REVISTA BIO CIENCIAS
http://revistabiociencias.uan.edu.mx
https://doi.org/10.15741/revbio.12.e1837
ISSN 2007-3380

Artículo original / Original article

Impact of three irrigation regimes on wheat grain yield in southern Sonora, Mexico

Impacto de tres regímenes de riego sobre el rendimiento de grano de trigo en el sur de Sonora, México

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Please cite this article as/Como citar este artículo: Marroquín Morales J. A., Lugo García G. A., Gayosso Barragán O., Hidalgo Ramos D. M., Borbón Gracia A. (2025). Impact of three irrigation regimes on wheat grain yield in southern Sonora, Mexico. *Revista Bio Ciencias*, 12, e1837. https://doi.org/10.15741/revbio.12.e1837

Article Info/Información del artículo
Received/Recibido: October 17th 2024.
Accepted/Aceptado: May 21h 2025.
Available on line/Publicado: June 04th 2025.

RESUMEN

Water scarcity for irrigation is affecting wheat production in Mexico, making it essential to select genotypes with greater water-use efficiency. This study aimed to evaluate grain yield and its components in seven durum wheat genotypes under three irrigation regimes during the 2021–2022 and 2022–2023 autumn–winter cycles. Five commercial varieties and two experimental lines were assessed under three gravity irrigation schedules (2, 3, and 4 supplemental irrigations). A completely randomized design was used, with a split-plot arrangement and three replications. The applied water depths for two, three, and four supplemental irrigations were 49.5, 63.4, and 72.5 cm, respectively. A significant difference ($p \leq 0.05$) was found in grain yield across irrigation treatments. The highest yield was obtained with four supplemental irrigations (8,482.9 kg ha^{-1}), followed by three (7,709.4 kg ha^{-1}) and two (6,645.9 kg ha^{-1}). The STOT line achieved the highest grain yield, followed by the TARRO line and the Noroeste C2021 variety, although the latter two showed statistically similar yields ($p \leq 0.05$) to the rest of the genotypes. Hectoliter weight exhibited the strongest correlation with grain yield.

PALABRAS CLAVE: *Triticum durum* L., water stress, genotypes, gravity irrigation, yield.

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Revista Bio ciencias
ISSN 2007-3380

ABSTRACT

La escasez de agua para riego está afectando la producción de trigo en México, por lo que es necesario seleccionar genotipos más eficientes con el uso del agua. El objetivo fue evaluar el rendimiento de grano y sus componentes de siete genotipos de trigo cristalino, bajo tres regímenes de riego durante los ciclos otoño–invierno 2021-2022 y 2022-2023. Se evaluaron cinco variedades y dos líneas experimentales bajo tres calendarios de riego por gravedad (2, 3 y 4 riegos de auxilio). Se utilizó un diseño completamente al azar bajo un arreglo de parcelas divididas con tres repeticiones. Las láminas aplicadas para dos, tres y cuatro riegos de auxilio fue de 49.5, 63.4 y 72.5 cm respectivamente. Se encontró diferencia significativa ($p \leq 0.05$) para rendimiento de grano entre regímenes de humedad. Con cuatro auxilios se obtuvo un rendimiento de 8,482.9 kg ha^{-1}, con tres auxilios 7,709.4 kg ha^{-1} y con dos auxilios el rendimiento fue de 6,645.9 kg ha^{-1}. La línea STOT presentó el mayor rendimiento de grano, al igual que la línea TARRO y la variedad Noroeste C2021, aunque estas dos últimas presentaron un rendimiento similar ($p \leq 0.05$) al resto de los materiales. El peso hectolítrico presentó la mayor correlación con el rendimiento de grano.

KEY WORDS: *Triticum durum* L., estrés hídrico, genotipos, riego por gravedad, rendimiento.

Introduction

Mexico is predominantly vulnerable to water scarcity, which directly impacts its agricultural production since a significant portion of the country's territory is classified as arid or semi-arid (Salinas *et al.,* 1998). In regions where droughts are recurrent, irrigated agriculture plays a crucial role in development. However, competition for water resources poses one of the greatest threats to growth in these areas. Therefore, it is essential to optimize water use in irrigated agriculture by reducing applied volumes without significantly compromising yields (Ojeda *et al.,* 2006).

