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Yield and physiological quality of wheat seeds produced under different irrigation depths and leaf Silicon

Produtividade e qualidade fisiológica de sementes de trigo produzidas sob diferentes lâminas de irrigação e Silício foliar

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Highlights

There was no effect of water irrigation levels and Si application on wheat yield.
There was no effect of Si on the germination of wheat seeds.
Wheat seeds of Si-fertilized plants produce more vigorous seedlings.

Abstract

Water availability is one of the main factors responsible for wheat productivity, as well as the quality of the produced seeds. Silicon (Si) has an important role in mitigating the effects of various biotic and abiotic stresses. Thus, Si application can be used to mitigate the effects of different irrigation depths on the production and quality of wheat seeds. The work aimed to evaluate the yield and physiological quality of wheat seeds produced from plants fertilized with leaf Si and grown under different irrigation depths. The experiment was laid out in a split-plot randomized block design, with four replications. The plots consisted of three irrigation depths (0, 50, and 100% of the total irrigation requirement [TIR]). Si treatments were allocated (without application [0 mM] and 5 mM SiO_2, applied at the tillering stage) in the subplots. The following parameters were evaluated: water balance of the system; soil moisture; yield; thousand seed weight; germination; electrical conductivity; accelerated aging; seedling length and emergence. The water balance of the system was negative for the 0% TIN irrigation depth after anthesis and there was less soil moisture in this irrigation depth. There was no effect of irrigation depths and Si application on plant yield. The smaller irrigation depths imposed reduced the thousand seed weight and increased the electrical conductivity of the seeds produced. Plants fertilized with Si did not differ in germination, but they produced

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more vigorous seedlings with greater growth and uniformity.
Key words: Abiotic stress. Physiological potential. Foliar fertilizers. *Triticum aestivum* L. Seed vigor.

Resumo

A disponibilidade de água é um dos principais fatores responsáveis pela produtividade do trigo, bem como da qualidade das sementes produzidas. O silício (Si) possui importante papel na atenuação dos efeitos de diversos estresses bióticos e abióticos. Desta forma, a aplicação de Si pode ser uma ferramenta para mitigar os efeitos de diferentes lâminas de irrigação na produção e qualidade de sementes de trigo. O objetivo do trabalho foi avaliar a produtividade e a qualidade fisiológica de sementes de trigo produzidas a partir de plantas fertilizadas com Si foliar e cultivadas sob diferentes lâminas de irrigação. O delineamento experimental foi blocos casualizados, em esquema de parcelas subdivididas, com quatro repetições. As parcelas foram constituídas por três lâminas de irrigação (0, 50 e 100% da irrigação total necessária [ITN]). Nas subparcelas foram alocados os tratamentos de silício (sem aplicação [0 mM] e 5 mM de SiO_2, aplicado na fase de perfilhamento). Foram avaliados: balanço hídrico do sistema; umidade do solo; produtividade; massa de mil sementes; germinação; condutividade elétrica; envelhecimento acelerado; comprimento e emergência de plântulas. O balanço hídrico do sistema foi negativo para a lâmina de 0% da ITN após a antese e houve menor umidade do solo nesta lâmina. Não houve efeito das lâminas de irrigação e da aplicação de Si na produtividade das plantas. As menores lâminas de irrigação impostas reduziram a massa de mil sementes e aumentaram a condutividade elétrica das sementes produzidas. Sementes produzidas em plantas fertilizadas com Si não diferiram quanto a germinação, porém originam plântulas mais vigorosas com maior crescimento e uniformidade.
Palavras-chave: Estresse abiótico. Potencial fisiológico. Fertilizante foliar. *Triticum aestivum* L. Vigor de sementes.

Introduction

Wheat (*Triticum aestivum* L.) belongs to the Poaceae family and is one of the most important grain cultures in the world. Wheat crops are cultivated in the most diverse environments and geographic regions, which extend from temperate to tropical climate zones. Due to the amount and quality of proteins contained in wheat, this cereal plays a strong role as a staple food for about one-third of the world population (Mori, 2015; Arif et al., 2021). Global wheat production is over 700 million tons (United States Department of Agriculture [USDA], 2020). Currently, 21.4 million hectares are cultivated with wheat in the world, the European Union being the biggest world producer, accounting for 154 million tons (USDA, 2020).

This and other crops are continuously exposed to climate changes related to factors such as CO_2 concentration, temperature, and water resources, which directly affect the production of cereal plants globally (Hatfield & Prueger, 2015; Van der Sleen et al., 2015; Y. Yang et al., 2016; Zhao et al., 2019). Among others, water is considered the main environmental factor, being responsible for several metabolic processes related to plant growth and development, such as transpiration, photosynthesis, assimilation of carbonated compounds, and others (Jia et al., 2015; Perdomo, Capó-Bauçà, Carmo-Silva, & Galmés, 2017).

