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Articles

Yield and water productivity in winter crops under deficit irrigation conditions

Rendimiento y productividad del agua en cultivos de invierno bajo riego deficitario

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Abstract

Deficit irrigation is a strategy to increase water productivity, especially in arid and semi-arid areas. To evaluate the effect of deficit irrigation (60, 80, and 100 % of evapotranspiration (ET)) on the yield and productivity of water in winter crops, fieldwork was carried out using an experimental design of plots divided into random blocks with four repetitions. The aforementioned ET percentages were used in the main plot under a drip irrigation system and a control with flood irrigation. The winter crops, divided into subplots, were: barley (*Hordeum vulgare* L.); canola (*Brassica napus* L.); triticale (*X Triticosecale* Wittmack); oats (*Avena* *sativa* L.), and safflower (*Carthamus tinctorius* L.). The results show that the biomass yield of the species and water productivity (WP) depend on irrigation. With 80 and 100 % of ET, the highest yields of green forage and dry forage were obtained in barley, triticale, and oats. The highest water productivity was found with the 60 and 80 % treatments (4 and 3.75 kg m^{-3}, respectively). Deficit irrigation at 60 % of ET maintained forage potential and water productivity in these winter crops.

Keywords: Evapotranspiration, drip irrigation, forage potential.

Resumen

El riego deficitario es una estrategia para incrementar la productividad del agua especialmente en las zonas áridas y semiáridas. Con el objetivo de evaluar el efecto del riego deficitario (60, 80 y 100 de la evapotranspiración, ET) sobre el rendimiento y la productividad del agua en cultivos de invierno, se estableció un trabajo de campo, para lo cual se utilizó un diseño experimental de parcelas divididas en bloques al azar con cuatro repeticiones. Los porcentajes de ET corresponden a la parcela principal (60, 80 y 100 %) bajo un sistema de riego por goteo y un testigo con riego por inundación los cultivos de invierno: cebada (*Hordeum vulgare* L.); canola (*Brassica napus* L.); triticale (*X Triticosecale Wittmack*); avena (*Avena sativa* L.), y cártamo (*Carthamus tinctorius* L.) como subparcelas. Los resultados muestran que el rendimiento de biomasa de las especies y la productividad del agua (PA) dependen del riego deficitario. Con la ET de 80 y 100 % se obtuvieron los mayores rendimientos de forraje verde y seco en la cebada, triticale y avena, respectivamente. La mayor productividad del agua corresponde a los tratamientos con 60 y 80 % de ET (4 y 3.75 kg m^{-3}). El riego deficitario con el 60 % de ET permite mantener el potencial forrajero y la productividad del agua en los cultivos de invierno.

Palabras clave: evapotranspiración, riego por goteo, potencial forrajero.

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Introduction

Milk production in Mexico for the year 2020 was 12,554 million liters. The country's Comarca Lagunera region contributes 21 % of the national milk production, which represents one of the region's main economic activities (SIAP, 2021). As Mexico's center of dairy production, the region requires large amounts of forage per year, and cattle feed is mainly based on corn and alfalfa (Sader, 2021). However, corn is produced only in the spring-summer cycle, and alfalfa production decreases in the winter because climatic conditions are not favorable for its development.

Given this situation, it is vital to use forage species that are adaptable to the climatic and soil conditions prevailing during the autumn-winter cycle. Crops such as triticale, barley, and safflower are capable of developing under limited water irrigation conditions and can provide highly nutritious forage during the winter period (Ochoa-Espinoza *et al.*, 2022a). Oats are a highly adaptable crop in arid and semiarid zones, with low water requirements and high-energy forage production (Servin-Palestina, Sánchez-Gutiérrez, Ramírez-Valle, Galindo-Reyes, & Gutiérrez-

Bañuelos, 2018). Another alternative for these edaphoclimatic conditions is canola, which can tolerate conditions of limited water and salinity. Under these conditions, it also withstands low temperatures and provides good quality forage with crude protein and net energy for lactation yields similar to spring cultivars (Reta-Sánchez, Serrato-Corona, Quiroga-Garza, Figueroa-Viramontes, & Gaytán-Mascorro, 2017). The aforementioned species could increase forage potential in the fall-winter cycle in Comarca Lagunera.

One of the main concerns for forage production in Comarca Lagunera is the low availability of water since high volumes of irrigation water are required to satisfy the high demand for cattle feed (Reyes, Franco, Hernández, & Maltos, 2020). Therefore, it is necessary to use techniques to obtain higher water productivity and increase crop yields. Subsurface drip irrigation is a system that minimizes water evaporation from the soil surface, resulting in enhanced biomass production and water use efficiency (Reyes *et al*., 2023).

Furthermore, evapotranspiration (ET) is fundamental for scheduling crop irrigation (Reyes *et al*., 2023). Different ET percentages have been applied in irrigation scheduling in several crops, including corn (Zavala-Borrego, Reyes-González, Álvarez-Reyna, Cano-Ríos, & Rodríguez-Moreno, 2022); alfalfa (Godoy-Ávila, Pérez-Gutiérrez, Torres, Hermosillo, & Reyes, 2003); wheat (Alghory & Yazar, 2019), and oats (Reyes-González *et al*., 2011); however, for barley, canola, and safflower, insufficient information is available for the region.

Deficit irrigation is a water-saving strategy commonly used in arid and semi-arid zones. It consists of applying lower quantities of water than the crop requires (Flores, Ojeda, Flores, Sifuentes, & Mejía, 2013).

The application of different irrigation levels based on percentages of ET and water deficit can maintain the productive potential of winter crops. Due to the aforementioned, the objective of this study was to evaluate the effect of deficit irrigation (100, 80, and 60 % of ET) on yield and water productivity in winter crops under a drip irrigation and flood irrigation system in Comarca Lagunera. The hypothesis is that yield and water productivity will be maintained by applying different irrigation levels based on evapotranspiration percentage and water deficit in Comarca Lagunera.

Materials and method

Location of study site

The study was carried out during the 2021–2022 autumn-winter cycle at La Laguna Experimental Field (CELALA) belonging to the National Institute of Forestry, Agriculture, and Livestock Research (INIFAP) in Matamoros, Coahuila, Mexico (25°32'N, 103°14'W and 1 150 masl). The experimental site's soil has a clay-loam texture, and its field capacity is 35.2 %, permanent wilting point is 20.57 %, bulk density is 1.3 g cm^{-3}, and pH is alkaline. It is also low in organic matter, phosphorus, and available nitrogen. The semi-warm dry climate (BWh) has low atmospheric humidity, a mean annual temperature of 22.6°C, an average annual precipitation of 215.5 mm, and a mean annual evaporation of 2,000 mm (García, 2004). The prevailing climatic conditions during the development of the crop were as follows: the minimum temperature increased from -4 to 16.5 °C; the maximum temperature ranged from 16.9 to 33.3 °C; and the average temperature during the cycle was in the range of 7 to 23.5

°C (Figure 1). The average evapotranspiration (ET) was 3.5 mm day^{-1} during the production cycle.

