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Article

Morphological and physiological components of corn yield in response to density and date of sowing in Toluca

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Abstract

Grain yield in corn is a function of the genotype, agronomic management, and environmental conditions where it is grown. This research aimed to study the impact of sowing date and plant density on grain yield and its components in four corn genotypes for the High Valleys of Mexico. The experiment was conducted in the Toluca Valley during the spring-summer cycle of 2022. The evaluation considered two three-way cross hybrids: Faisán® and Cherokee®, and two native cultivars: Nativo Blanco and Amarillo Zanahoria, under four plant densities: 50 000, 60 000, 70 000 and 80 000 plants ha^{-1}, on three sowing dates in March, April, and May. In each sowing date, a randomized complete block design was used, with four replications. The results showed the highest grain yield, 6.7 t ha^{-1}, in the May sowing, supported by an increase in biomass, harvest index, number of grains per m^2, number of grains per ear of corn, and plant height. Of the four genotypes assessed, the Faisán hybrid presented the highest grain yield, which was associated with a higher number of grains per m^2. The increase in plant density increased grain yield with 80 000 plants ha^{-1}, which was explained by a higher number of ears of corn per m^2. The interaction of date x cultivar x density revealed the highest grain yield, 8.3 t ha^{-1}, in the May sowing with the Nativo Blanco cultivar and a density of 80 000 plants ha^{-1}.

Keywords:

Zea mays L., plant density, sowing date.

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Introduction

Corn (*Zea mays* L.) is one of the most important cereals globally (Desloires *et al*., 2024). The world area sown with this crop is 203 470 007 ha, with a production of 1 163 497 383 t and an average yield of 5.7 t ha^{-1} (FAOSTAT, 2022). In Mexico, 6 777 997 ha were harvested in 2022, with a production of 26 625 693 t and an average yield of 3.9 t ha^{-1} (FAOSTAT, 2022).

Grain yield can be explained from the number of grains per m^2 and individual grain weight, growth and biomass partitioning (Andrade *et al*., 2023). The number of grains per m^2 is defined around anthesis, a period in which the crop requires optimal environmental conditions to determine the number of ears of corn per m^2 and the number of grains per ear (Andrade *et al*., 1999).

The ecophysiological processes that regulate the formation of reproductive structures are key to maximizing grain yield in corn (Andrade *et al*., 2023). This responds to genetic factors, agronomic management, and the environment of each site (García *et al*., 2020; Djaman *et al*., 2022).

It is known that modifying the sowing density and date produces morphological and physiological changes that regulate plant growth and development (Djaman *et al*., 2022). Likewise, it is also know that a high plant density reduces light interception, leaf area index, and leaf photosynthesis (Raza *et al*., 2019; Feng *et al*., 2019).

In contrast, a low plant density improves resources per plant, allowing for tillering expression and prolificacy (Maltense *et al*., 2022). In the southwestern United States, when evaluating six plant densities from 54 700 to 120 100 plants ha^{-1} in 2019 and 2020, Djaman *et al*. (2022) observed the highest yield, 16 800 kg ha^{-1}, under the density of 101 700 plants ha^{-1}, which was statistically similar to 17 000 kg ha^{-1} with a density of 88 000 plants ha^{-1}. For its part, the sowing on May 18 showed the highest grain yield, 17 000 kg ha^{-1}, with a density of 88 000 plants ha^{-1}.

In areas with environmental restrictions in Argentina, low plant density and late sowing stabilized grain yield by improving the use of resources, increasing the reproductive and vegetative plasticity of corn (Otegui and Mercau, 2021; Maddonni *et al*., 2021; Massigoge *et al*., 2022).

At this site, the density of 3.6 plants m^{-2} obtained a higher grain yield compared to 7.3 plants m^{-2}. In contrast, the hybrids DK69-10 and DM2738 showed yields of 6 952 kg ha^{-1}, with a 30.5% contribution to the total yield through tillers (Maltense *et al*., 2022).