For wheat, flowering and seed filling are considered the most water-demanding stages, because water shortage may affect yields (Farooq, Hussain, & Siddique, 2014), cause oxidative damages (Farooq, Wahid, Kobayashi, Fujita, & Basra, 2009), increase foliar senescence (Yang, Zhang, Wang, Zhu, & Liu, 2003), reduce carbon fixation and assimilation (Asada, 2006), cause pollen sterility (Cattivelli et al., 2008), among other harmful effects. Thus, lack of water during the reproduction stage can diminish crop yields, the quantity, and quality of seeds produced, and is therefore considered an essential input for the achievement of vigorous and uniform plants (Crusciol, Arf, Zucareli, Sá, & Nakagawa, 2001; Farooq, Irfan, Aziz, Ahmad, & Cheema, 2013; Finch-Savage & Bassel, 2016; Zhang et al., 2016; Abid et al., 2018).

Another key factor related to the quality of seeds produced is adequate plant nutrition, responsible for good embryo formation and reserve accumulation (Sá, 1994; Toledo et al., 2012). In this context, silicon (Si) is considered a beneficial micronutrient, with a major role against biotic and abiotic stresses.

In wheat, Si is accumulated at rates higher than 4% (Hodson, White, Mead, & Broadley, 2005) It acts mainly due to its physical-mechanical role, and is deposited in the form of silicon dioxide (SiO_2) mainly on the leaf cell walls, inhibiting excessive water loss by transpiration (Meena et al., 2014; Luyckx, Hausman, Lutts, & Guerriero, 2017). Si also promotes beneficial metabolic alterations under water stress conditions. Kim, Khan, Waqas and Lee (2017) cite that Si has the potential of inhibiting the formation of oxygen reactive species, which are formed on a larger scale in stress conditions, and can potentialize the action of enzymes of the antioxidant system. Applications of Si on wheat leaves are effective in alleviating the negative effects of water shortage, stimulating the plant growth and photosynthetic attributes, water relations, transpiration rate, and chlorophyll contents (Sattar et al., 2019).

The beneficial effect of Si on physiological seed quality has already been described for wheat cultures. Toledo et al. (2012) report that leaf application of Si increased the wheat seed mass without affecting germination and vigor. However, information on the effect of Si on the quality of seeds produced as well as its interaction with different water irrigation depths during the crop cycle (especially at the reproduction stage) is scarce and could bring about important responses about wheat plant tolerance to water restriction. Furthermore, Si application can be used as a strategy to mitigate the harmful effects caused by drought on the physiological quality of the seeds and, therefore, is an important tool to be used in plant breeding programs and seed production.

In this context, this study aimed to assess the yield and physiological quality of wheat seeds produced by plants fertilized with foliar application of Si and cultivated with different irrigation depths.

Material and Methods

The experiment was carried out in the Department of Agronomy of the Federal University of Viçosa, in Viçosa - MG (20° 45'S, 42° 15'W, at 650 m of altitude) from April to August 2017. The soil at the crop site is classified as dystrophic Red-Yellow Argisol (Santos et al., 2013), with a clay-loam texture, Cwa subtropical climate, and annual average precipitation of 1200 mm.

Wheat seeds of cultivar BRS 264 were used, which were supplied by the company Lagoa Bonita Sementes, produced in the municipality of Itaberá - SP. This is an early-cycle cultivar, with good seed yields, classified as bread wheat, and an average hectoliter weight of 80 kg hl^{-1} (Albrecht et al., 2006). The field experiment was installed by mechanical sowing on April 19, 2017, with an initial stand adjusted for 89 plants per meter. Management practices followed usual recommendations for wheat cultivation (Borém & Scheeren, 2015).

The soil in the experiment area was analyzed chemically and physically (Tables 1 and 2) and conventionally tilled. Acidity regulation and fertilization were performed based on the soil analysis, and the amount of acidity regulator and fertilizer as recommended by Ribeiro (1999).

Table 1
Chemical analysis of the soil in the wheat crop area. Viçosa – MG, 2017

pH	P	K	Ca^{2+}	Mg^{2+}	Al^{3+}	Si
H_2O	mg/dm^3			$cmol/dm^3$		mg/kg
6.3	54.5	210	2.7	1.0	0	9.27
H + AL	SB	CEC (t)	CEC (T)	V	M	
		$cmol/dm^3$			%	
3.0	4.2	4.2	7.2	59	0	

pH in water, KCl and CaCl – 1:2.5 ratio. P - K - Mehlich 1 Extractant. Ca - Mg - Al - Extraction: KCl - 1 mol/L. Si – Extraction: 0.01mol/L. H + Al – 0.5 mol/L calcium acetate extractant - pH 7.0; SB = Sum of Exchangeable Bases. CEC (t) – Effective Cation Exchange Capacity; CEC (T) – Cation Exchange Capacity at pH 7.0. V = Base saturation index. m = Aluminum saturation index.

The experimental design consisted of a split-plot randomized block design with four replications. The plots consisted of five rows of plants, spaced 0.20, ten meters in length. The subplots were assigned to the plots, which were divided in half. The net area considered for application of the treatments comprised the total area occupied by plants in the three central lines minus 0.20 m at the ends. The plots consisted of three irrigation depths, and the subplots two treatments with Si application.

