Revista Brasileira de Geografia Física v.18, n.03 (2025) 1886-1901.

Revista Brasileira de Geografia Física

ISSN:1984-2295

Homepage:https://periodicos.ufpe.br/revistas/rbgfe

The multivariate index allows the selection of white-grain maize hybrids in contrasting environments

Lorenzo Pérez López[1], Leandris Argentel-Martínez[2*], Ofelda Peñuelas-Rubio[3], Francisco Cervantes Ortiz[4], Franck Denis Torres Huaco[5], Cesar Leobardo Aguirre-Mancilla[6], Jorge González Aguilera[7], Paulo Eduardo Teodoro[8]

[1] Tecnológico Nacional de México/Instituto Tecnológico del Valle del Yaqui, C.P. 85276, Bácum, Sonora, México. E-mail: lperez.lopez@itvy.edu.mx; [2]Tecnológico Nacional de México/Instituto Tecnológico del Valle del Yaqui, C.P. 85276, Bácum, Sonora, México. E-mail: oleinismora@gmail.com; [3]Tecnológico Nacional de México/Instituto Tecnológico del Valle del Yaqui, C.P. 85276, Bácum, Sonora, México. E-mail: ofeperub@gmail.com; [4]Tecnológico Nacional de México/Instituto Tecnológico de Roque. C.P. 38110, Celaya, Guanajuato, Mexico. E-mail: frcervantes@itroque.edu.mx; [5]Escuela Profesional de Ingeniería Ambiental, Facultad de Ingeniería, Universidad Continental, Av. Los Incas, Arequipa, Perú. E-mail: huacofrank@yahoo.com; [6]Tecnológico Nacional de México/Instituto Tecnológico de Roque. C.P. 38110, Celaya, Guanajuato, Mexico. E-mail: depi_roque@itroque.mx; [7]Universidade Estadual de Mato Grosso do Sul (UEMS), Cassilândia, 79540-000, MS, Brazil. E-mail: jorge.aguilera@uems.br; [8]Universidade Federal de Mato Grosso do Sul (UFMS), Chapadão do Sul, 79560-000, MS, Brazil. E-mail: paulo.teodoro@ufms.br

[*]Corresponding author: oleinismora@gmail.com

Artigo recebido em 15/09/2014 e aceito em 24/01/2025

ABSTRACT

Maize is a crop of great economic, social and cultural importance in many countries worldwide, especially in Mexico. The objective of this work was to use a multivariate index to select white grain maize hybrids through agronomic and physiological traits obtained in two environments. A factorial design (2 × 15) was used: two environments (E1 and E2) and 15 hybrids, with four replications. The analysis of variance showed highly significant differences for all nine agronomic and eight physiological variables evaluated when considering the effect of environment and hybrids. The number of rows per ear and root water potential did not show interactions between factors. The heritabilities of the agronomic and physiological characteristics ranged from 5.85 to 75.88 and from 42.41 to 99.82%, respectively. High variability was found among hybrids in the two environments for the two sets of traits evaluated. The determination of a multivariate index from the index proposed by Lins Bins (Pi) allowed us to obtain three multivariate indices associated with agronomic (*Pim-agro*), physiological (*Pim-physiol*) and their combination (*PimAgro+Phisiol*) characteristics. The selection through these indices showed that it is possible to identify hybrids with high stability and general adaptability with favorable characteristics in white maize for the evaluated environments and showed the possibility of improving the selection criteria by using of the proposed multivariate index.

Key words: adaptability, Lins Bins, *Zea mays* L., agronomic, physiological

O índice multivariado permite a seleção de híbridos de milho de grão branco em ambientes contrastantes

RESUMO

O milho é uma cultura de grande importância econômica, social e cultural em muitos países do mundo, especialmente no México. O objetivo deste trabalho foi usar um índice multivariado para selecionar híbridos de milho de grão branco por meio de características agronômicas e fisiológicas obtidas em dois ambientes. Foi utilizado um delineamento fatorial (2 × 15): dois ambientes (E1 e E2) e 15 híbridos, com quatro repetições. A análise de variância mostrou diferenças altamente significativas para todas as nove variáveis agronômicas e oito fisiológicas avaliadas ao considerar o efeito do ambiente e dos híbridos. O número de fileiras por espiga e o potencial hídrico da raiz não mostraram interações entre os fatores. As herdabilidades das características agronômicas e fisiológicas variaram de 5,85 a 75,88 e de 42,41 a 99,82%, respectivamente. Foi encontrada alta variabilidade entre os híbridos nos dois ambientes para os dois conjuntos de características avaliadas. A determinação de um índice multivariado a partir do índice proposto por Lins Bins (*Pi*) permitiu obter três índices multivariados associados a características agronômicas *(Pim-agro*), fisiológicas (*Pim-physiol*) e sua combinação (*PimAgro+Phisiol)*. A seleção por meio desses índices mostrou que é possível identificar híbridos com alta estabilidade e adaptabilidade geral com características favoráveis em milho branco para os ambientes avaliados e mostrou a possibilidade de melhorar os critérios de seleção pelo uso do índice multivariado proposto.

Palavras-chave: adaptabilidade, Lins Bins, *Zea mays* L., agronômico, fisiológico

Introduction

Maize (*Zea mays* L.) is one of the most essential crops worldwide and plays a vital role in food and economic security (Ocwa et al., 2023). Its economic and cultural importance is particularly significant in countries such as Mexico, where maize not only serves as a staple food but is also an integral part of cultural identity (Donovan et al., 2022). In Mexico, the average yield of white maize has not exceeded 10 t ha^{-1} because the largest percentage of land cultivated under rainfed agricultural schemes (LaFevor, 2022; Pierre et al., 2022). To meet the growing demand for food and optimize maize production, hybrid breeding has become a prominent strategy for the genetic improvement of maize crop (Buenrostro-Robles et al., 2017).

The creation of maize hybrids aims to improve physiological and agronomic traits, increase yield and adaptation to different environmental conditions (Beyene et al., 2016). Efficient hybrid selection is a critical component of this process, and advanced methods are needed to address the complexity of the traits involved, as well as genetic stability (do Couto et al., 2023). Numerous methods have been proposed to evaluate genotypes stability and adaptability under different environments (Greveniotis et al., 2021). One of the methods proposed to evaluate genotype stability under different environments is the one proposed by Lins Bins (1988). This index estimates a parameter called Pi based on the mean square of the distance between the mean of the genotype and the maximum average response obtained in this environment. This method has been used by several researchers because it is based on nonparametric statistics (Menezes et al., 2015; Gabriel et al., 2018; Aguilera et al., 2019; Teodoro et al., 2019).

Therefore, this approach can be applied to diverse environments, genotypes and plant species. A modification of Lins Bins method was proposed by Teodoro et al. (2019) by integrating cotton fiber data and obtaining a multivariate index (*Pim*) with which they performed a better overall identification of genotypes on the basis of the multiple traits evaluated. Aguilera et al. (2019) employed such a method and were able to identify the 20 most tolerant wheat genotypes among 195 evaluated; these genotypes had the best combination of the main desirable traits, thus confirming the potential of the *Pim* method for selecting these plants. This method also, offers a comprehensive way to simultaneously evaluate physiological and agronomic traits, providing a better selection process and thus decreasing the problems often encountered when selecting genotypes when a wide number of variables are evaluated (Aguilera et al., 2019; Teodoro et al., 2019).

In this context, the present study aimed the application of the selection index of Lins Bins (1988) modified by Teodoro et al. (2019) to select the best white maize hybrids, considering physiological and agronomic characteristics under two different environments.

Materials and methods

Location of the experimental sites

The experiments were carried out in two environments. E1: Experimental field of the Tecnológico Nacional de México, Campus Roque, Celaya, Guanajuato, México. E2: experimental field of the Tecnológico Nacional de México-Campus Valle del Yaqui, Bácum, Sonora. The evaluation period was July to December 2022. The geolocation of the environments and their edaphoclimatic characteristics are presented in Table 1.

Table 1. Edaphoclimatic characteristics of the experimental environments.

Variable	Environment	
	E1	E2
Location	20°30'28"N-100°50'00"O	27°24'51"N-110°7'57"O
Altitude	1750 masl	26 masl
Average temperature	18.9 °C	17.2 °C
Relative humidity	66.4%	68.5%
Accumulated precipitation	332.7 mm	15.3 mm
Weather	semiwarm and subhumid	dry very warm and warm
Soil	pelic vertisol	Vertisol gleic

Source: Almazán et al. (2023); INEGI (2023); and Grajeda-Cabrera (2004).

Table 2. Results of the soil analyses corresponding to the environments studied.

