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Morphology and yield components of single hybrids white and yellow maize in the Yaqui Valley

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ABSTRACT: Maize breeding has evolved increasingly with the emergence of new scientific technologies, mainly hybridization. This technique allows new genetic combinations to be obtained in specific areas where some genotypes have desirable characteristics. By crossing them, hybrids with better morphological, physiological and agronomic performance are obtained. Based on the above, the objective of this research was to evaluate the morphological and reproductive variables, final plant height (FPH), ear height (EH), number of leaves above (NLAE) and below (NLBE) the ear, grain depth (GD), number of rows per ear (NRE), number of grains per row (NGE), volumetric weight (VW), and grain yield (Y), in four simple maize hybrids, two white-grain hybrids (WG1 and WG2), and two yellow-grain hybrids (YG1 and YG2). The crop was established in the period December-May 2023. These hybrids come from a dialelic of homozygous lines, carried out at the Tecnológico Nacional de México, campus Valle del Yaqui. Significant differences were found in all the variables evaluated. The GBI hybrid showed the highest FPH (264 cm), EF (159 cm) and NLAE (9.8). Similarly, this hybrid had the highest GD (2.1 mm) and NRE (16). The YG1 hybrid showed a higher number of grains per row (32) and volumetric weight (389 g), without differences from WG1. These two hybrids (WG1 and YG1) had the highest grain yield (11.8 t ha^{-1}). There was a positive and significant correlation between several variables, with the highest correlation between FPH and NLAE and between the variables NGE and Y.

Key words: correlations; dialelic; regionalization; reproductive

Morfología y componentes del rendimiento de híbridos simples de maíz blanco y amarillo en el Valle del Yaqui

RESUMEN: El mejoramiento del maíz ha evolucionado cada vez más con el surgimiento de nuevas tecnologías científicas, principalmente la hibridación. Esta técnica permite obtener nuevas combinaciones genéticas en zonas específicas donde algunos genotipos tienen características deseables. Al cruzarlos se obtienen híbridos con mejor comportamiento morfológico, fisiológico y agronómico. Con base en lo anterior, el objetivo de esta investigación fue evaluar las variables morfológicas y reproductivas, altura final de planta (FPH), altura de mazorca (EH), número de hojas arriba (NLAE) y debajo (NLBE) de la mazorca, profundidad de grano (GD), número de hileras por mazorca (NRE), número de granos por hilera (NGE), peso volumétrico (VW) y rendimiento de grano (Y), en cuatro híbridos simples de maíz, dos híbridos de grano blanco (WG1 y WG2) y dos híbridos de grano amarillo (YG1 y YG2). El cultivo se estableció en el período diciembre- mayo de 2023. Estos híbridos provienen de una dialélica de líneas homocigotas, realizada en el Tecnológico Nacional de México, campus Valle del Yaqui. Se encontraron diferencias significativas en todas las variables evaluadas. El híbrido GBI mostró las mayores FPH (264 cm), EF (159 cm) y NLAE (9.8). De manera similar, este híbrido tuvo el mayor GD (2.1 mm) y NRE (15). El híbrido YG1 presentó mayor número de granos por hilera (32) y peso volumétrico (389 g), sin diferencias con respecto a WG1. Estos dos híbridos (WG1 y YG1) tuvieron el mayor rendimiento de grano (11,8 t ha^{-1}). Hubo correlación positiva y significativa entre varias variables, siendo mayor la correlación entre FPH y NLAE y entre las variables NGE e Y.

Palabras clave: correlaciones; dialélica; regionalización; reproductiva

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Introduction

One of Mexico main strengths in agricultural production is the maize crop (Reyes-Santiago et al., 2022). This crop stands out for its great diversity of breeds, commercial varieties and hybrids, which among all converge in a national grain yield of 3.9 t ha^{-1}, according to the 2022 annual report of SIAP (2022). White and yellow grain maize are the most widely grown in Mexico, with an overall volume of 26.2 million tons (Espinosa-Calderón et al., 2021).

In recent years, there has been a strong focus on the maintenance of native breeds as part of germplasm conservation systems. Important efforts are also being made to continuously improve morphological and yield traits through hybridization in specific ecosystems (Woodmansee, 2022).