Table 2
Granulometry and texture classification of the soil in the wheat crop area. Viçosa – MG, 2017

Clay (%)	Silt (%)	Sand (%)	Texture classification	Soil type
34	21	45	Clay-loam	Average texture

The drip irrigation system was used to deliver water at a flow rate previously measured at each irrigation time by using the average water volume collected from the number of drippers during one minute. With this input data, the irrigation intensity in mm $hour^{-1}$ was calculated. The irrigation method was based on the FAO-56 Penman-Monteith standard method (Allen, Pereira, Raes, & Smith, 1998), by estimating the reference evapotranspiration (ET_0). To calculate the ET_0, we used the data recorded by the automatic meteorological station installed at the campus of the University of Viçosa. Real irrigation demand (RID) was calculated by the Water Balance of the system (Figure 1A), which was determined by subtracting the inputs (irrigation + effective rainfall) from the water outputs (evapotranspiration of the crop - ETc). To calculate the ETc, the equation proposed by Allen et al. (1998) was used:

$$ETc=ET_0*Kc$$

Where: ETc – evapotranspiration of the crop, in mm day^{-1};

ET_0 – reference evapotranspiration, in mm day^{-1};

Kc - coefficient of the crop, dimensionless.

To calculate the irrigation depth to be applied, the total irrigation requirement (TIR) was quantified for the crop, which is based on the ratio between the RID and the efficiency of application of the irrigation system used, which in the present study was 93.7%.

During the entire period of the experiment, the plants were irrigated in four-day shifts. Until anthesis (51 days after sowing [DAS]), when 50% of the plants exhibited anthers releasing pollen, all plants were irrigated with 100% of TIR. From anthesis, the plants were subjected to the following irrigation treatments: 100% of TIR (control), 50% of TIR, and 0% of TIR. The Kc values, as obtained by Libardi & Costa (1997), used for each plant stage were: germination/seedling: 0.29; tillering: 0.36; booting: 0.79; flowering: 1.11; seed filling: 1.16; and ripening/maturation: 0.45. In addition to the water balance (Figure 1A), after anthesis, data of temperature (maximum, medium, and minimum) and precipitation were also collected (Figure 1B).

The Si treatments consisted of one application with 5 mM of Si and control treatment, without application of the element. The foliar application with Si was performed in half of the plants of each plot (subplots), when the plants were at the tillering stage, which was identified according to the Feekes growth stages 4 and 5 (Large, 1954). The commercial product Supa Sílica® (potassium silicate - K_2SiO_2) was used as a source of Si, with 25.7% SiO_2 and 12.23% K_2O.

The plots were separated by an acrylic protective divider placed between the subplots to avoid spray drift during the Si application. At the time of applications, the environmental conditions such as wind speed and air humidity were monitored to avoid any influence at this stage. The product was sprayed on the leaves using a system consisting of a CO_2 pressurized cylinder and a boom with two TT 11002 nozzles, providing constant pressure of 3 bar and a spray rate of 260 L ha^{-1}.

During the period of application of the different irrigation levels (from anthesis to maturity), the soil moisture was monitored in samples collected from the plots moistened with different water volumes (Figure 2A). The soil moisture content was determined using the standard gravimetric method, in an oven at 105-110 ºC, for 24 hours, through the water mass/dry soil mass ratio (Klein, 2008).

Seeds were harvested manually, at the point identified by the yellow color of the spikes, leaves, and stem of the plants, typical of the senescence stage (110 days after sowing [DAS]). At this point, the seed moisture ranged from 14 to 16%. The spikes were threshed using experimental combined equipment (harvesting + threshing operations). The seeds were dried naturally under room condition up to 12% of moisture, and then the following parameters were determined:

Yield: determined by weighing the seeds harvested from the three central lines of each experimental unit, in kg ha^{-1}.

Thousand seed weight: for this purpose, eight subsamples of 100 seeds were weighed on a 0.001 g precision scale. The calculations were made according to the methodology described by the Rules for Seed Testing (Ministério da Agricultura, Pecuária e Desenvolvimento [MAPA], 2009). The results were expressed in milligrams.

Germination: Four replications were carried out with 50 seeds, which were uniformly distributed on two sheets of paper towel and covered by an additional one. The paper sheets were moistened at the rate of 2.5 times the weight of dry paper. They were kept in paper rolls in a "Mangelsdorf" germinator at 20 ºC. Evaluations consisted of counting the number of normal seedlings at the 4th (first count) and 8th day (final count) after the test was set up (MAPA, 2009). The results were expressed in percentage of normal seedlings. The first germination count consisted of the percentage of normal seedlings on the fourth day after the beginning of the test (MAPA, 2009).

Electrical conductivity: it was carried out with four replications of 50 seeds previously weighed and placed in plastic cups containing 75 mL of distilled water, and kept in a germinator at 25 °C for eight hours. During this period, no root protrusion in the imbibed seeds was observed, a fact that was observed in a preliminary test. After this period, the electrical conductivity (EC) of the solution was measured by a Digimed DM32 conductivity meter. The results were expressed in µS cm^{-1} g^{-1} of seed (Vieira & Marcos, 2020).

