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Performance of popcorn maize populations in South American Avatí Pichingá using diallel analysis

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Abstract

The Avatí Pichingá population contains genes for resistance to the fungal species that cause ear rot. This study aimed to develop populations of interest. For this purpose, the diallel analysis was carried out and combining ability associated with of grain yield (GY), popping expansion (PE), plant height (PH), ear height (EH) and days to silking (FF) were assessed from seven South American varieties of the maize race Avatí Pichingá. Performance for those populations was evaluated in a completely randomized block designs at four locations in Paraguay and one location in Brazil. The statistical approach was based on the individual and joint analysis of variance and diallel analysis (Gardner and Eberhart's and Griffing's methods). The results showed that varieties and heterosis effects were significant for all the studied traits. Highly significant differences were also detected for the interactions between heterosis and locations for all traits, in contrast to variety and location that were significant for GY only. Differences were significant for average, variety, and specific heterosis with 68% of variation from the varieties and 32% from the total heterosis for GY. Differences among locations, varieties, heterotic effects, interaction between variety and locations were highly significant for PE, PH, EH, and FF. However, specific heterosis was significant for PE only. Estimates of combining ability and heterosis showed that ´PAZM 2065` and ´PAZM 0131` are superior varieties for GY, and ´PAZM 7130` for PE, ´PAZM 6070` for PH and EH, and ´PAZM 7139` for early flowering, respectively.

Keywords: Grain yield; heterotic effects; popcorn; popping expansion; variety effects; *Zea mays*.
Abbreviations: CRIA_Centro Regional de Investigación Agrícola; COODETEC_Cooperativa Central de Pesquisa Agrícola; EH_ear height; FF_days to silking; GY_grain yield; PE_popping expansion; PH_plant height.

Introduction

In Brazil, the number of popcorn growers has been increasing because of the huge demand for this type of snack food in the national market (Arnhold et al., 2006, 2009). However, the availability of superior cultivars to supply the necessities of popcorn growers is still incipient because of several technological approaches. For example, the genetic base of American popcorn germplasm is narrow (Ziegler and Ashman, 1994) and provides a relatively limited number of lines from the flint germplasm. In 2013/2014, only the commercial genotypes as IAC 125 (three-way hybrid) and RS-20 and UFVM2-Barão-Viçosa (open-pollinated) varieties were available to the national. In general, these cultivars have been modified to maximize the popping expansion and improve the grain quality (Miranda et al., 2008). However, some of them are susceptible to diseases due to selection pressure by breeders for increasing the crop yield and popping expansion. The popcorn cultivars are more susceptible to fungal diseases than other maize cultivars. Furthermore, the popcorn cultivars dominating the market are susceptible to ear rot. In maize, fungal ear rot has been reported worldwide (Silva et al., 2007) which caused losses on the crop yield and grain quality (Reis et al., 2004). The most frequent fungal species causing ear rot are *Fusarium verticilliodes* Sheld [sin. *F. moniliforme*; teleomorph *Gibberella fujikuroi* (Sawada) Ito]; *Gibberella zeae* (Schwein.) Petch (anamorph: *Fusarium graminearum* Schwabe); *Fusarium* spp.; *Stenocarpella macrospora* (Earle) Sutton (sin. *Diplodia macrospora* Earle); and *S. maydis* (Berk.) Sutton [sin. *D. zeae* (Schwein.) Lév]. These diseases have had higher importance since the advent of no tillage in maize production systems and continuous sowing of the same crop in consecutive growing seasons. Therefore, breeding efforts could be wasted if disease resistance is not considered in any breeding program. Fortunately, the South American maize race Avatí Pichingá, race of popcorn that was managed and distributed by the Guarani Indians (Goodman and Brown, 1988), contains available resistant genes to overcome the threats of important maize diseases (Salhuana and Machado, 1999). Currently, the methods to breed popcorn must increase the frequency of resistance genes, which decrease in turn, the losses of crop yield. The successful development of advanced lines and cultivars in maize are dependent on parental selection and precise identification of heterotic groups (Melani and Carena, 2005).

