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GENE ACTION AND ORDER EFFECTS IN DOUBLE CROSS HYBRIDS OF MAIZE (*Zea mays* L.) FOR GRAIN YIELD UNDER DIVERSE AGROCLIMATIC ZONES OF TELANGANA

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ABSTRACT

Maize is the third most important cereal crop after rice and wheat in India. Seven inbreds were utilized for crossing programme to produce twenty one single crosses and 105 each three-way and double crosses in half diallel fashion and evaluated during *kharif* 2015 at three locations. Quadriallel analysis was conducted to study 1-line general, 2-line, 3-line and 4-line interaction effects, gene action and order effects for grain yield of double crosses. BML-51 had the highest 1-line general effect, BML-51 × BML-14 showed highest 2-line general effect. (BML-13 × BML-7) (- -) had the highest 2-line specific effect of (ij) (- -) type and (BML-32 × -) (BML-13 × -) had the highest 2-line specific effect of (i-) (j-) type. (BML-32 × BML-14) × (BML-51 × -) had the highest 3-line specific effect of (ij) (k-) type and (BML-51 × BML-6) × (BML-14 × BML-7) had the highest 4-line specific effect of (ij) (kl) type. Cross (BML-51 × BML-14) × (BML-10 × BML-7) showed high grain yield and had high 1-line general line and 2-line general effects. Additive and additive type of epistatic interactions and additive × dominance interactions were predominant in expression of grain yield.

INTRODUCTION

Maize is an important cereal food crop of the world with highest production and productivity as compared to rice and wheat. It is the most versatile crop which is being grown in more than 166 countries across the globe.

Development of high yielding three-way and double cross hybrids in maize could be a better option as compared to single cross hybrids owing to their low variation in performance over series of environments particularly under unfavorable ecologies, besides being cost effective. Single crosses had large hybrid × environmental interaction than double crosses (Sprague and Federer, 1951). Single crosses may not perform as stable as double and three-way crosses because single crosses being uniform they lack population buffering and possess only individual buffering, whereas three-way and double crosses have both population as well as individual buffering (Allard and Bradshaw, 1964).Under normal conditions in semi-arid zone, single crosses had no special advantage over three-way and double crosses (Petrenko, 1977; Oyekunle and Badu-Apraku, 2014).

Rawlings and Cockerham (1962) defined double-cross hybrids as the first generation progeny of the cross of two unrelated F_1 hybrids, symbolized as (AB) (CD), where, A, B, C and D are the four parents and (A×B) and (C×D) are the two F_1s. Actually, the double-cross hybrids are the diallel crosses among the F_1s (which, in turn, are also diallel among parents) with the restriction that no parent can appear twice in the same cross. Quadriallel analysis has some advantage over other designs in providing more estimates of components of epistatic nature and also in giving the information on the order effects of parents in double-cross hybrids. Order in which the parents go into a double cross hybrid is a deciding factor for its high or low performance (Singh and Chaudhary, 1977; Chaudhary, 1984).

Nature of gene action in the inheritance of character helps in the selection of breeding method for improvement of that character. Additive and non additive gene action plays a major role in control of yield in double crosses (Elshakhess *et al.*, 2009; El-Hashash, 2013). Therefore, the present investigation was planned to derive the information on gene action and importance of order effects for grain yield in double crosses of maize.

MATERIALS AND METHODS

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 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. Later these F_1's were involved in crosses with inbreds such that no parent appears twice in the same 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 comprised of seven parents, twenty one single crosses and 105 each three-way and double crosses and eighteen public /private checks were evaluated at three locations *viz*., MRC, ARI, Rajendranagar, ARS, Karimnagar and RARS, Palem. All these 256 entries were laid out in balanced lattice (16 × 16) in two replications at each location and all the intercultural operations were carried out in accordance with the recommended schedule (Vyavasaya panchangam, 2015).

Grain yield was recorded plot-wise (kg $plot^{-1}$) and was corrected for stand variation using the methodology of covariance (Mendes, 2015). Further, this hand harvested shelled corn of each entry was adjusted to 15.5 moisture in kg ha^{-1} similar to grain yield in bushels per acre at 15.5 moisture (Lauer, 2002). The statistical analysis for grain yield (kg ha^{-1}) for double-cross hybrids was done using quadriallel analysis, each environment separately (data not shown) and combined over the environments using the model of Rawlings and Cockerham (1962) 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).