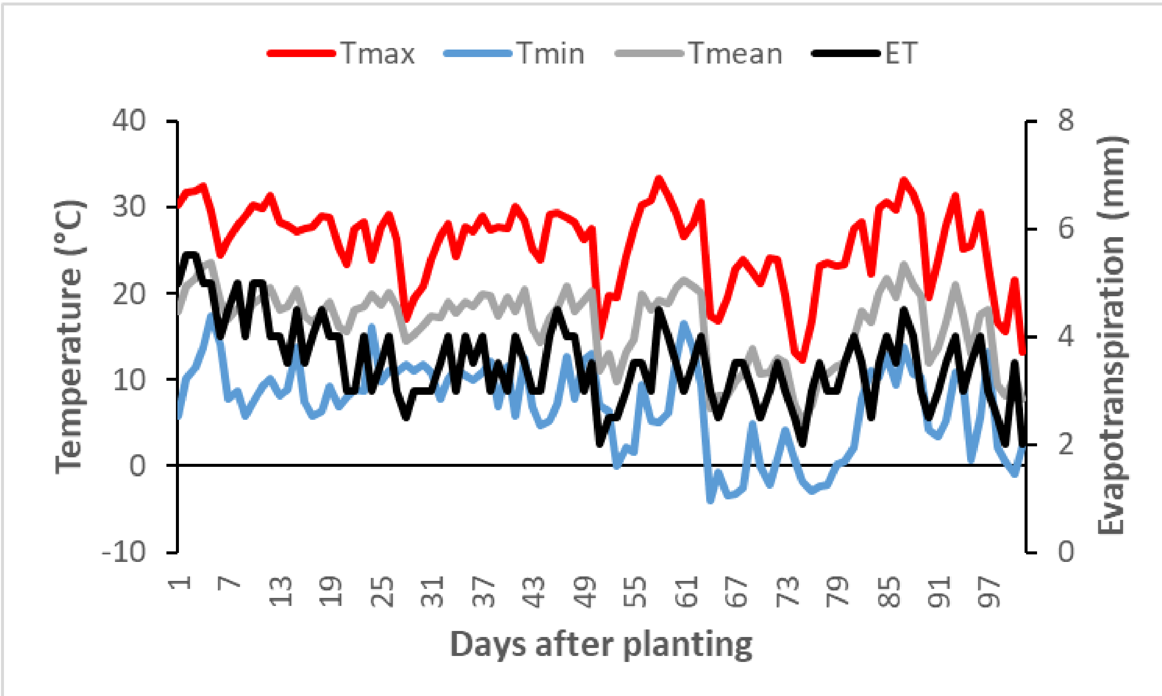

Figure 1. Minimum, maximum, and average temperatures and evapotranspiration during the production cycle for winter crops with different irrigation levels based on ET percentages and flood irrigation.

Site preparation

Land preparation consisted of subsoiling, leaving fallow, raking, leveling, and placing down the irrigation tape. Five crop species were evaluated: 1) Valencia barley; 2) IMC 205 canola; 3) Rio Nazas triticale; 4) Cuauhtémoc oats; and 5) Forrcart 2020 safflower. An experimental design of plots divided into randomized blocks with four replications was used. The different irrigation levels based on ET percentages were considered as a large plot (100, 80, and 60 % of ET) along with a control with flood irrigation, while the small plots consisted of the different crop species (barley, canola, triticale, oats, and safflower). Each experimental plot consisted of 15 rows with a distance between furrows of 0.20 and 5 m in (15 m^2). Sowing was performed manually on October 30th, 2021, with densities ranging from 15 to 80 kg ha^{-1}. The fertilization rate used for the different crops was: 200-100-00 (N-P_2O_5-K_2O), utilizing urea ($CO(NH_2)_2$) and ammonium sulfate ($(NH_4)_2SO_4$) as nitrogen sources and monoammonium phosphate (MAP) ($NH_4H_2PO_4$) as a phosphorus source. During sowing, all the phosphorus and half of the nitrogen were applied; the rest of the nitrogen was applied every 15 days during crop growth according to its requirement through the drip irrigation system using a Venturi injector. In flood irrigation, the other half of the nitrogen was manually applied at random 25 days after planting (DAP).

Irrigation

The irrigation tape used was RO-DRIP 8 mil (Rivulis Irrigation Inc., San Diego, CA, USA) with a wall thickness of 0.2 mm, inner diameter of 16 mm, emitters 0.2 m apart, and a loss of 0.5 l h^{-1} per emitter. The irrigation system operated at a pressure of 55.15 kilo pascals (8 PSI), with irrigation occurring every third day. In the flood or surface irrigation treatment, the irrigation frequency was every 25 days. For the estimation of reference ET, an atmometer (ETgage, model A marketed by ETgage Company Loveland, CO, USA) was used, located 50 m from the experimental site. Readings were taken daily and were multiplied by the crop coefficient (KC) of each crop to obtain crop evapotranspiration (CET).

Variables evaluated

Leaf water potential

Leaf water potential (Ψh) was measured weekly during the production cycle using the pressure pump proposed by Scholander Bradstreet, Hemmingsen and Hammel (1965). Two samplings per treatment and repetition were performed between 12:00 and 14:00 each day. Two healthy leaves were selected from the top of the crop for each treatment and repetition; these were covered with moistened cloths to avoid moisture loss in transfer before being measured (Alghory & Yazar, 2019).

Crop canopy temperature

A model 42530 digital infrared thermometer (Extech Instruments Inc., Boston, MA, USA) with an 8:1 field of view at 8 ft (2.4 m) distance was used to measure crop canopy temperature (°C). Temperatures were taken every week under direct radiation, starting at 35 DAP. Two readings per treatment and replicate were taken at a height of 25 cm above the crop canopy at an angle of inclination of 20° with respect to the perpendicular level of the crop canopy.

Plant height

At harvest time, the final average height of the plants was established by measuring three randomly selected plants in each treatment and replicate. A tape measure was used, and the measurement was taken from the base of the stem to the ear or last leaf of each plant.

Leaf area index

Leaf area index (LAI) was obtained using the AccuPAR model Lp-80 PAR/LAI ceptometer (Decagon Devices, Inc. Pullman, WA, USA). The ceptometer bar was placed at a 45° angle across the furrows in each of the crops to measure photosynthetically active radiation (PAR) interception. The LAI was measured between 12:00 and 14:00 hours, taking three readings above and below the crop canopy in each treatment and replicate. Readings were taken on clear days at seven-day intervals.

Yield

The barley, triticale, and oats were harvested when the grain ripening stage was at a milky, doughy stage (Xu *et al*., 1995), whereas canola was harvested at the final stage of flowering and safflower was harvested at the flower bud stage (Espinoza *et al*., 2023). Green forage (GF) and dry forage (DF) yields were determined for each of the cultivated species. GF yield was calculated by weighing two square meters of biomass for each of the crops and was averaged in each experimental unit of each treatment and repetition. Subsequently, a 500 g sample was taken and dried in a forced air oven (UF 260 Plus, Memmert, Germany) at a temperature of 65 °C until a constant weight was reached (Buthelezi, Mupangwa, Muchenje, & Nherera, 2019), to determine the percentage of dry matter (DM). The DF yield of each species was estimated based on GF production and DM percentage.

Water productivity

Water productivity (WP) was obtained by dividing the harvested dry yield (kg) of each forage species by the total volume of water applied (m^3) during the production cycle in each treatment (Fernández & Camacho, 2005).

Statistical analysis

A linear mathematical model with fixed effects was used for the analysis of variance for the statistical processing of the variables evaluated. Once the existence of differences was verified, Tukey's multiple means comparison test ($p \leq 0.05$) was used using the Statistical Analysis System Institute package, version 9.3 (SAS Institute Inc., Cary, NC, USA).

