

GENOTYPE-ENVIRONMENT INTERACTION ON THE SEED QUALITY OF MAIZE HYBRID PROGENITORS (*Zea mays* L.)

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ABSTRACT

The environmental conditions at the multiplication site have an impact on seed quality. Parents capable of counteracting changes in production environments are required to maintain and conserve the excellent attributes of maize (*Zea mays* L.) seed. This study sought to determine the effects of genotype and environment on the physical and physiological traits of single crosses and inbred lines, which are the progenitors of trilineal maize hybrids adapted to the High Valleys of Mexico. During the spring-summer 2014 and 2015 cycles, nine inbred lines, three single crosses, and three hybrids were evaluated in Coatlinchán, Celaya, and San Luis de la Paz, Mexico, in a randomized complete block design with three replications. The hectoliter and thousand-seeds weight, commercial seed percentage, standard germination, and after-cold test were evaluated. A pooled analysis of variance and multiple comparison of means with Tukey ($p \leq 0.05$) were performed. The site regression model (SREG) was used to account for the genotype-environment interaction. The best environments for physical quality were San Luis de la Paz 2014; for a thousand-seeds weight (295.3 g), Coatlinchán 2015; for hectoliter weight (74.7 kg hL⁻¹), Coatlinchán 2014; and for commercial seed percentage (76 and 73.3 %), San Luis de la Paz 2014. With the exception of Celaya 2014, the environments were statistically equal for physiological quality in standard germination, and San Luis de la Paz 2015 (82 %) was the best environment for germination after cold exposure. Regarding the genotype-environment interaction, parents M-47xM-46 and M-55xM-54 performed best for physical quality and M-43xM-44 for physiological quality at San Luis de la Paz; thus, seed production from these parents is possible in this location.

Key words: stability, High Valleys, Transition Zone, physical quality, germination.

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INTRODUCTION

The global maize production is 1423 million Mg, with an average yield of 4.9 Mg ha⁻¹ (FAO, 2022). Maize is the foundation of food in Mexico, and 27.5 million Mg are produced, equivalent to 1.9 % of world production, with average yields of 3.9 Mg ha⁻¹ (SIAP, 2022). One of the alternatives to increase yields is the adoption of certified seed; however, only 30 % of the area planted in Mexico with this crop is covered (Luna-Mena *et al.*, 2012).

Seeds are one of the most important inputs in production, marking the beginning of the life cycle of each plant, so ensuring its quality is a priority and a requirement to achieve high yields in all plant species (Milošević *et al.*, 2015). It is estimated that approximately 80 % of economically important crops are established with the direct or indirect use of seeds (Filho, 2015). Seed quality is the sum of genetic, physical, physiological, and sanitary attributes that affect the ability to perform vital functions related to germination, vigor, and longevity (Carranza-González *et al.*, 2022).

In any cropping system, seed germination and vigor are important attributes to ensure uniform emergence and establishment of a crop (Finch-Savage and Bassel, 2016); however, these factors are greatly influenced by the physical characteristics of the seed (Sulewska *et al.*, 2014). Seed size and the volumetric weight of a thousand seeds are considered indicators of physical quality, which is related to agronomic management and weather conditions during the development of the crop (Fernández-Sosa *et al.*, 2015). Quality is highly influenced by environmental factors such as parent plant nutrition (Filho, 2015), temperature (Hatfield and Prueger, 2015), moisture, soil fertility, and the presence of pathogens (Akinuoye-Adelabu and Modi, 2018), which have an effect on flowering, ripening, and harvest.

The evaluation of parents is critical for successful seed multiplication. It is important to understand the environmental impact on seed quality; therefore, the germination test is an essential component of seed production. Although it does not have a strong correlation with seedling emergence in the field (Navarro *et al.*, 2015), it is the fastest and most commonly used labeling assessment and is required for seed sales.

Due to the importance of quality in the production of registered and certified seed from simple progenitor lines, crosses, and maize hybrids, the objective of the study was to determine the effect of the genotype-environment interaction on the physical and physiological quality characteristics of inbred lines and simple crosses, which are the progenitors of trilinear maize hybrids adapted to High Valleys of Mexico that were previously evaluated exclusively in that area (Virgen-Vargas *et al.*, 2014; 2016). The present work also involves the Transition and El Bajío regions to evaluate the response in these alternative zones for seed multiplication.