RESULTS AND DISCUSSION

The analysis of variance showed that 2-line and 3-line arrangement effects were significant (Table 1). The effects arising due to the arrangements of lines are exclusively the results of dominance effects or interactions involving dominance components (Rawlings and Cockerham, 1962). The 1-line general effects are given in Table 2. As indicated by the data, BML-51 must be used as one parent, because it provides the highest effect. As four lines are used to produce a double cross hybrid, BML-51, BML-13, BML-14 and BML-32 and can be used with the same efficiency. The 2-line effects, with and without respect to their particular arrangement are also given in Table 2.

With regards to 2-line general effects, parents BML-51 and BML-14 in various combinations did the best followed by BML-14 and BML-7 and BML-51 and BML-13. About 50 per cent of the 2-line general effects were negative. The specific combination (BML-13 × BML-7) (- -) had the highest 2-line specific effect of (ij) (- -) type followed by (BML-32 × BML-6) (- -) and (BML-32 × BML-10) (- -). The 2-line specific effect of (i-)(j-) type was highest in case of (BML-32 × -) (BML-13 × -) followed by (BML-10 × -) (BML-7 × -) and (BML-51 × -) (BML-10 × -). Inbreds BML-51, BML-13 and BML-7 which did well in 2-line general effects were also included in the best 2-line specific combinations. Another very important point to be

Table 1: ANOVA of the Quadriallel analysis for grain yield (kg ha^{-1}) across locations

Variation sources	*df*	Mean square
Locations	2	38254028.00**
Hybrids	104	925147.81*
1 - line general	6	869804.00ns
2 - line specific	14	704179.50 ns
3 - line specific	14	790416.06 ns
2 - line arrangement	14	1154984.13*
3 - line arrangement	35	1082105.13*
4 - line arrangement	21	763273.81 ns
Error	208	633171.81

*,**Significant at $p < 0.05$ and $p < 0.01$, respectively; nsNot significant.

Table 2: One- line general (gi) and 2-line interaction (sij), t(ij)(- -), t(i -)(j -), effects for grain yield at pooled environments

Lines appear together	gi	Lines appear together	sij..	Lines appear together	sij..	Lines appear together	sij..
1...	65.768	12..	-6.118	24..	20.632	37..	-59.218
2...	7.946	13..	72.543	25..	43.715	45..	-70.357
3...	19.113	14..	53.365	26..	-54.257	46..	17.237
4...	44.49	15..	7.887	27..	27.687	47..	-0.902
5...	-14.382	16..	-45.868	34..	24.515	56..	16.943
6...	-61.426	17..	-16.04	35..	-48.596	57..	36.026
7...	-61.51	23..	-23.713	36..	53.582	67..	-49.063

1 = BML-51, 2 = BML-32, 3 = BML-14, 4 = BML-13, 5 = BML-10, 6 = BML-7, 7 = BML-6; gi = one-line general effects, sij = 2-line interaction effect of i and j lines irrespective of arrangement

Table 2 : Continued

Lines arran gement effect	t(ij) (- -)	Lines arran gement effect	t(ij) (- -)	Lines arran gement effect	t(ij) (- -)	Lines arran gement effect	t (i -)(j -)	Lines arran gement effect	t (i -)(j -)	Lines arran gement effect	t (i -)(j -)
(12)(..)	8.539	(24)(..)	-447.433	(37)(..)	-82.05	(1.)(2.)	-4.269	(2.)(4.)	223.717	(3.)(7.)	41.025
(13)(..)	25.311	(25)(..)	150.589	(45)(..)	106.633	(1.)(3.)	-12.656	(2.)(5.)	-75.294	(4.)(5.)	-53.317
(14)(..)	104.111	(26)(..)	-80.094	(46)(..)	316.683	(1.)(4.)	-52.056	(2.)(6.)	40.047	(4.)(6.)	-158.342
(15)(..)	-128.222	(27)(..)	270.928	(47)(..)	-43.411	(1.)(5.)	64.111	(2.)(7.)	-135.464	(4.)(7.)	21.706
(16)(..)	95.261	(34)(..)	-36.583	(56)(..)	-208.117	(1.)(6.)	-47.631	(3.)(4.)	18.292	(5.)(6.)	104.058
(17)(..)	-105	(35)(..)	22.817	(57)(..)	56.3	(1.)(7.)	52.5	(3.)(5.)	-11.408	(5.)(7.)	-28.15
(23)(..)	97.472	(36)(..)	-26.967	(67)(..)	-96.767	(2.)(3.)	-48.736	(3.)(6.)	13.483	(6.)(7.)	48.383