Accelerated aging: the accelerated aging test was carried out with four replications of 50 seeds placed on a metal sheet inserted in a plastic container containing 40 ml of distilled water. The containers were placed in a Biological Organism Development (BOD) chamber, at 43 ºC, for 48 hours (Fanan, Medina, Lima, & Marcos, 2006). Then, seed germination was assessed, according to the methodology described above, and the count of normal seedlings occurred at the 4th day after the test was set up (MAPA, 2009).

Shoot length and root length of the seedling: it was determined through four replications with ten seeds each, which were put to germinate according to the methodology described for the germination test. On the 8th day after the beginning of the test, the shoot and root lengths of the seedlings were measured, using a graduated ruler. The results were expressed in cm $seedling^{-1}$ (Krzyzanowski, França-Neto, Gomes & Nakagawa, 2020). Using the length data obtained, the statistical software program SeedCalc (Silva, Medeiros, & Oliveira., 2019) was used to determine the following: total length (TL) of the seedlings;

root-to-shoot ratio (RSR) (Benincasa, 2003); growth index (GI) (Sako, McDonald Fujimura, Evans, & Bennett, 2001); vigor index (VI) (Sako et al., 2001); corrected vigor index (CVI) (Medeiros & Pereira, 2018).

Dry matter of shoots and roots: The shoots and roots of the seedlings were separated and placed in an oven at 65 °C, where they remained for 72 hours. Afterward, the material was weighed in an analytical balance, with a precision of 0.001g, and the dry matter was determined and expressed in mg seedling^{-1} (Krzyzanowski et al., 2020).

Seedling emergence: four replications with 50 seeds were conducted, which were distributed at a depth of 1 cm in Styrofoam trays (35 x 25 x 5 cm) containing moistened sand and soil (70% of water holding capacity) (Krzyzanowski et al., 2020). Daily counts of the number of emerged seedlings (higher than 5 mm) were performed until stabilization and determination of the percentage of emergence.

The data were subjected to analysis of variance, and afterward, the normality of errors and homogeneity of variances were verified using the Shapiro-Wilk and Bartlett tests, respectively. The mean values of each irrigation depth were compared by the Tukey's test ($P < 0.05$), and the means obtained for the Si treatments were compared by the F test ($P < 0.05$). Data were also subjected to principal components analysis (PCA) for all evaluations performed. A "n x p" matrix was obtained, where "n" corresponds to the number of treatments (n = 6) and "p" the number of variables analyzed (p = 15). The eigenvalues and eigenvectors were calculated based on the covariance matrices and plotted on two-dimensional graphs (category ordering diagram and correlation circle), generated by the Factoextra package (Kassambara & Mundt, 2017). Data were analyzed using the R statistical software (R Core Team [R], 2019).

Results and Discussion

The water balance of the system during the period of application of different irrigation depths was negative for the 0% of TIR treatment, or absence of irrigation after anthesis. Otherwise, irrigation depths of 100 and 50% of TIR provided a positive water balance during this period. The positive water balance indicates that water inflows in the irrigation system and rainfall were higher than the outflows (evapotranspiration and draining), which configures a higher water supply applied in the 100 and 50% TIR treatments. Higher precipitation occurred at the beginning of the treatment application period, which raised the 0% depth of TIR and generated a positive water balance, comparable to the other treatments. The influence of these rains occurred up to approximately seven days after anthesis (DAA), and, afterward, the water balance for this treatment (0% of TIR) remained negative. Thus, we can see that the plants remained under water restriction until being harvested (Figure 1A and 1B).

The soil moisture decreased slowly until 54 DAA, and harvesting occurred at 60 DAA. Similar soil moisture values were found for the three treatments with irrigation depths up to 25 DAA, which were 20.9, 20.7, and 19.8% for the 100, 50, and 0% of TIR treatments, respectively (Figure 2). The similar values observed for the treatments are probably due to the higher precipitation that occurred at the beginning of the period of the water restriction treatments (4 and 6 DAA). The physical properties of the soil in the crop area, classified as of medium texture (34% of clay), probably accounted for the high water-holding rate, which, added to the initial rainfall occurred (Figure 1B), can explain the values obtained for soil moisture by 25 DAA in the treatments. On the other hand, concerning the water balance (Figure 1A), it was found a difference in soil moisture for all treatments during the rest of the days of the water restriction period. At 54 DAA, the soil moisture values were 21.1, 19.8, and 17.4%, for 100, 50, and 0% of TIR, respectively (Figure 2).

