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Water regime variability during the flowering phenophase of white and yellow grain maize hybrids and the relation with grain yield

Variabilidade do regime hídrico durante a fenofase de florescimento de híbridos de milho de grãos brancos e amarelos e sua relação com a produtividade de grãos

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ABSTRACT

The impact of low water availability on maize yield depends on the severity of the water deficit and the phenological stage of the crop. The objective of this study was to evaluate the variability of the water regime during flowering in white (GB) and yellow (GA) maize hybrids and its effects on grain yield. The study was conducted under field conditions in a pelic vertisol soil in Celaya, Guanajuato, Mexico. The drought condition of the crop was 75% of soil humidity with a soil water potential of -1.5 MPa. Hydraulic conductivity (Lp), water (*Ψr*) and osmotic (*Ψs*) potentials of the roots (during flowering phenophase), grain yield and water productivity were the evaluated variables. As results, significant variability of the water regime variables was obtained among the evaluated hybrids, resulting in variation of grain yield. The white-grain hybrids with the highest Lp were GB4 and GB5 and for yellow-grain GA2 and GA10, all exceeding 347.75 mg m^{-1} s^{-1} MPa^{-1}. In some hybrids *Ψr* and *Ψs*, decreased to more than -1.85 and -2.80 MPa, respectively, showing positive responsiveness during flowering to the drought condition of the soil. There was positive and significant correlation between Lp x Yield, and highly significant negative correlation between *Ψs* x Yield. The highest yielding hybrids were GB4 (8000 kg ha^{-1}) and GA2 (7800 kg ha^{-1}). These hybrids will continue to be evaluated for other variables for validation and recommendation for drought conditions.

Index terms: Hydraulic conductivity; osmotic potential; water potential; *Zea mays* L.

RESUMO

O impacto da baixa disponibilidade de água na produtividade do milho depende da gravidade do défice hídrico e do estádio fenológico da cultura. O objetivo deste estudo foi avaliar o regime hídrico durante a floração em híbridos de milho branco (GB) e amarelo (GA) e seus efeitos na produtividade de grãos. O estudo foi conduzido em condições de campo em um solo vertissolo pélico em Celaya, Guanajuato, México. A condição de seca da cultura foi de 75% da humedade do solo com potencial hídrico no solo de -1,5 MPa. As variáveis avaliadas foram condutividade hidráulica (Lp), potencial hídrico (*Ψr*) e osmótico (*Ψs*) radicular (durante a fenofase de florescimento), rendimiento de grãos e produtividade da água. Como resultados, obteve-se variabilidade significativa das variáveis do regime hídrico entre os híbridos avaliados, resultando em variação na produtividade de grãos. Os híbridos de grãos brancos com maior Lp foram GB4 e GB5 e para grãos amarelos GA2 e GA10, todos excedendo 347,75 mg m^{-1} s^{-1} MPa^{-1}. Em alguns híbridos *Ψr* e *Ψs*, diminuíram para mais de -1,85 e -2,80 MPa, respectivamente, mostrando responsividade positiva durante a floração à condição de seca do solo. Houve correlação positiva e significativa entre Lp x Rendimento, e correlação negativa altamente significativa entre *Ψs* x Rendimento. Os híbridos de maior produtividade foram GB4 (8.000 kg ha^{-1}) e GA2 (7.800 kg ha^{-1}). Esses híbridos continuarão a ser avaliados quanto a outras variáveis para validação e recomendação para condições de seca.

Termos para indexação: Condutividade hidráulica; potencial osmótico; potencial hídrico; *Zea mays* L.

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Introduction

Water deficit or drought stress occurs in plants in response to an environment of water scarcity, where the transpiration rate exceeds the absorption capacity of the roots (Rebolloza-Hernández et al., 2020). Water deficit occurs not only when there is little water in the environment, but also due to low temperatures and high soil salinity, but together they affect plant development and yield (Karvar et al., 2022).

Drought as an abiotic stress is a climatic and edaphic phenomenon, which varies with time and geographical site. This stress occurs when a deficit in the regional expected average precipitation occurs and for a sufficiently long period of time (Rolbiecki et al., 2022).

Maize (*Zea mays* L.) ranks eighth in the list of the world's most important agricultural products, with a production of close to 1.1 billion tons in 2020 (Erenstein, Chamberlin, & Sonder, 2021).

In Mexico, it is the most important crop from food, industrial, political and social perspectives. It contributes to about 65% of the volume of cereal production, and in 2020 it was grown on 7, 481,136.87 ha in a wide diversity of agroecosystems (Servicio de Información Agroalimentaria y Pesquera - SIAP, 2021). The same source reports that almost 80% of that area was cultivated in temporary agriculture conditions, in hot and dry environments. These factors contribute significantly to the variability of the varieties, making some varieties vulnerable to drought in order to obtain yields close to their genetic productive potential.