Diallel analysis is used to assess general and specific combining abilities (Griffing, 1956), using heterosis phenomena (Gardner and Eberhart, 1966) and to study the genetic control of quantitative traits (Hayman, 1954a, b). In popcorn breeding programs, there are reports of diallel analysis in different traits (Larish and Brewbaker, 1999; Scapim et al., 2002; Viana and Matta, 2003; Freitas Júnior et al., 2006; Miranda et al., 2008; Vieira et al., 2011; Moterle et al., 2012; Cabral et al., 2013). Miranda et al. (2008) evaluated genetic variability and heterotic groups among Brazilian popcorn varieties. They concluded that Brazilian popcorn populations have less heterosis and genetic variability for popping expansion compared to commercial cultivars. There is genetic variability among Brazilian popcorn populations that allows the exploitation of additive and non-additive effects for grain yield. It makes it possible to increase grain yield using local varieties.

In addition to the traits reported by Miranda et al. (2008), local landraces can be used as a source of disease resistance. The use of genotypes with the highest level of resistance is undoubtedly the main and most advantageous measure for the control of majority of pathogens that cause damage to popcorn. The South American maize, race Avatí Pichingá, contains the genes for resistance to the fungal species causing ear rot, can be used as a source of resistance in breeding programs (Salhuana and Machado, 1999).

This study was conducted to estimate the general and specific combining ability, and the heterosis effects of seven open-pollinated varieties of popcorn from the South American maize race, Avatí Pichingá, for grain yield, popping expansion, plant and ear height, and the number of days to silking. Consequently, they form a genetic basis to aid the development of composites, open-pollinated varieties, and popcorn hybrids with genes of resistance to ear rot disease.

Results and Discussion

Analysis of variance

For all traits, the maximum *F*-test did not significant heterogeneity ($P \leq 0.05$) for the mean square error of the individual analyses, but the joint analysis indicated significant differences in the mean squares of treatments and location. The interaction between treatment and location was significant ($F \leq 0.01$) for all the five traits (Table 2).

Diallel analysis for grain yield

The grain yields (GY) ranged from 2,448 (PAZM2065) to 989 kg ha^{-1} among varieties, and from 1,635 to 2,309 kg ha^{-1} (PAZM2065 x PAZM0131) among the hybrid combinations. The PAZM2065 and PAZM2065 x PAZM0131 had an outstanding GY, comparable to the control (Table 3). These responses were not as expected because of the conditions, in which the commercial hybrids were subjected in their breeding approach. However, reports from South and Southeast Brazil indicated high differences in GY between locations for the Zélia (Pinto et al., 2007) and IAC 112 hybrids (Freitas Júnior et al., 2006; Rangel et al., 2007; Rangel et al., 2008). All data showed GY as a trait under strong influence of environmental conditions, which confirmed the importance of the regional breeding programs. The coefficient of variation of 13.7% indicates average estimates precision (Fritsche-Neto et al., 2012).

The effects of varieties, heterosis, and significant interaction between heterosis and locations ($P \leq 0.01$) were detected for all traits, unlike for the varieties and location, where the differences were significant only for GY. These results suggest that there is sufficient genetic divergence among the South American parental varieties, resulting in favorable conditions for breeding, and the evaluations should be done in different locations.

There were significant differences ($P \leq 0.05$) for GY, in terms of average, variety, and specific heterosis. The total sum of squares for crop yield showed 68% of variety effects and 32% of total heterosis. These results suggest that the additive genes are the most important effect for achieving the best GY within this group of varieties. However, non-additive effects, such as genes complementation among each hybrid, have also been relevant for GY. Similar proportions of varieties and heterosis effects were also reported by Santos et al. (1994), Sinobas and Monteagudo (1996), San Vicente et al. (1998) and Araújo and Miranda Filho (2001) for common maize. Larish and Brewbaker, (1999) reported these effects for popcorn.