Several studies have demonstrated the contribution of some morphological characters to maize yield. For example, the leaf number, whose fundamental activity is photosynthesis, contributes to the synthesis of carbohydrates, which generally make up 70% of the grain (Illés et al., 2020). Other variables, such as ear height, are correlated with grain yield in maize (Guamán-Guamán et al., 2020). All these characteristics are desirable to obtain genetic materials with good agronomic performance (Torres-Morales et al., 2022).

In the state of Sonora, Mexico, the amount of land dedicated to maize production, mainly white and yellow grain, has increased to more than 5,100 ha (Portillo-Vázquez et al., 2023). This increase in productive areas will contribute to regional and national food security by considering that maize is the basic food for more than 90% of the Mexican population (Quintero-Herrera et al., 2023).

In Sonora, Mexico, there is agroclimatic potential for successful maize crop. Taking advantage of them, with the use of high-yielding genotypes, will contribute to import substitution and food sovereignty (Ortiz et al., 2023). The use of these potentialities becomes more effective when materials are generated from parents adapted to regional climatic conditions. For this reason, research was conducted to evaluate the morphological and agronomic performance of four white-grain and yellow-grain maize hybrids for their future recommendation as promising hybrids for the edaphoclimatic conditions of the Yaqui Valley, Sonora, Mexico.

Materials and Methods

Location of the experimental area

The study was developed in crop areas belonging to the Tecnológico Nacional de Mexico/Instituto Tecnológico Valle del Yaqui, located in Block 611 Bácum, Sonora, Mexico (27°25’20”N -110°08’02”W at 18 m of altitude).

The soil where the crop was established belongs to the clay loam grouping (Almazán et al., 2023) according to the genetic classification of agricultural soils in Mexico. The crop was established in the period December-May 2023 (sowing date: December 25, 2022).

These hybrids showed initial adaptability and super dominance with respect to their parents, in the locality where they were obtained. It was necessary to evaluate them in another environment (Yaqui Valley) that has different environmental and edaphic conditions, even under different crop dates, as initial step, to carry out an screening and obtain the most promising ones for future research. In the present study, only the comparison of the initial intra-hybrid response in the Yaqui Valley is shown.

Climatic variables in the growing season

The climatic variables during the experimental period were obtained from the REMAS platform (Red de Estaciones Meteorológicas y Agroclimáticas de Sonora) and were recorded by the agrometeorological station in the municipality of San Ignacio Río Muerto, Sonora, Mexico, classified as semi-arid region (Gonzáles et al., 2021) This data recording tower is located 4.6 km from the experimental site (Figure 1).

The temperature remained over 14.8 and 22.8 °C in the months of December 2022 to May 2023. January was the month with the lowest temperature, with an average of 14.8 °C, resulting in a cold month for the maize crop. Relative humidity was more stable, with values between 60-73%. Rainfall was very low. The most significant rainfall during the growing season of the crop was in December 2022 and March 2023, with 8 and 6 mm, respectively.

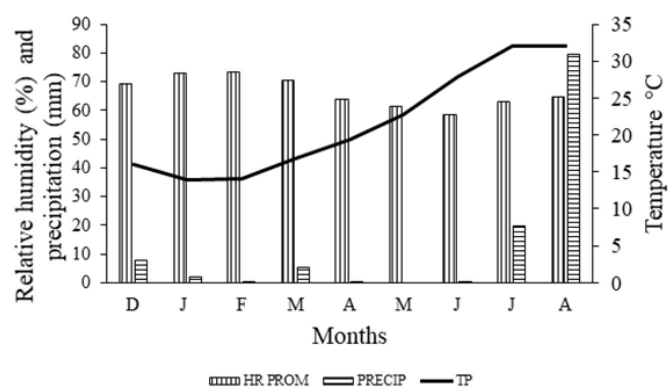

Figure 1. Climatic variables, temperature (TP), relative humidity (HR. PROM) and precipitation (PRECIP) from December 2022 to May 2023. (CESAVE, 2023).