Environment	Depth (cm)	pH	Organic matter (%)	Conductivity Electric $(dS\text{-}m)^{-1}$	Hydraulics $(cm\text{-}hr)^{-1}$	Bulk density $(g\text{-}cc)^{-1}$	Phosphorus (ppm)	Nitrogen $(kg\ ha)^{-1}$
E1*	0-30	7.25	0.37	0.135	<0.04	1.25	36.2	137
E2	0-30	7.65	0.59	4.81	<0.04	1.39	34.2	128

* E1: environment Tecnológico Nacional de México, Campus Roque (ITR) and E2: environment Tecnológico Nacional de México-Campus Valle del Yaqui (ITVY), Bácum, Sonora.

Soil analysis

Before the implementation of the experiment, soil samples were taken from the two experimental areas at depths of 0-30 cm, and the results are shown in Table 2. The analyses were carried out at the Soil and Plant Nutrition Laboratory of the "Norman E. Borlaug" Experimental Field in Ciudad Obregón, Sonora, Mexico.

Genetic material

To obtain the genetic materials (15 F1 hybrids) used in this research, a dialelic design was established using the Griffing I. method (Saavedra Guevara et al., 2021). Thirty crosses were obtained from 15 direct and 15 reciprocal crosses between six homozygous lines of white grain maize (L1. CML442, L2. CML545, L3. CML549, L4. CML550, L5. CML576 and L6.CML546). At the end of the crosses, eight direct crosses and seven reciprocal crosses were selected; these crosses produced a considerable number of healthy kernels, resulting in 15 F1 single hybrids (Table 3).

Table 3. The 15 experimental white grain maize hybrids evaluated in the two contrasting environments.

Code	F1 cross	Code	F1 cross
HB1	L4.CML550xL6.CML546	HB9	L4.CML550xL2.CML545
HB2	L1.CML442xL6.CML546	HB10	L4.CML550xL1.CML442
HB3	L1.CML442xL4.CML550	HB11	L6.CML546xL4.CML550
HB4	L3.CML549xL6.CML546	HB12	L6.CML546xL2.CML545
HB5	L1.CML442xL2.CML545	HB13	L5.CML576xL4.CML550
HB6	L3.CML549xL4.CML550	HB14	L6.CML546xL3.CML549
HB7	L3.CML549xL5.CML576	HB15	L5.CML576xL3.CML549
HB8	L2.CML545xL4.CML550	-	-

Agronomic management

The agronomic management of the crop was similar in both environments. Four fertilizer applications were applied: a base application of urea (46%) and a mixture of diammonium phosphate (DAP) (400 $kg\text{-}ha^{-1}$) during sowing. During groth phenophases, three other applications were applied prior to auxiliary irrigation, at a rate of 150 kg ha^{-1} of NPK.

Pest control

During the experiment, significant populations of thrips (*Rankliniella occidentalis*) and fall armyworm (*Spodoptera fugiperda*) were found; thus, Palgus® (spinetoran), Agresor® and chlorpyrifos methyl + permethrin were applied at a dose of 1.0 L ha^{-1}. A similar control was applied in environment E2, but the insecticides Rimon® Supra and Decís® (deltamethrin) were used.

For weeds control and improve soil aeration, two passes were made with a cultivator in addition to manual control (weeding, when necessary).

Irrigation

In both environments, there was one irrigation event during plants emergence. An amount of four auxiliary irrigations at an iirigation interval of 12 to 15 days were applied for environment E1 and one irrigation event for E2, with irrigation intervals of 39, 30, 24 and 15 days. These irrigations were applied superficially, by gravity, in furrows. The average irrigation lamina length was 250 mm for the bird irrigation treatment, and 110, 120, 110 and 110 mm for the remaining four irrigations.

Treatments and experimental design

In both environments, the 15 selected hybrids were subjected to four replications each, and a randomized complete block experimental design was used. Sowing was carried out in furrows with a length of 5 m, a distance of 0.20 m between plants and 0.80 m between furrows, for a total population of 62,500 plants ha^{-1}.

Variables analyzed

The following variables were evaluated during the flowering and the physiological maturity phenophases in the two environments:

The agronomic traits included: days to male flowering (DFM, days), days to female flowering (DFF, days), plant height (PH, cm), ear height (EH, cm), ear length (EL, cm), ear diameter (ED), cm), number of rows in the ear (NRE, unit), number of grains per ear (NGE, grains) and grain yield (Y, t ha^{-1}).

The physiological characteristics during the male and female flowering phenophases were: total soluble protein (TSP, mg g^{-1} MS^{-1}), total soluble carbohydrate (TSC, 55 mg g^{-1} MS^{-1}), root water potential (RWP, MPa), and root osmotic potential (ROP, MPa).

During physiological maturity phenophase the evaluated variables were: total leaf soluble proteins (TLSP, mg g^{-1} MS^{-1}), total leaf carbohydrates (TLC, mg g^{-1} MS^{-1}), total grain soluble proteins (TGSP, mg g^{-1} MS^{-1}) and total grain carbohydrates (TGC, mg g^{-1} MS^{-1}). The methodologies used to determine the TSP were described by Prakash and Prathapasenan (1988). for the TSC measurement the methodology described by Yoshida (1976) was used. For the RWP and ROP, were measured by using the presure pump (Scholander 670, OMS Instrument, Albany, NY, USA) (Sadok & Schoppach, 2019).

Statistical analysis

The experiments were conducted under a 2x15 factorial scheme, with the first factor being the environments evaluated (E1 and E2) and the evaluated hybrids as second factor (the 15 white maize hybrids selected). Two-way analysis of variance was performed for all the variables evaluated (agronomic and physiological traits). When significant differences between factors were found, the means were compared by the Scott–Knott test for p<0.05 (Bhering et al., 2008).

Initially, we performed individual analysis of variance (ANOVA) for each environment, followed by analysis of joint variance according to the statistical model described in Equation 1:

$$Y_{ijk} = \mu + B/E_{jk} + G_i + E_j + G \times E_{ij} + \varepsilon_{ijk} \quad (1)$$

where: Y_{ijk} is the observation of the k-th block evaluated in the i-th genotype and j-th environment; μ is the overall mean of the experiments; B/E_{jk} is the effect of block k within environment j; G_i is the effect of the i-th genotype considered as random; E_j is the effect of the j-th environment considered as fixed; $G \times E_{ij}$ is the random effect of the interaction between genotype i and environment j; and ε_{ijk} is the random error associated with Y_{ijk} observation. After that, the estimate of adaptability and stability (P_i) for each character proposed by Lin & Binns (1988) was calculated according to Equation 2:

$$P_i = \frac{\sum_{j=1}^{e}(Y_{ij} - Y_{mj})^2}{2e} \quad (2)$$

where Y_{ij} is the score of the i-th genotype in the j-th environment; Y_{mj} is the estimate of the ideal hypothetical genotype in environment j; and e is the number of environments. For the selection of genotypes with better performance considering the scores at the different agronomic and physiological variables and the two environments, the multivariate statistic *Pim* was used, according to Equation 3:

$$P_{im} = \sum_{k=1}^{v}\left[\frac{P_{ik}}{\hat{\sigma}_{Pik}}\right] \quad (3)$$

where: P_{ik} is the univariate estimator of the adaptability and stability of the i-th genotype associated with the k-th variable, P_{ifk} is the univariate estimator of the adaptability and stability of the i-th genotype in favorable environments associated with the k-th variable, and $\hat{\sigma}_{Pik}$ is the standard deviation of P_{ik} (Aguilera et al., 2019).

The *Pi* associated with general stability and adaptability was used to calculate the multivariate *Pi* (*Pim*) for agronomic characteristics (*Pim-agro*), physiological characteristics (*Pim-physiol*) and the combined index (*PimAgro+Phisiol*). The selection of the best white maize hybrids was carried out considering the lowest *Pi* values as proposed by Lins Bins (1988). All analyses were performed with the RBio program (Bhering, 2017), and SigmaPlot version 11.0 was used to construct the graphs.

Results

Agronomic characteristics

In Table 4 it is shows the ANOVA results obtained by using nine agronomic characteristics for the evaluation of 15 white grain maize hybrids in the two environments. For the variables plant height (PH), ear length (EL) and yield (Y), there were significant (p<0.05) and highly significant (p<0.001) differences in days to male (DFM) and female (DFF) flowering, ear height (EH), ear diameter (ED) and number of grains per ear (NGE), respectively. The exception was the number of ear rows (NRE), which showed no interaction among the factors (ExH) evaluated (Table 4). The coefficients of variation for most of the agronomic characteristics evaluated were less than 15%, revealing the precision of the obtained values according to Pimentel-Gomes (2023).