Wheat (*Triticum* spp.) is one of the most important crops worldwide, ranking among the top three most produced and consumed grains along with rice and corn (Neri *et al.,* 2021). In 2023, more than 565,000 hectares of wheat were planted in Mexico, with over 90 % of production occurring under irrigation conditions (SIAP, 2023), however, one of the main challenges for wheat production in the country is the limited water availability, with the state of Sonora being among the most affected due to its classification as a region experiencing high hydrological stress (CONAGUA, 2024). Despite these constraints, Sonora ranks first in national wheat production,

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with more than 260,000 hectares cultivated, followed by Guanajuato, Sinaloa, and Baja California (SIAP, 2024).

In recent years, droughts driven by global climate change have become more frequent, making research on plant responses to water deficits essential (Lan *et al.,* 2011). The impact of drought on crop productivity depends on various intrinsic factors, such as the phenological stage of the plant at the time of drought, the plant species, and the variety within a species (Robles, 2007; Rosabal *et al.,* 2014). Grain yield is influenced by the amount of water transpired by plants, the efficiency with which they convert that water into biomass, and the proportion of biomass allocated to grain formation (Sadras & McDonald, 2012). Achieving a balance between high water-use efficiency and high yields is critical for the sustainable development of wheat production (Xu *et al.,* 2018).

Controlled deficit irrigation is a technique that allows for precise water management without significantly compromising crop yield or quality (Sánchez, 2009). Implementing restricted irrigation based on phenological stages helps reduce the frequency and volume of water applied, minimizing yield losses (Mendoza *et al.,* 2016). The greatest reduction in wheat yield occurs when the water deficit coincides with the flowering stage, which is the critical period for determining the number of grains per spike (Sadras & McDonald, 2012). Grain yield is determined by factors such as the number of spikes per unit area, the number of grains per spike, and the average grain weight. Consequently, any variation in these components directly affects the final yield (Ataei, 2006). In this context, the present study aimed to evaluate grain yield and its components in seven durum wheat genotypes under three irrigation regimes during the 2021–2022 and 2022–2023 autumn–winter cycles in southern Sonora, Mexico.

Material and Methods

Location of the experiment

The experiment was conducted at the Norman E. Borlaug Experimental Field (CENEB) of the National Institute of Forestry, Agricultural, and Livestock Research (INIFAP) in the arid region of southern Sonora, Mexico. The study site is located in the Yaqui Valley at coordinates 27° 22’ 15’’ N and 109 ° 55’ 21’’ W, at an altitude of 39 masl. Two cropping cycles were evaluated: autumn–winter (AW) 2021–2022 and 2022–2023. The soil type is vertisol (>50 % clay). The average annual precipitation is 434.9 mm, with 83 % concentrated between June and October, while the remainder is distributed between November and March. The mean annual temperature is 24.6 °C, with an average annual minimum of 14.9 °C and a maximum of 34.3 °C. The annual average values of cumulative reference evapotranspiration (ET_O) range from 2,000 to 2,445 mm (CONAGUA, 2024), significantly exceeding the total annual precipitation.

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Agronomic management

The yield trial was conducted during the 2021–2022 and 2022–2023 autumn–winter cropping cycles, in both cycles, sowing took place during the first week of December, which falls within the optimal planting window. The crop was sown under dry soil conditions using an experimental tractor-powered seeder, at a seeding rate of 100 kg ha^{-1}, with double-row planting on the ridge of the furrow. After sowing, an emergence irrigation (EI) was applied. The fertilization rate was 276N-52P-00K, with the total amount of P and half of the N applied before sowing, and the remaining nitrogen applied before the first supplemental irrigation (SI). Fertilizer was band-applied alongside the plant rows using a wheat planter. Urea (46N-00P-00K) served as the N source, while monoammonium phosphate (11N-52P-00K) was used for P. The irrigation system employed gravity flow, using 1.5-inch aluminum siphons.

For broadleaf weed control, a post-emergence chemical application was carried out using Metsulfuron-methyl + Thifensulfuron-methyl at a rate of 30 g ha^{-1}. For narrow-leaf weeds, Pinoxaden (5.05 %) was applied at a rate of 1 L ha^{-1}. To manage the greenbug (*Schizaphis graminum*), an insecticide application of 250 mL ha^{-1} of Imidacloprid + Beta-cyfluthrin was performed. Herbicide and insecticide applications were carried out 35 days after sowing (DAS) across all irrigation regimes using a tractor-powered sprayer equipped with 12 nozzles and a water volume of 250 L ha^{-1}. No preventive or curative disease control measures were applied, as the evaluated varieties and lines exhibited resistance to major diseases, including leaf rust and stripe (yellow) rust.

