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# Wheat yield and irrigation water productivity in a Cerrado region of Minas Gerais, Brazil[1]

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## ABSTRACT

There is significant potential for expanding the wheat production chain in the Brazilian Cerrado. Studies addressing wheat crop performance in this region could help guide this expansion. This study hypothesizes that deficit irrigation can enhance irrigation water productivity without compromising wheat yield in the Cerrado region of Minas Gerais state. The aim was to evaluate the grain crop yield (Y), yield components, and irrigation water productivity ($W_{IRRI}$) of two wheat cultivars under different irrigation depths. The field experiment was carried out in a 2 x 5 factorial scheme with two cultivars (BRS 404 and ORS Feroz) in combination with five irrigation levels (120%, 100%, 80%, 60% and 40% replacement of crop evapotranspiration, ETc). The cultivar BRS 404 showed the highest plant height and highest thousand grain weight. ORS Feroz presented the highest number of ears $m^{-2}$. $W_{IRRI}$ and Y, as well as most components of yield, differed significantly depending on the irrigation level. The 54.4% reduction in total net irrigation depth caused a 29.1% reduction in yield but provided a 51.7% increase in irrigation water productivity. The adoption of deficit irrigation proved to be a viable strategy for maintaining reasonable wheat crop yield while conserving water under the experimental conditions.

**Keywords:** deficit irrigation, yield components, water resources, *Triticum aestivum*.

## INTRODUCTION

Wheat (*Triticum aestivum* L.) is the second most produced cereal crop worldwide, surpassed only by corn. Wheat crop area accounts for more than 17% of the world's arable land and contributes approximately 30% of global grain production, making it one of the most important cultivated species in the global agricultural economy.(1) Global wheat production for 2024/2025 is forecast at 798.2 million tons, an increase of 10.5 million compared to the previous one.(2) Global wheat exports for the July-June 2023/24 international marketing year increased by 1.3 million tons, reaching a record 216.7 million tons, driven mainly by higher exports from Ukraine, Russia, Egypt and Australia.(3)

It is estimated that 3.26 million hectares will be planted in Brazil for the period from August 2024 to July 2025, with a harvest of 9.6 million tons and mean crop yield of 2937 kg $ha^{-1}$. As production is not sufficient to meet domestic demand, an import quantity of 5.5 million tons is expected for the period.(4) The insufficiency of Brazilian wheat production to meet domestic demand tends to worsen with the occurrence of adverse weather events.(5) The effects of global climate change, due to increased temperatures and water scarcity, may negatively impact wheat production, especially in developing countries in tropical regions.(6)

The Cerrado region of Central Brazil, despite historically not being a traditional wheat-growing region, has great potential for expanding the wheat production chain. Among the positive aspects in the region, the edaphoclimatic conditions and the area extension stand out, which can contribute significantly to national cereal production.(7) As wheat cultivation expands into new areas, using cultivars adapted to local conditions is essential to achieving viable yields and driving significant progress in Brazil's wheat production landscape.

Irrigation is one of the management techniques that most influences the productive behavior of agricultural species in the field, especially in regions where rainfall is insufficient or irregular. Although wheat shows moderate resistance to water stress due to its origin in arid regions, irrigation can significantly improve both yield and quality.(8–10)

The large volume of water required in irrigated agriculture compared to other activities points to the need to search for techniques for the optimized and rational use of water resources. Irrigation management strategies that enhance water-use efficiency offer viable pathways to establishing sustainable agricultural production systems. In the search for high water use efficiency, one of the promising techniques is the deficit irrigation,(11–13) in which the amount of irrigation is less than that necessary to fully meet the crop water requirement. Under controlled conditions, deficit irrigation can improve plant response to water stress, enabling higher water productivity.

There are still no studies investigating the effects of water deficit on wheat productivity and yield components in the Cerrado biome of the central region of Minas Gerais state, specifically in the Metropolitan Region of Belo Horizonte and the Central Mineira mesoregions. These studies can support decisions regarding the applicability of deficit irrigation.