MATERIALS AND METHODS

Germplasm, evaluation environments, and agronomic management

Fifteen genotypes, nine inbred lines, three single crosses, and three trilinear hybrids used as controls (Table 1) were evaluated in three contrasting environments by altitude:

Table 1. Genealogy of maize (*Zea mays* L.) genotypes evaluated in five environments in the State of Mexico, and Guanajuato, Mexico.

Hybrid	Simple crossbreeding ♀ ¹	Genealogy	Line ♂ ²	Genealogy
H-70 ^a	M-55 ^a xM-54 ^a	(Tlax 151 SFC1-11-2-2-2) (Mich. 21 Comp.I-7-2-14-1-3)	CML-242 ^b	Bat 8785 MH 10-1-1-2TL- 1-3TL-3-1TL-b
H-66 ^a	M-43 ^a xM-44 ^a	(Mich 21-181-14-1-16-5) (Mich21 Comp I-7-2-11-9)	M-52 ^b	CML 169 BPVC-159-B-1- 1-1-2-BTL
H-44 ^a	M-47 ^a xM-46 ^a	(Tlax.77-2-1-2) (Mich 21-Comp I-7-2-14-5)	M-48 ^a	Pob87xSIB/-1-4-3

^aInbred lines obtained by the Instituto Nacional Forestry, Agricultural, and Livestock Research Institute (INIFAP); ^binbred lines obtained by the International Maize and Wheat Improvement Center (CIMMYT). ¹♀: Female; ²♂: Male.

1) High Valleys: Coatlinchán (COA), State of Mexico, located at 19° 29' 05" N, 98° 53' 11" W, and 2250 m altitude; 2) Transition Zone: San Luis de la Paz (SLP), Guanajuato, located at 20° 34' 40" N, 100° 49' 37" W, and 2004 m altitude; and 3) El Bajío: Celaya (CEL), Guanajuato, located at 21° 13' 11" N, 100° 29' 41" W, and 1765 m elevation. The first two were evaluated during 2014 and 2015, and the last one in 2014.

A randomized complete block experimental design with three replications was used. The experimental unit consisted of four 5-m long furrows. A total of five environments were studied, which were established under irrigated conditions. Fertilization was carried out using the 160-80-40 NPK formula, respectively. The stocking density was 65 000 plants ha⁻¹, and the rest of the agronomic management was carried out according to the recommendations of the National Forestry, Agricultural, and Livestock Research Institute (INIFAP) for each region.

Weather conditions of the test environments

The COA 2014 environment presented the highest precipitation (834 mm), as opposed to CEL 2014, which had the lowest value (461 mm). Precipitation for the 2015 agricultural cycle was lower than that of 2014 for the COA (9.8 %) and SLP (12.4 %) localities. Temperatures were similar in the COA and SLP environments, with maximum values of 23.8–25 °C and minimum values of 9.5–10.6 °C. CEL 2014 recorded the highest value for maximum (28.8 °C) and minimum (12.8 °C) temperatures. The High Valleys and Transition Zone environments presented similar climatic characteristics, unlike El Bajío, which was the most contrasting with higher temperature and precipitation at a lower altitude (Table 2).

For the inbred lines, the controlled pollination method was used with fraternal crosses to increase seed yield. The evaluation of the physical and physiological quality was

Table 2. Temperature and rainfall values recorded during the crop growth cycle at the five evaluation environments in the State of Mexico and Guanajuato, Mexico.

Localities	Temperature (°C)			Rainfall (mm)
	Maximum	Minumum	Mean	
COA-14	24	10	17	834
SLP-14	24	10	17	476
CEL-14	29	13	21	461
COA-15	25	10	13	752
SLP-15	25	11	18	417

COA: Coatlinchán; CEL: Celaya; SLP: San Luis de la Paz.

carried out at the seed analysis laboratory of the Genetic Resources and Productivity program of the Postgraduate College Montecillo Campus and the facilities of the Valley of Mexico Experimental Field (CEVAMEX) of the National Institute of Forestry, Agriculture and Livestock Research (INIFAP), both located in Texcoco, State of Mexico, Mexico.