For all the agronomic characteristics evaluated, wide variation was obtained in terms of the mean, minimum and maximum values obtained (Table 4). The heritability obtained for each agronomic characteristic presented high values (75.88% for EL, 71.71% for NRE and 61.65% for EH), moderate values (48.12% for DFM and 54.90% for DFF) and low values (5.85% for PH, 6.77% for ED, 17.45% for NGE and Y with 9.57%). This result allows us to conclude that there is great variability within the evaluated characteristics. There are some areas where there is a gain to be gained by exercise selection and improvement according to the values obtained. Heritability, as a genetic parameter, plays a fundamental role in determining the effectiveness of selection methods. Considering this trait is vital for ensuring that the traits chosen for selection are heritable (as the values are higher) and therefore susceptible to breeding and genetic gain in the selection process (Ponce-Encinas et al., 2022).

Table 4. Summary of ANOVA results for 15 maize hybrids at two different locations for the following agronomic characteristics: days to male (DFM) and female (DFF) flowering, plant height (PH), ear height (EH), ear length (EL), ear diameter (ED), number of rows in ear (NRE), number of grains per row (NGE) and yield per ha (Y).

Factors	GL	Significance								
		DFM* (days)	DFF (days)	PH (cm)	EH (cm)	EL (cm)	ED (cm)	NRE (unit)	NGE (grains)	Y (t ha^{-1})
Environments (E)	1	***	***	***	***	***	.	*	***	***
Hybrids (H)	14	***	***	**	***	***	***	***	***	**
E x H	14	***	***	**	***	**	***	.	***	**
CV (%)		0.93	0.93	8.41	6.96	7.22	3.90	10.17	7.84	13.06
Mean		94.90	97.04	223.80	128.55	17.22	5.10	14.80	33.54	10.33
h^2 (%)		48.12	54.90	5.85	61.65	75.88	6.77	71.71	17.45	9.57

*Significant differences ***, **, * and for probability values of 0.001, 0.01, 0.05 and 0.1, respectively, according to the F test.

The table 5 shows the interactions between the two factors (E × H) for the agronomic characteristics. In the E1environment, it was observed that the hybrid HB4 presented the highest number of days to male flowering (DFM), at 85.25 days. The rest of the hybrids presented lower values. In the E2 environment, there was greater differentiation among the seven different groups. The highest number of days to male flowering was obtained for hybrid HB15 (121.25 days), and the lowest values were obtained in HB1 and HB5 hybrids (108 and 109 days, respectively). When comparing the individual hybrids and the behavior between the two environments, it is evident that in E1, the hybrids evaluated presented more days to male flowering than in E2.

For the days to female flowering (DFF) variable in both environments, five different groups were formed. It was observed that in E1environment, the hybrids differed from each other, forming five different groups. The highest values were found in the hybrid HB4 (86.75 days), with significant differences ($p<0.05$). In the E2 environment, the HB15 hybrid stood out after 123.5 days. When comparing each hybrid and evaluating its performance in the two environments, the same behavior was observed for the DFM variable, in which the environmental conditions of E2 increased the time of occurrence to flowering in both males and females (Table 5). There were no significant differences in plant height (PH) among the hybrids evaluated (Table 5). The agronomic characteristics on the E2 environment showed different behaviors for the PH variable, with the formation of three different groups. In this group the most majority of the evaluated hybrids (11 hybrids) were grouped (>242 cm) and the lowest was HB14, which was 187 cm in height. When comparing each hybrid, it was observed that, with the exception of the previous one, most of the evaluated hybrids showed better performance in the E2 environment (Table 5).

The variable ear height (EH) was another agronomic characteristic that showed low variability in the two environments, considering that only two and three groups were formed in E1 and E2, respectively. In E1 environment, the best performance for this variable was shown in HB1, HB4, HB6 and HB14 hybrids, differing from the rest of the evaluated hybrids. In E2 environment, the best performance was obtained in HB2 and HB15 hybrids. For the ear height (AM) variable, the E2 environment promoted the best performance of the hybrids in all the cases (Table 5).

When the two factors evaluated for ear length (EL) were compared, the hybrids in the two environments exhibited different responses. In E1 environment, three different groups were formed, with the highest values obtained in HB2, HB3, HB5 and HB10 hybrids. In E2 environment, the behavior was similar in relation to the number of groups formed, with the highest performance obtained in the HB2 and HB14 hybrids (Table 5). When comparing the hybrids within each environment, the behavior was variable.

For the ear diameter (ED) variable, there were groups of hybrids formed in E1 environment, while in E2 environment, there was no differentiation among hybrids, as it is shown in Table 5. In environment E1, the hybrids that showed the highest values were HB1, HB2, HB3, HB4, HB5, HB6, HB7, HB9, HB11 and HB12, with values ranging from 5.22 to 5.50 cm, and the lowest performance for ED was for HB8.

When comparing within each hybrid the two environments evaluated, nine of the 15 hybrids showed no differences between environments; the rest of the hybrids (HB2, HB3, HB4, HB5, HB8 and HB9) were always superior in the environment E1 (Table 5).

The number of grains per ear (NGE) was low in all three groups of the E1 environment. All the groups exhibited significant differences. In the first group, there were four hybrids (HB1, HB4, HB6 and HB15) that showed no differences between the two environments, and ten hybrids that showed the highest values in the environment E1 in relation to the environment E2; ultimately, HB7 hybrid was the only one that was superior in the environment E2 (Table 5).

Grain yield (Y) of the hybrids in the E1 environment did not significantly differ, while in the E2 environment, the two groups were different. When comparing the hybrids in the two environments, we observed that for the hybrids HB2, HB8, HB9, HB10, HB11, HB13 and HB15, the performance was superior in the E1 environment, with yields variability of 29%, 57%, 43%, 43%, 22%, 39%, 27% and 27%, respectively, which were greater than those obtained in the E2 environment. The hybrid HB7 was the only one that, when comparing the two environments, stood out in the E2 environment, with 28% above. The yield of the remaining hybrids did not differ between the two environments.

Among the agronomic evaluated characteristics, the number of rows per ear (NRE) did not significantly differ among the factors (Figure 1). Figure 1A shows the behavior of the hybrids that were differentiated into two groups. The best performing hybrids (HB4), HB15 and HB6) did not differ from each other. For the comparison between environments for this same variable (NRE), the hybrids showed higher values in the environment E1 than in E2 (Figure 1B).

Physiological characteristics

The ANOVA results obtained for eight physiological characteristics when evaluating the 15 hybrids in two environments (Table 6) showed that for most of the variables, there was a highly significant interaction ($p< 0.01$), with the exception of root water potential (RWP), which showed no interaction between the evaluated factors and only a significant interaction for the E2 environment (Table 6). The coefficients of variation (CVs) for most of the physiological characteristics evaluated were less than 10%, indicating the precision of the values obtained according to Pimentel-Gomes (2023). RWP presented the highest CV (73.89%). The heritability (h^2) obtained for each physiological characteristic was high (99.82% for TLSP and 63.53% for TGSP), medium (34.95% for TSC and -42.41% for RWP) and low (19.50% for TSP, 28.10% for ROP, 26.56% for TLC and TGC with 17.77%), suggesting the possibility of practicing a selection by using some of them and having a gain in the selection process.

The results of the interaction between the hybrid and environmental factors on the basis of the physiological variables are presented in Table 7. For total soluble protein (TSP), high variability was observed in the response of the hybrids in the two environments evaluated. In E1 and E2, nine and seven different groups, respectively, were formed. This indicates that there is variability in the response of the hybrids to this physiological variable. Here, it was observed that the hybrids HB4, HB5, HB6 and HB9 presented the best performance, in contrast to the lowest performance, which was HB11 (26.15 mg g-1 DM-1) (Table 7).

Table 5. Comparison of the means obtained when evaluating the interaction between 15 maize hybrids in two different locations for the agronomic characteristics: days to male (DFM) and female (DFF) flowering, plant height (PH), ear height (EH), ear length (EL), ear diameter (ED), number of grains per row (NGE) and yield per ha (Y).