In the High Valleys of Mexico, Tadeo *et al*. (2015) evaluated the yield of four cultivars: Ixtlahuaca and Atlacomulco (native) and H-50 and H-52 (hybrids), under two sowing and harvesting dates, at a density of 60 000 plants ha^{-1}, and observed the highest yield in the sowing on May 17 and harvest at 177 and 160 days, 8 570 kg ha^{-1} and 7 488 kg ha^{-1}. On the other hand, the sowing on June 1 and harvesting at 162 and 145 days decreased grain yield, 7 185 kg ha^{-1} and 6 082 kg ha^{-1}.

Likewise, Martínez *et al*. (2018) evaluated the grain yield of 10 corn hybrids in five environments and sowing dates (Cuendó April 5, Jocotitlán April 13, Ixtlahuaca April 23, Temascalcingo May 3, and Jilotepec May 25), and a sowing density of 95 000 plants ha^{-1}, and observed that the hybrid with the highest productivity was Atziri Puma, 12 t ha^{-1}. For its part, the highest average yield was observed in Jocotitlán, with 12.4 t ha^{-1} of grain.

For their part, Quiroz *et al*. (2017), when evaluating 10 corn cultivars in three localities with three sowing densities, 104 167, 78 125, and 62 500 plants ha^{-1}, observed that at 104 167 plants ha^{-1}, the yield was 10.03 t ha^{-1}, whereas the cultivar P204W obtained the highest grain yield, 10 t ha^{-1}.

Finally, Espinosa *et al*. (2013), when evaluating the grain yield of early yellow-grained corn cultivars for the High Valleys of Mexico, planted in June under rainfed conditions, with 45 000 plants ha^{-1}, observed the highest grain yield with the cultivar Oro Ultra UNAM C, 6 913 kg ha^{-1}.

Therefore, the optimal sowing date and density should be determined according to local conditions (Djaman *et al*., 2022; Andrade *et al*., 2023). In the High Valleys area of Mexico, it is necessary to generate and update information regarding the generation of grain yield in corn. This research aimed to study the impact of sowing date and density on grain yield and its components for four corn cultivars in Toluca, state of Mexico.

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Materials and methods

Experimental site

The experiment was conducted in the spring-summer cycle of 2022 at the Faculty of Agricultural Sciences of the Autonomous University of the State of Mexico, located 18 km north of the city of Toluca, with geographical coordinates of 19° 15' 33" north longitude, 99° 39' 38" west latitude and at an altitude of 2 640 m. According to the Köppen climate classification, modified by García (1988), the predominant climate is type C (w2) (w) b (i), which corresponds to a temperate subhumid climate with rains in summer and little precipitation in winter (5%), average annual temperature of 14 °C, and average annual precipitation of 900 mm (González *et al*., 2009).

Treatments and experimental design

The evaluation considered two commercial three-way cross corn hybrids: Faisán and Cherokee (Table 1) and two native corn: Nativo Blanco, from the locality of El Cerrillo Piedras Blancas, and Amarillo Zanahoria from ICAMEX on three sowing dates (March 4, April 5, May 4) and four plant densities 50 000 plants ha^{-1} (plants 25 cm apart), 60 000 plants ha^{-1} (plants 20 cm apart), 70 000 plants ha^{-1} (plants 17 cm apart) and 80 000 plants ha^{-1} (plants 15 cm apart).

Table 1. Characteristics of hybrid corn evaluated.

	C	MOD	DTF	DTM	EH (m)	PH (m)	DEN	MASL
Genotype								
Cherokee	Intermediate	Irrigated and rainfed	90-95	185-190	1.39	2.1	90 000	2000-2700
Faisán	Late intermediate	Irrigated and rainfed	90-95	185-190	1.1-1.15	2.25-2.45	60 000	2000-2700

Cycle (C); modality (MOD); days to flowering (DTF); days to maturity (DTM); ear height (EH); plant height (PH); plant density (DEN); meters above sea level (MASL) (ASPROS®, 2022).

Each plot was made up of four rows 80 cm apart, with a length of 5 m each. Each date was considered as a particular environment, using an experimental design of randomized complete blocks with four replications.

General experiment conditions

To guarantee the desired densities, tapes marked with the distances between plants already mentioned were used. The March and April sowings had an initial irrigation, whereas the May sowing was under rainfed conditions. The crop was kept free of weeds by chemical control (Gesaprim Caliber 90© 2 kg of ai ha^{-1} as a pre-emergent herbicide and Peak Turbo© 500 g of ai ha^{-1} as a post-emergent herbicide).

