Agrociencia

DRY MATTER YIELD AND TOTAL DIGESTIBLE NUTRIENT CONTENT OF MAIZE (*Zea mays* L.) VARIETIES IN ARID AREAS UNDER DIFFERENT MOISTURE REGIMES

Ricardo Alonso **Sanchez-Gutierrez**[1*], Francisco Guadalupe **Echavarría-Chairez**[1], Omar Ivan **Santana**[2], Jorge Alonso **Maldonado-Jaquez**[3], Edith **Ramírez-Segura**[4], Hector **Gutierrez-Bañuelos**[5], Alejandro **Espinoza-Canales**[5]

[1]Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Campo Experimental Zacatecas. Carretera Zacatecas-Fresnillo km 24.5, Calera de Víctor Rosales, Zacatecas, Mexico. C. P. 98500.

[2]Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Campo Experimental Pabellon.

[3]Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Campo Experimental La Laguna .

[4] Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. Centro Nacional de Investigación Disciplinaria en Agricultura Familiar. Carretera Ojuelos-Lagos de Moreno, Ojuelos de Jalisco, Jalisco, Mexico. C. P. 47540.

[5]Universidad Autónoma de Zacatecas Francisco García Salinas. Unidad Académica de Medicina Veterinaria y Zootecnia. Carretera Zacatecas-Fresnillo km 31.5, El Cordovel, Enrique Estrada, Zacatecas, Mexico. C. P. 98500.

* Author for correspondence: rasanchez.gutiérrez@gmail.com

Citation: Sanchez-Gutierrez RA, Echavarría-Chairez FG, Santana OI, Maldonado-Jaquez JA, Ramírez-Segura E, Gutierrez-Bañuelos H, Espinoza-Canales A. 2025. Dry matter yield and total digestible nutrient content of maize (*Zea mays* L.) varieties in arid areas under different moisture regimes. **Agrociencia.** https://doi.org/ 10.47163/agrociencia.v59i5.3252

Editor in Chief:
Dr. Fernando C. Gómez Merino

Received: September 13, 2024.
Approved: August 12, 2025.
Published in Agrociencia: August 13, 2025.

ABSTRACT

The inappropriate selection of maize varieties with higher water demand or a late growth cycle is a factor that reduces yield in rainfed conditions in Northern Mexico. This study aimed to evaluate the dry matter yield (DMY), total digestible nutrient content (TDN), and yield stability of eight maize (*Zea mays* L.) varieties under four moisture conditions in an arid region of Mexico. A randomized complete block design with a split-plot arrangement was used, with three replicates per treatment. The main plot factor was the soil moisture level (rainfed conditions only and rainfed plus one supplemental irrigation). Subplots consisted of eight maize varieties or genotypes. Data were analyzed through combined analysis of variance, additive main effects and multiplicative interaction (AMMI) modeling, principal component analysis (PCA), and biplot visualization to evaluate genotype stability. Under rainfed conditions, the varieties CHLHW09029, V-209, and CAFIME showed the highest DMY, while 35p12 had the highest TDN content. Under rainfed plus irrigation conditions, Ocelote exhibited the greatest DMY, and CHLHY02502, V-209, and VS-204 recorded the highest TDN. The AMMI model for DMY indicated that CAFIME, V-209, and CHLHY02502 were stable in Rain Y17, Rain Y18, and Rain + Irrigation Y18, respectively. For TDN, the compatibility of varieties with specific MLs was as follows: 35p12 was most suited to Rain Y17, VS-204 aligned with Rain Y18, and CHLHY02502 performed well under any irrigation treatment. The CAFIME genotype demonstrated consistently high performance in all moisture conditions. Given its adaptability and the potential for seed reuse, it is recommended for smallholder farmers in arid and semi-arid regions of Mexico.

Keywords: hybrids, rainfed conditions.

INTRODUCTION

Maize (*Zea mays* L.) plays an important role in human food security and livestock systems. Due to its adaptability to different environmental conditions, it is one of the main crops cultivated worldwide. Under rainfed conditions, maize is the best alternative for farmers challenged by climate variability, as this crop usually presents scarce biomass loss from drought effects (Kumar *et al.,* 2019; Haarhoff *et al.,* 2020). In addition, maize has better water use efficiency than other forage crops, including Sudan grass, millet, soybean, common vetch, and oats, with an efficiency of up to 26.4 kg ha^{-1} mm^{-1} (Zhang *et al.,* 2018).