Physical seed quality

The thousand-seeds weight (TWS) was evaluated according to the recommendations of the International Seed Testing Association (ISTA, 2016), expressed in grams. The hectoliter weight (HW) was determined and expressed in kg hL⁻¹. The commercial seed percentage (PCS) was obtained by grading 1 kg of seed per experimental plot and refers to the amount of seed that remained on top of the sieve with a round perforation of 7 mm diameter.

Physiological quality

Seed from hand pollination was used to increase lines and form single crosses and hybrids. Standard germination (SG) was determined as a percentage according to ISTA (2016) recommendations, except that four replicates of 25 seeds per experimental plot were used.

To determine germination after-cold test (GACT), the coils were placed in a refrigerator for 7 d at 10 °C. After this time, they were placed in a germination chamber with light at a temperature of 25 °C and relative humidity of 95±1 %. Seven days later, germination evaluation (GE) was performed using the same methodology for the standard germination test. For statistical analysis, data in percent were transformed with the arcsine function.

Statistical analysis

A combined analysis of variance was performed when environments were considered as random effects and genotypes as fixed effects. Means were compared using Tukey's test ($p \leq 0.05$), and Pearson's correlation analysis was performed (SAS Institute Inc., 2011). The GEA-R program (Pacheco *et al.*, 2015) with the site regression model (SREG) was used for genotype-environment interaction analysis (GEI), which integrates analysis of variance and principal component analysis.

RESULTS AND DISCUSSION

Combined analysis of variance and comparison of means

The results of the combined analysis of variance (Table 3) for the thousand-seeds weight (TSW), hectoliter weight (HW), commercial seed (CS), standard germination (SG), and germination after-cold test (GACT) showed statistical differences ($p \leq 0.01$) among environments (E), genotypes (G), and for the genotype \times environment interaction (GEI) for all variables. Based on the magnitude of the mean squares for the physical quality variables, the most important source of variation was G, followed by E and GEI. Of the total variance for the expression of the TWS variable, G presented a greater importance by contributing 60.7 %, followed by the effect of E with 32.1 % and GEI with 7.3 %. For HW expression, G determined 57.1 % of the variance, followed by 39.2 % of A, while GEI contributed only 3.7 %. For CS expression, G influenced 67.6 %, E 29.1 %, and GEI 3.4 %.

Table 3. Mean squares of the combined variance and principal components analysis of the site regression model (SREG) for physical and physiological quality variables of maize (*Zea mays* L.) parents and hybrids evaluated in five environments in the State of Mexico and Guanajuato, Mexico.

S.V.	DF	Physical quality			Physiological quality		
		TSW	HW	CS	DF	SG	GACT
Environment (E)	4	10 098.2*	136.1*	1 095.8*	4	1 012.6*	2 313.5*
Genotype (G)	14	19 116.4*	198.3*	2 548.7*	14	598.1*	635.3*
G×A	56	2 284.6*	12.7*	126.6*	56	163.5*	127.5*
CP1	17	17 174.8*	165.5*	5 073.4*	17	507.0*	1 315.8*
CP2	15	4 118.2*	25.1*	409.8*	15	382.3*	460.3*
Error	33	3643	24.7	524.7	33	264.5	483.4*
CV (%)		9.2	2.5	12.3		9.5	10.4

*Significance at 1 % probability; S.V.: source of variation; DF: degrees of freedom; TSW: thousand-seeds weight; HW: hectoliter weight; CS: commercial seed; SG: standard germination; GACT: germination after-cold test.

As for physiological quality (germination before and after-cold test), unlike physical quality, the most important source of variation was A, followed by G and GEI. For GE, A presented greater importance with 57.1 % of the variance, followed by A with 33.7 %, while GEI contributed 9.2 %. For GACT, A contributed 75.2 %, followed by G with 20.6 % and GEI with 4.2 %. According to the coefficients of variation, the results are considered acceptable.