Genetic improvement for drought tolerance can overcome up to 25% of the grain yield losses that this adverse condition generates in maize (McMillen et al., 2022). In this context, the International Maize and Wheat Improvement Center (CIMMYT) performs conventional selection for drought tolerance and generated an increase of 100 kg ha^{-1} in grain yield in tropical maize populations, through traits associated with water stress.

In this order, breeding strategies for drought tolerance require phenotypic characterization of inbred progenies, which can be useful to optimize the efficiency of conventional breeding for water stress in maize (Ibarra Sánchez et al., 2020). Therefore, the evaluation of lines under drought stress allows the development of hybrids for environments prone to this stressor (Bushero, Tullu, & Kebede, 2021).

Tissue water requirement in the different phenological stages of the maize plant is variable (Rivera et al., 2021). In the early stages, the water requirement is low, while in the flowering and grain filling stages, water demand increases (Wang et al., 2023). During the physiological maturity stage, the water requirement decreases (Song, Jin, & He, 2019). Maize requires approximately 450 to 600 mm of water during the crop cycle (Moeletsi, Walker, & Landman, 2011); even though this cereal has a high adaptability to be grown in different environmental conditions, where drought predominates (Rocandio-Rodríguez et al., 2014). Drought is one of the abiotic conditions that generates the greatest variability in grain production (Prieto-Cornejo et al., 2019). The impact of low water availability on maize yield will depend on the severity and duration of the water deficit, as well as the phenological stage of the crop (Tahaei et al., 2022).

In relation to the variability of water requirements in the different crop phenological phase, flowering is one of the most affected, reducing pollen viability and fertilization (Sarkar et al., 2022). Therefore, under conditions of rainfed agriculture schemes, or for breeding programs for dry environments, the monitoring of the existing variability in the materials that make up the germplasm banks is essential (Guo et al., 2023). Obtaining materials that can sustain the necessary water demand during flowering even under conditions of water scarcity or drought would be of enormous genetic and economic importance for increasing production in fragile, degraded or scarce ecosystems, and would contribute to national food security and the substitution of maize imports in Mexico (Ibarra Sánchez et al., 2000; Espinosa et al., 2010). Based on the above, it is hypothesized that there are differences in the physiological response of tolerance to water deficit during flowering, in white and yellow grain corn hybrids in a selection program. The present research was conducted to evaluate the variability of the water regime, during flowering phenological phase, in simple hybrids of white and yellow grain and its effects on grain yield, evaluated for drought tolerance in the Bajío, Guanajuato State, Mexico.

Material and Methods

Location of the experimental area

The experiment was developed in the experimental field of the Tecnológico Nacional de México, Campus Roque, Celaya, Guanajuato, Mexico, located at 20°30°28” north latitude and 100°50’00” west longitude, at an altitude of 1750 meters above sea level. The crop was grown during the spring-summer agricultural cycle in the period July-September 2022. The predominant climate in this region is semi-warm and sub-humid with temperatures ranging from 14°C to 22°C. During the crop development cycle, no precipitation was recorded and the relative humidity ranged between 56-60%. The soil where the hybrids were established has a medium to fine granulometry, classified as pelic vertisol (Institute National of Statistics and Geography - INEGI, 2010; Grageda-Cabrera, 2004).

Biological material

Twenty-eight maize hybrids were used, 15 white-grain and 13 yellow-grain, obtained through a dialelic design using Griffing’s method I (Saavedra et al., 2021). The design consisted of direct crosses, reciprocal crosses with six lines of white-grain maize, and five of yellow-grain. There were 15 direct crosses, 15 reciprocal crosses and self-pollinations of each line in white-grain, and 10 direct crosses, 10 reciprocal crosses and self-pollinations in yellow-grain. The description of the hybrids used in the present work were described by Perez-Lopez et al. (2024). As a result of the two dialelic crosses, 28 hybrids were generated and evaluated in the present study (Table 1), being composed of single hybrids: 15 of white-grain maize (GB) and 13 of yellow (GA).

Experimental design

The treatments consisted of using the 28 maize hybrids. These materials were established following a randomized complete block design, with four replications. Each experimental plot consisted of a five meter long furrow. The furrow width was 0.80 m and the distance between plants was 0.20 m, for a population density of 62,500 plants ha^{-1}. The comparison between treatments was done independently between white and yellow hybrids.

Table 1: Hybrids of white-grain (15), and yellow-grain (13) maize obtained from the dialelic design.

