Production, nutritional quality and profitability of forage maize hybrids (*Zea mays* L.) in a semi-desert region of northern Mexico

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ABSTRACT

Objective: To evaluate yield, nutritional quality, and profitability of four forage-corn hybrids under two plant densities and subsurface drip irrigation across two growing seasons in the Laguna region.

Design/Methodology/Approach: The research was carried out at the La Laguna Experimental Field of INIFAP (National Institute of Forestry, Agriculture and Livestock Research). Four forage-corn hybrids were used: 2620, Zamorano, P3270 and P3097. Planting was performed manually on March 15 for the spring season and July 10 for the summer season. Two plant densities were tested: 100 000 and 150 000 plants per hectare. The experiment was arranged in a randomized complete block design with three replications. Subsurface drip irrigation was employed. Evaluated variables included plant height, leaf-area index, biomass accumulation, green forage yield, dry forage yield, water-use efficiency, nutritional quality and profitability. Treatment means differences were compared by Tukey's test ($\alpha = 0.05$).

Results: The density×hybrid and density×season interactions were not significant; however the season×hybrid interaction was significant. Green-forage and dry-forage yields were greater in the spring growing season. Hybrid P3270 achieved the highest yields of green forage ($81.77\,\text{t ha}^{-1}$) and dry forage ($25.29\,\text{t ha}^{-1}$). It also presented the highest starch concentration and the best benefit-to-cost (B/C) ratio (2.80), meaning that for every peso invested it returned 1.80 pesos.

Limitations/Implications: No limitations were identified in the present study.

Findings/Conclusions: Under the semi-arid conditions of the Comarca Lagunera in northern Mexico, increasing plant density to 150 000 plants ha^{-1} did not result in benefit. Yields of green and dry forage were higher in the spring season. Hybrid P3270 delivered the highest dry-forage yield, water-use efficiency, starch concentration and B/C ratio.

Keywords: water use, starch, plant density.

INTRODUCTION

Water scarcity is a global concern. Water demand worldwide has increased exponentially as a result of population growth, with agriculture accounting for 74% of total water use (Christ & Burritt, 2017). According to the FAO, the global population is projected to reach around nine billion by 2050, and food demand is expected to increase by 60% (Bijl *et al.*, 2017; Falcón *et al.*, 2022). Thus, one of the greatest challenges in achieving global food sovereignty is to produce more using limited natural resources such as water and soil (Yang *et al.*, 2022). Consequently, improving water use efficiency (WUE) through enhanced irrigation technology and increasing crop productivity has become a top priority. In this regard, drip irrigation is a modern and efficient method of irrigation in terms of water productivity, as it reduces water loss through percolation and evaporation (Flores *et al.*, 2021). Drip irrigation can significantly increase crop yields by 28.92%, 8.03%, and 2.32% compared to sprinkler, border, and furrow irrigation systems, respectively (Yang *et al.*, 2023). These improvements are achieved by applying irrigation in accordance with the crop's water needs, which vary depending on the phenological stage and climatic conditions (Reyes *et al.*, 2023). Forage corn (*Zea mays* L.) is one of the most important forage crops globally due to its high biomass yield and nutritional value (Fuksa *et al.*, 2023). Biomass yield varies depending on the hybrid used (Hong *et al.*, 2019), as each genotype forms a different canopy structure. Specifically, compact genotypes with high density tolerance can form an ideal canopy structure with a high light interception rate, increased photosynthetic area, and improved productivity (Li *et al.*, 2020). Thus, strategically increasing planting density stands out as an option to improve corn yield, as noted in recent studies (Zhang *et al.*, 2022). However, some studies suggest that high plant densities may reduce forage quality, primarily due to lower grain content (Pinter *et al.*, 1990). Negative relationships have been observed between planting density, yield, and quality parameters, particularly plant digestibility and starch content. The latter is closely associated with ear proportion, making it a key factor in determining the overall nutritional value of the plant (Hakl *et al.*, 2017; Graybill *et al.*, 1991). Therefore, considering the above, the aim of this study was to evaluate yield, nutritional quality, and profitability of four forage corn hybrids under two planting densities and subsurface drip irrigation across two growing seasons in a semi-arid region of northern Mexico.