Evaluation of environments

In the test of means (Table 4), statistical differences ($p \leq 0.05$) were observed for the physical and physiological quality variables. For physical quality, the highest value was obtained for TWS in E of SLP 2014, where a lower value of maximum temperature was presented in an interval between 10.3 and 23.8 °C during the crop cycle, in contrast to CEL 2014, which had the lowest TWS and A, with the highest temperature in an interval between 12.8 and 28.8 °C. In general, it was observed that the environments that presented better conditions for TWS expression were those with lower temperatures (High Valleys and Transition Zone). For the expression of HW, among environments, COA 2015 recorded the highest HW (74.7 kg hL⁻¹), while Celaya 2014 presented the lowest value (70 kg hL⁻¹), confirming the relationship that exists between the prevailing environmental conditions during crop development and the expression of seed HW (Fernández-Sosa *et al.*, 2015).

In general, the High Valleys and Transition Zone environments presented the highest values (71.2–74.7 kg hL⁻¹), unlike El Bajío. For the commercial seed variable, the highest values were presented in the 2014 cycle (76 %), and the best environments were COA 2014 and SLP 2014 (76 and 73.3 %, respectively). Seed size is determined by the production environment, cropping practices, and variety genetics; in general, larger

Table 4. Test of means between evaluation environments for physical and physiological quality variables of maize (*Zea mays* L.) parents and hybrids evaluated in five environments in the State of Mexico and Guanajuato, Mexico.

Environment	Physical quality			Physiological quality (% germination)	
	Weight of a thousand seeds (g)	Hectolitic weight (kg hL ⁻¹)	Commercial seed (%)	SG	GACT
SLP 2014	295.3a	71.4b	73.3a	87a	76c
COA 2015	272.5b	74.7a	62.0b	90a	80b
COA 2014	270.4b	71.2b	76.0a	90a	76c
SLP 2015	267.8c	72.2b	61.0b	91a	82a
CEL 2014	253.7d	70.0c	65.1b	81b	57d

SG: standard germination; GACT: germination after-cold test; COA: Coatlinchán; CEL: Celaya; SLP: San Luis de la Paz. Means with the same letter in each column are statistically equal ($p \leq 0.05$).

seeds perform better in the field (Ambika *et al.*, 2014). Seed development is dependent on nutrient accumulation, which is directly correlated with vigor, i.e., seed size and mass (Milošević *et al.*, 2015). In this way, the nutrients stored in the seed provide the necessary elements for seedling establishment.

The expression of physiological quality presented statistical differences ($p \leq 0.05$) for standard germination, where the SLP 2015 environment (91 %) showed the highest values; however, it was statistically equal to the SLP 2014 and COA 2014 and 2015 environments, unlike the Celaya locality, which had the lowest germination percentages. The standard germination test is the most commonly used for labeling seeds for sale, so it is recommended to perform it under ideal conditions. However, it is a poor predictor of field emergence because it takes place under favorable environmental conditions (Navarro *et al.*, 2015). However, it can be used as a reference point for seed marketing to compare the physiological quality of the lots and to determine sowing density. This allows to obtain comparable results and to define seed buying and selling relationships (ISTA, 2004).

The germination after-cold test (GACT) correlated negatively with the minimum average temperature ($r = -0.89$) and the altitude of the localities (m), with $r = 0.81$. The environments of the Transition Zone with maximum, minimum, and mean average temperatures of 24.5, 10, and 15 °C coincided with the expression of this character, followed by that of High Valleys. The lowest expression was obtained in the locality of El Bajío. For GACT, the 2015 cycle presented the best values, while A of SLP 2015 had the highest average (82 %) and A of CEL 2014 (57 %) had low germination percentages. The response of GACT expression was correlated with the parameters of maximum temperature ($r = -0.87$) and the altitude of the locations ($r = 0.73$), which coincided with the correlation parameters of the SG percentage, but with a different degree of correlation. Other reports mention that germination, vigor, and viability are highly influenced by environmental factors in the field (Jyoti and Malik, 2013; Hatfield and Prueger, 2015). These attributes should be evaluated under stress conditions (e.g., after-cold test) to ensure uniform emergence and crop establishment (Navarro *et al.*, 2015). In general, the best conditions for the expression of these characters were found in the High Valleys and Transition Zone environments and were negatively correlated with temperature.