		Simple hybrids	
Code	white	Code	yellow
GB1	L4 CML 550 X L6 CML 546	GA1	L1. CML 479 X L4. CML 101
GB2	L1 CML 442 X L6 CML 546	GA2	L1. CML 479 X L5. CML 103
GB3	L1 CML 442 X L4 CML 550	GA3	L3. CML 551 X L4. CML 101
GB4	L3 CML 549 X L6 CML 546	GA4	L1. CML 479 X L3. CML 551
GB5	L1 CML 442 X L2 CML 545	GA5	L2. CML 501 X L3. CML 551
GB6	L3 CML 549 X L4. CML 550	GA6	L2. CML 501 X L4. CML 101
GB7	L3 CML 549 X L5. CML 576	GA7	L4. CML 101 X L5. CML 103
GB8	L2 CML 545 X L4. CML 550	GA8	L5. CML 103 X L3. CML 551
GB9	L4 CML 550 X L2.CML 545	GA9	L3. CML 551 X L1. CML 479
GB10	L4 CML 550 x L1. CML 442	GA10	L5. CML 103 X L4. CML 101
GB11	L6 CML 546 X L4. CML 550	GA11	L5. CML 103 X L1. CML 479
GB12	L6 CML 546 X L2. CML 545	GA12	L4. CML 101 X L3. CML 551
GB13	L5 CML 576 X L4. CML 550	GA13	L4. CML 101 X L1. CML 479
GB14	L6 CML 546 X L3. CML 549		
GB15	L5 CML 576 X L3. CML 549		

Sowing, agronomic and phytosanitary management

Sowing was done on July 7, 2022, manually, placing one seed per "stroke". Birth irrigation was given immediately after sowing, to keep the soil moist and achieve a high percentage of germination and emergence. In total, four relief irrigations were applied. The nascence irrigation at an irrigation sheet of 16 mm. the second and therth irrigation were done with an irrigation sheet of 12 mm, at an irrigation interval of 15 days. No irrigation was applied during the flowering phenological phase. The absence of this irrigation was the rainfed condition imposed to evaluate the response variability of the hybrids. The last irrigation was applied in R1 phenological phase at an irrigation sheet of 12 mm. The total water volume applied to the hybrids was 5,200 m^3 ha^{-1}.

Fertilization was carried out in four fertilizer applications: a bottom application, based on urea and a mixture of DAP (400 kg ha^{-1}) and the remaining three fertilizations were carried out prior to the auxiliary irrigations at a rate of 150 kg ha^{-1} of NPK. The first fertilization was applied just at the moment of sowing together with the sowing irrigation. The following fertilizations were applied during the first three auxiliary irrigations during phenophase V_4 to V_{12}. The last fertilization was applied in R1 phenological phase in a combination with the irrigation. During the conduct of the experiment, the presence of thrips (*Rankliniella occidentalis*) and codling moth (*Spodoptera fugiperda*) was found to be significant. Both pests were controlled with the insecticides Palgus® (spinetoran) and Agresor® (chlorpyrifos methyl + permethrin) at a rate of 400 mL ha^{-1}, respectively.

Two passes with a cultivator were made to aerate the soil and for weed control. Most of the weed control was done manually (weeding).

Soil moisture content

To evaluate soil moisture content, 9 random samples were taken at a depth of 0-45 cm. These samples were pooled to form a combined sample and 5 sub-samples were taken to determine the moisture content (Or, Wraith, & Warrick, 2002). The initial mass of the soil was taken and subsequently disintegrated in plastic sheets and dried until a constant mass was obtained. Moisture content was determined by gravimetry using the methodology proposed by Quichimbo et al. (2016). The final soil humidity percentage of the samples was 75%.

Root hydraulic conductivity (Lp)

To evaluate this variable, root samples were taken 8 days after the flowering phenological phase (75 days and 78 after emergency, in average for yellow and white grain maize, respectively). In this date the soil humidity percentage was 75%, a soil water potential of -1.4 MPa and an hydraulic conductivity of 320 mg m^{-1} s^{-1} MPa^{-1}. For this trial, the plants were cut at the root collar level, extracting their roots and washing them carefully. Subsequently, they were placed in a container with Hoagland nutrient solution during 30 minutes. After that, the roots were introduced into Scholander pressure chamber (Scholander et al., 1965), leaving a part of the stem to the outside where a small section of capillary hose was fitted.

From that moment on, the pressure inside the chamber was increased until a constant flow of 0.5 MPa was obtained until a final pressure of 1.5 MPa was reached. Three exudates were extracted from each sample, measuring the volume extracted every three minutes. The hydraulic conductivity of the root was calculated using the Equation 1:

$$LP = \frac{J}{P \times L} \quad (1)$$

Where: Lp: is the hydraulic conductivity, expressed in mg m^{-1} s^{-1} MPa^{-1}; J: water flow rate through the entire root system (mg s^{-1}); P: applied hydrostatic pressure (MPa); L: root length (m).