MATERIALS AND METHODS

Study area

The study was conducted at the La Laguna Experimental Field, part of the National Institute of Forestry, Agricultural and Livestock Research (INIFAP), located in Matamoros, Coahuila, Mexico (25° 31' 51.31" N, 103° 14' 32.18" W) at an elevation of 1150 meters above sea level. The region experiences a maximum temperature of 45 °C, minimum temperatures ranging from 0 to 8 °C, and an annual average temperature of 24 °C. The average annual precipitation is 242 mm, and the reference evapotranspiration (ET) is approximately 2000 mm (Villa *et al.*, 2005). This northern region of Mexico, known as the Comarca Lagunera, is characterized by a semi-arid climate [BW(h')hw(e)], marked by low precipitation and cold winters.

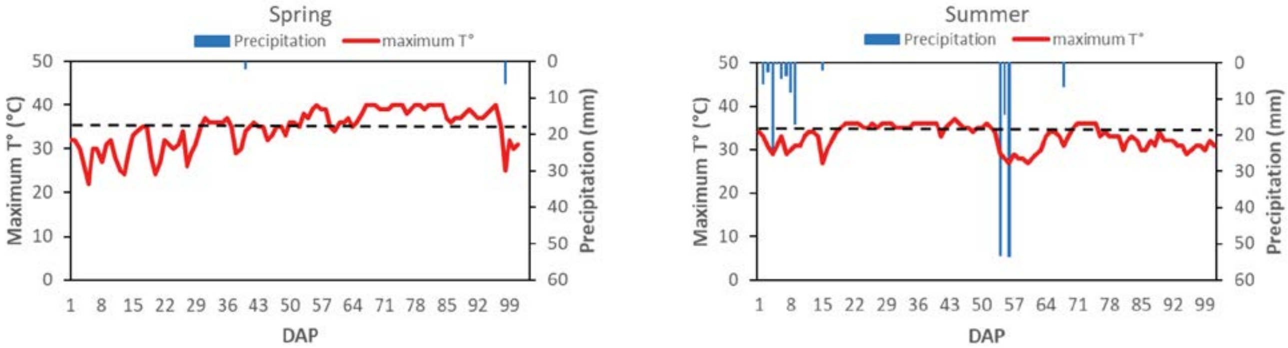

Figure 1. Precipitation and maximum temperature during the spring and summer cycles in the Comarca Lagunera, northern Mexico.

Climate

Rainfall events and daily maximum temperatures recorded during the cropping seasons are shown in Figure 1. In the spring cycle, a total of 6 mm of precipitation was recorded, while the summer cycle accumulated significantly more rainfall at 203 mm. During the study period, daily maximum temperature trends differed between the two cycles. In spring, peak temperatures occurred during the reproductive stage, whereas in summer, they were observed during the vegetative stage of the crop. The black dashed line indicates the critical maximum temperature threshold (35 °C), above which maize growth and development are inhibited (Lobell *et al.*, 2013).

Four maize hybrids (2620, Zamorano, P3270, and P3097) were evaluated. These hybrids are classified as intermediate-cycle materials (100-110 days), exhibit semi-erect leaves, and are suitable for high planting densities. Consequently, two population densities were assessed: 100,000 and 150,000 plants ha^{-1}. The first density corresponded to single-row planting with 0.76 m spacing between rows and an intra-row spacing of 12.5 cm. The second density used paired rows, with 20 cm between lines within the pair and 17.5 cm spacing between plants. Sowing was performed manually under dry conditions on 15 March 2024 for the spring cycle and on 10 July 2024 for the summer cycle. Land preparation consisted of plowing, disking, leveling, and installation of subsurface drip irrigation tape. Fertilization rates were 200-100-00 (N-P-K) for the 100,000-plant treatment and 300-100-00 (N-P-K) for the 150,000-plant treatment (Torres *et al.*, 2016). UAN-32 served as the nitrogen source and phosphoric acid as the phosphorus source. Fertilizers were split and applied weekly according to crop phenology through the subsurface drip irrigation system (SDI) using a Venturi injector. For the SDI system, RO-DRIP 8 mil irrigation tape (Rivulis Irrigation Inc., San Diego, CA, USA) was used, with a wall thickness of 0.2 mm, an internal diameter of 16 mm, emitter spacing of 0.2 m, and a discharge rate of 0.5 L h^{-1} per emitter. The tape was buried at a depth of 0.15 m and spaced 0.76 m apart. Irrigation was applied every third day. Total irrigation depth reached approximately 70 cm, and the operating pressure of the system was 0.05 MPa.

