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Artticle

Productivity and stability of free-pollinated corn varieties in the High Valleys of Mexico

Enrique I. Canales Islas[1]
Consuelo López López[2]
Alejandro Espinosa Calderón[2§]
Margarita Tadeo Robledo[3]
Antonio Turrent Fernández[4]
Benjamín Zamudio González[4]

1 Campo Experimental Santiago Ixcuintla-INIFAP. Carretera Internacional México-Nogales km 6, Entronque a Santiago Ixcuintla, Santiago Ixcuitla, Nayarit, México. CP. 63300. (enrique1784@yahoo.com.mx).

2 Secretaria Ejecutiva de la Comisión Intersecretarial de Bioseguridad de Organismos Genéticamente Modificados. Insurgentes Sur 1582, Col. Crédito Constructor, Benito Juárez, Ciudad de México. CP. 03940. (lopez8con@gmail.com, espinoale@yahoo.com.mx).

3 Facultad de Estudios Superiores Cuautitlán. Universidad Nacional Autónoma de México. Teoloyucan km 2.5, San Sebastián Xhala, Cuautitlán Izcalli, Estado de México. CP. 54714. (tadeorobledo@yahoo.com).

4 Campo Experimental Valle de México-INIFAP. Carretera Los Reyes-Texcoco km 13.5. Coatlinchán, Texcoco, Estado de México. CP. 56250. (aturrent37@yahoo.com.mx; bzamudiog@yahoo.com.mx).

Autor para correspondencia: espinoale@yahoo.com.mx.

Abstract

In the High Valleys of Central Mexico, improved white-grained and free-pollinated corn varieties are needed for medium-productivity conditions. This research aimed to determine the productive capacity and the stability of grain yield of a group of free-pollinated corn varieties using the AMMI procedure. Nine varieties of conical race of intermediate cycle corn were evaluated, four experimental from the Cuautitlán Faculty of Higher Studies of the National Autonomous University of Mexico, two experimental from the National Institute of Forestry, Agricultural and Livestock Research-Valle de México Experimental Field and three commercial control varieties from the National Institute of Forestry, Agricultural and Livestock Research- Valle de México Experimental Field, in the spring-summer cycle of 2016 to 2019, in two locations, the Cuautitlán Faculty of Higher Studies of the National Autonomous University of Mexico and the National Institute of Forestry, Agricultural and Livestock Research-Valle de México Experimental Field. A randomized complete block experimental design with four replications was used. Yield data and other variables were analyzed in a factorial arrangement, considering environments, genotypes, and their interactions as sources of variation. The AMMI procedure was used to evaluate the varieties for their stability in grain yield. The combined analysis of variance detected highly significant differences for all variables between environments, genotypes, and the genotype-by-environment interaction. The overall mean yield was 5 090 kg ha^{-1}. In the comparison of means between environments, in 2017, the Cuautitlán Faculty of Higher Studies of the National Autonomous University of Mexico had the best yield, with 9 163 kg ha-1. The Maíz Texotli Puma variety expressed the best yield with 6 491 kg ha-1. The free-pollinated corn varieties with the best stability in grain yield were V 80 Turrent and V 23 Huamantla.

Keywords:

Zea mays L., free-pollinated varieties, productivity, stability.

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Introduction

In Mexico, although 27.5 million tons of corn are produced (SIAP, 2022), which satisfies the 13 million tons required for direct consumption through the production of tortillas, it is necessary to increase corn production since more than 16 million tons of yellow grain are imported. This import volume, mostly transgenic, will be limited in accordance with the Presidential Decree of February 13, 2023 (DOF, 2023).

In the country, 7.5 million hectares of corn are grown annually, with an average production of 3.8 t ha^{-1} (SIAP, 2022). Of the national cultivated area, 1.4 million hectares are located at altitudes of 2 200 to 2 600 m, corresponding to the region of the High Valleys of Central Mexico, of which 1.06 million hectares are cultivated under rainfed conditions, with rains that occur late, limiting the date of sowing, the productivity of the crop and its exposure to the incidence of early frosts. Under these conditions, 404 000 ha are sown in the State of Mexico, with a productivity of 3.7 t ha^{-1} (SIAP, 2022).

The generation of improved varieties of free-pollinated (FP) corn, with adaptation to the agroclimatic conditions of the High Valleys of Central Mexico, has been scarce. For many years, the generation of this type of material has not been addressed. In 1980, varieties VS 22 and V 23 were released, as well as V-53 A, V-54 A, and V-55 A in 2009, 2010, and 2011, respectively (Espinosa *et al*., 2010; Espinosa *et al*., 2011). FP corn varieties are a viable option due to their affordability, easy maintenance, and the fact that there is no need to purchase seed each agricultural cycle.

