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YIELD STABILITY OF PURPLE CORN HYBRIDS (*Zea mays* L.) IN SOUTHERN SONORA, MEXICO

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ABSTRACT

Corn (*Zea mays* L.) production in Mexico is in deficit despite generating 27 million Mg. In southern Sonora, the planted area has grown significantly over the last four years, from 544 to 680 thousand Mg produced in 2018 and 2021, respectively. Ninety-seven percent of the production corresponds to improved white-colored maize from transnational companies; however, there are no commercial plantings of colored maize. The objective of this research was to estimate grain yield and its agronomic components in improved purple corn hybrids in southern Sonora, Mexico, over three years using the additive main effects and multiplicative interaction method (AMMI). A randomized, complete-block experimental design with three replications was used. The plots were two 4 m long furrows with a stocking density of 100 000 plants ha^{-1}. The variables recorded were: grain yield (RG), thousand-kernel weight (PMG), ear length (LM), grains per row (GH), rows per ear (HM), and hectoliter weight (PH). The results showed statistical differences among years, hybrids, and their interaction (AxH) in all variables. The AMMI model was highly effective, allowing the identification of hybrids 1, 2, 7, and 10 with greater stability in the year 2021 associated with RG, PH, and LM, obtaining outstanding averages in all variables and being more appropriate for the climatic conditions of southern Sonora. On the contrary, the most sensitive hybrid with the highest interaction was 4, associated with GH and HM; hybrids 3, 5, 6, 8, 9, 11, and 12 were stable with negative values in 2019 and 2020.

Keywords: purple hybrids, adaptability.

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INTRODUCTION

In the last four years, corn (*Zea mays* L.) cultivation in southern Sonora has expanded from 48 967 to 785 860 ha, yielding 544 to 680 thousand Mg in 2018 and 2021, respectively. Ninety-seven percent of production corresponds to improved white corn produced with appropriate technologies and economic resources for crop development. An adequate average grain yield of 13.7 Mg ha^{-1} was obtained (SIAP, 2022).

Although improved hybrids from transnational companies with excellent yield stability are being planted (Vázquez-Carrillo *et al*., 2020), there are no records or breeding programs for pigmented corn such as purple corn, which represents an alternative to be established due to its yield and antioxidant properties. For this reason, it is important to promote planting and carry out agricultural management innovations for purple corn that can improve productivity in the local and state markets, in addition to adapting to the edaphoclimatic conditions present in southern Sonora. These are important measures to bring competitive materials in yield, stability, and price to significantly enhance grain production in corn (Acevedo-Barona *et al*., 2019).

Grain yield is the most important trait to consider when evaluating maize in different environments, since environmental effects (E) have a greater impact on this crop than genotypes (G) and genotype-environment interaction (IGA) (López-Morales *et al*., 2019). IGA is the differential relative behavior shown by genotypes when evaluated in different environments (Ponce-Encinas *et al*., 2022). Therefore, when plant breeders seek genotypes with superior yields for different locations or environmental conditions, they face challenges such as stability and adaptability (Fayeun *et al*., 2018). Stability is the genotype's ability to behave at high or low levels of performance across settings, whereas adaptability is the genotype's ability to display optimal development under varied environmental conditions (Neisse *et al*., 2018). Eberhart and Russell (1966) pointed out that stability is a genetic trait and that genotypes with wide adaptability possess low IGA; therefore, it is important to determine stability and adaptability for selection and recommendation of maize genotypes in specific environments (Ponce-Encinas *et al*., 2022).

The AMMI is a multivariate model that combines analysis of variance (ANDEVA) and principal component analysis (CP) in one. It requires fewer replications, and better captures the variation of the treatments. Gauch (2006) pointed out that effectiveness increases with the size of the trial, which can be increased by establishing trials in different environments. Additionally, it allows the evaluation of a larger number of genotypes without losing precision or increasing the cost of the experiments (Gauch and Zobel, 1996; Crossa *et al*., 1990). Most of the work with AMMI has emphasized grain production for different crops.

