values describe the general usefulness of the parental form in terms of the concerned trait, whereas SCA indicates importance of the joint action of the genes of parental forms (Baker, 1978).Variability in SCA effects for a given trait in the initial material for breeding is unfavorable as it increases the probability of obtaining hybrid progenies with an average value of that trait. The amount of improvement expected to come from GCA and SCA will be proportional to their variances (Griffing, 1956).

Sumalini et al. (2016, 2018 & 2019) had performed genetic analysis for grain yield and its contributing characters over environments in single, three-way and double cross maize hybrids and reported the best general and specific combiners and also order effects through diallel, triallel and quadriallel analyses, respectively. In the present investigation, a comparative analysis of combining abilities of inbreds and single crosses in their respective three-way and double crosses was conducted based on the findings obtained at three different locations to estimate the contribution of superior general and specific combiners identified through diallel analysis in the development of potential multiple cross hybrids which can be potential alternatives to single crosses.

Materials and Methods

A set of single, three-way and double cross hybrids were developed and evaluated to identify promising single, three-way and double cross combinations (Sumalini et al., 2018 & 2019). Since the research findings of diallel, triallel and quadriallel analyses were already reported by the authors (Sumalini et al., 2016, 2018 & 2019), data from the same reports is used in the present paper to carry out comparative analysis of combining abilities of inbreds and single crosses in their respective three-way and double crosses. List of abbreviations used in text and tables is given appendix.

Results and discussion

1-line general effects of first and second kind

The data pertaining to diallel analysis of seven inbreds and 21 single crosses, along with data on good general combiners and top ranking specific combiners in desirable direction for yield and yield contributing characters are presented in Table 1 and 2. In triallel analysis, lines identified as good general combiners from diallel analysis had significant and desirable 1-line general effects of first kind (hi) while second kind (gi) was significant for days to 50% pollen shed, days to 50% silk emergence, kernel rows ear^{-1}, kernels row^{-1}, shelling percentage, 100-grain weight, fodder yield and grain yield while for the remaining traits good general combiners from diallel had either significant 1-line general effects of first or second kind in desirable direction indicating that good general combiners in diallel analysis could be used both as grandparents (hi) and/or immediate parents (gi) in triallel analysis. In quadriallel analysis, good general combiners of diallel analysis had expressed 1-line general line effects in desirable direction for all the traits studied indicating the trend that general combiners identified through diallel analysis must be involved as one of the parent out of four pa-

Table 1 - Good general combiners in diallel, triallel and quadriallel analysis.

Traits	Diallel analysis	Triallel analysis		Quadriallel analysis
	Parent (gca effect)	1-line general line effect of 1st kind i.e. as Grand parent (hi effect)	1-line general line effect of 2nd kind i.e. as Immediate parent (gi effect)	1-line general effects (gi effect)
Days to 50% pollen shed	BML-10 (-2.66**), BML-13 (-2.03**)	BML-13 (-0.98**), BML-10 (-0.64**)	BML-10 (-2.78**), BML-13 (-1.69**)	BML-13 (-0.66), BML-10 (-0.32), BML-14 (-0.26)
Days to 50% silk emergence	BML-10 (-2.22**), BML-13 (-1.89**)	BML-13 (-0.78**), BML-10 (-0.34*)	BML-10 (-2.15**), BML-13 (-1.48**)	BML-13 (-0.65), BML-14 (-0.31), BML-10 (-0.23)
Days to 75% dry husk	BML-13 (-1.70**), BML-10 (-1.39**), BML-51 (-0.67*)	BML-13 (-.80**), BML-51 (-0.47*)	BML-13 (-1.46**), BML-10 (-1.12**)	BML-13 (-0.35), BML-14 (-0.20)
Plant height (cm)	BML-51 (20.36**), BML-32 (11.23**), BML-7 (6.82**)	BML-51 (10.32**), BML-32 (5.37**)	BML-51 (14.57**), BML-32 (10.56**), BML-7 (6.25**)	BML-51 (4.81), BML-32 (2.07), BML-7 (1.87)
Ear height (cm)	BML-51 (13.40**), BML-6 (4.16**), BML-32 (3.05**)	BML-51 (6.21**), BML-6 (1.76*), BML-7 (1.50*)	BML-51 (7.65**), BML-6 (5.05**), BML-7 (3.49**)	BML-51 (2.52), BML-7 (1.51), BML-6 (0.72)
Ear length (cm)	BML-32 (1.02**), BML-51 (0.31*)	BML-32 (0.65**)	BML-32 (1.49**), BML-51 (0.32*)	BML-32 (0.34)
Ear diameter (cm)	BML-6 (0.13**), BML-7 (0.10**)	BML-7 (0.03*)	BML-6 (0.19**), BML-7 (0.10**)	BML-7 (0.03), BML-6 (0.0.03)
Kernel rows ear^{-1}	BML-6 (0.76**), BML-10 (0.46**), BML-7 (0.21**)	BML-6 (0.42**), BML-7 (0.25**), BML-10 (0.20**)	BML-6 (1.00**), BML-10 (0.37**), BML-7 (0.15**)	BML-6 (0.17), BML-10 (0.10), BML-13 (0.04)
Kernels row^{-1}	BML-6 (1.82**), BML-32 (1.73**)	BML-32 (0.99**), BML-6 (0.80**)	BML-32 (2.53**), BML-6 (0.86**)	BML-32 (0.65), BML-6 (0.12)
Shelling percentage (%)	BML-51 (2.09**), BML-13 (2.04**), BML-32 (1.34**)	BML-32 (1.20**), BML-51 (0.70**), BML-13 (0.48**)	BML-32 (1.78**), BML-13 (1.31**), BML-51 (1.03**)	BML-51 (1.17), BML-32 (0.67), BML-13 (0.28)
100-grain weight (g)	BML-51 (3.38**), BML-14 (3.33**)	BML-51 (1.70**), BML-14 (1.64**)	BML-14 (4.27**), BML-51 (2.52**)	BML-14 (0.87), BML-51(0.40)
Fodder yield (kg plot^{-1})	BML-51 (0.25**), BML-14 (0.13*)	BML-51 (0.16**), BML-14 (0.13*)	BML-51 (0.45**), BML-14 (0.32**)	BML-51 (0.10), BML-14 (0.06)
Grain yield (kg ha^{-1})	BML-51 (490.25**)	BML-51 (303.90**)	BML-51 (442.80**), BML-32 (336.30**), BML-14 (292.30*)	BML-51 (65.77), BML-13 (44.49), BML-14 (19.11)