Results and discussion

Leaf water potential (Ψh)

The different irrigation treatments affected the leaf water potential of the evaluated crops (Figure 2). The treatments of 80 and 100 % of ET presented the highest water status throughout the production cycle for all the crops with a range of -0.2 to -1.45 MPa. In contrast, irrigation treatments with 60 % of ET and flood irrigation had higher water stress (-0.3 to -2.10 MPa) due to soil moisture content. Treatments with higher soil moisture levels presented better water potential, while moisture deficiency generated more negative values (May-Lara, Pérez-Gutiérrez, Ruiz-Sánchez, Ic-Caamal, & García-Ramírez, 2011). Similar values for water potential were reported by Reyes-González *et al*. (2011) (-0.3 to -

2.0 MPa) when evaluating forage oat varieties and different percentages of ET. A similar trend in Ψh was reported by Zavala-Borrego *et al*. (2022) in fodder sorghum, where treatments of 60 % of ET and gravity-assisted irrigation recorded the most negative Ψh values.

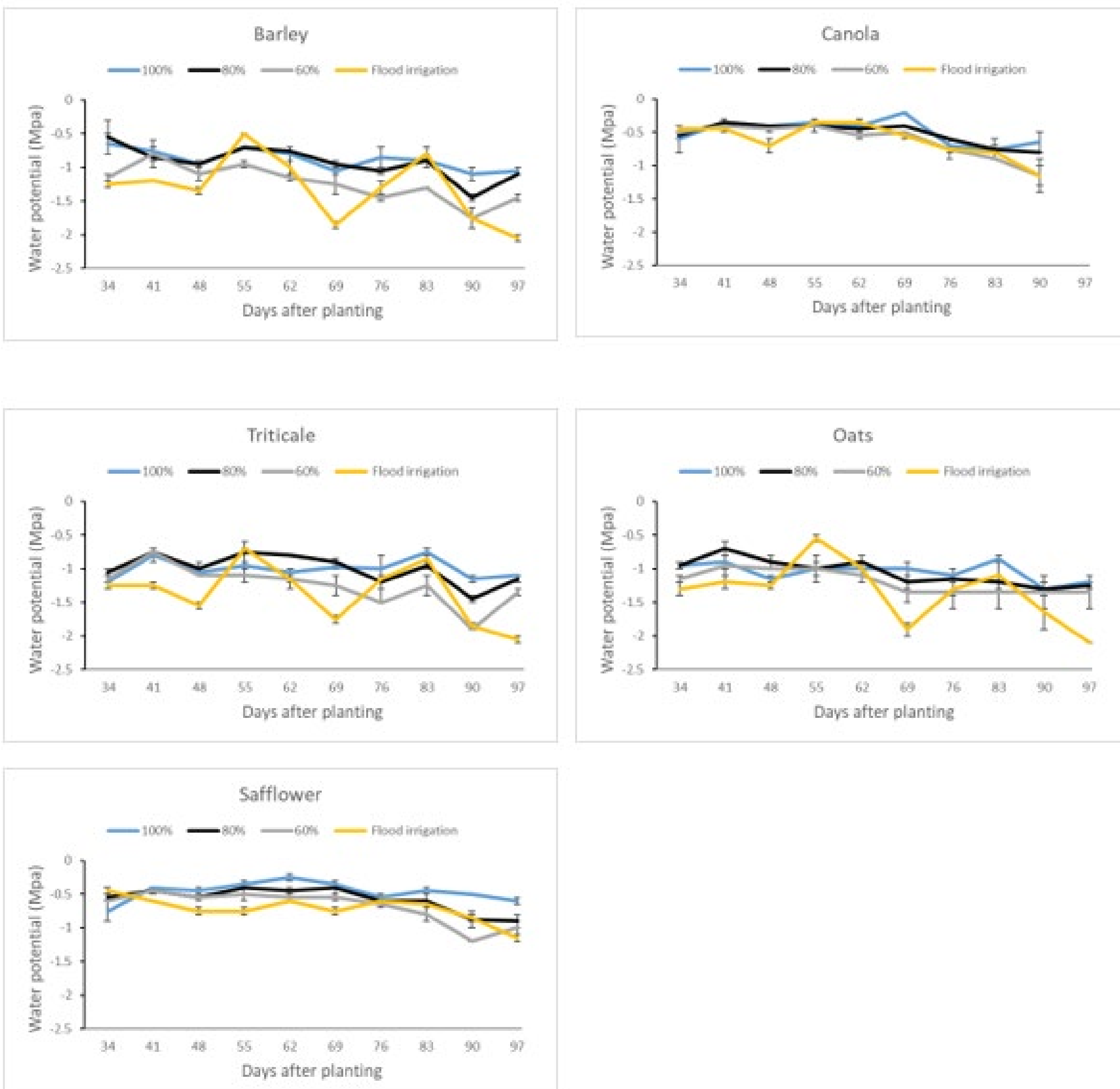

Figure 2. Leaf water potential in winter crops with different irrigation levels based on ET percentage and flood irrigation. Vertical bars indicate the standard deviation.

Safflower and canola had the best Ψh behavior, with less negative values in the different irrigation treatments; this is because these species have lower water requirements (Reta-Sánchez *et al*., 2017). In contrast, oats, triticale, and barley had the most negative values. These values corresponded to the flood irrigation treatment, which showed greater ups and downs in terms of water potential.

Canopy temperature

Canopy temperature was similar across the different crop species (Figure 3). The highest temperatures were recorded at 48 DAP for triticale and oats (25.4 and 25.5°C, respectively) in the flood irrigation treatment, while the minimum values occurred at 83 DAP in all species and irrigation treatments. In general, the highest temperatures were recorded with 60% of ET and flood irrigation. They, in turn, were the treatments that presented the most negative Ψh values, indicating moisture deficit, which resulted in higher leaf temperatures (Him-Lo *et al*., 2020). In the same vein, Reyes-González *et al*. (2019) observed that low moisture levels reduce transpiration due to stomatal closure, causing an increase in the crop’s leaf temperature.

