

Efficient use of water resources in rice genotypes grown under rainfed and with supplementary irrigation in Tabasco, Mexico

Uso eficiente del recurso hídrico en genotipos de arroz de temporal y bajo riego suplementario en Tabasco, México

Sergio Salgado-Velázquez¹ , Fabiola Olvera-Rincón² , Dante Sumano-López¹ , Pablo Ulises Hernández-Lara¹ , Sabel Freyre-Barrón¹ , David Julián Palma-Cancino^{3,4*} , Samuel Córdova-Sánchez⁴ 

¹ Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Campo Experimental Huimanguillo, km 1 carretera Huimanguillo-Cardenas, 86400, Huimanguillo, Tabasco, Mexico.

² Colegio de Postgraduados, Campus Tabasco, km 3.5 periferico Carlos A. Molina s/n, 86500, Cardenas, Tabasco, Mexico.

³ Colegio de Postgraduados, Campus Campeche, carretera Haltunchen Edzna, Champoton, Campeche, 24450, Champoton, Campeche, Mexico.

⁴ Universidad Popular de la Chontalpa, km 2 carretera Cardenas, Huimanguillo, 86529, Cardenas, Tabasco, Mexico.

*Corresponding author: plusdpc@gmail.com

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ABSTRACT

Efficient water use is essential to sustain rice (*Oryza sativa* L.) production under increasing climate variability. This study evaluated water productivity (WP) and water conversion efficiency (WCE) in 36 rice genotypes grown under rainfed conditions in Tabasco, Mexico, to identify materials with improved adaptation to limited water availability. The experiment was conducted using a randomized complete block design with three replications. Agronomic traits and water indicators based on crop evapotranspiration were analyzed. Significant differences were detected among genotypes ($p < 0.001$). Genotype T30 (cv. Golfo FL-16) showed the highest grain yield (4,127.2 kg ha⁻¹), greatest WP (0.54 kg m³), and lowest WCE (1.98 m³ kg⁻¹). Genotypes T15, T4, T16, and T25 also showed favorable performance, indicating exploitable variability for improving sustainability and resilience under climate change.

KEYWORDS

Water efficiency, evapotranspiration, *Oryza sativa*, grain yield, genetic improvement.

RESUMEN

El uso eficiente del agua es esencial para sostener la producción de arroz (*Oryza sativa* L.) ante la creciente variabilidad climática. Este estudio evaluó la productividad del agua (PA) y la eficiencia de conversión de agua (ECA) en 36 genotipos de arroz cultivados bajo condiciones de temporal en Tabasco, México, con el objetivo de identificar materiales con mayor adaptación a la disponibilidad limitada de agua. El experimento se estableció mediante un diseño de bloques completos al azar con tres repeticiones. Se analizaron variables agronómicas e indicadores hídricos basados en la evapotranspiración del cultivo. Se detectaron diferencias significativas entre genotipos ($p < 0.001$). El genotipo T30 (cv. Golfo FL-16) presentó el mayor rendimiento de grano (4,127.2 kg ha⁻¹), la mayor PA (0.54 kg m⁻³) y la menor ECA (1.98 kg m³). Los genotipos T15, T4, T16 y T25 también mostraron un desempeño favorable, lo que indica variabilidad aprovechable para mejorar la sostenibilidad y resiliencia ante el cambio climático.

PALABRAS CLAVE

Eficiencia hídrica, evapotranspiración, *Oryza sativa*, rendimiento de grano, mejoramiento genético.

INTRODUCTION

Rice (*Oryza sativa* L.) is one of the most important crops worldwide, both for its caloric contribution and its strategic role in food security. Globally, it is cultivated on more than 160 million hectares, with an annual production exceeding 740 million tons (Organización de las Naciones Unidas para la Agricultura y la Alimentación, 2023). However, the projected increase in demand by 2035, estimated at an additional 116 million tons (Yamano et al., 2016), faces serious constraints due to the reduction in arable land, competition for water, and the impacts of climate change (Long-Ping, 2014; López-Hernández et al., 2018; Salgado-Velázquez et al., 2025).

In Mexico, rice plays an important role in the national diet, ranking behind only corn, beans and wheat. However, the country has a significant domestic production deficit, producing only 252,000 tons from 36,000 hectares with an average yield of four tons per hectare in 2023 (Servicio de Información Agroalimentaria y Pesquera, 2023). As a result, Mexico depends on imports for more than 80 % of its rice consumption, highlighting the need to increase productivity and improve the efficiency of natural resource use, particularly water (Secretaría de Economía, 2021).

Climate change has intensified pressure on rice production systems, especially in tropical regions where rainfall variability and rising temperatures affect the duration of phenological stages, crop evapotranspiration (ETc), and water-use efficiency (Estrada et al., 2022). In Mexico, an average temperature increase of +0.6 °C has been documented since 1960, with projections of up to 3 °C by 2060. This could reduce yields by 24 % to 36 % in vulnerable areas if appropriate water management and varietal adaptation strategies are not implemented (Zhao et al., 2022). In this context, ETc and crop coefficient (Kc) are essential tools for estimating water demand and optimizing irrigation management or crop scheduling under rainfed conditions. These variables link physiological processes to agronomic performance, integrating aspects of energy balance, water availability, and photosynthetic efficiency. Likewise, water productivity (wP) and water conversion efficiency (wCE) provide a quantitative assessment of water-use

performance by relating the volume of water used to the yield obtained, which is essential for selecting genotypes with greater ecophysiological efficiency. Additionally, the duration of the phenological stages from emergence to physiological maturity directly influences biomass accumulation and crop water requirements. Proper synchronization between the phenological cycle and local climatic conditions can improve water use and reduce losses due to water stress (Salgado-Velázquez et al., 2026).

