CHILEAN JOURNAL
of AGRICULTURAL RESEARCH

CHILEANJAR
CHILEAN JOURNAL of AGRICULTURAL RESEARCH

RESEARCH ARTICLE

Physicochemical characterization of durum wheat (*Triticum durum* Desf.) under full irrigation conditions and water stress due to reduced irrigation

Francisco Cadena-Cadena[1], Alba Rocio Ochoa-Meza[1], Leandris Argentel-Martinez[1], Ofelda Peñuelas-Rubio[1], Andres Ochoa-Meza[2], and Joe Luis Arias-Moscoso[1*]

[1]Tecnológico Nacional de México, Instituto Tecnológico del Valle del Yaqui, Departamento de Ingenierías, Bacum, Sonora, México.
[2]Universidad de Sonora, Departamento de Agricultura y Ganadería, Hermosillo, Sonora, México.
[*]Corresponding author (jarias.moscoso@itvy.edu.mx).
Received: 31 August 2024; Accepted: 8 November 2024, doi:10.4067/S0718-58392025000300308

ABSTRACT

Durum wheat (*Triticum durum* Desf.), a vital crop for the global food supply, is facing significant challenges related to irrigation management and water stress. The objective of this study was to assess the impact of different irrigation regimes (full *vs*. reduced) on hectoliter weight, 1000-grain weight, and nutritional composition in several wheat cultivars during the 2021-2022 and 2022-2023 growing seasons. Full management included four irrigations, while reduced management omitted the final irrigation. The impact of irrigation on key grain quality parameters was evaluated through precise measurements and statistical analysis. The results demonstrated that full irrigation led to a notable enhancement in hectoliter weight and 1000-grain weight across the majority of varieties, with values reaching up to 81.40 and 60.52 g, respectively. Conversely, reduced irrigation tended to elevate protein content, reaching up to 15.56% in certain varieties. Furthermore, variations in carbohydrate, lipid, and mineral contents were observed depending on the irrigation regime. Certain genotypes demonstrated a higher accumulation of these nutrients under water stress. In conclusion, full irrigation generally favors grain density and size, while water stress induced by reduced irrigation can increase protein content. This highlights the importance of adapting irrigation management practices according to the specific characteristics of each variety to optimize wheat quality and yield.

Key words: Hectoliter weight, irrigation regimes, nutritional composition, 1000-grain weight, physicochemical characterization, *Triticum durum*, water stress.

INTRODUCTION

Durum wheat (*Triticum durum* Desf.) is one of the most widely cultivated cereals in the world, distinguished by its capacity to thrive in a multitude of agricultural settings (de Sousa et al., 2021). Wheat is a highly adaptable crop, making it one of the most important sources of food for humans and animals alike. In terms of volume and value, wheat is the most significant item in the foreign trade of agricultural products (de Sousa et al., 2021; Soto-Gómez and Pérez-Rodríguez, 2022).

In Mexico, wheat plays a pivotal role in both dietary intake and the country’s economic stability. It represents the third most important source of nutrients in the Mexican diet, surpassed only by maize and beans (Palacios-Rojas et al., 2020). The principal wheat-producing regions are the North-Northwest and regions Bajío (Valenzuela-Antelo et al., 2018). Sonora is the primary wheat-producing region in Mexico, contributing over 50% of the national harvest in 2023 (SIAP, 2024). A number of key factors contribute to its success, including a favorable climate, fertile irrigated land, the use of agricultural mechanization, and government support. The southern regions, particularly the Yaqui Valley, are the primary production centers due to their optimal conditions (Valenzuela-Antelo et al., 2018). However, wheat is among the crops most vulnerable to increasing water stress (Buenrostro-Rodríguez et al., 2023).

Wheat yield is typically evaluated in terms of its constituent components, including the number of ears per unit area, number of grains per ear, and size of the kernels. However, the physicochemical characteristics of grains are not taken into account (Vincke et al., 2022). The phenomenon of water stress has been demonstrated to exert a detrimental impact on both the yield and quality of grains (Stone, 2023). The quality of the grain is dependent upon its nutritional composition and functional properties, including the taste, color, and aroma of the product. In particular, color, as measured by chroma, hue, and lightness, is an important parameter for consumers and the industry (Abah et al., 2020). It may serve as a reflection of changes in grain composition due to water stress. The variation in the nutritional composition of grains under different growing conditions is of great consequence for human nutrition programs and the food industry, which require products with higher protein, fiber, and mineral content. Nutrient deficiency, soil acidity, and drought have been identified as factors that negatively impact grain productivity and quality (Zeibig et al., 2022). It is imperative to ascertain the protein, carbohydrate, mineral, and other qualitative constituents of grains cultivated under disparate conditions, as this is crucial for effective nutrition and human health management (Poole et al., 2021).

Our hypothesis is that the elimination of the final irrigation at the grain filling stage will impact the abundance of lipids, proteins, carbohydrates, and ash, leading not only to a reduction in productivity but also to a decline in grain quality. Given the varying degrees of susceptibility among genotypes and the impact of water deficit, restricted irrigation is a vital tool for assessing tolerance to water stress and for reducing water consumption while maintaining grain protein quality (Silva et al., 2020).

MATERIALS AND METHODS

Experimental site and conditions

Ten durum wheat (*Triticum durum* Desf.) genotypes were evaluated: MEXICALI C75, YAVAROS 79, ALTAR 84, ACONCHI 89, CIRNO C 2008, CEMEXI C 2008, CONASIST C2015, BAROBAMPO C2015, RIO BRAVO C2018, and DON LUPE C2020. The experiments were conducted at the Experimental Station of the University of Sonora during the fall-winter cycles 2021-2022 and 2022-2023. The genotypes were subjected to different irrigation managements, such as full (C) and reduced (R) levels. The full management included four supplemental irrigations throughout the crop cycle, while the reduced management consisted of eliminating the last irrigation, which corresponds to the grain filling stage.

The experimental design was a randomized complete block design with three replicates. Each plot consisted of three furrows in double rows, each 5 m long. The total area of each plot was 10.25 m², with an exclusion of 0.50 m at each edge to avoid edge effects.

Hectoliter weight and thousand kernel weight

To determine the 1000 kernel weight, 1000 kernels were randomly selected from a clean seed lot and weighed using a balance (BSM-1204, VENJOYIT, Shanghai, China). This procedure was done in triplicate to ensure accuracy and consistency of results. Each sample of 1000 kernels was weighed separately and the data obtained were averaged to calculate the final weight. Quantification was performed according to American Association of Cereal Chemists (AACC, 2024) procedure using a microscale. The procedure consisted of filling a 1 L container with grain and weighing it on an analytical balance. The hectoliter weight was determined by dividing the weight of the grains by the volume of the container and adjusting the result to a volume of 100 L (kg hL^{-1}). The test was performed with five replicates (AACC, 2024).