Based on this context, we consider hypothesize that deficit irrigation can improve irrigation water productivity without compromising wheat crop yield in the Cerrado region of the Minas Gerais state. The objective of this study was to evaluate the crop yield, yield components, and irrigation water productivity of two wheat cultivars under different irrigation depths in a Cerrado region of Minas Gerais.

## MATERIALS AND METHODS

The experiment was conducted under field conditions, whose geographic coordinates are 19° 28' 41.5" South latitude and 44° 11' 60.0" West longitude, with an altitude of 761 m.(14) The climate is Cwa in the Köppen climate classification, with hot, rainy summers and dry winters. The mean annual temperature is 22.2 °C and the mean annual precipitation is 1272 mm,(15) with the rainy season starting in October and the dry season starting in April.(16) During the six-month dry season, a significant water deficit is observed when comparing evapotranspiration demand to rainfall. The soil has a very clayey texture, with 67% clay, 17% silt and 16% sand.

The area had not been cultivated in the months prior to the experiment. The soil was prepared using a leveling harrow. Subsequently, the herbicide glyphosate was used to control invasive plants. Fertilization management was based on soil analysis in the experimental area.(14) At sowing, 300 kg $ha^{-1}$ of an NPK 8-28-16 fertilizer formulae ($N$-$P_2O_5$-$K_2O$) was applied. Top dressing with nitrogen was carried out using N in the ammonium sulfate source, being divided into two applications (50 kg $ha^{-1}$ applied at the beginning of tillering and 50 kg $ha^{-1}$ applied twenty days later).

The experiment was implemented in a randomized block design, in a 2 x 5 factorial scheme, with two wheat genotypes, BRS 404 [17] and ORS Feroz [18], and five irrigation levels (120%, 100%, 80%, 60% and 40% replacement of crop evapotranspiration, ETc), with four replications. Each plot comprised 7 rows 5 m long with 0.2 m spacing between plant rows. The 5 central rows were considered useful for data collection, disregarding 1.0 m at the ends, totaling 3.0 m² of useful area per plot.

The crop was sown manually at a depth of approximately 3 cm, with about 70 seeds per linear meter, on June 30, 2022. The harvest was performed manually and individually per experimental plot, on October 17, 2022, 109 days after sowing, when the grains were at the hard grain stage.

The irrigation system used was surface drip, with two lateral lines per experimental plot, spaced 0.6 m apart. The sketch of the experimental area, with an irrigation system and 40 experimental plots, is shown in Figure 1. The drippers were button-type, pressure-compensating drippers of the Netafim brand, model PCJ LCNL. Irrigation levels were differentiated in the experimental plots based on combinations of spacing between drippers and dripper flow (Table 1).

Irrigation uniformity was assessed in the field before the start of the experiment by calculating the Christiansen Uniformity Coefficient (CUC) and the Distribution Coefficient (DU) for each dripper arrangement.[19] The values obtained for CUC and DU were higher than 90%.

The crop water demand was estimated based on ETc, estimated by multiplying the crop coefficient (Kc) by the reference evapotranspiration (ET0). The wheat crop coefficient was used as proposed by FAO Bulletin 56,[20] including correction for high irrigation frequency and small infiltration depths for the initial crop stage. After correction, the Kc values considered were 1.15 for the initial, development and intermediate stages and 0.4 for the final Kc.

The calculation of daily ET0 (mm day$^{-1}$) was performed using the FAO Penman-Monteith method (20,21). Weather data obtained from the automatic station of the National Institute of Meteorology (INMET) in Sete Lagoas (3.77 km from the experiment area), code A569, were used. A rain gauge was installed adjacent to the experiment area to record rainfall data.