Maize is native to Mexico, where its cultivation is an important agricultural activity at the national level (Rasgado-Cabrera *et al.,* 2019; Martínez-Borrego and Vallejo-Román, 2019). In semi-arid areas of northern Mexico, the use of native varieties of maize for forage is still being adopted. Rivas-Jacobo *et al.* (2020) demonstrated that native maize produced similar yield and fibers to hybrid varieties in semiarid conditions, with a mean yield of 31 Mg ha^{-1}. Hernández *et al.* (2007) mentioned that achieving high yields under rainfed conditions requires implementing good management practices and varieties that present stability to the region.

The additive main effects and multiplicative interaction (AMMI) model allows to identify the stability of varieties and technologies under different environmental conditions or multiregional sites. This model uses analysis of variance and principal components to present an effective test, since it captures a large proportion of the sum of squares and accurately separates the main effects (genotype) from those corresponding to the interaction (genotypes × environment) (Crossa *et al.,* 1990; Legesse *et al.,* 2018). This model has helped other studies improve their interpretation of interactions (Božović *et al.,* 2020; Mousavi *et al.,* 2021).

In Zacatecas, Mexico, forage maize is grown in two agroecosystems: optimal and suboptimal, with the amount of precipitation being the primary distinguishing factor. Rainfall in optimal areas averages around 700 mm, with a forage maize area of 168 861 ha. In contrast, in the suboptimal area, the precipitation is around 450 mm, with an extended area of 1 471 613 ha planted to forage maize (Medina-García *et al.,* 2001). In 2019, 96 104 ha were planted under rainfed conditions in Zacatecas, but 24 % were reported as damaged, ranking first in damage at the national level (SIAP, 2019).

The inappropriate selection of varieties or hybrids with greater water demand or a late growth cycle is a factor that reduces yield; therefore, it is recommended to choose varieties adapted to the region. Nevertheless, in Zacatecas, there is scarce information about the yield performance of maize varieties for forage production and their adaptability under different rainfed conditions. Hence, the objective of this study was to determine dry matter yield and total digestible nutrient content of eight varieties of maize, as well as to test their stability under four moisture level conditions in an arid region of Zacatecas, Mexico.

MATERIALS AND METHODS

The study was carried out in 2017 and 2018 at the Zacatecas Experimental Station of the National Institute of Forestry, Agricultural and Livestock Research (INIFAP) in Mexico, located at 22° 54′ N and 102° 39′ W, with an altitude of 2197 m, an annual average temperature of 14.6 °C and 333 mm of precipitation (Figure 1), mainly recorded from June to September (Medina-García and Ruiz-Corral, 2004).

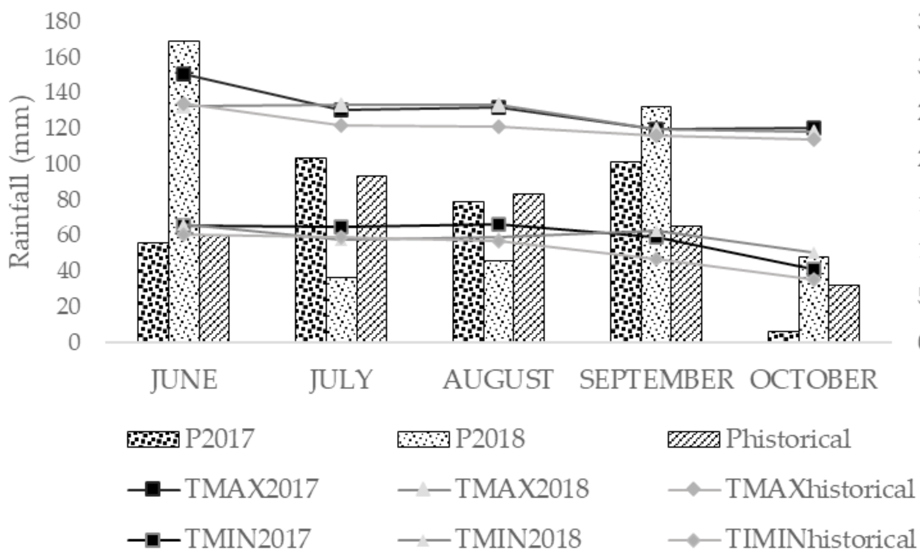

Figure 1. Monthly precipitation (mm) and temperature (°C, maximum and minimal) registered at the Zacatecas Experimental Station in 2017 and 2018.