Determining physicochemical characteristics

Moisture. Moisture was determined according to approved methods of the AACC (2024), method 44.0.1. The weight loss of a 2 g sample was measured after heating at 130 °C for 1 h in a circulating air oven (FE-291D, Felisa, Zapopan, Jalisco, México). The assay was performed in triplicate.

Proteins. AACC method 46.13.01, micro-Kjeldahl, was used for protein determination. A 0.15 g sample was digested with 5 mL sulfuric acid and selenium reagent mixture (Merck, Darmstadt, Germany) at 200 °C. During the distillation of the sample, previously diluted with 7 mL water, 30% NaOH solution and 4% boric acid were used as an indicator to obtain the distillate. Titration was performed with a titrated 0.1 N HCl solution. Crude protein was then calculated by multiplying the total N content by 5.85. The assay was performed in triplicate.

Lipids. Lipids were determined according to AACC (2004) method 30-25.01. Extractions were performed on 4 g samples of flour passed through an 80 mesh sieve using a Soxhlet and petroleum ether as solvent. The assay was performed in quadruplicate.

Ash. The AACC method 08-03.01 (AACC, 2004) was used for the determination of minerals. Samples were weighed between 5 g, placed in a porcelain crucible and incinerated in a muffle at 550 °C until a bright gray ash of constant weight was obtained. The incinerated samples were cooled in a desiccator and weighed. The test was performed in quadruplicate.

Carbohydrate (CHO). The carbohydrate content of the sample was calculated by difference from the other nutrients using the following formula:

$$\mathrm{CHO} = 100 - \%\ \mathrm{Protein} - \%\mathrm{Lipid} - \%\mathrm{Mineral} - \mathrm{Water\ content}$$

Color determination. The methodology described by Reyes-Moreno et al. (2002) was used. The color measurement of the samples was carried out using a colorimeter (WR 18, VTSYIQI, Shanghai, China), based on the tristimulus effect. The L parameter represents brightness and varies from 100 for perfect white to zero for black. The dimensions of chromaticity are represented by the parameters a and b, where positive values of a indicate red tones and negative values indicate green, while positive values of b correspond to yellow and negative values to blue.

To evaluate the color, approximately 100 g sample were used, placed in a Kimax glass Petri dish lid with a diameter of 15 cm, and the corresponding parameters L, a and b were measured. A white mosaic was used as a reference standard with known values (L = 97.63, a = -0.78, b = 2.85). The total color difference (ΔE) of the sample was calculated using the equation:

$$\Delta \mathrm{E} = \sqrt{(\Delta \mathrm{L}^2 + \Delta \mathrm{a}^2 + \Delta \mathrm{b}^2)}$$

where ΔE is total color difference between the standard and the sample; ΔL, Δa and Δb are absolute differences between the values of L, a and b, respectively, of the standard used and the corresponding values observed in the sample (Reyes-Moreno et al., 2002).

Statistical analysis

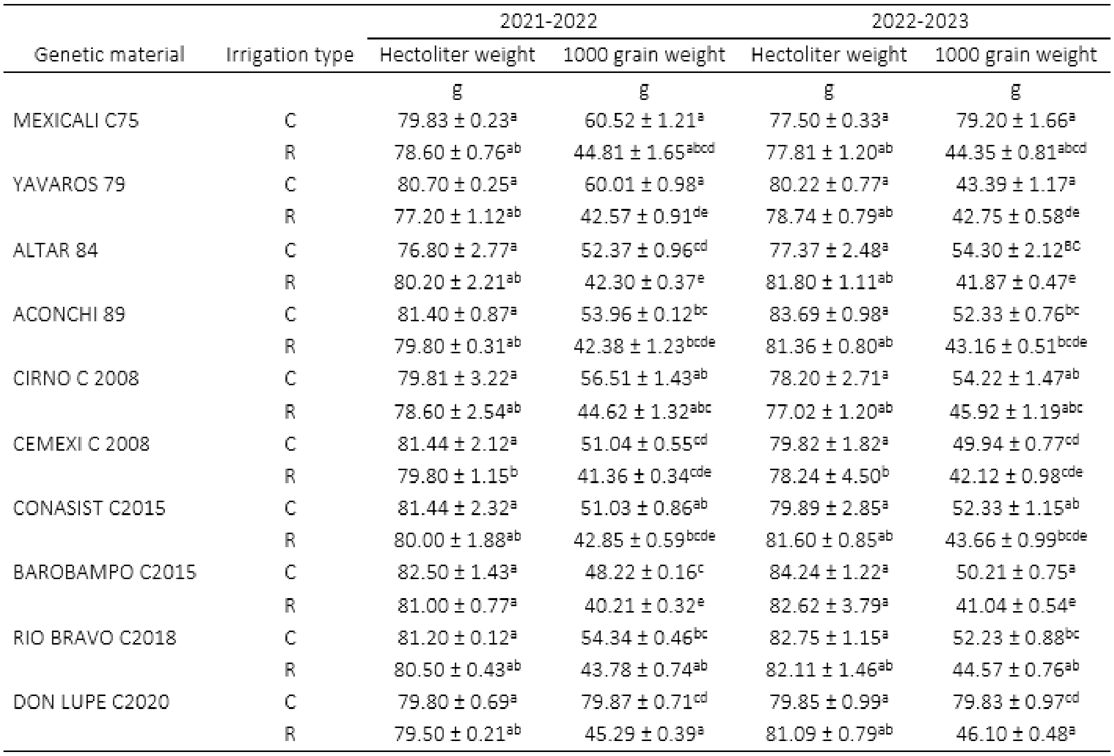
The data obtained were analyzed using an ANOVA. After verifying the significance of the R values, the least significant difference (MSD) test was applied with a significance level of 5% to compare the means of each of the sources of variation of interest. In addition, a simple linear correlation analysis was carried out between each pair of different varieties (Valenzuela-Antelo et al., 2018).

RESULTS AND DISCUSSION

Hectoliter weight and 1000-grain weight

Wheat cultivation requires a large amount of water (approximately 450 and 500 mL per crop cycle). However, it is necessary to reduce it due to water stress. The transpiration efficiency is about 20 kg grain per hectare for each milliliter of water transpired (Qiao et al., 2022). The number of grains is defined during the critical period of about 30 d from the appearance of the flag leaf to 10 d after anthesis (Farhad et al., 2022). However, different varieties react differently to irrigation reduction. Table 1 shows the effects of irrigation type (full *vs*. reduced irrigation) on two key grain quality parameters: Hectoliter weight and 1000 kernel weight, in different genetic materials during the 2021-2022 and 2022-2023 growing seasons. The results reveal a consistent trend suggesting that full irrigation has a significantly positive impact on both parameters compared to reduced irrigation.

