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Physiological potential of wheat seeds produced under water restriction in an irrigated area

Brenda Santos Pontes[1], Ricardo Ferreira Domingues[1], Daniel Teixeira Pinheiro[2], Pâmela Gomes Nakada Freitas[3], Ronaldo Cintra Lima[3], Hugo César Rodrigues Moreira Catão[1]*

ABSTRACT: The use of irrigation has led to expansion of the wheat crop in Brazil. Water restriction compromises the production of high-quality wheat seeds. Therefore, rational water use is necessary, as it is an increasingly limited resource. The effect of different water regimes on the development and quality of seeds has not been widely investigated. The objective was to evaluate the physiological potential of wheat seeds produced under water restriction through different irrigation levels – 70% and 100% of evapotranspiration (ETo). The experiment was conducted in the field using a 2 × 4 (irrigation levels × wheat seed lots) factorial arrangement. The evaluations included chlorophyll content, plant height, number of spikes, spike length, and yield. Physiological potential was assessed through the coefficient of variation of germination time, uncertainty of germination, germination synchronization index, germination, seedling length, seedling dry weight, electrical conductivity, seedling emergence, and germination and emergence speed index. The production of wheat seeds was compromised under water restriction, and plants under these conditions (70% ETo) produced seed lots with lower physiological potential compared to plants without water restriction (100% ETo), confirming the importance of adequate water supply.

Index terms: evapotranspiration, irrigation, physiological quality, seed production, *Triticum aestivum* L.

RESUMO: A restrição hídrica compromete a produção de sementes de trigo de alta qualidade, sendo o uso da irrigação responsável pela expansão da cultura no Brasil. O uso racional da água é necessário, por ser um recurso cada vez mais limitante. O efeito de diferentes regimes hídricos no desenvolvimento e qualidade de sementes é uma temática pouco explorada. Objetivou-se avaliar o potencial fisiológico de sementes de trigo produzidas sob restrição hídrica, por meio de diferentes lâminas de irrigação, com 70% e 100% da ETo (evapotranspiração). O experimento foi conduzido em campo em esquema fatorial 2 x 4 (lâminas x lotes de sementes de trigo). Foram avaliados o teor de clorofila, altura de plantas, número de espigas e comprimento de espigas e produtividade. O potencial fisiológico das sementes foi avaliado por meio do coeficiente de variação do tempo de germinação, incerteza da germinação, índice de sincronia da germinação, germinação, comprimento, massa seca de plântulas, condutividade elétrica, emergência de plântulas e índice de velocidade de germinação e emergência. A produção de sementes de trigo ficou comprometida sob restrição hídrica e plantas nessas condições (70% da ETo) produziram lotes de sementes com menor potencial fisiológico quando comparadas às plantas sem restrição hídrica (100% da ETo), reforçando a importância do fornecimento adequado de água.

Termos para indexação: evapotranspiração, irrigação, qualidade fisiológica, produção de sementes, *Triticum aestivum* L.

Corresponding author
hugo.catao@ufu.br

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[1]Instituto de Ciências Agrárias, Universidade Federal de Uberlândia, Uberlândia, MG, Brasil.

[2]Centro Universitário do Triângulo (Unitri), Uberlândia, MG, Brasil.

[3]Universidade Estadual Paulista (Unesp), Dracena, SP, Brasil.

INTRODUCTION

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops in agriculture worldwide, with current production of 10 million tons (CONAB, 2023). To exploit the capacity of this crop and achieve its yield potential, appropriate strategies regarding crop management, choice of growing environments, promising genotypes, and high-quality seeds are essential (Abati et al., 2018; Gama et al., 2021).

Brazil is not yet self-sufficient in wheat production and needs to import wheat from other countries of the Southern Common Market (*Mercado Comum do Sul* - MERCOSUL). Wheat growing was restricted to the South region of Brazil for many years, mainly because of climate conditions, as wheat requires low temperatures (Santos et al., 2012). However, the development of new adapted cultivars, the use of irrigation, and high-quality seeds have resulted in expansion of this cereal crop to other regions, such as the Cerrado (Boschini et al., 2011).

In general, success in establishing new areas for wheat growing depends on satisfactory production of seeds. It is increasingly important to recognize how quality traits respond to management practices, including irrigation, which has a considerable impact (Jornada et al., 2005). Irrigation directly contributes to achieving the yield potential of this crop.

Water is an increasingly limited resource for plant production and, at the same time, indispensable for success in crop fields as it is directly involved in processes such as photosynthesis (Aydi et al., 2023), respiration (Li et al., 2023), nutrient uptake and assimilation (Ali and Akmal, 2022; Cheraghi et al., 2023), pest resistance (Lin et al., 2023), and seed formation (Gooding et al., 2003), among others. In the wheat crop, water restriction mainly compromises the flowering and grain filling stages as they require greater water availability. However, it can also lead to an increase in leaf senescence, reduction in carbon capture and assimilation, and pollen grain sterility; as well as cause oxidative damage and yield reduction (Asada, 2006; Farooq et al., 2009; Farooq et al., 2014; Yang et al., 2016; Gama et al., 2021).