Hybrids	DFM (days)		DFF (days)		PH (cm)		EH (cm)		EL (cm)		ED (cm)		NGE (grains)		Y ($t\ ha^{-1}$)	
	E1*	E2	E1	E2	E1	E2	E1	E2	E1	E2	E1	E2	E1	E2	E1	E2
HB1	74.25 Cb	108.00 Ga	76.25 Db	110.00 Ga	213.00 Ab	260.25 Aa	119.75 Ab	161.00 Ba	16.87 Ca	16.50 Ba	5,500 Aa	5,250 Aa	33.50 Ca	32.25 Ba	10,458 Aa	9,759 Aa
HB2	74.75 Cb	112.25 Ea	76.75 Db	114.50 Ea	194.50 Ab	282.25 Aa	102.50 Bb	178.75 Aa	21.25 Aa	19.12 Ab	5,400 Aa	5,025 Ab	36.00 Ba	31.00 Bb	11,622 Aa	8,999 Bb
HB3	74.50 Cb	113.00 Da	76.75 Db	115.00 Ea	194.75 Ab	269.25 Aa	91.00 Bb	158.25 Ba	20.00 Aa	17.00 Bb	5,350 Aa	5,000 Ab	39.25 Aa	34.25 Ab	11,853 Aa	10,582 Aa
HB4	85.25 Ab	114.00 Da	86.75 Ab	117.00 Da	188.50 Ab	275.00 Aa	116.00 Ab	157.75 Ba	18.50 Ba	17.37 Bb	5,500 Aa	5,025 Ab	31.50 Ca	31.75 Ba	11,458 Aa	10,604 Aa
HB5	73.75 Cb	109.00 Ga	75.75 Eb	111.00 Ga	173.75 Ab	266.50 Aa	87.50 Bb	140.25 Ca	20.00 Aa	17.57 Bb	5,375 Aa	4,975 Ab	39.25 Aa	33.25 Ab	11,426 Aa	9,655 Aa
HB6	74.25 Cb	112.00 Ea	76.5 Db	113.00 Fa	203.25 Ab	257.00 Aa	110.00 Ab	143.50 Ca	16.50 Ca	16.00 Ca	5,325 Aa	5,150 Aa	33.75 Ca	33.00 Aa	11,249 Aa	10,645 Aa
HB7	78.00 Bb	113.00 Da	80.25 Bb	115.00 Ea	181.50 Ab	264.25 Aa	106.50 Bb	159.25 Ba	16-75 Ca	17.37 Ba	5,075 Aa	5,025 Aa	32.25 Cb	37.00 Aa	9,072 Ab	11,622 Aa
HB8	73.67 Cb	111.00 Fa	75.00 Eb	113.00 Fa	192.00 Ab	241.00 Ba	96.00 Bb	135.75 Ba	16.83 Ba	13.62 Db	3,466 Ca	5,075 Ab	35.33 Ba	24.25 Cb	10,722 Aa	6,850 Bb
HB9	75.25 Cb	111.00 Fa	77.50 Db	113.00 Fa	181.50 Ab	241.50 Ba	89.25 Bb	126.50 Ba	16.12 Ca	13.75 Db	5,425 Aa	4,975 Ab	33.75 Ca	27.50 Cb	10,458 Aa	7,291 Bb
HB10	77.25 Bb	111.00 Fa	79.25 Cb	114.00 Ea	189.25 Ab	265.25 Aa	95.50 Bb	154.00 Ba	20.00Aa	17.00 Bb	5,075 Ba	5,075 Aa	40.50 Aa	34.50 Ab	11,812 Aa	9,696 Ab
HB11	74.50 Cb	113.00 Da	76.75 Db	115.00 Ea	185.75 Ab	253.00 Aa	103.25 Bb	159.25 Ba	17.35 Ba	15.65 Ca	5,400 Aa	5,175 Aa	35.75 Ba	30.00 Bb	10,812 Aa	7,791 Bb
HB12	74.75 Cb	115.50 Ca	77.00 Db	117.75 Ca	199.25 Ab	238.25 Ba	100.25 Bb	159.25 Ca	18.20 Ba	17.00 Ba	5,225 Aa	5,225 Aa	37.25 Ba	31.00 Bb	11,249 Aa	9,999 Aa
HB13	75.00 Cb	118.00 Ba	77.00 Db	121.50 Ba	191.25 Ab	260.25 Aa	109.25 Bb	154.75 Ba	15.37 Ca	15.40 Ca	4,825 Ba	4,900 Aa	36.75 Ba	30.00 Bb	11,114 Aa	8,749 Bb
HB14	78.25 Bb	119.00 Ba	80.75 Bb	121.00 Ba	205.50 Aa	187.00 Ca	113.25 Ab	162.00 Ba	17.62 Ba	18.80Aa	4,875 Ba	5,100 Aa	36.25 Ba	31.50 Bb	11,697 Aa	10,176 Aa
HB15	77.25 Bb	121.25 Aa	79.25 Cb	123.50 Aa	198.00 Ab	253.00 Aa	101.75 Bb	167.50 Aa	16.25 Ca	16.67 Ba	4,825 Ba	5,075 Aa	34.25 Ca	31.00 Ca	12,449 Aa	9,799 Ab
Groups	3	7	5	7	1	3	2	4	3	4	3	1	3	3	1	2

* E1: environment Tecnológico Nacional de México, Campus Roque (ITR) and E2: environment Tecnológico Nacional de México-Campus Valle del Yaqui (ITVY), Bácum, Sonora. Different lowercase letters in the line and capital letters in the column indicate significant differences between means according to the Scott–Knott test for $p<0.05$.

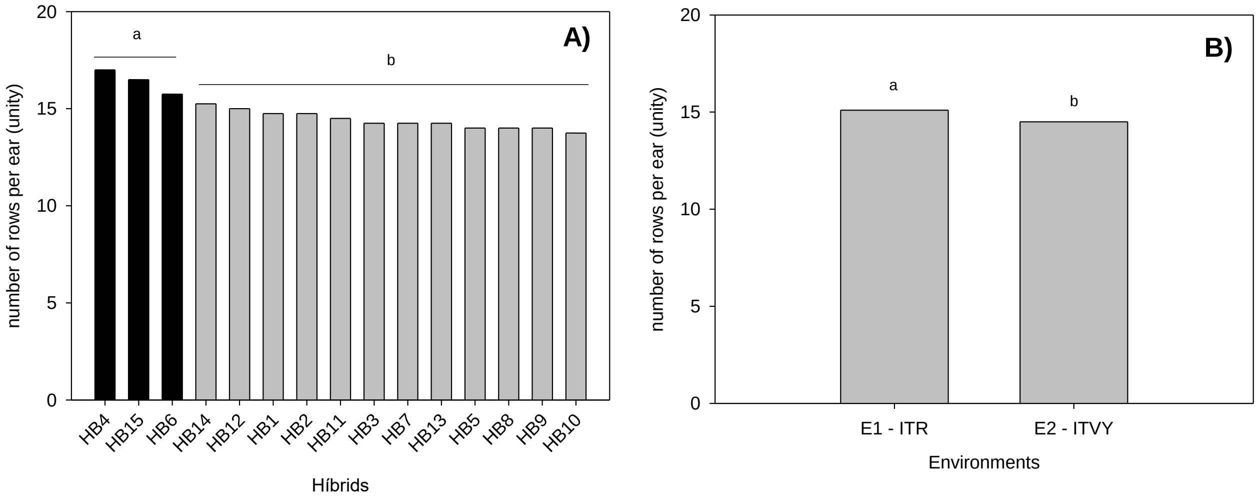

Figure 1. Performance of white maize hybrids (A) evaluated in two different environments (B) for the variable number of rows per ear. Different lowercase letters indicate significant differences between means according to the Scott–Knott test for *p<0.05*. E1: environment Tecnológico Nacional de México, Campus Roque (ITR) and E2: environment Tecnológico Nacional de México-Campus Valle del Yaqui (ITVY), Bácum, Sonora.

When the hybrids were compared individually, it was observed that HB4, HB11, HB13 and HB14 did not differ among the E2s. The hybrid HB12 presented the highest values in the E2 environment.

According to the total soluble carbohydrate (TSC) concentration, the hybrids formed 12 different groups in both environments, which showed that this variable was effective at differentiating most of the hybrids regardless of the environment evaluated. Similarly, compared with those of E2, the values of the hybrids HB7, HB8, HB13, HB14 and HB15 were significantly different, and the values were greater in E1 (Table 7). The root osmotic potential (ROP) allowed the formation of four groups in environment E1, with the lowest values obtained for hybrids HB4, HB5 and HB13 and the highest values obtained for hybrid HB1. In environment E2, the lowest values were obtained for the hybrids HB9, HB13 and HB15, which contrasted with the remaining hybrids, which did not differ from each other (Table 5). This variable showed equal behavior among all the hybrids compared in the two environments; environment E2 promoted the most negative values for all the hybrids evaluated.

Table 6. ANOVA performed to evaluate 15 maize hybrids in two different locations when considering physiological characteristics.

Factors	GL	Significance							
		TSP	TSC	RWP	ROP	TLSP	TLC	TGSP	TGC
Environments (E)	1	***	***	***	***	***	***	***	***
Hybrids (H)	14	***	***	.	***	***	***	***	***
E x H	14	***	***	.	***	***	***	***	***
CV (%)		0.41	0.22	73.89	-8.49	2.26	4.56	0.94	2.18
Mean		33.88	58.50	-0.97	-1.87	13.33	20.04	10.78	42.80
h^2 (%)		19.50	34.95	-42.41	28.10	99.82	26.56	63.53	17.77

*Total soluble proteins (TSP, mg g^{-1} MS^{-1}), total soluble carbohydrates (TSC, mg g^{-1} MS^{-1}), root water potential (RWP, MPa), root osmotic potential (ROP, MPa), total soluble proteins in leaves (TLSP, mg g^{-1} MS^{-1}), total carbohydrates in leaves (TLC, mg g^{-1} MS^{-1}), total soluble proteins in grains (TGSP, mg g^{-1} MS^{-1}) and total carbohydrates in grains (TGC, mg g^{-1} MS^{-1}). CV: coefficient of variation, h^2: broad-sense heritability. Significant differences ***, **, and * for probability values of 0.001, 0.01, 0.05 and 0.1, respectively, according to the F test.