*: significant at 5%, **: significant at 1%

Table 2 - First three good specific combiners in diallel analysis.

Traits	Good specific combiners
Days to 50% pollen shed	BML-51 × BML-14 (-3.01**), BML-13 × BML-6 (-2.73**), BML-51 × BML-6 (-2.58**)
Days to 50% silk emergence	BML-51 × BML-7 (-2.57**), BML-14 × BML-6 (-2.31**), BML-51 × BML-32 (-2.15*)
Days to 75% dry husk	BML-51 × BML-7 (-2.79**), BML-14 × BML-6 (-2.49**), BML-13 × BML-7 (-1.75*)
Plant height (cm)	BML-13 × BML-6 (27.08**), BML-51 × BML-6 (18.60**), BML-51 × BML-13 (18.56*)
Ear height (cm)	BML-10 × BML-7 (15.32**), BML-13 × BML-6 (15.25**), BML-14 × BML-13 (11.47**)
Ear length (cm)	BML-32 × BML-10 (3.30**), BML-32 × BML-13 (2.41**), BML-51 × BML-6 (2.07**)
Ear diameter (cm)	BML-32 × BML-6 (0.45**), BML-14 × BML-10 (0.45**), BML-14 × BML-13 (0.38**)
Kernel rows ear^{-1}	BML-32 × BML-6 (1.04**), BML-32 × BML-10 (1.00**), BML-10 × BML-6 (0.74**)
Kernels row^{-1}	BML-32 × BML-10 (5.59**), BML-32 × BML-13 (5.41**), BML-32 × BML-14 (5.11**)
Shelling percentage (%)	BML-14 × BML-6 (3.74**), BML-32 × BML-6 (2.60**), BML-7 × BML-6 (2.19**)
100-grain weight (g)	BML-14 × BML-13 (6.51**), BML-10 × BML-7 (6.38**), BML-51 × BML-6 (4.06**)
Fodder yield (kg plot^{-1})	BML-51 × BML-14 (1.99**), BML-14 × BML-13 (0.61**), BML-32 × BML-7 (0.58**)
Grain yield (kg ha^{-1})	BML-51 × BML-14 (2026.58**), BML-32 × BML-6 (1579.73**), BML-10 × BML-7 (1536.25**)

*: significant at 5%, **: significant at 1%

rents in double crosses (Table 1).

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

In triallel analysis first three crosses that had shown significant 2-line specific effects of first (dij) and second kind (sij) and 3-line interaction effects (tijk) in desirable direction for all the traits are furnished in Table 3. Perusal of the data suggest that all the traits except days to 50% pollen shed, days to 75% dry husk and fodder yield, a few lines observed to be good specific combiners from diallel analysis exhibited significant 2-line specific effects of first kind and second kind in desirable direction. Similarly, a few of the 3-line effects in respect of majority of the traits had resulted from a combination of a good specific combiner of diallel with a good general combiner suitable as immediate parent in triallel analysis. For *eg.* in case of grain yield, good specific combiners *i.e.* single crosses were involved as the grandparents or half parents in all significant 2-line and 3-line interaction effects except BML-10 × BML-6 in 2-line interaction effect of second kind and BML-13 × BML-10 in 3-line interaction effects. BML-51, a good general combiner for grain yield is involved as one of the parent in all the significant 3-line effects either as grand parent or immediate parent except (BML-32 × BML-10) × BML-7.

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

Quadriallel analysis (Table 4), had revealed that the first three crosses had shown high values in desirable direction for 2-line interaction effect of lines i and j due to a particular arrangement (ij) (- -) *i.e.* tij, (i-) (j-), *i.e.* ti.j. and sij, *i.e.* effect of i and j irrespective of arrangement. For all the traits, except days to maturity, specific combiners identified through diallel analysis had either one or two or all three crosses of tij, ti.j. and sij interaction effects in desirable direction.

Results on 3-line (tij.k) and 4-line (tij.kl) interaction effects in respect of top ranking three crosses due to a particular arrangement or otherwise *i.e.* sijk and sijkl, were in desirable direction (Table 5&6, respectively). Good specific combiners identified from diallel were grandparents in tij.k effects for majority of the traits and tij.kl effects for all the traits studied except shelling percentage. However, 3-line and 4-line interaction effects irrespective of arrangement *i.e.* sijk and sijkl effects, respectively had good specific combiners of diallel either as grand parents and/or half parents for all the traits studied.