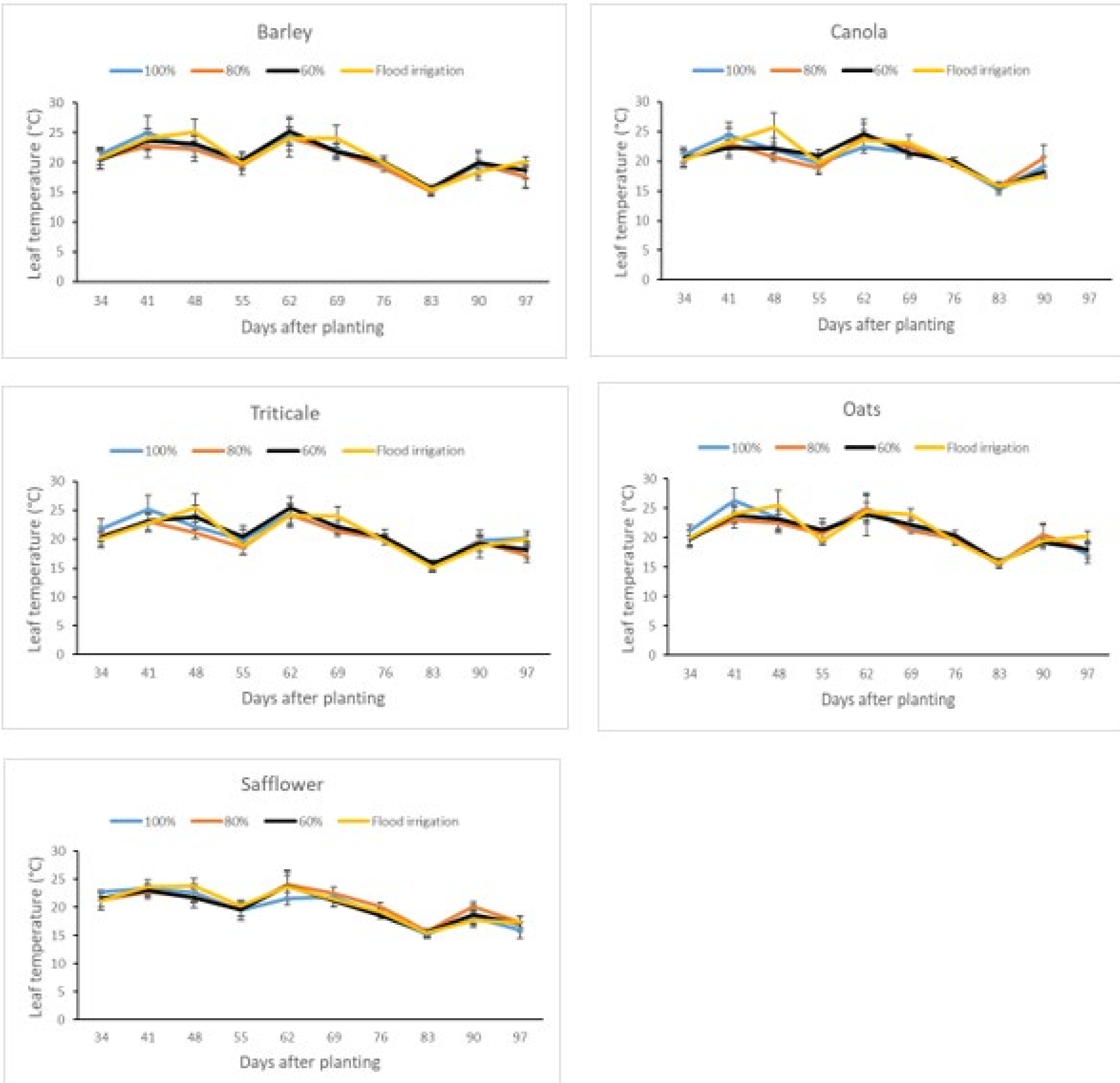

Figure 3. Canopy temperature in winter crops with different irrigation levels based on ET percentage and flood irrigation. Vertical bars indicate the standard deviation.

Plant height

Plant height was positively affected by the different treatments, with the greatest height achieved in the 80 and 100 % of ET treatments. The shortest heights were found with 60 % of ET and gravity-assisted irrigation (Figure 4a), which were statistically equal. This is because in the 80 and 100 % of ET treatments, the irrigation interval and amount applied favored moisture harnessing in the root system and boosted crop growth, generating greater biomass production (Reyes *et al*., 2023).

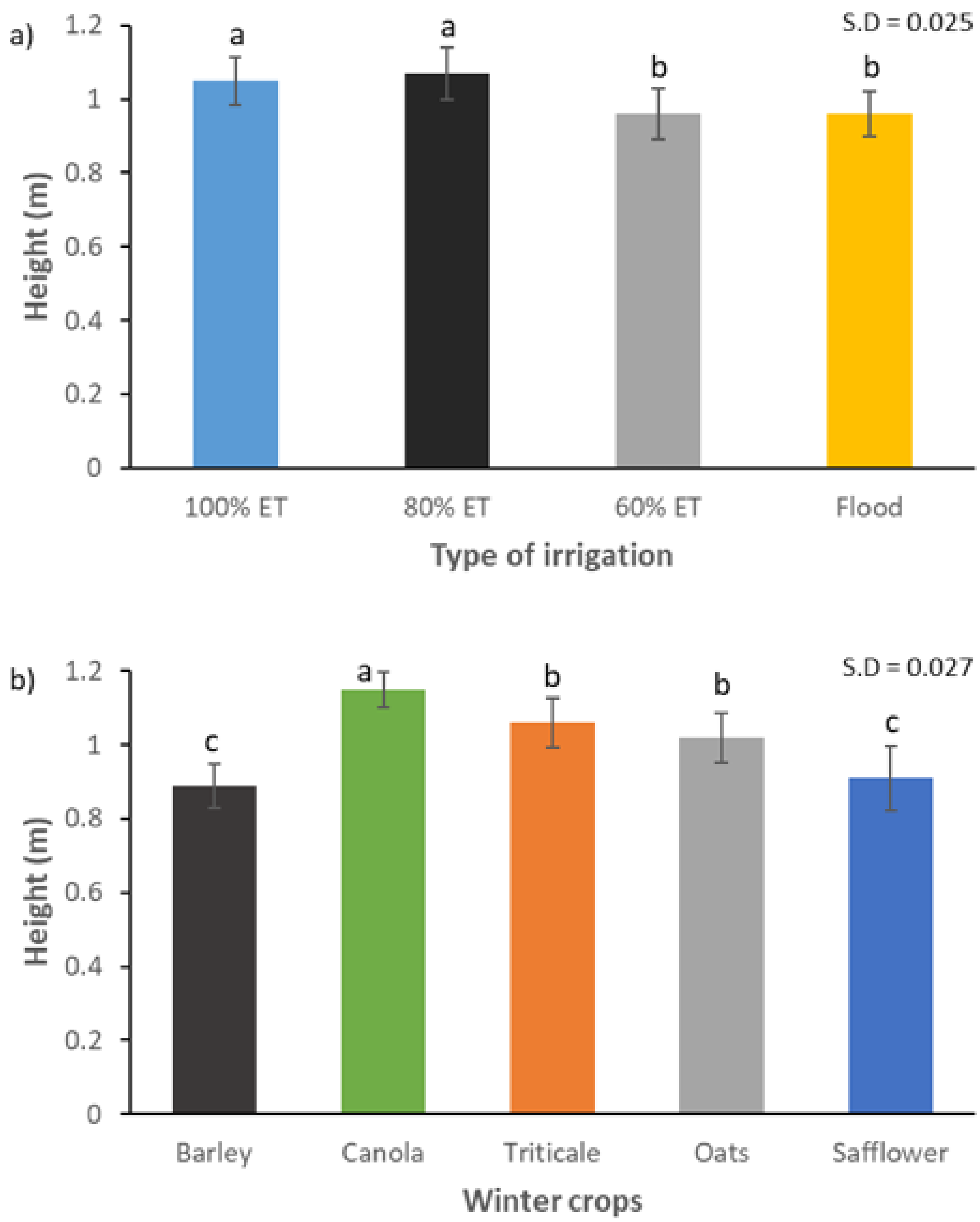

Figure 4. Plant height in (a) different types of irrigation and (b) different winter crops. The vertical bars indicate the standard deviation.

The canola crop registered the greatest height, being statistically different from the rest of the species. Triticale and oats were statistically similar, and the lowest height was recorded in safflower and barley, which were statistically equal (Figure 4b).

Zavala-Borrego *et al*. (2022) also reported greater plant height with 80 and 100 % of ET using a drip irrigation system compared to the gravity-assisted irrigation system. In turn, Ochoa-Espinoza *et al*. (2022b) obtained similar heights in the evaluation of the forage potential of safflower and small grain cereals in two production cycles using species similar to those of the present research.

Leaf area index (LAI)

Although there was no statistical difference between irrigation types, higher LAIs were observed in the treatments of 80 and 100 % of ET than those of 60 % of ET and gravity-assisted irrigation. This result is probably due to the fact that the soil's various moisture levels condition the turgor potential and stomatal closure, which limits biomass production. In this regard, Reyes *et al*. (2023) point out that water restriction limits the adequate development of leaves, so that the plant's capacity to capture light energy is affected, as is the LAI.

