Colegio de Postgraduados

Genotype by Environment Interaction of Maize (*Zea mays* L.) Hybrid Yield in Guanajuato, Mexico

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ABSTRACT
Objective: To evaluate phenological and yield parameters in experimental maize (*Zea mays* L.) hybrids across different environments.
Design/Methodology/Approach: The trials were conducted under gravity irrigation conditions with 21 experimental maize crosses and four commercial hybrids. The experiment was established in three communities in Guanajuato, Mexico, during the spring-summer agricultural cycle. A randomized complete block design with three replications was used in each environment. Genotype by environment interaction analysis was performed using the AMMI model.
Results: Genotypes 23, 21, and 16 achieved the highest yield, followed by genotypes 22, 6, 17, and 5, while genotypes 8 and 13 showed the lowest yield.
Limitations of the Study/Implications: The promotion of these hybrids in environments within the state of Guanajuato is desirable.
Findings/Conclusions: The genotypes exhibited high genetic divergence in the expression of yield parameters and their components. The outstanding hybrids were 23, 21, and 16, showing higher yields across all locations and demonstrating better adaptation to the three evaluation environments.

Keywords: Hybrids, Stability, Maize, Yield.

INTRODUCTION

The primary form of maize (*Zea mays* L.) consumption in Mexico is the tortilla, which is why it holds the top position in the basic food basket for the society. Mexico ranks seventh globally in maize production, with a total of 27.5 million tons produced in 2021 (FAOSTAT,

2023). In Mexico, maize cultivation is the leading crop, with six million hectares planted, followed by bean (*Phaseolus vulgaris* L.) production with one million hectares, and sorghum in third place with 1.367 million hectares (SIAP, 2022). In 2022, Guanajuato produced 1,734,381 tons of maize for grain with an average yield of 5.40 t ha^{-1} (SIAP, 2023). The state's main agricultural activity occurs during the spring-summer agricultural cycle, accounting for 75.5% of the cultivated area (SIAP, 2018). Given the importance of this crop, it is essential to implement strategies to provide the agricultural sector and society with viable alternatives for the use of elite maize materials that have good yield potential and are adaptable to diverse environmental factors.

An efficient option is the use of hybrids developed through the process of genetic improvement. In this context, the main objective of genetic breeding programs is to obtain genotypes with higher yields; however, in most cases, yield potential is masked by genotype by environment interaction (G×E). This occurs when genotypes respond differently to environmental variations (Gordón-Mendoza *et al.*, 2006). The genotype by environment interaction (G×E) model has been crucial in identifying the productive potential of varieties and hybrids in different crops (Williams *et al.*, 2021). Sprague and Eberhart (1977) mention that unpredictable environmental factors exist, which is why it is advisable to increase the number of environments for the evaluation of genetic materials. New multivariate methodologies not only allow for the description of genotype by environment interaction but also provide deeper insights into the nature of this interaction. Among these methodologies, the Additive Main Effects and Multiplicative Interaction (AMMI) model stands out for its ability to interpret many genotypes across various environments (Crossa *et al.*, 1990). This method is currently one of the most widely used for interpreting stability in maize (Ledesma *et al.*, 2012), wheat (Vázquez *et al.*, 2012), and sorghum (Williams *et al.*, 2021). In maize cultivation, this model has proven its efficiency in identifying outstanding and stable materials for different ecological niches (González *et al.*, 2009; Torres *et al.*, 2011; López *et al.*, 2019; Lopez *et al.*, 2017). There is evidence supporting the efficient use of the AMMI model for identifying genotypes in different locations; therefore, phenological and yield parameters were evaluated in outstanding experimental maize hybrids across three environments.

MATERIALS AND METHODS

Location and Genetic Material

The trials were conducted under gravity irrigation conditions with 21 experimental maize (*Zea mays* L.) crosses and four commercial hybrids (Puma, Cimarrón, DK-2061, and San Andrés). The evaluation was carried out in the communities of Soria in the municipality of Comonfort, Empalme Escobedo, and Juventino Rosas, in the state of Guanajuato, Mexico, during the spring-summer agricultural cycle of 2015.

Experimental Design and Agronomic Management

The experimental plot for each treatment consisted of two rows, each 5.2 meters long, with 0.76 meters between rows and 14 cm between plants. At planting, a chemical formula of 120N-80P-60K was applied, and during the second weeding, 120N-00P-00K was applied. A randomized complete block design with three replications was used in each environment. Agronomic management followed the technological package of INIFAP for irrigation conditions in the region (INIFAP, 2015).