Water and osmotic potentials

For water potential measurements, six random samples were taken from the roots of plants of each hybrid. Immediately after collection, roots were dissected to a length of 10 cm and water potential was measured with a *Scholander* pressure pump (PMS-100; PMS Instrument Company, Albany, OR, USA) (Scholander, 1965). During the measurements, the samples were quickly placed in double-sealed bags and sealed for subsequent measurement of osmotic potential. The leaves were then placed in the sample holder of the chamber and pressure was applied until sap exudate was observed in the developed cut.

The criteria for classifying hybrids based on their water potential value were as follows: high water potential Ψr > -1.0 MPa, moderately low stress between -1.0 < Ψr < -1.2 MPa and low, when water potential Ψr < - 1.4 MPa (Ruiz-Sánchez et al., 2017). The lower the water potential, the greater the suction force of plants to absorb water. At low water potential, plants perform higher metabolic adjustment to avoid drought stress (Liao et al., 2022).

For saturated osmotic potential (Ψs), measurements were given under saturated weight conditions, so 24 samples of roots and leaves per treatment were taken and placed in *Petri* dishes for rehydration with distilled water, which were placed in double *zip lock* bags and kept at 8 °C for 12 h. The samples were then wrapped with aluminum foil for freezing in liquid nitrogen and stored in an ultrafreezer at -80 °C. Subsequently, samples were thawed at room temperature and centrifuged at 3000 rpm for 3 min and cell juice was obtained from roots and leaves. Ψs was determined from 100 ml aliquots with a vapor pressure ohsmometer (Vapro 7120; ELITechGroup, Smithfield, RI, USA) (Argentel-Martínez, 2019).

Grain yield

Grain yield (Yield, kg ha^{-1}) was determined at 14% moisture following the methodology proposed by Inamullah et al. (2011). Twenty-eight plants were taken from each hybrid (4 replications of 7 plants in a linear meter), taking the ears and shelling them to weigh them and obtain the yield. Grain moisture was determined with Staeinlite® model 90 equipment and the scale to weigh the grains of each hybrid.

Water use efficiency

Water productivity (WP) was calculated by dividing the grain yield (kg ha^{-1}) of each hybrid evaluated by the total volume of water applied (V) (m^3 ha^{-1}) (Pérez-López et al., 2024). In this study the total volume of water was similar for all hybrids.

Statistical analysis

All statistical analyses were conducted using Statistica professional software (version 12.0) (StatSoft, 2014). Residuals were tested for normality and homogeneity and analysis of variance was performed according by Fisher (1935). When significant, (F-test at 5% probability), the data were subjected to a Tukey's test at 5% (Tukey, 1960). A Pearson's statistical correlation analysis ($p < 0.05$ for statistical significance and $p < 0.1$ as indicative) was performed in order to find the relations that best explain the results interaction (Dagnino, 2014).

Results and Discussion

By means of the analysis of variance, highly significant statistical differences were detected between the 15 white and the thirteen yellow simple hybrids (Table 3), for the variable Lp (F= 302, p = 0.00001 and F= 183, p = 0.00021, respectively). In both types of hybrids, the fixed effects linear mathematical model used for the analysis of variance explained more than 98% of the total variability ($R^2 = 0.99$ and $R^2 = 0.98$, for white and yellow, respectively) (Table 2).

The highest Lp values of the white colored hybrids were those of the single crosses GB4 (348.50 mg m^{-1} s^{-1} MPa^{-1}) and GB5 (348.25 mg m^{-1} s^{-1} MPa^{-1}), and the lowest values were the crosses GB1 (321.50 mg m^{-1} s^{-1} MPa^{-1}) and GB11 (315.50 mg m^{-1} s^{-1} MPa^{-1}). In the yellow hybrids those with the highest Lp. values were GA10 (348.25 mg m^{-1} s^{-1} MPa^{-1}) and GA2 (347.75 mg m^{-1} s^{-1} MPa^{-1}), and those with the lowest values were the GA1 crosses (321.25 mg m^{-1} s^{-1} MPa^{-1}) and GA6 (325.00 mg m^{-1} s^{-1} MPa^{-1}), those with the least prospects for maintaining good plant water status under water deficit conditions (Table 2).