In light of these considerations, this study aimed to evaluate water-use efficiency and its relationship with the agronomic performance of various rice genotypes grown under rainfed conditions in Tabasco, Mexico. The objective was to generate information to support the selection of genotypes with higher water-use efficiency and phenological stability, thereby promoting more sustainable and resilient production systems under climate change scenarios.

MATERIALS AND METHODS

Study area

The study was conducted on eutric fluvisol soil with a 20-year history of rice cultivation, located at the experimental fields of the Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP) in Huimanguillo, Tabasco, Mexico. The region has an average annual rainfall of 2,356 mm, with a dry season from February to May (276 mm), and an average minimum temperature above 20 °C. The crop cycle was established on June 15th, 2024 (Salgado-Velázquez et al., 2025).

Varieties and experimental lines

A total of 36 rice genotypes (experimental lines and commercial varieties) developed by INIFAP for rainfed and irrigated conditions were evaluated within the project “Mejora genética del arroz en México, para incorporar resistencia a problemas bióticos y abióticos causados por efectos del cambio climático”. The genotypes are listed in Table 1.

Table 1. Rice genotypes studied under rainfed conditions in Tabasco, Mexico.

Treat	Genealogies
1	Milagro (Zacatepec)
2	Miloax 98-2
3	INIFLAR RT-1
4	IR 69915-12MI-15UBN-22
5	IR8-2
6	El Silverio-2
7	INIFLAR RT-2
8	Tabasqueña A-17-2
9	Temporalero A-95
10	Pacifico-FL-15-1
11	FL06689-3P-1-4P-M
12	FL02768-2P-6-4P-1P-M-1P
13	Pacific FL15-2
14	FL084430-8P-4-3P-3P-M
15	PCTMADR-707-2-1-1-3SR-2P
16	PCTMADR-682-2L-2-3-3SR-2P
17	PCTMADR-707-2-1-4-2SR-1P
18	PCTMADR-707-2-1-4-2SR-2P
19	PCTMADR-707-2-1-2-4SR-1P
20	FL010030-12P-9-2P-1P-M
21	FL0 10127-7P-1-2P-2P-M
22	FL07162-7P-3-3P-3P-M
23	RC 88
24	IR11141-6-1-4
25	Choca A-05
26	Campeche A-80
27	El Silverio
28	INIFLAR R
29	Pacifico FL-15
30	Gulf FL-16
31	Veracruzana A-21-3
32	Temporalero A-95
33	Miloax 98 (2006)
34	Milver 05 (2008)
35	Miloax 38 (2012)
36	Filipino Miracle (2010) (Veracruz)

*Treat: study treatments.

Experimental design

The experiment was established using a randomized complete block design with three replications, where genotypes were considered as treatments. Each experimental plot consisted of six furrows, 6 m in length, spaced 0.2 m apart. The four central furrows were used as the net plot for data collection. The data were analyzed using the following linear model (1):

$$Y_{ij} = \mu + T_i + B_j + \varepsilon_{ij} \quad (1)$$

Where: Y_{ij} = is the observed value of the variable of interest for treatment i in block j , μ = is the overall mean, T_i = is the fixed effect of the i -th genotype, B_j = is the random effect of the j -th block, ε_{ij} = is the associated experimental error, assumed to be independent and normally distributed with mean zero and constant variance [$\varepsilon_{ij} \sim N(0, \sigma^2)$].

This model allows genotypes to be compared with respect to variables such as grain yield, plant height, ETC, WP, and WCE, evaluating whether the differences observed between treatments are statistically significant.

Agronomic management

Land preparation included mechanical removal using a shredder, followed by plowing and two passes with a harrow. The soil was leveled with a rototiller to ensure uniform water distribution. Sowing was performed by broadcasting seeds uniformly across the furrows. Fertilization was applied using a 130-40-120 N-P-K scheme: all the phosphorus and potassium were applied at sowing, while nitrogen (urea) was split into two applications at 30 and 35 days after germination (the latter at panicle formation). Pest control targeted the brown stink bugs (*Oebalus insularis* Stål), rice borers (*Rupela albinella* Cramer), and spider mites (*Steneotarsonemus spinki* Smiley), using imidacloprid (0.25 L ha⁻¹), methamidophos (1 L ha⁻¹), and cypermethrin (0.5 L ha⁻¹), with six applications during the crop cycle. Weed control included a pre-emergence application of pendimethalin and clomazone two days after the first irrigation. One month after sowing, propanil, fenoxaprop-*p*-ethyl, bispyribac-sodium, cyhalofop-butyl, 2,4-D, and bentazone were applied.

Manual weeding was performed, mainly along rows and plot borders (Jiménez-Chong et al., 2016).

Water management

Irrigation was managed based on water requirements, estimated from ET_c and K_c for each phenological stage. During tillering, heading, and flowering, irrigation maintained saturated soil conditions, with an initial depth of 5 cm, adjusted according to crop demand. Water depth was maintained until physiological maturity. This management enabled estimation of WP and WCE , allowing evaluation of each genotype's ability to convert water into grain yield.

Study variables

During reproductive and physiological maturity stages, the following variables were recorded: plant height (PH): measured from the base to the apex of the main panicle in 10 plants per plot. Number of grains per panicle (NGP): determined by counting all grains per selected panicle (Álvarez Hernández et al., 2018). Grain yield (GY): panicles in each plot were harvested, threshed, placed in a brown paper bag, and labeled. They were then weighed on an analytical balance and the moisture content of each sample was determined using a Delmhorst G-7 meter. Yield was adjusted to 14 % moisture content using the corresponding equation (2) (Barrios-Gómez et al., 2023):

$$GY \left(\frac{kg}{ha} \right)_{14\% \text{ moisture content}} = \frac{(100 - M) \times \text{plot yield}(kg) \times 10000}{(100 - 14) \times \text{plot area}, m^2} \quad (2)$$

Where: M is the moisture content of the grain sample. It is multiplied by 10,000 for conversion from m^2 to ha.