Evaluated Variables

The following variables were evaluated: days to male flowering (DMF), plant height (PH), ear height (EH), rust (R) (*Puccinia sorghi*), and incidence and severity of Exserohilum (HLM). For the assessment of incidence and severity, the scale proposed by Arrieta *et al.* (2007) was used, which classifies severity on a scale from 1 to 9, where: 1=no disease (0%), 2=minimal presence of disease (1-10%), 3=light infection (11-20%), 4= value between light and moderate (21-34%), 5=moderate infection (35-49%), 6=value between moderate and severe (50-64%), 7=severe infection (65-78%), 8=value between severe and very severe (79-89%), and 9=very severe infection (>90%).

The number of plants affected by stem rot caused by *Fusarium moniliforme* (FUS) was quantified, as well as ear coverage (EC) using a scale from 1 to 5, where: 1=excellent coverage (100% of the population with covered ears), 2=fair coverage (75-99% of the population with covered ears), 3=exposed tip (50-74% of the population with covered ears), 4=exposed grain (25-49% of the population with covered ears), and 5=completely unacceptable (>25% of the population with covered ears).

Four ears were harvested to estimate post-harvest variables. The following measurements were taken weight of 500 grains (W500G), weight of grain per ear (WGE), number of rows (ROW), grain yield in tons per hectare adjusted to 14% moisture (YIELD), grains per ear (G×E), grains per row (G×ROW), ear perimeter (PER), and ear length (EL).

A combined analysis of variance (ANOVA) was performed for the main effects of genotype (G) and environment (E) using the following model:

$$Y_{ijk} = \mu + G_i + A_j + (GA)_{ij} + Bk\left(A_j\right) + E_{ijk}$$

where: Y_{ijk}=average yield of the *i*-th genotype obtained in the *j*-th environment and *k*-th replication, μ=overall mean effect, G_i=effect of the *i*-th genotype, Aj=effect of the *j*-th environment, $(GA)_{ij}$= interaction effect between the *i*-th genotype and the *j*-th environment, $Bk\left(A_j\right)$=effect of the *k*-th replication in the *j*-th environment, E_{ijk}=random error effect associated with the *i*-th genotype in the *j*-th environment and *k*-th replication.

A Principal Components Analysis (PCA) was also conducted to evaluate the non-additive effects of the G×E interaction (Gollob, 1968). This model, known as AMMI (Additive Main Effects and Multiplicative Interaction), developed by Gauch and Zobel (1988), includes both additive and multiplicative parameters. The data were analyzed using the SAS statistical package (SAS, 2006). Mean comparisons for agronomic traits were performed using Tukey's test ($p \leq 0.05$). The analysis of genotype by environment interaction using the AMMI model was carried out with the R software (R Core Team, 2012).

RESULTS AND DISCUSSION

The principal components analysis related to the eigenvalues of the correlation matrix showed that the first two components accounted for 51.6% of the variation with respect to the evaluated variables (Figure 1). Principal Component 1 (PC1) explained 36% and PC2 explained 15.6%. These values are considered acceptable for representing reliability with respect to the total variance relationships of the parameters under study (Arroyo *et al.*, 2005).

PC1 showed a positive association with the variables EL, G×ROW, EH, PH, G×E2, WGE2, YIELD, and DMF (Figure 2a), while PC2 recorded a positive association with the variables R and PL and a negative association with the variables ROW and PER (Figure 2b).

The color measurement indicates the percentage contribution of the evaluated variables (PC1 and PC2), where colors closer to red represent higher percentages of contribution, while colors closer to blue indicate lower percentages. The variables of interest are those with shades closest to red and higher percentages (Figure 3).

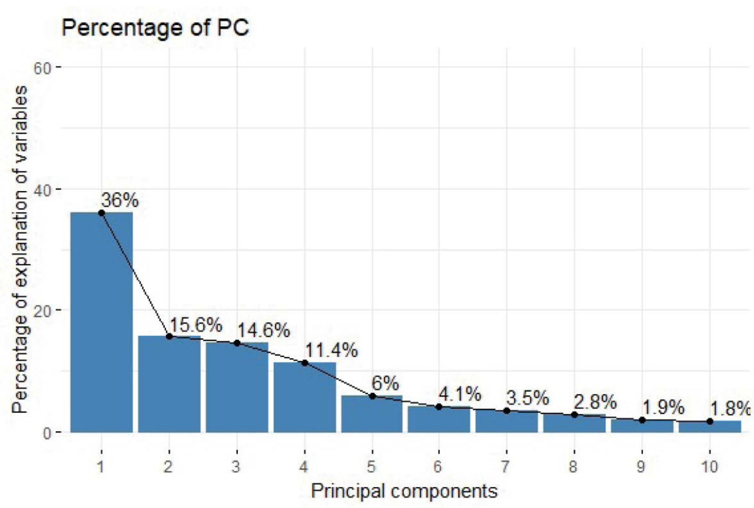

Figure 1. Percentage contribution of the principal components.