According to Brunetta et al. (2006), wheat requires high rainfall amounts, as well good distribution of the rainfall throughout its cycle, to achieve yields of around 3.5 $t.ha^{-1}$. In this context, the use of irrigation improves water distribution throughout the crop cycle (Silva et al., 2020) and helps increase the yield of the crop fields intended for seed production, especially in cases where soil moisture is a limiting factor, ensuring good vegetative development before flowering (Crusciol et al., 2000; Jornada et al., 2005).

Morsy et al. (2021) evaluated different wheat genotypes under water restriction and found that plants under 50% of the crop evapotranspiration (ETc) had reduced plant development and lower grain yield. Similarly, Rahimi-Moghaddam et al. (2023) estimated significant reductions in wheat grain yield under dry conditions. Gama et al. (2021) evaluated the relationship between water restriction and silicon (Si) supply on the yield and physiological quality of wheat seeds and observed that the lower irrigation levels imposed did not statistically affect seed production, but reduced the weight and vigor of the seeds produced.

Therefore, more information on the effect of different water regimes on the development and physiological potential of wheat seeds is important for increasing crop yield per volume unit of water applied, aiming at conservation of this natural resource. In light of the above, the aim of this study was to evaluate the physiological potential of wheat seeds produced under water restriction.

MATERIAL AND METHODS

Wheat seeds were produced in an irrigated area in the municipality/county of Dracena, SP, Brazil, at an altitude of 373 m and geographic coordinates of 21°27’28.2” S and 51°38’8.1 W”. The climate in the region is Aw according to the Köppen classification, with mean annual temperature of 23 °C, mean relative humidity of 64.23%, and mean annual rainfall of 1,246 mm. The climate conditions during the crop cycle are presented in Figure 1, with data regarding rainfall and variations in air temperature collected from the weather station with a Campbell Scientific Datalogger CR10X, set up at UNESP/FCAT, at approximately 450 m from the experimental area.

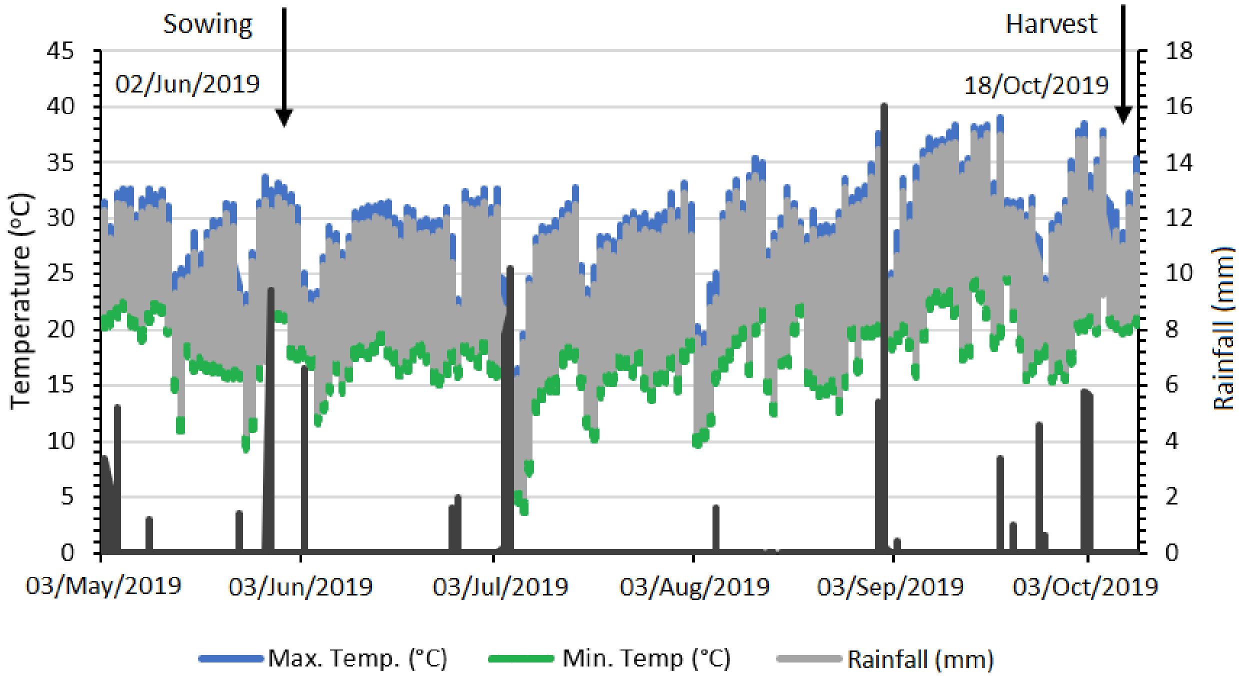

Figure 1. Rainfall (mm) and air temperature (°C) variation in the wheat seed production period.

Table 1. Chemical characterization of the soil in the 0-20 cm layer carried out before establishing the wheat crop.

Depth (cm)	P. resin $mg.dm^{-3}$	O.M. $g.dm^{-3}$	pH ($CaCl_2$)	K	Ca	Mg	H+Al	Al	CEC	V
				$mmolc.dm^{-3}$						(%)
0-20	3	12	4.8	1.6	7	5	20	2	32.1	38

The soil in the study area was classified as an Argissolo Vermelho-Amarelo Distrófico (Santos et al., 2018). Soil samples were collected and chemical analysis was performed (Table 1). Subsequently, 300 $kg.ha^{-1}$ of the NPK 04-30-10 formulation was applied in the sowing furrows. Topdressed fertilizer was applied with N and K at the rates of 48 and 30 $kg.ha^{-1}$, respectively, in the form of urea (CH_4N_2O) and potassium chloride (KCl) at 30 days after tillering. Fertilizers were applied according to the methodology proposed by Camargo et al. (1996).