The mean heterosis for GY ranged from 33.2% to -27.5% at the different locations (Table 5). In comparison with common maize (Hallauer et al., 2010; Araújo and Miranda Filho, 2001), some heterosis values (location 1: 15.3%; location 3: 17.0%; and location 5: 33.2%) can be considered fairly high for the variety crosses. High average heterosis (33%) and crosses with heterotic effects as high as 101% were also reported by Paterniani and Lonnquist (1963) from the South American races of maize. These results indicate that GY can be added successfully through exploiting the heterosis by the inter-population methods. In addition, all effects from the partition of heterosis and variety presented significant values for the interactions with locations. Based on this background, all the effects depend on the environmental conditions or location for achieving the best GY.

Diallel analysis for popping expansion and other traits

For popping expansion (PE), plant (PH) and ear height (EH), and days to silking (FF), the differences from locations, varieties, all the partition of heterosis effects, the interaction between the varieties and locations, and average heterosis and locations were significant ($F \leq 0.01$). These results suggest that these landrace genotypes were different in their genic frequencies dispersion, and their effects were influenced by the environmental conditions at either location. Specific heterosis was significant at ($P \leq 0.05$) only for PE, which suggests differences among varieties at levels of genic frequency complementation. The percentage of heterosis (21.8%) indicated that the hybrid performance can be predicted by parental varieties, and the inter-population breeding method may provide genetic gain for PE.

The popping expansion ranged from 5.7 (PAZM 6070) to 10.4 mL mL^{-1} (PAZM 7130) among varieties, and from 8.9 (PAZM 7127 x PAZM 7139) to 11.9 mL mL^{-1} (PAZM 7130 x PAZM 7127) in the hybrid combinations (Table 3). These low indices between 8 and 10, except for PAZM 6070, are normal for varieties. The coefficient of variation of 20.6% indicated acceptable precision, although it should be higher (Vendruscolo et al., 2001; Scapim et al., 2002). Low responses for popping expansion of Brazilian popcorn populations were also reported by Miranda et al. (2008). In terms of PE; however, the potential for breeding varieties from

Table 1. Description of using populations from the Avatí Pichingá maize race.

Populations	Paraguayan Department	Description
PAZM 07130	Itapúa	na
PAZM 07127	Itapúa	na
PAZM 08080	Misiones	Typical Avatí Pichingá Round[a]
PAZM 07139	Itapúa	Typical Avatí Pichingá Round
PAZM 02065	San Pedro	Typical Avatí Pichingá Aristado[b]
PAZM 06070	Caazapa	Typical Avatí Pichingá Aristado
PAZM 10131	Alto Paraná	na

[a] Population with rounded grains, short plants with small ears, large glumes, late in days to flowering, and requires 1005 heat units to shed pollen. Slim stalk is slim, and sometimes develops tillers. [b] Late flowering population, requires 1056 heat units to shed pollen, similar to the Pichinga Round for height, and wide stalk; na = Non-available.

Table 2. Analysis of variance for five traits from five locations following the diallel model II of Gardner and Eberhart (1966) and the method 2, model I proposed by Griffing (1956).

Sources of variation	df	Mean square				
		Grain yield	Popping expansion	Plant height	Ear height	Flowering
Blocks / locations (L)	4	11.500.898.88**	167.53**	79656.87**	54726.82**	851.61**
Entries (E)	27	1.278.152.74**	26.83**	1072.59**	799.21**	70.66**
Varieties	6	3.901.196.16**	16.96**	2497.90**	1273.23**	71.85**
Heterosis	21	528.711.76**	29.65**	665.36**	663.77**	70.32**
Average heterosis (AH)	1	371.830.24*	281.35**	1366.15**	5813.35**	1181.27**
Variety heterosis (VH)	6	1.361.411.38**	25.94**	1115.44**	618.64**	33.81**
Specific heterosis (SH)	14	183.046.33**	13.26**	422.41**	315.29**	6.61 ns
E x L	108	332.162.69**	9.88**	1085.80**	784.55**	14.65**
Varieties x L	24	212.784.52**	7.14ns	80.38ns	75.63ns	2.85ns
Heterosis x L	84	366.270.74**	10.67**	1373.07**	987.10**	18.03**
AH x L	4	3.823.325.96**	63.40**	26379.48**	18088.96**	331.23**
VH x L	24	172.631.98**	6.19ns	62.54ns	41.84ns	2.46ns
SH x L	56	202.326.26**	8.82**	148.55ns	170.65ns	2.32ns
Pooled error	290	70.746.73	4.32	138.85	113.15	3.94

* and ** Significant at 0.05 and 0.01 probability levels by F-test, respectively.