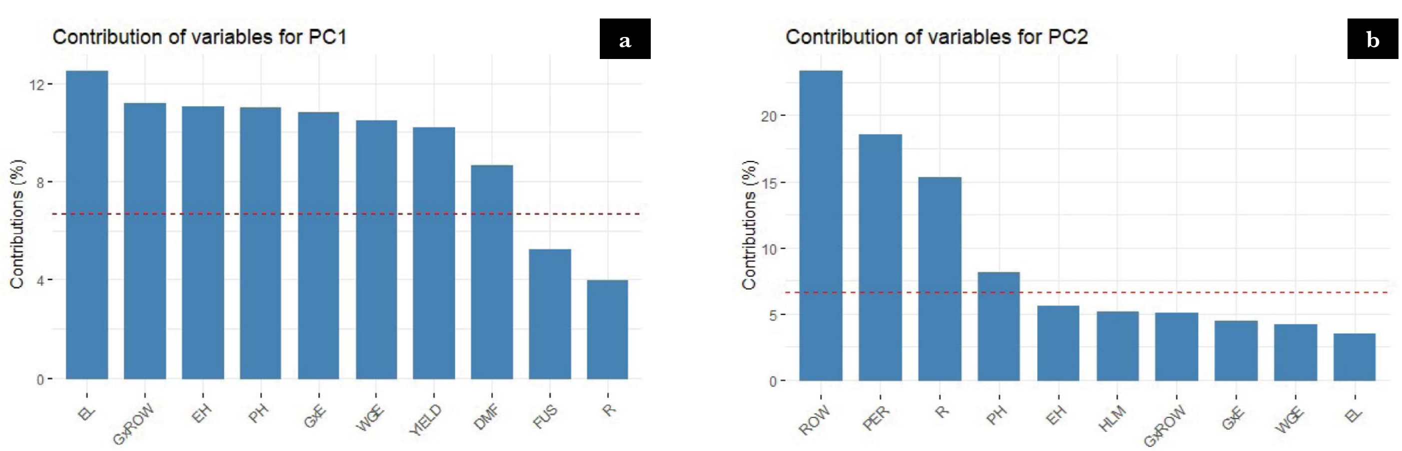

Figure 2. a) Percentage contribution explained by PC1. b) PC2 in relation to the study variables.

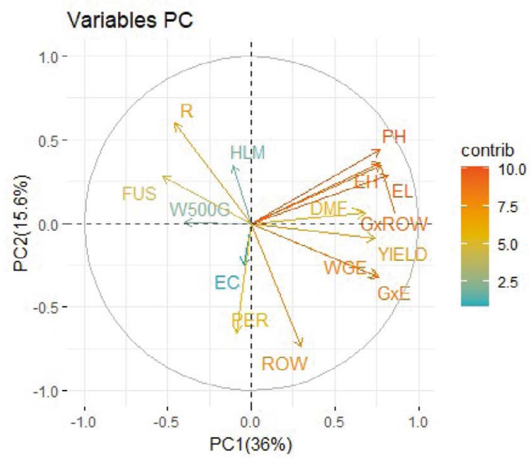

Figure 3. Biplot of agronomic variables evaluated in 25 maize hybrids across three locations in Guanajuato, Mexico.

The angle of the vectors explains the association between variables, such that smaller angles between vectors indicate a strong association, while larger angles indicate no association. Therefore, a strong relationship was observed among the variables PH, EH, G×ROW, EL, DMF, YIELD, WGE, and G×E, as well as between PER and ROW, R, and FUS. A low relationship was observed between FUS and G×E and GWE.

Analysis of variance across environments

The analysis of variance across locations (Table 1) detected highly significant differences (P≤0.01) for the sources of variation among locations and treatments concerning all the studied traits. Regarding the interaction between locations and treatments, highly significant differences (P≤0.01) were found for the variables DMF, PH, EH, HLM, FUS, R, EC, W500G, and YIELD, indicating an interaction between locations concerning the treatments. Concerning repetitions within locations, there were differences (P≤0.01) in DMF, PH, EH, EC, WGE, and YIELD, but discrepancies (P≤0.05) in G×E. The coefficients of variation ranged from 1.3% to 24.0%, which are acceptable values for ensuring the study's reproducibility over time and space. Therefore, these data demonstrate the reliability of the findings throughout this research.