12 = BML-51 × BML-32, 13 = BML-51 × BML-14, 14 = BML-51 × BML-13, 15 = BML-51 × BML-10, 16 = BML-51 × BML-7, 17 = BML-51 × BML-6,24 = BML-32 × BML-13, 25 = BML-32 × BML-10, 26 = BML-32 × BML-7, 27 = BML-32 × BML-6, 34 = BML-14 × BML-13, 35 = BML-14 × BML-10,36 = BML-14 × BML-7, 37 = BML-14 × BML-6, 45 = BML-13 × BML-10, 46 = BML-13 × BML-7, 47 = BML-13 × BML-6, 56 = BML-10 × BML-7,57 = BML-10 × BML-6, 67 = BML-7 × BML-6;t(ij) (- -) = 2-line interaction effect of lines i and j due to the particular arrangement both as grand parents t (i -)(j -) = 2-line interaction effect of lines i and j due to the particular arrangement one as grandparent and another as half parent.

Table 3: Three-line interaction effects of lines tij.k and sijk for grain yield at pooled environments

Lines arrangement effect	t(ij) (- -)	Lines arrangement effect	t(ij) (- -)	Lines arrangement effect	t(ij) (- -)	Lines arrangement effect	t(ij) (- -)	Lines arrangement effect	t(ij) (- -)	Lines appear together	s(ijk)	Lines appear together	s(ijk)
(12)(3.)	42.464	(16)(3.)	-77.964	(25)(4.)	134.581	(35)(6.)	-301.386	(46)(7.)	58.311	123	1.91	247	30.368
(12)(4.)	82.147	(16)(4.)	349.178	(25)(6.)	-64.25	(35)(7.)	130.322	(47)(1.)	148.925	124	11.129	256	38.993
(12)(5.)	-129.647	(16)(5.)	-341.861	(25)(7.)	34.358	(36)(1.)	-58.456	(47)(2.)	239.839	125	-4.923	257	124.16
(12)(6.)	-156.608	(16)(7.)	-77.589	(26)(1.)	103.633	(36)(2.)	275.406	(47)(3.)	5.317	126	-43.832	267	-89.957
(12)(7.)	153.106	(17)(2.)	184.997	(26)(3.)	-108.111	(36)(4.)	-233.678	(47)(5.)	-139.456	127	23.479	345	-32.473
(13)(2.)	-461.153	(17)(3.)	48.158	(26)(4.)	-63.392	(36)(5.)	71.622	(47)(6.)	-211.214	134	19.557	346	46.493
(13)(4.)	69.328	(17)(4.)	-127.775	(26)(5.)	295.108	(36)(7.)	-27.928	(56)(1.)	109.914	135	108.56	347	-18.36
(13)(5.)	190.653	(17)(5.)	141.108	(26)(7.)	-147.144	(37)(1.)	-87.6	(56)(2.)	-230.858	136	-32.651	356	42.813
(13)(6.)	136.419	(17)(6.)	-141.489	(27)(1.)	-338.103	(37)(2.)	-26.778	(56)(3.)	229.764	137	47.71	357	-143.137
(13)(7.)	39.442	(23)(1.)	418.689	(27)(3.)	109.297	(37)(4.)	95.025	(56)(4.)	-46.669	145	-41.962	367	28.027
(14)(2.)	-79.961	(23)(4.)	40.45	(27)(4.)	-417.503	(37)(5.)	-47.419	(56)(7.)	145.967	146	125.243	456	-81.46
(14)(3.)	-55.997	(23)(5.)	-306.797	(27)(5.)	227.392	(37)(6.)	148.822	(57)(1.)	5.2	147	-7.237	457	13.027
(14)(5.)	75.636	(23)(6.)	-167.294	(27)(6.)	147.989	(45)(1.)	245.186	(57)(2.)	-261.75	156	-45.182	467	-19.601
(14)(6.)	-22.639	(23)(7.)	-82.519	(34)(1.)	-13.331	(45)(2.)	-123.819	(57)(3.)	-82.903	157	-0.718	567	78.721
(14)(7.)	-21.15	(24)(1.)	-2.186	(34)(2.)	-123.05	(45)(3.)	-113.933	(57)(4.)	275.644	167	-95.315		
(15)(2.)	307.411	(24)(3.)	82.6	(34)(5.)	103.35	(45)(6.)	22.122	(57)(6.)	7.508	234	33.813		
(15)(3.)	55.994	(24)(5.)	-10.761	(34)(6.)	169.956	(45)(7.)	-136.189	(67)(1.)	219.078	235	-72.954		
(15)(4.)	-320.822	(24)(6.)	200.117	(34)(7.)	-100.342	(46)(1.)	-326.539	(67)(2.)	-0.844	236	22.482		
(15)(6.)	231.947	(24)(7.)	177.664	(35)(1.)	-246.647	(46)(2.)	-136.725	(67)(3.)	-120.894	237	-32.676		
(15)(7.)	-146.308	(25)(1.)	-177.764	(35)(2.)	384.311	(46)(3.)	63.722	(67)(4.)	152.903	245	2.154		
(16)(2.)	52.975	(25)(3.)	-77.514	(35)(4.)	10.583	(46)(5.)	24.547	(67)(5.)	-153.475	246	-36.201		