A randomized block design (RBD) was used in the field in a 4 × 2 factorial arrangement, with four replications. The treatments consisted of four seed lots of the cultivar TBIO Toruk, with water replenished through irrigation levels at 70% and 100% of the evapotranspiration (ETo). Lots 1 and 2 came from seed production fields of Arapoti, PR; while Lots 3 and 4 were produced in Santo Antônio da Platina, PR, in the 2018 crop year. The initial germination of the seed lots were 94%, 86%, 90%, and 96%, respectively.

Irrigation was applied when the cumulative crop evapotranspiration (ETc) reached values near the soil critical available water (SCAW) at the different crop phenological stages, with a four-day irrigation interval. Sowing was performed mechanically, with between-row spacing of 0.22 m and 100 seeds per linear meter. Seeds were treated with the fungicide/insecticide Standak Top® (Fipronil + Pyraclostrobin + Thiophanate methyl at 100 g of the active ingredient / 100 $kg.seeds^{-1}$).

Reference evapotranspiration (ETo) was calculated using the Penman-Monteith method (Allen et al., 1998) and obtained from the daily climate variables of mean air temperature (°C), relative humidity (%), wind speed ($m.s^{-1}$) at 2 m, and total daily net radiation ($MJ.m^{-2}.d^{-1}$), which were collected from the Campbell Scientific Datalogger CR10X

Table 2. Coefficient (K) used to estimate the evapotranspiration of irrigated wheat based on reference evapotranspiration (ETo), considering the crop development stage.

Development stages*	0 – 2	3	4 – 10	10.1 – 10.5.4	11.1	11.12
Crop coefficient (K) **	0.36	0.58	0.84	0.96	0.84	0.62

* Scale from Feeks & Large (Large, 1954); ** K = Kc.

weather station. The ETc was calculated from the ETo × Kc (crop coefficient); and the SCAW was calculated based on the available water capacity (AWC) × p factor, which varies according to the crop group and evapotranspiration. Six crop coefficients K (Kc) were used (distributed across six different growth periods from seedling emergence to harvest) (Table 2). K values were suggested by the Wheat and Triticale Technical Commission – 2015 crop season (Cunha and Caierão, 2014).

When necessary, water was replenished using a sprinkler irrigation system equipped with a NaanDanJain sectorial sprinkler, model 427, with a 2.8 mm nozzle with 80% efficiency. The sprinklers were set up at a spacing of 12 × 12 m between sprinklers and lines, respectively. The operating pressure was 3 bar and the average net application rate was 12.39 $mm.h^{-1}$, as measured in the field, with 88% uniformity of water distribution, evaluated using the Christiansen Uniformity Coefficient - CUC (Christiansen, 1942).

During seed production, the plant chlorophyll content was evaluated at flowering using a digital chlorophyll meter (SPAD 502 PLUS), measuring the middle third of the flag leaf from five plants per plot. Plant height (cm) was measured from the soil surface to the tip of the spikes, excluding the awns. Prior to harvest, the number of spikes/$meter^2$ per plot was determined, and spike length (cm) was checked using a millimeter ruler. After that, the three center rows of each plot were harvested, and the following features were determined: the number of spikelets/spike, weight of seeds/spike (g), and seed yield ($kg.ha^{-1}$), where the moisture content was adjusted to 13% (wet basis).

Subsequently, the seeds were processed and placed in labeled multilayer paper bags. The physiological quality of the seeds was evaluated in the Seed Laboratory (LASEM) of the Universidade Federal de Uberlândia (UFU). The seed moisture content was determined in a drying oven set to a temperature of 105 °C for a period of 24 hours, with results expressed in percentage (Brasil, 2009).

The germination test was conducted with four replications of 50 seeds, sown on germination paper that had been moistened with distilled water in the amount of 2.5 $mL.g^{-1}$ of dry paper. The seeds were placed in a Mangelsdorf-type seed germinator at a constant temperature of 20 °C, under a 12-hour photoperiod (Brasil, 2009).

For germination assessment, normal seedling development was analyzed through daily counts at 12-hour intervals up to stabilization. After that, the initial germination (to), mean germination (MGT), and final germination (tf) times were determined according to the proposal of Labouriau (1983), and the results were expressed in days. The coefficient of variation of germination time (CVt), mean germination rate (MGR), germination uncertainty (I), and the germination synchronization index (Z) were calculated according to the methodology proposed by Ranal and Santana (2006). Final germination (G) was expressed as the percentage of normal seedlings calculated in the test according to Brasil (2009), and the germination speed index (GSI) was calculated according to the formula proposed by Maguire (1962), whose mathematical expression relates the number of germinated seeds to time.

To study the relative frequency of germination (fi), the model proposed by Ranal and Santana (2006) was used, following the study of germination distribution over the time of the experiment. Frequency distribution graphs (%) were constructed for each seed lot per irrigation level.

$$f_i = \frac{n_i}{\sum_{i=1}^{k} n_i}$$

where

fi: relative frequency of germination;

ni: number of seeds germinated on day i.

