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Article

Technified gravity irrigation in corn hybrids for the High Valleys

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Abstract

The technical design of gravity irrigation represents an opportunity for water savings and is an option in conditions of scarcity to improve the production of the corn crop. This work aimed to assess the effect of three moisture management conditions on the agronomic variables of white corn hybrids for the High Valleys of central Mexico. The experimental design consisted of a factorial arrangement of 10 hybrids (G1-G10) under three moisture (M) conditions, traditional irrigation (M1), technified irrigation (M2), and rainfed conditions (M3) in a design of three randomized complete blocks, established at the Cuautitlán Faculty of Higher Studies of the National Autonomous University of Mexico in Cuautitlán Izcalli, state of Mexico. The overall mean grain yield was 8.28 t ha^{-1} with a water utility of 1.5 kg m^{-3}; it was 7.9 t ha^{-1} and 1.2 kg m^{-3} under traditional irrigation, 8.6 t ha^{-1} and 1.4 kg m^{-3} under technified irrigation, and 8.26 t ha^{-1} and 1.8 kg m^{-3} under rainfed conditions, respectively. The CUXI PUMA hybrid resulted with the highest productivity (9.95 t ha^{-1} and 1.7 kg m^{-3}). The highest yield was obtained under technified irrigation; however, under rainfed irrigation, hybrids showed greater water utility. Under conditions of water restriction, it is advisable to produce corn under rainfed conditions because irrigation did not significantly increase yield, this would be expected in soil and climatic conditions similar to those of this experiment.

Keywords:

Zea mays, marginal water productivity, rainfed conditions.

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Introduction

In the country, the gravity irrigation method predominates in irrigated agriculture (Flores-Gallardo *et al*., 2014; Mendoza-Pérez *et al*., 2016) and it is expected that its use will continue to predominate in the coming years (Shmulik, 2023) as it is applied to more than 80% of the irrigated area. This irrigation method is applied to corn crops (Mendoza-Pérez *et al*., 2016) and currently comprises more than 85% of the area sown with this crop under irrigation.

The nature of gravity irrigation implies low efficiency due to opportunity times deferred along the furrows; ideally, the transfer time should be 25% of the total irrigation time, which is controlled with the flow applied per furrow (Rosano-Méndez *et al*., 2001; Mendoza-Pérez *et al*., 2016; Prado-Hernández *et al*., 2017).

The production of corn under irrigation in Mexico, due to the planted area, consumes about 40% of the water destined for agriculture; therefore, the actions of technification of irrigation in this crop affect water and food security, since it is the main crop in the country and its irrigation has low efficiencies in the use of water at the plot level. In this sense, efficient irrigation management in corn contributes to sustainable agriculture (Flores-Gallardo *et al*., 2014; Inzunza-Ibarra *et al*., 2018; Guzmán-Luna *et al*., 2023).

The technification of irrigation is applied in the cultivation of grains such as corn because of its wide distribution in Mexico and because it is the main food input in the country (Inzunza-Ibarra *et al*., 2018; Tadeo-Robledo *et al*., 2022a; Guzmán-Luna *et al*., 2023).

Corn yield is sensitive to water deficit in the soil at the female flowering stage and is susceptible when established under rainfed conditions since water availability is random. Traditional irrigation uses qualitative observations to determine the timing of irrigation, and it is also susceptible to a deficit during the critical stage (Rosano-Méndez *et al*., 2001; Flores-Gallardo *et al*., 2014); on the other hand, under technified irrigation, the evolution of moisture in the soil is identified in order to irrigate in a timely manner (Prado-Hernández *et al*., 2017).

In the current context of water scarcity in irrigation systems and lack of self-sufficiency in corn production that limit water and food security (Guzmán-Luna *et al*., 2023), it is necessary to carry out studies of the water conditions related to corn grain production. In this context, the study aimed to define the performance of 10 corn hybrids under three moisture management conditions. The hypothesis was that, if irrigation is technified, then, at least in one hybrid, the amount of water applied is reduced without negatively affecting grain yield and increasing water use.

Materials and methods

Experimental site

The experiment was carried out in the spring-summer agricultural cycle of 2022 in the experimental field (Rancho Almaraz) of the Cuautitlán Faculty of Higher Studies (FES-C, for its acronym in Spanish) of the National Autonomous University of Mexico (UNAM), for its acronym in Spanish in Cuautitlán Izcalli, state of Mexico, located at 2 253 masl at coordinates 19° 41’ 48” north latitude and 99° 11’ 36” west longitude.