Hydraulic conductivity determines the water and nutrient transport capacity of plants. Good hydraulic conductivity improves water status and water use efficiency. Lp is considered as one of the main factors controlling water movement through the soil-plant system (Zhang et al., 2020), therefore, it will have an important influence on plant transpiration and related physiological processes. In a work by Sinclair and Jafarikouhini (2022), they found Lp values of 300 mg m^{-1} s^{-1} MPa^{-1} in soils with water potential of -2.0 MPa in sweet maize hybrids. This result is in agreement with that obtained in the materials evaluated in the present study where all hybrids exceeded 300 mg m^{-1} s^{-1} MPa^{-1} at a water potential of -1.4 MPa (Table 2). This result allows inferring that the selected hybrids can be promising for rainfed conditions.

Table 2: Average root hydraulic conductivity (Lp) expressed in mg m^{-1} s^{-1} MPa^{-1} in white and yellow maize.

White-grain hybrids	Lp	Yellow-grain hybrids	Lp
GB11	315.50g	GA1	321.25g
GB1	321.50f	GA6	325.00f
GB10	327.75e	GA3	342.25e
GB12	340.75d	GA12	343.00
GB2	343.50cd	GA7	343.50
GB7	343.50cd	GA9	344.00
GB3	344.50bc	GA8	344.50cde
GB15	345.50abc	GA4	344.50cde
GB14	345.50abc	GA11	344.75cde
GB6	347.50ab	GA13	345.25bcd
GB13	347.50ab	GA5	347.25abc
GB9	347.50ab	GA2	347.75ab
GB8	347.75a	GA10	348.25a
GB5	348.25a		
GB4	348.50a		
SE	1.33		1.11
CV	3.02		2.34
R^2	0.98		0.99

Means with the same letter in the same column are statistically equal (Tukey, ≤0.05); Lp= Root hydraulic conductivity. CV: Coefficient of variation; SE: Standard error of treatments; R^2: coefficient of determination unadjusted.

Hydraulic conductivity has been studied in different vegetables, for example, in tomato (Morales, 2013) with values above 400 mg m^{-1} s^{-1} MPa^{-1} under saline conditions, demonstrating tolerance to physiological drought associated with the presence of salts. High hydraulic conductivity in saline and dry soil conditions contributes to ensure good crop yields (Morales, 2013) thus improving water use efficiency (Sade et al. 2010; Toro et al., 2023).

Variability of water (Ψr) and osmotic (Ψs) potentials in the genotypes evaluated

There were significant differences between the *Ψr* and *Ψs* values of the white-grain hybrids. These values ranged from -0.9 to -2.8 MPa. Only hybrids GB1, GB11 and GB10 maintained a potential lower than that of the soil where they were established (-1.4 MPa.). The single white-grain hybrids with the greatest decrease in *Ψr* and *Ψs* were GB4 and GB5 (Figure 1).

The measurement of water potential (*Ψr*) is of great importance as it allows us to predict how water will move under various conditions and soil moisture regimes, since water moves spontaneously in regions with differences in water concentration (Queiroz et al., 2019).

These results are below those obtained by Villalobos-González et al. (2016), a study on maize hybrids grown in Montencillo, State of Mexico, Mexico. In this study, under rainfed conditions, during flowering, at 75% CC, due to drought effects the ψ decreased to -1.8, -2.2 and -1.5 MPa in three maize genotypes, indicating greater ability to adjust metabolism to decrease the osmotic potential and as a consequence manage to maintain in good status the water relations of plants (Liao et al., 2022).

In the yellow-grain maize hybrids, it was observed that for both variables evaluated (*Ψr* and *Ψs*) there were also highly significant differences (Figure 2) but the greatest variability was observed in *Ψs*. Hybrids GA2 and GA10 presented the lowest values of (*Ψr*), while GA6 and GA1 presented the closest values to the soil water potential evaluated in the flowering phenological phase.

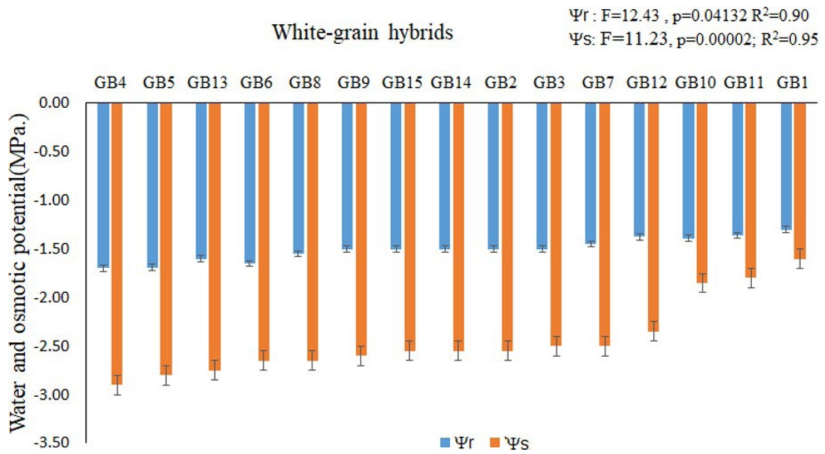

Figure 1: Water (*Ψr*) and osmotic (*Ψs*) potential of white-grain maize hybrids. Rectangular bars represent standard deviations of the means of each hybrid. F: Fisher's calculated value and p: Probability of error. R^2: coefficient of determination unadjusted.