In contrast, there was a significant difference when analyzing the different winter species. Safflower registered the lowest LAI (Figure 5) because safflower grows on a main stem, while the other cereals form additional stems (Prado, Gallardo, Kruk, & Miralles, 2017) except canola, whose very large leaves are responsible for its greater LAI. This is an important characteristic that depends on solar interception, which determines the amount of forage during the crop production cycle (Reta, Sánchez, Ochoa, Reyes, & Rodríguez, 2023).

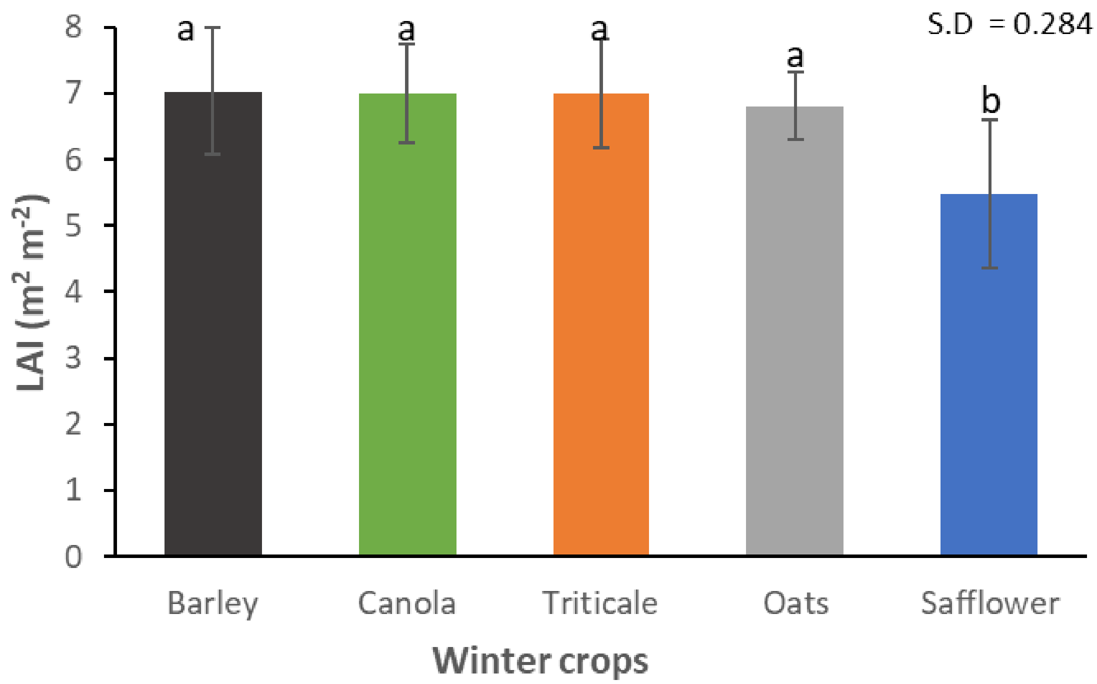

Figure 5. Leaf area index in winter crops. Vertical bars indicate the standard deviation.

The results of this research were higher than those obtained by Ochoa-Espinoza *et al*. (2022a), who found LAI values of 5.34 to 7.95 in five forage species watered using flood irrigation in Comarca Lagunera.

Green forage (GF) plants

Significant differences in GF production were found across irrigation treatments and species evaluated. The highest GF production was observed in the 80 % and 100 % of ET treatments, with statistically equal average yields of 64.21 and 66.11 t ha^{-1}, respectively. The treatment with the lowest GF yield was 60 % of ET, followed by gravity-assisted irrigation (Figure 6a). As for the species evaluated, canola and oats were statistically superior to the other crops. Safflower had the lowest GF yield with a production of 50.66 t ha^{-1} (Figure 6b).

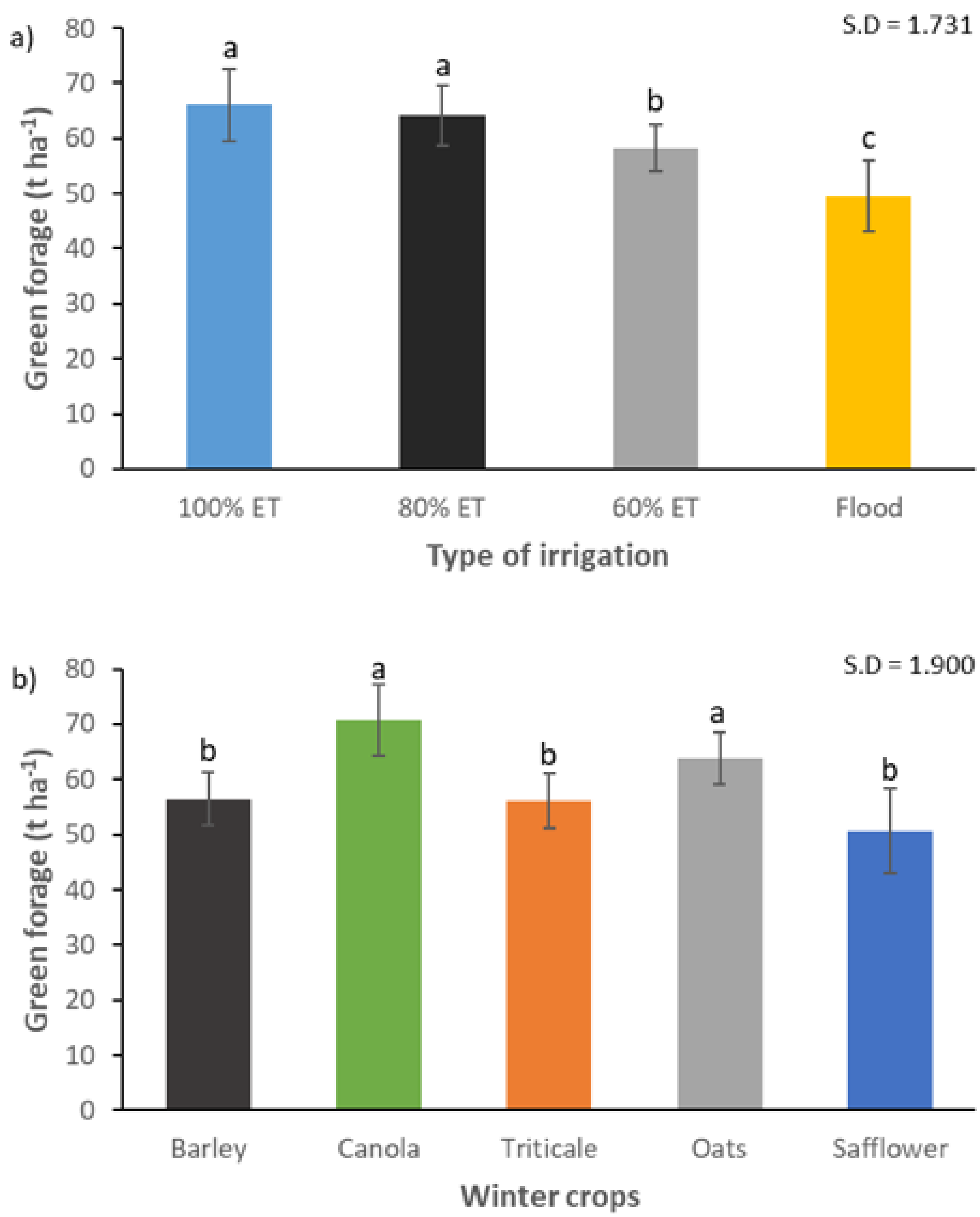

Figure 6. Green forage yields in (a) different types of irrigation and (b) different winter crops. Vertical bars indicate the standard deviation.