Mean comparisons for locations showed that the shortest days to male flowering (DMF) were recorded in Soria with 71 days, while the longest were in Juventino Rosas with 75 days (Table 2). Extreme values for plant height (PH) and ear height (EH) were observed between Comonfort (243 for PH and 130 for EH) and Juventino Rosas (198 for PH and 103 for EH). In terms of Helminthosporium (HLM), the location with the highest damage to genotypes was Soria (3.2%), while the lowest presence was in Juventino Rosas (3%). These values are low according to the scale proposed by Arrieta *et al.* (2007), indicating that the evaluated hybrids are tolerant to HLM, showing only a slight infection of this pathogen. Regarding Fusarium (FUS), the location with the highest damage was Comonfort with 7.4%, while the lowest incidence was observed in Juventino Rosas with 3.8%. On the other hand, for the variable of rust (R), the location with the most damage

Table 1. Mean squares across locations for variables in three locations of the experiment.

S.V.	D.F	DMF	PH	EH	HLM	FUS	R	EC	W500G	WGE	ROW	YIELD	G×E	G×ROW	PER	EL
Loc	2	313.2**	41823.3**	13761.6**	7.0**	243.3**	21.1**	1.9**	10921.0**	224056.0**	13.4**	154.6**	29582.4**	93.3**	9.0**	132.4**
Rep(Loc)	6	3.3**	423.3**	329.6**	0.4	0.6	0.5	1.2**	368.0	26502.9**	3.0	3.8**	8180.0*	14.5	1.1	8.8
Treat	24	38.5**	1190.1**	1111.6**	2.6**	34.6**	3.9**	4.0**	2091.6**	16158.6**	12.6**	22.7**	29442.7**	60.7**	2.2**	5.4**
Loc×Treat	48	9.8**	220.9**	248.5**	0.9**	25.1**	1.0**	1.0**	557.1**	6790.2	2.3	3.5**	4290.7	11.6	0.7	2.1
Error	144	1.0	68.9	63.3	0.3	0.3	0.2	0.2	201.2	5923.5	1.6	0.8	3211.3	9.5	0.7	1.6
C.V. (%)		1.3	3.7	6.7	19.2	11.4	19.9	24.0	7.9	14.2	8.3	7.0	10.5	8.9	5.1	8.2
Media		73.6	223.9	117.3	2.9	5.4	2.6	2.1	179.3	540.1	15.5	13.1	536.0	34.5	16.5	15.7

S.V.=Source of variation; DF=Degrees of Freedom, DMF=Days of Male Floration; PH=Plant Height; EH=Ear Height; HLM=helmitosporium; FUS=fusarium; R=Rust; EC=Ear coverage; W500G=Weight of 500 grains; WGE=Weight of grain per ear; ROW=Number of rows; YIELD=Grain Yield tons per hectare; G×E=Grains per Ear; G×ROW=Grains per Row; PER=Ear Perimeter; EL=Ear length; Loc=Locations; Rep(Loc): replicates by location; Treat=Treatment; Loc×Treat=Location by treatment; C.V.=Coefficient of Variation. *Significance levels: *, **=different at P≤0.05 and 0.01, respectively.

Table 2. Mean comparisons by location for the traits measured in the experiment.

Location	DMF	PH	EH	HLM	FUS	R	EC	W500G	GWE	ROW	YIELD	G×E	G×ROW	PER	EL
Comonfort	74.42 b	243.26 a	130.44 a	2.64 c	7.42 a	2.48 b	2.30 a	187.12 a	592.45 a	15.78 a	14.37 a	558.96 a	35.48 a	16.46 b	17.30 a
Juventino Rosas	75.13 a	198.65 c	103.38 c	2.93 b	3.88 c	2.20 c	1.99 b	165.48 b	483.40 c	15.06 b	11.57 c	523.65 b	35.77 a	16.19 b	14.88 b
Soria	71.29 c	231.06 b	118.16 b	3.25 a	5.10 b	3.22 a	2.12 ab	185.55 a	544.47 b	15. 81 a	13.54 b	525.54 b	33.29 b	16.88 a	15.13 b
DHS	0.39	3.21	3.07	0.21	0.24	0.20	0.19	5.48	29.76	0.49	0.35	21.90	1.19	0.32	0.50