Table 1. Effects of the type of irrigation (full and reduced) on hectoliter weight and weight of 1000 grains in different genetic materials of durum wheat during the 2021-2022 and 2022-2023 agricultural cycles. Different letters in the column indicate significant differences according to the Tukey test ($P \leq 0.05$). C: Full irrigation; R: reduced irrigation.



		2021-2022		2022-2023	
Genetic material	Irrigation type	Hectoliter weight	1000 grain weight	Hectoliter weight	1000 grain weight
		g	g	g	g
MEXICALI C75	C	79.83 ± 0.23^{a}	60.52 ± 1.21^{a}	77.50 ± 0.33^{a}	79.20 ± 1.66^{a}
	R	78.60 ± 0.76^{ab}	44.81 ± 1.65^{abcd}	77.81 ± 1.20^{ab}	44.35 ± 0.81^{abcd}
YAVAROS 79	C	80.70 ± 0.25^{a}	60.01 ± 0.98^{a}	80.22 ± 0.77^{a}	43.39 ± 1.17^{a}
	R	77.20 ± 1.12^{ab}	42.57 ± 0.91^{de}	78.74 ± 0.79^{ab}	42.75 ± 0.58^{de}
ALTAR 84	C	76.80 ± 2.77^{a}	52.37 ± 0.96^{cd}	77.37 ± 2.48^{a}	54.30 ± 2.12^{BC}
	R	80.20 ± 2.21^{ab}	42.30 ± 0.37^{e}	81.80 ± 1.11^{ab}	41.87 ± 0.47^{e}
ACONCHI 89	C	81.40 ± 0.87^{a}	53.96 ± 0.12^{bc}	83.69 ± 0.98^{a}	52.33 ± 0.76^{bc}
	R	79.80 ± 0.31^{ab}	42.38 ± 1.23^{bcde}	81.36 ± 0.80^{ab}	43.16 ± 0.51^{bcde}
CIRNO C 2008	C	79.81 ± 3.22^{a}	56.51 ± 1.43^{ab}	78.20 ± 2.71^{a}	54.22 ± 1.47^{ab}
	R	78.60 ± 2.54^{ab}	44.62 ± 1.32^{abc}	77.02 ± 1.20^{ab}	45.92 ± 1.19^{abc}
CEMEXI C 2008	C	81.44 ± 2.12^{a}	51.04 ± 0.55^{cd}	79.82 ± 1.82^{a}	49.94 ± 0.77^{cd}
	R	79.80 ± 1.15^{b}	41.36 ± 0.34^{cde}	78.24 ± 4.50^{b}	42.12 ± 0.98^{cde}
CONASIST C2015	C	81.44 ± 2.32^{a}	51.03 ± 0.86^{ab}	79.89 ± 2.85^{a}	52.33 ± 1.15^{ab}
	R	80.00 ± 1.88^{ab}	42.85 ± 0.59^{bcde}	81.60 ± 0.85^{ab}	43.66 ± 0.99^{bcde}
BAROBAMPO C2015	C	82.50 ± 1.43^{a}	48.22 ± 0.16^{c}	84.24 ± 1.22^{a}	50.21 ± 0.75^{a}
	R	81.00 ± 0.77^{a}	40.21 ± 0.32^{e}	82.62 ± 3.79^{a}	41.04 ± 0.54^{e}
RIO BRAVO C2018	C	81.20 ± 0.12^{a}	54.34 ± 0.46^{bc}	82.75 ± 1.15^{a}	52.23 ± 0.88^{bc}
	R	80.50 ± 0.43^{ab}	43.78 ± 0.74^{ab}	82.11 ± 1.46^{ab}	44.57 ± 0.76^{ab}
DON LUPE C2020	C	79.80 ± 0.69^{a}	79.87 ± 0.71^{cd}	79.85 ± 0.99^{a}	79.83 ± 0.97^{cd}
	R	79.50 ± 0.21^{ab}	45.29 ± 0.39^{a}	81.09 ± 0.79^{ab}	46.10 ± 0.48^{a}

The genetic material 'MEXICALI C75' was observed to exhibit significantly higher yields under full irrigation, with a hectoliter weight of 79.83 g and a 1000-grain weight of 60.52 g during the 2021-2022 cycle. These values markedly exceed those obtained under reduced irrigation (78.6 and 44.81 g, respectively). This trend is sustained in the 2022-2023 cycle, thereby demonstrating the sustained advantage of full irrigation for this genetic material. The observed increase in hectoliter weight and 1000-kernel weight under full irrigation suggests an increase in kernel density and size, which can be correlated with an improvement in kernel quality. Similarly, 'YAVAROS 79' material demonstrates a notable enhancement in both parameters with full irrigation in comparison to reduced irrigation. In the 2021-2022 cycle, the hectoliter weight under full irrigation was observed to be 80.7 g, in comparison to 77.2 g with reduced irrigation. Similarly, the 1000-grain weight was found to be 60.01 g under full irrigation, in contrast to 42.57 g with reduced irrigation. This improvement is also observed in the 2022-2023 cycle, thereby confirming the efficacy of full irrigation in improving grain quality in this material.

The performance of 'ALTAR 84' exhibits some variability in response to irrigation regimes. In the 2021-2022 cycle, the application of full irrigation resulted in a reduction in hectoliter weight in comparison to the reduced irrigation treatment. However, in the 2022-2023 cycle, reduced irrigation also resulted in an improvement in hectoliter weight. Notwithstanding the aforementioned observations, the 1000-kernel weight was consistently higher under full irrigation in both cycles. This pattern suggests that full irrigation may be more effective in maintaining or increasing grain size, although the effects may vary between cycles. This variability may be attributed to water stress associated with reduced irrigation, which has been demonstrated to negatively affect grain filling in previous studies (Qi et al., 2022). Furthermore, greenhouse research has demonstrated that the application of K can serve to mitigate the adverse effects of water stress, thereby improving water status, DM translocation, maintaining chlorophyll indices, and grain quality (Ali et al., 2022).

The materials ‘ACONCHI 89’, ‘CIRNO C 2008’, and ‘CEMEXI C 2008’ also demonstrated a distinct superiority of full irrigation. In the case of ‘ACONCHI 89’, full irrigation resulted in a hectoliter weight of 81.4 g and a 1000 kernel weight of 53.96 g, in comparison to 79.8 and 42.38 g, respectively, under reduced irrigation. A similar trend was observed in the case of ‘CIRNO C 2008’ and ‘CEMEXI C 2008’, with higher values for hectoliter weight and 1000-grain weight under full irrigation. This lends further support to the hypothesis that full irrigation is conducive to improved grain quality.