Normal seedling development was then analyzed. To evaluate shoot length (SL) and primary root length (RL), four replications of twenty seeds were placed to germinate under the same conditions as the germination test. The seeds were arranged in two rows and evenly spaced to allow free development of the seedlings. At four days, the lengths were measured using a ruler, and the values were expressed in centimeters (Gehling, 2014).

Next, the seedlings were separated into shoot and root parts using a scalpel, and their parts were placed in labeled paper bags and dried in a forced-air circulation oven previously set to 65 °C for 96 hours. At the end of drying, the materials were cooled in a desiccator and weighed on an analytical scale with precision of 0.001 g, and seedling dry matter (SDM) was determined (Krzyzanowski et al., 2020).

The electrical conductivity test was carried out with four replications of 50 pure seeds, which were weighed on a precision scale with two decimal places and placed in plastic cups (200 mL) containing 75 mL of deionized water. They were then placed in a germination chamber previously set to 25 °C for 24 hours. After that period, the containers were removed from the chamber, and the solutions containing the seeds were lightly stirred using a glass rod for uniform distribution of the leachates. Immediately afterwards, readings were taken using a conductivity meter (MCA-150), with a cell constant of 1, and readings were made up to 2000 $\mu S.g^{-1}.cm^{-1}$, with a coefficient of variation of 2.02% and standard solution of 1408 $\mu S.g^{-1}.cm^{-1}$ at 25 °C (Vieira and Marcos-Filho, 2020).

To calculate the seedling emergence speed index (ESI), the equation proposed by Maguire (1962) was used. To do so, sowing was carried out with four replications of 50 seeds, distributed on a sand layer placed in polyethylene trays (30 × 20 × 7 cm) with a 3-L capacity. After sowing, the seeds were covered with 3 cm of sand. The trays were kept in a greenhouse and moistened daily to approximately 60% of the water holding capacity. Evaluations were made up to stabilization of emergence.

A completely randomized experimental design was used, and the treatments were in a 4 × 2 factorial arrangement (seed lots × irrigation levels), with four replications. Analysis of variance was conducted on the data using the F-test, and means were compared using Tukey's test at 5% probability. In addition, a multivariate principal component analysis (PCA) was performed on the traits evaluated. The R statistical software was used (R Core Team, 2023) for that purpose.

RESULTS AND DISCUSSION

There was a significant effect of irrigation levels on the wheat seed yield components (Table 3). Wheat seed yield ($kg.ha^{-1}$) was higher for the 100% ETo irrigation level, with a yield increase of more than 899 kg ha^{-1} compared to the 70% ETo irrigation level. This increase in yield may be related to greater plant height (cm), longer spike length (cm), and greater photosynthetic activity, as analyzed by the chlorophyll content (SPAD) (Table 3).

Water restriction is the main limiting factor during the reproduction phase, and it can reduce crop yields by negatively affecting the quantity and quality of seeds produced. Water is therefore an essential input to obtain vigorous and uniform plants (Zhang et al., 2016; Abid et al., 2018; Kirkham, 2023). Thus, proper water distribution throughout

Table 3. Wheat seed yield components as a function of irrigation levels (ET_0).

Irrigation level (ET_0)	Yield ($kg.ha^{-1}$)	No. spikes.m^{2-1}	Plant height (cm)	Spike length (cm)	Chlorophyll (SPAD)
70%	1988 b	446 a	57.81 b	7.23 b	52.56 b
100%	2887 a	504 a	68.11 a	8.04 a	55.38 a
CV (%)	10.65	14.77	3.10	3.31	4.21

* Mean values followed by the same letter in the column do not differ from each other according to Tukey's test at 5% significance.

the plant cycle is necessary to meet the needs of the plant so that it can achieve its full yield potential. In this regard, in general, the 100% ETo irrigation level led to greater increases in the production traits of wheat seeds (Table 3).

Yield, seedling height, and spike length differed in each of the seed lots according to irrigation levels, showing a direct relationship with water availability (Table 4).

Among the limitations that cause yield reduction, water deficit is the main factor that affects final wheat yield (Ali and Akmal, 2022), and this is confirmed upon observing other yield components, such as plant height and spike length (Table 4). For the wheat crop, flowering and seed filling are the phenological phases that most require water, for water shortage can affect yields through pollen grain sterility, inefficiency in the transfer of photoassimilates, and flower abortion (Farooq et al., 2014; Gama et al., 2021).

Rivera-Hernández et al. (2010) reported that the decrease in maize ear length under water deficit may be related to decreased chlorophyll content and plant biomass. Wheat plant chlorophyll declined under the 70% ETo irrigation level, and shorter spike length was also observed (Tables 3 and 4). At the 100% ETo irrigation level, the plants had longer spike length, leading to higher yields.

Silva et al. (2015) state that the chlorophyll content in the leaves increases as irrigation levels increase, and that the content of this pigment declines along with water deficit in wheat plants. In environments with water restriction, plants tend to close their stomata to conserve water, reducing losses through transpiration. This may limit CO2 absorption in leaves for photosynthesis (Flexas et al., 2009; Pinheiro and Chaves, 2011). The lower transpiration rate means less water loss to the atmosphere and conserves water for the plant (Aydi et al., 2023).