DMF=Days to male flowering; PH=Plant height; EH=Ear height; HLM=Helminthosporium; FUS=Fusarium; R=Rust; EC=Ear Coverage; W500G=Weight of 500 grains; GWE=Grain weight per ear; ROW=Number of rows; YIELD=Grain yield in tons per hectare; G×E=Grains per ear; G×ROW=Grains per row; PER=Ear Perimeter; EL=Ear length; HSD=Honest significant difference.

was Soria, and the least damage was in Juventino Rosas. For ear coverage, the location with the highest coverage in genotypes was Comonfort (2.3%), while the lowest coverage was in Juventino Rosas (2%). This indicates that the materials had regular coverage relative to the total population, which is a very important characteristic for obtaining high-quality grain by preventing the ear from being exposed to physical damage from pests and diseases. For the weight of 500 grains (W500G) and number of rows (ROW), Comonfort and Soria were the locations with the highest W500G and ROW, while Juventino Rosas exhibited lower W500G and ROW.

Regarding maize ear weight (WGE), the location with the highest ear weight was Comonfort, while the lowest ear weight was observed in Juventino Rosas. Concerning grain yield (YIELD), the genotypes showed the highest yield in Comonfort with 14 t ha^{-1}, and the lowest yield in Juventino Rosas with 11 t ha^{-1}. There was a difference of 3 t ha^{-1} between the locations with the highest and lowest grain yield. For grains per ear (G×E) and ear length (EL), Comonfort was found to have the highest G×E and EL, while Juventino Rosas and Soria had lower values. In terms of grains per row (G×ROW), Comonfort and Juventino Rosas had the highest values, with Soria showing the lowest. However, for ear perimeter (PER), Soria had the largest perimeter, while Comonfort and Juventino Rosas had the smallest. It is noteworthy that in Comonfort, the genotypes expressed their highest genetic potential in most of the studied variables, which is an important factor for achieving high grain yield.

In Table 3, the mean comparisons of the studied variables across the three evaluation environments are presented. It was observed that nine hybrids were statistically superior to the average yield of the check varieties, which were hybrids 23, 21, 16, 20, 22, 6, 17, 5, and 2, with yield increases of 17.2%, 16.6%, 16.5%, 15.8%, 8.6%, 7.7%, 7.5%, 5.6%, and 0.75%, respectively. These results demonstrate that there are experimental hybrids with similar or better performance compared to the genotypes used as checks, as seven hybrids from the selected group based on the average yield of the checks showed superior yields of over 14 t ha^{-1}. Regarding the DMF variable, the earliest hybrid was number 11 with 70 days, while the latest-maturing hybrid was number 25 with 77 days. On the other hand, the hybrids with the greatest plant height were 17 (241 cm) and 25 (239 cm), while the shortest was hybrid 7 with 200 cm. The hybrid with the greatest ear height was 22 with 146 cm, and the lowest was hybrid 7 with 100 cm. For the HLM variable, the hybrid with the highest percentage was 14 with a rating of 4.00, and the lowest was hybrid 2 with 1.6% damage. Regarding cob coverage, the hybrid with the highest rating was 14 with 3.8%, while the lowest was hybrid 4 with a rating of 1.2%. For the Fusarium variable, the hybrid with the most damage was 13 with 11%, and the least was 21 with 2.5%. In the rust variable, the hybrid with the highest rating was 13 with 3.8% damage, while hybrids 4 and 1 showed the least damage, both with a rating of 1.4%. The hybrid with the highest 500-grain weight was 10 with 216.8 g, while the hybrid with the lowest weight was 17 with 154 g. Regarding WGE, the hybrids behaved similarly, with a range from 428.7 to 600.4, corresponding to genotypes 13 and 16. Materials 6 and 8 showed the highest number of rows with 17, followed by material 14 with 17; however, the hybrid with the fewest rows was 13 with 12 rows. For the yield variable, hybrids 23, 21, and 16 had the highest yields

Table 3. Mean Comparisons of the Traits Measured in the Experiment Evaluated in the Three Locations in Mexico.