For total soluble leaf protein (TSPH), there was a significant interaction between E and H (Table 5). In environment E1, the hybrids HB8 and HB9 had the highest values, while hybrid HB11 had the lowest leaf protein content; however, in environment E2, the hybrids HB8, HB9 and HB11 had the highest leaf protein content. Three and four groups of total leaf carbohydrates (TLC) were detected in environments E1 and E2, respectively (Table 7). The hybrids with the highest leaf carbohydrate content in environment E1 were HB4, HB5, HB6, HB8 and HB9.

In the grain, the soluble protein content (TGSP) exhibited high variability among the environments, forming 11 and 12 groups in E1 and E2, respectively (Table 7). In the E1 environment, the highest values were obtained for the hybrids HB8 and HB9; in the E2 environment, the variation was greater for the hybrid HB15. When comparing the environments, it was observed that hybrid HB11 did not differ from hybrids HB4, HB6, HB8, HB9 and HB10, which stood out in environment E1, while the rest of the hybrids performed better in environment E2 (Table 7). The total carbohydrate content in this organ was observed that the effect of E vs H was significant. The variation found within the environments allowed the formation of four and five groups. In environment E1, the highest values were obtained for the hybrids HB6, HB5 and HB8. In environment E2, the highest values were obtained for hybrid HB1. A comparison of the hybrids revealed that, within the evaluated environments, there was a greater content of total carbohydrates in the grain of the hybrids under the conditions of the environmental E2 (Table 7).

Figure 2 shows that, among the physiological variables, the root water potential (RWP) did not differ among the hybrids (Figure 2A) but did differ among the environments. There were no significant differences among the hybrids (Figure 2B).

Application of the multivariate index for hybrid selection

The comparisons of the agronomic (Table 5 and Figure 1) and physiological data (Table 7 and Figure 2) showed that the behavior of the hybrids was highly variable and that it was difficult to recommend a superior hybrid when considering the 17 variables that were shown in this work through univariate ANOVA. Thus, taking advantage of this information of 17 variables in a multivariate way allows a better selection of hybrids. For this purpose, the methodology described by Lins Bins (1988) and modified by Teodoro et al. (2019) was used, and the results are shown in Table 6.

This method, initially proposed by Lins Bins (1988), calculates a *Pi* for each of the variables; in this work, the general *Pi*, which reflects the stability and adaptability of a certain genotype, can be used to determine its general characteristics. Lower values of this index are always associated with greater stability and adaptability of a given genotype in a given environment. This same principle was maintained in the modification proposed by Teodoro et al. (2019), who selected genotypes considering the means of several characteristics in several environments. Thus, considered several variables in a single index calculated in this work associated with agronomic (*Pim-agro*) and physiological (*Pim-physiol*) characteristics and the combination of these two indices to form a *PimAgro+Fisiol,* as shown in Table 8.

By considering the nine agronomic variables, the lowest *Pim-agro* values allowed us to select the five hybrids (HB4 (5.65), HB15 (6.98), HB2 (8.86), HB3 (9.18) and HB14 (9.32)) that were most stable for these characteristics. Considering the eight physiological variables, the lowest *Pim-physiol* values allowed us to select the five hybrids (HB6 (4.63), HB9 (5.11), HB5 (5.96), HB2 (6.30) and HB3 (6.90)) that were most stable for these characteristics. After analyzing the lowest *Pim-Agro+Fisiol* values, the five hybrids (HB4 (12.62), HB15 (14.96), HB2 (15.16), HB6 (15.88) and HB3 (16, 08)) most stable for these traits, including agronomic and physiological traits, were selected (Table 6).

Discussion

The identification of the best hybrid combinations for white grain maize is the main focus of the present work. The characterization and selection of individuals is not always an easy task because there is often a wide diversity of responses. These results are generally obtained when contrasting genotypes are crossed (Ponce-Encinas et al., 2022). This diversity is used as the main indicator of the selection of superior individuals for a given trait. Diversity within genetic improvement programs is always necessary, and selection is made on this basis, considering often the genotype × environment interaction or even the same diversity within a trait in a single environment (Aguilera et al., 2019; Teodoro et al., 2019).

When working with a large number of traits and having great diversity within them, this factor often makes selection difficult because we generally select for some traits and consider others (Rebolloza-Hernández, 2020). Positive or negative correlations between characteristics largely determine the possibility of selecting in one direction, in favor of superior values for one direction and being carrying another in a negative direction, mainly when the genes being selected are pleiotropic (Coca et al., 2019)

Table 7. Comparison of means obtained when evaluating 15 maize hybrids in two different environments for physiological characteristics.

Hybrids	TSP		TSC		ROP		TLSP		TLC		TGSP		TGC	
	E1*	E2	E1	E2	E1	E2	E1	E2	E1	E2	E1	E2	E1	E2
HB1	31.15 Fa	30.82 Gb	53.45 Kb	54.10 Ka	-1.60 Ab	-1.28 Aa	20.70 Fa	3.12 Bb	27.34 Ca	7.40 Db	8.90 Ib	11.23 Ea	13.34 Db	72.38 Aa
HB2	35.25 Ca	34.85 Db	60.25 Eb	62.15 Ea	-2.55 Cb	-1.25 Aa	24.60 Ca	2.85 Cb	30.66 Ba	8.15 Db	10.10 Gb	12.24 Ba	16.66 Cb	68.28 Ca
HB3	35.25 Ca	34.75 Db	59.55 Fb	60.20 Fa	-2.50 Cb	-1.23 Aa	24.80 Ca	2.88 Cb	27.90 Ca	8.31 Db	10.30 Fb	11.92 Ca	16.40 Cb	69.50 Ca
HB4	36.25 Ba	36.22 Aa	66.45 Bb	67.15 Ba	-2.90 Db	-1.15 Aa	25.63 Ba	2.32 Db	33.87 Aa	9.27 Cb	11.40 Ca	11.12 Eb	18.50 Bb	70.37 Ba
HB5	36.45 Aa	36.12 Ab	66.55 Bb	66.77 Ca	-2.80 Db	-1.32 Aa	25.93 Ba	2.16 Db	33.98 Aa	10.24 Bb	10.80 Eb	12.32 Ba	19.97 Ab	69.98 Ba
HB6	36.55 Aa	36.12 Ab	67.60 Aa	67.50 Aa	-2.65 Cb	-1.22 Aa	25.75 Ba	2.80 Cb	34.44 Aa	9.15 Cb	11.80 Ba	11.27 Eb	20.43 Ab	70.30 Ba
HB7	34.65 Da	33.87 Fb	60.72 Da	60.27 Fb	-2.50 Cb	-1.25 Aa	24.20 Da	3.16 Bb	30.96 Ba	11.34 Ab	11.20 Db	12.22 Ba	16.96 Cb	68.86 Ca
HB8	36.60 Aa	35.85 Cb	66.60 Ba	66.22 Db	-2.65 Cb	-1.20 Aa	26.10 Aa	3.64 Ab	33.92 Aa	9.42 Cb	12.30 Aa	11.77 Db	19.91 Ab	65.44 Ea
HB9	36.65 Aa	37.17 Ab	65.35 Cb	66.12 Da	-2.60 Cb	-1.45 Ba	26.31 Aa	3.88 Ab	33.30 Aa	8.30 Db	12.40 Aa	11.23 Eb	19.30 Bb	69.28 Ca
HB10	34.60 Da	NA	57.25 Ia	NA	-1.85 Bb	-1.22 Aa	26.83 Ea	3.44 Bb	29.21 Ba	10.18 Bb	11.80 Ba	10.23Hb	15.19 Cb	67.24 Da
HB11	26.25 Ha	26.15 Ia	52.65 Lb	53.20 The	-1.80 Bb	-1.20 Aa	15.20 Ha	3.67 Ab	26.92 Ca	9.13 Cb	8.40 Ka	8.51 Ia	12.93 Db	67.33 Da
HB12	28.50 Gb	29.12 Ha	55.37 Jb	56.15 Ja	2.35 Cb	-1,075 Aa	18.00 Ga	3.46 Bb	28.25 Ca	8.17 Db	8.57 Jb	7.75 Ja	14.21 Db	65.15 Ea
HB13	34.40 Ea	34,300 Ea	59.25 Ga	58.82 Gb	-2.75 Db	-1.53 Ba	23.80 Ea	3.33 Bb	30.15 Ba	11.80 Ab	10.10 Gb	10.86 Ga	16.15 Cb	70.18 Ba
HB14	34.40 Ea	34.22 Ea	58.50 Ha	57.82 Ib	-2.55 Cb	-1.55 Ba	23.50 Ea	3.41 Bb	29.83 Ba	11.43 Ab	9.62 Hb	11.02 Fa	15.84 Cb	69.38 Ca
HB15	34.55 Da	34.12 Eb	59.35 Ga	58.60 Hb	-2.55 Cb	-1.65 Ba	24.20 Da	3.25 Bb	30.25 Ba	8.15 Db	9.58 Hb	12.48 Aa	16.24 Cb	68.38 Ca
Groups	8	10	12	13	4	2	8	4	3	4	11	10	4	5