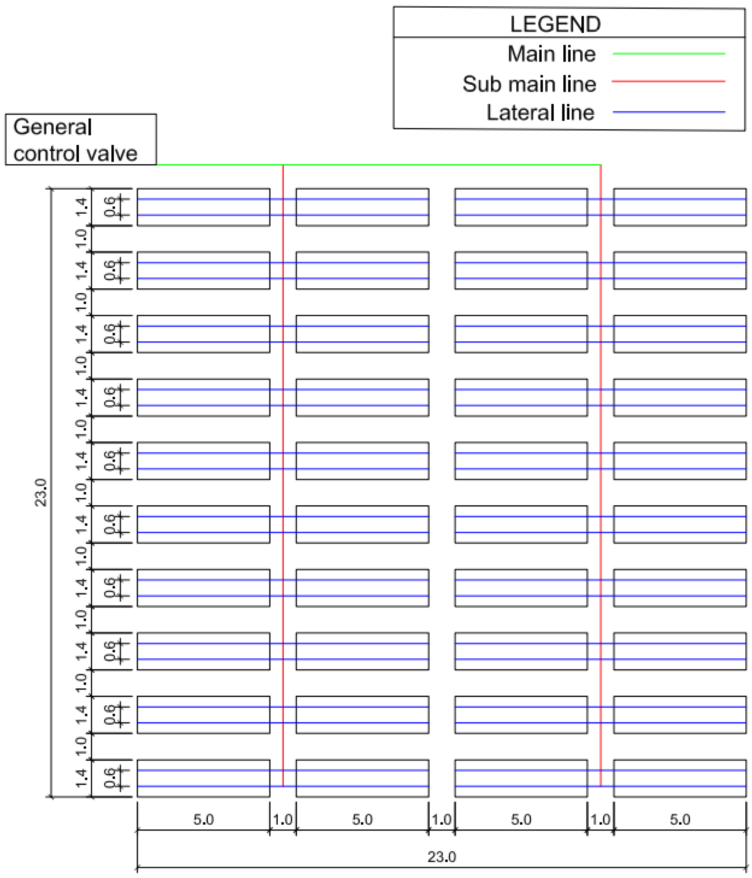


**Figure 1.** Sketch of the area with 40 experimental plots and drip irrigation system, Sete Lagoas, MG, Brazil.

**Table 1.** Arrangement of drippers to obtain different irrigation levels, considering the percentage in relation to crop evapotranspiration (ETc)

| Irrigation level | Percentage in relation to ETc | Dripper flow rate ($L\ h^{-1}$) | Spacing between drippers on the lateral line (m) |
|---|---|---|---|
| 1 | 120% | 4.0 | 0.39 |
| 2 | 100% | 2.0 | 0.23 |
| 3 | 80% | 2.0 | 0.29 |
| 4 | 60% | 2.0 | 0.39 |
| 5 | 40% | 1.2 | 0.35 |

Pre-sowing irrigation was carried out, starting three days before wheat sowing. Furthermore, to promote ideal germination and development conditions, until full tillering (23 days after sowing), a mean net irrigation depth of 3.4 mm was applied daily, except on Sundays, in all treatments. This irrigation was equivalent to the ETc during the period. For this purpose, sprinklers spaced 12 x 12 meters apart were used in the experimental area. Immediately after this period, different irrigation levels were imposed on the respective treatments, using the drip irrigation system. The water supply was suspended 84 days after sowing, coinciding with the onset of the crop's physiological maturity stage.

Assessments were made for the wheat crop yield, yield components (plant height, number of ears per unit area, number of grains per ear, and weight of 1000 grains), as well as the irrigation water productivity ($W_{IRRI}$, kg $m^{-3}$), calculated by applying Equation 1[12,22,23]:

$$W_{IRRI} = \frac{Y}{T_{IRRI}} \quad (1)$$

where Y is the wheat grain yield (kg $ha^{-1}$) and $T_{IRRI}$ is the total gross irrigation depth ($m^3\ ha^{-1}$). The efficiency of 95% was considered for drip irrigation. For sprinkler irrigation (initial period of the experiment), the irrigation efficiency was estimated at 78%, by comparing the previously measured irrigation at soil surface level with the ETc.

The number of ears per unit area was estimated by measuring the total number of ears contained in a 0.3 $m^2$ sample of each experimental plot. The number of grains per ear was obtained after manual threshing, counting the average number of grains from six ears harvested at random when physiological maturity was observed. At harvest time, grain moisture was determined using the oven drying method. The weight of the grains harvested in each plot had its moisture corrected to 13% to calculate Y.