At sowing, it was fertilized with the NPK dose (69-46-60) using urea, triple calcium superphosphate, and potassium chloride as sources. Subsequently, after 70 days, it was fertilized with 138 kg of N ha^{-1}. Phenological follow-up was recorded throughout the cycle.

Yield and its components

Morphological components: at physiological maturity of the two central furrows of each plot, 10 plants with full competence were selected, each one was measured in height, and the ears were harvested and counted. These were shelled separately to obtain the dry weight of the grain, which was adjusted to 14% moisture in the drying oven. Grain yield was calculated by adding the grain of the 10 plants, weighing it, and dividing it by the area they covered.

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The total ears harvested from the 10 plants was divided by the area they covered to obtain the number of ears per m^2. The number of grains per ear was obtained by counting the grains of each ear, and the number of grains per m^2 was obtained by dividing the total grains of the 10 plants by the area they occupied. The weight of 1 000 grains was determined by counting and weighing 1 000 grains taken from the total grains of the 10 plants. Finally, the prolificacy index was obtained by dividing the sum of the harvested ears in the 10 plants by 10.

Physiological components: the dry matter of the 10 plants was weighed and divided by the area they occupied to obtain the biomass. The harvest index was obtained by dividing the grain yield by the biomass.

Climatic conditions

The temperature and precipitation for the stages (E= emergence, VT= male flowering, R1= female flowering, R6= physiological maturity) were taken from the Davis® Vantage Pro-2 weather station located at the site where the experiment was conducted.

Statistical analysis

The response variables of the experiment were subjected to a combined analysis of variance. When the F-test of the analyses of variance was significant, the separation of means was performed through the honestly significant difference (HSD), or Tukey test at a significance level of 5%. The statistical package used was R for Windows version 4.0.5.

Results and discussion

Climatic conditions

The climatic conditions during the experiment are shown in Figure 1, in which it is observed that the high temperature and low precipitation occurred from the vegetative period until flowering for the corn planted in March, replicating in the vegetative period of the corn planted in April. In contrast, for corn planted in May, these conditions were favorable during the cycle.

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Figure 1. Agroclimatic conditions that occurred during the conduct of the experimental work. E= emergence; VT= male flowering; R1= female flowering; R6= physiological maturity.