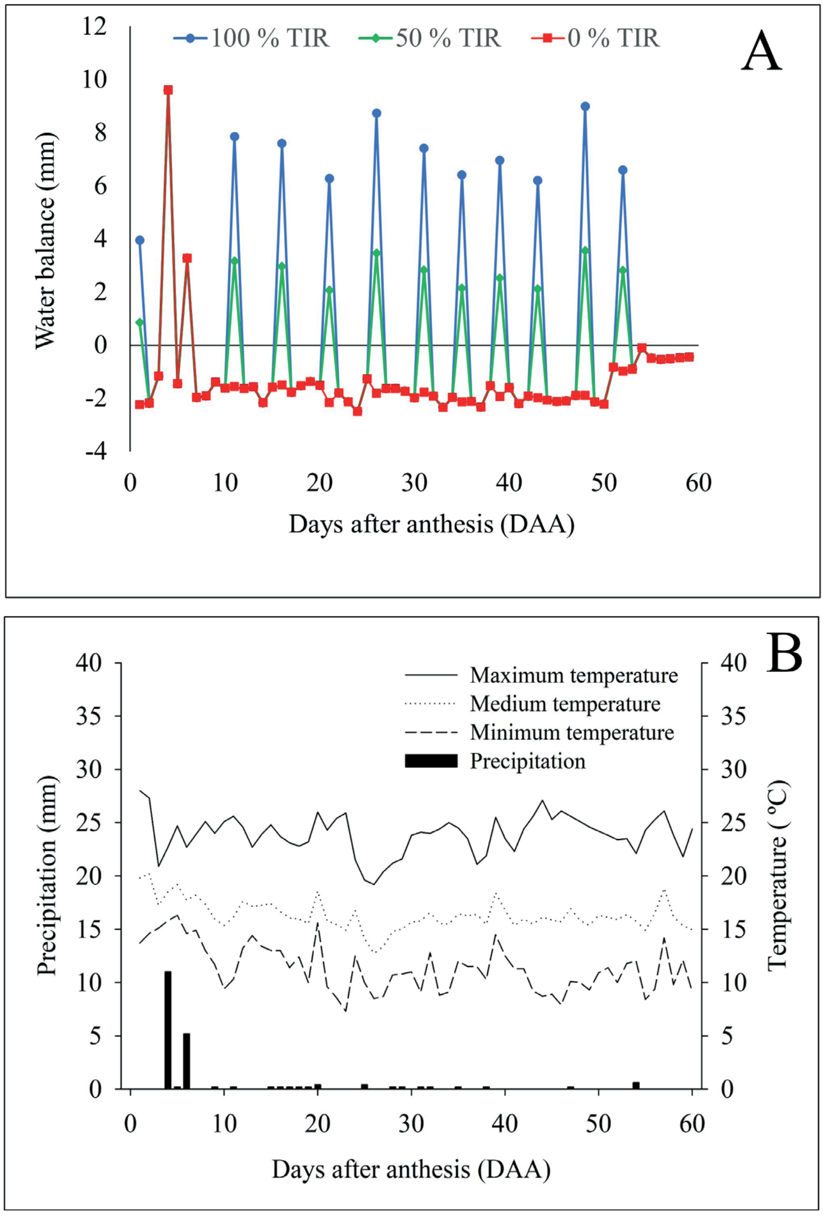

Figure 1. Water balance (A) and daily precipitation, maximum, mean, and minimum temperature (B) during application of 0; 50 and 100% of total irrigation requirement (TIR). Viçosa-MG, 2017.

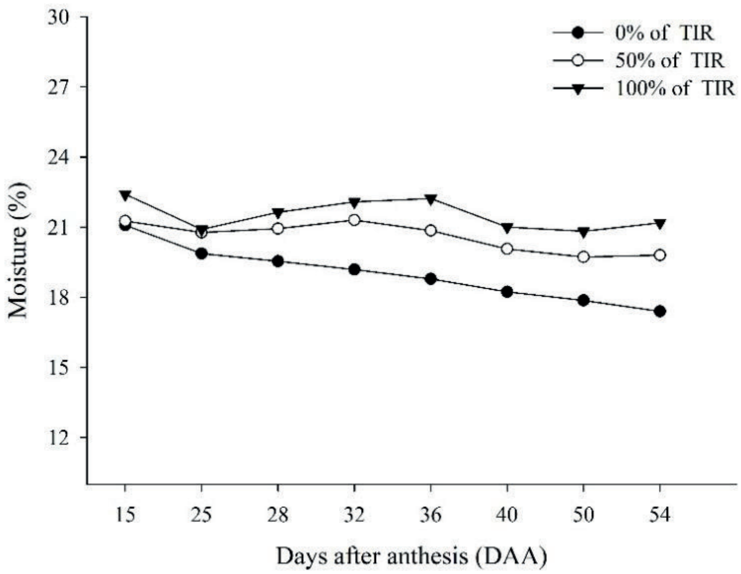

Figure 2. Soil moisture (%) after anthesis, according to the 0, 50 and 100% of total irrigation requirement (TIR). Viçosa-MG, 2017.

The analysis of variance did not indicate a significant interaction between the factors studied. Thus, the study of the main factors was carried out separately. Seed yield was not affected by the irrigation depths and foliar application of Si. The average yield was 4,263 kg ha^{-1}. Concerning seed quality, it was found a significant effect of the irrigation depths only for the 1000-seed weight and electrical conductivity (Table 3). The irrigation depth corresponding to 100% of TIR provided the highest 1000-seed weight compared with the other irrigation regimes. A similar result was observed by Li, Zhang, Li, Chang and Jing (2015), who evaluated the contribution of favorable alleles for water-soluble carbohydrates to wheat grain weight under drought conditions. According to these authors, the grain filling efficiency under drought conditions was lower than that without water restriction. Drought stress induces translocation of carbon reserves from wheat tillers to the main stem spike, which makes that this photosynthesis reserve is almost sufficient to ensure good grain performance of the main spike (Blum, 1998; Lawlor, Day, Johnston, Legg, & Parkinson, 1981; Li, Zhang, Li, Chang, & Jing, 2015). As observed in this study, the water restrictions imposed on the plants were responsible for reducing the 1000-seed weight (Table 3). Oliveira et al. (2020) observed that soybean seeds under drought had a higher consumption and lower translocation of reserves to the embryo, reducing the seedling vigor. Therefore, the results found can be related to the efficiency of reserve translocation from the wheat plants to the seeds, without, however, affecting yield.