The collected data were subjected to analysis of variance (ANOVA) using the ExpDes.pt package[24] in R software, version 4.3.3.[25] Regression analysis was performed when ANOVA indicated significant effects.

## RESULTS AND DISCUSSION

Along the wheat development cycle, the maximum, average and minimum temperatures were 36.6, 20.5, and 5.4 °C. Reference evapotranspiration (ET0) reached a maximum of 5.6 mm $day^{-1}$ and a minimum of 1.9 mm $day^{-1}$. Total effective rainfall was 56.6 mm, concentrated in the last 26 days of the crop season (Figure 2).

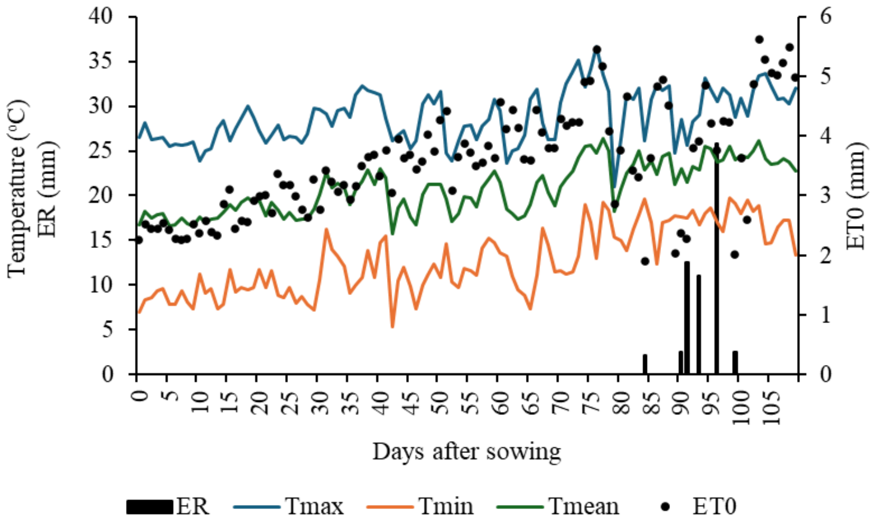


**Figure 2.** Variation of meteorological elements during the crop cycle (June 30th to October 17th, 2022): effective rainfall (ER), maximum (Tmax), mean (Tmean) and minimum (Tmin) temperature, and reference evapotranspiration (ET0) (Sete Lagoas, MG, Brazil).

The ETc accumulated over the crop season was 415 mm, with a daily average of 3.8 mm day$^{-1}$. The values of total irrigation and total water (net irrigation + rainfall) throughout the wheat development cycle, for the different irrigation levels, are presented in Table 2. The cumulative irrigation depths for sprinkler irrigation and the five drip irrigation levels, as well as the cumulative ETc, are shown in Figure 3, together with the daily irrigation. The water supply must be interrupted when the wheat ears are in the grain development phase, in the hard dough stage, at which point the grains no longer receive photoassimilates.[26] Thus, $W_{IRRI}$ practically represented water productivity in this study, since the plants were already close to reaching this stage when the rain occurred, and irrigation was interrupted.

**Table 2.** Total gross irrigation, total net irrigation, and total water (total net irrigation + rainfall) depths throughout the wheat cycle for different irrigation levels, in Sete Lagoas, MG, Brazil

| Irrigation level | Total gross irrigation | Total net irrigation | Total water |
|---|---|---|---|
| (percentage of ETc) | (mm) | (mm) | (mm) |
| 120% | 413 | 377 | 434 |
| 100% | 359 | 326 | 383 |
| 80% | 305 | 275 | 331 |
| 60% | 250 | 223 | 280 |
| 40% | 196 | 172 | 228 |

The analysis of variance revealed no significant interaction between cultivars and irrigation depths (Table 3). The cultivar factor was significant for the analyses of plant height, number of ears per m² and thousand grain weight. Regarding irrigation depths, the results were significant for all variables.