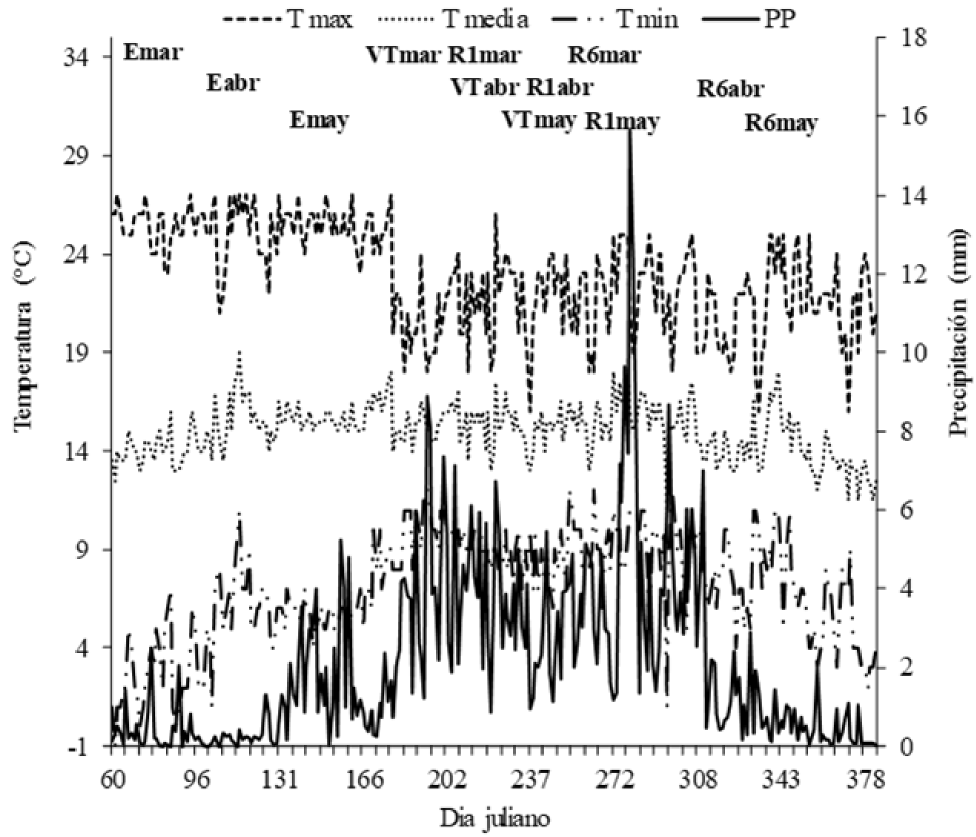

Table 2 shows the F-values and their statistical significance for the variables studied, where significant effects are seen in most of the variables for the date and cultivar factors. For the density factor, there were significant differences for grain yield, biomass at maturity, number of grains per m^2, number of ears per m^2, and plant height.

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Table 2. F-values and their statistical significance for yield*.

SV	df	YIE	HI	BIOMM	NG	W1000G	PI	NE	NGEA	PH
Date	2	69.7**	6.7*	103**	467.6**	29.3**	11.8**	119.3**	210.8**	425.6**
Cultivar	3	118.5**	3*	113.5**	46.4**	30.6**	1.8ns	80.8**	46.6**	1354.7**
Density	3	140.7**	0.2ns	218.5**	60.3**	1.7ns	0.8ns	196.9**	4**	13.7**
C x De	9	7.2**	1.5ns	12.4**	1.5ns	2*	1.4ns	9**	5.1**	15.4**
Da x C	6	34.2**	9.7**	11.5**	9.7**	11.9**	0.7ns	13.2**	17.5**	38.9**
Da x De	6	4.9**	2.3*	10.1**	5.7**	4.1**	0.6ns	2.9*	4.0**	21.6**
Da x C x De	18	2.6**	2.9**	13.5**	4.1**	6.4**	0.6ns	5.9**	5.2**	17.3**
Error (MS)	135	2535.6	0.001	10920.5	53763.3	487.4	0.003	0.2	707.6	0.06
CV (%)		3.3	9.4	6.5	12	21	15.9	6.8	10.1	3.6

Souece of variation (SV); degrees of freedom (df); yield of grain (YIE); harvest index (HI); biomass at maturity (BIOMM); number of grains per m^2 (NG); weight of one thousand grains (W1000G); prolificacy index (PI); number of ears per m^2 (NE); number of grains per ear (NGEA) and plant height (PH) for four corn cultivars in Toluca, Mexico. MS= mean square; *= significant at 0.05; **= significant at 0.01 and ns= not significant.

In the cultivar-by-density interaction, there were significant effects in most variables, except for the harvest index, number of grains per m^2, weight of 1 000 grains, and prolificacy index. For the date-by-cultivar interaction, significant effects (p< 0.05) were observed in most variables, except for the prolificacy index.

In the date-by-density interaction, there were significant effects on grain yield, biomass at maturity, number of grains per m^2, weight of 1 000 grains, number of grains per ear, and plant height. For the date-by-cultivar-by-density interaction, significant effects were observed for grain yield, harvest index, biomass at maturity, number of grains per m^2, weight of 1 000 grains, number of ears per m^2, number of grains per ear, and plant height.

Table 3 shows that the corn sown in May was higher than the corn sown in April and March. In grain yield, by 18% and 15%, harvest index by 8% and 2%, biomass at maturity by 6% and 11%, number of grains per m^2 by 36% and 32%, and plant height by 7% and 23%, respectively. In contrast, the corn planted in March was higher than the corn planted in April and May in terms of the weight of 1 000 grains.

Table 3. Comparison of averages for yield.