Combining ability and per se performance

Per se performance of top five crosses in desirable direction for ear and yield contributing characters in case of single, three way and double crosses is presented in Table 7.For all the studied traits, majority or all of the top five desirable crosses in each category i.e. single, three-way and double crosses had significant combining ability effects. For *e.g.* for grain yield, good specific combiners were good yielders in case of single crosses while significant 2-line and 3-line interaction effects were observed in top five high yielding three way crosses and the same trend of high 2-line/3-line/4-line interactions were noticed in top high yielding double crosses. Further, all the top five high yielding

Table 3 - First three significant 2- line specific effects of first (dij) and second kind (sij) and 3-line specific effects (tijk) in Triallel analysis.

Traits	dij	sij	tijk
Days to 50% pollen shed	BML-14 × BML-13 (-0.66*)	BML-13 × BML-10 (-0.90**), BML-32 × BML-14 (-0.88**), BML-51 × BML-10 (-0.63**)	(BML-51 × BML-13) × BML-7 (-1.57**), (BML-51 × BML-10) × BML-32 (-1.39**),(BML-10 × BML-6) × BML-7 (-1.39**)
Days to 50% silk emergence	-	BML-13 × BML-10 (-0.79**), BML-51 × BML-6 (-0.61*)	(BML-51 × BML-14) × BML-7 (-1.86**),(BML-7 × BML-6) × BML-32 (-1.63**),(BML-32 × BML-6) × BML-51 (-1.58**)
Days to 75% dry husk	-	-	(BML-51 × BML-13) × BML-7 (-2.72**),(BML-14 × BML-10) × BML-7 (-1.88*),(BML-51 × BML-10) × BML-32 (-1.85*)
Plant height (cm)	BML-7 × BML-6 (4.78*), BML-32 × BML-13 (4.74*), BML-51 × BML-13 (3.96*)	BML-51 × BML-6 (6.33**), BML-14 × BML-7 (4.64**)	(BML-14 × BML-7) × BML-13 (9.72**),(BML-51 × BML-32) × BML-14 (7.48*),(BML-32 × BML-7) × BML-6 (7.36*)
Ear height (cm)	BML-10 × BML-7 (3.20*)	BML-51 × BML-6 (4.44**), BML-14 × BML-13 (2.74*)	(BML-7 × BML-6) × BML-10 (7.68**), (BML-14 × BML-7) × BML-13 (7.42**),(BML-14 × BML-10) × BML-6 (5.92*)
Ear length (cm)	BML-7 × BML-6 (0.57**), BML-32 × BML-14 (0.55**), BML-32 × BML-13 (0.42*)	BML-13 × BML-7 (0.61**), BML-10 × BML-6 (0.45*), BML-32 × BML-13 (0.41*)	(BML-14 × BML-6) × BML-13 (1.35**),(BML-51 × BML-32) × BML-10 (1.07**), (BML-14 × BML-7) × BML-32 (0.93*)
Ear diameter (cm)	BML-32 × BML-6 (0.10**), BML-51 × BML-6 (0.08*), BML-10 × BML-7 (0.08**)	BML-51 × BML-32 (0.09**), BML-10 × BML-7 (0.05*)	(BML-7 × BML-6) × BML-10 (0.18**),(BML-7 × BML-6) × BML-51 (0.17**),(BML-14 × BML-7) × BML-13 (0.15**),(BML-10 × BML-6) × BML-7 (0.15**)
Kernel rows ear^{-1}	BML-7 × BML-6 (0.37**), BML-51 × BML-14 (0.29**)	BML-51 × BML-32 (0.36**), BML-32 × BML-10 (0.31**), BML-13 × BML-6 (0.29**)	(BML-51 × BML-32) × BML-13 (0.46**),(BML-32 × BML-10) × BML-6 (0.42**),(BML-10 × BML-7) × BML-13 (0.35*)
Kernels row^{-1}	BML-32 × BML-13 (0.93*), BML-10 × BML-6 (0.90*)	BML-10 × BML-6 (0.85*), BML-13 × BML-6 (0.81*)	(BML-14 × BML-6) × BML-13 (2.08**),(BML-32 × BML-6) × BML-7 (1.59*)
Shelling percentage (%)	BML-32 × BML-10 (0.74*), BML-10 × BML-6 (0.72*)	BML-10 × BML-6 (0.76**)	(BML-32 × BML-6) × BML-7 (1.58**), (BML-13 × BML-7) × BML-6 (1.39*),(BML-32 × BML-7) × BML-10 (1.21*)
100-grain weight (g)	BML-51 × BML-7 (1.24*), BML-51 × BML-10 (1.23*), BML-32 × BML-14 (1.19*), BML-13 × BML-7 (1.19*)	BML-51 × BML-10 (1.90**), BML-51 × BML-13 (1.83**), BML-32 × BML-13 (1.80**)	(BML-51× BML-13) × BML-7 (3.19**), (BML-32 × BML-10) × BML-51 (2.60*),(BML-7 × BML-6) × BML-32 (2.58*)
Fodder yield (kg plot^{-1})	BML-32 × BML-13 (0.29**)	BML-10 × BML-6 (0.22*), BML-32 × BML-13 (0.21*)	(BML-14 × BML-6) × BML-51 (0.50*), (BML-32 × BML-13) × BML-14 (0.47*), (BML-51× BML-7) × BML-14 (0.43*)
Grain yield (kg ha^{-1})	BML-32 × BML-13 (543.40**), BML-51 × BML-6 (414.20*)	BML-51 × BML-6 (659.40**), BML-32 × BML-13 (434.70**), BML-10 × BML-6 (432.70**)	(BML-32 × BML-10) × BML-7 (1175.10**),(BML-51× BML-7) × BML-14 (868.00**),(BML-51 × BML-14) × BML-7 (644.50*)