There was a significant effect of wheat cultivars on plant height. The average heights were 100.9 and 81.0 cm, respectively, for the cultivars BRS 404 and ORS Feroz. This difference is related to the established agronomic characteristics of each material. Lodging occurred in some experimental plots of the BRS 404 cultivar. The height of the wheat plant is directly related to lodging. According to Chagas et al.,[17] the BRS 404 cultivar is indicated for cultivation in a dryland system, in the second harvest period, being moderately resistant to lodging and presenting an average plant height of approximately 77 cm. Irrigation promoted greater plant height development, which increased susceptibility to lodging under the experimental conditions, although it also enabled yield gains. Although the application of growth regulators is not recommended for the BRS 404 cultivar under rainfed conditions,[17] their use in irrigated systems with soil and climate conditions similar to those of the experiment may reduce the risk of lodging. On the other hand, the ORS Feroz is a low height cultivar,[7] a plant architecture trait that can improve lodging resistance.

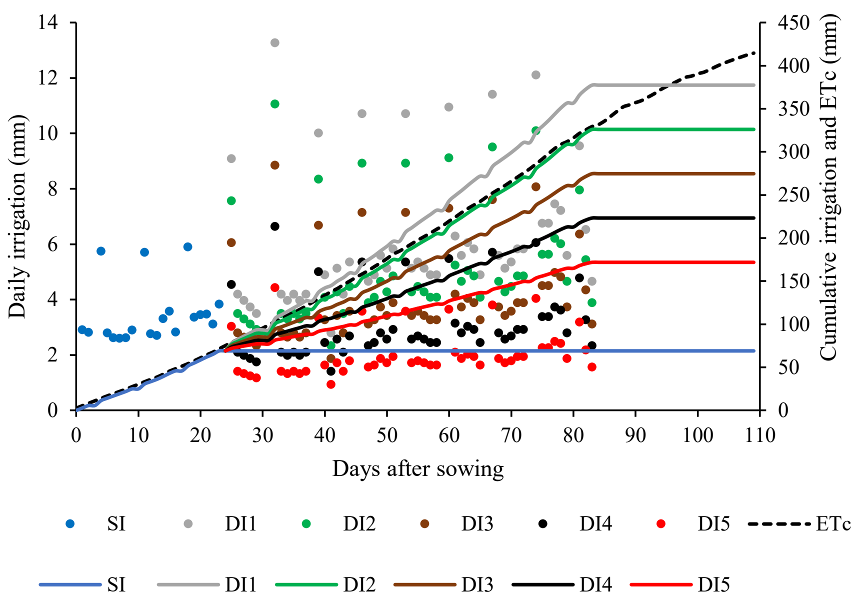


**Figure 3.** Daily and cumulative net irrigation throughout the crop cycle (June 30th to October 17th, 2022) for different irrigation levels; SI, DI1, DI2, DI3, DI4, and DI5 represent sprinkler irrigation, level 1 (120% ETc), level 2 (100% ETc), level 3 (80% ETc), level 4 (60% ETc), and level 5 (40% ETc) of drip irrigation, respectively; and cumulative crop evapotranspiration (ETc) (Sete Lagoas, MG, Brazil).

**Table 3.** Summary of analysis of variance for plant height (PH), number of ears per m² (NEM), number of grains per ear (NGE), thousand grain weight (TGW), wheat grain crop yield (Y), and irrigation water productivity ($W_{IRRI}$) of wheat cultivars (C) subjected to different supplementary irrigation depths (I). Sete Lagoas, MG, Brazil

| Fonte de variação | PH | NEM | NGE | TGW | Y | $W_{IRRI}$ |
|---|---|---|---|---|---|---|
| Block | NS | NS | NS | ** | * | NS |
| C | ** | ** | NS | ** | NS | NS |
| I | ** | * | * | * | ** | ** |
| C x I | NS | NS | NS | NS | NS | NS |
| CV (%) | 5.0 | 11.9 | 9.0 | 5.2 | 11.9 | 13.8 |

NS : not significant; * $p < 0.05$ by F-test, ** $p < 0.01$ by F-test.