The process of identifying and selecting outstanding varieties with agronomic characteristics, good yield, and stability requires their evaluation in environments, considering the effects of the genotype-environment interaction (GEI). Wolde *et al*. (2018) suggest using a statistical model that provides tools to identify stable genotypes, such as the additive main effects and multiplicative interaction (AMMI) model (Vélez-Torres *et al*., 2018; Wang *et al*., 2020).

The AMMI model combines the techniques of analysis of variance and principal component analysis (PCA). The analysis of variance allows the study of the main effects of genotypes and environments, while GEI is treated in a multivariate manner by means of the PCA (Zobel *et al*., 1988). This model makes it possible to identify the genotypes with the best stability based on their grain productivity and thus define the genotypes adapted to specific environments.

This research aimed to determine the productive capacity and stability of grain yield of a group of free-pollinated corn varieties through the AMMI analysis.

Materials and methods

During the spring-summer cycle of 2016 to 2019, nine varieties, six of white grain, two of blue grain, and one variety of yellow grain (Table 1), were evaluated in uniform trials at the Valle de México Experimental Field (CEVAMEX), for its acronym in Spanish of INIFAP, located in Texcoco, State of Mexico at an altitude of 2 240 m, with an average rainfall of 625 mm. The texture of the soil is sandy loam. The other location was in the Cuautitlán Faculty of Higher Studies (FESC)-UNAM, for its acronym in Spanish, Field 4, of the National Autonomous University of Mexico (UNAM), for its acronym in Spanish; the texture of the soil is clay loam, at an altitude of 2 274 m and its average rainfall is 609 mm (García, 2004).

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Table 1. Free-pollinated corn varieties of different grain colors evaluated in the spring-summer cycles of 2016 to 2019, in the High Valleys of Mexico.

Name of the varieties	Grain color
V 80 Turrent, V 62, Centli Puma, VS-334 C, V 23 Huamantla (Carballo and Mendoza, 1981), Cuxi Puma	White
V 54 A (Espinosa *et al.,* 2010)	Yellow
Maíz Matlalli Puma, Maíz Texotli Puma	Blue

The experiments were established under irrigation tip conditions. Each test environment consisted of the location and year in which the experiment was established; the evaluation environments were nine in total and were listed as follows: A1. FESC UNAM 2016; A2. INIFAP CEVAMEX 2016; A3. FESC UNAM 2017; A4. INIFAP CEVAMEX 2017 A; A5. INIFAP CEVAMEX 2017 B; A6. FESC UNAM 2018; A7. INIFAP CEVAMEX 2018; A8. FESC UNAM 2019; 9. INIFAP CEVAMEX 2019.

The experiments were established under a randomized complete block design with four replications. The experimental plot consisted of a furrow 5 m long by 0.8 m wide, and the population density was 45 000 plants ha^{-1}.

In the field, the variables recorded were days to male flowering, female flowering, plant height, and ear height. The harvest was done manually. The yield and its components, such as volumetric weight, weight of 200 grains, ear length, percentage of dry matter (% DM), and percentage of grain (% G), were determined.

Statistical analysis was performed in a factorial arrangement; the sources of variation were environments (9), genotypes (9), and GEI. The means were compared with Tukey's test (*p*# 0.05). The statistical package of SAS version 9.1 (SAS Institute Inc, 2004) was used for all analyses.

Likewise, the behavior of the varieties was evaluated for their stability for grain yield by performing the GEI with the additive main effects and multiplicative interaction (AMMI) model procedure. It was implemented with the AMMI programming routines described by Gauch (2013), under the following mathematical model:

$$Y_{ij}= \mu+g_i+e_j+\sum_{k=1}^{n}\lambda_k\alpha_{ik}\gamma_{jk}+E_{ij}$$

Where: Y_{ij}= yield of the i-th genotype in the j-th environment; μ= overall mean; g_i= mean deviations of the i-th genotype; e_j= mean deviations of the j-th environment; λ_k = square root of the eigenvalue of the k-axis of the principal component analysis (PCA); α_{ik} γ_{jk}= ratings of the PCA of the genotype and the environment for the PCA k-axis; n= number of PCA axes retained in the model; E_{ij}= error.