TREAT	DMF	PH	EH	HLM	FUS	R	EC	W500G	GWE	ROW	YIELD	G×E	G×ROW	PER	EL	%/CON
1(T)	75.33 bcd	214.33 g-k	113.00 e-i	1.88 fg	7.33 c	1.44 h	2.44 c-f	174.22 c-h	547.00 ab	16.44 ab	12.95 c-h	565.11 a-f	34.44 b-e	16.84 abc	15.38 abc	−3.34
2(T)	73.66 def	221.55 d-h	105.11 hi	1.66 g	6.77 cd	1.66 fgh	2.33 d-g	193.77 a-d	561.44 ab	15.55 a-d	13.94 b-e	503.33 d-h	32.44 c-f	16.44 a-d	15.72 abc	4.05
3(T)	74.33 cde	220.88 e-h	107.11 hi	2.33 d-g	4.66 ghi	2.22 d-h	1.55 f-i	170.11 d-h	554.56 ab	16.44 ab	13.43 c-g	569.56 a-f	34.77 b-e	16.56 a-d	15.00 abc	0.26
4(T)	76.00 abc	230.55 a-f	123.55 b-g	2.00 efg	4.22 ghi	1.44 h	1.22 i	168.11 e-h	520.56 ab	16.00 abc	13.29 c-g	548.89 b-f	34.33 b-e	16.26 a-d	16.11 abc	−0.81
5	73.77 def	229.66 a-f	123.22 b-g	2.88 cde	5.11 efg	2.22 d-h	3.55 ab	17.94 c-h	575.11 a	16.66 ab	14.15 a-d	597.33 a-d	35.88 a-e	16.32 a-d	16.66 ab	5.63
6	72.44 fgh	234.66 a-e	125.22 b-f	3.00 bcd	4.55 ghi	2.44 c-g	1.66 e-i	172 d-h	595.56 a	17.33 a	14.43 a-d	630.67 ab	36.44 a-e	17.20 ab	16.50 ab	7.74
7	72.66 efg	200.11 k	100.88 i	3.88 ab	9.66 b	3.22 abc	2.22 d-h	177.00 c-h	504.22 ab	15.55 a-d	11.62 hij	492.00 e-h	31.77 ef	16.61 a-d	14.38 bc	−13.23
8	71.11 ghi	203.77 kj	107.66 hi	3.33 abc	5.77 def	3.44 ab	2.77 bcd	193.77 a-d	487.78 ab	17.33 a	10.29 j	495.33 e-h	28.44 f	17.14 ab	14.00 c	−23.21
9	71.77 ghi	224.44 b-h	110.66 ghi	3.22 a-d	5.77 def	2.88 b-e	2.11 d-i	184.61 b-f	509.22 ab	16.22 ab	12.38 e-h	504.89 d-h	31.44 ef	16.74 a-d	15.50 abc	−7.61
10	70.88 hi	205.44 ijk	107.11 hi	3.11 a-d	6.33 dc	2.77 b-e	2.11 d-i	216.88 a	494.33 ab	13.33 ed	11.41 hij	415.78 h	31.22 ef	16.33 a-d	14.70 abc	−14.79
11	70.44 hi	212.77 h-k	111.88 ghi	2.88 cde	5.77 def	2.55 b-f	1.88 d-i	169.77 d-h	523.67 ab	15.55 a-d	11.81 g-j	548.44 b-f	35.33 b-e	16.77 a-d	15.38 abc	−11.84
12	70.88 hi	216.33 f-j	112.55 f-i	3.22 a-d	7.00 c	3.00 a-d	1.77 e-i	178.16 c-h	511.44 ab	15.11 a-d	11.61 hij	519.78 c-g	34.44 b-e	17.05 abc	14.90 abc	−13.32
13	71.55 ghi	228.44 a-g	109.66 ghi	3.11 a-d	11.00 a	3.88 a	1.55 f-i	172.38 d-h	428.78 b	12.66 e	10.49 ij	420.67 gh	33.22 c-f	15.31 d	15.33 abc	−21.65
14	70.11 ghi	218.55 f-i	105.33 hi	4.00 a	4.22 ghi	3.33 abc	3.88 a	159.22 gh	525.44 ab	17.11 a	11.80 g-j	604.67 abc	35.44 a-e	16.40 a-d	15.33 abc	−11.92
15	72.11 f-i	235.88 a-d	115.22 d-g	3.22 a-d	4.11 g-j	3.11 a-d	1.88 d-i	184.44 b-f	498.44 ab	13.77 cde	12.80 d-h	481.11 fgh	34.88 b-e	15.63 cd	16.44 ab	−4.44
16	72.33 fgh	224.00 c-g	127.55 bcd	2.88 cde	3.11 jk	2.55 b-f	2.11 d-i	186.88 b-f	600.44 a	14.44 b-e	15.61 a	540.00 b-f	37.33 abc	16.23 a-d	16.88 a	16.55
17	76.66 ab	241.00 a	128.00 bcd	2.66 c-f	6.66 dc	1.55 gh	1.33 hi	154.27 h	556.56 ab	16.00 abc	14.41 a-d	650.67 a	40.77 a	16.15 a-d	16.83 a	7.56
18	75.00 bcd	212.88 h-k	112.11 f-i	2.77 c-f	4.77 fgh	2.00 e-h	2.00 d-i	158.77 gh	519.56 ab	16.22 ab	13.50 c-f	570.22 a-f	35.22 b-e	15.80 bcd	15.47 abc	0.75
19	75.33 bcd	222.55 c-h	108.33 hi	2.88 cde	3.66 ij	2.77 b-e	1.44 ghi	206.66 ab	587.78 a	15.11 a-d	12.40 e-h	482.00 fgh	31.88 def	17.60 a	16.27 abc	−7.44
20	73.77 def	227.77 a-g	117.00 c-h	3.11 a-d	3.88 hij	3.11 a-d	1.88 d-i	197.77 abc	578.44 a	14.44 b-e	15.52 ab	500.44 d-h	34.66 b-e	16.70 a-d	16.14 abc	15.87
21	75.00 bcd	223.88 c-h	126.88 b-e	3 bcd	2.55 k	2.22 d-h	2.55 cde	182.11 b-g	583.33 a	15.77 abc	15.63 a	542.67 b-f	34.44 b-e	16.62 a-d	16.33 ab	16.69
22	74.77 cd	236.66 abc	146.11 a	3.00 bcd	6.44 dc	3.22 abc	2.00 d-i	189.55 b-f	575.11 a	15.22 a-d	14.56 abc	530.00 c-f	35.00 b-e	16.44 a-d	16.27 abc	8.69
23	76.00 abc	238.88 b-f	125.66 b-f	2.88 cde	3.66 ij	2.66 b-e	3.33 abc	190.22 b-e	595.56 a	16.22 ab	15.71 a	533.56 b-f	32.88 c-f	16.93 abc	16.05 abc	17.25
24	76.00 abc	235.55 bc	129.33 bc	3.00 bcd	3.77 hij	2.77 b-e	1.66 e-i	164.77 fgh	534.22 ab	15.77 abc	12.03 f-i	585.56 a-e	37.22 a-d	16.38 a-d	16.00 abc	−10.17
25	77.33 a	239.22 ab	135.00 ab	3.55 abc	5.88 de	3.33 abc	2.11 d-i	166.00 e-h	542.11 ab	14.66 b-e	13.30 c-g	568.67 a-f	38.88 ab	16.30 a-d	16.61	−0.75
DHS	1.80	14.61	14.00	1.00	1.10	0.92	0.90	24.95	135.36	2.27	1.63	99.66	5.43	1.48	2.29	