Meteorological data (air temperature, precipitation and evaporation) was obtained from a weather station located near 100 m from the experimental site. Extraterrestrial radiation ($MJ m^2 day^{-1}$) was estimated following FAO guidelines (Allen et al., 2006; Ares et al., 2020). The data were recorded daily and plotted as monthly and cumulative averages. Crop evapotranspiration (ET_c , mm). Evapotranspiration reference (ET_o) was calculated using the Penman-Monteith equation (3), and ET_c was estimated as (Allen et al., 2006):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (3)$$

Where: R_n is the net radiation at the crop surface ($MJ m^2 day^{-1}$), G is the soil heat flux ($MJ m^2 day^{-1}$), T is the mean daily air temperature ($^{\circ}C$), u_2 is the wind speed at a height of 2 m ($m s^{-1}$), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), Δ is the slope of the vapor pressure curve ($kPa ^{\circ}C^{-1}$), and γ is the psychrometric constant ($kPa ^{\circ}C^{-1}$). The meteorological data were obtained from the weather station at the experimental field located 100 m from the study area. Crop evapotranspiration was calculated as follows using equation 4:

$$ET_c = K_c ET_o \quad (4)$$

Crop coefficient (K_c) values were 1.05 (vegetative stage), 1.20 (reproductive stage), and 0.90-0.60 (maturity stage) (Allen et al., 2006).

Water productivity

Water productivity (WP , in $kg m^3$) was estimated as the ratio of grain yield ($kg ha^{-1}$) to total water consumption during the rice development cycle ($m^3 ha^{-1}$), expressing the result in kilograms of grain per cubic meter of water ($kg m^3$). This metric allows the efficiency with which each genotype converts available water resources into harvestable biomass to be evaluated. The following equation (5) was used for its calculation:

$$\wp \left(\frac{kg}{m^3} \right) = \frac{yeld \left(\frac{kg}{ha} \right)}{(mm)10} \quad (5)$$

Where: WP = water productivity ($kg m^3$); Crop yield ($kg ha^{-1}$), obtained at 14 % moisture content; ET_c = crop evapotranspiration ($m^3 ha^{-1}$), determined from the water balance and ET_o multiplied by K_c , adjusted to each phenological stage of rice.

It was assumed that all the water used by the crop came from effective precipitation, considering only 70 % of precipitation and supplemental irrigation, taking into account excess runoff and deep percolation in medium to heavy textured soils, typical of the rice-growing areas of Tabasco.

Water conversion efficiency (wce , in $m^3 kg^{-1}$) was calculated as the volume of water consumed per unit of grain production, expressed in cubic meters per kilogram of rice produced ($m^3 kg^{-1}$). This variable quantifies the amount of water needed to produce one kilogram of dry grain and is an inverse indicator of water productivity, providing a complementary perspective on the efficient use of water resources. Equation 6 was used for its calculation:

$$WCE\left(\frac{m^3}{kg}\right) = \frac{ETc\left(\frac{m^3}{ha}\right)}{Grain\ yield\left(\frac{kg}{ha}\right)} \quad (6)$$

Where: WCE = water conversion efficiency ($m^3 kg^{-1}$); ETc = crop evapotranspiration ($m^3 ha^{-1}$); crop yield ($kg ha^{-1}$), adjusted to a standard moisture content of 14 %.

The joint analysis of wce and water productivity (wp) allowed for a comprehensive evaluation of the water performance of the genotypes, facilitating the identification of varieties that optimize water use to maximize production under the specific seasonal conditions in Tabasco.

Statistical analysis

All variables were subjected to analysis of variance (ANOVA), under randomized complete block design, where the treatments were the different genotypes (experimental lines and varieties). When significant differences were detected, Tukey's test ($p \leq 0.05$) was applied for mean comparison (Álvarez-Hernández et al., 2022). Analysis was performed in RStudio (R Core Team, 2023) using ANOVA, Agricolae, and GGplot packages.

RESULTS AND DISCUSSION

Climate behavior in the study area

During the growth period of the rice genotypes under study, climatological data were collected from the weather station located in the INIFAP experimental field in Huimanguillo, Tabasco, Mexico, near the evaluation plot. Figure 1 shows the climogram of the average monthly maximum and minimum temperatures, mean monthly temperature, and accumulated monthly evaporation and precipitation recorded by the weather station used in this study.