*: significant at 5%, **: significant at 1%

single crosses had either BML-51 or BML-32 as one of the parent, proved to be good general combiners for yield and yield contributing traits. In three way crosses, either BML-51 as grandparent/immediate parent or BML-32 or BML-14 as immediate parent was involved. Similarly double crosses had either BML-51 or BML-14 or BML-13 as grandparents and all these inbred lines had good general combining ability for yield and yield contributing traits. Previous reports on comparative study on actual yield of double crosses with non-parental single crosses also revealed that the average yields of double crosses were high or similar to average of performance of non-parental single crosses at Karimnagar and Palem locations and locations combined (Sumalini et al., 2017). Two of the top high yielding double crosses *viz.*, (BML-51 × BML-10) × (BML-32 × BML-7) and (BML-51 × BML-13) × (BML-32 × BML-14) were in top 25% of the total 105 double crosses predicted based on non-parental single crosses. These results again confirmed the utility of good general / specific combiners as grandparents/immediate parents in three way crosses and good specific combiners in double crosses. There is every chance of obtaining high yielding promising multiple crosses rather than proceeding to hectic and resource consuming hybridization programme.

Table 4 - First three desirable 2-line interaction effect of lines i and j due to the particular arrangement (ij) (- -), i.e. tij, (i-) (j-), i.e. ti.j. and sij, i.e. effect of i and j lines irrespective of arrangement in Quadriallel analysis

Traits	tij	ti.j.	sij
Days to 50% pollen shed	BML-13 × BML-7 (-1.26), BML-51 × BML-32 (-0.43), BML-32 × BML-14 (-0.34)	BML-32 × BML-13 (-0.38), BML-51 × BML-14 (-0.22), BML-32 × BML-7 (-0.20)	BML-13 × BML-10 (-0.25), BML-13 × BML-6 (-0.11), BML-51 × BML-10 (-0.11)
Days to 50% silk emergence	BML-13 × BML-7 (-1.36), BML-14 × BML-6 (-0.42), BML-51 × BML-32 (-0.37)	BML-32 × BML-13 (-0.39), BML-7 × BML-6 (-0.31), BML-13 × BML-10 (-0.27)	BML-13 × BML-10 (-0.26), BML-51 × BML-14 (-0.14), BML-14 × BML-7 (-0.14)
Days to 75% dry husk	BML-13 × BML-10 (-0.57), BML-14 × BML-6 (-0.51), BML-14 × BML-7 (-0.34)	BML-51 × BML-13 (-0.29), BML-7 × BML-6 (-0.20), BML-10 × BML-7 (-0.20)	BML-13 × BML-6 (-0.25), BML-13 × BML-10 (-0.19), BML-14 × BML-7 (-0.14)
Plant height (cm)	BML-51 × BML-13 (6.81), BML-13 × BML-10 (3.58), BML-7 × BML-6 (3.06)	BML-13 × BML-6 (1.74), BML-32 × BML-13 (1.59), BML-10 × BML-7 (1.54)	BML-51 × BML-32 (2.31), BML-32 × BML-7 (1.54), BML-14 × BML-7 (1.20)
Ear height (cm)	BML-51 × BML-13 (2.94), BML-32 × BML-10 (1.96), BML-32 × BML-6 (1.70)	BML-10 × BML-7 (1.48), BML-13 × BML-6 (1.09), BML-32 × BML-13 (0.95)	BML-14 × BML-7 (0.83), BML-51 × BML-6 (0.61), BML-51 × BML-10 (0.58)
Ear length (cm)	BML-7 × BML-6 (0.19), BML-13× BML-7 (0.19), BML-32 × BML-6 (0.16)	BML-14 × BML-7 (0.18), BML-51× BML-6 (0.09), BML-32 × BML-13 (0.08)	BML-32 × BML-13 (0.09), BML-51× BML-32 (0.08), BML-32 × BML-14 (0.06)
Ear diameter (cm)	BML-14 × BML-7 (0.05), BML-10 × BML-6 (0.04), BML-32 × BML-6 (0.04), BML-51 × BML-14 (0.04)	BML-14 × BML-6 (0.06), BML-32 × BML-13 (0.05), BML-51 × BML-10 (0.03)	BML-10 × BML-7 (0.03), BML-14 × BML-13 (0.02), BML-32 × BML-6 (0.02)
Kernel rows ear^{-1}	BML-51 × BML-14 (0.21), BML-7 × BML-6 (0.13), BML-10 × BML-6 (0.11)	BML-14 × BML-6 (0.10), BML-10 × BML-7 (0.09), BML-14 × BML-13 (0.06)	BML-10 × BML-6 (0.07), BML-32 × BML-13 (0.06), BML-7 × BML-6 (0.05)
Kernels row^{-1}	BML-32 × BML-14 (0.73), BML-13 × BML-7 (0.58), BML-32 × BML-6 (0.54)	BML-14 × BML-7 (0.38), BML-32 × BML-13 (0.38), BML-51 × BML-32 (0.23)	BML-32 × BML-13 (0.19), BML-32 × BML-10 (0.18), BML-32 × BML-7 (0.10)
Shelling percentage (%)	BML-13 × BML-7 (1.10), BML-14 × BML-6 (0.61), BML-51 × BML-10 (0.52)	BML-10 × BML-7 (0.34), BML-32 × BML-13 (0.20), BML-14 × BML-13 (0.16)	BML-32 × BML-10 (0.25), BML-13 × BML-10 (0.20), BML-51 × BML-32 (0.19)
100-grain weight (g)	BML-14 × BML-7 (1.34), BML-51 × BML-13 (0. 82), BML-32 × BML-6 (0.78)	BML-13 × BML-7 (0.53), BML-32 × BML-14 (0.41), BML-51 × BML-14 (0.38)	BML-14 × BML-7 (0.36), BML-10 × BML-7 (0.30), BML-14 × BML-13 (0.30)
Fodder yield (kg $plot^{-1}$)	BML-14 × BML-13 (0.16), BML-51 × BML-32 (0.10), BML-13 × BML-10 (0.06)	BML-32 × BML-13 (0.06), BML-51 × BML-10 (0.05), BML-13 × BML-6 (0.04)	BML-51 × BML-13 (0.07), BML-14 × BML-7 (0.04), BML-51 × BML-10 (0.04)
Grain yield (kg ha^{-1})	BML-13 × BML-7 (316.68), BML-32 × BML-6 (270.93), BML-32 × BML-10 (150.59)	BML-32 × BML-14 (223.72), BML-10 × BML-7 (104.06), BML-51 × BML-10 (64.11)	BML-51 × BML-14 (72.54), BML-14 × BML-7 (53.58), BML-51 × BML-13 (53.37)