For electrical conductivity, a higher value was found for 0% of TIR. This indicates a lower seed vigor in this treatment, where the permeability of the plasma membrane of the seed cells was affected due to the water shortage imposed on the plants after anthesis. It has been reported that water stress causes increased ABA levels and decreased cytokinin, leading to early senescence (Yang et al., 2003). To protect themselves against environmental stresses during maturation, seeds have mechanisms of tolerance to desiccation such as the accumulation of sugars, which stabilize the plasma membranes, liposomes, and proteins (Buitink et al., 2006; Battaglia & Covarrubias, 2013; Ishibashi, Yuasa, & Iwaya-Inoue, 2018). These mechanisms are triggered at the end of the maturation stage and, possibly, the early senescence rate of the plants in this treatment (visually observed) did not allow that the mechanisms of tolerance to desiccation appeared in the seeds produced by the plants cultivated under lower irrigation depths. So, this fact explains the higher ion leaching from the interior of the cell to the solution. Increased electrical conductivity in wheat seeds was also observed by Eskandari and Alizadeh-Amraie (2017) when they examined the effect of water restriction imposed on plants on the physiological quality of the seeds produced. Even with the negative effects of the lower irrigation depths observed for the 1000-seed weight and electrical conductivity of the seeds obtained with 0 and 50% of TIR, germination was not affected by the water limitation imposed on irrigation levels (Table 3). In all treatments, seed germination was over 90%, a value that is higher than the minimum required for commercialization of wheat basic seeds (70%) and other seed categories (80%) (MAPA, 2013).

Table 3
Mean values of germination and vigor index of wheat seeds produced at different irrigation depths and foliar application of Si. Viçosa – MG, 2017

Irrigation depth	G	FGC	TSW	AA	EC	EM
0% TIR	96	93	41.44 c	91	20.98 a	97
50% TIR	97	92	42.47 b	88	19.80 b	96
100% TIR	96	91	43.55 a	86	19.44 b	94
$Tukey_{0.05}$	6.35	7.81	0.69	11.84	0.89	4.85
$F_{0.05}$	0.06	0.31	43.56*	0.67	15.46*	1.40
CV (%)	4.30	5.53	1.06	8.77	2.89	3.31
Silicon						
0 mM	96	91	42.58	87	20.05	96
5 mM	96	93	42.39	89	20.10	95
$F_{0.05}$	0.00	2.95	0.51	0.49	0.01	0.17
CV (%)	3.11	2.83	1.53	6.59	5.28	4.07

G – Germination (%); FGC – First germination count (%); TSW – Thousand seed weight (g); AA – Accelerated aging (%); EC – Electrical conductivity (μS cm^{-1} g^{-1}); EM – Emergence (%). Means followed by different letter in column, for each irrigation depth, differ from each other by the Tukey's test (P ≤ 0.05). For the silicon treatments, the means followed by different letters differ from each other by the F test (P ≤ 0.05). * significant by the F test (P ≤ 0.05).

The soil at the site of the experiment exhibited a Si content of 9.27 mg kg^{-1} (Table 1). According to Marafon (2011), soils with Si levels below 20 mg kg^{-1} are considered poor for this nutrient. According to Wang and Galleta (1998), small amounts of leaf application with Si can be an alternative to soil absorption and can then stimulate the beneficial effects of this element. In this study, leaf application of Si (5 mM) at the tillering stage contributed to better and more uniform growth of wheat seedlings.

It was found a significant effect on root length (RL), RSR, GI, VI, and CVI. Si applications provided higher mean values compared with the control plants (Table 4). However, the irrigation levels did not influence the seedling growth. The GI, VI indexes (Sako et al., 2001) and CVI (Medeiros & Pereira, 2018) had higher values for the treatment with foliar application of Si on the plants. These indexes are based on the shoot length and root length of the seedlings, to classify seed lots according to their vigor. Therefore, seed lots that produce larger and more uniform seedlings have higher values for these indexes. Thus, the results found show the importance of leaf application of Si for the physiological quality of wheat seeds.