1 = BML-51, 2 = BML-32, 3 = BML-14, 4 = BML-13, 5 = BML-10, 6 = BML-7, 7 = BML-6,12 = BML-51 × BML-32, 13 = BML-51 × BML-14, 14 = BML-51 × BML-13, 15 = BML-51 × BML-10, 16 = BML-51 × BML-7, 17 = BML-51 × BML-6,24 = BML-32 × BML-13, 25 = BML-32 × BML-10, 26 = BML-32 × BML-7, 27 = BML-32 × BML-6, 34 = BML-14 × BML-13, 35 = BML-14 × BML-10,36 = BML-14 × BML-7, 37 = BML-14 × BML-6, 45 = BML-13 × BML-10, 46 = BML-13 × BML-7, 47 = BML-13 × BML-6, 56 = BML-10 × BML-7,57 = BML-10 × BML-6, 67 = BML-7 × BML-6

t(ij) (k -) = 3-line interaction effect of lines i and j together as grandparents and line k as half parent. s(ijk) = 3-line interaction of lines i,j and k irrespective of the arrangement.

Table 4: Four-line interaction effects of lines tij.kl and sijkl for grain yield at pooled environments

Lines arrangement effect	t(ij) (k -)	Lines arrangement effect	t(ij) (k -)	Lines arrangement effect	t(ij) (k -)	Lines arrangement effect	t(ij) (k -)	Lines arrangement effect	t(ij) (k -)	Lines appear together	s(ijkl)	Lines appear together	s(ijkl)
(12)(34)	30.322	(14)(25)	-77.156	(16)(25)	-46.231	(23)(56)	96.781	(27)(34)	-148.681	1234	-87.127	2346	95.896
(12)(35)	426.017	(14)(26)	333.533	(16)(27)	50.267	(23)(57)	74.172	(27)(35)	-239.411	1235	39.068	2347	82.471
(12)(36)	-158.569	(14)(27)	-133.142	(16)(34)	14.108	(23)(67)	-294.189	(27)(36)	13.778	1236	-113.377	2356	82.232
(12)(37)	-297.769	(14)(35)	82.178	(16)(35)	-239.439	(24)(35)	-57.894	(27)(45)	438.358	1237	167.165	2357	-350.36
(12)(45)	-134.239	(14)(36)	-114.15	(16)(37)	-225.925	(24)(36)	112.861	(27)(46)	-156.536	1245	-144.354	2367	2.696
(12)(46)	121.758	(14)(37)	155.208	(16)(45)	275.597	(24)(37)	-147.881	(27)(56)	92.492	1246	270.826	2456	-174.649
(12)(47)	-17.842	(14)(56)	-101.169	(16)(47)	165.586	(24)(56)	96.017	(34)(56)	-269.45	1247	-5.957	2457	315.268
(12)(56)	-285.289	(14)(57)	96.147	(16)(57)	10.072	(24)(57)	-249.517	(34)(57)	185.417	1256	-53.829	2467	-300.677
(12)(57)	-6.489	(14)(67)	-118.214	(17)(23)	-76.544	(24)(67)	246.414	(34)(67)	114.356	1257	144.346	2567	263.226
(12)(67)	322.1	(15)(23)	-251.475	(17)(24)	150.983	(25)(34)	-22.628	(35)(46)	-82.15	1267	-235.115	3456	-66.057
(13)(24)	92.914	(15)(24)	211.394	(17)(25)	297.928	(25)(36)	31.931	(35)(47)	57.867	1345	157.962	3457	-199.524
(13)(25)	-174.542	(15)(26)	331.519	(17)(26)	-372.367	(25)(37)	165.239	(35)(67)	450.3	1346	17.751	3467	91.89
(13)(26)	-292.686	(15)(27)	-291.439	(17)(34)	-151.092	(25)(46)	288.625	(36)(45)	351.6	1347	-29.915	3567	52.043
(13)(27)	374.314	(15)(34)	106.661	(17)(35)	-268.756	(25)(47)	-188.842	(36)(47)	-350.311	1356	60.221	4567	29.579
(13)(45)	-188.839	(15)(36)	-223.672	(17)(36)	496.392	(25)(67)	-274.325	(36)(57)	-159.858	1357	68.429		
(13)(46)	100.042	(15)(37)	368.486	(17)(45)	47.481	(26)(34)	140.986	(37)(45)	-243.283	1367	-62.549		
(13)(47)	-4.117	(15)(46)	-174.428	(17)(46)	-47.372	(26)(35)	-128.711	(37)(46)	235.956	1456	-33.252		
(13)(56)	463.111	(15)(47)	-143.628	(17)(56)	-76.653	(26)(37)	280.411	(37)(56)	-290.442	1457	-106.243		
(13)(57)	-99.731	(15)(67)	66.581	(23)(45)	80.522	(26)(45)	-384.642	(45)(67)	-242.556	1467	120.404		
(13)(67)	-270.467	(16)(23)	451.256	(23)(46)	-253.847	(26)(47)	-89.878	(46)(57)	-32.047	1567	-108.685		
(14)(23)	-123.236	(16)(24)	-455.292	(23)(47)	296.561	(26)(57)	181.833	(47)(56)	274.603	2345	10.198		