Genotype evaluation

Among the female inbred lines, the one with the highest TWS was M-55, which is the female parent of the single female cross (SFC) of H-70, with 247.2 g (Table 5). Higher values (270.83 g) have been reported in progenitor lines of maize hybrids in the High Valleys of Mexico (Zepeda-Bautista *et al.*, 2021), which contrasts with the present study as different environments were assessed. The female with the lowest TWS was M-47, sire of H-44. Of the six male lines, the highest TWS (286.5) was M-48, parent of H-44, followed by M-46 and M-54; the male lines with the lowest TWS were M-52 and M-44. Likewise, the SFC M-43xM-44 outperformed its H-70 and H-44 equivalents in TWS.

Table 5. Comparison of physical and physiological quality variables of maize (*Zea mays* L.) parents and hybrids evaluated in five environments in the State of Mexico and Guanajuato, Mexico.

Genotype	Physical quality			Physiological quality (% germination)	
	Weight of a thousand seeds (g)	Hectolitic weight (kg hL ⁻¹)	Commercial seed (%)	SG	GACT
M-43	243.1 g	69.3 j	48.6 d	85 e	68 g
M-47	222.3 h	74.1 d	20.3 e	89 c	71 f
M-55	247.2 f	70.3 i	55.8 d	88 c	68 g
M-48	286.5 d	75.9 b	73.8 b	90 c	83a
M-46	266.6 e	68.5 k	79.3 b	83 f	71 f
M-54	250.5 f	64.0 m	71.7 c	78 g	57 i
M-52	214.1 i	71.0 h	29.4 e	87 c	76 d
M-44	243.6 g	66.5 l	82.4 b	86 d	69 g
CML-242	250.3 f	72.9 e	73.9 b	76 h	65 h
M-47xM-46	295.4 c	73.0 e	74.8 b	89 c	73 e
M-43xM-44	311.9 b	72.6 f	76.4 b	92 c	81 b
M-55xM-54	305.2 b	72.6 g	83.4 b	93 b	79 c
H-44	313.9 b	76.5a	75.0 b	95a	84a
H-66	309.4 b	75.0 c	81.1 b	92 c	82a
H-70	319.0a	76.0 b	86.5a	94a	85a

GE: standard germination; GACT: germination after cold test. Means with the same letter in each column are statistically equal ($p \leq 0.05$).

In hybrid seed production, the number of seeds per kilogram is important to determine the seeding density of the female and male parents (Virgen-Vargas *et al.*, 2014), and it also serves as an indicator of seed size. The female line M-47 expressed higher HW (74.1 kg hL⁻¹), followed by M-55 and M-43, while the male line M-48 presented higher HW (75.9 kg hL⁻¹) and outperformed its similar lines. Virgen-Vargas *et al.* (2016), using progenitor lines of maize hybrids from High Valleys in locations in the State of Mexico and Tlaxcala, reported a lower HW (71.75 kg hL⁻¹) than those obtained in this evaluation. When evaluating the physicochemical quality of maize for the dough and tortilla industry in hybrids from the central High Valleys of Mexico, Vázquez-Carrillo *et al.* (2020) reported a higher HW (77.2 and 78.4 kg hL⁻¹) than that obtained in this study for H-66 and H-70 (75 and 76 kg hL⁻¹).

For the commercial seed variable, the female lines M-55 and SFC M-55xM-54, progenitors of the hybrid H-70, had the highest value, followed by H-66 and H-44. The male line M-44, progenitor of the SFC of H-66, had the highest commercial seed value (82.4 %), presenting a high correlation ($r = 0.75$) with the TWS.

Regarding the percentage of SG, the female line with the highest germination was M-47 (89 %), while M-48 was the highest from the male inbred lines (90 %), both progenitors of H-44; the male lines CML-242 (76 %) and M-54 (78 %) presented the lowest germination values, a response associated with the first signs of disorganization and loss of integrity of the cell membrane system caused by lipid peroxidation, which reduces the physiological potential of the seed (Filho, 2015) as a consequence of inbreeding depression due to the increased frequency of homozygotes (de Farias and de Miranda, 2000), unlike hybrids. In terms of the germination percentage, the SFC of H-70 performed better than that of its H-44 and H-66 counterparts.