Table 3. Mean values of crop yield, popping expansion, plant and ear height, and days to silking from seven populations and their hybrids from a complete diallel.

Genotypes	Grain yield (kg ha^{-1})	Popping expansion(mL mL^{-1})	Plant height(cm)	Ear height(cm)	Flowering(days)
1. PAZM 7130	2.043	10.4	178	99	76
2. PAZM 7127	989	9.1	175	94	77
3. PAZM 8080	1.443	7.9	166	94	78
4. PAZM 7139	2.288	10.1	173	92	72
5. PAZM 2065	2.448	8.8	186	101	76
6. PAZM 6070	1.970	5.7	146	81	78
7. PAZM 0131	2.064	8.6	181	109	78
1x2	1.635	11.9	173	105	73
1x3	1.919	11.1	177	103	72
1x4	1.660	10.1	177	105	72
1x5	1.851	9.5	194	116	73
1x6	1.905	10.4	179	108	74
1x7	2.180	10.1	181	109	73
2x3	1.738	10.3	170	98	71
2x4	1.902	8.6	176	103	73
2x5	1.940	11.1	172	100	73
2x6	1.779	10.8	177	107	73
2x7	2.064	11.8	174	103	72
3x4	1.676	11.0	172	103	72
3x5	2.015	11.4	184	103	71
3x6	1.879	10.8	173	107	72
3x7	2.091	9.6	179	109	73
4x5	2.151	11.8	173	96	71
4x6	2.069	10.2	161	93	73
4x7	2.162	9.4	173	96	72
5x6	2.173	10.4	177	106	74
5x7	2.309	10.9	180	111	73
6x7	2.080	10.4	181	109	74
Zélia	1.162	23.8	134	65	62
BRS Angela	1.337	21.3	146	73	62
Diallel overall mean	1.944	10.1	175	102	73
CV (%)	13.7	20.6	6.7	10.4	2.7

Table 4. Estimates of varieties effects ($\hat{v}_i$), general combining ability ($\hat{g}_i$), varietal heterorsis ($\hat{h}_i$), overall mean, average heterosis and, heterosis effects percent for grain yield following the model II of Gardner and Eberhart (1966) and the method 2, model I, proposed by Griffing (1956).

Populations	Grain yield (kg ha^{-1})																	
	Average locations			Location I			Location II			Location III			Location IV			Location V		
	$\hat{v}_i$	$\hat{g}_i$	$\hat{h}_i$	$\hat{v}_i$	$\hat{g}_i$	$\hat{h}_i$	$\hat{v}_i$	$\hat{g}_i$	$\hat{h}_i$	$\hat{v}_i$	$\hat{g}_i$	$\hat{h}_i$	$\hat{v}_i$	$\hat{g}_i$	$\hat{h}_i$	$\hat{v}_i$	$\hat{g}_i$	$\hat{h}_i$
PAZM 7130	150.8	-23.8	-198.4	151.7	-11.2	-174.1	148.7	82.1	15.5	150.6	-69.5	-289.5	144.2	37.2	-69.8	159.0	-157.7	-474.4
PAZM 7127	-903.0	-296.5	310.1	-903.2	-253.8	395.6	-899.6	-229.3	441.1	-904.7	-416.0	72.8	-902.1	-233.8	434.6	-905.3	-349.5	206.4
PAZM 8080	-449.0	-157.0	135.1	-449.2	-239.7	-30.1	-448.0	-171.6	104.8	-448.3	-87.9	272.5	-450.1	-158.7	132.7	-449.6	-127.0	195.7
PAZM 7139	396.1	84.6	-226.9	398.0	1.8	-394.5	394.0	69.5	-255.1	396.3	61.4	-273.5	406.6	103.5	-199.7	385.6	187.0	-11.6
PAZM 2065	555.2	206.2	-142.9	554.7	239.3	-76.1	552.0	248.4	-55.3	557.6	168.3	-221.0	552.6	126.8	-299.0	559.3	248.2	-63.0
PAZM 6070	78.0	31.5	-15.1	76.3	46.2	16.0	80.6	-91.8	-264.2	75.9	159.9	243.9	79.9	36.2	-7.5	77.3	6.9	-63.6
PAZM 0131	171.9	155.0	138.1	171.7	217.5	263.2	172.3	92.8	13.2	172.6	183.7	194.8	168.9	88.8	8.7	173.7	192.1	210.5
Overall mean	1.892.2			1.893.0			1.892.0			1.892.7			1.891.1			1.892.3		
Average heterosis	68.7			290.0			-520.7			321.9			-375.7			628.1		
Percentage of Heterosis	3.6			15.3			-27.5			17.0			-19.9			33.2		