*-=Range of the means for each treatment, C=control; DMF=days to male flowering; PH=plant height; EH=ear height; HLM=Helminthosporium; FUS=Fusarium; R=rust; EC=ear coverage; W500G=500-grain weight; WGE=grain weight per ear; ROW=number of rows; YIELD=grain yield in tons per hectare; G×E=grains per ear; G×ROW=grains per row; PER=ear circumference; EL=ear length; %/CON=percentage relative to the average yield of the controls; TREAT=treatment; HSD=honest significant difference.

with 15.7, 15.6, and 15.6 t ha^{-1}, respectively, while hybrid 8 had the lowest yield with 10 t ha^{-1}. The hybrid with the most grains per ear was 17, with 650 grains, and the one with the fewest grains was 10, with 415 grains, a crucial characteristic influencing high and low yields in the genotypes. Regarding grains per row, hybrid 17 had 40 grains, while hybrid 8 had the fewest with 28 grains. For the perimeter of the ear (PER), hybrid 19 had the largest perimeter with 17.6 cm, and hybrid 13 had the smallest with 15.3 cm. Finally, concerning the length of the ear (EL), hybrids 16 and 17 had the greatest length, both with 16.8 cm, while the genotype with the shortest length was 8, with 14 cm.

Genotype-Environment Interaction Analysis

The analysis of variance (Table 4) showed a highly significant effect of the environment ($P \leq 0.01$), accounting for 30.2% of the total sum of squares (TSS). The genotype factor was also highly significant ($P \leq 0.01$), registering 53.3% of the TSS. The genotype-by-environment interaction was significant ($P \leq 0.01$), contributing 16.4% to the TSS. The AMMI model showed that the first two principal component axes were highly significant ($P \leq 0.01$), explaining 75.7% and 24.2% of the interaction sum of squares, respectively. The AMMI model retained 96% of the TSS (E+G+E*G) utilizing 51 degrees of freedom (2 for E, 24 for G, and 25 for the first principal component).