There was significant interaction between the seed lots and irrigation levels for the variables of number of spikes and seed weight/spike. Differences were not observed among the seed lots regarding the number of spikelets/plant; however, at the 100% ETo irrigation level, an increase in this variable was found compared to the 70% ETo irrigation level. The seed weight/spike varied depending on the seed lots at the 70% ETo irrigation level, and the highest seed weight was in Lot 3. In the seeds in Lot 4, differences in seed weight were observed between the irrigation levels (Table 5). The main reasons for reduction in seed weight under water stress are the decrease in net photosynthesis due to metabolic interruptions, oxidative damage to chloroplasts, and closing of stomata (Farooq et al. 2014; Jaberledar et al., 2017).

It should be emphasized that water deficit during seed maturation can compromise deposition in seed reserves, particularly starch, thus reducing seed weight and significantly affecting seed performance (Peres et al., 2018; Aumonde et al., 2019). However, under water deficit, plants may also produce fewer seeds, with greater individual dry weight (Pushpavalli et al., 2015; Moura et al., 2023), and this may have occurred with the seeds from Lot 3.

Table 4. Yield, plant height, and spike length in each wheat seed lot as a function of irrigation levels (ET_0).

Lot	Irrigation level (ET_0)	Yield ($kg.ha^{-1}$)	Plant height (cm)	Spike length (cm)
1	70%	1928 b	56.95 b	7.16 b
	100%	2925 a	67.83 a	7.66 a
2	70%	1900 b	57.71 b	7.33 b
	100%	3180 a	66.10 a	8.08 a
3	70%	2081 b	58.03 b	7.19 b
	100%	2838 a	68.97 a	8.30 a
4	70%	2042 b	58.55 b	7.24 b
	100%	2603 a	69.55 a	8.11 a
CV (%)	-	10.65	3.10	3.31

*Mean values followed by the same letter in the column do not differ from each other according to Tukey's test at 5% probability.

Table 5. Number of spikelets per spike and seed weight per spike of wheat as a function of seed lots and irrigation levels (ET_0).

Lot	Number of spikelets / spike		Seed weight / spike (g)	
	70% level	100% level	70% level	100% level
1	26.21 aB	31.35 aA	0.720 abA	0.700 aA
2	30.24 aB	35.25 aA	0.793 abA	0.803 aA
3	25.97 aB	33.25 aA	0.867 aA	0.883 aA
4	19.40 aB	33.10 aA	0.497 bB	0.867 aA
CV (%)	9.43		17.63	

* Mean values followed by the same lowercase letter in the column, comparing the lots, and uppercase letter in the row, comparing the irrigation levels, do not differ from each other according to Tukey's test at 5% probability.

Table 6. Mean values of moisture content (MC), beginning time (t_0) and final time (t_f) of germination, coefficient of variation of germination time (C*Vt*) and germination rate (G) of wheat seed lots.

Lot	MC	t_0	t_f	C*Vt*	G
	%	(days)	(days)	(%)	(%)
1	11.2	2.5	3.68 a	17.21 b	97 a
2	11.2	2.5	3.81 b	16.56 ab	98 a
3	11.1	2.5	3.83 b	16.55 ab	99 a
4	10.9	2.5	3.83 b	15.78 a	99 a
CV (%)	-	0.00	2.59	5.00	1.08

* Mean values followed by the same letter in the column do not differ from each other according to Tukey's test at 5% probability.

The moisture content of the wheat seeds ranged from 10.9% to 11.2% (Table 6). This is an important point, since uniformity of moisture content is essential for obtaining consistent results in quality tests; differences in moisture levels should not exceed 2% (Marcos-Filho, 2015).

The seed lots showed significant effects on the germination parameters analyzed in Table 6. The initial germination time (t_0) of the seeds occurred at 2.5 days, and this was not statistically different among the seed lots evaluated. The seeds from Lot 1 completed the germination process earlier than the other lots, and thus required less time to reach the final germination time (t_f). Faster germination is advantageous under field conditions, in which seeds are subjected to adverse conditions. Evaluation of the coefficient of variation of germination time (CVt) shows that Lot 4 had less variation of germination compared to Lot 1. The coefficient of variation of germination time reflects the spread of the germination process around the mean time (Ranal and Santana, 2006). Thus, the seeds from Lot 4 had greater germination synchronization, while the seeds from Lot 1 had germination over a longer time period. Seeds are subject to diverse conditions that affect their quality, and especially vigor, during the field production phase; soil properties, the occurrence of pests and diseases, and water availability have the greatest effect (Corrêa et al., 2022).

Though the CVt is different among the seed lots, it can be observed that the four lots had germination rates greater than or equal to 97% and did not differ from each other. The wheat seeds evaluated met the minimum standard for germination (80%) established by legislation for seed commercialization (Brasil, 2013). The germination test is the official method for determining the physiological quality of seed lots, and it is conducted under optimal conditions of water availability, aeration, and temperature (Brasil, 2009). For that reason, other tests are necessary, such as vigor tests, as they evaluate characteristics that the germination test often does not detect since it is performed under optimal testing conditions (Catão et al., 2019).