Additionally, ‘CONASIST C2015’ and ‘BAROBAMPO C2015’ exhibited favorable outcomes with full irrigation. However, ‘BAROBAMPO C2015’ exhibited a slight decline in 1000-kernel weight under full irrigation during the 2023-2024 cycle, which could indicate inconsistency in the response to irrigation type. Nevertheless, the hectoliter weight was found to be higher with full irrigation in both cycles, indicating that full irrigation continues to be advantageous in terms of grain density.

The results of ‘RIO BRAVO C2018’ and ‘DON LUPE C2020’ experiments corroborate the general trend observed in previous studies, namely that full irrigation results in higher hectoliter weight and 1000 kernel weight compared to reduced irrigation. These findings underscore the significance of full irrigation for enhancing grain quality, although the extent of the impact may fluctuate contingent on the genetic material and crop cycle. The data indicate that full irrigation generally provides substantial benefits with respect to grain quality for the majority of the genetic materials under evaluation. These results may prove useful in optimizing irrigation management practices according to the specific characteristics of each genetic material, with the aim of maximizing grain quality and yield.

The slight decrease in 1000-kernel weight observed in ‘BAROBAMPO C2015’ under full irrigation in the 2023-2024 cycle, despite the higher hectoliter weight, can be attributed to water stress. Although full irrigation generally improves hectoliter weight, suggesting higher grain density, the variability in 1000 kernel weight could reflect a negative impact of excess water on grain filling (Zhao et al., 2020).

One potential explanation for this phenomenon is the inherent variability in plant response to full irrigation, which can be attributed to a number of factors, including environmental conditions and agronomic management practices (Yepes and Buckeridge, 2011). While full irrigation typically enhances hectoliter weight, an indicator of elevated kernel density, the 1000-kernel weight response may be influenced by additional factors, including nutrient availability, inter-plant competition, and the specific physiology of the genetic material. It is possible that excessive irrigation may have influenced the balance between grain size and DM content, resulting in a slight decrease in 1000-grain weight despite an overall higher grain density (Yepes and Buckeridge, 2011; Qi et al., 2022). An additional hypothesis is that the reduction in 1000-grain weight may be associated with fluctuations in water distribution and uptake throughout the growth cycle. It is possible that plants may experience varying degrees of water stress or competition for water, which could result in uneven impacts on kernel development and size. Furthermore, additional factors, including irrigation management, distribution of water in the field, and crop’s response to specific climatic conditions, may have contributed to this observed variability (Beral et al., 2020).

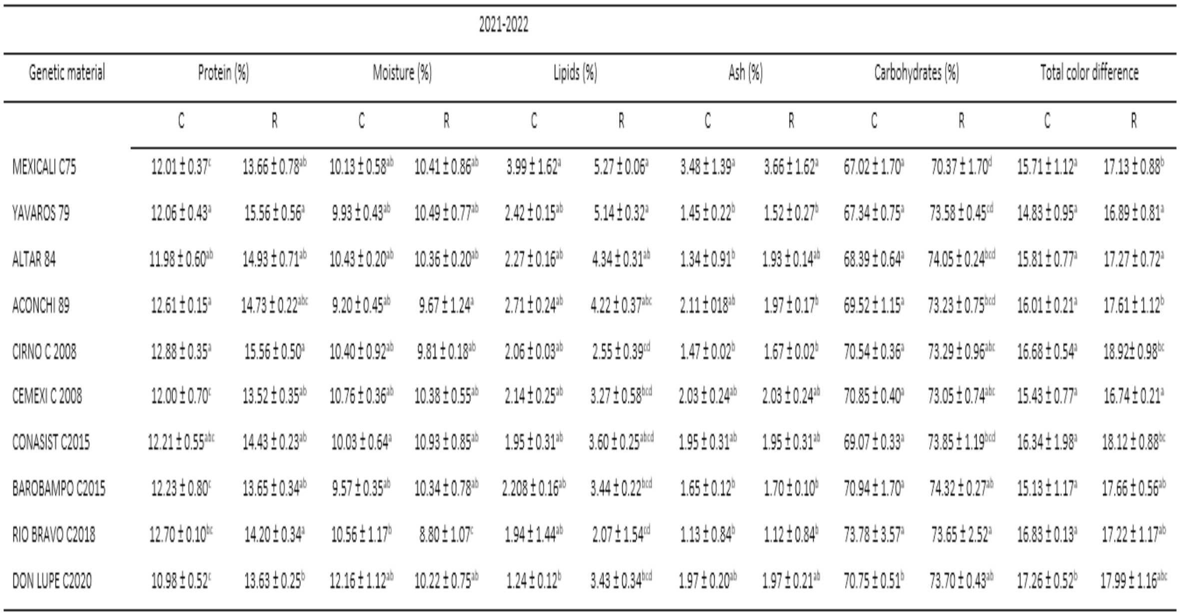
The observed discrepancies in the impact of full irrigation on 1000-kernel weight may be attributed to a multifaceted interplay between genetic composition and environmental factors. It is possible that the genetic material in question may exhibit specific thresholds for response to irrigation, which may vary according to the crop cycle and environmental conditions. For example, some materials may exhibit greater benefits from full irrigation in terms of grain density and size, while others may demonstrate a less uniform response (Yepes and Buckeridge, 2011; Zandalinas et al., 2021).

The impact of water stress, whether resulting from a water deficit or excess, on grain development and quality is complex and multifaceted. In the case of full irrigation, the presence of excess water may have impeded the efficient translocation of nutrients and DM into the grain, ultimately resulting in a reduction in grain size despite an increase in density. Furthermore, full irrigation can result in saturated soil conditions, which has been demonstrated to negatively impact root aeration and may impede optimal grain development (Zhao et al., 2020). In contrast, ‘RIO BRAVO C2018’ and ‘DON LUPE C2020’ demonstrated consistent enhancements in both parameters under full irrigation, indicating that these genetic materials may exhibit greater tolerance to excess water and benefit from higher grain density and size. This lends further support to the notion that full irrigation is, on the whole, beneficial, although the response may vary depending on the ability of the genetic material in question to cope with water stress. It is of paramount importance to gain an understanding of the interactions between irrigation, environmental conditions, and the specific characteristics of each genetic material in order to optimize irrigation practices and improve grain quality and yield.