	YIE (g m^2)	HI	BIOMM (g m^2)	NG (m^2)	W1000G(g)	PI	NE (m^2)	NGEA	PH (m)
				Date					
March	578.14b	0.38ab	1511.42c	1677.58c	334a	1.21a	7.81a	323.17a	1.91c
April	564.14b	0.36b	1597.95b	1792.86b	317.34b	1.22a	7.93a	243.2b	2.28b
May	673.34a	0.39a	1695.97a	2300.58a	303.51c	1.1b	6.95b	323.17a	2.44a
HSD	28.09	0.02	35.9	60.52	11.12	0.07	0.19	14.94	0.05
				Cultivar					
Cherokee	591.06c	0.38a	1518.83b	1871.71b	323.16b	1.23a	8.13a	244.93b	1.89c
C. Blanco	637.52b	0.37a	1759.56a	1931.54b	340.85a	1.17a	6.98b	281.29a	2.77a
Faisán	689.33a	0.39a	1710.85a	2221.71a	301.2c	1.16a	8.16a	286.08a	2.32b
A. Zanahoria	502.92d	0.37a	1417.88c	1669.73c	307.91c	1.14a	6.99b	233.37b	1.87c
HSD	26.73	0.01	55.49	123.12	11.72	0.09	0.27	14.12	0.04
				Density					
50 000	490.92c	0.38a	1291.98d	1545.79c	322.52a	1.18a	6.09d	265.33ba	2.22a

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	YIE (g m^2)	HI	BIOMM (g m^2)	NG (m^2)	W1000G(g)	PI	NE (m^2)	NGEA	PH (m)
60 000	586.27b	0.37a	1593.5c	1974.48b	318.62a	1.2a	7.66c	255b	2.23a
70 000	674.33a	0.38a	1725.27b	2130.58a	319.54a	1.15a	7.98b	270.41a	2.15b
80 000	669.31a	0.37a	1796.38a	2043.83ba	312.45a	1.16a	8.53a	254.93b	2.25a
HSD	26.73	0.01	55.49	123.12	11.72	0.09	0.27	14.12	0.04
Mean	605.2	0.37	1601.78	1923.67	318.28	1.17	7.56	261.41	2.21

Yield of grain (YIE); harvest index (HI); biomass at maturity (BIOMM); number of grains per m^2 (NG); weight of one thousand grains (W1000G); prolificacy index (PI); number of ears per m^2 (NE); number of grains per ear (NGEA) and plant height (PH) for four corn cultivars in Toluca, Mexico. Means with the same letter within columns do not differ significantly from each other at a significance level of 0.05 of the Tukey test.

For the genotype factor, Faisán showed superiority in grain yield, by 8.5%, 16% and 30% and in number of grains per m^2 by 15%, 18% and 28% compared to Nativo Blanco, Cherokee and Amarillo Zanahoria, respectively. On the other hand, Nativo Blanco was superior in weight of 1 000 grains by 5.5%, 12% and 10%, and plant height by 40%, 18% and 40% to the cultivars Cherokee, Faisán and Amarillo Zanahoria, respectively.

Finally, for the density factor, with 80 000 plants ha^{-1}, a higher biomass production at maturity was achieved, by 4%, 12%, and 31% and a higher number of ears per m^2 by 7%, 12%, and 33% compared to 70 000, 60 000 and 50 000 plants ha^{-1}, respectively.

In general, for the three sowing dates, the four cultivars showed increases in their yields as the sowing density increased. Grain yield increased by 95.2 kg from March to May (Figure 2, Table 3). In the March sowing, Faisán presented the highest grain yield (7.9 t ha^{-1}) with 80 000 plants ha^{-1}, whereas Cherokee, Amarillo Zanahoria and Nativo Blanco showed a reduction in grain yield when going from 70 000 to 80 000 plants ha^{-1}.