There was a significant effect for irrigation levels on the variables analyzed in Tables 7 and 8. The seeds that were produced under the 100% ETo irrigation level proved to have greater vigor than those that were produced under the 70% ETo irrigation level (Tables 7 and 8). The seeds produced under the 100% ETo irrigation level had a better distribution of the coefficient of variation of germination time (CVt). However, there was no statistical difference in germination synchronization (Z) between the seeds produced under the 70% and 100% ETo irrigation levels (Table 7).

The mean germination time (MGT) was higher under the 100% ETo irrigation level, both for the irrigation level factor and for the seed lots (Tables 7 and 8). That may have occurred because these seeds had a larger amount of reserves, which increases the time for digestion, mobilization, and transport to the embryo (Marcos-Filho, 2015). Tables 7 and 8 also show that the seeds produced under the 100% ETo irrigation level had high vigor (GSI, EC, RL, SDM), both in comparison between irrigation levels and among seed lots. Pereira et al. (2015) and Catão et al. (2024) reported that dry weight is directly related to the availability of reserves. Therefore, seeds of larger size and initial weight may

Table 7. Mean values of the data for mean germination time (MGT), coefficient of variation of germination time (C*Vt*), synchronization index (Z), germination speed index (GSI), electrical conductivity (EC) of seeds, and root length (RL) and seedling dry matter (SDM) of wheat seedlings as a function of irrigation levels (ETo).

Irrigation level (ETo)	MGT (days)	C*Vt* (%)	*Z*	GSI	EC (μS.cm^{-1}.g^{-1})	RL (cm)	SDM (mg.seedling^{-1})
70%	2.72 b	17.03 a	0.32 a	17.80 b	13.68 a	4.33 b	0.0321 b
100%	2.83 a	16.02 b	0.35 a	18.58 a	11.82 b	4.58 a	0.0371 a
CV (%)	1.80	5.00	11.03	2.44	4.65	11.95	12.41

* Mean values followed by the same letter in the column do not differ from each other according to Tukey's test at 5% probability.

Table 8. Mean values of the data for mean germination time (MGT), germination speed index (GSI), and electrical conductivity (EC) of seed lots, and root length (RL) of wheat seeds for each irrigation level (ETo).

Lot	Irrigation level (ETo)	MGT (days)	GSI	EC (μS.cm^{-1}.g^{-1})	RL (cm)
1	70%	2.69 b	17.81 b	13.80 a	4.38 a
	100%	2.83 a	18.68 a	11.50 b	4.41 a
	Mean	2.76	18.24	12.65	4.39
2	70%	2.76 b	17.51 b	13.52 a	4.17 b
	100%	2.85 a	18.37 a	11.72 b	4.54 a
	Mean	2.80	17.94	12.62	4.35
3	70%	2.72 b	18.08 a	13.66 a	4.31 b
	100%	2.80 a	18.68 a	12.41 b	4.80 a
	Mean	2.76	18.38	13.03	4.55
4	70%	2.74 b	17.80 b	13.74 a	4.46 a
	100%	2.85 a	18.61 a	11.65 b	4.57 a
	Mean	2.79	18.20	12.69	4.51
CV (%)	-	1.80	2.44	4.65	11.95

* Mean values followed by the same letter in the column do not differ from each other according to Tukey's test at 5% probability.

contain a larger amount of reserves for seedling development (Pádua et al., 2010; Pereira et al., 2013). Gama et al. (2021) observed that water restriction through irrigation levels did not directly affect yield statistically, but it reduced the weight and the vigor of the wheat seeds produced.

Regarding the effect of water availability on seed formation, Silva et al. (2014) found that lower water availability reduced the yield and the quality of rice seeds. Furthermore, Carvalho and Nakagawa (2012) state that water availability is of utmost importance for seed quality during and even before seed formation, since damage to plant development and flowering can impact seed vigor and viability.

The synchronization index (Z) has low values, near 0 ($0.32 < Z < 0.35$), and these values do not differ statistically between the irrigation levels (Table 7). This suggests a lack of overlap in seed germination over time, as reported by Ranal and Santana (2006). The coefficient of variation of germination time (CVt) has a lower percentage for the 100% ETo irrigation level. The synchronization index showed uniformity, indicating that germination was not spread out over time (Alves et al., 2012).

The seeds produced under the 70% ETo irrigation level show higher results in the electrical conductivity test. This test is based on the principle that the higher the conductivity of the solution, the lower the reorganization capacity of the membranes and the greater their permeability, which therefore indicates lower vigor. In light of that, it should be emphasized that physiological quality is impacted by the environmental conditions to which seeds are exposed, and this can affect wheat fields in various production regions, leading to changes in the wheat seed (Pellizzaro et al., 2016).

Table 9 shows significant interaction between seed lots and irrigation levels. The seedlings from Lot 1 originating from seeds produced under the 70% ETo irrigation level had shorter shoot length compared to the seedlings originating from seeds from Lot 4. Environmental conditions strongly impact physiological quality, particularly vigor (Corrêa et al., 2022).

However, no significant differences were observed in the shoot length of wheat seedlings coming from the four seed lots produced under the 100% ETo irrigation level. Comparison of the 70% and 100% ETo irrigation levels shows greater development of the shoots of seedlings coming from the seeds of Lot 1 under the higher water regime (Table 9). The greater accumulation of reserves in the seed during maturation when the environmental conditions are adequate leads to better performance because these reserves are redirected to initial growth of the seedling, supplying the embryo energy demands (Ferreira and Borghetti, 2004; Kaur et al., 2021). No statistical difference was found in the ESI of seedlings coming from the four lots of wheat seeds produced under the 70% ETo irrigation level (Table 9). The seeds from Lot 2 had greater vigor when produced under the 100% ETo irrigation level, while the seeds coming from Lot 4 had lower vigor as estimated by the ESI.