Climatic and soil conditions

In the FES-C, UNAM, the precipitation and average temperature normals are 647 mm and 15.4 °C. During the experiment, there were 462 mm and 16.6 °C, respectively. The evapotranspiration of the crop, estimated at 342 mm based on the crop coefficient approach, did not exceed the observed precipitation; for its part, the actual evapotranspiration based on the weighing lysimeter was 514 mm. The estimation of the requirements was made from the daily water balance, considering precipitation.

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The soil in Cuautitlán is predominantly clay loam and has high hydraulic conductivity (Ks= 3.4 cm h^{-1}), usable moisture (UM) of 10.4%, saturation point of 46%, bulk density of 1.11 g cm^{-3}, low stoniness (<1%), and good fertility as a residual effect of annual applications.

Irrigation

The water for irrigation from the Guadalupe dam was applied in the furrows using siphons in the traditional and technified treatments, where the topographic slope in the longitudinal direction was 0.2% and separation of 0.8 m. In the traditional irrigation treatment, a total of 207.5 mm was applied in two irrigations when the plants showed symptoms of leaf wilt. For technified irrigation, the irrigation sheets were defined from the daily water balance and a total of 165 mm were applied in two irrigations. Irrigation expenditure and time were identified with the Rigrav 3.0 algorithm developed by Rendón *et al*. (2017).

The software was fed with data on soil characteristics at a depth of 0-0.3 m, initial moisture was determined with the TDR-350 spectrum soil moisture meter, moisture content at saturation was identified in the laboratory, hydraulic conductivity was measured with disc infiltrometer, and wetting front suction from the tabulated values reported by Rendón *et al*. (2017); Prado-Hernández *et al*.(2017).

Hydraulic conductivity, saturation point, and wetting front suction were calibrated as indicated by Rendón *et al*. (2017). In addition, the software was fed with the calibrated parameters of the infiltration model based on evaluations of the irrigation phases that were carried out in the same plot. The evaluation and design procedure were performed based on Rosano-Méndez *et al*. (2001); Flores-Gallardo *et al*. (2014).

The soil characteristics for technified irrigation resulted in an initial moisture content of 0.07 cm^3 cm^{-3}, saturation content of 0.51 cm^3 cm^{-3}, field capacity of 0.26 cm^3 cm^{-3}, hydraulic conductivity of 3.3 cm h^{-1} and wetting front suction of 83 cm. The design irrigation sheet of 10.3 cm to the 65 m furrows with 0.2% longitudinal slope. The unit flow was 4.1 L s^{-1} m^{-1} and with the furrow width of 0.8 m, the applied flow was 3.2 L s^{-1} m^{-1} with the design irrigation time of 46.9 min.

The flow applied to the furrows was controlled by means of two-inch polyethylene siphons, previously calibrated in the laboratory, in which the necessary load was established to provide the required flow during the irrigation time that resulted from the design.

Genotypes and experimental design

The experimental design was formed by the genotype (G) factor with 10 corn genotypes (G1-G10), five three-way cross hybrids obtained at UNAM: TSIRI PUMA (Tadeo *et al*., 2016), TLAOLI PUMA (Tadeo-Robledo *et al*., 2022 a), ATZIRI PUMA (Tadeo-Robledo *et al*., 2022 b), IXIM PUMA and CUXI PUMA, three generated at CEVAMEX-INIFAP, two three-way cross hybrids: H-49 AE (Espinosa-Calderón *et al*., 2022) and H-53 AE; a double-cross hybrid: H-50 (Espinosa-Calderón *et al*., 2003), an experimental three-way cross hybrid 246 x 242 x MIA46, and the Cedillo variety. All are materials for the agroecological region of the High Valleys of Mexico.

Several of these materials contain in their conformation a source of latent germplasm material, generated by the engineer Gilberto Palacios de la Rosa (Espinosa-Calderón *et al*., 2003; Villalobos-González *et al*., 2023). The other factor was moisture (M) management with traditional irrigation (M1), technified irrigation (M2), and rainfed conditions (M3). The factorial experiment in randomized complete blocks was established with three replications and the combination of the levels of the factors 10G x 3M resulted in 30 treatments and 90 elementary plots. Complete treatments were randomized in each block into experimental units (EUs) 5 m long and 0.8 m wide.

Management tasks

The corn was sown manually on June 13, 2022, adjusting to a density of 70 000 plants ha^{-1}. The volumetric moisture content was 9.2%, there was rain the day after sowing, so irrigation was not applied, and it presented moisture of 12%, four days after sowing (das), the moisture increased to 24.8% (average of a systematic sample of 16 observations with the TDR 350 spectrum).