The segmented analysis of information in the study of IGA has been carried out in previous works such as that of Eberhart and Russell (1966), who used stability parameters to analyze grain yield. They also separated the environments based on yield, carrying out the corresponding analysis for each group of environments; in addition, they proposed a new classification of genotypes. For this reason, the objective of this research was to estimate grain yield and its agronomic components in southern Sonora in improved purple corn hybrids over three years using the AMMI method.

MATERIALS AND METHODS

Genetic material and experimental site

Twelve improved purple corn hybrids provided by CIMMYT (International Corn and Wheat Improvement Center) were used (Table 1).

Table 1. Genetic material for purple corn hybrids (*Zea mays* L.) evaluated over a three-year period in southern Sonora, Mexico.

Hybrid	Genealogy	Hybrid	Genealogy
1	GUAT1130/CML376//CML321///CML373	7	GUANGP28//CML373///CML376
2	MOR297/CML373//CML312///CML376	8	GUAT1130/CML376///CML373
3	GUAT1130/CML376///CML373	9	MOR297/CML373///CML376
4	LIM88/CML376//CML373	10	GUANGP24/CML313///CML376
5	MOR297/CML373//CML381///CML376	11	LIM88/CML313//CML373///CML311
6	MOR297/CML373//CML360	12	LIM88/CML374//CML312///CML376

The trials were established for three years of evaluation in the experimental field of the National Technological Institute of Mexico, Campus Valle del Yaqui, in Ciudad Obregón, Sonora, Mexico, located in the south of Sonora, between the Sierra Madre Occidental and the Gulf of California (27° 41′ 37″ N and 100° 13′ 19″ W) at an altitude of 13 m. The predominant climate is BW (h), which is very hot and extreme, with an annual mean temperature of 24 °C and a mean maximum of 31 °C. From July to August, the maximum is 48 °C and in January, the minimum is 16 °C, with an average annual rainfall of 450 mm. Arable soils are fertile, rich in clay, and generally located in sub-humid and arid areas with wet hydration and exposure, cracking when dry (García, 2004).

Agronomic management

Plantings were made on November 15, 2019, December 15, 2020, and January 15, 2021. The fertilization formula 250 N, 100 P, and 00 K was applied in two stages: 50 % of N and total P at the time of planting, and the rest at weeding 30 days after planting. Gravity irrigation was applied, ensuring that there was no lack of moisture in the soil.

Design and experimental unit

A randomized, complete block experimental design with three replications was used. The experimental unit consisted of two 4 m long rows, using spatial arrangements of 0.8 m spacing between rows and 12.5 cm distance between plants, with an expected population of approximately 100 000 plants ha^{-1}.

Response variables

The trials were established and harvested manually in each test environment. To determine the effect of the genotype-environment interaction and the productive potential in the studied hybrids, grain yield (RG) adjusted to 15 % moisture, grains per row (GH), rows per ear (HM), thousand-kernel weight (PMG), ear length (LM), and hectoliter weight (PH) were used.

Statistical analysis

Statistical analysis was performed by individual and combined analysis of variance (ANDEVA) for the mean of each experimental unit, using the GLM procedure of SAS, version 9.4 (SAS Institute, 2012). The combined ANDEVA was performed according to the following model:

$$Y_{ijkl} = \mu + t_i + R_j\,(l) + \beta k\,(R_{jl}) + \lambda l + \tau\lambda il + \varepsilon_{ijkl}$$

which considered the observation obtained in genotype I and evaluated in replicate j within each test year l, in block k; μ was the overall mean; ti was fixed effect of genotype; βk (jl) the random effect of block within replicate and year; λl the random effect by year; $\tau\lambda il$ the random effect of the interaction between genotype and year; and ε_{ijkl} the error associated with the observation Y_{ijkl}, according to Steel and Torrie (1988).