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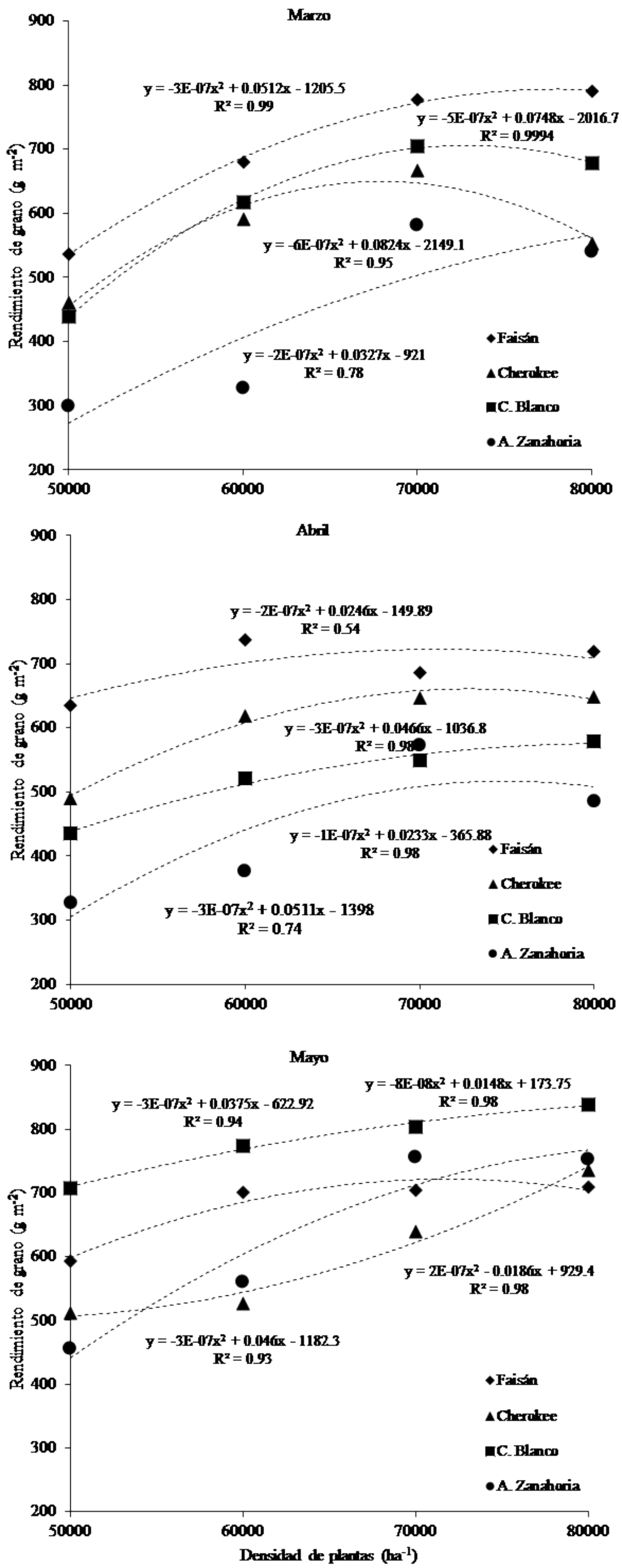
Figure 2. Relationship between grain yield and plant density for four corn varieties grown at four densities and three dates of sowing in Toluca, Mexico.



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At the April sowing, the response to the increase in the plant density of the hybrids was the increase in grain yield compared to native cultivars. Again, Faisán had the highest grain yield (7.3 t ha^{-1}) with 60 000 plants ha^{-1}.

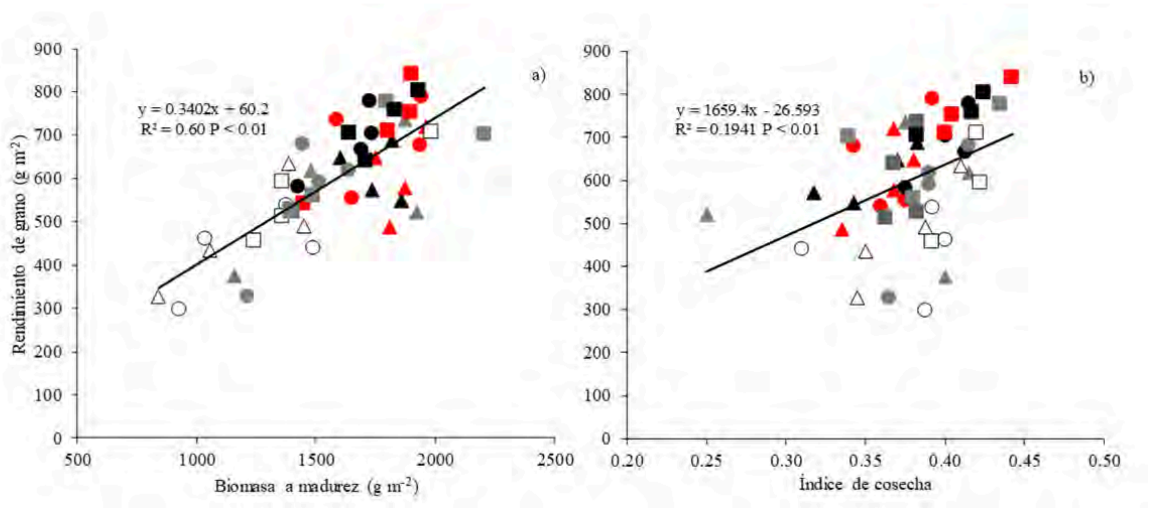
On the contrary, in the May sowing, the best response to the increase in sowing density was of the native cultivars, where the highest grain yield (8.3 t ha^{-1}) was observed with the Nativo Blanco cultivar with 80 000 plants ha^{-1} (Figure 2).