In addition, the Biplot tool was used to evaluate corn varieties in multienvironments (Yan *et al*., 2000): the AMMI1 Biplot (a principal component and yield) and the AMMI2 Biplot (two principal components).

Results and discussion

The combined analysis of variance detected statistical differences (*p*# 0.01) between environments, between genotypes (varieties), and in GEI for all variables. Thus, the environments were different, the varieties were genetically contrasting, and each variety had a differential response in each evaluation environment. The overall mean yield was 5 090 kg ha^{-1}, in contrast to that recorded for the State of Mexico, which is 1 398 kg ha^{-1} (SIAP, 2022). The coefficients of variation ranged from 1% for male flowering and female flowering to 8.6% for yield, indicating an acceptable control (< 20%) of experimental variability (Table 2).

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Table 2. Mean squares, statistical significance, and coefficients of variation of the combined analysis of the evaluation of free-pollinated corn varieties from the High Valleys in the spring-summer cycle of 2016 to 2019.

Variables	Sources of variation					CV (%)	Mean
	Environment	Block (environment)	Genotype	GEI	Error		
DF	8	27	8	64	216		
Yield	128020525**	406275**	57438376**	4552213**	193423	8.6	5090
Male flowering	223**	1.4**	281**	18.4**	0.59	1	76
Female flowering	230**	2**	263**	18.2**	1	1	78
Plant height	20497**	68**	7997**	496**	35.1	2.8	210
Ear height	7007**	21*	2804**	176**	12.7	3.4	104
Volumetric weight	344**	7.1**	187**	27**	3.1	2.4	72.5
Weight of 200 g	3455**	25**	829**	167**	10.9	6	54.8
Ear length	34**	1*	19.1**	2.7**	0.7	5.7	14.5
(%) dry matter	553**	3.8**	17**	4.9**	1.5	1.4	85.6
(%) grain	120**	5.6	168.5**	26**	4.5	2.6	82

GEI= genotype-by-environment interaction; DF= degrees of freedom; *= $p< 0.05$; **= $p< 0.01$; CV= coefficient of variation.

Between environments, the significance of the yield expression and the other variables was due to the precipitation differential between the years evaluated and the distribution of precipitation during crop development. The yield means of the varieties in the locations showed that the grain productivity in FESC UNAM was 5 874 kg ha^{-1}, higher than in INIFAP CEVAMEX, with 4 462 kg ha^{-1}, similar results were presented in evaluations by López *et al*. (2017).

In FESC UNAM, the average grain yield was 31.6% higher than in INIFAP CEVAMEX; the environment of FESC UNAM 2017 had the best grain yield, with 9 163 kg ha^{-1}, significantly different from the other locations (Figure 1). The lowest yield corresponded to INIFAP CEVAMEX 2017 A, with 2 965 kg ha^{-1}; this last experiment was affected by the drought and hailstorms that occurred in the region. The experiment at INIFAP CEVAMEX 2017 B decreased its grain yield by 56.4% due to hailstorms, compared to the FESC-UNAM 2017 environment.

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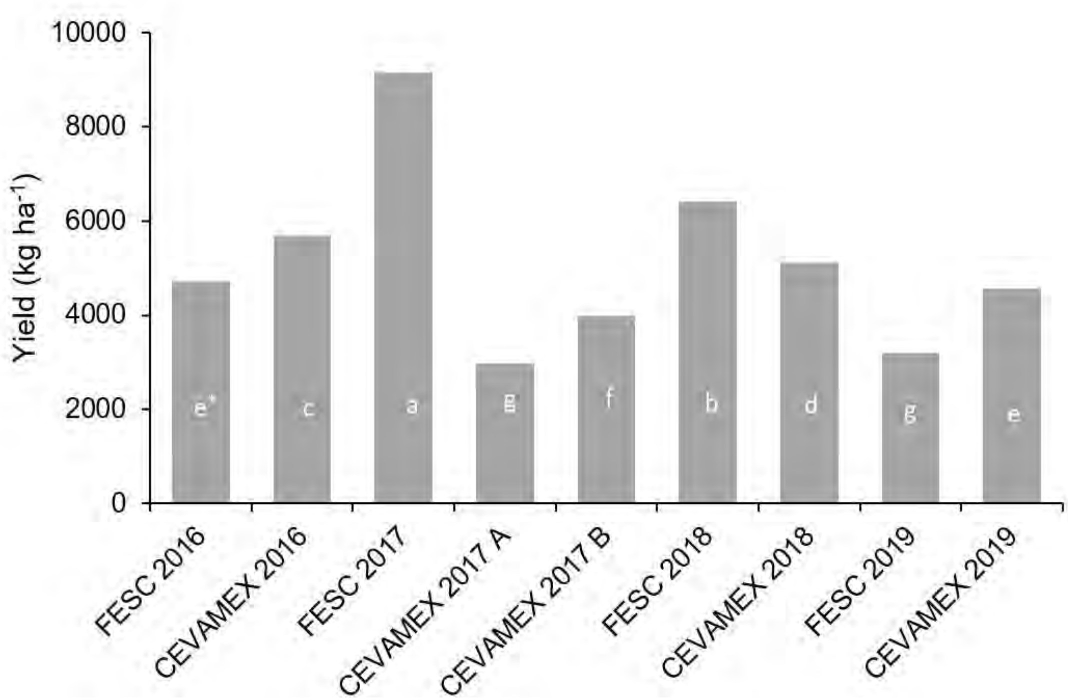
Figure 1. Comparison of means between environments in grain yield, considering the average of nine free-pollinated corn varie es evaluated from 2016 to 2019 in the High Valleys of Central Mexico. *Equal le ers are statis tically the same; different letters are statistically different, with the least significant difference being 343 kg.