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Soil fertilization was with the 80-40-00 formula in a single application using granulated urea and diammonium phosphate. The weeds were controlled with two applications at five and 40 das with the mixture of atrazine (2 kg ha^{-1}), S-metolachlor (1 L ha^{-1}), and mesotrione (1.5 L ha^{-1}).

Response variables

Plant height (PH) and ear height (EH) were determined by measuring variables in the field. At harvest, 190 das, all the ears of each experimental plot were collected to obtain their field weight (FW). A sample of five ears was taken at random from each EU to characterize them and perform laboratory determinations.

In the laboratory, the ears were characterized based on their length (EL), measured with a tape measure, their diameter (ED), obtained with a vernier, number of rows (RE) and number of grains per row (GR), counted manually, and grains per ear (GE) with the product of RE x GR. The yield (YIE) was determined by the formula: YIE= (W*DM*%G*CF)/8600. Where: W= weight of the ears harvested in the EU, in kg; DM= percentage of dry matter, it was determined by subtracting the moisture content from the weight of the wet grain; %G= percentage of grain, it was obtained by weighing the grain of the five shelled ears and relating it to the weight of the ears with cob; CF= conversion factor, it is determined with the quotient of the area of one hectare and the size of the EU in m^2; 8 600= constant to estimate the yield with moisture of 14%.

Water use (WU) was determined with the formula: WU=YIE/S. Where: YIE= grain yield in kg and S= water sheet that entered each treatment, calculated with the sum of rainfall plus the applied irrigation sheet. The analysis of variance and the verification of its precepts were performed in the SAS 9.0 software (SAS Inc., 2002) to know the effect and interactions of the factors (p< 0.05); the same level of significance was used to conduct the tests of means by simple effects or interactions using Tukey's method.

Results and discussion

The genotype factor showed a highly significant effect (p< 0.01) on PH, EH, ED, RE, GE, YIE, and WU and a significant effect on GR. The moisture factor only had a highly significant statistical effect on water use (Table 1). The results in this regard are similar to the work by Mendoza-Pérez *et al*.(2016) in a study on moisture management in corn experiments. The interaction of the factors had a highly significant statistical effect for EH and RE; moreover, the effect was statistically significant for ED and GE.

Table 1. Mean squares and significance of the response of 10 corn genotypes under three moisture management treatments in the High Valleys of Mexico. Spring-summer cycle, 2022.

SV	YIE	PH	EH	EL	ED	RE	GR	GE	WU
Block	3.2	532.8	311.5	0.3	0.1	2.3	2.1	5083	0.08
G	15.2**	1 346.9**	1620.5**	2.2	0.2**	6.5**	16.6*	13196.2**	0.5**
M	2.9	133.3	16.2	1.1	0.1	2.4	10.1	8308.9	2.8**
GxM	3.3	311.6	504.7**	1.5	0.1*	4.4**	9.3	8323.9*	0.1
Mean	8.3	198.8	91.3	15.1	4.6	15.7	31.3	491.7	1.5
CV	18.4	5.5	14.9	8.1	5.1	8.7	8.6	13.6	18.2

*= $p\leq$ 0.05; **= $p\leq$ 0.01; YIE= grain yield; PH= plant height; EH= ear height; EL= ear length; ED= ear diameter; RE= rows per ear; GR= grains per row; GE= grains per ear; WU= water use; G= genotype; M= moisture; GxM= genotype-by-moisture interaction; CV= coefficient of variation.

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The average grain yield was 8.28 t ha^{-1} and the water use was 1.5 kg m^{-3}, it is noted that the yield was outstanding, but that was not case for the use of water since it was lower than that reported by Robaina *et al*. (2015), of 1.7 kg m^{-3}, and López-Hernández *et al*. (2019), of 1.8 kg m^{-3}. However, water use was close to 1.6 kg m^{-3}, which is reported as an optimal value by Inzunza-Ibarra *et al*.(2018).

The overall means of the variables evaluated were lower than those reported by Alonso-Sánchez *et al*. (2023) for hybrids evaluated in the High Valleys under irrigation tip, where rainfall exceeded the 669.5 mm of the treatment with the highest water availability in this study.

In the results with lower mean values, the effect of rainfed moisture is also implicated because the water deficit limits the expression of the hybrids, as reported by Castellanos *et al*. (2019); Alonso-Sánchez *et al*. (2022). The coefficients of variation were homogeneous and are related to the experimental control (Table 1).