Treatments and experimental design

Seven genotypes were evaluated, five of which correspond to commercial durum wheat varieties released by INIFAP's wheat breeding program, while the remaining two are advanced lines from the International Maize and Wheat Improvement Center (CIMMYT) (Table 1). These genotypes were selected for their favorable agronomic and production traits and represent the most widely used supplies in southern Sonora. Additionally, the variety CIRNO C2008 was chosen as a control, as it is the most widely cultivated in the region. All genotypes were evaluated under three different irrigation regimes: 2 supplemental irrigations (T1), 3 supplemental irrigations (T2), and 4 supplemental irrigations (T3), the latter serving as the control since it provided optimal water conditions for crop development. A completely randomized design was used with a split-plot treatment arrangement, where the main plots corresponded to the number of irrigations and the subplots to the genotypes, with three replications. The experimental unit consisted of two furrows, each five meters long, spaced 0.80 cm apart, for a total area of 8 m^2.

Table 1. Lines and varieties used in the present research for the two agricultural cycles.

No.	Genealogy	**Status**
1	CIRNO C2008	*Control
2	CENEB Oro C2017	Variety
3	Don Lupe C2020	Variety
4	Noroeste C2021	Variety
5	ROELY HP C2024	Variety
6	STOT	Line
7	TARRO	Line

*Most planted wheat variety in the region

Study variables

The agronomic variables were evaluated following the methodology described by Pietragalla & Pask (2013). These included plant height (PH), measured in centimeters from the soil surface to the top of the spike using a measuring rod; days to flowering (DTF), recorded as the number of days from sowing until 50 % of the plants had initiated flowering; and physiological maturity (DPM), measured as the number of days from sowing until 50 % of the plants exhibited yellow peduncles and glumes beginning to change color. To assess yield components, the methodology described by Miranda *et al.* (2016) was used. The thousand-grain weight (TGW) was measured in grams using a digital scale, with a randomly collected composite sample from the harvested grain. The harvest index (HI) was calculated as the ratio GYI/BYI, where GYI = grain yield from 25 stems in the plot, and BYI = biological yield from 25 stems in the plot. The number of spikes per square meter (SPSM) was determined by counting the number of spikes per m^2 in each genotype replication. The hectoliter weight (HW) was obtained from a clean 500 g sample, measured with a volumetric balance (Seedburo Equipment Co., Chicago, IL), and expressed in kg hL^{-1}. Grain yield was determined by harvesting the entire experimental plot (8 m^2), with the yield extrapolated to kg ha^{-1}. The harvest was carried out using an experimental thresher, and the final yield was adjusted to 12 % moisture content.

The evaluated water variables included net irrigation depth (NI), gross irrigation depth (GI), and application efficiency (AE). Additionally, the phenological stage at which each supplemental irrigation (SI) was applied and the days to irrigation (DTI) were recorded. To measure volumetric soil moisture before irrigation (HV_{act}), a Time Domain Reflectometer (TDR) sensor was used during both germination and supplemental irrigations. The net irrigation depth required to bring the soil to field capacity (FC) was determined using Equation 1.

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Equation 1. $$NI = (FC - HV_{act}) * Sd$$

where FC and HV_{act} are expressed in $cm^3\ cm^{-3}$, and Sd represents soil depth (cm).

The gross irrigation depth (GI) was determined using Equation 2.

Equation 2. $$GI = \frac{Q * t}{A}$$

where Q is the volume of water applied to the plot ($m^3\ s^{-1}$), t is the irrigation time (s), and A is the irrigated area (m^2).

The application efficiency (AE) was calculated using Equation 3.

Equation 3. $$AE = \frac{NI}{GI} * 100$$

where NI and GI are expressed in cm.

Statistical analysis

A combined analysis of variance was performed for the two cropping cycles using a completely randomized split-plot design, where the main plots corresponded to the number of supplemental irrigations and the subplots to the durum wheat varieties. Mean comparisons among treatments were conducted using Tukey's test to determine the least significant difference ($p \leq 0.05$). Data analysis was performed through SAS 9.4 (Statistical Analysis System, 2013) for Windows.