Determination of proximate characteristics

Protein and carbohydrate content. Wheat is a globally significant food crop, with a nutritional composition that varies according to variety and treatments applied. Tables 2 and 3 illustrate the proximate content of various wheat varieties during the 2021-2022 and 2022-2023 cycles, respectively, under two irrigation treatments: Full irrigation and reduced irrigation. In the context of full irrigation, the wheat 'CIRNO C 2008' and 'ACONCHI 89' exhibited the highest protein percentages, at 12.88% and 12.61%, respectively. In the context of reduced irrigation, 'YAVAROS 79' and 'CIRNO C 2008' exhibited the highest protein content (15.56%). These cultivars are notable for their capacity to maintain a high protein content under both optimal and water-stressed conditions. In contrast, 'DON LUPE C2020' exhibits the lowest protein content, with 10.98% in full irrigation and 13.63% in reduced irrigation. This indicates that this variety is less efficient in terms of protein content compared to the other cultivars analyzed. Similar outcomes have been observed in wheat (in Brazil), bean, barley, and soybean cultivars, wherein reduced irrigation resulted in elevated protein content (Shrief and Abd El-Mohsen, 2014; Silva et al., 2020). This increase can be attributed to a reduction in N partitioning and fixation, as well as a decrease in C fixation due to the partial closure of stomata. Nevertheless, the remobilization of N from the leaves to the grain is not affected, resulting in a reduction in grain weight but an increase in protein percentage (Silva et al., 2020).

Table 2. Nutritional composition and color of different genetic varieties of durum wheat during the 2021-2022 cycle. Different letters in the column indicate significant differences according to the Tukey test (*P* ≤ 0.05). C: Full irrigation; R: reduced irrigation. Total color difference is the difference between the standard and the sample.



2021-2022												
Genetic material	Protein (%)		Moisture (%)		Lipids (%)		Ash (%)		Carbohydrates (%)		Total color difference	
	C	R	C	R	C	R	C	R	C	R	C	R
MEXICALI C75	12.01 ± 0.37^{c}	13.66 ± 0.78^{ab}	10.13 ± 0.58^{ab}	10.41 ± 0.86^{ab}	3.99 ± 1.62^{a}	5.27 ± 0.06^{a}	3.48 ± 1.39^{a}	3.66 ± 1.62^{a}	67.02 ± 1.70^{a}	70.37 ± 1.70^{d}	15.71 ± 1.12^{a}	17.13 ± 0.88^{b}
YAVAROS 79	12.06 ± 0.43^{a}	15.56 ± 0.56^{a}	9.93 ± 0.43^{ab}	10.49 ± 0.77^{ab}	2.42 ± 0.15^{ab}	5.14 ± 0.32^{a}	1.45 ± 0.22^{b}	1.52 ± 0.27^{b}	67.34 ± 0.75^{a}	73.58 ± 0.45^{cd}	14.83 ± 0.95^{a}	16.89 ± 0.81^{a}
ALTAR 84	11.98 ± 0.60^{ab}	14.93 ± 0.71^{ab}	10.43 ± 0.20^{ab}	10.36 ± 0.20^{ab}	2.27 ± 0.16^{ab}	4.34 ± 0.31^{ab}	1.34 ± 0.91^{b}	1.93 ± 0.14^{ab}	68.39 ± 0.64^{a}	74.05 ± 0.24^{bcd}	15.81 ± 0.77^{a}	17.27 ± 0.72^{a}
ACONCHI 89	12.61 ± 0.15^{a}	14.73 ± 0.22^{abc}	9.20 ± 0.45^{ab}	9.67 ± 1.24^{a}	2.71 ± 0.24^{ab}	4.22 ± 0.37^{abc}	2.11 ± 018^{ab}	1.97 ± 0.17^{b}	69.52 ± 1.15^{a}	73.23 ± 0.75^{bcd}	16.01 ± 0.21^{a}	17.61 ± 1.12^{b}
CIRNO C 2008	12.88 ± 0.35^{a}	15.56 ± 0.50^{a}	10.40 ± 0.92^{ab}	9.81 ± 0.18^{ab}	2.06 ± 0.03^{ab}	2.55 ± 0.39^{cd}	1.47 ± 0.02^{b}	1.67 ± 0.02^{b}	70.54 ± 0.36^{a}	73.29 ± 0.96^{abc}	16.68 ± 0.54^{a}	18.92 ± 0.98^{bc}
CEMEXI C 2008	12.00 ± 0.70^{c}	13.52 ± 0.35^{ab}	10.76 ± 0.36^{ab}	10.38 ± 0.55^{ab}	2.14 ± 0.25^{ab}	3.27 ± 0.58^{bcd}	2.03 ± 0.24^{ab}	2.03 ± 0.24^{ab}	70.85 ± 0.40^{a}	73.05 ± 0.74^{abc}	15.43 ± 0.77^{a}	16.74 ± 0.21^{a}
CONASIST C2015	12.21 ± 0.55^{abc}	14.43 ± 0.23^{ab}	10.03 ± 0.64^{a}	10.93 ± 0.85^{ab}	1.95 ± 0.31^{ab}	3.60 ± 0.25^{abcd}	1.95 ± 0.31^{ab}	1.95 ± 0.31^{ab}	69.07 ± 0.33^{a}	73.85 ± 1.19^{bcd}	16.34 ± 1.98^{a}	18.12 ± 0.88^{bc}
BAROBAMPO C2015	12.23 ± 0.80^{c}	13.65 ± 0.34^{ab}	9.57 ± 0.35^{ab}	10.34 ± 0.78^{ab}	2.208 ± 0.16^{ab}	3.44 ± 0.22^{bcd}	1.65 ± 0.12^{b}	1.70 ± 0.10^{b}	70.94 ± 1.70^{a}	74.32 ± 0.27^{ab}	15.13 ± 1.17^{a}	17.66 ± 0.56^{ab}
RIO BRAVO C2018	12.70 ± 0.10^{bc}	14.20 ± 0.34^{a}	10.56 ± 1.17^{b}	8.80 ± 1.07^{c}	1.94 ± 1.44^{ab}	2.07 ± 1.54^{cd}	1.13 ± 0.84^{b}	1.12 ± 0.84^{b}	73.78 ± 3.57^{a}	73.65 ± 2.52^{a}	16.83 ± 0.13^{a}	17.22 ± 1.17^{ab}
DON LUPE C2020	10.98 ± 0.52^{c}	13.63 ± 0.25^{b}	12.16 ± 1.12^{ab}	10.22 ± 0.75^{ab}	1.24 ± 0.12^{b}	3.43 ± 0.34^{bcd}	1.97 ± 0.20^{ab}	1.97 ± 0.21^{ab}	70.75 ± 0.51^{b}	73.70 ± 0.43^{ab}	17.26 ± 0.52^{b}	17.99 ± 1.16^{abc}

Table 3. Nutritional composition and color of different genetic varieties of durum wheat during the 2022-2023 Cycle. Different letters in the column indicate significant differences according to the Tukey test ($P \leq 0.05$). C: Full irrigation; R: reduced irrigation. Total color difference is the difference between the standard and the sample.