Plant material, treatments and experimental design

Four simple hybrids generated from a dialelic design were evaluated using Griffing I. method (Saavedra-Guevara et al., 2021), which consisted of direct crosses, reciprocal crosses with the p^2 families (complete dialelic) and included p, DC and RC ($p + Cp^2 + Cp^2$), in six lines of white grain maize, and five of yellow grain. In this equation, p: represents the parents; DC: direct crosses; RC: reciprocal crosses; Cp^2: square of the cross of the parents. There were 15 direct crosses, 15 reciprocal crosses and self-pollinations of each line in white grain, and 10 direct crosses, 10 reciprocal

Table 1. Crossing scheme of homozygous white and yellow grain lines.

	Homozygous white lines					
	L1.CML 442	**L2. CML 545**	**L3. CML 549**	**L4. CML 550**	**L5. CML 576**	**L6.CML 546**
L1. CML 442	L1 X L1	L1 X L2	L1 X L3	L1 X L4	L1 X L5	L1 X L6
L2. CML 545	L2 X L1	L2 X L2	L2 X L3	L2 X L4	L2 X L5	L2 X L6
L3. CML 549	L3 X L1	L3 X L2	L3 X L3	L3 X L4	L3 X L5	L3 X L6
L4. CML 550	L4 X L1	L4 X L2	L4 X L3	L4 X L4	L4 X L5	L4 X L6
L5. CML 576	L5 X L1	L5 X L2	L5 X L3	L5 X L4	L5 X L5	L5 X L6
L6. CML 546	L6 X L1	L6 X L2	L6 X L3	L6 X L4	L6 X L5	L6 X L6
	Homozygous yellow lines					
	L1. CML 479	**L2. CML 501**	**L3. CML 551**	**L4. CML 101**	**L5. CML103**	
L1. CML 479	L1 X L1	L1 X L2	L1 X L3	L1 X L4	L1 X L5	
L2. CML 501	L2 X L1	L2 X L2	L2 X L3	L2 X L4	L2 X L5	
L3. CML 551	L3 X L1	L3 X L2	L3 X L3	L3 X L4	L3 X L5	
L4. CML 101	L4 X L1	L4 X L2	L4 X L3	L4 X L4	L4 X L5	
L5. CML103	L5 X L1	L5 X L2	L5 X L3	L5 X L4	L5 X L5	

crosses and self-pollinations in yellow grain (Table 1). The parents were supplied by the International Maize and Wheat Improvement Center (CIMMYT), El Batám, Texcoco, Mexico.

From this design, a total of 28 hybrids (13 of yellow grain (YG) and 15 of white grain (WG)) were obtained. From these genetic material the following simple white grain maize hybrids were selected for the evaluation: L3. CML 549 X L5. CML 576 (WG1) and L2. CML 545 X L4. CML 550 (WG2), and simple yellow grain maize hybrids: L4. CML 101 X L5. CML 103 (YG1) and L3. CML 551 X L1. CML 479 (YG2), with conformed treatments.

These materials were established under experimental field conditions, following a randomized Complete Block experimental design, in a master plot of more than 45 years of cultivation. Experimental plots were formed with an area of 285.6 m^2 in furrows of 2 m in length at a sowing distance of 0.20 × 0.80 m.

Agronomic management

Prior to planting, background fertilization was performed with urea and a mixture of DAP [400 kg ha^{-1} (200-80-00)]. The remaining three fertilizations were made prior to auxiliary irrigation at a rate of 150 kg ha^{-1} of NPK each.

Pest management was carried out through visual observations of the crop. The presence of thrips (*Rankliniella occidentalis*) and fall armywarm (*Spodoptera frugiperda*) was found to be significant. These pests were controlled with the insecticides Rimon® Supra and Decís® (deltamethrin) at a dose of 1.0 L ha^{-1}, respectively.

Presowing irrigation was applied with an irrigation lamina of 30 cm and four auxiliary irrigations, with irrigation intervals of 39, 30, 24 and 15 days, considering the evapotranspiration values calculated for this crop.