Results and Discussion

The phenological stages corresponding to the application of each SI, DTI, NI, GI, and AE were recorded for each irrigation treatment (Table 2). For germination irrigation, a NI of 17.3 cm was applied across all three treatments, equivalent to 1,730 $m^3\ ha^{-1}$. In Treatment 1 (T1), plants experienced severe water stress during tillering and moderate stress during the booting stage. A GI of 15.7 cm was applied in the first SI and 16.5 cm in the second, having a cumulative

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total of 49.5 cm; with an average AE of 60.3 %. The gross irrigation depth values obtained in this study align with those reported by Sifuentes *et al.* (2021), who applied a total GI of 50.6 cm throughout the maize growing cycle in northern Sinaloa under a gravity irrigation system, including one germination irrigation and 2 supplemental irrigations. Treatment 2 (T2) was subjected to mild stress during tillering to avoid water stress during booting and grain filling, as water deficit during these critical stages significantly reduces grain yield. Ayed *et al.* (2017) specified that grain yield and certain yield components are negatively affected when water availability is reduced during grain filling. The GI values applied in this treatment were 15.4 cm, 16.7 cm, and 14.0 cm for the 1^{st}, 2^{nd}, and 3^{rd} SI, respectively, resulting in a total Gi of 63.4 cm and an average AE of 61.0 %. These values are consistent with those reported by Ledesma *et al.* (2010) in Celaya, Guanajuato, where three supplemental irrigations were applied to wheat. In Treatment 3 (T3), SI was applied during tillering, stem elongation, flowering, and grain filling, with GI values of 14.0 cm, 13.0 cm, 14.9 cm, and 13.3 cm, respectively, resulting in a total Gi of 72.5 cm and an application efficiency of 58.9 %.

Analysis of variance

Table 3 presents the analysis of variance, showing highly significant differences ($p \leq 0.01$) between growing cycles for all evaluated variables, except for grain yield (GY), indicating variation across the two years of evaluation. Significant differences ($p \leq 0.01$) were found among irrigation treatments for all evaluated variables, demonstrating that the amount of water available in the soil influenced crop growth and development. These findings align with those reported by Ul *et al.* (2018), who observed that grain yield is affected by irrigation, genotype, and nitrogen application. Highly significant differences ($p \leq 0.01$) were also found among genotypes for all variables, indicating genetic diversity among the evaluated materials. Significant interactions ($p \leq 0.01$) were detected between cycle * genotypes for DTF, HW, and TGW, while no significant differences were found for REP*IN across all evaluated variables. The interaction IN*GEN showed a significant difference only for TGW (Table 3).

Table 2. Net irrigation, gross irrigation, and application efficiencies in irrigation treatments for seven durum wheat genotypes, Norman E. Borlaug Experimental Field, Obregón, Sonora, Mexico.

Treatments	Irrigation	Phenological stage	DTI	NI (cm)	GI (cm)	AE (%)
T1	Germination	Sowing	0	10.6	17.3	61.2
	1 SI	Tillering	50	9.8	15.7	62.4
	2 SI	Booting	85	9.5	16.5	57.5
Total				29.9	49.5	181.1
Average				9.9	16.5	60.3

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Continuation

Table 2. Net irrigation, gross irrigation, and application efficiencies in irrigation treatments for seven durum wheat genotypes, Norman E. Borlaug Experimental Field, Obregón, Sonora, Mexico.

Treatments	Irrigation	Phenological stage	DTI	NI (cm)	GI (cm)	AE (%)
T2	Germination	Sowing	0	10.6	17.3	61.2
	1 SI	Tillering	43	9.5	15.4	61.6
	2 SI	Booting	76	10.3	16.7	61.4
	3 SI	Grain filling	99	8.4	14.0	59.9
Total				38.8	63.4	244.1
Average				9.7	15.8	61.0
T3 Control	Germination	Sowing	0	10.6	17.3	61.2
	1 SI	Tillering	36	9.0	14.0	64.2
	2 SI	Stem elongation	67	8.1	13.0	62.3
	3 SI	Flowering	88	7.0	14.9	46.9
	4 SI	Grain filling	104	8.0	13.3	60.1
Total				42.7	72.5	294.7
Average				8.5	14.5	58.9

DTI: days to irrigation; Ni: net irrigation; GI: gross irrigation; AE: application efficiency; SI: supplemental irrigation.

Table 3. Analysis of variance, mean squares, and statistical significance of the evaluated variables in irrigation treatments for seven durum wheat genotypes, autumn-winter cycles 2021-2022, 2022-2023, Norman E. Borlaug Experimental Field, Obregón, Sonora, Mexico.