The soil texture is clay loam, with a pH of 7.7, 1.6 % organic matter, and a bulk density of 1.4 g cm^{-3}. Planting was done manually in moist soil from rainfall at a seeding rate of 44 000 seeds per hectare on July 8, 2017, and July 1, 2018. A complete randomized block experimental design with three replicates under a split-plot arrangement was used annually. The main plots were assigned to two soil moisture treatments: 1) rainfed conditions and 2) rainfed plus a single irrigation event during the vegetative stage. Subplots included eight maize genotypes: 35P12 (Pioneer), Ocelote (Asgrow), CHLHY02502 (CIMMYT), CHLHW09029 (CIMMYT), VS-209 (INIFAP), VS-204 (INIFAP), VS-201 (INIFAP), and CAFIME (INIFAP). Each experimental unit consisted of four rows, 8 m in length and spaced 0.76 m apart. Data collection was performed on the two central rows, with samples taken from 7 m of row length after excluding 0.5 m at each end.

Fertilization was carried out at sowing with a rate of 80 kg ha^{-1} of nitrogen (N) and 40 kg ha^{-1} of phosphorus (P). After plant emergence, a surface drip system was installed on plots with rainfed plus irrigation treatment. The separation between irrigation tapes was 76 cm, and the distance between emitters was 20 cm, with a discharge of 1 L h^{-1}. In 2017 and 2018, supplemental irrigation of 12 mm was applied 20 and 25 d after planting, respectively. This decision was based on the absence of rainfall during the 10 d preceding irrigation and a low probability of rainfall in the subsequent 5 d, as indicated by our internal forecasting system.

Harvest was carried out manually at the doughy grain stage. The measured variables included dry matter yield (DMY, kg ha^{-1}) and total digestible nutrient content (TDN, %), which was calculated based on the chemical composition determined through wet chemistry following AOAC methods. To assess DMY, the two central rows of each plot were cut at a height of 0.15 m and weighed to estimate fresh forage production. Additionally, two plants were randomly sampled and dried in a forced-air oven at 55 °C for 72 hours, or until constant weight, to determine dry matter content.

The chemical composition used to estimate TDN was obtained as follows: total nitrogen (N) was measured by dry combustion (FP-528, Leco Instruments, St. Joseph, MO, USA). Neutral detergent fiber (NDF), acid detergent fiber (ADF), and lignin content were determined sequentially using a fiber analyzer (A200, Ankom Tech., Macedonia, NY, USA). The NDF analysis included the use of α-amylase and sodium sulfite, ADF was determined using CTAB solution, and lignin was analyzed with 72 % sulfuric acid in beakers. Ash content was quantified by incinerating samples at 600 °C for 6 h. The ether extract value was assumed to be 2.89 (NRC, 2001). TDN values were calculated based on the NRC (2001) guidelines using the chemical composition data obtained.

Prior to statistical analysis, a normality test and homogeneity of variance test were applied to the dry matter yield dataset. The arcsine function was used to convert the total digestible nutrients. The total digestible nutrients were transformed using the arcsine function. A combined analysis of variance (ANOVA) was conducted to determine the main effects of year and varieties, as well as the interaction effect (Year × Genotype) under each moisture condition. Replication was nested within moisture level to improve precision (Fotso *et al*., 2018). To evaluate the stability of the varieties across moisture regimens, an AMMI analysis was performed. This included an ANOVA to assess the F-values associated with varieties, moisture regimes, and their interaction. Finally, a principal component (PC) analysis was conducted to derive eigenvectors and visualize the stability of the varieties in a biplot (SAS, 2011).

RESULTS AND DISCUSSION

Under rainfed conditions, dry matter yield (DMY) and total digestible nutrient content (TDN) showed statistically significant differences ($p \leq 0.05$) between years and among varieties. However, no significant differences were observed for the Year × Genotype interaction ($p > 0.05$). Varietal performance was superior in 2017, with higher values for DMY (7664 kg ha^{-1}) and TDN (49 %) compared to 2018. Regarding varietal comparisons, the DMY reported for VS-204 (5485 kg ha^{-1}) was significantly surpassed ($p \leq 0.05$) by CHLHW09029, V-209, and CAFIME. In terms of TDN, the hybrid 35P12 achieved the highest mean value (50.45 %), followed by CHLHW09029, VS-204, and CAFIME, which showed similar percentages.