Comparison of means between moisture management conditions

Water use was higher under rainfed conditions, with 1.8 kg m^{-3}, as a response to the lower availability of water and acceptable yield; on the other hand, traditional irrigation presented the lowest water use, with 1.2 kg m^{-3}, which led to a lower grain production in relation to the volume of water, which is related to the empirical management of irrigation where water losses occur, as referred to by Rosano-Méndez *et al*. (2001) and Mendoza-Pérez *et al*. (2016).

The best use of water in the evaluated hybrids occurred under rainfed conditions because this variable shows a nonlinear differential response for the gradients of moisture availability, so there is maximum use for an optimal amount of water, which mathematically corresponds to the value of the maximum slope of a function that relates the yield and the total amount of water used.

The grain yield in the three treatments did not present a statistical difference and was similar in all three cases to the national average of irrigated corn, which is reported with a value of 8.7 t ha^{-1} (SIAP, 2024). The lowest yield occurred under traditional irrigation with 7.96 t ha^{-1} and differed by 0.63 t ha^{-1} from the highest yield, 8.6 t ha^{-1}, expressed under technified irrigation; the difference was only 0.34 t ha^{-1} between technified irrigation and rainfed conditions (8.26 t ha^{-1}); these results are similar to those reported by Fernández-Ortiz *et al*. (2022), where the irrigation results were better than rainfed management.

The grain yield under rainfed conditions was not statistically different from the other treatments; on the other hand, the total water volume was lower, which coincides with what was reported by Montesillo-Cedillo (2016), where the production of rainfed corn presented a lower social and environmental cost in terms of water.

The irrigation results are consistent with what was reported by Rosano-Méndez *et al*. (2001), where technified irrigation did not show a statistical difference but was higher by up to 0.3 t ha^{-1} compared to conventional irrigation in addition to representing a water saving of 37%. In this work, the difference in sheet was 42.5 mm, which represented a 6.4% saving of water when using technification. Flores-Gallardo *et al*. (2014) found a difference between the application of technified gravity irrigation in corn and traditional gravity irrigation; in this case, management variants, such as alternate furrow irrigation, were applied, which improved the indicators of plot efficiency. The relevance of these results for the High Valleys allows us to make informed decisions about the technification of irrigation of one of the main crops in the region.

Comparison of means between genotypes

The means between genotypes showed statistical differences as a single effect in some variables. PH was higher in the Cedillo variety with 2.2 m, whereas the ATZIRI PUMA hybrid had the lowest height with 1.85 m. The highest number of grains per row was shown by the H-50 hybrid (34 grains) (Table 2).

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Table 2. Comparison of means of the variables by simple effect of the genotype factor in the spring-summer cycle of 2022.

Genotype	PH (cm)	GR	YIE (t ha^{-1})	WU (kg m^{-3})
Cedillo variety	224a	30ab	5.81c	1c
H-49 AE	198bc	32ab	8.83ab	1.5ab
H-53 AE	204ac	32ab	8.99ab	1.5ab
H 50	212ab	33a	9.93a	1.7a
(246 x 242) x MIA46	201bc	32ab	8.12ac	1.4ab
TSIRI PUMA	189c	30ab	7.43bc	1.3bc
TLAOLI PUMA	188cd	31ab	8.95ab	1.5ab
ATZIRI PUMA	185c	29b	7.33bc	1.3bc
IXIM PUMA	192bc	32ab	7.44bc	1.3bc
CUXI PUMA	194bc	32ab	9.95a	1.7a
HSD	22	4.19	2.36	0.41

The means with the same letter, by variable, are statistically equal (Tukey, $p < 0.05$); PH= plant height; GR= grains per row; YIE= grain yield; WU= water use; HSD= honestly significant difference.

Grain yield and water use behaved similarly since they are variables with a direct relationship. The highest averages were shown by the IXIM PUMA and H-50 hybrids, both with 9.9 t ha^{-1} and 1.7 kg m^{-3}, whereas the Cedillo variety had 5.8 t ha^{-1} and 1 kg m^{-3}. The highest productivity presented in the study was higher than the optimal value reported by Inzunza-Ibarra *et al*. (2018) and is related to the productive potential of the IXIM PUMA and H-50 hybrids in the High Valleys, as reported by Espinosa-Calderón *et al*. (2022).