12 = BML-51 × BML-32, 13 = BML-51 × BML-14, 14 = BML-51 × BML-13, 15 = BML-51 × BML-10, 16 = BML-51 × BML-7, 17 = BML-51 × BML-6, 23 = BML-32 × BML-14, 24 = BML-32 × BML-13, 25 = BML-32 × BML-10, 26 = BML-32 × BML-7, 27 = BML-32 × BML-6, 34 = BML-14 × BML-13, 35 = BML-14 × BML-10, 36 = BML-14 × BML-7, 37 = BML-14 × BML-6, 45 = BML-13 × BML-10, 46 = BML-13 × BML-7, 47 = BML-13 × BML-6, 56 = BML-10 × BML-7, 57 = BML-10 × BML-6, 67 = BML-7 × BML-6.
t(ij) (kl) = 4-line interaction effect of lines i,j,k and l due to particular arrangement i.e.(ij).(kl);s(ijkl) = 4-line interaction of lines i,j,k and l irrespective of the arrangement.

Table 5: Order effects with respect to per se performance for grain yield (kg ha^{-1}) pooled over locations in double crosses

Crosses		Grain yield (kg ha^{-1})	Crosses	Grain yield (kg ha^{-1})		Crosses Grain yield (kg ha^{-1})
Group-1			Group-10		Group-19	
1	(BML-51 × BML-32) × (BML-14 × BML-13)	7555	(BML-51 × BML-32) × (BML-7 × BML-6)	6921	(BML-51 × BML-13) × (BML-7 × BML-6)	7352
2	(BML-51 × BML-14) × (BML-32 × BML-13)	6727	(BML-51 × BML-7) × (BML-32 × BML-6)	6902	(BML-51 × BML-7) × (BML-13 × BML-6)	7584
3	(BML-51 × BML-13) × (BML-32 × BML-14)	8081	(BML-51 × BML-6) × (BML-32 × BML-7)	5867	(BML-51 × BML-6) × (BML-13 × BML-7)	6864
Group-2			Group-11		Group-20	
1	(BML-51 × BML-32) × (BML-14 × BML-10)	7828	(BML-51 × BML-14) × (BML-13 × BML-10)	7916	(BML-51 × BML-10) × (BML-7 × BML-6)	6978
2	(BML-51 × BML-14) × (BML-32 × BML-10)	6868	(BML-51 × BML-13) × (BML-14 × BML-10)	7572	(BML-51 × BML-7) × (BML-10 × BML-6)	6928
3	(BML-51 × BML-10) × (BML-32 × BML-14)	7482	(BML-51 × BML-10) × (BML-14 × BML-13)	7200	(BML-51 × BML-6) × (BML-10 × BML-7)	6806
Group-3			Group-12		Group-21	
1	(BML-51 × BML-32) × (BML-14 × BML-7)	6916	(BML-51 × BML-14) × (BML-13 × BML-7)	7934	(BML-32 × BML-14) × (BML-13 × BML-10)	7077
2	(BML-51 × BML-14) × (BML-32 × BML-7)	6295	(BML-51 × BML-13) × (BML-14 × BML-7)	7008	(BML-32 × BML-13) × (BML-14 × BML-10)	6966
3	(BML-51 × BML-7) × (BML-32 × BML-14)	7966	(BML-51 × BML-7) × (BML-14 × BML-13)	7908	(BML-32 × BML-10) × (BML-14 × BML-13)	7380
Group-4			Group-13		Group-22	
1	(BML-51 × BML-32) × (BML-14 × BML-6)	6996	(BML-51 × BML-14) × (BML-13 × BML-6)	7651	(BML-32 × BML-14) × (BML-13 × BML-7)	7663