The results of the AMMI analysis facilitated the graphical representation (biplot) of genotypes and environments in the same space (Figure 4). On the abscissa axis (x), the grain yield of genotypes and environments is presented. The line perpendicular to this axis indicates the mean yield, which was 13 t ha^{-1}. Likewise, entries with lower yield are plotted to the left of the X-axis, while genotypes and environments with higher yield are located to the right.

The Y-axis, on the other hand, measures the stability of genotypes and environments: those with values close to zero are stable, while those with high values of the first principal component are unstable. According to this information, genotypes 23, 21, 16, and 20 achieved the highest yields, followed by genotypes 22, 6, 17, and 5. In contrast, genotypes 8 and 13 showed the lowest yields, these data are consistent with the averages mentioned in Table 3. The locality of Comonfort achieved the highest yield, followed by Soria; the locality of Juventino Rosas recorded yields below the average. On the other hand, the most

Table 4. Analysis of Variance of the AMMI Model for 25 Maize Hybrids Evaluated in 3 Environments.

S.V.	D.F	S.S	% TSS
Environment (E)	2	309 **	30.21
Genotype (G)	24	546 **	53.32
G*E	48	169 **	16.47
PC1	25	128 **	75.75
PC2	23	41 **	24.25

S.V.=Source of variation; DF=Degrees of Freedom; SS=Sum of Squares; %TSS=percentage of total sum of squares; G*E=genotype by environment interaction; PC=Principal Component.

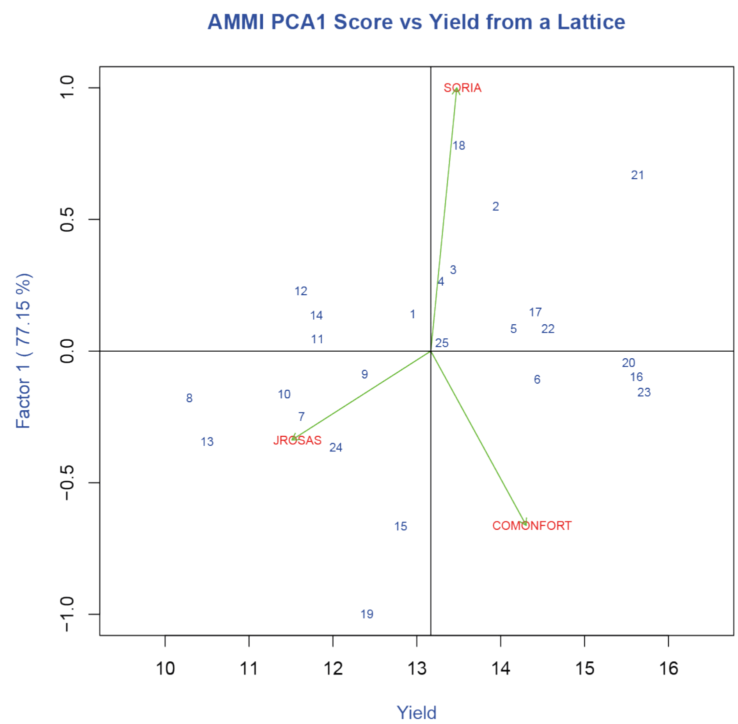

Figure 4. Biplot of grain yield for 25 maize hybrids evaluated in the experiment.

stable genotypes, with low or near-zero PC1 values, were genotypes 20, 16, 23, 17, 22, 6, 5, 25, 4, 1, 9, 11, 14, 7, and 8. However, genotypes 20, 16, and 23 stood out the most in terms of yield, indicating that these materials performed well across all environments. Genotypes 21, 18, and 19, along with the Soria environment, contributed the most to the first axis of interaction, making them the most unstable. Regarding the environments, Yan *et al.* (2000) notes that those with an angle less than 90° between them tend to classify genotypes in a similar manner, while those with an angle close to 180° tend to order genotypes inversely, making material selection more challenging due to their contrasting nature, as observed in the environments of Soria and Comonfort. Given the length of the vectors, the environments that best discriminated the genotypes in the evaluation were Soria and Comonfort, according to was explained by Kempton (1984).

CONCLUSIONS

There is high genetic divergence in the expression of yield and phenological parameters. The outstanding hybrids in this experiment were 23, 21, and 16, as they revealed the best yields across all locations.

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