Once the presence of the genotype-environment interaction was detected, the multivariate analysis was performed to obtain the singular values of the first significant AMMI terms for the genotypes and environments. The calculation was based on the procedures reported by Vargas and Crossa (2000) using only the adjusted means, so it was necessary to provide the program with the information corresponding to the value of the combined error estimator, the degrees of freedom of this error, and the number of replications, according to the following mathematical model:

$$Y_{ijkl} = \mu + t_i + R_j\,(l) + \beta k\,(R_{jl}) + \lambda l + \tau\lambda il + \varepsilon_{ijkl}$$

where Y_{ij} represented the mean of genotype i in environment (year) j; μ the overall mean; *gi* and aj the effects of genotype and environment, respectively; n the number of principal components (CP) retained in the model; k the singular value for each CP; *ik* were values of the genotype vectors for each CP; *jk* the values of the environment vectors for each CP; *ij* the residual of the IGA; and ε_{ij} the mean experimental error.

Genotypic and environmental values were obtained using the PROC GML procedure of SAS. The significance of each CP was measured by Fisher's test at 0.05 probability, comparing the mean square of each CP with the mean square of the experimental error, according to Crossa *et al*. (1990). The number of possible axes (CP) that the model can retain in AMMI is the minimum (G-1; E-1); the axes that were not significant were included in the residual and the values of CP1 and the mean yield of genotypes/environments were used to construct the double biplot representation of the AMMI model (García *et al*., 2020).

RESULTS AND DISCUSSION

Statistical differences ($p \leq 0.01$) were evident in all study variables (Table 2). According to the additive main effects and multiplicative interaction model (AMMI), performed with the routine developed by Vargas and Crossa (2000) that contemplates replications as a main factor, it was observed that in years, hybrids, and the years x hybrids interaction (IGA), the variables PMG and GH obtained higher values in the mean squares, followed by PH and LM. The inequality between maize hybrids and environments (years) manifested a wide genetic difference in the environmental conditions that occurred by year (López-Morales *et al*., 2019). The significant statistical differences for the mean squares of all sources of variation in the analysis of variance coincide in significance with those reported in the two models, AMMI and SREG (Ponce-Encinas *et al*., 2022; García-Mendoza *et al*., 2021).

Table 2. Mean squares and significance of AMMI for grain yield and its agronomic traits of 20 purple corn hybrids (*Zea mays* L.) evaluated in southern Sonora, Mexico.

FV	GL	RG	PMG	PH	LM	HM	GH
Replication	2	0.86	0.09	0.14	0.50	0.50	0.10
Years (A)	2	9.98**	576.69**	38.17**	23.26**	86.40**	330.18**
Hybrids (H)	11	7.98**	36441.01**	61.86**	14.25**	44.79**	139.33**
A*H	22	0.17**	1.68**	0.10*	0.90**	2.20**	0.80*
CP1	12	7.32	33404.67	56.73	13.53	42.47	127.89
CP2	10	0.24	2.36	0.15	0.98	2.69	1.31
Residual	72	0.19	18.66	0.74	1.80	4.35	7.73
CV(%)		6.1	5.14	7.29	9.22	13.7	3.09

*,**Significant at 0.05 and 0.01 probability, respectively. FV: sources of variation; GL: degrees of freedom; RG: grain yield; PMG: thousand-kernel weight; LM: ear length; GH: grains per row; HM: rows per ear; PH: hectoliter weight; CP1: principal component 1; CP2: principal component 2; CV (%): coefficient of variation.