Recent studies have shown that changes in the harvest index are a consequence of genetic improvement and not of corn agronomic management (Ruiz *et al*., 2023). This component has not presented significant changes and increases in grain yield in corn have been attributed to increases in sowing density, that is, a higher biomass production per m^2 (Hütsch and Schubert, 2017).

In this research, it was observed that the Faisán and Nativo Blanco cultivars planted in May at 80 000 plants ha^{-1} presented the best values in biomass production (Table 3). This could be explained by the average contribution rate of biomass and harvest index to grain yield, of 73% and 26%, respectively, reported by Liu *et al*. (2020).

The three sowing dates showed an increase in grain yield as plant density increased (Figure 2). The changes in grain yield when considering the cultivar and the date and density of sowing were mainly explained by the changes in biomass production at maturity (r^2= 0.6, p< 0.01) (Figure 3a) and not by the harvest index (r^2= 0.19, p< 0.01), which showed greater stability as reported by Liu *et al*. (2020); Ruiz *et al*. (2023) (Figure 3b).

Figure 3. Relationship between grain yield and biomass at maturity (a) and harvest index (b) for four corn cultivars grown under four plant densities on three sowing dates in Toluca, Mexico. Triangle= April sowing, circle= March sowing, square= May sowing; white= 50 000; gray= 60 000; black= 70 000 and red= 80 000 plants ha^{-1}.



In their study, Jiang *et al*. (2020) mention that the late sowing date negatively affects grain yield through low biomass production. However, in this research, the highest grain yield attributable to higher biomass production was observed in corn planted in May, which was favored by environmental conditions (Figure 1), with the Nativo Blanco cultivar standing out (Figure 3a).

The results show that the changes in grain yield due to the joint effect of the date and density of sowing are mainly explained by the changes in the number of grains per m^2 (r^2= 0.65, p< 0.01) (Figure 4a), mainly in densities of 70 000 and 80 000 plants ha^{-1}. In contrast, grain weight is mainly affected by other factors such as nitrogen input (Fernández *et al*., 2022).

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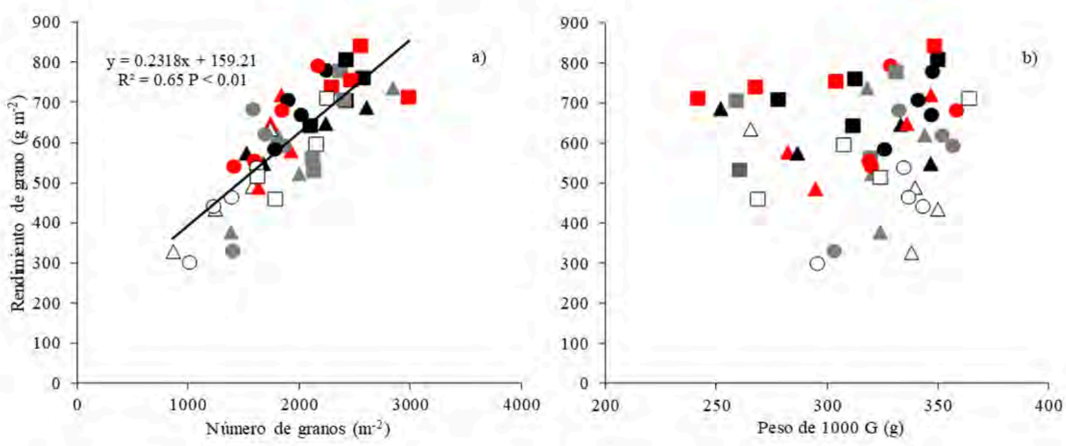
Figure 4. Relationship between grain yield per m^2 and number of grains per m^2 (a) and weight of 1 000 grains (b) for four corn cultivars grown under four plant densities on three sowing dates in Toluca, Mexico. Triangle= April sowing, circle= March sowing, square= May sowing; white= 50 000; gray= 60 000; black= 70 000 and red= 80 000 plants ha^{-1}.