*: significant at 5%, **: significant at 1%

Conclusions

Finally, it can be concluded that high yielding specific combiners BML-51 × BML-6 as half parents in three-way crosses, BML-51 × BML-7 as half parents in double crosses, BML-51 × BML-14, BML-32 × BML-13 and BML-32 × BML-6 as half or grandparents in three-way and double crosses resulted in high yielding hybrids and all these had either BML-51, a good general combiner for grain yield or BML-32, a good general combiner for yield contributing traits as parent. Thus the parental lines identified as general combiners or specific combiners through diallel analysis could be utilized for obtaining high yielding multiple crosses, the performance of which can be further confirmed by large scale evaluation in targeted environments so that climate resilient hybrids are identified

Table 5 - First three desirable 3-line interaction effects with particular arrangement and irrespective of arrangement in Quadriallel analysis

Traits	3-line interaction effects	
	tij.k (particular arrangement)	sijk (irrespective of arrangement)
Days to 50% pollen shed	(BML-7 × BML-6) × BML-14 (-0.97), (BML-10 × BML-6) × BML-13 (-0.91), (BML-32 × BML-13) × BML-14 (-0.82)	(BML-32 × BML-14) × BML-13 (-0.21), (BML-51 × BML-13) × BML-7 (-0.19), (BML-32 × BML-13) × BML-10 (-0.18)
Days to 50% silk emergence	(BML-7 × BML-6) × BML-14 (-0.97), (BML-32 × BML-13) × BML-14 (-0.83), (BML-10 × BML-7) × BML-51 (-0.82)	(BML-32 × BML-14) × BML-13 (-0.24), (BML-51 × BML-13) × BML-7 (-0.23), (BML-51 × BML-14) × BML-6 (-0.23)
Days to 75% dry husk	(BML-10 × BML-6) × BML-13 (-0.79), (BML-14 × BML-6) × BML-51 (-0.71), (BML-7 × BML-6) × BML-14 (-0.53)	(BML-14 × BML-7) × BML-6 (-0.26), (BML-14 × BML-13) × BML-10 (-0.25), (BML-51 × BML-32) × BML-14 (-0.23)
Plant height (cm)	(BML-13 × BML-10) × BML-51 (4.25), (BML-13 × BML-6) × BML-10 (4.1), (BML-10 × BML-7) × BML-6 (3.62)	(BML-14 × BML-10) × BML-7 (1.59), (BML-51 × BML-32) × BML-13 (1.52), (BML-51 × BML-32) × BML-7 (1.47)
Ear height (cm)	(BML-13 × BML-10) × BML-51 (3.51), (BML-32 × BML-10) × BML-6 (3.09), (BML-51× BML-6) × BML-10 (2.86)	(BML-14 × BML-10) × BML-7 (1.02), (BML-51 × BML-14) × BML-7 (0.75), (BML-51 × BML-32) × BML-7 (0.64)
Ear length (cm)	(BML-14 × BML-7) × BML-32 (0.41), (BML-51 × BML-7) × BML-13 (0.41), (BML-32 × BML-7) × BML-10 (0.38)	(BML-32 × BML-13) × BML-7 (0.12), (BML-51 × BML-32) × BML-6 (0.08), (BML-32 × BML-10) × BML-6 (0.06)
Ear diameter (cm)	(BML-14) × BML-6) × BML-7 (0.09), (BML-10 × BML-7) × BML-14 (0.08), (BML-51 × BML-10) × BML-32 (0.07)	(BML-10 × BML-7) × BML-6 (0.04), (BML-51 × BML-10) × BML-6 (0.03), (BML-32 × BML-14) × BML-13 (0.02)
Kernel rows ear^{-1}	(BML-14 × BML-6) × BML-13 (0.29), (BML-7 × BML-6) × BML-14 (0.29), (BML-13 × BML-7) × BML-6 (0.26)	(BML-14 × BML-7) × BML-6 (0.06), (BML-32 × BML-7) × BML-6 (0.06), (BML-14 × BML-10) × BML-6 (0.06)
Kernels row^{-1}	(BML-14 × BML-7) × BML-32 (0.82), (BML-32 × BML-14) × BML-6 (0.66), (BML-14 × BML-13) × BML-51 (0.63)	(BML-32 × BML-14) × BML-10 (0.23), (BML-32 × BML-13) × BML-7 (0.22), (BML-51 × BML-32) × BML-6 (0.19)
Shelling percentage (%)	(BML-10 × BML-7) × BML-13 (0.64), (BML-32 × BML-14) × BML-6 (0.55), (BML-51 × BML-7) × BML-13 (0.51)	(BML-32 × BML-13) × BML-10 (0.29), (BML-51 × BML-32) × BML-14 (0.20), (BML-32 × BML-14) × BML-13 (0.19)
100-grain weight (g)	(BML-13 × BML-10) × BML-51 (1.7), (BML-14 × BML-6) × BML-7 (1.62), (BML-32 × BML-14) × BML-51 (1.56)	(BML-14 × BML-10) × BML-7 (0.48), (BML-51 × BML-32) × BML-6 (0.43), (BML-14 × BML-13) × BML-7 (0.35)
Fodder yield (kg plot^{-1})	(BML-51 × BML-10) × BML-32 (0.17), (BML-32 × BML-14) × BML-51 (0.16), (BML-32 × BML-6) × BML-10 (0.14)	(BML-51 × BML-13) × BML-10 (0.06), (BML-51 × BML-14) × BML-10 (0.06), (BML-32 × BML-14) × BML-7 (0.05)
Grain yield (kg ha^{-1})	(BML-32 × BML-14) × BML-51 (418.69), (BML-14 × BML-10) × BML-32 (384.31), (BML-51× BML-7) × BML-13 (349.18)	(BML-51 × BML-13) × BML-7 (125.24), (BML-32 × BML-10) × BML-6 (124.16), (BML-51 × BML-14) × BML-10 (108.56)