In seed production, the standard laboratory germination criteria for line certification are based on field inspections and tolerances. The producer is responsible for the quality of the line; however, a minimum of 90 % germination is recommended for the production of single crosses and hybrids in the basic and registered category. According to the evaluation results, all genotypes meet this criterion, with the exception of M-47xM-46 (SNICS, 2020). In GACT, the female line M-47 (71 %) and the male line M-48 (83 %), progenitors of H-44, showed the highest values, coinciding with GE. Therefore, these lines are considered as genotypes with good physiological potential to perform their vital functions under favorable and unfavorable environmental conditions (Filho, 2015). The SFC of H-66 outperformed its equivalents, while the female line M-43 (68 %) and the male line M-54 (57 %) showed low germination values in the after-cold test.

Genotype-environment interaction

By decomposing the sum of squares of the GEI into principal components (CP), the SREG analysis showed five components. The first three were significant ($p \leq 0.01$) for the parameters of physical and physiological quality. However, most of the variation is explained by the first two (Figures 1 and 2), accumulating values greater than 89 % for the evaluated variables, so they are considered valid parameters for the study of the GEI of maize hybrids (Cossa, 1990; Vázquez-Carrillo *et al.*, 2012). In the Cartesian planes, the behavior of E, G, and the GEI is observed, while the environments are located in quadrants I and IV (Figures 1 and 2).

Weight of a thousand seeds

Two major components explain 89.43 % of the total variation (Figure 1A) due to the interaction expressed in TWS. The environments were concentrated in two sectors (mega-environments): sector one, located in quadrants I and IV, which concentrate four environments, and sector two, where the CEL 2014 environment is observed, being positioned in a different sector as it has contrasting altitude, temperature, and precipitation, unlike the rest of the environments.

In terms of genotypes, two classification groups can be seen, considering the trilinear hybrids (H-70, H-44, and H-66), simple crosses (M-47xM-46, M-43xM-44, and M-55xM-54), and the M-48 line as the first group, located in the first sector, and the remaining progenitor lines located in sectors 2, 3, 4, 5, and 6. The expression response