*E1: Tecnológico Nacional de México, Campus Roque (ITR) and E2: Tecnológico Nacional de México-Campus Valle del Yaqui (ITVY), Bácum, Sonora. Total soluble proteins (TSP, mg g^{-1} MS^{-1}), total soluble carbohydrates (TSC, mg g^{-1} MS^{-1}), root osmotic potential (ROP, MPa), total soluble proteins in leaves (TLSP, mg g^{-1} MS^{-1}), total carbohydrates in leaves (TLC, mg g^{-1} MS^{-1}), total soluble proteins in grains (TGSP, mg g^{-1} MS^{-1}) and total carbohydrates in grains (TGC, mg g^{-1} MS^{-1}) were measured. Different lowercase letters in the line and uppercase letters in the column indicate significant differences between means according to the Scott–Knott test for $p<0.05$.

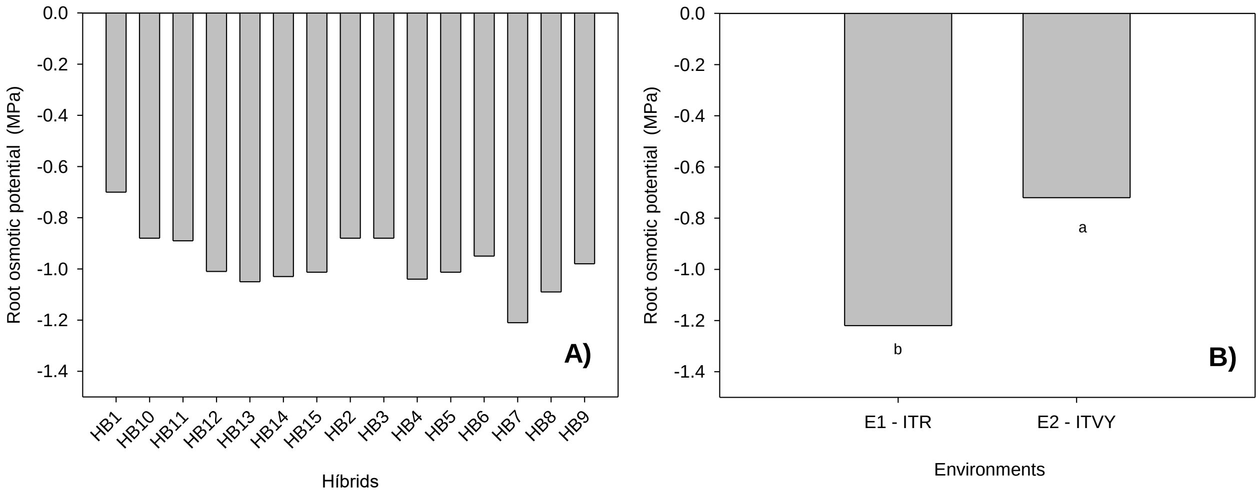

Figure 2. Performance of white maize hybrids (A) evaluated at two different locations (B) for the variable root water potential. Different lowercase letters indicate significant differences between means compared by the Scott–Knott test for *p<0.05* probability. E1: environment Tecnológico Nacional de México, Campus Roque (ITR) and E2: environment Tecnológico Nacional de México-Campus Valle del Yaqui (ITVY), Bácum, Sonora.

This process allows breeders to characterize and select those traits of interest, allowing more in-depth knowledge of the existing relationships between traits (Aguilera et al., 2016; Aguilera et al 2019, Alam et al., 2022).

This work evaluated nine agronomic and eight physiological variables, for a total of 17 variables, used as a basis for selecting the best white grain maize hybrids in relation to the best stability and adaptability response using the index proposed by Lins Bins (1988) and modified by Teodoro et al. (2019). Initially, the hybrids were compared in relation to agronomic and physiological variables, revealing that the highest variability was obtained for DFM and DFF, both with up to seven groups and TSP with up to 10 groups; TSC with up to 13 groups; and TGSP with up to 11 groups (Table 5 and Table 7), thus demonstrating the potential of these hybrids for selection in the evaluation of white grain maize hybrids.

Linares-Holguín et al. (2019), when characterizing phenotypically and agronomically 144 native maize plants from Sinaloa, Mexico, verified that among the 27 characteristics evaluated, DFM and DFF were among the characteristics that contributed most to the diversity of the collection, as verified in the present work. The days to male and female flowering are characteristics commonly used by breeders, and these two characteristics determine the behavior of the flowering process in maize depending on the environmental conditions of the locations where the crop is established, thus determining the crop cycle (Russell & Hallauer, 1980). Artificial pollination strategies are conducted using the days to male and female flowering as prior knowledge; hence, it is important to know these parameters when determining the genotypes used as parents for maize. Both the DFM and DFF traits and the E2 environment [Tecnológico Nacional de México-Campus Valle del Yaqui (ITVY), Bácum, Sonora] always promoted the longest flowering interval. Compared with E1, E2 has an average temperature of 17.2 °C, with a difference of 1.7 °C, indicating the variability in the response of the hybrids to this variable.

Evaluating characteristics related to crop quality from a physiological point of view is always a way to identify the nutritional potential of the crops produced. In white maize grains, adequate protein contents are between 8 and 11% (Ewu & Messing, 2014), and for carbohydrates, adequate protein contents are approximately between 60 and 72% (Jahangirlou et al., 2020). The total soluble protein (TSP), total protein in leaves (TLSP) and total protein in grains (TGSP) contents ranged from 26.15 to 37.00 mg g^{-1} MS^{-1}, 2.11 to 26.32 mg g^{-1} MS^{-1} and 7.75 to 12.47 mg g^{-1} MS^{-1}, respectively (Table 5 and Table 7). These results showed that within the hybrids obtained, there is potential to select superior genotypes for this trait and thus improve the protein content in white-colored grains.

Table 8. Stability and adaptability values proposed by Lins Bins (1988) and modified by Teodoro et al. (2019) obtained by evaluating 15 white-grain maize hybrids at two different locations for agronomic and physiological traits.

Hybrids	**DFM***	**DFF**	**PH**	**EH**	**EL**	**ED**	**NRE**	**NGE**	**Y**	***Pim-agro***	**TSP**	**TSC**	**RWP**	**ROP**	**TLSP**	**TLC**	**TGSP**	**TGC**	***Pim-fisiol***	***PimAgro+Fisiol***
HB1	74.1	73.1	127	78.8	6.51	0	2.81	17.9	1.91	13.61	17.6	94.9	0.00391	0.01	835	17.5	3.46	12.6	7.82	21.43
HB2	47.8	45.2	85.6	74.4	0	0.0152	2.56	14.1	1.91	**8.86**	1.84	20.7	0.0564	0.233	727	6.91	1.34	7.76	**6.30**	**15.16**
HB3	45.9	43.1	129	312	1.52	0.0213	4.06	2.28	0.375	**9.18**	1.96	29.5	0.0508	0.208	721	13.8	1.18	6.13	**6.90**	**16.08**
HB4	13.1	10.6	165	114	2.66	0.0127	0	31.9	0.531	**5.65**	0.266	0.361	0.111	0.424	700	1.68	0.708	1.94	6.98	**12.62**
HB5	70.6	69.3	451	631	0.991	0.0228	5	3.91	1.26	14.87	0.286	0.407	0.0956	0.376	692	0.664	0.649	1.49	**5.96**	20.82
HB6	51.6	53.8	190	334	8.08	0.0102	1.06	15.4	0.63	11.25	0.278	0	0.0714	0.281	696	1.76	0.452	1.08	**4.63**	**15.88**
HB7	30.2	28.6	334	139	5.83	0.0578	5.31	17	2.94	11.82	3.72	24.9	0.173	0.21	737	3.09	0.379	6.11	7.87	19.69
HB8	62.3	65.1	538	592	11.8	1.03	4.62	46.3	6.47	26.61	0.44	0.656	0.104	0.28	686	1.49	0.125	12.1	6.94	33.55
HB9	51.3	49	673	915	13.8	0.0203	4.5	34	5.73	22.00	0	1.74	0.0702	0.285	681	3.38	0.384	2.72	**5.11**	27.11
HB10	42.3	36.6	218	300	1.32	0.0528	5.56	1.56	1.05	10.04	534	1490	0.0345	0.0213	0.0479	7.51	1.35	13.5	12.99	23.03
HB11	45.9	43.1	407	163	6.77	0.00391	3.62	17.9	4.38	13.52	57.4	107	0.0425	0.0139	1002	15.9	7.93	20.4	14.36	27.88
HB12	35.8	32	542	328	3.38	0.0191	3.12	11.6	1.05	10.24	32.8	69.6	0.0703	0.141	915	12.9	9.25	22.7	14.46	24.70
HB13	28.9	24.8	245	172	12.1	0.145	4.06	15.8	2.54	12.24	3.33	36.2	0.0983	0.381	748	4.62	1.97	5.78	8.13	20.37
HB14	13.5	10.6	1661	80.7	3.31	0.103	1.81	12.1	0.683	**9.32**	3.44	44.1	0.0789	0.282	756	5.34	2.46	7.51	7.52	16.84
HB15	16	14.1	278	113	8.07	0.122	0.125	18.8	0.675	**6.98**	3.43	36.8	0.0781	0.308	737	7.73	2	8.38	7.98	**14.96**