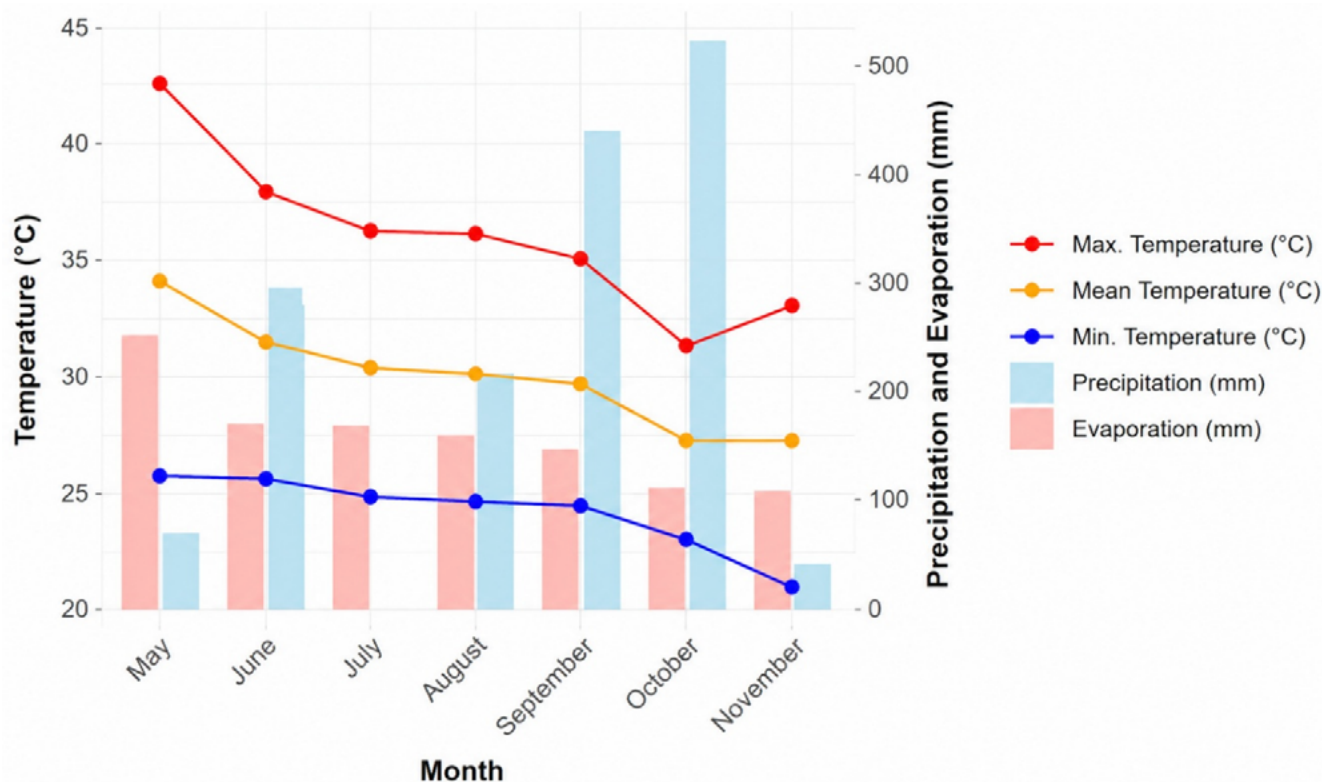


Figure 1. Climogram showing temperature, evaporation, and precipitation recorded during the evaluation of rice genotypes under tropical conditions in Huimanguillo, Tabasco, Mexico.

During the spring-summer cycle (June–November, 2024), mean temperature was 29.2 °C, with maximum and minimum values of 41.9 °C and 20.1 °C. Accumulated precipitation reached 1,651.3 mm, while total evaporation was 819.3 mm (Figure 1). Temperature conditions at sowing (25.3–37.5 °C) were suitable for germination, within the optimal range of 25–30 °C (Lu et al., 2022). During tillering (24.3–35.6 °C), temperatures slightly exceeded the reported optimum (~ 31 °C) (Xu et al., 2021). At flowering, temperatures (24.1–34.9 °C) remained within the tolerable range, although near thresholds associated with reduced fertility (Buelvas Jiménez, 2021).

During grain filling, solar radiation (28.9–36.4 MJ m² day⁻¹) was adequate to promote panicle maturity (López-Hernández et al., 2018). Despite adequate total water availability, the irregular distribution required supplemental irrigation, maintaining an average depth of 5 mm during critical stages. Water demand was estimated at 983.3 m³ month⁻¹ during tillering and 578.9 m³ month⁻¹ during physiological maturity. Considering that between 1,900 and 5,000 L of water per kg of grain are required (Jarin et al., 2024) and that the reproductive phase is highly sensitive to water deficit (Yang et al., 2019; Zhang et al., 2023), these results highlight the importance of strategic water management to optimize productivity under tropical rainfed systems.

Genotypic variability and water-use efficiency

Analysis of variance revealed highly significant differences ($p < 0.001$) among genotypes for all evaluated variables (PH, NGP, GY, WP, and WCE), evidencing substantial genotypic variability under rainfed conditions. Significant variability ($p < 0.001$) was observed in PH, with values ranging from 68.4 cm (T36) to 98.6 cm (T4). Taller genotypes (T4, T23, T30, and T16) may favor light interception, whereas shorter genotypes could present lower lodging risk, depending in environmental conditions (Li et al., 2019).

Significant differences ($p < 0.001$) were also detected in NGP, with values ranging from 83.3 (T10) to 141.3 (T33). Genotypes with higher NGP showed superior efficiency in the formation of reproductive structures, in agreement with Lu et al. (2022) and Liu et al. (2024), who demonstrated that this component is positively correlated with yield, although it must be

balanced with grain filling and weight to maximize productivity.

GY showed the greatest variability ($p < 0.001$), ranging from 101.5 kg ha⁻¹ to 4,127.2 kg ha⁻¹, with an overall average of 2,042.7 kg ha⁻¹. Genotype T30 (Golfo FL-16 variety) showed the highest yield, followed by T15, T4, and T16 (> 3,000 kg ha⁻¹). The variation reflects genotype × environment interaction, consistent with previous reports (Huang et al., 2021), who demonstrated that multi-environmental evaluation allows for the identification of genotypes with high yield and adaptability. In addition, the Golfo FL-16 variety showed resistance to key pests and diseases such as the *sogata-vhb* complex and *Pyricularia oryzae*, as well as tolerance to “spotted grain” and borers (Hernández Aragón et al., 2019), while lines T15, T4, and T16 were considered promising for release (Hernández-Aragón et al., 2023). The high coefficients of variation observed for grain yield and related components (Table 2) may be attributable to the wide genetic variability and differential response of the evaluated genotypes, reflecting real differences among materials and their interaction with the test environment (Zúñiga Orozco & Carrodegua González, 2022). Recent research on rice has shown that traits directly associated with yield, such as number of grains per panicle, number of panicles per plant, and total yield, exhibit high phenotypic and genotypic coefficients of variation, indicating considerable heterogeneity among genotypes that influences these traits. This variability is useful for selecting cultivars with better yield potential, but it also results into high coefficients of variation in field trials (Debsharma et al., 2022; Hang et al., 2024).