The AMMI analysis explained 98.91 % of the IGA (Figure 1) between grain yield and its components across the three years of evaluation, while hybrids H-1, H-2, H-6, H-7, and H-10 were more stable in RG, PH, and LM in 2021. In these variables, only the first principal component was highly significant, suggesting that the interactions of hybrids with years were more complex, probably due to differences in the maize studied, which undoubtedly influenced the coefficient of variation reported in that

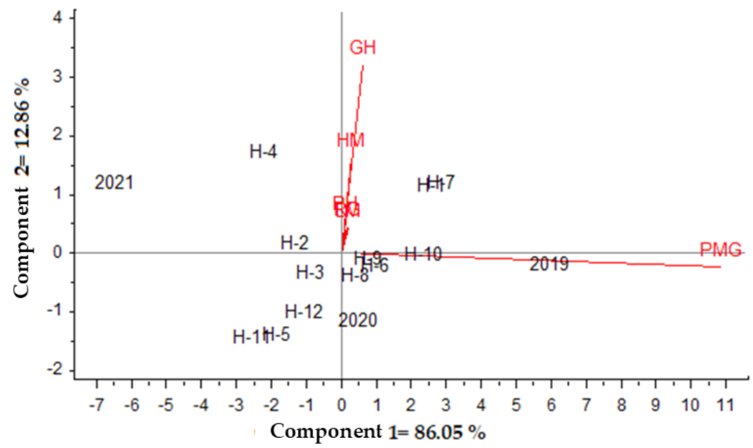

Figure 1. Genotype-environment interaction for grain yield and its components in purple corn hybrids (*Zea mays* L.) evaluated in southern Sonora, Mexico.

variable (Martínez-Gutiérrez *et al*., 2018). On the other hand, hybrids H-3, H-5, H-6, H-8, H-9, H-11, and H-12 in 2019 and 2020 were stable but presented negative values associated with PMG; however, the one with the highest interaction was hybrid H-4, which that had associations with GH and HM for being more distant to the center of origin and had yields lower than the overall mean (6.39 Mg ha^{-1}). These results coincide with those reported by Lozano-Ramírez *et al*. (2015).

Grain yield

The analysis graph for grain yield (Figure 2) shows that two components explained 98.81 % of the total variation in IGA. By plotting a polygon between the hybrids farthest from the origin and perpendicular lines going from the origin to each side of the polygon, the hybrids, and environments with response, it could be identified that hybrid H-6 had better yield in 2019 and 2021, with values higher than the overall average (6.58 Mg ha^{-1}), while the hybrids H-2, H-3, H-4, H-6, H-10, and H-12 were far from the vector, with yields lower than the overall mean, with average values of 6.12, 6.35, 5.78, 7.8, and 5.9 Mg ha^{-1}, respectively (Vázquez-Carrillo *et al*., 2018; López-Morales *et al*., 2019).

Environments (years) with long vectors are known to discriminate better among genotypes; in that sense, if we want to know how a hybrid adapts in the three years, we can trace an imaginary line from the origin where hybrids H-11 and H-8 presented low yields in 2020, having yields below the general average with 6.50, 6.43, and 6.36 Mg ha^{-1}, respectively. In this research, hybrids with high yields were located at the vertices that formed a polygon in the three years of evaluation that were outside the polygon and allowed discrimination among hybrids (Yan *et al*., 2016).