This result demonstrates the lower capacity of these genotypes to sustain a good water status in this phenological phase, which is crucial to achieve fertilization and the onset of grain filling (Hemati et al., 2022).

Grain yield of white and yellow maize hybrids

All white-grain maize hybrids yielded more than 5,500 kg ha^{-1} (Figure 3a). This result, for the deficit irrigation regime condition in maize is high when compared to the reports of Tadeo-Robledo et al. (2020) who obtained, in simple white grain maize hybrids, a yield of 8.5 to 12.5 t ha^{-1} in a studied carried out in Tamaulipas yielded an average yield of 6,928 kg ha^{-1}. In this same study, but evaluating 16 yellow-grain maize hybrids, an average of 7,254 kg ha^{-1} was obtained (Figure 3b), showing yield superiority for the 75% CC condition. The highest yield of white-grain hybrids were GB5 and GB4, while the most productive yellow-grain hybrids were GA10 and GA2.

Studies developed by Villalobos-González et al. (2016) under drought conditions showed a delay in male and female flowering, a prolongation of the anthesis-female flowering interval, and consequently reduced average grain yield in maize hybrids, by 46% with respect to when soil moisture content was at 84%. The materials that presented a yield higher than 4,400 kg ha^{-1} under rainfed conditions were classified as tolerant. Based on this study, it can be inferred that in the present research they are considered high, since all of them presented a yield higher than 5500 kg ha^{-1}. The results shown here also exceed those obtained by Grant et al. (1989) and Bäzinger et al. (2000), who reported on the susceptibility of maize hybrids to drought conditions, with a 35% reduction in grain yield.

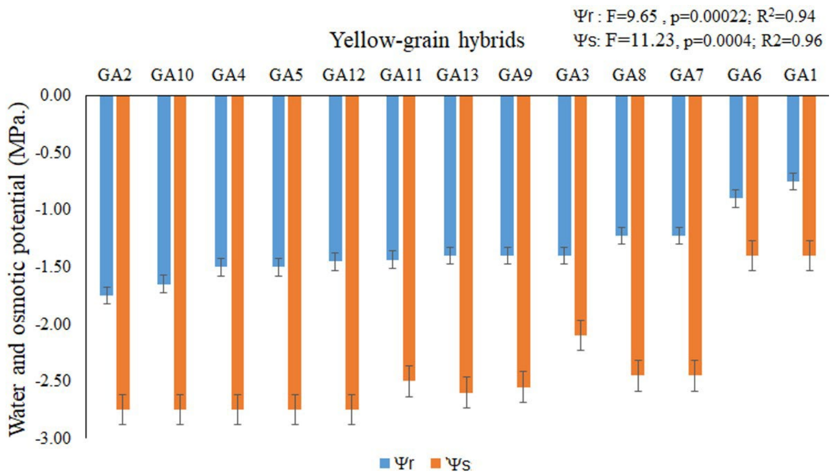

Figure 2: Water (*Ψr*) and osmotic (*Ψs*) potential of roots of yellow-grain maize hybrids. Rectangular bars represent standard deviations of the means of each hybrid. F: Fisher's calculated value and p: probability of error. R^2: coefficient of determination unadjusted.