Comparison of the two irrigation levels shows that Lots 1 and 2 have a lower ESI under the 70% ETo irrigation level. However, the seeds from Lot 4 have lower vigor in the 100% ETo irrigation level than the seeds produced under the 70% ETo irrigation level.

Table 9. Mean values of shoot length of seedlings (SL) and emergence speed index (ESI) of wheat seeds as a function of seed lots and irrigation levels (ETo).

Lot	SL (cm)		ESI	
	70% level	100% level	70% level	100% level
1	1.21 bB	1.44 aA	9.95 aB	11.06 abA
2	1.25 abA	1.24 aA	10.76 aB	12.22 aA
3	1.25 abA	1.33 aA	10.51 aA	11.10 abA
4	1.31 aA	1.30 aA	11.09 aA	9.94 bB
CV (%)	10.38		5.72	

* Mean values followed by the same lowercase letter in the column and uppercase letter in the row do not differ from each other according to Tukey's test at 5% probability.

Figure 2 shows the frequency distribution of the germination percentage of wheat seed lots produced under the 70% and 100% ETo irrigation levels.

The wheat seeds began the germination process 24 hours after imbibition (Figure 2), with the highest percentage of germinated seeds occurring at 60 hours, on both irrigation levels. In the seeds coming from Lots 1 and 2, the germination response was similar under the two irrigation levels; however, germination was moderate for the 70% ETo irrigation level. Seeds coming from Lot 3 had approximately 41% germination for the 70% ETo irrigation level after 60 hours. For the 100% ETo irrigation level, germination was linear, beginning at 12 hours and reaching the highest percentage (25%) after 84 hours. Seeds coming from Lot 4 reached approximately 45% and 54% germination at 60 hours for the 70% and 100% ETo irrigation levels, respectively. In general, a tendency of more uniform and quicker germination is observed as a result of the 100% ETo irrigation level, except for the seeds coming from Lot 3. No displacement from the polygon line of germination time was found. According to Alves et al. (2011) and Padilha et al. (2018), displacement of the polygon line to the right or to the left of the germination time means delay in the germination process or reduction in seed vigor, and it negatively affects the plant development stages (Piña-Rodrigues et al., 2015)

Principal component analysis (PCA) helped summarize the data, since principal component 1 (PC1) and 2 (PC2) accounted for 64.7% and 13.9%, respectively, of the total data variability, for a total of 78.6% (Figure 3).

In general, the treatments without water restriction (L1-100, L2-100, L3-100, and L4-100) were concentrated in the positive scores of PC1, near variables related to production – such as yield (YLD), plant height (PH), spike length (SPL), number of spikelets/spike (NSS), and seed weight/spike (SWS) – and to physiological quality – such as mean germination time (MGT), germination speed index (GSI), root length (RL), shoot length (SL), and emergence speed index (ESI). In contrast, the lots produced under water restriction (L1-70, L2-70, L3-70, and L4-70) were concentrated in the negative scores of PC1, near the electrical conductivity (EC) variable, showing the lower yield and physiological quality of these lots.