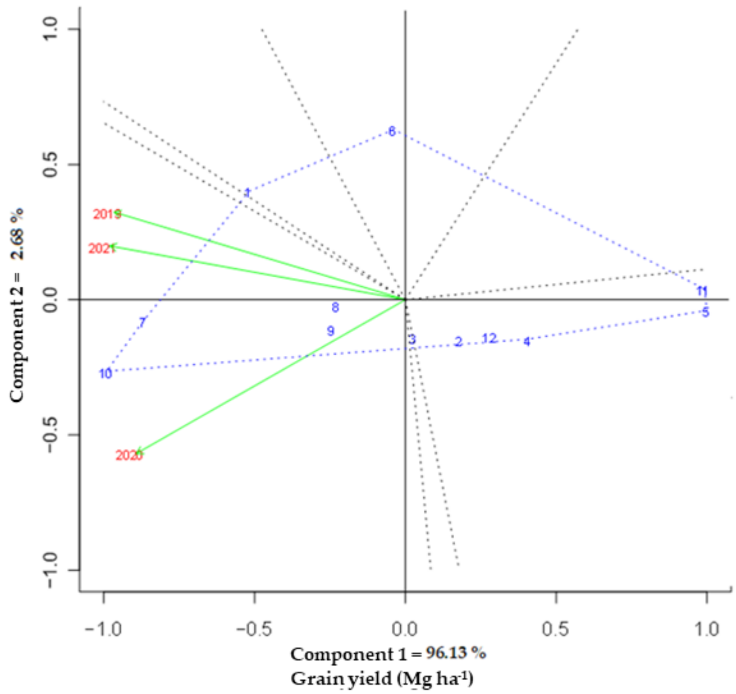

Figure 2. Biplot of the first two components of grain yield in purple hybrids (*Zea mays* L.) evaluated in southern Sonora, Mexico.

This type of classified stability is useful in agriculture, given that producers demand cultivars with desirable agronomic stability that show consistent behavior across environments while also responding favorably to environmental improvements; this means cultivars that present the best performance under any environmental condition (Acevedo-Barona *et al*., 2019).

Thousand-kernel weight

For the thousand-kernel weight, the components explained 99.94 % of the total variation in IGA (Figure 3). The hybrids with the highest weight were H-11, H-4, H-5, H-1, H-7, and H-10, with a sowing date in November 2019, which produced the best yields (7.88 Mg ha^{-1}) and could be considered a suitable environment with outstanding potential in the stability of these hybrids (García *et al*., 2020).

These findings suggest that thousand-kernel weight is the most important direct behavior in indirect yield selection for genotypes. In this sense, it can be inferred that the yields obtained in this research were due to agronomic management during crop development, which was strongly related to thousand-kernel weight. On the other hand, hybrids H-3, H-12, H-6, H-9, H-2, and H-8 obtained lower weights and were concentrated in the most distant vectors, presenting greater interaction.

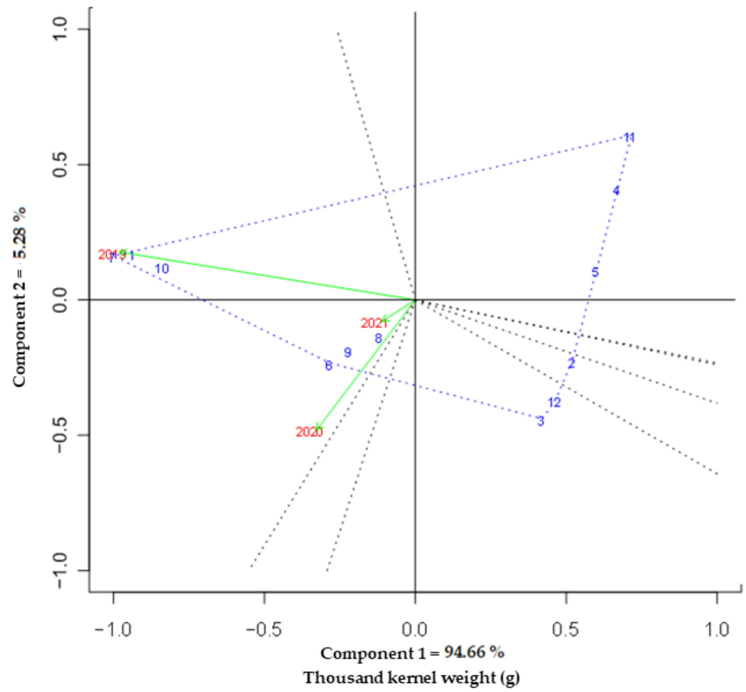

Figure 3. Biplot of the first two components of thousand-kernel weight (g) in purple hybrids (*Zea mays* L.) evaluated in southern Sonora, Mexico.