*Days to Male (DFM, days) and Female (DFF, days) Flowering, Plant Height (PH, cm), Ear Height (EH, cm), Ear Length (EL, cm), Ear Diameter (ED, cm), Number of Rows in Ear (NRE, unit), Number of Grains per Row (NGE, unit) and Yield per ha (Y, t ha^{-1}), Total Soluble Proteins (TSP, mg g^{-1} DM^{-1}), Total Soluble Carbohydrates (TSC, 55 mg g^{-1} MS^{-1}), Root Water Potential (RWP, MPa), Root Osmotic Potential (ROP, MPa), Total Soluble Proteins in Leaf (TSLP, mg g^{-1} MS^{-1}), Total Leaf Carbohydrates (TLC, mg g^{-1} MS^{-1}), Total Grain Soluble Proteins (TGSP) and Total Grain Carbohydrates (TGC, mg g^{-1} MS^{-1}). The values in bold indicate selected hybrids for each *Pim*.

The present work demonstrated that there is great potential within the hybrids obtained for most of the physiological and agronomic traits when evaluated in two different environments, and to improve the selection of hybrids, a multivariate index proposed by Teodoro et al. (2018) was used. Multivariate methods have been employed in numerous works, such as those involving wheat (Aguilera et al., 2019), cotton (Teodoro et al., 2019; Peixoto et al., 2022), coffee (Partelli et al., 2022), tomato (Djidonou et al., 2020), soybean (Almeida et al., 2021; Steiner et al., 2021), and forage species (Zuffo et al., 2022), and this type of selection has been shown to be more efficient than univariate analyses. The present work considered 17 variables and two environments, and through the confection of multivariate indices using the method proposed by Lins Bins (1988) and modified by Teodoro et al. (2019), we obtained indices associated with the agronomic (*Pim-agro*) and physiological (*Pim-physiol*) data individually and in combination (*Pim-Agro+Fisiol*). When the *Pim-agro* index was considered, the hybrids HB2, HB3, HB4, HB14 and HB15 were selected because they presented the lowest *Pi* of the nine agronomic characteristics, thus showing that these hybrids are the most adaptable and stable in the two environments evaluated (Table 8). According to Lins Bins (1988), lower *Pi* values are associated with greater stability and adaptability of genotype performance in various environments. When selection was considered on the basis of the behavior of the hybrids in relation to physiological variables, HB2 and HB3 were the most stable hybrids, and HB5, HB6 and HB9 were added (Table 8). Several works have shown that combining phenotypic data of different natures, such as those obtained in this work for agronomic and physiological characteristics, results in improved selection of individuals (Aguilera et al., 2019; Teodoro et al., 2019; Peixoto et al., 2022). Selection performed by employing the multivariate index *Pim-Agro+Fisiol* revealed that the superior genotypes were HB2, HB3, HB4, HB6 and HB15, which presented the lowest values for this index (Table 8). The hybrid HB2 resulting from the cross-comparison of the homozygous L1-CML442 and L6-CML546 plants exhibited the highest stability and adaptability for the variables PH (*Pi*= 85.6), EH (*Pi=74*.4) and EL (*Pi=0*.0). The hybrid HB3 resulting from the cross L1-CML442 × L4-CML550 had a Pi value of 0.375 and shared the same parent as HB2, indicating the potential of this parent to result in superior white-grain hybrids (Table 8). The hybrid HB4 obtained from the cross of L3-CML549xL6-CML546 had Pi values within the ranges for the variables DFM (13.1), DFF (10.6) and NRE (0.0) and shared the same parent as HB2; hence, it performed similarly to the *Pim-Agro+Fisiol* index. The hybrid HB6 (L3-CML549xL4-CML550) stands out when considering the *Pim-Agro+Physiol* index and has the lowest *Pi* values and thus the best overall stability and adaptability in terms of the TSC (*Pi=0*.0) and TGC (*Pi=1*.08) variables. The hybrid HB6 shares the same parents as HB4 and HB3 when considering the male and female parents, respectively (Table 1). Finally, the hybrid HB15 resulting from the cross-occurrence of L5-CML576xL3-CML549 had the second lowest values of *Pim-agro* and *PimAgro+Fiiol,* as well as the best stability and adaptability, with values of 6.98 and 14.96, respectively (Table 8). This hybrid shares the same parental material (L3-CML549) used to obtain HB4 and HB6, with the difference that these parental materials were used in a reciprocal way in relation to how they were used in these two hybrids (Table 1).

In this work, the use of the Pim proposed by Teodoro et al. (2019) as a multivariate stability and adaptability index demonstrated the feasibility of using multivariate indices for efficient hybrid selection via combined comparisons of the effects of genotypes and environments.

Conclusions

There was a wide variability in the responses of the 15 hybrids to the two environments evaluated when 17 agronomic and physiological variables were considered.

The proposed multivariate indices allowed the selection of superior hybrids (HB2, HB3, HB4, HB6 and HB15) in relation to agronomic and physiological variables and their combinations, thus revealing the power that this method has and that it can be easily implemented within the breeding program of white grain maize, as well as in other maize selection schemes.

Author contributions

1 Lorenzo Pérez López; Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Validation, Visualization, Writing—original draft, Writing—review and editing.

2 Leandris Argentel-Martínez; Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing—original draft, Writing—review and editing.

3 Ofelda Peñuelas-Rubio; Formal analysis, Funding acquisition, Investigation, Methodology, Validation, Visualization, Writing—original draft, Writing—review and editing.

4 Francisco Cervantes Ortiz; Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing—original draft, Writing—review and editing.

5 Franck Denis Torres Huaco; Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing—original draft, Writing—review and editing.

6 Cesar Leobardo Aguirre-Mancilla; Data curation, Formal analysis, Funding acquisition, Investigation, Validation, Visualization, Writing—original draft, Writing—review and editing.

7 Jorge González Aguilera; Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing—original draft, Writing—review and editing.

8 Paulo Eduardo Teodoro; Formal analysis, Investigation, Methodology, Validation, Visualization, Writing—original draft, Writing—review and editing.

Conflicts of Interest: The authors declare no conflicts of interest.

References

Aguilera, J.G., Minozzo, J.A.D., Barichello, D., Fogaça, C.M., da Silva, J.P. Jr, Consoli, L., Pereira, J.F., 2016. Alleles of organic acid transporter genes are highly correlated with wheat resistance to acidic soil in field conditions. *Theor Appl Genet. 129*(7), 1317-1331. https://doi.org/10.1007/s00122-016-2705-3.