Morphological and agronomical variables evaluated

Morphological variables were evaluated: final plant height (FPH, cm), ear height (EH, cm), number of leaves below (NLBE, unit) and above (NLAE, unit) the ear, in a total of 15 randomized plants taken in each simple hybrid evaluated.

In addition, the yield component variables grain depth (GD, cm), number of rows per ear (NRE, unit), number of grains per row (NGR, unit), volumetric weight (VW, g) and yield (Y) were expressed in t ha^{-1}. For each variable, four replicates were taken for each single hybrid evaluated.

For the evapotranspiration (ETc) calculus, the Equation 1 proposed by Allen et al. (2006) was used (Figure 2).

$$\mathrm{ETc} = \mathrm{ET0} \times \mathrm{Kc} \quad (1)$$

where: ET0 is the reference evapotranspiration and Kc is the crop coefficient.

Crop coefficients for maize were taken based on studies developed by Muñoz et al. (2023).

Crop evapotranspiration remained between 0.1 and 9 mm day^{-1} during crop phenology (Figure 2). The highest ETc values occurred in the male (FM) and female (FF) flowering phenophases and from R2 to R4, where the plants had the highest water demand due to the existing leaf area.

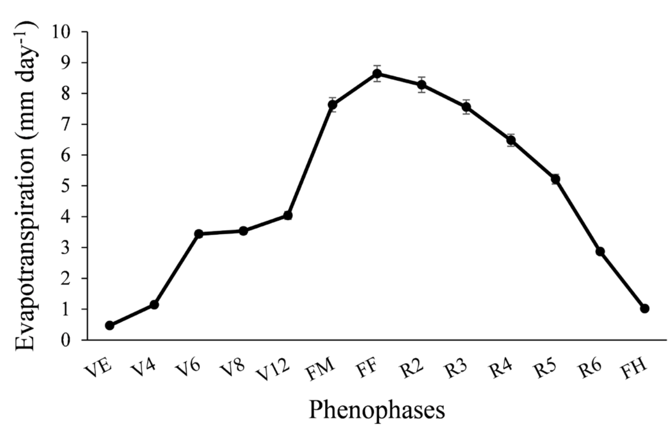

Figure 2. Crop evapotranspiration during the biological cycle (VE: emergence; V4, V8 and V12: formation of the first four, eight and 12 leaves, respectively; MF: male flowering; FF: female flowering; R2; R3; R4: R5; R6: grain formation (blister), milky grain, pasty grain, jagged grain, physiological maturity, respectively; FH: fruit harvest). Error bars represent the standard deviation of the means.

Statistical analysis

The compliance of the theoretical assumptions of normality and homogeneity of variances was tested in the obtained data. Subsequently, an analysis of variance of simple classification was performed to identify possible significant differences between the single hybrids evaluated. When significant differences were detected, Tukey multiple comparison test was used for a significance level of 1%. The statistical indicators coefficient of variation (CV), coefficient of determination, and unadjusted (R^2) were determined for each variable. Finally, a correlation network was constructed between the variables evaluated to verify the degree of association between them. All analyses were performed in the professional statistical package Statistica, version 14.0 for Windows.

Results and Discussion

Variability of morphological variables

All the evaluated variables showed highly significant differences ($p < 0.01$) (Table 2). Coefficients of variation between 9.98 and 12.81% were obtained for all the variables evaluated. These coefficients of variation obtained are considered appropriate for this research, being lower than 21%, maximum value recommended for agronomical sciences, according to Dey et al. (2021). The variable with the lowest variability was FPH, and hybrid WG1 had the highest value in this variable, with significant differences with respect to the other three single hybrids evaluated. This same hybrid presented the highest ear height (EH) with a similar statistical response to the variable explained above (FPH). In addition, WG1 was the hybrid with the highest number of leaves above the ear (NLAE) and the lowest number of leaves below the ear (NLBE).

Seminario-Cunya et al. (2021) found phenotypic stability in simple crosses and commercial hybrids of maize in a study developed with 10 hybrids compared to control varieties. In this study, single crosses were more stable than commercial hybrids; however, there was sensitivity in PH, which varied significantly among hybrids and with respect to controls.