WP showed highly significant differences ($p < 0.001$), ranging from 0.08 kg m⁻³ (T33) to 0.54 kg m⁻³ (T30), with an average of 0.31 kg m⁻³. The Golfo FL-16 genotype showed the highest efficiency, producing 0.54 kg of grain per cubic meter of water consumed. This result is consistent with Hussain et al. (2022), who highlighted the potential of selecting genotypes with high water productivity to improve crop sustainability in environments with limited water availability. WCE also showed significant differences ($p < 0.001$), ranging from 1.98 m³ kg⁻¹ (T30) to 29.47 m³ kg⁻¹ (T36), and an overall average of 5.66 m³ kg⁻¹. Genotypes T30, T16, T4, T25, and T11 stood out for requiring less water to produce one kilogram of grain, making them suitable for water-limited

Table 2. Analysis of variance and Tukey's means for productivity and water efficiency of rice genotypes established in the 2024 rainy season in Tabasco, Mexico

Treatment	PH (cm)	NGP	GY (kg ha ⁻¹)	WP (kg m ³)	WCE (m ³ kg ⁻¹)
1	84.7 abcd*	104.2 ab	1,623.6 ab	0.21 ab	13.17 ab
2	82.5 abcd	124.8 ab	2,033.9 ab	0.34 ab	11.09 ab
3	82.3 abcd	91.9 ab	1,126 ab	0.18 ab	14.3 a
4	98.6 a	93.9 ab	3,236 ab	0.43 ab	2.37 c
5	81.7 abcd	110.2 ab	2,450.1 ab	0.36 ab	3.12 b
6	81.2 abcd	116.9 ab	780.3 b	0.13 ab	29.44 a
7	84.3 abcd	100.4 ab	2,338.8 ab	0.33 ab	3.19 b
8	83 abcd	122 ab	2,491.5 ab	0.36 ab	2.93 b
9	85.5 abcd	104.3 ab	2,029.6 ab	0.26 ab	14.19 a
10	90.4 abc	83.3 b	2,561.4 ab	0.34 ab	8.14 ab
11	87.6 abcd	107.3 ab	2,523.8 ab	0.39 ab	2.82 c
12	88.5 abc	83.7 b	2,838.4 ab	0.39 ab	2.72 c
13	88.2 abc	103.9 ab	2,291.8 ab	0.3 ab	5.48 ab
14	79.2 abcd	93.5 ab	1,998.5 ab	0.26 ab	4.31 b
15	93.6 ab	105.6 ab	3,415.7 ab	0.46 ab	2.86 c
16	94.7 ab	122.4 ab	3,157.4 ab	0.47 ab	2.36 c
17	89.8 abc	105 ab	2,655.7 ab	0.37 ab	3.05 b
18	80 abcd	102.3 ab	1,856.7 ab	0.25 ab	5.23 b
19	81.8 abcd	112 ab	1,757.1 ab	0.25 ab	4.59 b
20	83.2 abcd	131.3 ab	2,006.1 ab	0.29 ab	3.63 b
21	82.6 abcd	140.4 a	1,982.5 ab	0.29 ab	4.28 b
22	91.7 ab	96 ab	2,466.6 ab	0.32 ab	4.39 b
23	98.7 a	108.7 ab	2,603.2 ab	0.27 ab	3.94 b
24	79.9 abcd	88.5 ab	1,149.3 ab	0.16 ab	7.75 ab
25	86.6 abcd	113.4 ab	3,117.6 ab	0.46 ab	2.37 c
26	75.6 bcd	91.1 ab	664.0 b	0.1 b	11.18 ab
27	81.6 abcd	114.4 ab	1,099.3 ab	0.16 ab	12.12 ab
28	79.3 abcd	105.1 ab	1,710.2 ab	0.26 ab	7.74 ab
29	84.9 abcd	92.9 ab	1,895.7 ab	0.25 ab	10.1 ab
30	97.7 a	130 ab	4,127.2 a	0.54 a	1.98 c
31	77.6 bcd	83.4 b	1,691.7 ab	0.24 ab	5.34 ab
32	88.7 abc	91.8 ab	2,866.3 ab	0.4 ab	2.76 c
33	81.2 abcd	141.3 a	552.7 b	0.08 b	13.74 ab
34	72.4 d	97.8 ab	917.1 b	0.12 ab	15.76 a
35	80.8 abcd	136.5 ab	840.2 b	0.12 ab	9.76 ab
36	68.4 d	100.4 ab	681.3 b	0.1 b	29.47 a
Average	84.7	106.9	2,042.7	0.29	5.66
C.V. (%)	10.4	15.6	45.85	54	44
Prob. F.	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
DMS	19.73	54.54	3064.6	0.2	12.8

*Different letters within the same column indicate significant differences. ns: not significant; DMS: minimum significant difference; Prob. F: Fisher's F probability at $p \leq 0.05$.

conditions (Mongiano et al., 2020). These findings are consistent with those reported by Bouman et al. (2007), who emphasize that improving water-use efficiency through genetic selection and appropriate agronomic practices is essential for the sustainability of rice under climate change. Overall, the ANOVA results indicate significant genotypic differences in agronomic and water-use efficiency variables, highlighting the Golfo FL-16 (T30) genotype as the most efficient and productive material under seasonal conditions in the humid tropics of Tabasco (Cordero Flores & Manzaneda Delgado, 2021).