Some variables, such as the number of grains per row, are positively correlated with yield and therefore with water use. The differences between the hybrids are due to their genetic conformation and the conditions that prevailed throughout the experiment as a genotype-environment expression (Fernández-Ortiz *et al*., 2022).

Means of interactions

The significant interaction of hybrid by moisture management presented by the highest ear height (1.4 m) with the Cedillo variety under rainfed conditions, an outstanding characteristic of this variety for conditions of low water availability; on the other hand, the ATZIRI PUMA hybrid had the lowest ear height (72 cm) under technified irrigation conditions, which represents an advantage because, under irrigated conditions, if the plants are tall, they are more susceptible to lodging when the soil is moistened, as also reported by Alonso-Sánchez *et al*. (2022).

The number of rows per ear was higher (18 rows) for the experimental three-way cross hybrid (246 x 242) x MIA46 under traditional irrigation, whereas it was lower for the same hybrid under technified irrigation (12 rows). This response indicates a differential behavior for this hybrid depending on moisture availability. The ear diameter was superior (4.9 cm) for the H-50 under rainfed conditions and the lowest was (4 cm) for the experimental three-way cross hybrid with technified irrigation; this response contradicts the larger diameters under irrigation conditions reported by Castellanos *et al*. (2019) for corn hybrids from El Bajío.

The interactions of the variables in Table 3 are related to the total amount of water that entered each treatment and their determination when interacting with the genotypes (Alonso-Sánchez *et al*., 2023). The interactions did not present significance in the yield and water use of the hybrids, which indicated their stability in production when subjected to gradients of moisture availability in the same environment, as also reported by Mendoza-Pérez *et al*. (2016); however, water management differentials represent an opportunity to reduce the amount of water in the case of hybrids under irrigation, which should be verified with more research related to deficit irrigation using the same genotypes, if possible.

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Table 3. Comparison of means of three variables with interaction of the factors: corn hybrids and moisture availability management in the spring-summer cycle of 2022.

Hybrid	EH (cm)			RE (No.)			ED (cm)		
	CI	TI	RAI	CI	TI	RAI	CI	TI	RAI
Cedillo	127ab	92bd	141a	14ac	15ac	13bc	4.3ac	4.5ac	4.1bc
H-49 AE	85bd	102ad	82cd	16ac	17ab	16ac	4.5ac	4.8ab	4.7ac
H-53 AE	99ad	95bd	90bd	16ac	17ab	16ac	4.4ac	4.8ac	4.7ac
H 50	111ad	94bd	106ad	17ac	16ac	17ab	4.8ab	4.8ab	4.9a
(246 x 242) x MIA46	83cd	125ac	86bd	18a	12c	15ac	4.7ac	4c	4.6ac
TSIRI PUMA	79d	80d	82cd	17ac	14ac	16ac	4.8ac	4.5ac	4.5ac
TLAOLI PUMA	71d	87bd	80d	15ac	16ac	14ac	4.7ac	5a	4.4ac
ATZIRI PUMA	81d	72d	73d	16ac	16ac	17ac	4.6ac	4.6ac	4.4ac
IXIM PUMA	80d	85bd	87bd	14ac	14ac	16ac	4.4ac	4.8ab	4.6ac
CUXI PUMA	87bd	81cd	90bd	16ac	15ac	16ac	4.8ab	4.7ac	4.6ac
HSD		43.7			4.4			0.7	

EH= ear height; RE= rows per ear; ED= ear diameter; RE= rows per ear; HSD= honestly significant difference; CI= conventional irrigation; TI= technified irrigation and RAI= rainfed conditions. The means with the same letter within the columns of each response variable are statistically equal (Tukey, $p < 0.05$).

The production of hybrids under rainfed conditions represents an opportunity for sustainable food production (Alonso-Sánchez *et al*., 2022) due to the fact that the use of dams or wells is null. The results of this research could be a reference for other work aimed at contributing to the water and food security of corn production in order to identify genotypes tolerant to water deficit conditions in a scenario of resilience to climate variability.

Conclusions

The hybrids evaluated showed stability in yield since some share parents in their genetic structure, except for the Cedillo variety, which had the lowest yield. The cultivation of rainfed corn continues to be the option with which good productivity is obtained as long as there are genotypes tolerant to adverse water conditions.

Under conditions similar to those of this work, it turns out to be an alternative to reduce water consumption by irrigation and use it for other uses, such as water for human consumption. The hybrids did not show a reduction in yield compared to conventional irrigation in this experiment, considering the edaphic, climatic, and genotype conditions.

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