2	(BML-51 × BML-14) × (BML-32 × BML-6)	7491	(BML-51 × BML-13) × (BML-14 × BML-6)	7538	(BML-32 × BML-13) × (BML-14 × BML-7)	7222
3	(BML-51 × BML-6) × (BML-32 × BML-14)	7805	(BML-51 × BML-6) × (BML-14 × BML-13)	6863	(BML-32 × BML-7) × (BML-14 × BML-13)	7337
Group-5			Group-14		Group-23	
1	(BML-51 × BML-32) × (BML-13 × BML-10)	7387	(BML-51 × BML-14) × (BML-10 × BML-7)	8362	(BML-32 × BML-14) × (BML-13 × BML-6)	7993
2	(BML-51 × BML-13) × (BML-32 × BML-10)	7532	(BML-51 × BML-10) × (BML-14 × BML-7)	7351	(BML-32 × BML-13) × (BML-14 × BML-6)	6798
3	(BML-51 × BML-10) × (BML-32 × BML-13)	6596	(BML-51 × BML-7) × (BML-14 × BML-10)	6476	(BML-32 × BML-6) × (BML-14 × BML-13)	7083
Group-6			Group-15		Group-24	
1	(BML-51 × BML-32) × (BML-13 × BML-7)	7639	(BML-51 × BML-14) × (BML-10 × BML-6)	7560	(BML-32 × BML-14) × (BML-10 × BML-7)	6727
2	(BML-51 × BML-13) × (BML-32 × BML-7)	7874	(BML-51 × BML-10) × (BML-14 × BML-6)	7212	(BML-32 × BML-10) × (BML-14 × BML-7)	7694
3	(BML-51 × BML-7) × (BML-32 × BML-13)	7184	(BML-51 × BML-6) × (BML-14 × BML-10)	7066	(BML-32 × BML-7) × (BML-14 × BML-10)	7327
Group-7			Group-16		Group-25	
1	(BML-51 × BML-32) × (BML-13 × BML-6)	8044	(BML-51 × BML-14) × (BML-7 × BML-6)	6991	(BML-32 × BML-14) × (BML-10 × BML-6)	5962
2	(BML-51 × BML-13) × (BML-32 × BML-6)	7063	(BML-51 × BML-7) × (BML-14 × BML-6)	6795	(BML-32 × BML-10) × (BML-14 × BML-6)	6542
3	BML-51 × BML-6) × (BML-32 × BML-13)	7045	(BML-51 × BML-6) × (BML-14 × BML-7)	7214	(BML-32 × BML-6) × (BML-14 × BML-10)	7443
Group-8			Group-17		Group-26	
1	(BML-51 × BML-32) × (BML-10 × BML-7)	6137	(BML-51 × BML-13) × (BML-10 × BML-7)	6850	(BML-32 × BML-14) × (BML-7 × BML-6)	6221
2	(BML-51 × BML-10) × (BML-32 × BML-7)	8086	(BML-51 × BML-10) × (BML-13 × BML-7)	6708	(BML-32 × BML-7) × (BML-14 × BML-6)	6789
3	(BML-51 × BML-7) × (BML-32 × BML-10)	6921	(BML-51 × BML-7) × (BML-13 × BML-10)	7844	(BML-32 × BML-6) × (BML-14 × BML-7)	7770
	Group-9				Group-18	Group-27
1	(BML-51 × BML-32) × (BML-10 × BML-6)	7305	(BML-51 × BML-13) × (BML-10 × BML-6)	7775	(BML-32 × BML-13) × (BML-10 × BML-7)	6002
2	(BML-51 × BML-10) × (BML-32 × BML-6)	7421	(BML-51 × BML-10) × (BML-13 × BML-6)	6244	(BML-32 × BML-10) × (BML-13 × BML-7)	7925
3	(BML-51 × BML-6) × (BML-32 × BML-10)	7997	(BML-51 × BML-6) × (BML-13 × BML-10)	7275	(BML-32 × BML-7) × (BML-13 × BML-10)	6762

Table 5: Cont...