Results obtained under rainfed conditions plus one irrigation showed statistically significant differences ($p \leq 0.05$) across both years and varieties. However, no significant Year × Genotype interaction was detected ($p > 0.05$). Under these conditions, the year 2017 exhibited the best forage characteristics, with a DMY of 10 697 kg ha^{-1} and TDN of 70.83 %. The Ocelote hybrid recorded the highest DMY (11 302 kg ha^{-1}) and was superior ($p \leq 0.05$) to V-209 and VS-204, but there was no significant difference ($p > 0.05$) compared to the other varieties. The genotypes CHLHY02502, V-209, and VS-204 accumulated more than 70 % TDN and were statistically different from VS-201 (Table 1).

Table 1. Dry matter yield (DMY) and total digestible nutrient content (TDN) of eight maize varieties (*Zea mays* L.) under different moisture regimes, evaluated in 2017 and 2018 at the Zacatecas Experimental Station, Mexico.

	Soil moisture level condition			
	Rainfed		Rain + irrigation	
Year	DMY (kg ha^{-1})	TDN (%)	DMY (kg ha^{-1})	TDN (%)
2017	7664 a	49.6 a	10697 a	70.83 a
2018	6339 b	48.04 b	8907 b	68.06 b
Varieties				
35p12	6995 ab	50.45 a	10829 ab	69.34 ab
Ocelote	7070 ab	46.37 c	11302 a	68.64 ab
CHLHY02502	6472 ab	48.67 b	10758 ab	70.43 a
CHLHW09029	7528 a	49.49 ab	10651 ab	69.11 ab
V-209	7921 a	47.03 c	8667 bc	70.71 a
VS-204	5485 b	50.15 ab	7467 c	70.1 a
VS-201	6850 ab	48.88 b	9271 abc	67.33 b
CAFIME	7691 a	49.51 ab	9473 abc	69.92 ab
Year × Genotype (significance level)	0.4109	0.399	0.644	0.51

Ns: no significance.

During the evaluation years, total precipitation exceeded the historical average of 333 mm, with accumulations of 11.7 mm in 2017 and 98 mm in 2018. However, in 2018, the months of July (36 mm) and August (45 mm) received only 61 and 45 %

of their respective historical averages (Figure 1). Only 2017 showed a precipitation pattern comparable in both accumulation and distribution to the historical average. Due to the irregular rainfall distribution in 2018, yields under both moisture levels decreased by 18 to 20 %. This reduction aligns with previous reports suggesting that water restrictions during maize development can lead to yield losses of 15 to 20 % (Siatwiinda *et al*., 2021).

The amount of accessible water during the growing season is critical. Some authors have observed that water shortages from the tasseling to milk stage can reduce yield more severely than shortages during the vegetative stage (Gheysari *et al*., 2017; Marković *et al*., 2021). In both years, rainfall was concentrated in September, benefiting the tasseling stage (65 d after sowing), as rainfall exceeded the historical average. Therefore, the vegetative stage emerged as the critical period for water availability in this region.

To address this, auxiliary irrigation of approximately 12 mm was applied, resulting in yield increases equivalent to more than 2.4 Mg ha^{-1}. This additional forage could feed a 450 kg cow for 178 d during a drought period. Moreover, TDN, which indicates the projected energy content of a feedstuff (NRC, 2001), varied significantly between moisture treatments. Under rainfed conditions, TDN values ranged from 47 to 50.5 %, while the addition of irrigation increased TDN values to 67–70.4 %.

Water restriction during the vegetative stage can decrease photosynthetic rate, limiting leaf area and ear growth, and leading to increased fiber content and reduced digestibility (Gallo *et al*., 2014; Johansouz *et al*., 2014). Thus, the application of 12 mm of irrigation not only enhances yield but also significantly improves forage nutritional quality, contributing to the dietary requirements of cows from mid-gestation to delivery (van Die and Entz, 2022).

The AMMI analysis for DMY showed highly significant differences ($p \leq 0.0001$) for the moist level (ML), while the ML × Genotype interaction was not significant ($p > 0.05$). ML was the main factor affecting dry matter, resulting in 53.7 % of the total variation, while the other sources contributed less than 18 % (Table 2).