The increase in biomass in the ET treatments is owing to the fact that irrigation water is applied efficiently and constantly, creating favorable moisture conditions for good crop development from its early stages. This results in higher biomass production (Reta-Sánchez, Cueto-Wong, Gaytan-Mascorro, & Santamaria-Cesar, 2007; Sánchez-Hernández *et al*., 2013) in addition to the fact that yield is influenced by cultivar type, sowing date, and the agronomic traits of each species (Ochoa-Espinoza *et al.*, 2022a). In this regard, Zavala-Borrego *et al.* (2021) observed an increase in GF yield in treatments where drip irrigation was applied based on ET levels (80 and 100 %) compared to flood irrigation.

Dry forage (DF)

The production of DF did not show significant differences according to irrigation type. The highest yields were found for 80 and 100 % of ET, with yields of 12.68 and 12.76 t ha^{-1}, respectively (Figure 7a). The production of DF did show significant differences according to crop (Figure 7b). The crops with the highest DF were barley, triticale, and oats, with 13.26, 13.24, and 12.89 t ha^{-1}, respectively. The above is related to the fact that these species have a greater capacity for additional stem forming and generate a higher LAI, which favors an increase in biomass and consequently higher forage yields (Prado *et al*., 2017). The lowest yields were reported in safflower (11.47 t ha^{-1}) and canola (10.25 t ha^{-1}). This behavior is associated with abiotic stress present in the plants, causing alterations in physiological functions (photosynthetic capacity and metabolic activities) that reduce grain and ear formation and thus affect forage yields (Nurunnaher & Islam, 2017).

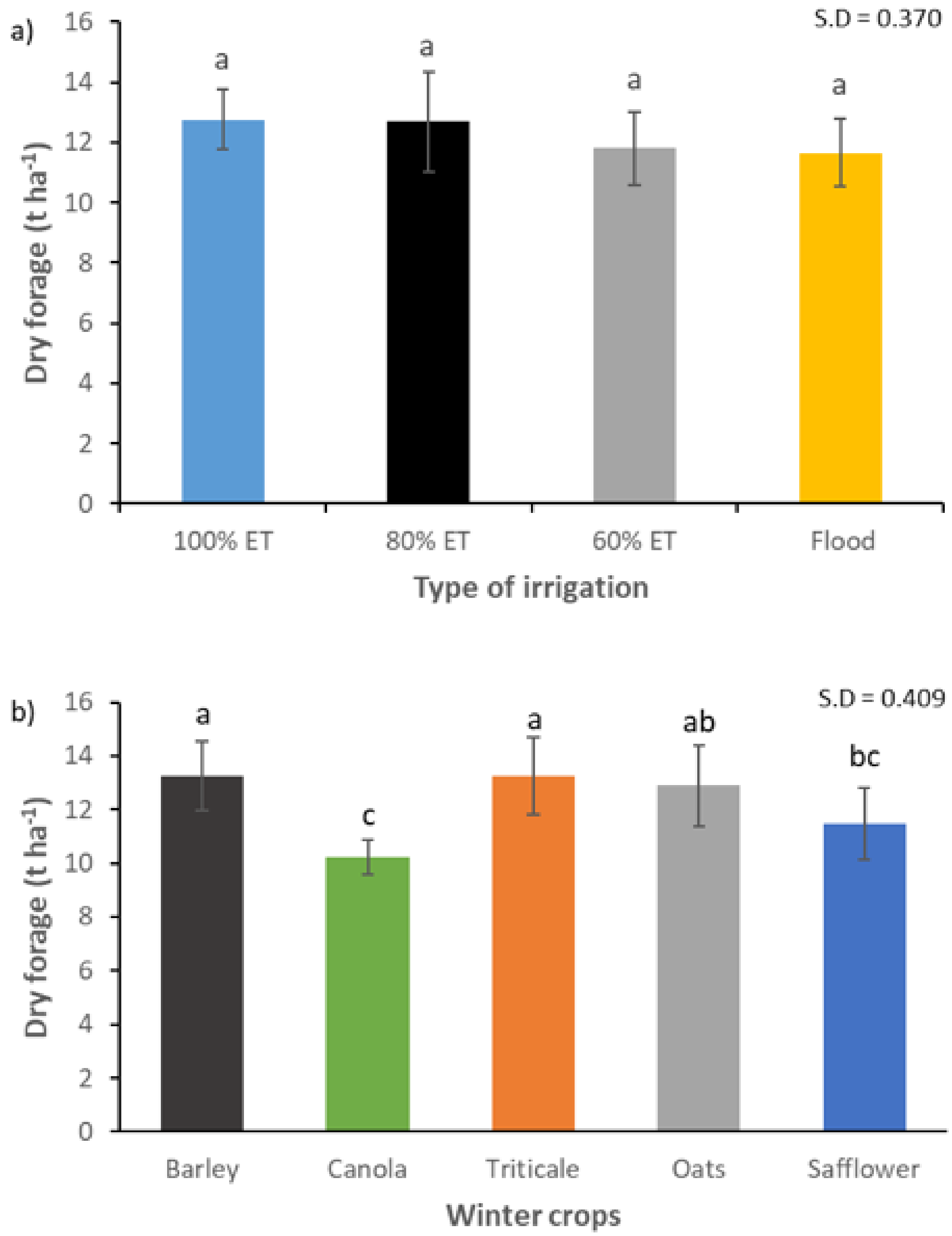

Figure 7. Dry forage yields in (a) different irrigation types and (b) different winter crops with different irrigation levels based on ET percentage and flood irrigation. Vertical bars indicate the standard deviation.

López-Jara *et al.* (2022) reported higher dry matter yields in barley and triticale than canola and safflower during the fall-winter cycle, similar to the results of this research. But the yields of the present study are higher than those reported by Ochoa-Espinoza *et al.* (2022a), who obtained lower FS yields in five forage species (barley, triticale, oats, wheat, and safflower) in the fall-winter 2017–2018 production cycle.

Water productivity (WP)

WP showed significant differences between the different irrigation treatments and cultivated species. The highest WP was obtained in the 60 and 80 % of ET treatments, with average values of 4.00 and 3.75 kg FS m^{-3}, exceeding flood irrigation by 35.5 and 31.2 %, respectively (Figure 8a). Barley, oats, and triticale obtained the highest WP values since they have lower water requirements (Reta *et al*., 2017), while canola had the lowest WP value (Figure 8b).