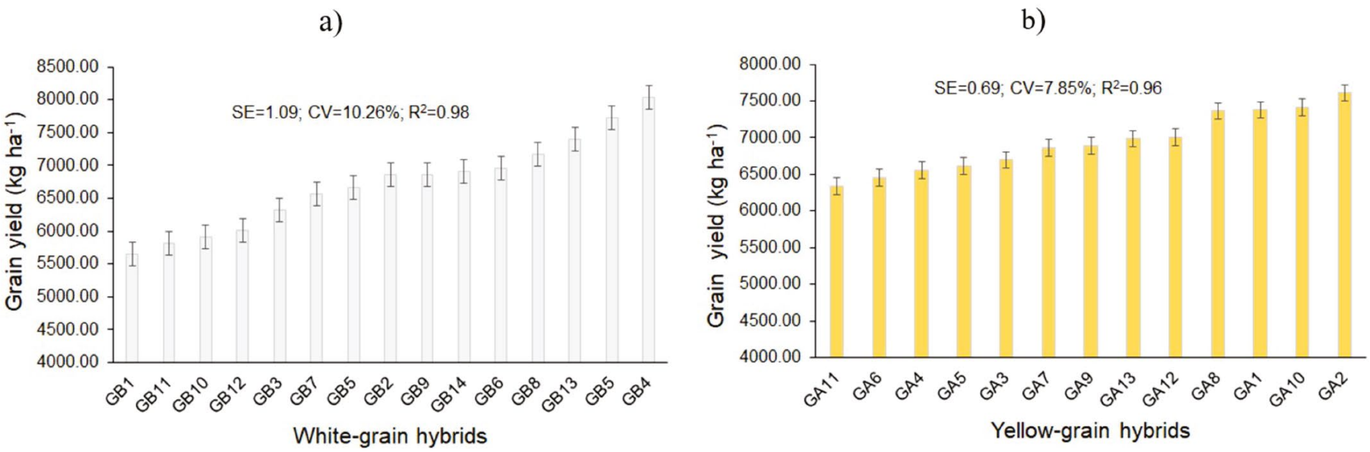

Figure 3: Grain yield of white-grain (a) and yellow-grain (b) maize hybrids. Rectangular bars represent standard deviations from the mean of treatments. SE: standard error of treatments; CV: coefficient of variation of treatments, R^2: coefficient of determination unadjusted).

It has been shown that water deficit generates yield losses of 32% (Wang, 2022). These losses are due to the difficulty of plants to mobilize elaborated substances and osmolytes to the grain due to the existing drought condition (Prazeres & Coelho, 2020).

Water productivity

The water productivity of white grain maize hybrids (Figure 4a) remained between 1 and 1.7 kg m^{-3} in most hybrids, with the exception of hybrid GB5, which presented the highest value (greater than 2.5 kg m^{-3}), being the one with the greatest response. However, the yellow grain values (Figure 4b) presented lower productivity and lower variability among themselves. This response was a function of the yield obtained since the volume of water applied was constant.

Currently, the study of water productivity under deficit of irrigation or drought condition is being evaluated due to the scarcity of water in the most majority of maize production ecosystems in Mexico (Gonzalez, 2023). This responds to current drought scenarios and forecasts for the coming years. The selection of genotypes with higher productivity will contribute to national food security in Mexico (Estrada et al., 2023). For these conditions of water scarcity during flowering phenological phase, it would be recommended to use white grain maize hybrids, particularly GB5.

Correlation between water regime variables and grain yield in white and yellow-maize hybrids

For the white-grain maize hybrids, there was a negative and highly significant correlation between the variables Lp x *Ψr*, and between Lp x *Ψs*. The variables Lp x Yield presented positive and highly significant correlation similar to Lp x WP (Table 2). Similar response in the correlations was found (Lp x *Ψr*; and between Lp x *Ψs*; Lp x Yield) in the yellow-grain maize hybrids, however, the correlation values were higher in absolute value (Table 3). In both types of hybrids, the greater decrease in *Ψr* correlated with yield, demonstrating that the greater the capacity of plants to decrease their water potential, the greater the suction force at a relatively low soil water potential (-1.4 MPa), which allows them to ensure a good water status in the flowering phenological phase. This behavior of *Ψr* favors a good grain yield, such as that obtained in GB5 and GB4 white-grain, and GA2 and GA10 yellow-grain.