Among varieties, the Maíz Texotli Puma genotype had the best average grain yield with 6 491 kg ha^{-1}, followed by Maíz Matlalli Puma with 6 455 kg ha^{-1} and Cuxi Puma with 5 998 kg ha^{-1}. The white grain variety V 80 Turrent had an average yield of 5 706 kg ha^{-1}, 12.1% less than Maíz Texotli Puma. The results obtained indicate that the materials could compete in the Mexican grain corn market as they surpassed the yellow grain variety V 54 A, which obtained a yield of 5 383 kg ha^{-1}. The V-62 variety had the lowest yield, with 3 178 kg ha^{-1} (Table 3).

Table 3. Comparison of means between free-pollinated corn varieties evaluated from 2016 to 2019 in the High Valleys of Mexico.

Genotypes	Variables									
	YIELD	MF	FF	PH	EH	VW	W200G	EL	%DM	%GR
Maíz Texotli Puma	6491 a	78 b	80 b	224 a	105 bc	71.6 d	61 a	15 b	85 b	84 ab
Matlalli Puma Azul	6455 a	80 a	82 a	223 a	113 a	73.4 bc	61 a	14 c	84 c	81 de
Cuxi Puma	5998 a	76 c	78 c	216 b	107 b	73.4 bc	55 b	16 a	85 b	82 bc
V 80 Turrent	5706 bc	76 c	78 c	213 b	103 c	72.9 c	56 b	15 b	86 a	82 bc
V 54 A	5383 c	73 f	75 e	216 b	107 b	76.1 a	57 b	15 b	85 b	83 b
V 23 Huamantla	4893 d	74 e	76 de	223 a	116 a	68.8 e	55 b	14 c	86 a	86 a
VS-334 C	4520 e	80 a	82 a	201 c	100 c	71 d	50 c	14 c	85 b	79 f

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Genotypes	Variables									
	YIELD	MF	FF	PH	EH	VW	W200G	EL	%DM	%GR
Centli Puma	3185 f	74 e	76 d	191 d	91 d	71.5 d	47 d	15 b	86 a	80 cd
V-62	3178 f	75 d	76 d	183 e	90 d	74.8 b	50 c	13 d	86 a	81 d
LSD	325	1	1	4	3	1.3	2	1	1	2

Yield= grain yield; MF= male flowering; FF= female flowering; PH= plant height; EH= ear height; VW= volumetric weight; W200G = weight of 200 grains; EL= ear length; RE= rows per ear; GR= grains per row; GE= grains per ear;% DM= percentage of dry matter; %GR= grain percentage; LSD= least significant difference.

The Maíz Matlalli Puma and VS-334 C varieties showed the latest male flowering with 81 days and 82 days to female flowering, respectively. On the other hand, the V 54 A variety expressed the earliest male flowering with 73 and 75 days to female flowering. Plant height varied from 183 cm in the V 62 variety to 224 cm in the Maíz Texotli Puma variety. Ear height ranged from 90 cm in the V 62 variety to 116 cm in the V 23 Huamantla variety (Table 3).