Ear height is a trait closely related to the mobilization rate of elaborate substances. Pugh & Layrisse (2005) used advanced generations of single hybrids as parents of maize double hybrids and found highly significant differences in EH, indicating little genetic stability for this trait.

A study developed by Torres-Flores et al. (2011) demonstrated the importance of EH on grain yield in trilineal hybrids and propulations of maize in Valles Altos of central Mexico. In this work, there were highly significant differences in EH ranging from 106 to 124 cm. These results indicate that the hybrids compared here, in the present investigation, presented greater PH and greater EH (134 cm on average). Cieza-Ruiz et al. (2020) found a 51% correlation between PFH-EH variables when evaluating the agronomic characteristics, grain yield and its components of maize hybrids in high and dry regions of Peru.

One of the works carried out for testing materials with variations in planting density and fertilization doses are those presented by Martínez-Gutiérrez et al. (2022). These authors obtained values of 16 rows and 28 grains per row in the ear. The results obtained in the present investigation are close to these values. On the other hand, works carried out at the Universidad Autónoma Agraria Antonio Narro, Laguna Unit, in Torreón, Mexico, evaluating five maize hybrids, reported that the number of rows per ear (NRE) presented significant differences with lower values (14.66 rows). The general average NRE in the evaluated hybrids averaged 15.24, which is similar to the value reported by Martínez-Gutiérrez et al. (2022).

Variability of yield component variables

In Table 3, it is shown that all yield component variables showed significant differences among hybrids. The variability of these variables was between 7 and 18%. The variable with the highest variability was VW with 18.16%, and the variable with the lowest variability was GD with 7.22%.

The hybrid with the greatest grain depth (GD) was WG1, which had the highest number of rows in the ear, although the number of grains per row was lower than that of the YG1 hybrid, with 37 grains on average. In general, the WG2 hybrid presented the lowest values for the variables evaluated, except for volumetric weight (VW).

Grain yield showed highly significant differences among the single hybrids evaluated ($p = 0.04231$) (Figure 3). However, the linear fixed effects model used for the analysis of variance only contributed to explaining 82% of the total variability in yield ($R^2 = 0.82$), since two of the hybrids compared did not show significant differences (WG1 and YG1), obtaining the highest grain yield (11.8 t ha^{-1}). The single hybrid WG2 presented the lowest grain yield, reaching only

Table 2. Morphological variables evaluated in yellow grain (YG) and white grain (WG) maize hybrids [FPH: final plant height; EH: ear height; NLAE: number of leaves above ear and NLBE: number of leaves below ear.

Hybrids	FPH (cm)	EH (cm)	NLAE (unit)	NLBE (unit)
YG1	238 ± 3.43 b	131 ± 2.14 b	6 ± 0.91 b	11 ± 0.98 a
YG2	240.5 ± 2.06 b	130 ± 1.81 b	6.25 ± 1.1 b	9.25 ± 0.89 a
WG1	264.25 ± 2.11 a	159.25 ± 2.11 a	9.75 ± 1.3 a	5.5 ± 1.0 b
WG2	241 ± 3.43 b	136.75 ± 2.0 b	5.25 ± 1.1 b	10.0 ± 1.1 a
SE	1.53	3.8	0.18	0.28
CV	9.98	10.96	10.59	12.81

Means with equal letters do not differ statistically in the column by Tukey test for p ≥ 0.01). Tukey value: T(4;12)=3.76; Number of cases: n=16, number of treatment t=4; SE: standard error of the mean of treatments; CV: coefficient of variation.

Table 3. Yield variables evaluated in yellow grain (YG) and white grain (WG) maize hybrids [GD: grain depth (mm), NRE: number of rows per ear, NGR: number of grains per row, VW: volumetric weight (g)].