Evapotranspiration of rice crops under seasonal conditions

The behavior of reference evapotranspiration (ET_o) and crop evapotranspiration (ET_c) during the 2024 fall-winter cycle showed dynamics closely associated with the phenological stages of rice (Table 3). On average, ET_o values ranged from 3.8 mm day⁻¹ to 5.8 mm day⁻¹ while ET_c ranged from 2.8 mm day⁻¹ to 6.7 mm day⁻¹ showing a variable response to atmospheric evaporative demand and crop coefficient (K_c) at each stage of development.

The highest ET_c value (6.7 mm day⁻¹) was recorded during the flowering stage, coinciding with the highest crop coefficient (K_c = 1.36). This behavior reflects the maximum water demand during the reproductive phase, when water consumption increases due to greater transpiration and leaf expansion, as reported by Chatterjee et al. (2021) and Kumari et al. (2022). In contrast, the emergence and physiological maturity stages showed the lowest ET_c values (4.2 mm day⁻¹ and 2.8 mm day⁻¹, respectively), associated with a reduced leaf area and lower transpiration rates.

The tillering phase represented the longest period (83 days), accounting for a considerable proportion of the total water demand, with an average ET_c of 4.8 mm day⁻¹. Although the daily consumption was moderate, the duration of this stage contributed significantly to total water use (Rahman et al., 2023).

Overall, cumulative evapotranspiration throughout the cycle reached an estimated average of 28.6 mm day, consistent with values reported for rainfed rice systems in humid tropical regions (Hu et al., 2021; Reavis et al., 2021). This pattern indicates that water management should prioritize the tillering and flowering stages, where evapotranspiration demand is highest and where improvements in water-use efficiency are most critical.

These results highlight the importance of selecting genotypes with greater water-use efficiency during the most water-demanding stages, particularly in rainfed systems with irregular water availability (Khan et al., 2023). This knowledge allows for the optimization and development of management strategies aimed at sustainably increasing yield and water productivity in rice cultivation under tropical conditions.

CONCLUSIONS

This study identified rice genotypes with high potential for adaptation to rainfed conditions in Tabasco, Mexico and confirmed that the region presents favorable climatic conditions for crop development. The analysis of variance revealed significant differences in plant height, number of grains per panicle, grain yield, water productivity, and water conversion efficiency, confirming the existence of wide genetic variability among the genotypes evaluated. The highest-yielding materials

Table 3. Evapotranspiration (ET_o) behavior of rice crops under seasonal conditions in the 2024 autumn-winter cycle in Tabasco, Mexico.

Stage	K _c	ET _o	ET _c	Duration
Emergency	0.72	5.8	4.2	9
Tillering	0.88	5.4	4.8	83
Flower primordia	1.12	5.4	6.0	10
Flowering	1.36	4.9	6.7	7
Grain filling	1.07	3.8	4.1	10
Physiological maturity	0.67	4.1	2.8	12
			Total	131

Stage = phenological stage; K_c = crop coefficient; ET_o = reference evapotranspiration; ET_c = crop evapotranspiration; Duration = stage duration (days).

(T15, T4, and T16) exhibited outstanding agronomic performance and represent promising candidates for release as new varieties adapted to the humid tropics. WP and WCE proved to be effective indicators for evaluating rational water-use efficiency in rice, constituting key tools for selecting genotypes with greater sustainability and resilience under climate change scenarios. In particular, genotype T30 (Golfo FL-16) stood out for combining the highest grain yield and plant height with the most favorable WP (0.54 kg m³) and WCE (1.98 m³ kg⁻¹) values, reflecting highly efficient water use. It is recommended that the most promising genotypes be validated across different seasonal environments and under diverse agronomic management conditions to confirm their productive stability and adaptability to variable water availability.