	2022-2023											
Genetic material	Protein (%)		Moisture (%)		Lipids (%)		Ash (%)		Carbohydrates (%)		Total color difference	
	C	R	C	R	C	R	C	R	C	R		
MEXICALI C75	11.64 ± 0.76^{c}	13.25 ± 0.46^{a}	9.82 ± 0.77^{ab}	10.05 ± 0.56^{abc}	3.87 ± 0.23^{a}	5.18 ± 0.66^{a}	3.37 ± 0.21^{a}	3.59 ± 0.31^{a}	68.01 ± 1.68^{b}	71.28 ± 1.68^{c}	14.97 ± 1.21^{ab}	16.13 ± 0.44^{a}
YAVAROS 79	11.97 ± 0.41^{a}	14.78 ± 0.41^{ab}	9.43 ± 0.33^{ab}	9.88 ± 0.41^{abc}	2.30 ± 0.17^{b}	4.81 ± 0.29^{a}	1.38 ± 0.09^{b}	1.47 ± 0.08^{b}	68.97 ± 0.66^{a}	74.91 ± 0.47^{bc}	15.01 ± 0.96^{ab}	17.89 ± 0.21^{b}
ALTAR 84	12.49 ± 0.63^{ab}	15.20 ± 0.63^{abc}	10.95 ± 0.88^{ab}	10.88 ± 0.21^{ab}	2.38 ± 0.23^{b}	4.51 ± 0.33^{ab}	1.40 ± 0.14^{b}	2.05 ± 0.10^{b}	67.30 ± 0.72^{ab}	72.75 ± 1.00^{c}	15.16 ± 0.83^{ab}	18.27 ± 0.53^{b}
ACONCHI 89	12.09 ± 1.12^{a}	13.76 ± 1.12^{a}	8.74 ± 0.92^{b}	9.12 ± 1.18^{bc}	2.58 ± 0.23^{ab}	4.01 ± 0.47^{b}	2.01 ± 0.16^{b}	1.81 ± 0.18^{b}	71.28 ± 1.59^{a}	74.57 ± 0.75^{ab}	16.01 ± 0.25^{ab}	18.61 ± 1.87^{ab}
CIRNO C 2008	12.38 ± 0.34^{a}	14.98 ± 0.44^{ab}	10.08 ± 0.97^{ab}	9.37 ± 0.97^{abc}	1.99 ± 0.03^{b}	2.47 ± 0.04^{ab}	1.42 ± 0.02^{b}	1.62 ± 0.02^{b}	71.53 ± 0.36^{ab}	74.10 ± 0.78^{ab}	15.13 ± 0.99^{ab}	19.07± 0.65^{bc}
CEMEXI C 2008	11.46 ± 0.66^{c}	12.98 ± 0.66^{ab}	10.22 ± 0.44^{ab}	9.78 ± 0.52^{abc}	2.03 ± 0.24^{ab}	3.10 ± 0.37^{b}	1.93 ± 0.21^{b}	1.97 ± 0.22^{b}	72.18 ± 0.99^{a}	74.40 ± 0.92^{a}	15.52 ± 1.34^{abc}	16.35 ± 0.30^{a}
CONASIST C2015	11.95 ± 0.89^{abc}	14.43 ± 0.54^{ab}	9.83 ± 0.78^{a}	11.04 ± 0.89^{a}	1.87 ± 0.29^{ab}	3.53 ± 0.57^{a}	1.91 ± 0.31^{b}	1.91 ± 0.31^{b}	69.07 ± 0.90^{a}	74.41 ± 1.44^{bc}	16.17 ± 1.12^{abc}	18.88 ± 1.63^{ab}
BAROBAMPO C2015	11.99 ± 0.39^{c}	13.32 ± 0.79^{ab}	9.38 ± 0.23^{ab}	10.13 ± 0.34^{ab}	2.18 ± 0.14^{b}	3.32 ± 0.65^{a}	1.62 ± 0.10^{b}	1.66 ± 0.12^{b}	71.53 ± 1.41^{a}	74.81 ± 0.32^{ab}	14.11 ± 1.70^{ab}	17.64 ± 0.78^{ab}
RIO BRAVO C2018	11.93 ± 1.24^{a}	13.35 ± 0.91^{a}	9.93 ± 0.77^{c}	8.27 ± 0.98^{c}	1.82 ± 0.02^{b}	2.88 ± 0.22^{b}	1.06 ± 0.79^{b}	1.02 ± 0.71^{b}	74.41 ± 1.70^{c}	75.23 ± 1.13^{d}	15.72 ± 0.39^{ab}	17.92 ± 0.29^{b}
DON LUPE C2020	10.24 ± 0.33^{b}	12.81 ± 0.49^{b}	11.43 ± 0.49^{a}	9.58 ± 1.12^{abc}	1.17 ± 0.11^{ab}	3.22 ± 0.11^{b}	1.81 ± 0.18^{b}	1.85 ± 0.22^{b}	72.51 ± 0.12^{c}	75.28 ± 0.44^{d}	17.06 ± 0.41^{c}	18.19 ± 0.33^{b}

In the case of carbohydrates under full irrigation, the highest percentages are observed for 'CIRNO C 2008' (70.54%) and 'CEMEX I C 2008' (70.85%). In the context of reduced irrigation, the highest levels were observed for 'BAROBAMPO C2015' (74.32%) and 'ALTAR 84' (74.05%). This suggests that these cultivars are highly efficient in accumulating carbohydrates, particularly under conditions of reduced irrigation. The lowest carbohydrate content was observed in 'MEXICALI C75' under both full and reduced irrigation conditions, suggesting a lower accumulation compared to other varieties. Carbohydrates are a vital component of the human diet, serving as the primary source of energy for the body. It is of paramount importance to maintain the nutritional value of the grain, irrespective of the biotic or abiotic stresses the plant has encountered during its life cycle. Nevertheless, the diminution of starch in the grain, which represents the principal form of energy storage in cereals, has an adverse impact on productivity (Silva et al., 2020). The process of photosynthesis, which requires water, is adversely affected during periods of water stress, resulting in a reduction in the availability of carbohydrates (Guo et al., 2021). This phenomenon occurs as a result of the degradation of photosynthetic pigments in leaves, which subsequently leads to a reduction in C assimilation (Zahra et al., 2023). Furthermore, water stress has been shown to result in an increase in grain protein content, which can be attributed to a reduction in starch synthesis (Ullah et al., 2023). In the course of our investigation, we observed that the carbohydrate content exhibited variation in accordance with the water regime, and this was found to be correlated with the protein content. The results of the analyses demonstrated a robust correlation between carbohydrate and protein content in the cultivars, analogous to the findings reported by Silva et al. (2020) in wheat and bean cultivars and in heat-stressed wheat genotypes (Gare et al., 2018).