Table 2. Analysis of variance by the additive main effects and multiplicative interaction (AMMI) model for dry matter yield (DMY) under four moisture levels and eight maize varieties (*Zea mays* L.) evaluated in 2017 and 2018 in Zacatecas, Mexico.

Source of variation	Degrees of Freedom	Sum of squares	Percentage of sum of squares	F value
ML	3	276 526 506	53.77	26.1**
Rep(ML)	12	92 101 588	17.91	2.17*
Varieties	7	65 394 221	12.72	2.65*
ML × Genotype	21	80 215 544	15.60	1.08 Ns

ML: moisture level; Rep(ML): repetition by moisture level; ML × Genotype: interaction between moisture level and varieties; *($p \leq 0.05$); **($p \leq 0.0001$); $^{\lambda}$Ns: no significance.

Principal component analysis of DMY showed that the first and second components accounted for 51.05 and 32.43 % of the total variance, respectively, together explaining 83.49 % of the variation. The biplot analysis revealed notable differences in moisture levels, and the evaluated varieties exhibited distinct performance patterns for DMY, each occupying separate sectors. Among the varieties tested, CAFIME, VS-209, and CHLHY02502 displayed longer vectors and demonstrated stability under varying moisture conditions corresponding to Rain Y17, Rain Y18, and Rain + Irrigation Y18, respectively (Figure 2).

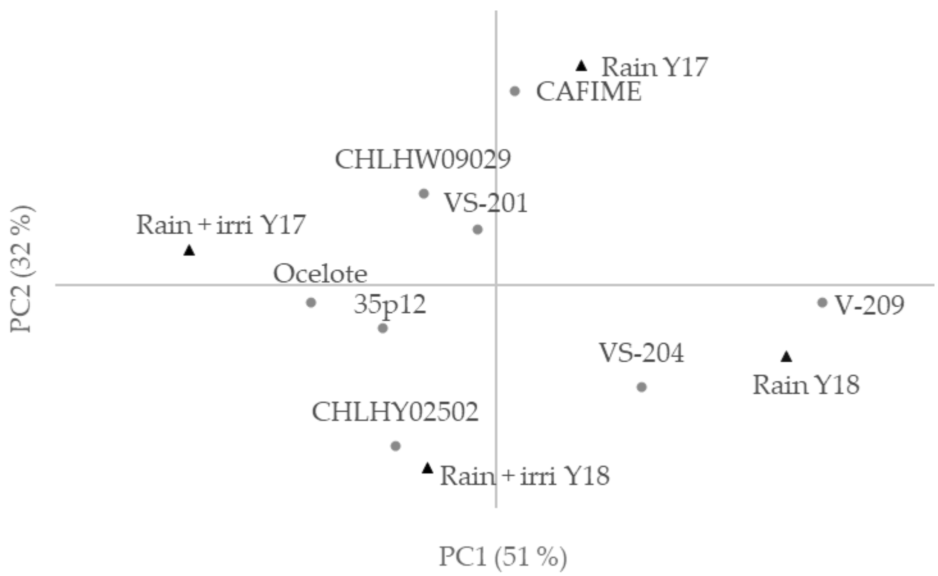

Figure 2. Biplot of dry matter yield of eight maize varieties (*Zea mays* L.) evaluated on four different moisture levels in Zacatecas, Mexico. Moisture level (▲); genotype (●).

Varieties CAFIME and V-209 performed particularly well under rainfed conditions (Rain Y17 and Rain Y18), suggesting they are suitable alternatives for smallholder farmers in north-central Zacatecas. According to Luna-Flores *et al*. (2005), these varieties have an early development cycle, reaching tasseling between 59 and 65 d, which facilitates seed production for future planting cycles. Additionally, Rumayor-Rodríguez *et al*. (2006) found that the V-209 genotype is beneficial in drought mitigation strategies in rainfed agriculture due to its lower risk of yield loss under water stress. Conversely, the Ocelote hybrid is better adapted to high soil moisture environments and is therefore recommended for the southwestern region of Zacatecas, where rainfall is more abundant and consistent (Medina-García and Ruiz-Corral, 2004).
The AMMY analysis for TDN revealed significant differences ($p \leq 0.0001$) in moisture levels. Furthermore, there were significant differences ($p \leq 0.05$) between varieties

and the ML × Genotype interaction. Moisture levels were the primary effect of TDN, accounting for 97.83 % of total variation; the remaining sources explained less than 2.2 % of the variation (Table 3).