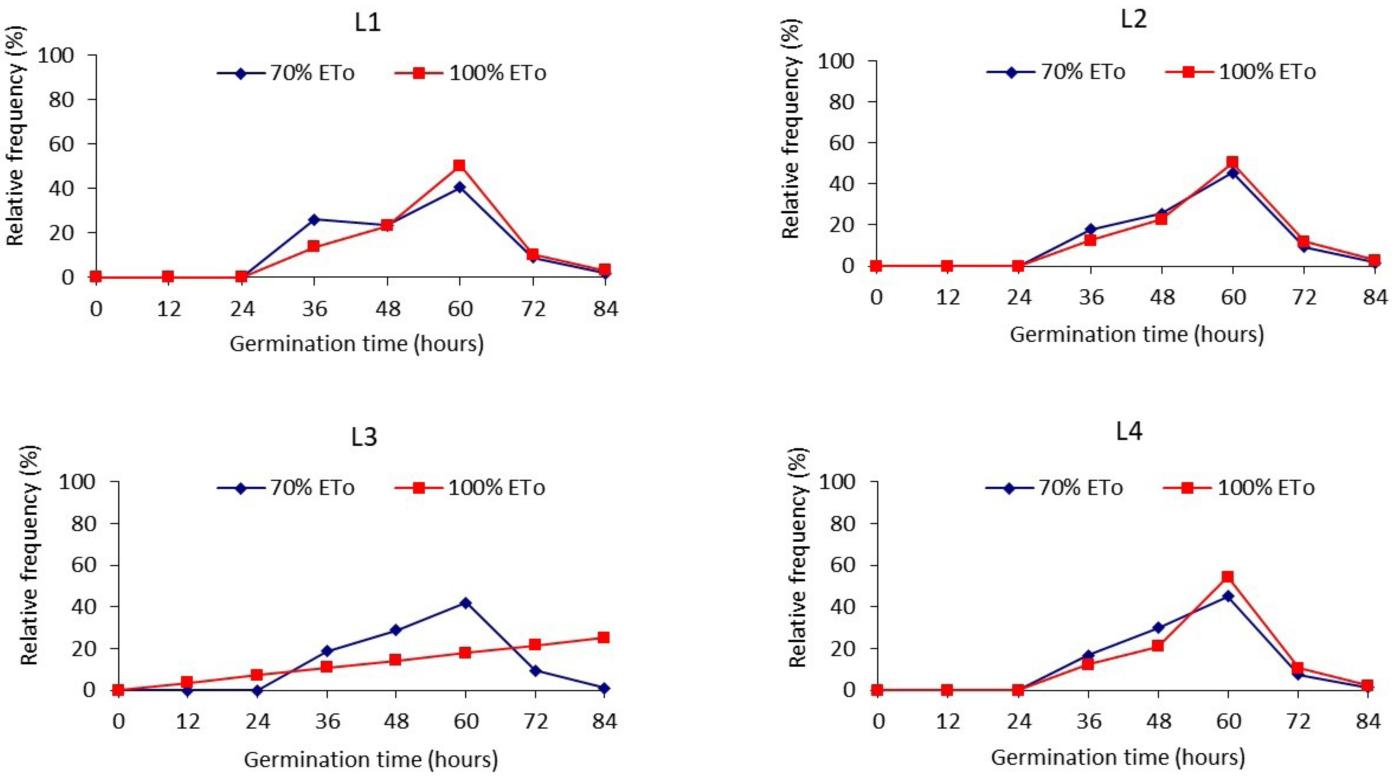

Figure 2. Frequency distribution of the germination percentage of the wheat seed lots (L1, L2, L3, and L4) produced under irrigation levels of 70% and 100% ETo.

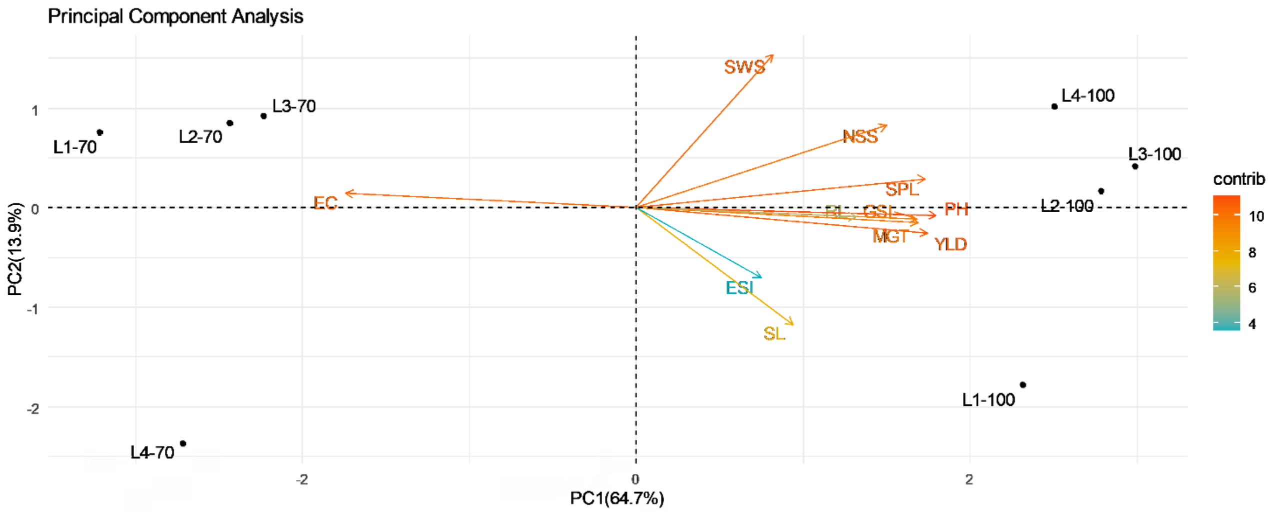

Figure 3. Principal component analysis (PCA) obtained from the linear combination of the variables analyzed in wheat seeds under the different irrigation levels in the field. Principal Component 1 (PC1), Principal Component 2 (PC2), yield (YLD), plant height (PH), spike length (SPL), number of spikelets / spike (NSS), seed weight / spike (SWS), mean germination time (MGT), germination speed index (GSI), emergence speed index (ESI), shoot length (SL), root length (RL), electrical conductivity (EC).

Therefore, as previously discussed, these results indicate that water restriction led to direct adverse effects on wheat seed yield and quality.

CONCLUSIONS

The production of wheat seeds was compromised under water restriction, and plants under these conditions (70% ETo) produced seed lots with lower physiological potential compared to plants without water restriction (100% ETo), highlighting the importance of adequate water supply.

AUTHORS' CONTRIBUTION

Hugo César Rodrigues Moreira Catão contributed with: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Visualization, Writing - original draft; Brenda Santos Pontes and Ricardo Ferreira Domingues contributed with: Formal analysis, Data curation, Visualization, Writing—review & editing; Daniel Teixeira Pinheiro, Pâmela Gomes Nakada Freitas and Ronaldo Cintra Lima contributed with: Conceptualization, Methodology, Formal analysis, Data curation, Visualization, Writing—review & editing.

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