Evaluated variables

Plant height (cm), leaf area index, and biomass accumulation (BA; g plant^{-1}) were recorded following the methodology proposed by Reyes *et al.* (2023).

Green and dry forage production

Harvest occurred at approximately 100 days after planting (DAP) in both cycles, when kernels reached one-third milk-line progression. Green forage yield (GF; t ha^{-1}) was determined from the biomass collected within three linear meters from the two central rows of each treatment (4.56 m^2). Subsequently, a 500-g subsample was oven-dried at 65 °C for 72 h to determine dry matter (DM) content. Dry forage yield (DF; t ha^{-1}) was calculated based on GF yield and DM concentration.

Water use efficiency

Water use efficiency (WUE; kg m^{-3} of DF) was estimated by dividing dry forage yield (DF) by the total volume of water applied (m^3) in each treatment and replicate.

Nutritional quality

Nutritional quality analyses were conducted on 400-g dry-basis samples. The samples were submitted to a private laboratory (Rock River Lab México, Torreón, Coahuila) for near-infrared reflectance spectroscopy (NIRS; Model 951, Foss Electric, Hillerød, Denmark). Each fresh forage sample was homogenized and oven-dried at 66.7 °C until a constant weight was achieved. Samples were then ground using a blender, followed by a 1-mm screen mill. Neutral detergent fiber (NDF), acid detergent fiber (ADF), *in vitro* NDF digestibility at 30 h (NDFD30h), and starch concentration were quantified. Nutritional estimations were based on prediction equations and databases generated by "Rock River Laboratory, Inc. Agricultural Analysis," as described by Granados-Niño *et al.* (2021).

Profitability

Profitability was determined using the benefit-cost ratio (B/C) for the four forage maize hybrids. Yield (t ha^{-1}) corresponded to the production obtained per cycle. The sale price was the regional market value for maize forage ($1,500 MXN per ton). Income was calculated by multiplying yield by the sale price. The B/C ratio was obtained by dividing total income by total production cost.

Statistical analysis

An analysis of variance (ANOVA) was performed using the GLM procedure of SAS 9.3 (SAS Institute Inc., Cary, NC, USA) under a randomized complete block design with three replications and arranged in a split-plot structure. Planting density (100,000 and 150,000 plants ha^{-1}) was assigned to main plots, whereas maize hybrids (2620, Zamorano, P3270, and P3097) constituted the subplots. Mean separation was conducted using Tukey's test (α=0.05). The general structure of the model was:

$$Y_{ijkl} = \mu + DP_i + H_j + CP_k + DP_i \times H_j + DP_i \times CP_k + H_i \times CP_k + E_{ijk}$$

Where: Y_{ijkl}=Productive, quality and/or profitability variable; μ=general mean that characterizes the population; DP_i=fixed effect of the i-th population density (i=100 or 150 thousand plants ha^{-1}); H_j=fixed effect of the j-th variety (j=2620, Zamorano, P3270 and P3097); CP_k=random effect of the k-th productive cycle (k=spring, summer); $DP_i \times H_j$, $DP_i \times CP_k$, $H_i \times CP_k$=interaction effects density×hybrid, density×productive cycle and hybrid×productive cycle; E_{ijk}=random error, which was assumed to be random for all components normally distributed with zero mean and common variance.

RESULTS AND DISCUSSION

Plant height

Plant height exhibited similar patterns across both cropping cycles (Figure 2). Although initial vegetative growth was faster during the summer cycle, this response was primarily associated with the higher temperatures recorded during the early developmental stages. In contrast, during the spring cycle, the greatest final height was observed in hybrid P3270 (242 cm), whereas the shortest height corresponded to hybrid Zamorano (220 cm). In the summer cycle, hybrid P3270 likewise reached the greatest height (240 cm), while hybrid 2620 exhibited the lowest value (221 cm). Significant differences were detected both between cycles and among hybrids (α=0.05). Comparable findings were reported by Reyes *et al.* (2023), who documented final plant heights ranging from 224 to 241 cm across three hybrids evaluated in the same region. Higher values, reaching up to 292 cm in forage maize grown under subsurface drip irrigation, were reported by Olague *et al.* (2006). These differences in plant height were attributed to favorable climatic conditions for maize growth and to the specific characteristics of the hybrid (Aspros 900), which is known to reach heights of up to 3 m.