The plant height characteristic adjusted to a simple linear regression model, showing an increasing trend as larger water depths were provided, with a coefficient of determination of 0.96 (Figure 4). A unitary increase (mm) in the total net irrigation depth implied a positive variation of 0.907 mm in plant height, according to the regression model. Quantifying the response of plant height to soil water availability is important due to its positive influence on crop yield.[27]

It was observed that plant height is directly related to water availability, with a negative effect of water stress on height and elongation rate, as found in other studies applied to wheat crops.[23,28] Under water limitation, turgor pressure is reduced, eliminating the driving force of cell elongation and, consequently, causing changes in plant growth.

The results showed that the wheat cultivars evaluated presented different behaviors for the number of ears per square meter (NEM). Higher NEM values were observed for the ORS Feroz cultivar, with a mean of 544 ears $m^{-2}$, while for BRS 404 a mean of 469 ears $m^{-2}$ was obtained.

Regression analysis revealed a positive linear relationship between NEM and irrigation depth, with an increase of 0.422 ears $m^{-2}$ per 1 mm increment in total net irrigation depth and a coefficient of determination of 0.91 (Figure 5).

In general, plants subjected to water deficit have lower NEM, when compared to plants that develop in adequate water availability conditions. The NEM variable presented the maximum value in the regression model equal to 550 ears $m^{-2}$, for the irrigation depth of 377 mm. For the 172 mm irrigation depth, the model indicated 463 ears $m^{-2}$. The effect of water availability on the number of ears per unit area has been recorded for different experimental conditions for wheat crops.[29-31]

A second-degree linear regression model (Figure 6) was adjusted for the variable number of grains per ear (NGE) in relation to the total net irrigation depths. A pattern different from that of the other wheat yield components was observed for the NGE variable. The minimum point of the regression model was equivalent to an irrigation depth of 257.1 mm and 37.5 grains per ear. Li et al.[30] found no effect of irrigation depth on the number of grains per ear in a first-year experiment and a reduced effect in a second year, for winter wheat. Rao et al.[31] obtained lower values of grains per ear for the three lowest irrigation levels, out of a total of 5 irrigation levels considered. In general, reduced water supply to plants results in increased senescence and leaf abscission. With fewer leaves to provide photoassimilates, plants growing in suboptimal conditions may also produce smaller seeds in smaller quantities.

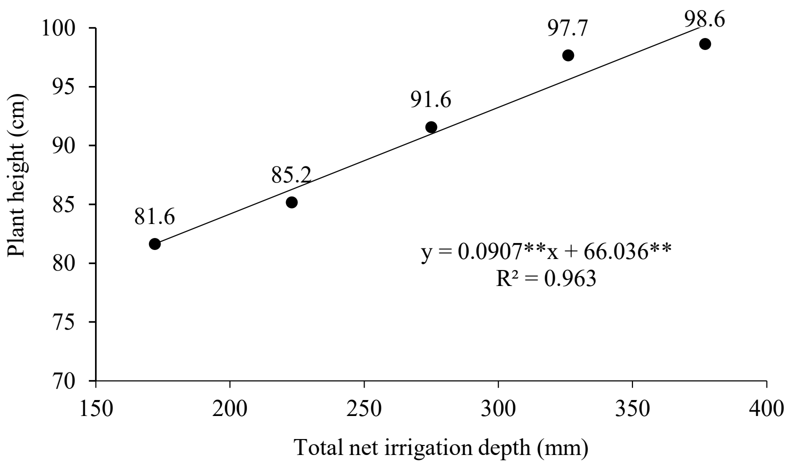


**Figure 4.** Regression for plant height of wheat cultivars as a function of total net irrigation depths in Sete Lagoas, MG, Brazil. **$p < 0.01$.