Crosses		Grain yield (kg ha^{-1})	Crosses	Grain yield (kg ha^{-1})	Grain yield (kg ha^{-1})	Crosses
Group-28			Group-31		Group-34	
1	(BML-32×BML-13)×(BML-10×BML-6)	7013	(BML-14×BML-13)×(BML-10×BML-7)	6820	(BML-14×BML-10)×(BML-7×BML-6)	7148
2	(BML-32×BML-10)×(BML-13×BML-6)	7910	(BML-14×BML-10)×(BML-13×BML-7)	7225	(BML-14×BML-7)×(BML-10×BML-6)	7107
3	(BML-32×BML-6)×(BML-13×BML-10)	8223	(BML-14×BML-7)×(BML-13×BML-10)	7217	(BML-14×BML-6)×(BML-10×BML-7)	7006
Group-29			Group-32		Group-35	
1	(BML-32×BML-13)×(BML-7×BML-6)	6672	(BML-14×BML-13)×(BML-10×BML-6)	7084	(BML-13×BML-10)×(BML-7×BML-6)	6666
2	(BML-32×BML-7)×(BML-13×BML-6)	6255	(BML-14×BML-10)×(BML-13×BML-6)	6707	(BML-13×BML-7)×(BML-10×BML-6)	7902
3	(BML-32×BML-6)×(BML-13×BML-7)	7089	(BML-14×BML-6)×(BML-13×BML-10)	6265	(BML-13×BML-6)×(BML-10×BML-7)	6654
Group-30			Group-33		S.E.±	649.7
1	(BML-32×BML-10)×(BML-7×BML-6)	7079	(BML-14×BML-13)×(BML-7×BML-6)	7253		
2	(BML-32×BML-7)×(BML-10×BML-6)	7497	(BML-14×BML-7)×(BML-13×BML-6)	6313		
3	(BML-32×BML-6)×(BML-10×BML-7)	7934	(BML-14×BML-6)×(BML-13×BML-7)	8190		

Table 6: Estimates of genetic components of variance for grain yield at pooled environments

Components	Estimate
Additive	1223057.464
Dominance	-1390234.187
Additive × additive	-4248790.085
Additive × dominance	5127913.372
Dominance × dominance	-1727046.050
Additive × additive × additive	12227119.348

noted here is the order effect of the parents. For instance, the specific combination (BML-13 × BML-7) (- -) which had the highest 2-line specific effect (316.683), gave the negative effect, when used in another combination, *i.e.* (BML-13 × -) (BML-7 × -) (-158.342). Similarly, parents BML-32 and BML-6, which were good in specific combination of (BML-32 × BML-6) (- -) (270.928), showed the negative 2-line specific effect when used in combination as (BML-32 × -) (BML-6 × -) (-135.464). Obviously, the order in which the parents were involved in double-crosses was important. This means that due consideration should be given to this parameter while attempting multiple crosses. The evidence of order effects in quadriallel analysis was reported by Chaudhary (1984) and Singh and Chaudhary (1977) in barley crop for spikes per plant and grain yield, respectively. Similarly, in triallel analysis also the order effects were reported by Rajamani (2014) in cotton, Chaudhary *et al*. (1978) in barley and by Ponnuswamy *et al.* (1974) in maize.

Considering the specific order effect of three out of four parents, *i.e.*, (ij) (k-) type in double crosses, we found that (BML-32 × BML-14) × (BML-51 × -), (BML-14 × BML-10) × (BML-32 × -), (BML-51 × BML-7) × (BML-13 × -) and (BML-51 × BML-10) × (BML-32 × -) combinations were the best (Table 3). All these crosses had either BML-51 or BML-32 or both in different arrangements in different triplets and the best triplet included the parents BML-51, BML-32 and BML-14. However, on the basis of the overall performance of any three parents in all possible combinations, without respect to arrangement (S_{ijk}), the best triplet was (BML-32 × BML-10) × (BML-6 × -) followed by (BML-10 × BML-7) × (BML-6 × -) and (BML-14 × BML-13) × (BML-7 × -). How the order of these parents in a cross matters can be seen by changing the arrangement of the parents of a particular cross. For example, a change in the arrangement of the parents of the best combination of three parents (BML-32 × BML-14) × (BML-51 × -) which had highest desirable positive effect (418.689) into another combination, *i.e.* (BML-51 × BML-32) × (BML-14 × -) had the specific effect (42.464). Another combination, in which the same three parents were involved, but in some other order, *i.e.* (BML-51 × BML-14) × (BML-32 × -) had a specific combination effect of -461.153 and sum of all the three alternate forms is zero. This observation clearly shows the significance of the order in which the parents are involved in multiple crosses.