Leaf Area Index (LAI)

Leaf Area Index (LAI) values for the four hybrids are presented in Figure 3. LAI values were initially low due to slow early growth (initial stage), followed by a marked increase during the vegetative stage until reaching a maximum and relatively stable plateau during the reproductive stage. Thereafter, LAI declined progressively as a consequence of leaf senescence (final stage). Overall, slightly higher LAI values were observed during the spring cycle particularly during the reproductive phase compared

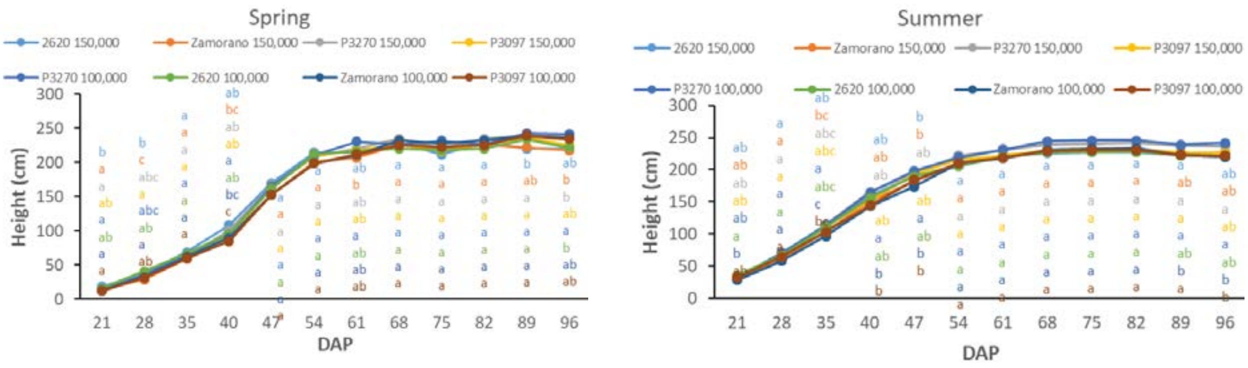

Figure 2. Plant height dynamics of four maize hybrids under two population densities across two production cycles in a semi-desert region of northern Mexico. Means followed by a common letter are not significantly different according to Tukey's test (α=0.05).

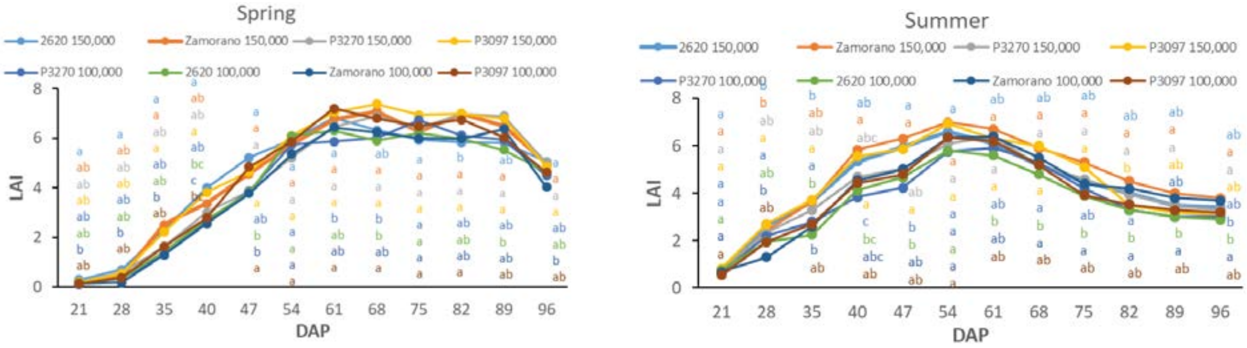

Figure 3. Leaf Area Index (LAI) dynamics of four maize hybrids under two population densities during the spring and summer cycles in a semi-desert region of northern Mexico. Means followed by a common letter are not significantly different according to Tukey's test ($\alpha=0.05$).

with the summer cycle. Similar LAI dynamics have been reported by Guevara et al. (2005), Sánchez *et al.* (2011), Montemayor *et al.* (2018), Reyes *et al.* (2023), and Kou *et al.* (2024). These authors describe LAI curves that exhibit a characteristic pattern consistent with that observed in the present study and described above. Furthermore, most of these studies were conducted in the Comarca Lagunera under drip-irrigated maize production, comparable to the conditions reported by Kou *et al.* (2024) in an arid region of northwestern China.