Lipid and ash content. A reduction in water availability prompts a series of metabolic alterations in plants, including elevated lipolytic and peroxidative activities, as well as a curtailment in lipid biosynthesis, which is associated with a decline in membrane lipids. In the context of full irrigation, the genotype 'MEXICALI C75' (3.99%) exhibits the highest lipid content. In the context of reduced irrigation, 'MEXICALI C75' (5.27%) and 'YAVAROS 79' (5.14%) also demonstrate elevated lipid levels, thereby indicating that these cultivars are capable of accumulating lipids even under conditions of water stress. Conversely, 'CIRNO C 2008' (2.06%) under full irrigation and 'YAVAROS 79' (2.42%) under reduced irrigation exhibited the lowest lipid percentages, indicating a diminished accumulation compared to other cultivars. In certain plants, such as canola (*Brassica napus* L.), abesoda (*Nigella sativa* L.), peas (Akçura et al., 2021), sunflower (Vancostenoble et al., 2022), maize (Ma et al., 2023), wheat, and beans (Silva et al., 2020). A lack of water, particularly during the grain-filling stage, has been shown to impact the accumulation of lipids in seeds, which in turn affects the quality and quantity of the resulting crop (Abdou et al., 2023; Secchi et al., 2023). However, the specific effects observed depend on the species and genotypes in question (Silva et al., 2020).

With regard to mineral content, under conditions of full irrigation, 'CEMEXI C 2008' (2.03%) and 'ACONCHI 89' (2.11%) exhibited the highest percentages of minerals. In the context of reduced irrigation, 'YAVAROS 79' (1.52%) and 'BAROBAMPO C2015' (1.65%) also demonstrate elevated mineral content. In contrast, 'YAVAROS 79' and 'CIRNO C 2008' exhibit the lowest mineral content in both conditions, which may suggest a greater translocation of mineral nutrients from the roots to the grains. Conversely, when soil moisture is limited, all ions become less mobile due to the replacement of water by air in the pore spaces between soil particles. This increases the tortuosity and retention of ions by soil colloids, thereby reducing root uptake (Bhattacharya, 2021).

Moisture. With regard to moisture content, 'YAVAROS 79' (9.93%) and 'ALTAR 84' (10.43%) exhibited the lowest moisture percentages under conditions of full irrigation. In the context of reduced irrigation, 'RIO BRAVO C2018' exhibited the lowest moisture content, which may be indicative of a higher concentration of solids due to the limited availability of water. 'YAVAROS 79' and 'BAROBAMPO C2015' exhibited elevated moisture levels under reduced irrigation, which may be attributed to water retention within the grain.

A comparison of the 2021-2022 and 2022-2023 cycles reveals that 'CIRNO C 2008' and 'ACONCHI 89' continue to demonstrate the highest protein content, with 'CIRNO C 2008' exhibiting the highest protein percentage under both full and reduced irrigation in both cycles, indicating its consistent performance in protein yield. 'YAVAROS 79' also continues to demonstrate remarkable performance, particularly under reduced irrigation. However, it is noteworthy that its protein content exhibited a slight decline under full irrigation during the 2022-2023 cycle. In terms of moisture content, 'RIO BRAVO C2018' exhibits the lowest moisture levels under reduced irrigation conditions in both cycles, with a slight reduction observed in the second cycle. This may be indicative of a higher solids concentration due to water stress. 'YAVAROS 79' and 'ALTAR 84' demonstrate fluctuations in moisture content. Notably, 'ALTAR 84' exhibited an increase in moisture under full irrigation conditions during the 2022-2023 cycle. 'MEXICALI C75' maintains its position as the cultivar with the highest lipid content in both cycles, although there is a slight decrease in the most recent cycle under full irrigation. In terms of mineral content, 'CEMEXI C 2008' and 'ACONCHI 89' remain the varieties with the highest percentages of minerals, despite a slight reduction in the 2022-2023 cycle. In terms of carbohydrates, 'RIO BRAVO C2018' exhibits the highest content under reduced irrigation in the most recent cycle, whereas 'YAVAROS 79' demonstrates a decline in its carbohydrate content under full irrigation in comparison to the previous cycle. These observations indicate that, despite some variations, certain cultivars demonstrate consistent nutritional composition, while the response to irrigation conditions can significantly impact the concentration of various components. These data can inform the selection and management of varieties to optimize yield and crop quality in accordance with specific conditions.

CONCLUSIONS

Research on durum wheat cultivation and its quality characteristics under different irrigation regimes highlights the significant influence of irrigation on hectoliter weight, 1000 kernel weight, and the nutritional composition of the grain. Full irrigation generally improves both parameters compared to reduced irrigation, indicating greater kernel density and size, and therefore, better quality. However, some cultivars show variable responses, suggesting a complex interaction between water stress and the agricultural cycle. Regarding nutritional composition, protein and carbohydrate content varies with the irrigation regime. Water deficit seems to increase protein content due to reduced starch synthesis. Concerning lipids, some varieties accumulate more lipids under water stress, while others show lower lipid percentages. Mineral and moisture content are also affected by the irrigation regime. Some cultivars present high mineral content under full irrigation, while others show higher moisture content under reduced irrigation. The stability of the nutritional composition of certain varieties suggests that they may be preferred to optimize crop yield and quality. Full irrigation offers significant benefits in terms of grain quality, although the response varies depending on the genetic material's ability to handle water stress. Variety selection should consider the desired nutrient composition based on irrigation conditions and specific crop objectives.

Author contribution

Conceptualization: J.L.A-M., Methodology: A.L.M-O. Software: F.C-C. Validation: A.O-M. Formal analysis: F.C-C. Investigation: F.C-C. Resources: A.R.O-M. Data curation: A.R.O-M. Writing-original draft: O.P-R. Writing-review & editing: L.A-M. Visualization: J.L.A-M. Supervision: A.R.O-M. Project administration: F.C-C. Funding acquisition: J.L.A-M. All co-authors reviewed the final version and approved the manuscript before submission.

References

AACC. 2024. Approved methods of the American Association of Cereal Chemists. American Association of Cereal Chemists (AACC), St. Paul, Minnesota, USA.

Abah, C.R., Ishiwu, C.N., Obiegbuna, J.E., Oladejo, A.A. 2020. Nutritional composition, functional properties and food applications of millet grains. Asian Food Science Journal 14(2):9-19.

Abdou, N.M., Roby, M.H.H., Al-Huqail, A.A., Elkelish, A., Sayed, A.A.S., Alharbi, B.M., et al. 2023. Compost improving morphophysiological and biochemical traits, seed yield, and oil quality of *Nigella sativa* under drought stress. Agronomy 13(4):1147.

Akçura, S., Ismail T., Kökten, K., Kaplan, M., Bengü, A.Ş. 2021. Effects of irrigation intervals and irrigation levels on oil content and fatty acid composition of peanut cultivars. Notulae Botanicae Horti Agrobotanici Cluj-Napoca 49(2):12224-12224.

Ali, N., Anjum, M.M., Khan, G.R., Ali, R. 2022. Unraveling wheat grain quality, physiological indices, dry matter accumulation, and attenuating water stress adverse effect via foliar potassium application at different growth stages. Gesunde Pflanzen 74(1):41-52. doi:10.1007/s10343-021-00587-x.