The 4-line interactions with and without respect to particular arrangements of the parents in double crosses are given in Table 4. A critical perusal of the data in this table clearly showed that best combinations were (BML-51 × BML-6) × (BML-14 × BML-7), (BML-51 × BML-14) × (BML-10 × BML-7) and (BML-51 × BML-7) × (BML-32 × BML-14). What it exactly means is that the four parents say, BML-51, BML-14, BML-7 and BML-6 in a specific order given above, i.e. (BML-51 × BML-6) × (BML-14 × BML-7) form the most effective combination (496.392) but not in other orders. For instance the same parents in a cross (BML-51 × BML-14) × (BML-7 × BML-6) in this order, had in contrast the negative value (-270.467). Similarly, the best 4 line combination (BML-51 × BML-14) × (BML-10 × BML-7) in this order when combined in another order, such as (BML-51 × BML-7) × (BML-14 × BML-10) produced the negative effect (-239.439).These results again 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). Considering the general effect of a set of any four parents (the data in the parenthesis in Table 4) in various combinations, irrespective of the order, it is obvious that the parents BML-32, BML-13, BML-10 and BML-6 formed the best combination for grain yield which is evident in cross (BML-32 × BML-6) (BML-13 × BML-10) with grain yield of 8223 kg ha^{-1}.

Criterion of *per se* performance was followed to compare the order effects in double crosses.105 double crosses were classified in to thirty five groups of three crosses each. Crosses of each group involved four parents in different orders (Table 5). Among the thirty five groups, twenty nine groups exhibited superior *per se* performance of double crosses with particular order arrangement in that particular group. For example in the group 7, double cross (BML-51 × BML-32) × (BML-13 × BML-6) had superior *per se* performance with a grain yield of 8044 kg ha^{-1} than other arrangements namely (BML-51 × BML-13) × (BML-32 × BML-6) with 7063 kg ha^{-1} and (BML-51 × BML-6) × (BML-32 × BML-13) with 7045 kg ha^{-1}. While the parents involved in the groups *viz.,* 15,16,20,21,22,31 and 34 had given the double crosses with comparable performance irrespective of arrangement in that particular group. Out of 105 double crosses, five crosses belonging to various groups expressed superior performance. They are namely (BML-51 × BML-14) × (BML-10 × BML-7), (BML-32 × BML-6) × (BML-13 × BML-10), (BML-14 × BML-6) × (BML-13 × BML-7), (BML-51 × BML-10) × (BML-32 × BML-7) and (BML-51 × BML-13) × (BML-32 × BML-14). Further, it is interesting to note that parent BML-51 as one of the grand parent and parents BML-32, BML-14, BML-10, BML-13 and BML-7 either as grand parent or immediate parent were involved in three out of five superior crosses. Cross (BML-51 × BML-14) × (BML-10 × BML-7) had superior *per se* performance for grain yield (8362 kg ha^{-1}) and exhibited high 1-line general effects for BML-51, BML-14, high 2-line interaction effect irrespective of arrangement for BML-51 × BML-14, high 3-line arrangement effect of (ij) (k -) type and high 4-line arrangement effect of (ij) (kl) type suggesting that there is possibility of getting promising double crosses by involving good general combiners and good specific combining single crosses as parents.

Gene action involved in the expression of grain yield has been reported to be additive as well as non- additive. Hence, it was considered to partition the digenic component of epistatic variation. Additive variance was found to be more than dominance variance (Table 6). Among the epistatic interactions, Additive × additive type of epistatis was least and additive × dominance and additive × additive × additive interactions were high. Contrary to this, El-Hashash (2013) reported that additive × additive type of epistatic interaction was high followed by additive × dominance in double cross hybrids of Cotton, while Elshakhess *et al*. (2009) noticed all types of epistatic interaction in double crosses of Sesame. As the additive and additive type of epistatic interactions and additive × dominance interactions were predominant, there is a possibility of exploitation through heterosis breeding by identifying promising hybrids for cultivation and deriving potential inbreds through pedigree breeding.

Finally, the high yielding double crosses viz., (BML-51 × BML-14) × (BML-10 × BML-7) and (BML-32 × BML-6) × (BML-13 × BML-10) with grain yields of 8362 kg ha^{-1} and 8223 kg ha^{-1}, respectively were also tested in multilocation trials during *kharif* 2016 and found promising. However, depending upon the consistency in performance, these hybrids will be released for commercial cultivation.

For successful plant breeding, to combat deficiencies in genotypes, it is essential to bring the effect of several genotypes into unified action in one component genotype. The quadriallel analysis helps in identifying the gene action involved in the population and it also provides information from which genetic parameters can be estimated. Thus, in a double cross hybrid several desirable characteristics can be successfully combined by crossing selected parents in a particular order without any reduction in yield. This aspect needs to be exploited.

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