Biomass accumulation (BA)

Biomass accumulation per plant for the four maize hybrids during the spring and summer cycles is presented in Figure 4. Similar to the LAI pattern, biomass values were comparable between the two cycles. In both cycles, early biomass accumulation was alike across treatments. However, after 60 days after sowing (DAS), differences associated with planting density became evident: the 100,000-plant ha^{-1} treatment exhibited the highest biomass values compared with the 150,000-plant ha^{-1} treatment. These results align with the expected physiological response, as lower population densities (100,000 plants

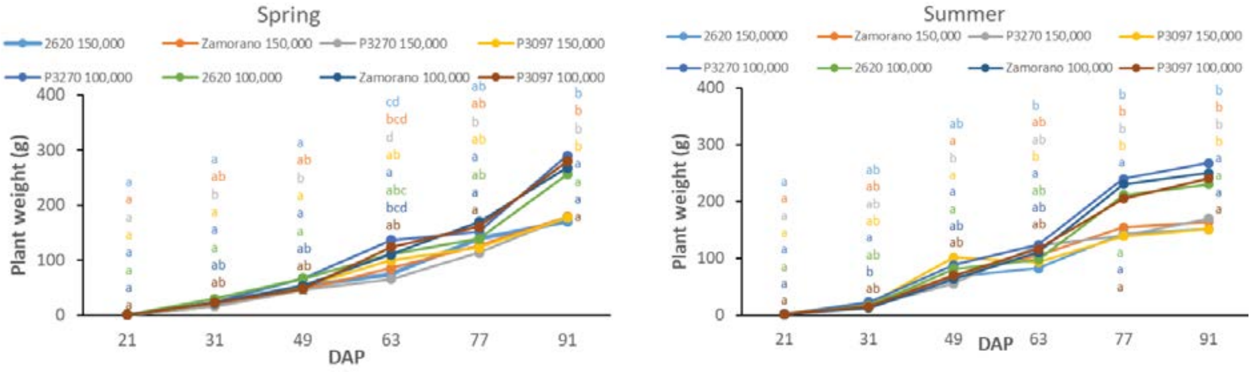

Figure 4. Biomass accumulation per plant of four maize hybrids under two population densities across two production cycles in a semi-desert region of northern Mexico. Means followed by a common letter are not significantly different according to Tukey's test ($\alpha=0.05$).

ha^{-1}) allow individual plants to develop thicker stalks and larger ears, which substantially contribute to greater biomass accumulation per plant (Hong *et al*., 2019).

Green and dry forage production

No significant interactions were detected for density×hybrid or density×cycle ($p>0.05$); however, the hybrid×production cycle interaction was significant ($p<0.05$) (Table 1). Green forage production was highest during the spring cycle. Hybrid P3270 (spring) recorded the greatest yield (81.77 t ha^{-1}), whereas hybrid 2620 (summer) exhibited the lowest production (48.81 t ha^{-1}). Similarly, hybrid P3097 yielded 78.43 t ha^{-1} in spring and 53.40 t ha^{-1} in summer, representing a 32% reduction. Overall, green forage yields declined by an average of 25% in summer compared with the spring cycle. This reduction was associated with slightly lower LAI values (6.4) and biomass accumulation (260 g plant^{-1}) in summer relative to spring (7.1 and 280 g plant^{-1}, respectively), which explains the diminished green forage yields.

For dry forage, the hybrid×cycle interaction was also significant ($p<0.05$) (Table 1). The highest dry forage yields were observed in spring, ranging from 21.60 t ha^{-1} in hybrid Zamorano to 25.29 t ha^{-1} in hybrid P3270. In summer, yields ranged from 16.29 t ha^{-1} in hybrid 2620 to 22.85 t ha^{-1} in hybrid P3270. Dry forage production in summer decreased by 20% relative to spring, primarily due to high temperatures (>35 °C) during the vegetative stage (Figure 1). This reduction aligns with observations by Rivera *et al.* (2013), who reported decreases of 20-30% in forage maize yields under similar conditions. Likewise, Granados-Niño *et al.* (2022) found that spring plantings produced more dry forage than summer plantings in the same region. In contrast, Reyes *et al.* (2024), in a study evaluating maize across multiple cropping cycles, reported higher yields during the summer cycle, a response attributed to atypically high temperatures (40 °C) during the spring, which adversely affected crop productivity.