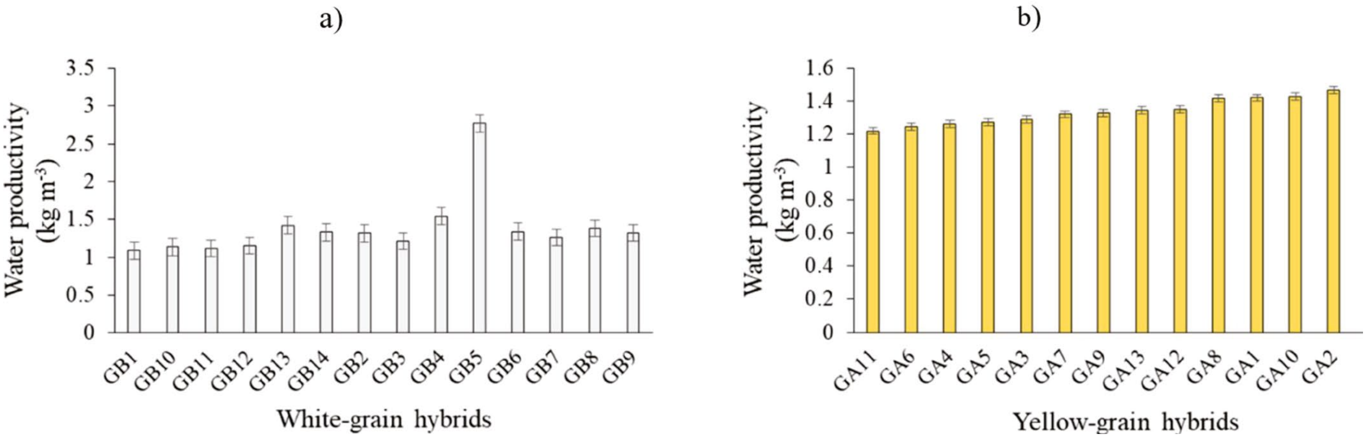

Figure 4: Water productivity of white-grain (a) and yellow-grain (b) maize hybrids. Rectangular bars represent standard deviations from the mean of treatments.

Table 3: Correlation between the variables [Lp: root hydraulic conductivity, *Ψr*: root water potential, *Ψs*: root osmotic potential, Yield: grain yield and WP: Water productivity of white and yellow maize hybrids].

Correlation between variables										
	White					Yellow				
	Lp	Ψr	Ψs	Yield	WP	Lp	Ψr	Ψs	Yield	WP
Lp	1.00					1.00				
Ψr	-0.86**	1.00				-0.88**	1.00			
Ψs	-0.85**	0.97	1.00			-0.89**	0.98	1.00		
Yield	0.89**	-0.93**	-0.91**	1.00		0.94**	-0.96**	-0.93**	1.00	
WP	0.88**	-0.92**	-0.92**	1.00	1.00	0.93**	-0.96**	-0.92**	1.00	1.00

** represent highly significant Pearson correlations.

The decrease in *Ψs*, which in both types of hybrids correlated with yield in a highly significant negative way, denotes the capacity of synthesis of osmoprotective compounds without compromising the reserves of photoassimilates intended for grain filling, under conditions of deficit irrigation regime or drought itself (Resende et al., 2019).

The ability of crop species such as maize and wheat to decrease their water and osmotic potential is an accurate indicator in breeding programs (Nunes et al., 2019). These hybrids guarantee a good water regime, maintain viable pollen and achieve good fertilization and grain filling.

In our study, some hybrids, both white-grain and yellow-grain, were found that although they did not present the greatest reductions in water and osmotic potentials, at least they reduced them to values lower than the water potential associated with 75% CC, which allows them to be recommended for hybrid regionalization programs in rainfed agriculture schemes conditions, where the soil water potential does not drop more than -1.4 MPa.

The success of flowering and fertilization depends significantly on the water status of the plants where the roots play a major role during the water absorption process (Hemati et al., 2022; Abd El-Fattah et al., 2023), hence the importance of the evaluation of the water regime of white and yellow-grain maize hybrids developed.

For future works it will be necessary to include important genetic variables that contribute to the validation of the results and greater expression of the genotype-environment interaction. For example, the use of phenotypic plasticity (Pennacchi et al., 2021). In addition, involve some other physiological variables such as gas exchange (Garcia et al., 2021). These studies, with the use of multivariate selection techniques will allow to obtain greater precision in the results obtained here with the use of white and yellow maize hybrids as experimental model for water regime variability.

Conclusions

In both types of hybrids, there was variability of water relations during flowering. In white-grain hybrids, 80% exceeded 340 mg m^{-1} s^{-1} MPa^{-1}, while in yellow-grain hybrids it was 84%. Even with the drought condition established during flowering, both types of hybrids achieved yields above 5000 kg ha^{-1}, with yellow-grain hybrids showing the highest values. Water productivity was higher in white grain maize than in yellow ones. The hybrids with the best yields were GB4, GB5, GA2 and GA10.

Author Contribution

Conceptual idea: Pérez-López, L.; Argentel-Martínez, L.; Methodology design: Pérez-López, L.; Argentel-Martínez, L.; Peñuelas-Rubio, O.; Ortiz, F.C.; Aguilera, J. G.; Gil-Núñez, J. C.; Data collection: Pérez-López, L.; Argentel-Martínez, L.; Peñuelas-Rubio, O.; Ortiz, F.C.; Gil-Núñez, J. C.; Data analysis and interpretation: Pérez-López, L.; Argentel-Martínez, L.; Peñuelas-Rubio, O.; Ortiz, F.C.; Aguilera, J. G.; Gil-Núñez, J. C., and Writing and editing: Pérez-López, L.; Argentel-Martínez, L.; Peñuelas-Rubio, O.; Ortiz, F.C.; Aguilera, J. G.; Gil-Núñez, J. C.

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