Hybrids	GD (mm)	NRE (unit)	NGR (unit)	VW (g)
YG1	2.12 ± 0.1 a	17.0 ± 1.0 a	32.25 ± 6.1 b	389.75 ± 12.0 b
YG2	1.88 ± 0.06 bc	13.0 ± 1.3 b	31.5 ± 5.4 b	407.75 ± 9.2 a
WG1	2.07 ± 0.2 ab	15.0 ± 0.9 ab	37.0 ± 5.4 a	365.75 ± 8.5 c
WG2	1.80 ± 0.2 c	13.65 ± 1.1 b	24.25 ± 3.7 c	389.75 ± 12.1 b
SE	0.04	0.05	1.03	1.96
CV (%)	7.22	13.87	16.75	18.16

Means with equal letters do not differ statistically by Tukey's test for p ≥ 0.01). Tukey value: T(4;12)=3.76; Number of cases: n=16, number of treatment t=4; SE: standard error of the mean of treatments; CV: coefficient of variation.

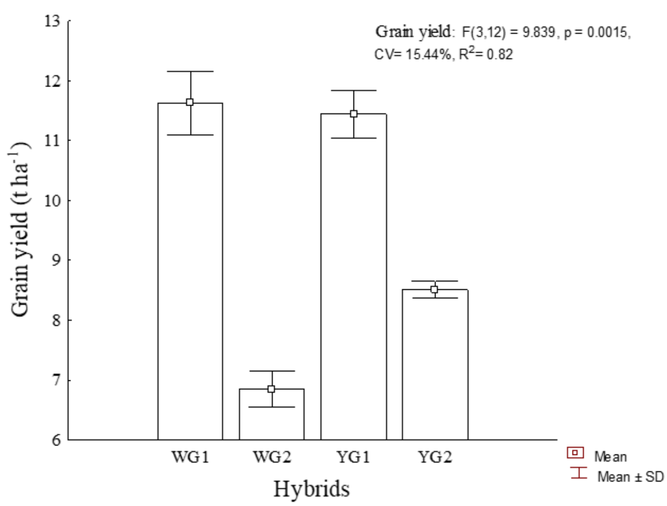

Figure 3. Grain yield of white (WG) and yellow (YG) grain maize hybrids. Error bars represent the standard deviation of the mean of treatments. F (3; 12): Fisher calculated value; p: probability of error; R^2: coefficient of determination without adjustment; CV: coefficient of variation.

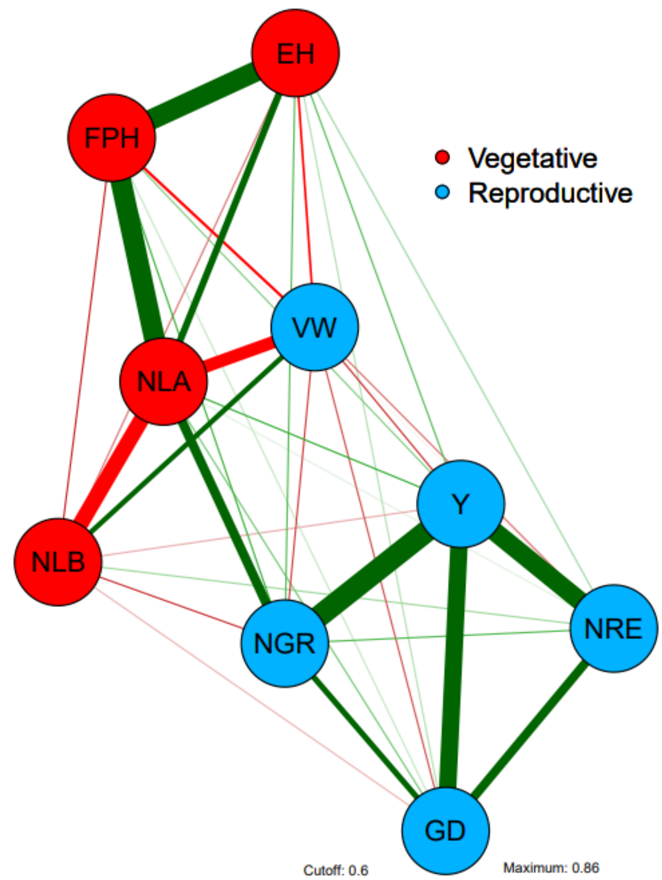

Figure 4. Correlation network between vegetative variables [EH: ear height; FPH: final plant height; NLAE: number of leaves below ear; NLBE: number of leaves below ear] and reproductive variables [NRE: number of rows per ear; NGR: number of grains per row; GD: grain depth; VW: volumetric weight; Y: grain yield]. Green and red lines represent positive and negative correlations, respectively. Thicker lines indicate higher correlation.