Water use efficiency (WUE)

Analysis of variance revealed significant differences ($p<0.05$) for the hybrid×production cycle interaction in WUE (Table 1), with clear variability among hybrids. The highest WUE was observed in hybrid P3270 (3.51 kg m^{-3} of DF), whereas the lowest corresponded to hybrid 2620 (2.51 kg m^{-3} of DF) during the summer cycle. It is noteworthy that, on average, the spring cycle exhibited the highest WUE values (3.20 kg m^{-3} of DF), largely due to the greater dry forage yields achieved during this period. Overall, WUE ranged from 2.51 to 3.51 kg m^{-3} of DF, which falls within the range commonly reported in the literature for forage maize. Comparable values were reported by Reyes *et al.* (2023), who found WUE values of 3.0 kg m^{-3} of DF in three forage maize hybrids evaluated in the same region. Similarly, Yescas *et al.* (2015) reported mean WUE values of 3.02 kg m^{-3} of DF across different planting densities in drip-irrigated forage maize. However, our results were slightly lower than those reported by Zavala *et al.* (2022), who documented average WUE values of 3.5 kg m^{-3} of DF in three forage maize hybrids grown under subsurface drip irrigation. These findings highlight opportunities for further improvement to enhance production system efficiency.

Table 1. Green forage yield (GF), dry forage yield (DF), and water use efficiency (WUE) based on DF yield for four forage maize hybrids during the spring and summer 2024 cycles in the Comarca Lagunera.

Cycle	**Hybrid**	**Variables**		
		GF (t ha^{-1})	**DF (t ha^{-1})**	**WUE (kg m^3 de FS)**
Spring	2620	71.75 bc*	24.52 ab	3.30 abc
	Zamorano	67.58 c	21.60 bc	2.88 cd
	P3270	81.77 a	25.29 a	3.38 ab
	P3097	78.43 ab	24.48 ab	3.27 abc
Summer	2620	48.81 d	16.29 d	2.51 d
	Zamorano	54.79 d	19.77 c	3.04 bc
	P3270	68.36 c	22.85 ab	3.51 a
	P3097	53.40 d	18.98 cd	2.92 cd
SE		1.73	0.63	0.09
		P value		
Cycle (C)		<.0001	<.0001	0.0034
Density (D)		0.1399	0.4867	0.4893
Hybrid (H)		<.0001	<.0001	<.0001
C×D		4629	0.3154	0.3134
C×H		0.0003	<.0001	<.0001
C×D×H		0.649	0.7413	0.7392
D×H		0.0500	0.1635	0.1599

* Means with a common letter are not significantly different according to Tukey's test (α=0.05).

Nutritional quality

A significant hybrid×production cycle interaction was detected for neutral detergent fiber (NDF) and acid detergent fiber (ADF) concentrations (Figure 5; $p<0.05$). The highest concentrations of both ADF and NDF were observed in hybrid Zamorano during the spring cycle, whereas in summer, hybrid P3270 exhibited the lowest fiber concentrations. During spring, the greatest NDF concentrations were recorded in hybrids Zamorano and P3270. Likewise, the high ADF concentration in Zamorano was statistically similar to that of hybrids P3270 and P3097 during the spring cycle. Fiber concentrations observed across hybrids were consistent with those reported for the same region, where NDF values ranged from 36.8% to 60.53% and ADF values from 30.4% to 51.27% (Gutiérrez-Guzmán *et al.*, 2022). Moreover, higher ADF concentrations have also been reported in spring (30.04%) compared with summer (28.06%) in a forage maize hybrid evaluated over three cropping cycles in this region (Granados-Niño *et al.*, 2022). The nutritional quality of the hybrids used in that study was comparable to those evaluated in the present work (particularly P3270).