Salinas-Moreno *et al*. (2010) reported that large kernels have a weight greater than 380 g, medium sizes between 330 and 379 g, and small kernels have values less than 330 g. Based on this classification, only hybrid H-11 had large kernels (384.67 g); hybrids H-16, H-14, H-6, H-19, and H-15 were of medium size, while the rest had small kernels. It was observed that the grains obtained in 2021 were heavier than in 2019 and 2020; this could be a consequence of the sowing date in mid-November, which had a positive influence during the grain filling period. Vázquez-Carrillo *et al*. (2018) observed similar results regarding the positive effect of sowing date on grain filling and its effect on weight.

Hectoliter weight

The hybrids that presented favorable hectoliter weight were H-6, H-10, H-8, and H-4 (Figure 4), which were higher than the general mean with 83.7, 82.13, 80.63, and 80.44 kg hL^{-1}, respectively, being considered with greater stability, while hybrids H-9, H-1, H-3, and H-2 obtained values lower than the general mean (77.69 kg hL^{-1}).

Ninety percent of the hybrids had a hectoliter weight greater than 74 kg hL^{-1}, which is an indicator of grain hardness among the hybrids evaluated. This value indicates that the above hybrids are more crystalline than hybrids H-5, H-7, H-11, and H-12, whose

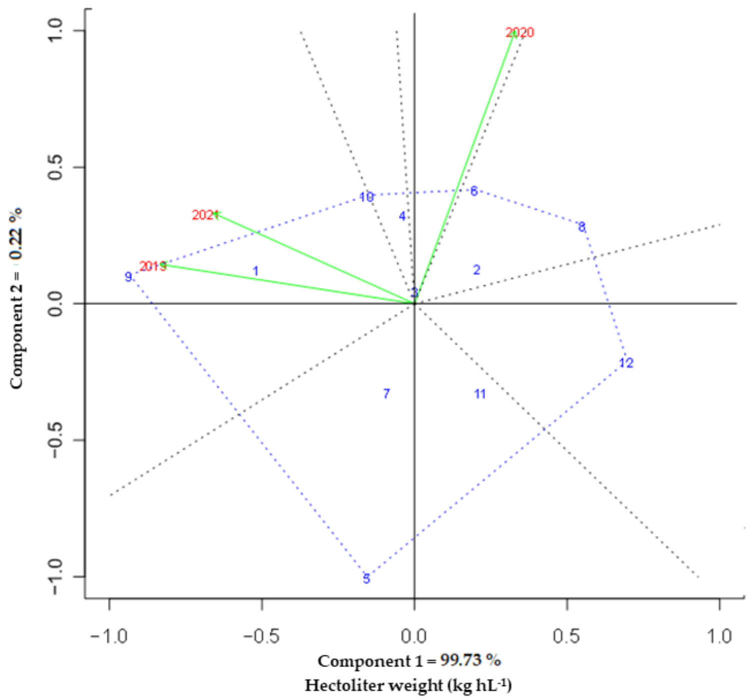

Figure 4. Biplot of the first two components of hectoliter weight in purple hybrids (*Zea mays* L.) evaluated in southern Sonora, Mexico.

values were lower than 74 kg hL^{-1} and negative, so they can be used as processed cereals (Vázquez-Carrillo *et al*., 2018).

Rows per ear

Hybrids H-2, H-8, and H-11 had the highest number of rows per ear in 2019 and 2021 (Figure 5), but hybrids H-4 and H-7 had lower values than the general average. Ponce-Encinas *et al*. (2022) reported that the hybrids standing out for their wide stability and adaptability in the genotype-environment interaction are the most suitable to be considered within a breeding program when they present higher values. On the other hand, the hybrids with the lowest number of rows per ear and negative values were H-12, H-8, H-10, H-6, H-9, and H-1, which contributed less to the number of rows per ear, in the December 2020 planting. This indicates that the selection of superior maize germplasm for grain yield is based on the consideration of traits such as the number of rows per ear, kernel size, or number of ears per plant (Ponce-Encinas *et al*., 2022).