Beral, A., Rincent, R., Le Gouis, J., Girousse, C., Allard, V. 2020. Wheat individual grain-size variance originates from crop development and from specific genetic determinism. PLOS ONE 15(3):e0230689.

Bhattacharya, A. 2021. Mineral nutrition of plants under soil water deficit condition: A review. p. 287-391. In Soil water deficit and physiological issues in plants. Springer, Singapore.

Buenrostro-Rodríguez, J.F., Covarrubias Prieto, J., Solís Moya, E., Ledesma Ramirez, L., González Figueroa, S.S., Mandujano Bueno, A., et al. 2023. Efecto del estrés hídrico sobre el rendimiento, clorofila y biomasa en trigo. Revista Fitotecnia Mexicana 46(3):245-253.

de Sousa, T., Ribeiro, M., Sabença, C., Igrejas, G. 2021. The 10,000-year success story of wheat! Foods 10(9):2124.

Farhad, M., Tripathi, S.B., Singh, R.P., Joshi, A.K., Bhati, P.K., Vishwakarma, M.K., et al. 2022. Multi-trait selection of bread wheat ideotypes for adaptation to early sown condition. Crop Science 62(1):67-82.

Gare, S., Wagh, R.S., Ingle, A.U., Soni, N. 2018. Effect of temperature on stem reserve mobilization for grain development in wheat. Journal of Pharmacognosy and Phytochemistry 7(5):1119-1123.

Guo, X., Peng, C., Li, T., Huang, J., Song, H., Zhu, Q., et al. 2021. The effects of drought and re-watering on non-structural carbohydrates of *Pinus tabulaeformis* seedlings. Biology 10(4):281.

Ma, B., Zhang, L., He, Z. 2023. Understanding the regulation of cereal grain filling: The way forward. Journal of Integrative Plant Biology 65(2):526-547.

Palacios-Rojas, N., McCulley, L., Kaeppler, M., Titcomb, T.J., Gunaratna, N.S., Lopez-Ridaura, S., et al. 2020. Mining maize diversity and improving its nutritional aspects within agro-food systems. Comprehensive Reviews in Food Science and Food Safety 19(4):1809-1834.

Poole, N., Donovan, J., Erenstein, O. 2021. Agri-nutrition research: Revisiting the contribution of maize and wheat to human nutrition and health. Food Policy 100:101976.

Qi, Y., Zhang, Q., Hu, S., Wang, R., Wang, H., Zhang, K., et al. 2022. Effects of high temperature and drought stresses on growth and yield of summer maize during grain filling in north China. Agriculture 12(11):1948.

Qiao, Y., Li, D., Qiao, W., Li, Y., Yang, H., Liu, W., et al. 2022. Development and application of a relative soil water content-transpiration efficiency curve for screening high water use efficiency wheat cultivars. Frontiers in Plant Science 13:967210.

Reyes-Moreno, C., Milán-Carrillo, J., Rouzaud-Sandez, O., Garzón-Tiznado, J.A., Mora-Escobedo, R. 2002. Dehulling/softening/extrusion (dse): Technological alternative to improve nutritional quality of chickpea (*Cicer arietinum* L.) Agrociencia 36(2):181-189.

Secchi, M.A., Fernandez, J.A., Stamm, M.J., Durrett, T., Prasad, P.V.V., Messina, C.D., et al. 2023. Effects of heat and drought on canola (*Brassica napus* L.) yield, oil, and protein: A meta-analysis. Field Crops Research 293:108848.

Shrief, S.A., Abd El-Mohsen, A.A. 2014. Effect of different irrigation regimes on grain and protein yields and water use efficiency of barley. Scientia 8(3):140-147.

SIAP. 2024. Anuario estadístico de la producción agrícola. Servicio de Información Agroalimentaria y Pesquera (SIAP), Ciudad de México.

Silva, A. do N., Ramos, M.L.G., Júnior, W.Q.R., de Alencar, E.R., da Silva, P.C., de Lima, C.A., et al. 2020. Water stress alters physical and chemical quality in grains of common bean, triticale and wheat. Agricultural Water Management 231:106023.

Soto-Gómez, D., Pérez-Rodríguez, P. 2022. Sustainable agriculture through perennial grains: Wheat, rice, maize, and other species. A review. Agriculture, Ecosystems & Environment 325:107747.

Stone, P. 2023. The effects of heat stress on cereal yield and quality. p. 243-291. In Crop responses and adaptations to temperature stress. CRC Press, Boca Raton, Florida, USA.

Ullah, A., Zhao, C., Zhang, M., Sun, C., Liu, X., Hu, J., et al. 2023. Nitrogen enhances the effect of pre-drought priming against post-anthesis drought stress by regulating starch and protein formation in wheat. Physiologia Plantarum 175(2):e13907.

Valenzuela-Antelo, J.L., Bénitez-Riquelme, I., Villaseñor-Mir, H.E., Huerta-Espino, J., Lobato-Ortiz, R., Bueno-Aguilar, G., et al. 2018. Comparación del rendimiento de trigos harineros y cristalinos a través de diferentes ambientes de riego. Revista Fitotecnia Mexicana 41(2):159-166.

Vancostenoble, B., Blanchet, N., Langlade, N.B., Bailly, C. 2022. Maternal drought stress induces abiotic stress tolerance to the progeny at the germination stage in sunflower. Environmental and Experimental Botany 201:104939.

Vincke, D., Mercatoris, B., Eylenbosch, D., Baeten, V., Vermeulen, P. 2022. Assessment of kernel presence in winter wheat ears at spikelet scale using near-infrared hyperspectral imaging. Journal of Cereal Science 106:103497.

Yepes, A., Buckeridge, M.S. 2011. Respuestas de las plantas ante los factores ambientales del cambio climático global: Revisión. Colombia Forestal 14(2):213-232.

Zahra, N., Hafeez, M.B., Kausar, A., Al Zeidi, M., Asekova, S., Siddique, K.H.M., et al. 2023. Plant photosynthetic responses under drought stress: Effects and management. Journal of Agronomy and Crop Science 209(5):651-672.

Zandalinas, S.I., Sengupta, S., Fritschi, F.B., Azad, R.K., Nechushtai, R., Mittler, R. 2021. The impact of multifactorial stress combination on plant growth and survival. New Phytologist 230(3):1034-1048.

Zeibig, F., Kilian, B., Frei, M. 2022. The grain quality of wheat wild relatives in the evolutionary context. Theoretical and Applied Genetics 135(11):4029-4048.

Zhao, W., Liu, L., Shen, Q., Yang, J., Han, X., Tian, F., et al., 2020. Effects of water stress on photosynthesis, yield, and water use efficiency in winter wheat. Water 12(8):2127.