Location I, II, IV and V: Capitán Miranda, Department of Itapúa, Paraguay. Locations III: Palotina, State of Paraná, Brazil.

Table 5. Estimates of varieties effects ($\hat{v}_i$), general combining ability ($\hat{g}_i$), varietal heterosis ($\hat{h}_i$), mean, and average heterosis of four traits following the model II of Gardner and Eberhart (1966) and the method 2, model I, proposed by Griffing (1956).

Populations	Popping expansion (mL mL^{-1})			Plant height (cm)			Ear height (cm)			Flowering (days)		
	$\hat{v}_i$	$\hat{g}_i$	$\hat{h}_i$	$\hat{v}_i$	$\hat{g}_i$	$\hat{h}_i$	$\hat{v}_i$	$\hat{g}_i$	$\hat{h}_i$	$\hat{v}_i$	$\hat{g}_i$	$\hat{h}_i$
PAZM 7130	1.7	0.4	-0.9	5.6	3.6	1.6	3.2	3.0	2.7	-0.1	0.1	0.3
PAZM 7127	0.4	0.2	-0.1	2.8	-0.8	-4.3	-1.3	-1.3	-1.3	0.2	0.1	-0.1
PAZM 8080	-0.7	-0.1	0.6	-6.1	-1.8	2.6	-1.4	-0.6	0.2	1.8	0.1	-1.7
PAZM 7139	1.5	0.2	-1.1	0.8	-2.4	-5.6	-3.8	-3.9	-3.9	-4.6	-1.5	1.6
PAZM 2065	0.1	0.2	0.3	13.9	5.6	-2.7	5.3	1.9	-1.5	-0.4	-0.1	0.2
PAZM 6070	-2.9	-0.8	1.4	-26.2	-7.6	11.1	-14.6	-3.3	8.1	1.6	0.9	0.1
PAZM 0131	-0.1	-0.2	-0.2	9.2	3.3	-2.7	12.8	4.3	-4.3	1.5	0.6	-0.4
Overall mean	8.7			172.2			95.8			76.3		
Average heterosis	1.9			4.2			8.6			-3.9		
Percent of Heterosis	21.8			2.4			9.0			-5.1		

Avatí Pichingá can be detected from the results of Larish and Brewbaker (1999), in which they reported 30.4 mL mL^{-1} in the genotypes Avatí Pichingá. These genotypes were inbreeding by half-sib selections. Based on the outlier of 5.7 mL mL^{-1} of PAZM 6070, Salhuana and Machado (1999) characterized this landrace as a typical example of the Avatí Pichingá maize race. In the other traits, the means of varieties ranged from 146 (PAZM 6070) to 186 cm (PAZM 2065) for plant height (PH); from 81 (PAZM 6070) to 109 cm (PAZM 0131) for ear height (EH); and from 72 (PAZM 7139) to 78 days to silking (PAZM 8080, PAZM 6070 and PAZM 0131) (Table 3). The level of precision of PH and EH can be considered as average (Fritsche-Neto et al., 2012).