*: significant at 5%, **: significant at 1%

Table 6 - First three desirable 4-line interaction effects with particular arrangement and irrespective of arrangement in Quadriallel analysis

Traits	4-line interaction effects	
	tij.kl (particular arrangement)	sijkl (irrespective of arrangement)
Days to 50% pollen shed	(BML-13 × BML-6) × (BML-10 × BML-7) (-1.17), (BML-51 × BML-14) × (BML-10 × BML-7) (-1.11), (BML-14 × BML-13) × (BML-10 × BML-6) (-1.09)	(BML-51 × BML-13) × (BML-7 × BML-6) (-0.43), (BML-51 × BML-14) × (BML-10 × BML-7) (-0.40), (BML-32 × BML-14) × (BML-7 × BML-6) (-0.40)
Days to 50% silk emergence	(BML-13 × BML-6) × (BML-10 × BML-7) (-1.23), (BML-51 × BML-14) × (BML-10 × BML-7) (-1.15), (BML-32 × BML-10) × (BML-14 × BML-6) (-1.06)	(BML-51 × BML-14) × (BML-10 × BML-6) (-0.48), (BML-51 × BML-14) (BML-7 × BML-6) (-0.44), (BML-32 × BML-13) × (BML-10 × BML-6) (-0.42)
Days to 75% dry husk	(BML-51 × BML-13) × (BML-10 × BML-6) (-1.15), (BML-51 × BML-14) × (BML-13 × BML-6) (-1.13), (BML-14 × BML-6) × (BML-13 × BML-7) (-1.13)	(BML-32 × BML-13) × (BML-10 × BML-6) (-0.72), (BML-14 × BML-13) (BML-10 × BML-7) (-0.44), (BML-51 × BML-32) × (BML-14 × BML-7) (-0.42)
Plant height (cm)	(BML-51 × BML-6) × (BML-14 × BML-7) (6.91), (BML-32 × BML-6) × (BML-13 × BML-10) (5.10), (BML-14 × BML-13) × (BML-7 × BML-6) (4.60)	(BML-51 × BML-32) × (BML-13 × BML-7) (4.30), (BML-32 × BML-14) (BML-10 × BML-7) (2.79), (BML-51 × BML-32) × (BML-10 × BML-6) (2.65)
Ear height (cm)	(BML-51 × BML-6) × (BML-14 × BML-7) (5.83), (BML-14 × BML-13) × (BML-7 × BML-6) (4.62), (BML-32 × BML-13) × (BML-10 × BML-7) (4.11)	(BML-51 × BML-32) × (BML-13 × BML-7) (2.20), (BML-51 × BML-32) × (BML-10 × BML-6) (1.97), (BML-32 × BML-14) (BML-10 × BML-7) (1.35)
Ear length (cm)	(BML-32 × BML-14) × (BML-13 × BML-6) (0.50), (BML-51 × BML-7) × (BML-32 × BML-10) (0.47), (BML-51 × BML-7) × (BML-13 × BML-6) (0.42)	(BML-51 × BML-32) × (BML-10 × BML-6) (0.26), (BML-51 × BML-32) × (BML-13 × BML-7) (0.25), (BML-32 × BML-14) (BML-10 × BML-7) (0.20)
Ear diameter (cm)	(BML-51 × BML-10) × (BML-14 × BML-13) (0.13), (BML-32 × BML-6) × (BML-14 × BML-13) (0.12), (BML-32 × BML-7) × (BML-14 × BML-6) (0.12)	(BML-32 × BML-14) × (BML-13 × BML-10) (0.07), (BML-51 × BML-32) × (BML-10 × BML-6) (0.05), (BML-13 × BML-10) (BML-7 × BML-6) (0.05)
Kernel rows ear^{-1}	(BML-14 × BML-10) × (BML-7 × BML-6) (0.28), (BML-32 × BML-6) × (BML-14 × BML-13) (0.27), (BML-51 × BML-6) × (BML-32 × BML-14) (0.25)	(BML-51 × BML-32) × (BML-10 × BML-6) (0.16), (BML-32 × BML-14) × (BML-13 × BML-10) (0.15), (BML-51 × BML-32) (BML-13 × BML-6) (0.12)
Kernels row^{-1}	(BML-51 × BML-32) × (BML-7 × BML-6) (1.33), (BML-51× BML-13) × (BML-32 × BML-7) (1.29), (BML-32 × BML-7) × (BML-10 × BML-6) (1.25)	(BML-51 × BML-32) × (BML-10 × BML-6) (0.59), (BML-32 × BML-13) × (BML-10 × BML-7) (0.47), (BML-32 × BML-14) (BML-7 × BML-6) (0.46)
Shelling percentage (%)	(BML-51 × BML-10) × (BML-14 × BML-7) (0.75), (BML-51× BML-7) × (BML-10 × BML-6) (0.73), (BML-51 × BML-10) × (BML-13 × BML-6) (0.71)	(BML-32 × BML-14) × (BML-13 × BML-10) (0.77), (BML-32 × BML-10) × (BML-7 × BML-6) (0.57), (BML-51 × BML-32) (BML-14 × BML-6) (0.48)
100-grain weight (g)	(BML-51 × BML-10) × (BML-14 × BML-6) (1.81), (BML-14× BML-7) × (BML-13 × BML-10) (1.35), (BML-32 × BML-13) × (BML-7 × BML-6) (1.30)	(BML-32 × BML-14) × (BML-10 × BML-7) (1.16), (BML-51 × BML-32) × (BML-14 × BML-6) (1.11), (BML-51 × BML-14) (BML-13 × BML-10) (0.95)
Fodder yield (kg plot^{-1})	(BML-51 × BML-14) × (BML-32 × BML-6) (0.28), (BML-51× BML-32) × (BML-14 × BML-7) (0.27), (BML-51 × BML-14) × (BML-10 × BML-7) (0.25)	(BML-32 × BML-14) × (BML-10 × BML-7) (0.17), (BML-51 × BML-14) × (BML-13 × BML-10) (0.16), (BML-14 × BML-13) (BML-7 × BML-6) (0.12)
Grain yield (kg ha^{-1})	(BML-51 × BML-6) × (BML-14 × BML-7) (496.39), (BML-51× BML-14) × (BML-10 × BML-7) (463.11), (BML-51 × BML-7) × (BML-32 × BML-14) (451.26)	(BML-32 × BML-13) × (BML-10 × BML-6) (315.27), (BML-51 × BML-32) × (BML-13 × BML-7) (270.83), (BML-32 × BML-10) (BML-7 × BML-6) (263.23)