Grains per row

The number of grains per row (Figure 6) shows that hybrids H-6, H-10, H-7, H-9, H-12, and H-8 had greater stability in 2019, which were sown in November. Other hybrids with low responses were H-1, H-2, H-3, H-5, H-4, and H-11. Such behavior could be

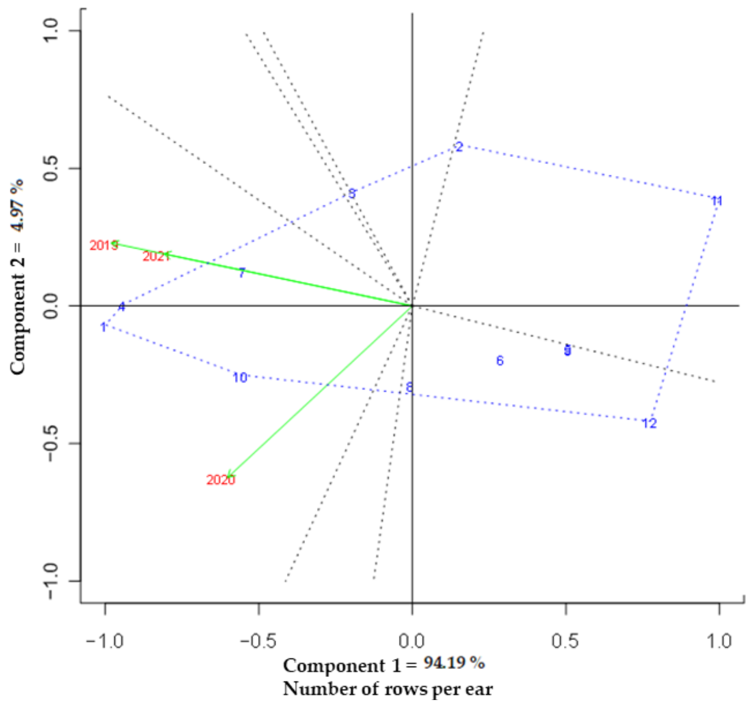

Figure 5. Biplot of the first two components of rows per ear in purple hybrids (*Zea mays* L.) evaluated in southern Sonora, Mexico.

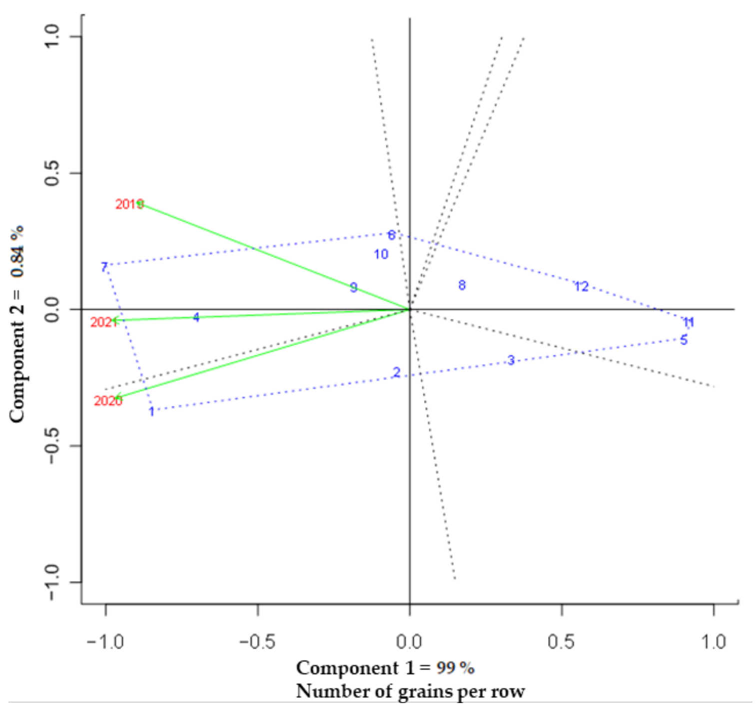

Figure 6. Biplot of the first two components of grains per row in purple hybrids (*Zea mays* L.) evaluated in southern Sonora, Mexico.