Table 3. Analysis of variance of the additive main effects and multiplicative interaction (AMMI) model for the total digestible nutrient content (TDN) under different moisture levels and eight maize varieties (*Zea mays* L.) evaluated in 2017 and 2018 in Zacatecas, Mexico.

Source of variation	Degrees of freedom	Sum of squares	Percentage of sum of squares	F value
ML	3	9248.9	97.83	1007.5**
Rep(ML)	11	24.9	0.263	0.73 Ns
Genotype	7	76.8	0.81	3.57*
ML × Genotype	21	103.34	1.09	1.76*

ML: moisture levels; Rep(ML): repetition by moisture levels; ML × Genotype: interaction between moisture levels and varieties; *($p \leq 0.05$); **($p \leq 0.0001$); Ns: No significance.

Principal component analysis of TDN content revealed that the first (76.21 %) and second (16.23 %) components together account for 92.44 % of the total variance. The biplot analysis identified three distinct moisture level groupings based on TDN content. One of these moisture levels includes Rain + Irrigation Y17 and Rain + Irrigation Y18, as they are positioned in the same sector of the biplot. The remaining conditions, Rain Y1 and Rain Y2, each form independent moisture levels, being located in different sectors.

Regarding varietal performance, genotypes with the longest vectors and highest compatibility with specific moisture levels included 35P12 (under Rain Y17), VS-204 (close to Rain Y18), and CHLHY02502 (across all irrigation treatments) (Figure 3). Hybrids 35P12 and CHLHW09029 and the open-pollinated varieties VS-204 and CAFIME exhibited high TDN content under both irrigated and rainfed conditions. Among these, CAFIME produced a higher DMY than VS-204, making it the most suitable option for forage production under rainfed systems.

To enhance forage quality and fiber digestibility, the adoption of higher cutting heights at harvest is recommended, particularly for V-209 and potentially for CAFIME as well (Dejene *et al*., 2021; Kolar *et al*., 2022). Additionally, breeding efforts for V-209 should prioritize improvements in nutritional quality, as this genotype holds potential as a climate-resilient forage alternative for rainfed areas.

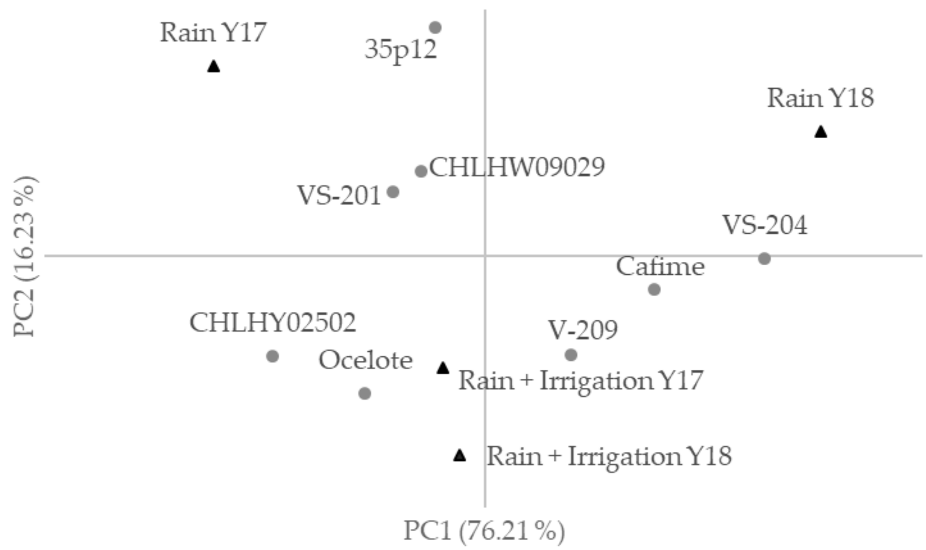

Figure 3. Biplot of total digestible nutrient content of eight genotypes evaluated on four different moisture levels in Zacatecas, Mexico. Moisture level (▲); genotype (●).

CONCLUSIONS

The additive main effects and multiplicative interaction (AMMI) analysis revealed high variability in moisture level conditions for both dry matter yield and total digestible nutrient (TDN) content. The genotypes CAFIME, VS-209, and CHLHW09029 exhibited stability in the environments Rain Y17, Rain Y18, and Rain + Irrigation Y18, respectively. Additionally, 35p12 performed best in Rain Y17, VS-204 in Rain Y18, and CHLHW09029 showed superior TDN content across all irrigation treatments. Although CAFIME did not display stability under certain conditions, its performance consistently matched or slightly exceeded the overall mean. Therefore, CAFIME is recommended for smallholder farmers, as it enables seed saving from their own harvests, contributing to self-sufficiency.