*: significant at 5%, **: significant at 1%

Table 7 - *Per se* performance of single, three-way and double crosses at pooled locations for ear and yield contributing traits.

Single crosses	Three-way crosses	Double crosses
	Ear length (cm)	
BML- 32 × BML-10 (21.0)*	(BML- 14 × BML-7) × BML-32 (21.3)c	(BML- 32 × BML-14) × (BML-13 × BML-6) (20.3)2,3
BML- 32 × BML-13 (20.8)*	(BML- 7 × BML-6) × BML-32 (21.2)a	(BML- 51 × BML-13) × (BML-32 × BML-7) (20.2)3,7
BML- 32 × BML-7 (20.1)*	(BML- 32 × BML-14) × BML-51 (21.0)a	(BML- 51 × BML-32) × (BML-7 × BML-6 (20.1)3
BML- 13 × BML-7 (20.1)*	(BML- 51 × BML-14) × BML-32 (20.8)	(BML- 32 × BML-14) × (BML-10 × BML-7) (20.1)3,7
BML- 32 × BML-14 (19.8)*	(BML- 51 × BML-10) × BML-32 (20.7)	(BML- 51 × BML-10) × (BML-32 × BML-7) (20.0)3
	Ear diameter (cm)	
BML- 32 × BML-6 (4.7)*	(BML- 14 × BML-10) × BML-6 (4.8)a,c	(BML- 13 × BML-7) × (BML-10 × BML-6) (4.7)3,7
BML- 51 × BML-6 (4.5)*	(BML- 10 × BML-6) × BML-7 (4.8)b,c	(BML- 32 × BML-10) × (BML-14 × BML-7) (4.6)3
BML- 14 × BML-7 (4.5)*	(BML- 32 × BML-14) × BML-6 (4.7)	(BML- 32 × BML-6) × (BML-10 × BML-7) (4.6)1,3
BML- 7 × BML-6 (4.5)	(BML- 13 × BML-7) × BML-6 (4.7)a	(BML- 32 × BML-7) × (BML-10 × BML-6) (4.6)3
BML- 14 × BML-10 (4.5)	(BML- 13 × BML-7) × BML-32 (4.6)a	(BML- 51 × BML-6) × (BML-10 × BML-7) (4.6)2,3
	Kernel rows ear^{-1}	
BML- 10 × BML-6 (15.2)*	(BML- 7 × BML-6) × BML-10 (15.5)a,b	(BML- 14 × BML-10) × (BML-7 × BML-6) (15.4)3,6
BML- 32 × BML-6 (15.0)*	(BML- 32 × BML-10) × BML-6 (15.5)c	(BML- 13 × BML-7) × (BML-10 × BML-6) (15.0)3,7
BML- 32 × BML-10 (14.6)*	(BML- 7 × BML-6) × BML-13 (15.3)a	(BML- 32 × BML-6) × (BML-13 × BML-7) (14.7)3
BML- 10 × BML-7 (14.5)*	(BML- 13 × BML-7) × BML-6 (15.2)b	(BML- 14 × BML-6) × (BML-13 × BML-10) (14.6)2,3,5
BML- 7 × BML-6 (14.4)	(BML- 32 × BML-7) × BML-10 (15.2)b	(BML- 32 × BML-13) × (BML-10 × BML-6) (14.5)3
	Kernels row^{-1}	
BML- 32 × BML-6 (38.3)*	(BML- 7 × BML-6) × BML-32 (38.8)	(BML- 51 × BML-13) × (BML-32 × BML-7) (37.6)2,3,6
BML- 32 × BML-13 (37.9)*	(BML- 51 × BML-7) × BML-32 (37.8)	(BML- 32 × BML-10) × (BML-13 × BML-7) (37.1)2,3,7
BML- 51 × BML-6 (37.3)*	(BML- 13 × BML-7) × BML-32 (37.6)	(BML- 51 × BML-6) × (BML-32 × BML-14) (37.0)2,5
BML- 13 × BML-6 (36.6)*	(BML- 51 × BML-13) × BML-32 (37.1)	(BML- 32 × BML-7) × (BML-10 × BML-6) (36.6)3,6
BML- 32 × BML-10 (36.1)*	(BML- 51 × BML-6) × BML-32 (37.0)	(BML- 51 × BML-10) × (BML-32 × BML-7) (36.6)2,3
	100-grain weight (g)	
BML- 51 × BML-14 (41.8)*	(BML- 32 × BML-13) × BML-14 (40.9)	(BML- 32 × BML-10) × (BML-14 × BML-7) (39.7)2,3
BML- 14 × BML-13 (40.2)*	(BML- 13 × BML-10) × BML-14 (40.1)	(BML- 51 × BML-13) × (BML-14 × BML-7) (39.6)1,2,3
BML- 14 × BML-7 (37.7)*	(BML- 51 × BML-32) × BML-14 (40.1)c	(BML- 51 × BML-7) × (BML-32 × BML-14) (38.4)3
BML- 51 × BML-7 (36.7)	(BML- 13 × BML-7) × BML-14 (39.7)a	(BML- 14 × BML-7) × (BML-13 × BML-10) (38.3)1,3,5,6
BML- 10 × BML-7 (36.6)*	(BML- 51 × BML-7) × BML-14 (39.5)a	(BML- 51 × BML-7) × (BML-14 × BML-13) (38.2)2,3