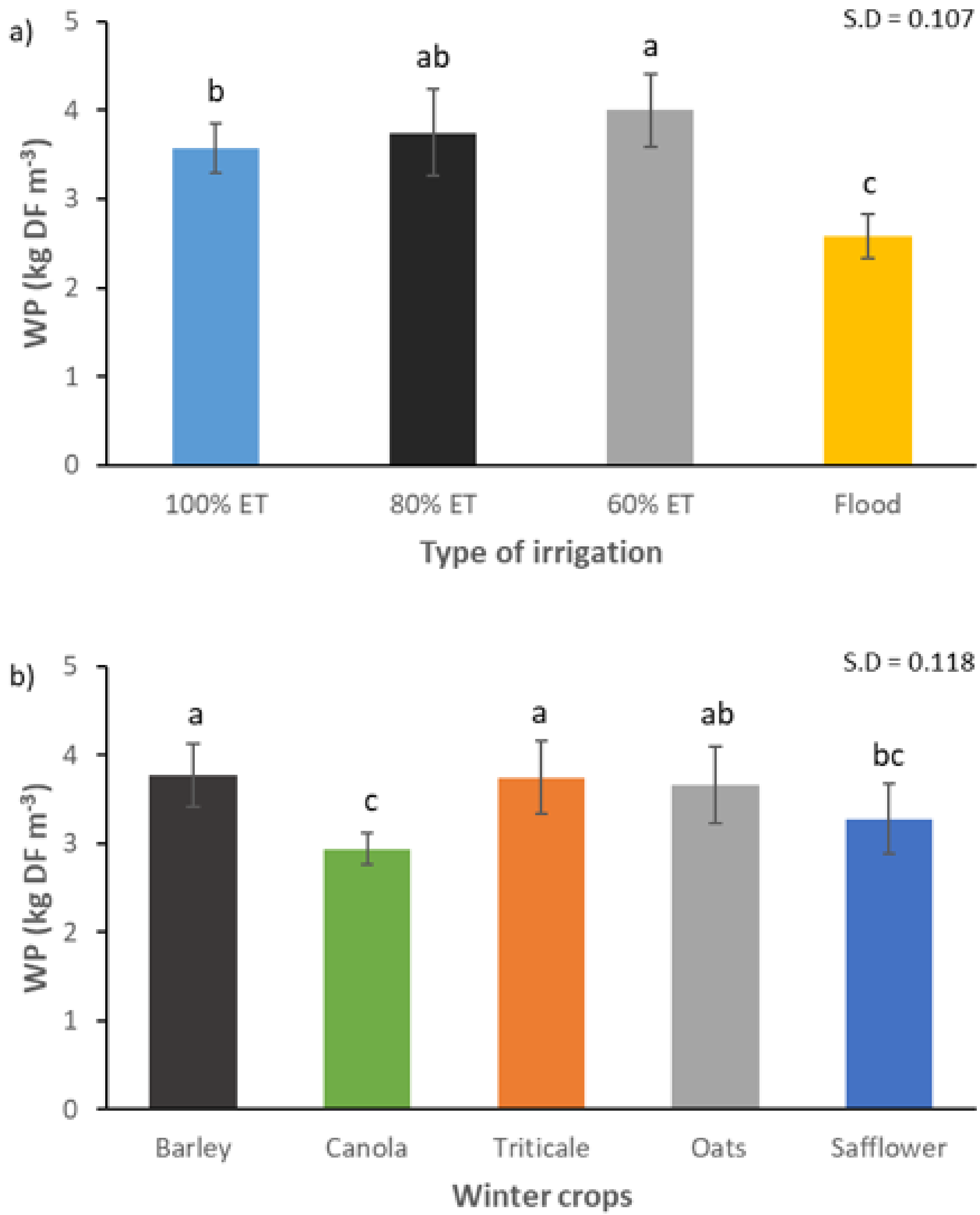

Figure 8. Water productivity in (a) different types of irrigation and (b) different winter crops. Vertical bars indicate the standard deviation.

The increase in WP with 60 and 80 % of ET is due to the fact that less irrigation water was used in comparison to 100 % of ET and flood irrigation. This is related to the fact that the highest WP is obtained when less irrigation water is used (Zavala-Borrego *et al*., 2022). In this regard, Núñez-Ramírez *et al*. (2020) reported higher WP in the evaluation of four different soil moisture tensions (10, 20, 30, and 40 kPa), obtaining better results with lower moisture values in the production of six maize genotypes. The results obtained in the present investigation are similar to those reported by Reyes *et al*. (2023), who evaluated three levels of ET (60, 80, and 100 %) and gravity-assisted irrigation in forage corn. Those researchers reported higher WP in drip irrigation (3.60 kg FS m^{-3} with 60 % of ET) and lower in gravity-assisted irrigation (2.21 kg FS m^{-3}).

Conclusions

In this study, there was no interaction between the levels of the two factors. However, different levels of evapotranspiration affected biomass yield and water productivity. At 80 and 100 % of ET, the highest biomass yields (green forage and dry forage) were obtained in barley, triticale, and oats. Water productivity was highest in the 60 and 80 % of ET treatments. Meanwhile, the highest WP according to winter crop corresponded to barley, triticale, and oats. Applying 60 % of ET is advisable since there are no differences between 60 and 80 % in terms of yield (dry forage) or water productivity. In general, the results indicate that the drip irrigation treatments with different irrigation levels based on ET percentages and water deficit maintain the productive potential of winter crops in Comarca Lagunera, Mexico.

References

Alghory, A., & Yazar, A. (2019). Evaluation of crop water stress index and leaf water potential for deficit irrigation management of sprinkler-irrigated wheat. *Irrigation Science*, 37(1), 61-77. DOI: 10.1007/s00271-018-0603-y

Buthelezi, L. S., Mupangwa, J. F., Muchenje, V., & Nherera, Ch. (2019). Influence of drying technique on chemical composition and ruminal degradability of subtropical *Cajanus cajan L*. *Animal Nutrition*, 5, 95-100. DOI: 10.1016/j.aninu.2018.03.001

Espinoza, X. M. O., Aguilera-Molina, N. A., Barreras, C. I. C., Gracia, A. B., Casillas, E. Á., Bolivar, E. H. G., & Jiménez, J. N. (2023). Comportamiento de líneas élite y variedades de cártamo del tipo oleico en el sur de Sonora/Performance of elite lines and varieties of carthamus of the oleic type in southern Sonora. *Brazilian Journal of Animal and Environmental Research*, 6(3), 2998-3007. DOI: 10.34188/bjaerv6n3-081

Fernández, R.E., & Camacho, F. (2005). Eficiencia en el uso del agua. *Revista Viveros*. *Horticultura Internacional*, (1), 86-89.

Flores, G. H., Ojeda, B. W., Flores, M. E., Sifuentes, I. E., & Mejía, S. E. (2013). Simulación del rendimiento de maíz (*Zea Mays L*.) en el norte de Sinaloa usando el modelo Aquacrop. *Agrociencia*, 47(3), 347-359.

García, E. (2004). *Modificaciones al sistema de clasificación climática de Köppen, para adaptarlo a las condiciones de la República Mexicana* (núm. 6) (pp. 90-93). Ciudad de México, México: Instituto de Geografía, Universidad Nacional Autónoma de México.

Godoy-Ávila, C., Pérez-Gutiérrez, A., Torres, C. A., Hermosillo, L. J., & Reyes, I. (2003). Uso de agua, producción de forraje y relaciones hídricas en alfalfa con riego por goteo subsuperficial. *Agrociencia*, 37(2), 107-115.