ACKNOWLEDGEMENTS

The authors thank students Angilberto Arturo Berumen González and Juan González Bañuelos for the collaborations on the field, and Julio Cesar González Márquez (certified technician in sustainable agriculture by CIMMYT) for donating seed of CIMMYT varieties for this study.

REFERENCES

AOAC. (Association of Official Analytical Chemists). 2000. Official methods of analysis of AOAC International (17th ed.). Association of Official Analytical Chemists, Gaithersburg, MD, USA.

Božović D, Popović V, Rajičić V, Kostić M, Filipović V, Kolarić L, Ugrenović V, Spalević V. 2020. Stability of the expression of the maize productivity parameters by AMMI models and GGE-biplot analysis. Notulae Botanicae Horti Agrobotanici Cluj-Napoca 48 (3): 1387–1397. https://doi.org/10.15835/nbha48312058

Crossa J, Gauch HG, Zobel RW. 1990. Additive main effects and multiplicative interactions analysis of two interactional maize cultivar trials. Crop Science 30 (3): 493–500. https://doi.org/10.2135/cropsci1990.0011183x003000030003x

Dejene M, Dixon RM, Walsh KB, McNeill D, Seyoun S, Duncan AJ. 2021. High-cut harvesting of maize stover and genotype choice can provide improved feed for ruminants and stubble for conservation agriculture. Agronomy Journal 114 (1): 187–200. https://doi.org/10.1002/agj2.20874

Fotso Ak, Hanna R, Kulakow P, Parkes E, Iluebbey P, Ngome FA, Suh C, Massussi J, Choutnji I, Wirnkar VL. 2018. AMMI analysis of cassava response to contrasting environments: case study of genotype by environment effects on pest and diseases, root yield, and carotenoids content in Cameroon. Euphytica 214 (9): 155. https://doi.org/10.1007/s10681-018-2234-z

Gallo A, Giuberti G, Masoero F, Palmonari A, Fiorentini L, Moschini M. 2014. Response on yield and nutritive value of two commercial maize hybrids as a consequence of a water irrigation reduction. Italian Journal of Animal Science 13 (3): 594–599. https://doi.org/10.4081/ijas.2014.3341

Gheysari M, Sadeghi SH, Loescher HW, Amiri S, Javad ZM, Majidi MM, Asgarinia P, Payero JO. 2017. Comparison of deficit irrigation management strategies on root, plant growth and biomass productivity of silage maize. Agricultural Water Management 182: 126–138. https://doi.org/10.1016/j.agwat.2016.12.014

Haarhoff SJ, Kotzé TN, Swanepoel PA. 2020. A prospectus for sustainability of rainfed maize production in South Africa. Crop Science 60 (1): 14–28. https://doi.org/10.1002/csc2.20103

Hernández AJA, Rosales NC, Beltrán LS, Loredo C. 2007. Variedades de forrajes anuales para temporal en el altiplano y zona media de San Luis Potosí. Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. San Luis Potosí, México. 19 p.

Johansouz JM, Ashfar RK, Heidari H, Hashemi M. 2014. Evaluation of yield and quality of sorghum and millet as alternative forage crops to corn under normal and deficit irrigation regimens. Jordan Journal of Agricultural Sciences 10 (4): 699–715.

Kolar S, Vranić M, Božić L, Bošnjak K. 2022. The effect of maize crop cutting height and the maturity at harvest on maize silage chemical composition and fermentation quality in silo. Journal of Central European Agriculture 23 (2): 290–298. https://doi.org/10.5513/jcea01/23.2.3504

Kumar KM, Sridhara CJ, Hanumanthappa M, Marimuthu S. 2019. A Review of impact and mitigation strategies of climate change on dryland agriculture. Current Journal of Applied Science Technology 33: 1–12. https://doi.org/10.9734/cjast/2019/v33i430085

Legesse W, Tolera K, Berhanu T, Gezahegn B, Adefris T, Beyene A. 2018. Mega-environment targeting of maize varieties using AMMI and GGE biplot analysis in Ethiopia. Ethiopian Journal Agriculture Science 28: 65–84.