6.8 t ha^{-1}. The variability found in grain yield (coefficient of variation) was 15% among the four simple hybrids evaluated.

The analysis of the variable NRE, when compared with other studies, indicates that it is in the range of 16, a result that agrees with that obtained by Martínez-Gutiérrez et al. (2022) in simple hybrids, who compared the yield of maize hybrids in response to foliar fertilization with biostimulants and obtained an average of 16 rows in 11 hybrids evaluated.

Correlations between variables

There was a positive and highly significant correlation between the variables FPH and EH (r = 0.98**). Additionally, between FPH and NLAE (r = 0.96**). The variables NLAE and NLBE were negatively and significantly correlated (r = -0.81). The variables NLBE and VW correlated negatively (r = -0.76) (Figure 4).

Grain yield (Y) correlated positively with NRE (r = 0.99** and r = 0.96**, respectively). Less correlation, although also highly significant, was found between Y and GD (r = 0.93**). Among the vegetative and reproductive variables, only NLAE and NGR were found to be positively and significantly correlated. The variables NLAE and VW correlated negatively (r = -0.82**).

Recent studies developed by Salinas et al. (2023) demonstrate the existence of a positive and significant correlation between the variables NRE and Y and NGE and Y in native maize cultivated in Chiapas, Mexico. In the study presented here, no significant correlation was found between NRE and NGE.

The study carried out with the hybrids obtained from the dialelic design, in the present research, allows the identification of the best adapted materials to the specific conditions where they were obtained (Southern Sonora, Mexico). It is essential for maize breeding programs to select homogeneous materials with high yield and stable morphological and agronomic attributes (Ponce-Encinas et al., 2022).

It is important to determine stability and adaptability for the selection and recommendation of genotypes in specific environments, since it is known that with the new climate change scenarios predicted and occurring mainly in northwestern Mexico, environmental conditions change 'year after year', even in the same localities (Estrada et al., 2022). Therefore, it is advisable to evaluate diverse genotypes (experimental and commercial varieties, as well as locally obtained hybrids) to contribute to increasing local production and thus to the stability of national food security. Hence, the practical importance of the present research.

Conclusions

The evaluation of the reproductive variables allow the selection of hybrids WG1 and YG1 as those with the best agronomic performance, with superiority in the values of the yield component variables, with respect to the other hybrids evaluated.

These two hybrids (WG1 and YG1) obtained the highest grain yield (11.8 t ha^{-1}) and a high degree of biological association between several of the variables evaluated, with the highest values in final plant height (FPH) – number of leaves above (NLAE) as morphological variables and between number of grain per ear (NRE)- grain yield (Y) in the reproductive variables.

These genetic materials will be investigated in future regionalization programs according to the variability of the edaphoclimatic conditions between the experimental site and the places where they are intended to be established.

Compliance with Ethical Standards

Author contributions: Conceptualization: LPL, LAM; Data curation: LPL, LAM, OPR, FCO; Formal analysis: LPL, LAM, OPR, FCO, CLAM, JGA; Funding acquisition: LPL, LAM, CLAM, JGA; Investigation: LPL, OPR, FCO, CLAM, JGA; Methodology: LPL, LAM, JGA; Project administration: LAM; Resources: LAM, OPR, FCO, CLAM, JGA; Software: LPL, OPR, FCO, CLAM, JGA; Supervision: LPL, LAM, FCO, CLAM; Validation: LPL, LAM, OPR, FCO, CLAM, JGA; Visualization: LPL, LAM, OPR, FCO, CLAM, JGA; Writing – original draft: LPL, LAM, OPR, FCO, CLAM, JGA; Writing – review & editing: LPL, LAM, OPR, FCO, CLAM, JGA.

Conflict of interest: The authors have declared that there is no possible conflict of interest (professional or financial) that could influence the article.

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