For the volumetric weight between varieties, the values ranged from 68.8 kg hl^{-1} for the V 23 Huamantla variety to 76.1 kg hl^{-1} for the V 54 A variety; the overall mean was 72.5 kg hl^{-1}, a slightly low value according to the NMX 034 standard of 2002 (DOF, 2002), for corn intended for nixtamalization (74 kg hl^{-1}). Only the V 62 variety had an acceptable weight (74.8 kg hl^{-1}) based on the standard. Grain percentage varied from 79% in the VS-334 C variety to 86% in the V 23 Huamantla variety. The most productive locations were associated with higher grain percentages (Table 3).

The analysis of variance of the AMMI model for grain yield detected highly significant differences (*p*# 0.01) between environments, between genotypes, and in the genotype-by-environment interaction (GEI), which justifies the use of the AMMI procedure in the study. The total contribution to the sum of squares by the environmental factor was 53.03%, genotypic effects contributed 25.2%, and GEI contributed 15.9% of the total variation, results similar to those obtained by Vélez *et al*. (2018); Mushayi *et al*. (2020).

They reported the dominance of environmental effects as a source of variation in multienvironments, indicating that the agricultural system, soil, fertilizers, varieties, and climatic factors affect corn yield differently (Li *et al*., 2019). With the help of Gollob (1968) test, high significance (*p*# 0.01) was identified in the principal components and the residuals.

PC1 accounted for 49.6% of the variability of GEI, while PC2 accounted for 24.3%, for a total of 73.9%, results that agree with what was reported by Gauch (2013), who pointed out that the AMMI procedure is broadly predicted by the first two principal components (Table 4).

Table 4. AMMI analysis of variance for grain yield of nine free-pollinated corn varieties evaluated in the spring-summer cycles of 2016 to 2019.

Source of variation	DF	SS	MS	(%) SS
Blocks	3	255996	85332	0.01†
Environments	8	1024164094	128020512**	53.03†
Genotypes	8	459505697	57438212**	25.2†
GE interaction	64	291342455	4552226**	15.9†
PC1	15	144391335	9626089**	49.6
PC2	13	70690496	5437730**	24.3
Residuals	35	75372384	9182887.5**	25.8
Error	240	52493013	218721	2.9†
Total	323	1827761255		

DF= degrees of freedom; SS= sum of squares; MS= mean squares; (%) SS= percentage of the sum of squares; PC1= principal component 1; PC2= principal component 2; †= with respect to the SS of the total; *= $p \leq 0.05$; **= $p \leq 0.01$.

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In the GEI study, the analysis with the AMMI1 Biplot identified that the genotypes with the most significant effects on GEI were Centli Puma (G3), V-62 (G2), and Maíz Texotli Puma (G10) due to their high PC1 values. The varieties that had a lower effect of GEI, due to their PC1 values very close to zero (Zobel *et al*., 1988), were V 80 Turrent (G1), V 23 Huamantla (G5), and Cuxi Puma (G9); that is, they contributed, to a lesser extent, to GEI and were considered stable (Figure 2).

Figure 2 AMMI1 Biplot, PC1 and yield in kg ha^{-1} of nine free-pollinated corn varieties evaluated in nine environments.