Based on these results, we suggest that plant and ear heights are dispensable in the studies, in which the goal is the indication of the best hybrid response. This decision could reduce the costs of labor work in different locations. Ji et al. (2006) suggested that plant and ear height had great importance as criteria of plant selection in most tropical maize evaluation by diallel analysis. For these authors, ear height had special importance because the high ear position may induce greater susceptibility to root and stalk lodging. Thus, the elimination of these traits is critical in popcorn breeding selection because popcorn plants are more fragile in comparison with the common maize, although the high correlations among these traits in popcorn (Coimbra et al., 2001) indicate that it is not necessary to measure both of them in the field experiments.

Indication of promising varieties

The effect of varieties ($\hat{v}_i$) and general combining ability ($\hat{g}_i$) were used for choosing the most promising varieties for developing superior hybrids, composite population, or both. The $\hat{v}_i$ and $\hat{g}_i$ estimates for grain yield in five locations are presented in Table 4. The overall mean of five locations for the other traits are presented in Table 5.

The PAZM 2065 and PAZM 0131 were the most outstanding varieties for GY. They showed high v_i considering each location and the overall mean from five locations. The g_i effects are useful for selecting populations due to the relation $\hat{g}_i = 0.5\hat{v}_i + \hat{h}_i$ (Miranda Filho and Chaves, 1992). Also considering the $\hat{g}_i$ effects, PAZM 2065 and PAZM 0131 were unquestionably the most promising varieties (Table 4). Therefore, both were considered as most promising for breeding programs by intra-population breeding methods. Based on the mean heterosis, PAZM 0131 provides superior hybrids than the other varieties. This indicates a favorable condition for inter-population breeding. Nevertheless, according to v_i and $\hat{g}_i$ values, PAZM 7127 and PAZM 8080 were the worst parents for increasing the GY (Table 4).

The PAZM 7130 presented the better positive $\hat{g}_i$ values for popping expansion, and PAZM 6070 was the worst variety because the PE was reduced for all the hybrid combinations. The PAZM 2065 and PAZM 0131, which presented better $\hat{g}_i$ for GY, expressed medium values of $\hat{g}_i$ for PE, which indicates that they are similar for comparing the diallel overall mean. For PE, the positive heterosis indicates favorable conditions by using inter-population methods. Similar results were found by Sawazaki et al. (1986), who worked in diallel set of popcorn populations.

For the other traits (PH, EH and FF), the interest for breeding refers to the varieties with relevant negative effects of $\hat{v}_i$ and $\hat{g}_i$ i.e., identification of parents which present lower architecture and early flowering. The PAZM 6070 was the most outstanding varieties for PH ($\hat{v}_i$ = -15.1; $\hat{g}_i$ = -26.2) and EH ($\hat{v}_i$ = -6.5; $\hat{g}_i$ = -14.6), and PAZM 7139 presented negative and relevant $\hat{v}_i$ and $\hat{g}_i$ for EH, indicating that this parent can reduce the ear height. Considering early flowering, PAZM 7139 presented a better value ($\hat{v}_i$ = -4.6; $\hat{g}_i$ = -3.0).

Materials and Methods

Plant materials

Seven open-pollinated varieties of popcorn, PAZM 02065, PAZM 06070, PAZM 07127, PAZM 07130, PAZM 07139, PAZM 08080 and PAZM 10130, from the South American maize race Avatí Pichingá were collected from maize growers in the several Paraguayan Departments (Table 1). Performance of these varieties were assessed in a complete diallel without the reciprocals hybrids in the total of 21 combinations. These varieties were planted in 0.9 m rows with 0.4 m between plants in field plots at Centro Regional de Investigación Agrícola, CRIA, Paraguay to obtain the hybrids. At flowering, kraft paper bags were used to collect pollen grain, and plants were manually pollinated.