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due to differences in sowing dates, which were in December and January 2020 and 2021, respectively (López-Morales *et al*., 2019).

Ear length

In terms of ear length (Figure 7), it was possible to identify those hybrids that adapted better, such as H-4 and H-10, which were closer to the vector direction, resulting in lengths greater than the overall average (15.2 cm) in 2019 and 2021. On the other hand, hybrids H-8, H-5, H-9, and H-7 were far from the vector, so their lengths were lower than the general average with values below 13 cm and presenting negative interactions with the first component, which is expected to have lower production. These results indicate that low-length hybrids were highly affected by IGA in the 2020s, which were sown in December.

Yan *et al*. (2016) reported that planting date and climatic conditions present during the crop cycle are factors that negatively influenced grain yield and other agronomic traits, such as thousand-kernel weight, hectoliter weight, ear length, kernels per row, and rows per ear; this was the case in this research, where planting in 2020 affected this variable by its lower values and consequently limited its agronomic utilization. On the contrary, hybrids in which greater lengths were obtained and were more stable may be viable in industrial and agronomic processing, which will allow farmers to

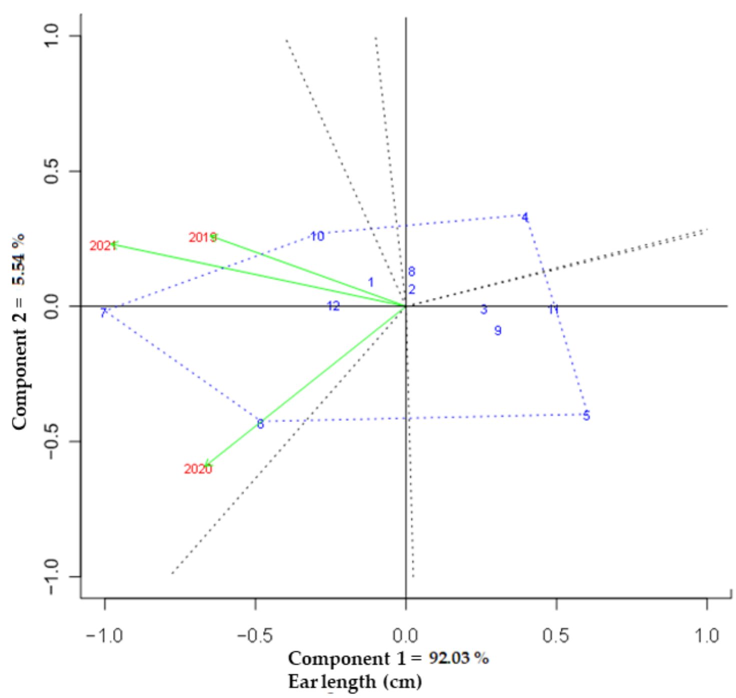

Figure 7. Biplot of the first two components of ear length in purple hybrids (*Zea mays* L.) evaluated in southern Sonora, Mexico.

offer hybrids with potential for the climatic conditions of southern Sonora (Acevedo-Barona *et al*., 2019).

CONCLUSIONS

Hybrids H-1, H-2, H-6, H-7, H-8, H-10, and H-11 were the most outstanding for their wide stability and adaptability in the genotype-environment interaction in 2021, being appropriate for grain production in the present climatic conditions of southern Sonora, Mexico. The additive main effects and multiplicative interaction model was useful to understand the genotype-environment interaction in grain yield and its components in the discrimination of the evaluated hybrids. The biplots allowed the identification of hybrids with higher grain yields and desirable agronomic characteristics.

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