Table 4
Mean values of the development variables (vigor) or wheat seedlings grown from seeds produced with three different irrigation depths, with and without foliar application of silicon. Viçosa -MG, 2017

Irrigation depth	SL	RL	TL	SDM	RDM	RSR	GI	VI	CVI
0% TIR	9.0	7.13	16.11	7.00	5.22	0.79	731.48	812.0	779.5
50% TIR	8.9	7.42	16.36	6.69	5.33	0.83	756.95	829.8	800.5
100% TIR	8.6	7.88	16.52	6.88	5.90	0.92	795.80	857.0	827.2
$Tukey_{0,05}$	1.14	2.16	3.06	0.8	1.61	0.19	203.12	142.18	136.92
$F_{0,05}$	0.49	0.57	0.08	0.67	0.98	2.03	0.47	0.47	0.57
CV (%)	8.40	18.90	12.23	7.68	19.17	14.78	17.38	11.12	11.12
Silicon									
0 mM	8.9	6.91 b	15.80	6.96	5.22	0.78 b	711.13 b	797.7 b	768.4 b
5 mM	8.8	8.04 a	16.86	6.75	5.75	0.91 a	811.68 a	868.1 a	836.4 a
$F_{0,05}$	0.08	8.94*	4.13	2.10	4.39	11.93*	8.32*	8.32*	8.35*
CV (%)	6.71	12.32	7.78	4.94	11.15	11.36	11.21	7.17	7.17

SL – Shoot length (cm $seedling^{-1}$); RL- Root length (cm $seedling^{-1}$); TL – Total length (cm $seedling^{-1}$); SDM – Shoot dry matter (mg seedling-1); RDM – Root dry matter (mg seedling-1); RSR – Root/shoot ratio; GI – Growth index; VI – Vigor index; CVI – Corrected vigor index. Means followed by different letters in column, for each irrigation depth, differ from each other by the Tukey's test (P ≤ 0.05). For the treatments with silicon, means followed by different letters differ from each other by the F test (P ≤ 0.05). * significant by the F test (P ≤ 0.05).

The Si role on plant growth is largely reported in the literature. This micronutrient can change the properties of the cell wall, providing cell elongation and, consequently, plant growth (Toledo et al., 2012). Furthermore, Si is involved with water attributes in plants and its presence helps maintain higher turgor pressure, contributing to supporting higher leaf and root expansion rates (Hajiboland, Moradtalab, Eshaghi, & Feizy, 2018). In this context, these hypotheses support the findings of this study concerning the growth and development of wheat seedlings grown from seeds produced with leaf application of Si. Leaf application of Si and its effect on seedling development was also reported by Toledo et al. (2012) for a white oat crop, who observed an increased root growth of the seedlings. Wu, Mock, Giehl, Pitann and Mühling (2019) observed that Si supplementation in wheat mitigates cadmium (Cd) toxicity by modulating the deposits of suberin on the cell walls, which can also be related with greater development of wheat seedlings.

The greater initial growth of the wheat plants in the treatment where the plants were fertilized with Si indicates the better physiological quality of the seeds produced in this treatment. According to Oliveira, Lemes, Meneghello, Tavares and Barros (2015), because they have higher initial growth, they consequently are more productive due to the larger leaf area, which allows a higher rate of photosynthesis. Moreover, these authors cite advantages in using environmental resources due to the higher growth speed at the early stage of plant development. Toledo et al. (2012) report that wheat seed quality can be positively influenced by an indirect supply of Si, which provides good conditions for the development of the mother plant. These same authors mention the contribution of this nutrient to lignin synthesis, which acts by strengthening the seed coating, reducing metabolite leaching.

The effects of the irrigation depths and leaf application of Si on the plants for physiological seed quality and development of the wheat plants can be seen with more precise details in the principal components analysis (PCA). The sum of the two first principal components (PC1 and PC2) explained 74.1% of the total data variation (PC1 = 51.4% and PC2 = 22.7%) (Figure 3). This value is higher than 70% and can be considered suitable to provide a good image of the data structure (Varmuza & Filzmoser, 2009). It can also be observed that the treatment with 0% of TIR, with Si application, was displayed in PC1-/PC2+, close to the vectors of variables AA, FGC, SL, EC, and SE. The treatment with 100% of TIR, without foliar application of Si, in PC1+/PC2-, was displayed close to the vectors G and TSW. These treatments were positioned close to the vectors with the highest contribution to PC2, which indicates higher values of these variables.

The most pronounced effects of the irrigation depths were found for the variables TSW and EC, and the highest TSW and lowest EC were observed for the treatment with 100% of TIR (Table 3). It can be seen, in the plotted PCA, that the irrigation depths of 0% of TIR, regardless of the application or not of silicon, were positioned close to the vector of the EC variable, indicating a higher correlation with this variable and higher EC values for this treatment. However, the treatments with irrigation depths of 100% of TIR, regardless of foliar application of Si, were displayed close to the TSW vector, indicating a higher correlation with this variable. This result points to higher vigor of the seeds produced with an irrigation depth of 100% of TIR.