Experimental design

Phenotyping traits were carried out in a completely randomized block design with three replications at four locations in the experimental area of the CRIA, in Capitán Miranda, Department of Itapua, Paraguay. The fifth location was in the experimental area at the Cooperativa Central de Pesquisa Agrícola, COODETEC, in Palotina, Western Paraná, Brazil.

Seven parental varieties, their 21 hybrids, and the commercial genotype Zélia, a three-way hybrid from the Pioneer Seeds, and the BRS-Angela, an open-pollinated variety developed by Embrapa as the two controls were the 30 treatments. Plots were arranged in 5.0 m long single rows spaced 0.9 m apart and with 25 established plants per plot after thinning. Plots were fertilized with 4-14-8 at 500 kg ha^{-1} and N at 40 kg ha^{-1} side dressed to the plants at the growth stage V_4. All experimental plots had two additional border rows.

Studied traits

Every plot had the grain yield (GY) obtained by weighing the threshed grains and converting them into kg ha^{-1} after adjusting the moisture contents to 15.5%. The popping expansion (PE) (in mL mL^{-1}) was obtained as the ratio of the popped volume to the grain mass. Grain samples of 30 mL were popped at temperature of 237 ºC for two minutes in an electrical popper with automatic temperature control, which was developed by Embrapa-CNPDIA. The volume of the popped grain was measured in a graduated cylinder of 1,000 mL. The grain mass was collected at the mid-portion of ears. Grain samples and a control weighing 1.0 kg were stored in a cold dry chamber. These samples were monitored for moisture before evaluating the popping expansion. The popping expansion was evaluated when the control sample reached the moisture content of about 12% (Hoseney et al., 1983). The plant height (PH) (in cm) was measured from the ground level, up to the insertion of the flag leaf from six healthy plants. The ear height (EH) (in cm) was measured from the ground level, up to the insertion of the uppermost ear on the same six plants and, finally, days to silking (FF).

Statistical analysis

The Levene's test and the Kolmogorov-Smirnov method were first applied to data set to test the homogeneity of variances and error distribution. Data transformations were not necessary. Next, every data set was submitted to the analysis of variance (ANOVA) following the statistical model: $Y_{ij} = \mu + t_i + b_j + \varepsilon_{ij}$, in which Y_{ij} were the values collected at i^{th} treatment and j^{th} replication-block, μ was the overall mean of the each trait, t_i were the effect from treatments i, b_j were the effect from blocks j and ε_{ij} were the error for each observation ij.

Every location had the homogeneity of the residual variances tested by maximum F-test at 5% of probability. Joint analysis of variance was carried out following the statistical model $Y_{ijk} = \mu + (b/l)_{jk} + t_i + l_k + tl_{ik} + \varepsilon_{ijk}$ in which Y_{ijk} were the observed values at i^{th} treatments, j^{th} blocks and k^{th} locations, μ was the overall mean of the evaluated for every trait, $(b/l)_{jk}$ were the j^{th} block effect in the k^{th} location, tl_{ik} was the interactive effect between i^{th} treatments and k^{th} location and ε_{ijk} was the error for every observation ijk. In the combined analyses, locations were considered as random effect and the entries were the fixed effects. The pooled error mean square was used to test the significance of entry versus location. Main effects were compared by their respective interactions with locations.

Based on the ANOVA, the sum of squares for hybrids and parents were partitioned into varieties and heterosis effects. The model II of Gardner and Eberhart (1966) was fit to every proper data along with the method 2, and the model I of Griffing (1956) was used to estimate the combining ability of varieties.

The ANOVA assumptions were made by SAS 9.1, Windows version (SAS Institute, Cary, NC). The ANOVA and the diallel analyses were performed by the GENES (Cruz, 2013).

Conclusion

The diallel analysis showed ´PAZM 2065` and ´PAZM 0131` as superior varieties for grain yield, and ´PAZM 7130` for popping expansion, ´PAZM 6070` for plant height and ear height, and ´PAZM 7139` for early flowering.

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