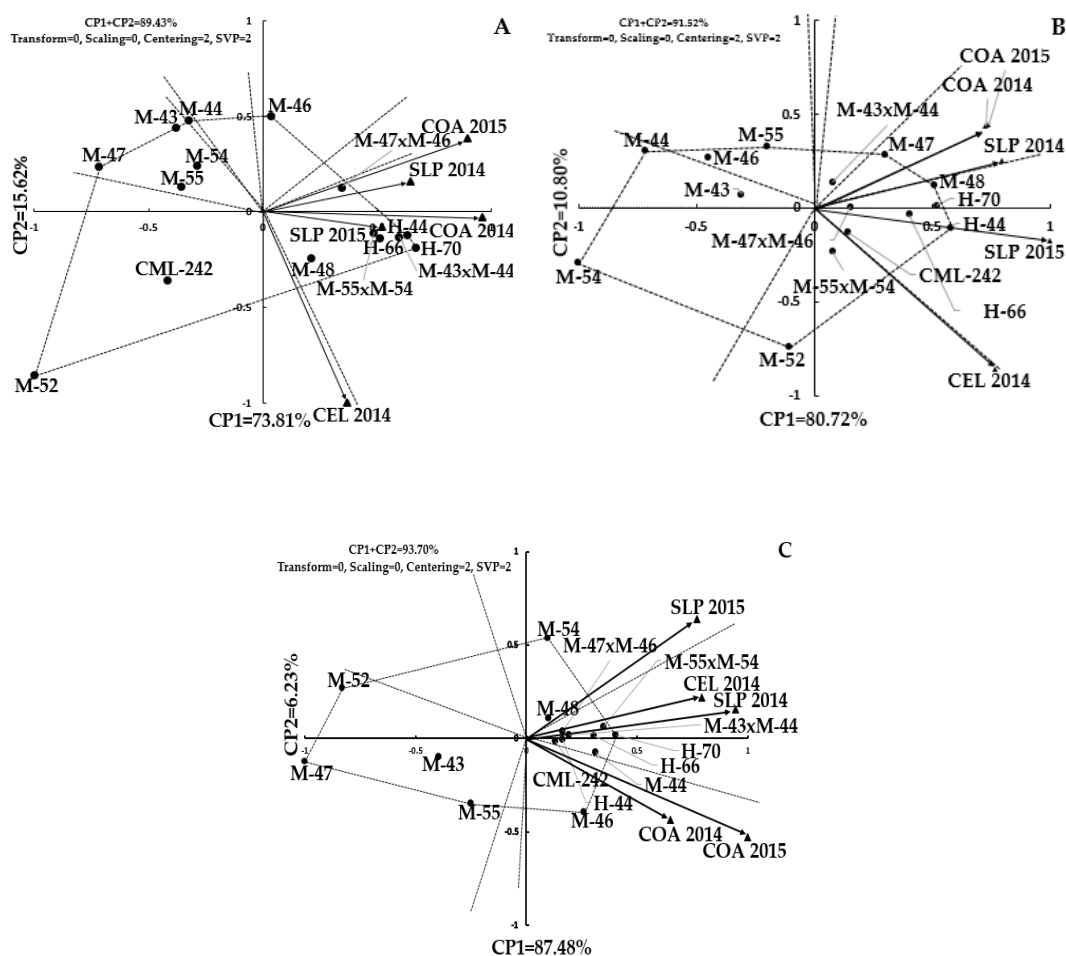


Figure 1. Genotype and environment dispersion based on the first two principal components of the site regression model (SREG) for physical quality in seed production of maize (*Zea mays* L.) parents and hybrids evaluated in five environments in the State of Mexico and Guanajuato, Mexico. A: thousand-seeds weight; B: hectoliter weight; C: commercial seed.

of line M-48 was associated with its vigor as a result of deriving lines from the cross between genotypes with different geographical origins (High Valleys × temperate and subtropical weather). The response of the second group (inbred lines) is related to the negative effect of inbreeding on the reduction of the mean of quantitative traits, as a consequence of recessive deleterious alleles known as inbreeding depression (de Farias and de Miranda, 2000).

The genotype located at the vertex with the highest TWS was H-70 in the mega environment formed by the localities of Coatlinchán and San Luis de la Paz. This hybrid presented adaptability to High Valleys and Transition Zone for the expression of this character, followed in magnitude by genotypes H-66, H-44, M-43xM-44, and

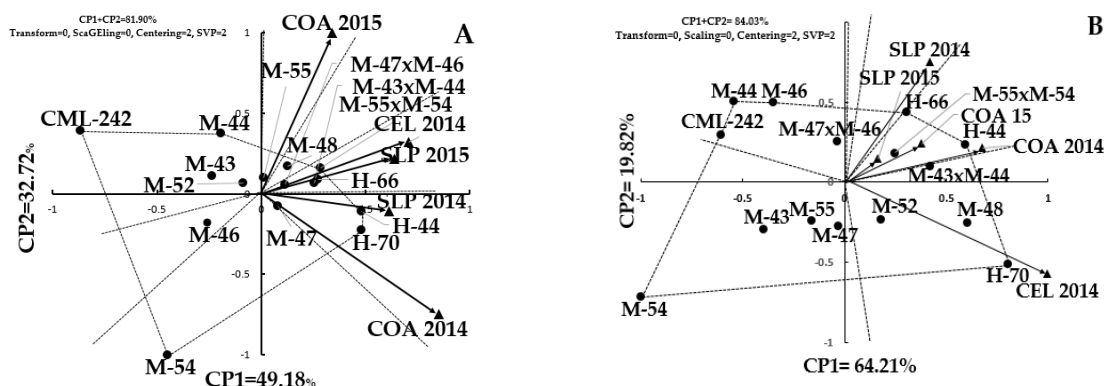


Figure 2. Cartesian plane of the genotype and environment contribution to the interaction using the first two principal components of the site regression model (SREG) on seed yield of maize (*Zea mays* L.) parents and hybrids evaluated in five environments in the State of Mexico and Guanajuato, Mexico. A: standard germination percentage; B: after-cold test.