LITERATURE CITED

- Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (2006). *Evapotranspiración del cultivo: Guías para la determinación de los requerimientos de agua de los cultivos*. Organización de las Naciones Unidas para la Alimentación y la Agricultura. <https://www.fao.org/4/x0490s/x0490s.pdf>
- Álvarez Hernández, J. C., Tapia Vargas, L. M., Hernández Pérez, A., Barrios Gómez, E. J., & Pardo Melgarejo, S. (2018). Production stability of advanced rice lines long thin grain in Michoacán Mexico. *Revista Mexicana de Ciencias Agrícolas*, 9(3), 629-637. <https://doi.org/10.29312/remexca.v9i3.606>
- Álvarez-Hernández, J. C., Tapia-Vargas, L. M., Hernández-Aragón, L., Tavitas-Fuentes, L., & Apaéz-Barrios, M. (2022). Productive potential of rice 'Lombardía FLAR 13', genotype of long and thin grain of the rice-rowing area of Michoacán. *Revista Mexicana de Ciencias Agrícolas*, 13(6), 1117-1127. <https://doi.org/10.29312/remexca.v13i6.3037>
- Ares, M. G., Varni, M., & Chagas, C. 2020. Runoff response of a small agricultural basin in the Argentine Pampas under dry and wet conditions. *Hydrological Processes*, 34(4), 908-924. <https://doi.org/10.1002/hyp.13782>
- Barrios-Gómez, E. J., Canul-Ku, J., Hernández-Arenas, M., Canales-Islas, E. I., & Patishtan-Pérez, J. (2023). Nayarita 22, variedad de arroz tipo milagro filipino para México. *Revista Fitotecnia Mexicana*, 46(2), 211-213. <https://doi.org/10.35196/rfm.2023.2.211>
- Bouman, B. A. M., Humphreys, E., Tuong, T. P., & Barker, R. (2007). Rice and water. *Advances in Agronomy*, 92, 187-237. [https://doi.org/10.1016/S0065-2113\(04\)92004-4](https://doi.org/10.1016/S0065-2113(04)92004-4)
- Buelvas Jiménez, M. (2021). Importancia de los factores climáticos en el cultivo de arroz. *Ciencia y Tecnología Agropecuaria*, 6(1), 28-34. <https://doi.org/10.24054/cyta.v6i1.1080>
- Chatterjee, S., Stoy, P. C., Debnath, M., Nayak, A. K., Swain, C. K., Tripathi, R., Chatterjee, D., Mahapatra, S. S., Talib, A., & Pathak, H. (2021). Actual evapotranspiration and crop coefficients for tropical lowland rice (*Oryza sativa* L.) in eastern India. *Theoretical and Applied Climatology*, 146, 155-171. <https://doi.org/10.1007/s00704-021-03710-0>
- Cordero Flores, P., & Manzaneda Delgado, F. (2021). Evaluación agronómica de seis variedades de arroz (*Oryza sativa* L.) sembradas en dos épocas bajo riego, en el municipio de San Buenaventura, Bolivia. *Revista de Investigación e Innovación Agropecuaria y de Recursos Naturales*, 8(1), 7-16. <https://doi.org/10.53287/xivu8492oe20n>
- Debsharma, S. K., Syed, M. A., Ali, M. H., Maniruzzaman, S., Roy, P. R., Brestic, M., Gaber, A., & Hossain, A. (2022). Harnessing on genetic variability and diversity of rice (*Oryza sativa* L.) genotypes based on quantitative and qualitative traits for desirable crossing materials. *Genes*, 14(1), 10. <https://doi.org/10.3390/genes14010010>
- Estrada, F., Mendoza-Ponce, A., Calderón-Bustamante, O., & Botzen, W. (2022). Impacts and economic costs of climate change on Mexican agriculture. *Regional Environmental Change*, 22, 126. <https://doi.org/10.1007/s10113-022-01986-0>
- Hang, S., Wang, Q., Wang, Y., & Xiang, H. (2024). Evolution of rice cultivar performance across China: A multi-dimensional study on yield and agronomic characteristics over three decades. *Agronomy*, 14(12), 2780. <https://doi.org/10.3390/agronomy14122780>
- Hernández Aragón, L., Tavitas Fuentes, L., Álvarez Hernández, J. C., Tapia Vargas, L. M., Ortega Arreola, R., Esqueda Esquivel, V., Jiménez Chong, J. A., & López López, R. (2019). Pacífico FL 15 y Golfo FL 16, multi-environmental varieties of rice with extra long grain for Mexico. *Revista Mexicana de Ciencias Agrícolas*, 10(1), 23-34. <https://doi.org/10.29312/remexca.v10i1.1544>
- Hernández-Aragón, L., Tavitas-Fuentes, L., Álvarez-Hernández, J. C., & de la O-Olán, M. (2023). Origen y características de la diversidad genética del arroz