SV	DF	GY	PH	DTF	DPM	HW	TGW
CYCLE	1	341744.7^{ns}	340.0**	1308.2**	1116.0**	4240.9**	23684.0**
IN	2	35726357.6**	458.3**	35.6**	215.4**	5755.4**	213.3**
REP*IN	6	226090.9^{ns}	1.4^{ns}	0.6^{ns}	2.1^{ns}	13.7^{ns}	11.0^{ns}
GEN	6	554393.2**	118.2**	19.9**	21.3**	2214.5**	171.4**
IN*GEN	12	181610.5^{ns}	4.3^{ns}	1.0^{ns}	1.8^{ns}	12.5^{ns}	22.9*
CYCLE*GEN	6	121821.1^{ns}	9.2^{ns}	6.3**	1.0^{ns}	94.8**	32.8**
ERROR	92	104747.9**	5.9**	1.2**	1.4**	17.3**	10.6**
R^2	-	0.8	0.7	0.9	0.9	0.9	0.9
CV (%)	-	4.2	2.7	1.4	1.0	0.5	5.2

*, **: significant at $p \leq 0.05$ and $p \leq 0.01$, respectively; ns: not significant; SV: source of variation; IN: irrigation number; GEN: genotypes; REP: repetitions; DF: degrees of freedom; GY: grain yield; PH: plant height; DTF: days to flowering; DPM: days to physiological maturity; HW: hectoliter weight; TGW: thousand-grain weight; CV: coefficient of variation.

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ISSN 2007-3380

When comparing the two evaluation cycles (Table 4), differences were identified in the environmental conditions that influenced the expression of the genotypes. In the AW 2021–2022 cycle, 589 accumulated cold hours were recorded, while in the AW 2022–2023 cycle, this number increased to 754 hours (REMAS, 2024), resulting in a longer cycle duration for the second evaluation period. According to Gizaw *et al.* (2016), ambient temperature and soil moisture availability explain 86 % of yield variability. The higher number of accumulated chilling hours during the AW 2022–2023 cycle led to increased plant height (PH), a greater number of days to flowering (DTF), days to physiological maturity (DPM), and a higher thousand-grain weight (TGW). The lowest recorded temperatures in this period (≤ 5 °C) occurred during the tillering stage, between 38 and 53 days after sowing (DAS), coinciding with the first supplemental irrigation (SI) for the evaluated treatments. These results align with those reported by Buenrostro *et al.* (2022). In contrast, during the AW 2021–2022 cycle, significant reductions in PH, DTF, DPM, and TGW were observed, attributed to higher temperatures during crop growth and development. Previous studies conducted by Zarazúa *et al.* (2011) indicate that wheat experiences unfavorable conditions when temperatures exceed the critical threshold. Additionally, drought and high temperatures can have combined effects (Kaur & Behl, 2010). According to Paquini *et al.* (2016), the interaction between drought and extreme temperatures during grain filling is a key factor in reducing yield components. The results show similar grain yield ($p \leq 0.05$) for both agricultural cycles, which can be attributed to the stability of the evaluated genotypes.

When comparing the number of irrigations (2, 3, and 4 SI), it was observed that greater soil water availability allowed the evaluated genotypes to express their maximum yield potential. The highest grain production ($p \leq 0.05$) was obtained with four supplemental irrigations (8,482.9 kg ha^{-1}), followed by the three-irrigation treatment (7,709.4 kg ha^{-1}) and finally the two-irrigation treatment (6,645.9 kg ha^{-1}). These results align with those reported by Martínez *et al.* (2020) in a study conducted in Celaya, Guanajuato, where, under restricted irrigation conditions, they detected reductions in the grain-filling period, the number of spikes per square meter, biological yield, harvest index, and grains per square meter, leading to a decline in yield. Regarding PH, DTF, and TGW, no differences ($p \leq 0.05$) were found between three and four SI, with only DPM and HW being superior in the four-irrigation treatment. Meanwhile, the two-irrigation treatment recorded the lowest values ($p \leq 0.05$) for PH, DTF, DPM, PH, and TGW (Table 4). These results are consistent with Blum (2002), who states that water deficit accelerates wheat flowering. The reductions in yield components resulted in the lowest yield since irrigation was suspended during the booting stage, causing a lack of soil moisture during the grain-filling period and preventing the crop from reaching its maximum yield potential. According to Madani *et al.* (2010), the effects of drought are reflected in a decreased grain-filling rate and reduced dry matter distribution. Similarly, this aligns with the findings of Thapa *et al.* (2019) and Valdés *et al.* (2017), who concluded that yield and some crop components decrease with lower irrigation applications. Likewise, Solís *et al.* (2013) concluded that with two supplemental irrigations, grain yield could decrease by up to 13 % compared to three irrigations in wheat cultivation. Similarly, Shamsi & Kobraee (2011) state that drought stress significantly reduces yield, thousand-grain weight, and the number of grains per square meter. This study demonstrates the effectiveness of genetic improvement in Mexico (Table 5). However, as Blum (2011) remarks, despite significant