The cycle×hybrid interaction also significantly affected lignin concentration (Figure 6; P=0.03) and 30-hour *in vitro* NDF digestibility (NDFD30h; P=0.05) in the evaluated hybrids. The highest NDFD30h value was observed in hybrid P3270 grown during the summer cycle; this response was statistically similar to that of hybrids 2620

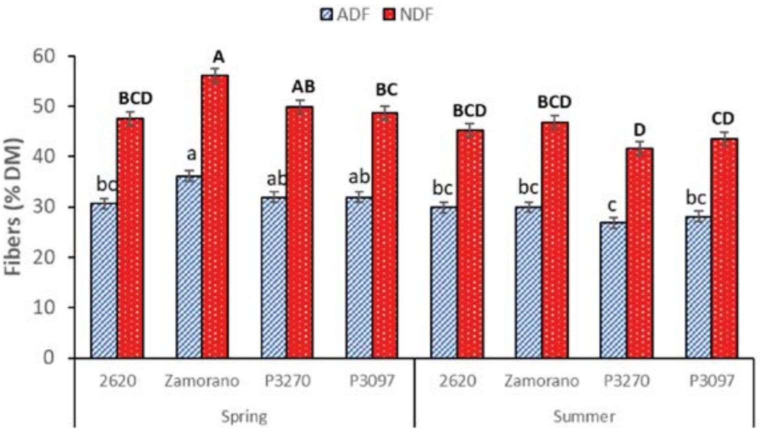

Figure 5. Cycle×hybrid interaction for acid detergent fiber (ADF; P=0.045; SE=1.00) and neutral detergent fiber (NDF; P=0.049; SE=1.30) concentrations on a dry matter (DM) basis in forage maize hybrids. Different letters indicate significant differences according to Tukey's test (α=0.05).

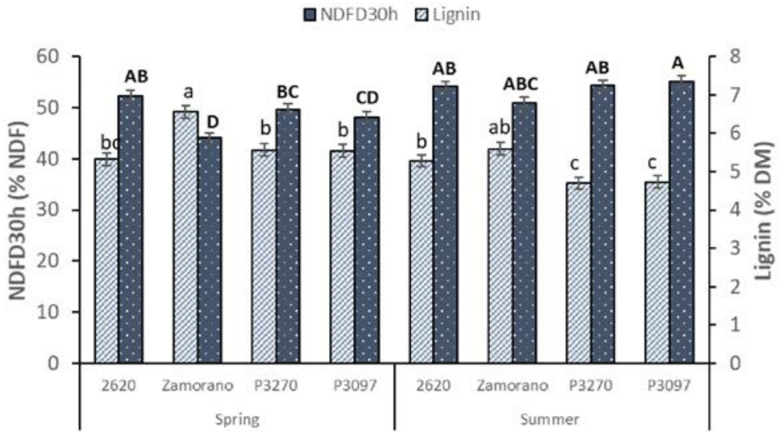

Figure 6. Cycle×hybrid interaction for lignin concentration (P=0.03; SE=0.16) and 30-hour *in vitro* NDF digestibility (NDFD30h; P=0.05; SE=1.00) on a dry matter basis in forage maize hybrids. Different letters indicate significant differences according to Tukey's test (α=0.05).

and Zamorano evaluated in the same cycle, as well as to hybrid P3097 grown in both spring and summer. Hybrids exhibiting greater NDF digestibility consistently showed lower lignin concentrations. Hybrids P3270 and P3097 grown in summer presented the lowest lignin content, whereas hybrid Zamorano grown in spring exhibited the highest lignin concentration. The same hybrid Zamorano in spring also showed the lowest NDF digestibility. Lignin is considered an anti-nutritional component in forages because it exerts a negative effect on fiber digestibility (Jung, 1989), thereby directly reducing the digestible energy value of the forage (Moore & Jung, 2001).

Contrary to the pattern observed in the present study, higher NDFD30h values in spring (57.39%) compared with summer (49.52%) have been reported in a forage maize hybrid evaluated over three years in the same region (Granados-Niño *et al.*, 2022).

Starch concentration in the forage was also influenced by the hybrid×production cycle interaction (Figure 7; P=0.03). Hybrid P3270 grown during the summer cycle exhibited the highest starch concentration, a value that was statistically similar to those observed in Zamorano during the same cycle and in hybrids 2620 and P3097 grown in both spring and summer. Conversely, hybrid Zamorano grown in spring showed the lowest starch concentration compared with its performance in summer. It is plausible that the higher starch content observed in the hybrids grown during summer (Figure 7), combined with their lower fiber (Figure 5) and lignin concentrations (Figure 6), contributed to the higher NDFD30h values recorded in this cycle.