Him-Lo, T., Rudnick, D. R., DeJonge, K. C., Bai, G., Njuky-Nakabuye, H., Katimbo, A., & Heeren, D. M. (2020). Differences in soil water changes and canopy temperature under varying water×nitrogen sufficiency for maize. *Irrigation Science*, 38, 519-534. DOI: 10.1007/s00271-020-00683-2

López-Jara, A. G., Reta-Sánchez, D. G., Reyes-González, A., Santana, O. I., López-Calderón, M. J., & Sánchez-Duarte, J. I. (2022). Composición nutritiva y productividad de forrajes alternativos de otoño-invierno en diferentes fechas de siembra del norte de México. *Revista Mexicana de Ciencias Agrícolas*, 13(SPE28), 125-135. DOI: 10.29312/remexca.v13i28.3268

May-Lara, C., Pérez-Gutiérrez, A., Ruiz-Sánchez, E., Ic-Caamal, A. E., & García-Ramírez, A. (2011). Efecto de niveles de humedad en el crecimiento y potencial hídrico de *Capsicum chinense* Jacq. Y su relación con el desarrollo de f *Bemisia tabaci* (Genn.). *Tropical and Subtropical Agroecosystems*, 14(3), 1039-1045. DOI: 10.56369/tsaes.1104

Nurunnaher, A., & Islam, M. R. (2017). Efectos y manejo del estrés por calor en el trigo. Una revisión. *Agronomía para el Desarrollo Sostenible*, Dev. 5(37), 1-37. DOI: 10.1007/s13593-017-0443-9

Núñez-Ramírez, F., Escobosa-García, I., Cárdenas-Salazar, V., Santillano-Cázares, J., Ruelas-Islas, J. D. R., Preciado-Rangel, P., & Díaz-Ramírez, J. (2020). Tensión de humedad del suelo, crecimiento, eficiencia en el uso del agua y rendimiento de maíz cultivado en el noroeste de México. *Terra Latinoamericana*, 38(4), 805-815. DOI: 10.28940/terra.v38i4.763

Ochoa-Espinoza, X. M., Reta-Sánchez, D. G., Cano-Ríos, P., Sánchez-Duarte, J. I., Ochoa-Martínez, E., García-Martínez, J. E., & Quiroga-Garza, H. M. (2022a). Rendimiento y valor nutritivo de cereales y cártamo forrajero en la Comarca Lagunera. *Biotecnia*, 24(2), 142-148. DOI: 10.18633/biotecnia.v24i2.1620

Ochoa-Espinoza, X. M., Reta-Sánchez, D. G., Cano-Ríos, P., Sánchez-Duarte, J. I., Ochoa-Martínez, E., García-Martínez, J. E., & Reyes-González, A. (2022b). Nutritional yield and composition of spiny and spineless varieties of safflower (L.) forage harvested at four phenological stages. *The Open Agriculture Journal*, 16(1), 1-8. DOI: 10.2174/18743315-v16-e2201250

Prado, S. A., Gallardo, J. M., Kruk, B. C., & Miralles, D. J. (2017). Strategies for yield determination of bread wheat and two-row barley growing under different environments: A comparative study. *Field Crops Research*, 203, 94-105. DOI: 10.1016/j.fcr.2016.12.013

Reyes-González, A., Martínez-Rodríguez, J. G., Palomo-Rodríguez, M., Faz-Contreras, R., Cruz-Chaires, J. J., & Sánchez-Duarte, J. I. (2011). Producción de avena forrajera con riego por goteo subsuperficial en la Comarca Lagunera. En: *Memoria de la XXIII Semana Internacional de Agronomía FAZ-UJED* (pp. 189-195). Gómez Palacio, México: Facultad de Agricultura y Zootecnia, Universidad Juárez del Estado de Durango.

Reyes, G. A., Kjaersgaard, J., Trooien, T., Reta, S. D. G., Sánchez, D. J. I., Preciado, R. P., & Fortis, H. M. (2019). Comparison of leaf area index, surface temperature, and actual evapotranspiration estimated using the METRIC model and in situ measurements. *Sensors*, 19(8), 1857. DOI: 10.3390/s19081857

Reyes, G. A., Franco, G. I., Hernández, L. E., & Maltos, B. J. (2020). Evaluación del potencial hídrico, temperatura foliar y rendimiento en sorgo (*sorghum* spp.) forrajero bajo riego por goteo. *Ciencia e Innovación*, 3(1), 83-90.

Reyes, A. G., Reta, D. G. S., Sánchez, J. I. D., Preciado, P. R., Rodríguez, V. M. M., & Ruiz, O. Á. (2023). Uso del atmómetro y coeficiente de cultivo en la programación del riego en maíz forrajero. *Ecosistemas y Recursos Agropecuarios,* 10(1), 1-14. e3160. DOI: 10.19136/era.a10n1.3160

Reta-Sánchez, D. G., Cueto-Wong, J. A., Gaytan-Mascorro, A., & Santamaria-Cesar, J. (2007). Rendimiento y extracción de nitrógeno, fosforo y potasio de maíz forrajero en surcos estrechos. *Agricultura Técnica en México*, 33, 145-151. DOI: 10.35196/rfm.2017.2.227-233

Reta-Sánchez, D. G., Serrato-Corona, J. S., Quiroga-Garza, H. M., Figueroa-Viramontes, U., & Gaytán-Mascorro, A. (2017). Potencial forrajero de cultivares de canola primaverales e invernales en la Comarca Lagunera, México. *Revista Fitotecnia Mexicana*, 40(2), 227-233.

Reta, D. G. S., Sánchez, J. I. D., Ochoa, E. M., Reyes, A. G., & Rodríguez, K. H. (2023). Intercepción de radiación solar y rendimiento de forraje de brásicas y cereales de otoño-invierno. *Agrofaz*, 5(1), 3-9.

Sader, Secretaría de Agricultura y Desarrollo Rural. (2021). Secretaría de Agricultura y Desarrollo Rural-Delegación en la Región Lagunera, Sector Agropecuario. *El Siglo de Torreón*, suplemento especial, 24.

Sánchez-Hernández, M. A., Aguilar-Martínez, C.U., Valenzuela-Jiménez, N., Joaquín-Torres, B. M., Sánchez-Hernández, C., Jiménez-Rojas, M. C. & Villanueva-Verduzco, C. (2013). Rendimiento en forraje de maíces del trópico húmedo de México en respuesta a densidades de siembra. *Revista Mexicana de Ciencias Pecuarias*, 4, 271-288.

Scholander, P. F., Bradstreet, E. D., Hemmingsen, E. A., & Hammel, H. T. (1965). Sap pressure in vascular plants Negative hydrostatic pressure can be measured in plants. *Proceedings of the National Academy of Sciences*, 148(3668), 339-346. DOI: 10.1126/science.148.3668.339

Servin-Palestina, M., Sánchez-Gutiérrez, R. A., Ramírez-Valle, O., Galindo-Reyes, M. A., & Gutiérrez-Bañuelos, H. (2018). Modelos para programación y optimización de agua de riego en avena forrajera. *Revista Mexicana de Ciencias Pecuarias*, 9(4), 667-684. DOI: 10.22319/rmcp.v9i4.4404

SIAP, Sistema de Información Agroalimentaria y Pesquera. (2021). *Escenario mensual de productos agroalimentarios*. Ciudad de México: México: Sistema de Información Agroalimentaria y Pesquera.

Xu, S., Harrison, J. H., Kezar, W., Entrikin, N., Loney, K. A., Riley, R. E., & Hunt, C. (1995). Evaluation of yield, quality, and plant composition of early-maturing corn hybrids harvested at three stages of maturity. *The Professional Animal Scientist*, 11(3), 157-165. DOI: 10.15232/S1080-7446(15)32580-8

Zavala-Borrego, F., Reyes-González, A., Álvarez-Reyna, V. D. P., García-Carrillo, M., Rodríguez-Moreno, V. M., & Preciado-Rangel, P. (2021). Efecto de diferentes niveles de evapotranspiración sobre área foliar, temperatura superficial, potencial hídrico y rendimiento en sorgo forrajero. *Terra Latinoamericana*, 39(1), 1-14. e954. DOI: 10.28940/terra.v39i0.954

Zavala-Borrego, F., Reyes-González, A., Álvarez-Reyna, V. D. P., Cano-Ríos, P., & Rodríguez-Moreno, V. M. (2022). Efecto de la tasa de evapotranspiración en área foliar, potencial hídrico y rendimiento de maíz forrajero. *Revista Mexicana de Ciencias Agrícolas*, 13(3), 407-420. DOI: 10.29312/remexca.v13i3.2294