M-55xM-54 that adapted to SLP 2015, given that the temperature and altitude conditions were similar to the environment from which they were generated (High Valleys). Line M-52 outperformed CML-242 in TWS at the CEL 2014 location, while lines M-46, M-44, M-43, M-54, M-55, and M-47 did not perform well in any environment.

Hectoliter weight

The environments were concentrated in three sectors (mega-environments) (Figure 1B). The COA 2015 and COA 2014 environments presented similar conditions for HW expression, unlike CEL 2014, which presented the best behavior. Genotype M-47 showed adaptation and better HW response to the COA 2014 and COA 2015 environments. In the second sector, the apex genotype with the highest HW (76.5 kg hL⁻¹) was H-44, which presented greater adaptability to San Luis de la Paz 2015 and 2014, followed by H-70 and H-66, while M-48 had better adaptability to SLP 2014, followed by H-70 at that location. The genotypes with the lowest HW values were lines M-54, M-44, M-46, M-43, and M-55, which did not perform well in the environments evaluated.

Commercial seed

For this parameter, the environments were concentrated in three sectors (mega-environments) (Figure 1C). The best environment was COA 2015, unlike COA 2014, which had the lowest percentage of commercial seed. In terms of genotype response, in general, no differentiation between hybrids and lines was observed, as lines M-48, M-54, M-44, and CML-242 grouped with trilinear hybrids and single crosses. The genotype with the highest expression in commercial seed production was H-70 in the CEL and SLP environments, both in 2014. Genotypes M-54 and M-48 were best

adapted to SLP 2015; CML-242, H-44, M-44, H-66, M-47xM-46, and M-55xM-54 were best adapted to CEL 2014 and SLP 2014, while genotype H-70 presented the highest value in all environments. The M-46 genotype showed specific behavior in the COA environment. Lines M-55, M-43, M-47, and M-52 did not perform well.

Standard germination

In this case, the environments were concentrated in three sectors (mega-environments), where the best was COA 2014, in contrast to SLP 2015 (Figure 2A). The genotypes that presented the highest germination were H-70 in COA 2014 and H-44 in SLP 2014, while M-54, CML-242, and M-44 did not excel in any environment; M-55xM-54 presented its best response in COA 2015. The M-55 line showed a specific adaptation to COA 2015. The single female crosses M-55xM-54, M-43xM-44, and M-47xM-46 showed higher adaptability to CEL 2014 and SLP 2015, and line M-47 and hybrids H-44 and H-70 in COA 2014 and SLP 2014 environments. The apex genotypes H-44 and H-70 showed higher germination than M-47 in COA-15 and CEL-14, which could be an effect of inbreeding in the parents and vigor among hybrids (Guo *et al.*, 2013; Omar *et al.*, 2022).

Germination after-cold test

For this variable, the environments were concentrated in three mega-environments (Figure 2B), showing that the best environment was CEL 2014, unlike SLP 2015, which presented greater variation in the variable. No definite differentiation was observed in the response between hybrids and lines; the hybrids evaluated, the single crosses, M55xM54 and M43xM44, as well as the lines M48 and M52, were the ones that presented higher germination after low-temperature stress, so their genotype-environment interaction improved their response in the cold test. Genotypes H-66, M-55xM-54, and H-44 showed adaptability to COA 2015, COA 2014, and SLP 2015 environments. Hybrid H-70 presented the highest germination percentage after-cold test in CEL 2014, and genotype M-48 showed specific behavior in CEL 2014, while the most unstable genotype was line M-54.

CONCLUSIONS

Environmental conditions influenced physical and physiological quality characteristics of maize parents, especially hectoliter weight and marketable seed percentage. The parents M-47xM-46 and M-55xM-54 showed the best performance for physical quality and the latter for physiological quality, so that seed production from these parents can be carried out at San Luis de la Paz, Guanajuato. The production of hybrids H-66 and H-44 is suggested to be carried out in locations with altitudes of 2000 m, since they showed specific adaptation to the SLP 2015 environment in terms of physical quality.

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