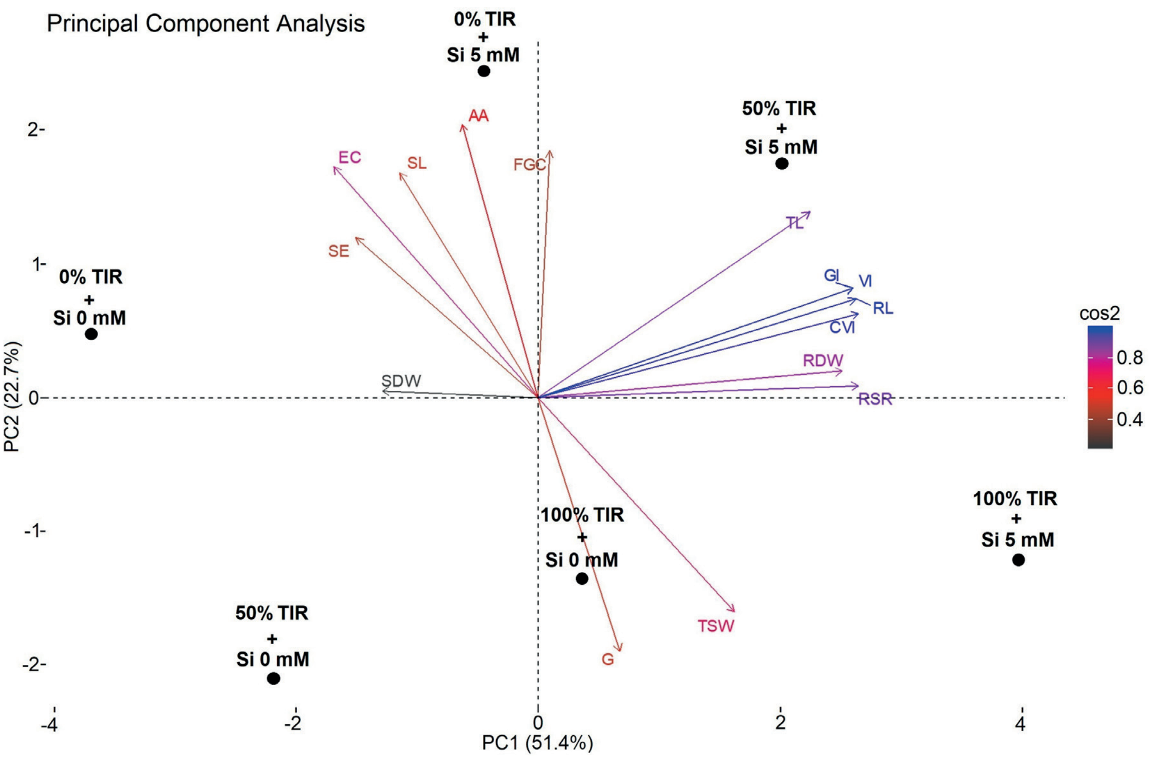

Figure 3. Biplot obtained from the linear combination of the variables related to the physiological and growth characteristics of wheat seedlings, grown from seeds produced at three irrigation depths (0; 50 and 100% of total irrigation requirement [TIR]), with and without leaf application of Si. PC1 – Principal component 1; PC2 – Principal component 2; G – Germination (%); FGC – First germination count (%); TSW – 1000-seed weight (g); AA – Accelerated aging (%); EC – Electrical conductivity (µS cm^{-1} g^{-1}); SE – seedling emergence (%); SL – Shoot length (cm $seedling^{-1}$); RL- Root length (cm $seedling^{-1}$); TL – Total length (cm $seedling^{-1}$); SDW – Shoot dry weight (mg $seedling^{-1}$); RDW – Root dry weight (mg $seedling^{-1}$); RSR – Root/shoot ratio; GI – Growth index; VI – Vigor index; CVI – Corrected vigor index.

The irrigation treatments with 0 and 50% of TIR, without foliar application of Si, were arranged in PC1-/PC2+ and PC1-/PC2- respectively (Figure 3). These treatments occupied opposite positions to the vectors of variables with the highest contribution to PC1. These vectors refer to the plant development variables (TL, GI, VI, CVI, RL, RDW, and RSR), showing that in these treatments, lower values were achieved. Thus, lower irrigation levels, when not combined with foliar application of Si, resulted in less growth of the seedlings grown from seeds produced in these conditions. On the other hand, an opposite arrangement was observed for the treatments with irrigation depths of 50% and 100% of TIR, with foliar application of Si, positioned, respectively, in PC1+/PC2+ and PC1+/PC2-. Similar to what occurred with the vectors of the variables with the highest contribution to PC2, these treatments were also displayed close to the vectors of variables of the highest contribution now for PC1. Thus, these treatments provided higher seed quality, which, in turn, produced higher and more uniform seedlings.

Therefore, the treatments with 100% of TIR, irrespective of Si application, and 50% of TIR associated with foliar application of Si are the treatments that provided better physiological seed quality. These treatments were displayed in the positive scores of PC1, corresponding to the direction of the plant germination and growth vectors (Figure 3).

Briefly, a higher 1000-seed weight and lower electrical conductivity were observed for the seeds produced with the highest irrigation level (100% of TIR) (Table 3). However, foliar application of Si was effective in producing seeds with higher physiological quality. In this regard, they produced more vigorous seedlings (Table 4), in optimal production conditions (irrigation level of 100% TIR) and under moderate water shortage (irrigation level of 50% TIR) (Figure 3).

Conclusions

Different irrigation depths beginning at anthesis do not affect yield and germination of wheat seeds, but less water irrigation (50% of TIR) and absence of irrigation (0% of TIR) reduces the seed vigor.

Leaf application of 5 mM of Silicon on wheat plants provides more vigorous seeds.

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