Nonetheless, this study did not evaluate this effect, but it could explain the non-existent relationship between weight and grain yield in terms of the effect of sowing date and plant density (Figure 4b). On the other hand, Ferraris *et al*. (2020), in a study carried out in Argentina using sowing densities of 65 000, 75 000 and 90 000 plants ha^{-1}, concluded that, in late sowings, grain yield is positively correlated with the number of grains and plant height, coinciding with the results of this research (Figure 4a and Table 3).

When analyzing the components of the number of grains m^2, the variations in this component were associated to a greater extent with the number of ears per m^2. Regarding this component, the corn sown in March (7.8) and April (7.9) were statistically equal, whereas between Cherokee and Faisán (8.1), there was no difference.

Finally, the density of 80 000 plants ha^{-1} with (8.5) was higher than the rest of the plant densities evaluated (Table 3 and Figure 5b). In the number of grains per ear, no statistical differences were observed (Table 3 and Figure 5a), which coincides with Espinosa *et al*. (2013), who did not find significant differences in the number of grains per ear when determining the productive capacity of yellow-grained cultivars.

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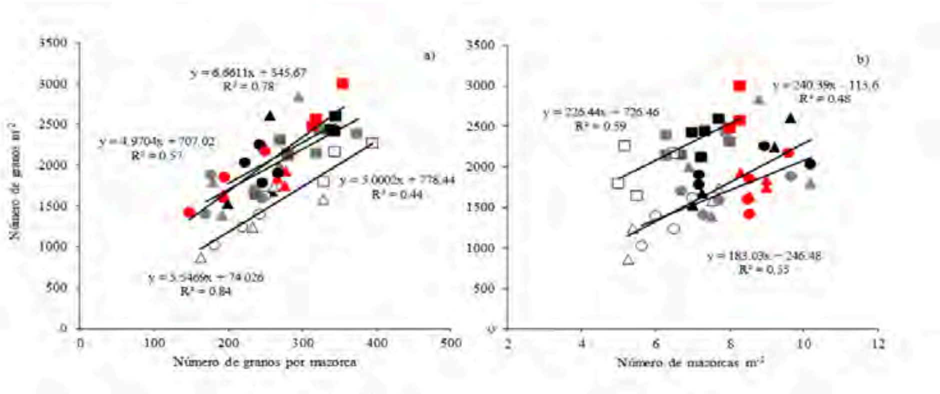
Figure 5. Rela onship between the number of grains per m2 and the number of grains per ear (a) and the number of ears per m2 (b) for four corn cul vars grown under four plant densi es on three sowing dates in Toluca, Mexico. Triangle= April sowing, circle= March sowing, square= May sowing; white: 50 000; gray= 60 000; black= 70 000; and red= 80 000 plants ha^{-1}.



Conclusions

Sowing densities and dates influenced the grain yield of the four cultivars. The late sowing date increased the biomass, number of grains per m^2, number of grains per ear, and plant height. Faisán showed the highest grain yield, which was associated with a higher number of grains per m^2, but not in the May sowing. The increase in plant density increased grain yield with 80 000 plants ha^{-1}, which is explained by a higher number of ears per m^2.

Climate change was emphasized in 2022, so the sowings in March and April were affected by the high temperatures and low rainfall after the emergence. The date-by-cultivar-by-density interaction revealed the highest grain yield, 8.3 t ha^{-1}, in May sowing with the Nativo Blanco cultivar at 80 000 plants ha^{-1}.

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