	Shelling percentage (%)	
BML- 32 × BML-13 (85.6)	(BML- 51 × BML-32) × BML-13 (84.9)	(BML- 32 × BML-10) × (BML-13 × BML-7) (84.8)2,3,5
BML- 51 × BML-13 (83.7)	(BML- 51 × BML-13) × BML-32 (84.9)	(BML- 32 × BML-10) × (BML-14 × BML-13) (84.8)3,7
BML- 32 × BML-10 (83.5)*	(BML- 32 × BML-13) × BML-51 (84.8)	(BML- 32 × BML-14) × (BML-13 × BML-10) (84.8)2,3,5,7
BML- 32 × BML-6 (83.4)*	(BML- 51 × BML-6) × BML-13 (84.6)	(BML- 51 × BML-10) × (BML-32 × BML-7) (84.3)3
BML- 14 × BML-13 (83.2)	(BML- 32 × BML-10) × BML-13 (84.6)a	(BML- 51 × BML-32) × (BML-14 × BML-6) (84.2)3,5,7
	Grain yield (kg ha^{-1})	
BML- 51 × BML-14 (8732)*	(BML- 14 × BML-6) × BML-51 (8395)b	(BML- 51 × BML-14) × (BML-10 × BML-7) (8362)2,3,5,6
BML- 51 × BML-6 (8096)*	(BML- 32 × BML-6) × BML-51 (8378)b	(BML- 32 × BML-6) × (BML-13 × BML-10) (8223)1
BML- 32 × BML-6 (7801)*	(BML- 51 × BML-10) × BML-6 (8349)b	(BML- 14 × BML-6) × (BML-13 × BML-7) (8190)3
BML- 51 × BML-7 (7797)*	(BML- 13 × BML-7) × BML-32 (8214)b	(BML- 51 × BML-10) × (BML-32 × BML-7) (8087)
BML- 32 × BML-13 (7637)*	(BML- 32 × BML-13) × BML-14 (8137)a	(BML- 51 × BML-13) × (BML-32 × BML-14) (8081)3

Note: *- significant sca effects in single crosses

a,b,c indicate significant dij, sij and tijk effects, respectively in triallel analysis

1,2,3 indicate higher 2-line interaction effects tij, ti.j. and sij, respectively in quadriallel analysis

4,5 indicate higher 3-line interaction effects tij.k and and sijk, respectively in quadriallel analysis

6,7 indicate higher 4-line interaction effects tij.kl and sijkl, respectively in quadriallel analysis

Appendix

hi	1-line general line effect of 1st kind *i.e.* as Grand parent.
gi	1-line general line effect of 2nd kind *i.e.* as Immediate parent.
dij	2-line interaction effects of first kind, dij *i.e.* lines i and j due to a particular arrangement in three-way crosses [(i×j)×-].
sij	2-line specific effects of second kind sij *i.e.* lines i and j appearing together irrespective of arrangement either as grandparent or immediate parent in three-way crosses [(i×-)×j].
tijk	3-line interaction effects tijk *i.e.* lines i, j and k due to a particular arrangement in three-way crosses [(i×j)×k].
t(ij) (- -)	2-line interaction effects of lines i and j due to the particular arrangement (i×j) (-×-) in double crosses.
t(i-) (j-)	2-line interaction effect of lines i and j due to the particular arrangement (i×-) (j×-) in double crosses.
s(ij) (- -)	2-line interaction effect of lines i and j appearing together irrespective of arrangement in double crosses.
t(ij) (k -)	3-line interaction effect of lines i, j and k due to the particular arrangement (i×j) (k×-) in double crosses.
s(ij) (k-)	3-line interaction effect of lines i, j and k appearing together irrespective of arrangement in double crosses.
t (ij) (kl)	4-line interaction effect of lines i, j, k and l due to the particular arrangement (i×j) (k×l) in double crosses.

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