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advances in wheat yield under adverse conditions worldwide, much remains to be done to further optimize its productivity under increasingly challenging environmental conditions.

Table 4. Mean values for evaluated cycles and irrigation treatments in seven hard wheat genotypes, autumn-winter cycles 2021-2022, 2022-2023, Norman E. Borlaug Experimental Field, Obregón, Sonora, Mexico.

Cycle	**GY**	**PH**	**DTF**	**DPM**	**HW**	**TGW**
2022/2023	7560.6[a]	90.1[a]	82.6[a]	123.4[a]	816.0[b]	75.8[a]
2021/2022	7664.8[a]	86.8[b]	76.1[b]	117.4[b]	827.6[a]	58.4[b]
LSD	114.5	0.8	0.4	0.4	1.4	1.1
Irrigations	GY	PH	DTF	DPM	HW	TGW
4	8482.9[a]	90.0[a]	79.9[a]	122.3[a]	829.9[a]	63.9[a]
3	7709.4[b]	90.6[a]	79.9[a]	121.0[b]	827.0[b]	62.8[a]
2	6645.9[c]	84.6[b]	78.3[b]	117.9[c]	808.4[c]	59.6[b]
LSD	168.2	1.2	0.5	0.6	2.1	1.6

Means followed by the same letter in the columns are statistically equal (Tukey, $p \leq 0.05$). GY: grain yield (kg ha^{-1}); PH: plant height (cm); DTF: days to flowering (days); DPM: days to physiological maturity (days); HW: hectoliter weight (g); TGW: thousand-grain weight (g); LSD: Tukey's least significant difference ($p = 0.05$).

Grain yield and its components

Regarding grain yield, the STOT and TARRO lines and the Noroeste C2021 variety stood out statistically. However, the latter two were statistically equal ($p \leq 0.05$) to the rest of the evaluated materials. CIRNO C2008 had the lowest average yield in the study, with 7,400.5 kg ha^{-1} (Table 5), but it was only statistically surpassed by the STOT line. Notably, CIRNO C2008 exhibited a statistically higher TGW ($p \leq 0.05$) than the rest of the materials; however, it recorded the lowest grain yield, contrary to what Espitia *et al.* (2021) reported, stating that thousand-grain weight and the number of grains per square meter are the key factors determining the crop's yield potential. Regarding SPSM and HI, no significant differences were found among the evaluated genotypes (Table 5), likely due to the stability and high yield of the materials assessed in this study and their favorable response to the irrigation regimes. Martín *et al.* (2011) indicate that the number of SPSM is a fundamental component in determining the number of grains per square meter.

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Table 5. Mean values of agronomic variables evaluated in seven durum wheat genotypes during the 2021–2022 and 2022–2023 fall-winter cycles at the Norman E. Borlaug Experimental Field, Obregón, Sonora, Mexico.

Genotypes	GY	PH	DTF	DPM	HW	TGW	SPSM	HI
CIRNO C2008	7400.5^{b}	84.8^{c}	80.5^{a}	120.7^{bc}	817.7^{c}	67.8^{a}	368.4^{a}	54.6^{a}
CENEB Oro C2017	7542.6^{b}	91.2^{a}	77.7^{d}	119.1^{d}	833.7^{a}	61.0^{bc}	403.3^{a}	53.8^{a}
Don Lupe C2020	7469.8^{b}	87.7^{b}	79.0^{bc}	120.6^{bc}	809.5^{d}	61.8^{b}	353.3^{a}	53.8^{a}
Noroeste C20221	7708.5^{ab}	86.1^{bc}	79.6^{ab}	121.2^{ab}	829.2^{b}	61.9^{b}	408.4^{a}	54.0^{a}
ROELY HP C2024	7579.7^{b}	90.3^{a}	78.3^{cd}	119.8^{cd}	828.9^{b}	57.8^{c}	368.3^{a}	53.4^{a}
STOT	7932.6^{a}	91.3^{a}	80.0^{ab}	122.1^{a}	828.3^{b}	63.7^{b}	389.6^{a}	52.8^{a}
TARRO	7655.3^{ab}	87.5^{b}	80.4^{a}	119.2^{d}	805.1^{e}	60.5^{bc}	395.4^{a}	52.4^{a}
Average	7612.7	88.4	79.3	120.4	821.81	62.1	383.8	53.6
CV (%)	4.2	2.7	1.4	1.0	0.5	5.2	9.8	5.2
LSD	325.2	2.4	1.1	1.2	4.17	3.2	55.8	4.1