Aguilera, J.G., Teodoro, P.E., da Silva, J.P., Pereira, J.F., Zuffo, A.M., Consoli, L., 2019. Selection of Aluminum-Resistant Wheat Genotypes Using Multienvironment and Multivariate Indices. *Agronomy Journal, 111*(6), 2804-2810. https://doi.org/10.2134/agronj2019.06.0470

Alam, M.A., Rahman, M., Ahmed, S., Jahan, N. et al., 2022. Genetic variation and genotype by environment interaction for agronomic traits in maize (*Zea mays* L.) hybrids. *Plants, 11*(11), 1522. https://doi.org/10.3390/plants11111522

Almeida, H.C., Soares, A.P.L., Poersch, N.L., Izidorio, T.H., Teodoro, L.P.R., Teodoro, P.E., 2021. Adaptability and stability of soybean cultivars in the region of Chapadões. *Revista Ceres, 68*:326-332. https://doi.org/10.1590/0034-737X202168040010

Beyene, Y., Semagn, K., Mugo, S., Prasanna, B.M. et al., 2016. Performance and grain yield stability of maize populations developed using marker-assisted recurrent selection and pedigree selection procedures. *Euphytica 208*, 285-297. https://doi.org/10.1007/s10681-015-1590-1

Bhering, L.L., Cruz, C.D., de Vasconcelos, E.S., Ferreira, A., de Resende, Jr M.F.R., 2008. Alternative methodology for Scott–Knott test. *Crop Breeding and Applied Biotechnology 8*(1). https://doi.org/10.12702/1984-7033.v08n01a02

Bhering, L.L., 2017. Rbio: A Tool For Biometric And Statistical Analysis Using The R Platform. *Crop Breeding and Applied Biotechnology, 17*(2), 187-190. https://doi.org/10.1590/1984-70332017v17n2s29

Buenrostro-Robles, M., Lobato-Ortiz, R., García-Zavala, J.J., Sánchez-Abarca, C., 2017. Rendimiento de líneas de maíz exótico irradiado con rayos gamma y de híbridos de cruza simple. *Revista Fitotecnia Mexicana, 40*(3):351-358. https://doi.org/10.35196/rfm.2017.3.351-358

Coca, E.H.H., Diaz, A.V.C., Jiménez, J.E., 2019. Heterosis útil y caracteres asociados al rendimiento en híbridos de maíz amarillo duro bajo condiciones de secano en Tarapoto. *Análes científicos, 80*(1):259-268. http://dx.doi.org/10.21704/ac.v80i1.1393

Djidonou, D., Leskovar, D.I., Joshi, M., et al., 2020. Stability of yield and its components in grafted tomato tested across multiple environments in Texas. *Scientific Reports, 10*(1), 13535. https://doi.org/10.1038/s41598-020-70548-3

do Couto, D.P., Oliveira, W.B.D.S., de Oliveira, J.S., et al., 2023. Analysis of the Effect of the Interaction of Genotype and Environment on the Yield Stability of Maize Varieties. *Genetic Resources for Breeding. Agronomy, 13*(8), 1970. https://doi.org/10.3390/agronomy13081970

Donovan, J., Rutsaert, P., Domínguez, C., Peña, M., 2022. Capacities of local maize seed enterprises in Mexico: Implications for seed systems development. *Food Security, 14,* 509–529. https://doi.org/10.1007/s12571-021-01247-8

Ewu, Y., Messing, J., 2014. Proteome balancing of the maize seed for higher nutritional value. *Front. Plant Sci., 5,* 240. https://doi.org/10.3389/fpls.2014.00240

Gabriel, A., Faria, M.V., Battistelli, G.M., Rossi, E.S., Da Silva, C.A., De Marck, D.F., Gava, E., 2018. Desempenho agronômico e estabilidade de topcrosses de milho avaliados em Minas Gerais e Paraná. *Revista Brasileira de Milho e Sorgo*, *17*(2), 303-316. https://doi.org/10.18512/1980-6477/rbms.v17n2p303-316

Greveniotis, V., Bouloumpasi, E., Zotis, S., Korkovelos, A., Ipsilandis, C.G., 2021. Estimations on trait stability of maize genotypes. *Agriculture, 11*(10), 952. https://doi.org/10.3390/agriculture11100952

Jahangirlou, M.R., Akbari, G.A., Alahdadi, I., Soufizadeh, S., Parsons, D., 2020. Grain quality of maize cultivars as a function of planting dates, irrigation and nitrogen stress: a case study from semiarid conditions of Iran. *Agriculture 11*(1), 11. https://doi.org/10.3390/agriculture11010011

LaFevor, M.C., 2022. Spatial and temporal changes in crop species production diversity in Mexico (1980–2020). *Agriculture 12*(7), 985. https://doi.org/10.3390/agriculture12070985

Lin, C.S., Binns, M.R., 1988. A method of analyzing cultivar x location x year experiments: a new stability parameter. *Theoretical and Applied Genetics, 76*, 425-430. https://doi.org/10.1007/BF00265344

Linares-Holguín, O.O., Rocandio-Rodríguez, M., Santacruz-Varela, A., López-Valenzuela, J.Á., Córdova-Téllez, L., Parra-Terraza, S., ... Sánchez-Peña, P., 2019. Caracterización fenotípica y agronómica de maíces (*Zea mays* ssp. *mays* L.) nativos de Sinaloa, México. *Interciencia, 44*(7), 421-428.

Menezes, C.B., Tardin, F.D., Portugal, A.F., Ribeiro, A.D.S., De Carvalho, A.J., De Almeida, F.H.L., ... Dos Santos, C.V., 2015. Adaptabilidade e estabilidade de linhagens de sorgo em ambientes com e sem restrição hídrica. *Revista Brasileira de Milho e Sorgo, 14*(1), 101-115.

Ocwa, A., Harsanyi, E., Széles, A., Holb, I.J., Szabó, S., Rátonyi, T., Mohammed, S., 2023. A bibliographic review of climate change and fertilization as the main drivers of maize yield: implications for food security. *Agriculture Food Security, 12*(1), 1-18. https://doi.org/10.1186/s40066-023-00419-3

Partelli, F.L., da Silva, F.A., Covre, A.M., Oliosi, G., Correa, C.C.G., Viana, A.P., 2022. Adaptability and stability of *Coffea canephora* to dynamic environments using the Bayesian approach. *Scientific Reports, 12*(1), 11608. https://doi.org/10.1038/s41598-022-15190-x

Peixoto, M.A., Evangelista, J.S.P.C., Coelho, I.F., Carvalho, L.P., Farias, F.J.C., Teodoro, P.E., Behring, L.L., 2022. Genotype selection based on multiple traits in cotton crops: The application of genotype by yield*trait biplot. *Acta Scientiarum. Agronomy, 44*, e54136. https://doi.org/10.4025/actasciagron.v44i1.54136

Pierre, J.F., Latournerie-Moreno, L., Garruña-Hernández, R., Jacobsen, K.L., Guevara-Hernández, F., Laboski, C.A., Ruiz-Sánchez, E., 2022. Maize legume intercropping systems in southern Mexico: A review of benefits and challenges. *Ciência Rural, 52*, e20210409. https://doi.org/10.1590/0103-8478cr20210409

Ponce-Encinas, M.C., López-Morales, F., Chura-Chuquija, J., Hernández-Leal, E., Hernández-Salinas, G., Aragón-García, A., 2022. Interacción genotipo-ambiente del rendimiento en híbridos de maíz amarillo mediante AMMI y SREG. *Revista mexicana de ciencias agrícolas, 13*(7), 1247-1258. https://doi.org/10.29312/remexca.v13i7.3070

Prakash, L., Prathapasenan, G., 1988. Effect of NaCl salinity and putrescine on shoot growth, tissue ion concentration and yield of rice (*Oryza sativa* L. var. GR-3). *Journal of Agronomy and Crop Science 160*(5), 325-34. https://doi.org/10.1111/j.1439-037X.1988.tb00630.x

Rebolloza-Hernández, H., Cervantes-Adame, Y.F., Broa-Rojas, E., Bahena-Delgado, G., Olvera-Velona, A., 2020. Fenotipeo y selección de líneas S1 segregantes de maíz tolerantes a estrés hídrico. *Biotecnia, 22*(3), 20-28.

Russell, W.A., Hallauer, A.R., 1980. Maize. Hybridization of crop plants, 299-312. https://doi.org/10.2135/1980.hybridizationofcrops.c19

Saavedra Guevara, C., Pérez López, D.D.J., González Huerta, A., Franco Martínez, J., Rubí Arriaga, M., Ramírez Dávila, J.F., 2021. Métodos de Griffing: revisión sobre su importancia y aplicación en fitomejoramiento convencional. *Revista mexicana de ciencias agrícolas, 12*(7), 1275-1286. https://doi.org/10.29312/remexca.v12i7.3040

Sadok, W., Shoppach, R., 2019. Potential involvement of root auxins in drought tolerance by modulating nocturnal and daytime water use in wheat. *Annals of botany, 124*(6), 969-978. https://doi.org/10.1093/aob/mcz023

Steiner, F., Zuffo, A.M., Teodoro, P.E., Aguilera, J.G., Teodoro, L.P.R., 2021. Multivariate adaptability and stability of soya bean genotypes for abiotic stresses. *Journal of Agronomy and Crop Science, 207*(2), 354-361. https://doi.org/10.1111/jac.12446

Teodoro, P.E., Farias, F.J.C., de Carvalho, L.P., Ribeiro, L.P., Nascimento, M., Azevedo, C.F., ... Bhering, L.L., 2019. Adaptability and stability of cotton genotypes regarding fiber yield and quality traits. *Crop Science, 59*(2), 518-524. https://doi.org/10.2135/cropsci2018.04.0250

Zuffo, A.M., Steiner, F., Aguilera, J.G., et al., 2022. Selected Indices to Identify Water-Stress-Tolerant Tropical Forage Grasses. *Plants, 11*(18), 2444. https://doi.org/10.3390/plantE11182444