Luna-Flores M, Gutierrez-Sánchez JR, Peña-Ramos A, Echavarría-Chairez FG, Martinez-Gómez J. 2005. Behavior of early corn varieties in the semiarid and arid central-northern region of Mexico. Revista Fitotecnia Mexicana 28 (1): 39–45. https://doi.org/10.35196/rfm.2005.1.39

Markovic M, Šoštarić J, Josipović M, Rastija M, Matoša KM, Andrišić K. 2021. Yield and yield components of maize hybrids (*Zea mays* L.) as affected by irrigation. Journal of Agriculture and Food 9: 1–11.

Martínez-Borrego E, Vallejo-Román J. 2019. Pluriactividad, consumo y persistencia del maíz en dos municipios del noroeste del Estado de México. Revista Euroamericana de Antropología 7: 41–53. https://doi.org/10.14201/rea201974153

Medina-García G, Ruiz-Corral JA. 2004. Estadísticas climatológicas básicas del Estado de Zacatecas. Libro Técnico 3. Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. Centro de Investigación Regional Norte Centro, Campo Experimental Zacatecas. Calera, México. 41 p.

Medina-García G, Salinas-González H, Rubio-Aguirre F. 2001. Potencial productivo de especies forrajeras en el Estado de Zacatecas, Libro técnico 1. Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. Centro de Investigación Regional Norte Centro, Campo Experimental Zacatecas. Calera, México. 157 p.

Mousavi SMN, Bojtor C, Illés A, Nagy J. 2021. Genotype by trait interaction (GT) in maize hybrids on complete fertilizer. Plants 10 (11): 2388. https://doi.org/10.3390/plants10112388

NRC (National Research Council). 2001. Nutrient requirements of beef cattle (Seventh revised edition). National Academy Press: Washington, DC, USA.

Rasgado-Cabrera VE, Castañeda-Hidalgo E, Lozano-Trejo S, Pérez-León MI, Santiago-Martínez GM. 2019. Sustentabilidad de agroecosistemas de maíz de la planicie costera del Istmo, Oaxaca, México. Revista de la Facultad de Agronomía 118 (2). https://doi.org/10.24215/16699513e028

Rivas-Jacobo MA, Mendoza-Pedroza SI, Sangerman-Jarquín D, Sánchez-Hernández MÁ, Herrera-Corredor CA, Rojas-García AR. 2020. Forage evaluation of maize from various origins of Mexico in the semi-arid region. Revista Mexicana de Ciencias Agrícolas 24: 93–104. https://doi.org/10.29312/remexca.v0i24.2361

Rumayor-Rodríguez A, Medina-García G, Echavarría-Chairez F, Luna-Flores M, Vallejo-Díaz J. 2006. Estrategias de mitigación de la sequía en el estado de Zacatecas. *In* Bravo AG, Amador MD, Serna A, Medina G. (eds.), Sequía: Vulnerabilidad, Impacto y Tecnología para Afrontar en el Norte Centro de México. Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Campo Experimental Zacatecas: Zacatecas, México, pp: 231–267.

SAS Institute. 2011. SAS/STAT 9.3 User´s Guide. SAS Institute Inc. Cary, NC, USA.

SIAP (Servicio de Información y Estadística Agroalimentaria y Pesquera Información Agrícola). 2022. Avance mensual por estado. Estadísticas 2019. Gobierno de México. Secretaría de Agricultura y Desarrollo Rural. Servicio de Información y Estadística Agroalimentaria y Pesquera Información Agrícola. Ciudad de México, México. https://nube.agricultura.gob.mx/avance_agricola/ (Retrieved: June 2022).

Siatwiinda SM, Supit I, Hove B, Yerokun O, Ros GH, de Vries W. 2021. Climate change impacts on rainfed maize yields in Zambia under conventional and optimized crop management. Climatic Change 167 (3–4). https://doi.org/10.1007/s10584-021-03191-0

van Die M, Entz MH. 2022. Mid-summer annual forage performance in organic, grass-fed production. Canadian Journal of Plant Science 102 (3): 566–574. https://doi.org/10.1139/cjps-2021-0112

Zhang Q, Bell LW, Shen Y, Wish JPM. 2018. Indices of forage nutritional yield and water use efficiency amongst spring-sown annual forage crops in north-west China. European Journal of Agronomy 93: 1–10. https://doi.org/10.1016/j.eja.2017.11.003