Means followed by the same letter within columns are statistically equal (Tukey, $p \leq 0.05$). GY: grain yield (kg ha^{-1}); PH: plant height (cm); DTF: days to flowering (days); DPM: days to physiological maturity (days); HW: hectoliter weight (g); TGW: thousand-grain weight (g); SPSM: spikes per square meter; HI: harvest index; CV: coefficient of variation; LSD: Tukey's least significant difference ($p = 0.05$).

Table 6 presents the Pearson correlations between grain yield and its components for the three evaluated irrigation schedules. Grain yield exhibited strong positive correlations with hectoliter weight and moderate correlations with plant height, days to physiological maturity, and harvest index. These results align with Espitia *et al.* (2021), who reported positive correlations between grain yield, plant height, and harvest index, with values of 0.4 and 0.54, respectively. Similarly, they partially agree with the findings by Beche *et al.* (2014) and Zhou *et al.* (2014), who reported correlations above 0.9 between harvest index and grain yield, higher values than those observed in this study. Days to flowering and days to physiological maturity showed a strong positive correlation with TGW, while the latter exhibited a negative correlation with test weight. These findings are consistent with those reported by Lavilla (2022), who found negative correlations between TGW and HW in wheat cultivation.

Conclusions

The highest grain yield is achieved with the highest irrigation level; however, reducing one supplemental irrigation only decreases grain yield by 9 %, making it the most viable option in a water-scarce scenario.

Applying two supplemental irrigations negatively affects grain yield and its components, which is attributed to water stress during the grain-filling stage. Under limited water availability,

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applying supplemental irrigation during the crop's most critical phenological stages is crucial to optimize water use.

The STOT and TARRO lines and the Noroeste C2021 variety stand out for their high grain yield, with STOT statistically outperforming the commercial control CIRNO C2008.

Table 6. Pearson correlations of yield components under different irrigation schedules.

	GY	PH	DTF	DPM	HW	TGW	SPSM	HI
GY	1	0.47**	0.13	0.43**	0.58**	0.04	-0.03	0.44**
PH		1	0.35**	0.53**	0.42**	0.34**	0.04	-0.03
DTF			1	0.84**	-0.27**	0.91**	-0.08	0.04
DPM				1	0.04	0.82**	-0.02	0.28*
HW					1	-0.27**	0.08	0.35**
TGW						1	-0.01	0.26*
SPSM							1	-0.07
HI								1

*, **: significant at $p \leq 0.05$ and $p \leq 0.01$, respectively. GY: grain yield; PH: plant height; DTF: days to flowering (days); DPM: days to physiological maturity (days); HW: hectoliter weight (g); TGW: thousand-grain weight (g); SPSM: spikes per square meter; HI: harvest index.

Author contributions

Work conceptualization: MMJA, LGGA; methodology development: MMJA, LGGA, GBO, HRDM; software management: MMJA, GBO; experimental validation: BGA, HRDM; data analysis: LGGA, GBO, MMJA, BGA; data management: MMJA, LGGA; manuscript writing and preparation: MMJA; drafting, review, and editing: MMJA, LGGA, GBO, HRDM, BGA; project administration: BGA.

All authors of this manuscript have read and approved the published version.

Funding

This research did not receive external funding.

Ethical statements

Not applicable.

Statement of informed consent

Not applicable.

Acknowledgments

The authors thank the Consejo Nacional de Humanidades, Ciencias y Tecnologías (CONAHCYT) for the doctoral scholarship awarded (826667).

The authors also thank INIFAP for providing the necessary facilities to conduct and complete this project.

Conflict of interest

The authors declare that they have no conflict of interest.

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