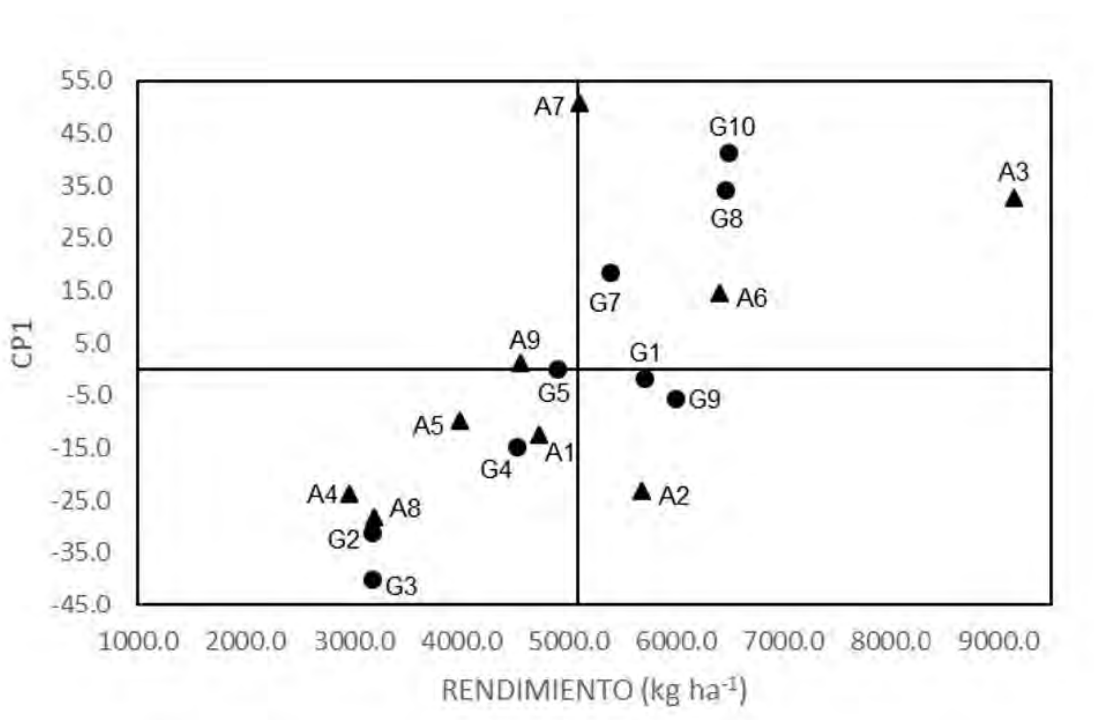

Figure 3, AMMI2 Biplot, shows that the varieties with the greatest stability in grain yield and wide adaptation were V 80 Turrent (G1) and V 23 Huamantla (G5), and they were located closer to the origin in the biplot graph; on the contrary, the varieties farther from the origin showed greater variation in their behavior (Yan *et al*., 2000), such as Cuxi Puma (G9), Maíz Texotli Puma (G10), V 54 A (G7) and Centli Puma (3).

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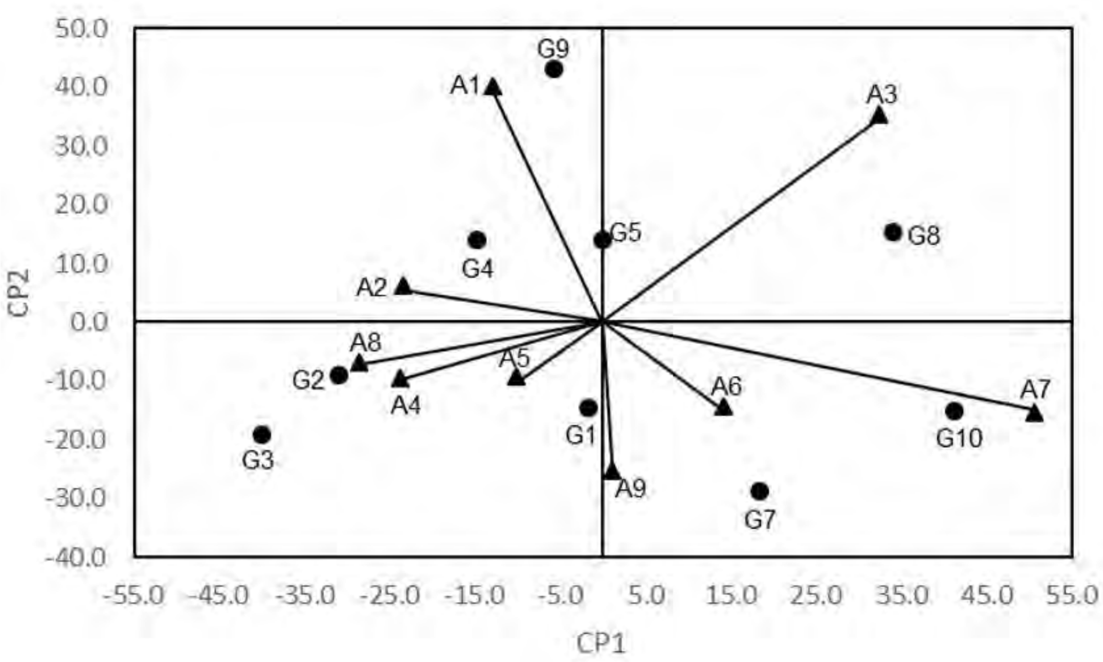
Figure 3. AMMI2 Biplot, PC1 and PC2 of nine free-pollinated corn varieties evaluated in nine environments.



Conclusions

It was determined that the free-pollinated blue corn varieties Maíz Texotli Puma and Maíz Matlalli Puma had the best grain yields and showed excellent agronomic behavior in the evaluation environments from 2016 to 2019. The free-pollinated corn varieties V 80 Turrent and V 23 Huamantla showed better stability in grain yield and as the V 80 Turrent variety is a recently generated variety, its commercial release is recommended due to its agronomic behavior and productive potential.

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