- en México. *Revista Fitotecnia Mexicana*, 46(4), 461-469. <https://doi.org/10.35196/rfm.2023.4.461>
- Hu, X., Chen, M., Liu, D., Li, D., Jin, L., Liu, S., Cui, Y., Dong, B., Khan, S., & Luo, Y. (2021). Reference evapotranspiration change in Heilongjiang Province, China from 1951 to 2018: The role of climate change and rice area expansion. *Agricultural Water Management*, 253, 106912. <https://doi.org/10.1016/j.agwat.2021.106912>
- Huang, X., Jang, S., Kim, B., Piao, Z., Redona, E., & Koh, H.-J. (2021). Evaluating genotype × environment interactions of yield traits and adaptability in rice cultivars grown under temperate, subtropical and tropical environments. *Agriculture*, 11(6), 558. <https://doi.org/10.3390/agriculture11060558>
- Hussain, T., Hussain, N., Tahir, M., Raina, A., Ikram, S., Maqbool, S., Fraz Ali, M., & Duangpan, S. (2022). Impacts of drought stress on water use efficiency and grain productivity of rice and utilization of genotypic variability to combat climate change. *Agronomy*, 12(10), 2518. <https://doi.org/10.3390/agronomy12102518>
- Jarin, A. S., Islam, M. M., Rahat, A., Ahmed, S., Ghosh, P., & Murata, Y. (2024). Drought stress tolerance in rice: Physiological and biochemical insights. *International Journal of Plant Biology*, 15(3), 692-718. <https://doi.org/10.3390/ijpb15030051>
- Jiménez-Chong, J. A., López-López, R., & Esqueda-Esquivel, V. (2016). *Guía para producir arroz en el estado de Tabasco*. Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias.
- Khan, M. A. R., Mahmud, A., Ghosh, U. K., Hossain, M. S., Siddiqui, M. N., Islam, A. K. M. A., Anik, T. R., Rahman, M. M., Sharma, A., Abdelrahman, M., Ha, C. V., Mostofa, M. G., & Tran, L.-S. P. (2023). Exploring the phenotypic and genetic variabilities in yield and yield-related traits of the diallel-crossed f5 population of Aus rice. *Plants*, 12(20), 3601. <https://doi.org/10.3390/plants12203601>
- Kumari, A., Upadhyaya, A., Jeet, P., Al-Ansari, N., Rajput, J., Sundaram, P. K., Saurabh, K., Prakash, V., Singh, A. K., Raman, R. K., Gaddikeri, V., & Kuriqi, A. (2022). Estimation of actual evapotranspiration and crop coefficient of transplanted puddled rice using a modified non-weighing paddy lysimeter. *Agronomy*, 12(11), 2850. <https://doi.org/10.3390/agronomy12112850>
- Li, R., Li, M., Ashraf, U., Liu, S., & Zhang, J. (2019). Exploring the relationships between yield and yield-related traits for rice varieties released in China from 1978 to 2017. *Frontiers in Plant Science*, 10, 543. <https://doi.org/10.3389/fpls.2019.00543>
- Liu, K., Zhang, K., Zhang, Y., Cui, J., Li, Z., Huang, J., Li, S., Zhang, J., Deng, S., Zhang, Y., Huang, J., Ren, L., Chu, Y., Zhao, H., & Chen, H. (2024). Optimizing the total spikelets increased grain yield in rice. *Agronomy*, 14(1), 152. <https://doi.org/10.3390/agronomy14010152>
- Long-Ping, Y. (2014). Development of hybrid rice to ensure food security. *Rice Science*, 21(1), 1-2. [https://www.ricesci.org/EN/10.1016/S1672-6308\(13\)60167-5](https://www.ricesci.org/EN/10.1016/S1672-6308(13)60167-5)
- López-Hernández, M. B., López-Castañeda, C., Kohashi-Shibata, J., Miranda-Colín, S., Barrios-Gómez, E. J., & Martínez-Rueda, C. G. (2018). Tolerancia a sequía y calor en arroz (*Oryza sativa*). *Ecosistemas y Recursos Agropecuarios*, 5(15): 373-385. <https://doi.org/10.19136/era.a5n15.1558>
- Lu, Y., Chuan, M., Wang, H., Chen, R., Tao, T., Zhou, Y., Li, P., Yao, Y., Xu, C., & Yang, Z. (2022). Genetic and molecular factors in determining grain number per panicle of rice. *Frontiers in Plant Science*, 13, 964246. <https://doi.org/10.3389/fpls.2022.964246>
- Mongiano, G., Titone, P., Pagnoncelli, S., Sacco, D., Tamborini, L., Pilu, R., & Bregaglio, S. (2020). Phenotypic variability in Italian rice germplasm. *European Journal of Agronomy*, 120, 126131. <https://doi.org/10.1016/j.eja.2020.126131>
- Organización de las Naciones Unidas para la Agricultura y la Alimentación. (2023). *FAOSTAT*. <https://www.fao.org/faostat/es/#data/QCL>
- R Core Team. (2023). *The R Project for Statistical Computing*. R Foundation. <https://www.R-project.org/>
- Rahman, M. A., Ali, M., Mojid, M. A., Anjum, N., Haq, M. E., Kainose, A., & Dissanayaka, K. D. C. R. (2023). Crop coefficient, reference crop evapotranspiration and water demand of dry-season Boro rice as affected by climate variability: A case study from northeast Bangladesh. *Irrigation and Drainage*, 72(1), 148-165. <https://doi.org/10.1002/ird.2754>
- Reavis, C. W., Suvočarev, K., Reba, M. L., & Runkle, B. R. K. (2021). Impacts of alternate wetting and drying and delayed flood rice irrigation on growing season evapotranspiration. *Journal of Hydrology*, 596, 126080. <https://doi.org/10.1016/j.jhydrol.2021.126080>
- Salgado-Velázquez, S., Olvera-Rincón, F., Ramos-López, D. R., Sumano-López, D., Hernández-Lara, P. U., Inurreta-Aguirre, H. D., & Palma-Cancino, D. J. (2025). EcoCrop model approach for agroclimatic suitability of rice

- (*Oryza sativa* L.) cultivation. *Agro Productividad*, 18(2), 107-114. <https://doi.org/10.32854/agrop.v18i2.3248>
- Salgado-Velázquez, S., Barrios-Gómez, E., Hernández-Aragón, L., Hernández-Lara, P. U., Olvera-Rincón, F., Sumano-López, D., Inurreta-Aguirre, H. D., & Palma-Cancino, D. J. (2026). Advances in rice agronomic technologies in Latin America in the face of climate change. *Crops*, 6(1), 8. <https://doi.org/10.3390/crops6010008>
- Secretaría de Economía. (2021). *Sistema de información arancelaria vía internet. SIAVI 5.0*. SE. <http://www.economia-snci.gob.mx/>
- Servicio de Información Agroalimentaria y Pesquera. (2023). *Anuario estadístico de la producción agrícola*. SIAF. https://nube.agricultura.gob.mx/cierre_agricola/
- Xu, Y., Chu, C., & Yao, S. (2021). The impact of high-temperature stress on rice: Challenges and solutions. *The Crop Journal*, 9(5), 963-976. <https://doi.org/10.1016/j.cj.2021.02.011>
- Yamano, T., Arouna, A., Labarta, R. A., Huelgas, Z. M., & Mohanty, S. (2016). Adoption and impacts of international rice research technologies. *Global Food Security*, 8, 1-8. <https://doi.org/10.1016/j.gfs.2016.01.002>
- Yang, X., Wang, B., Chen, L., Li, P., & Cao, C. (2019). The different influences of drought stress at the flowering stage on rice physiological traits, grain yield, and quality. *Scientific Reports*, 9, 3742. <https://doi.org/10.1038/s41598-019-40161-0>
- Zhang, Y., Zhao, X., Liu, F., Zhu, L., & Yu, H. (2023). Effect of different water stress on growth index and yield of semi-late rice. *Environmental Sciences Proceedings*, 25(1), 84. <https://doi.org/10.3390/ECWS-7-14318>
- Zhao, Y., Xiao, D., Bai, H., Liu, D. L., Tang, J., Qi, Y., & Shen, Y. (2022). Climate change impact on yield and water use of rice-wheat rotation system in the Huang-Huai-Hai plain, China. *Biology*, 11(9), 1265. <https://doi.org/10.3390/biology11091265>
- Zúñiga Orozco, A., & Carrodegua González, A. (2022). Variabilidad morfo-agronómica en genotipos de arroz en el Pacífico Central, Costa Rica. *Revista Ciencia y Agricultura*, 19(1), 1-14. <https://doi.org/10.19053/01228420.v19.n1.2022.12567>