Profitability

Table 2 presents the yield, sale price, total production cost, and benefit-cost (B/C) ratio of four maize hybrids across two cropping cycles. In the present study, the highest B/C ratio (2.80) was recorded for hybrid P3270 during the spring cycle. This value indicates that, for every peso invested in forage maize production using this hybrid, a

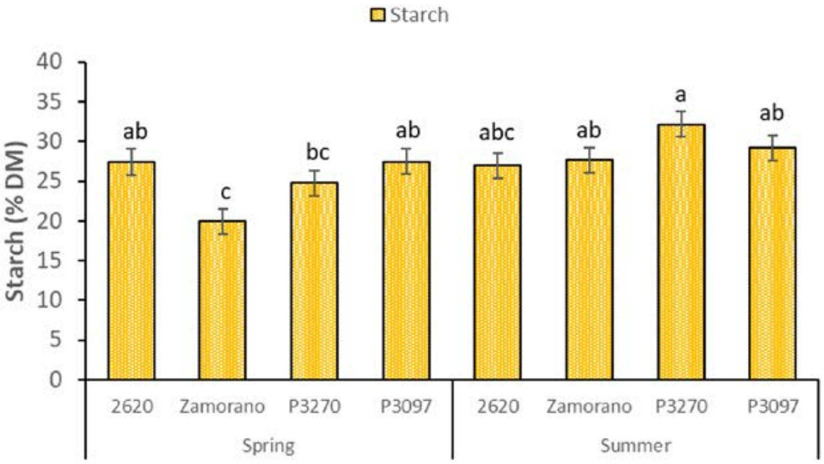

Figure 7. Cycle×hybrid interaction for starch concentration (P=0.03; SE=1.60) on a dry matter (DM) basis in forage maize hybrids. Different letters indicate significant differences according to Tukey's test (α=0.05).

Table 2. Yield, sale price, total production cost, and benefit-cost (B/C) ratio of four maize hybrids across two cropping cycles in the Comarca Lagunera.

Cycle	Hybrid	GF (t ha^{-1})	Sale price ($ t^{-1})	Total income ($)	Production cost ($)	B/C ratio
Spring	2620	71.75	1,500	107,628	42,000	2.6
	Zamorano	67.58	1,500	101,367	40,400	2.5
Summer	P3270	81.77	1,500	122,658	44,600	2.8
	P3097	78.43	1,500	117,650	44,600	2.6
	2620	48.81	1,500	73,218	42,000	1.7
	Zamorano	54.79	1,500	82,182	40,400	2.0
Cycle Spring	P3270	68.36	1,500	102,535	44,600	2.3
	P3097	53.40	1,500	80,103	44,600	1.8
	Hybrid	GF (t ha^{-1})	Sale price ($ t^{-1})	Total income ($)	Production cost ($)	B/C ratio
	2620	71.75	1,500	107,628	42,000	2.6

FV: Green forage. Source: Data based on the Statistical Yearbook of Agricultural Production, 2024 agricultural cycle. SADER, Comarca Lagunera Delegation, Ciudad Lerdo, Durango, Mexico.

gross gain of \$1.80 MXN was obtained, considering the established sale price of green forage (\$1,500.00 MXN per ton) for that production cycle. Lower B/C ratios have been reported by Ortiz *et al*. (2024) and Montemayor *et al*. (2006), who documented values of \$2.20 and \$1.80, respectively, for forage maize grown under drip irrigation conditions in the Laguna region.

CONCLUSIONS

Based on the observed results, planting density did not exert a significant effect on the evaluated variables. Under the semi-desert conditions of the Lagunera Region, increasing plant density to 150,000 plants ha^{-1} provides no agronomic advantage; therefore, raising production costs related to seed, fertilizer, and irrigation pumping is unnecessary. Dry forage production and water use efficiency were higher during the spring cycle, whereas summer yields decreased by approximately 20%. Hybrid P3270 exhibited the greatest yields in both cycles and showed the highest starch concentration. This hybrid also achieved a B/C ratio of 2.80, indicating that for every peso invested in its production, a gross return of \$1.80 MXN was obtained.

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