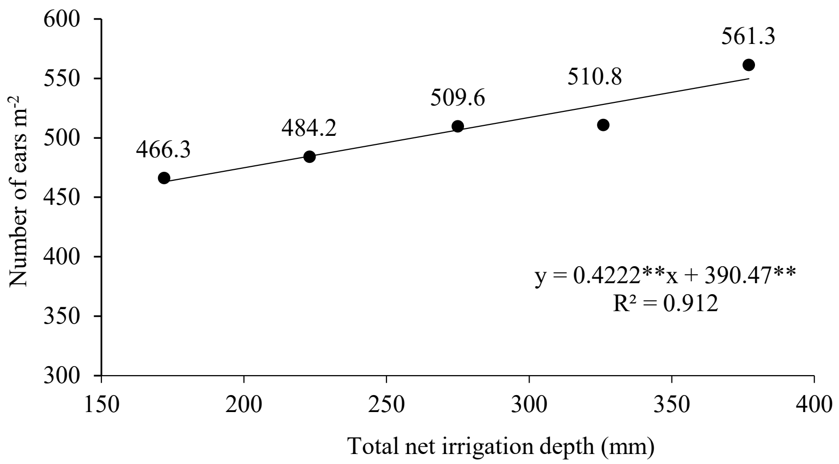


**Figure 5.** Regression of the number of ears per $m^{-2}$ in wheat cultivars as a function of total net irrigation depths in Sete Lagoas, MG, Brazil. **$p < 0.01$.

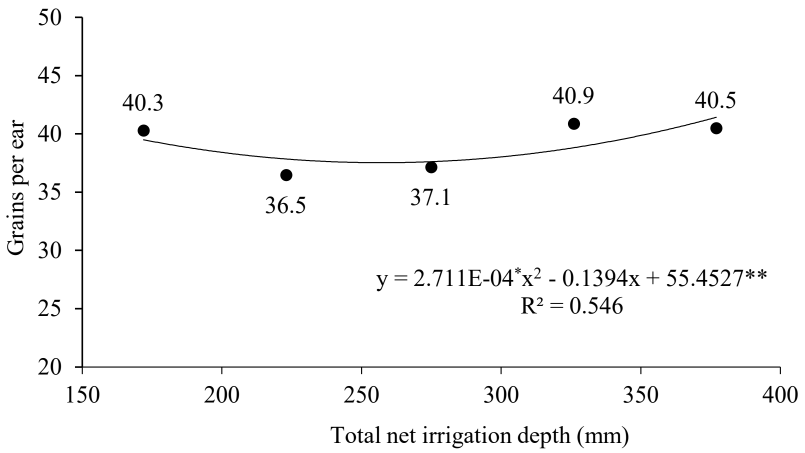


**Figure 6.** Regression of the number of grains per ear of wheat cultivars as a function of total net irrigation depths in Sete Lagoas, MG, Brazil. *$p < 0.05$; **$p < 0.01$.

The cultivars presented different responses in relation to the thousand grain weight (TGW) characteristic. A higher mean TGW was obtained for the BRS 404 variable (38.3 g) compared to that observed for the ORS Feroz cultivar (35.0 g). These results may be related to the inherent characteristics of each cultivar. The wheat cultivar BRS 404 stands out for its high grain yield.[17] Although BRS 404 showed a higher thousand grain weight (TGW), the greater number of ears per square meter (NEM) observed in ORS Feroz may have compensated for this difference in terms of grain yield, for which no significant difference was observed between the cultivars.

Irrigation levels had a significant positive effect on TGW, and a linear regression model was adjusted, with a coefficient of determination of 0.76 (Figure 7). Each mm added to the total net irrigation depth resulted in an increase of 0.0142 g in TWG. Higher TWG associated with higher irrigation levels have been recorded for different experimental contexts for wheat crops.[29] Li et al.[30] observed that the level of gain in TGW in response to irrigation level is influenced by the amount of nitrogen applied.

There was no significant effect on wheat grain yield (Y) in response to the cultivar factor. Both cultivars are recommended for the state of Minas Gerais, for rainfed agriculture conditions in the Cerrado of Central Brazil.[7] However, considering the estimated available water in the soil at 97 mm $m^{-1}$ based on soil texture, sowing is not recommended after March in the local of the experiment, according to the Agricultural Climate Risk Zoning (ZARC) for wheat crops in rainfed agriculture. For irrigated agriculture, sowing is recommended until the first ten days of June, including the indication of the ORS Feroz cultivar, but not BRS 404.

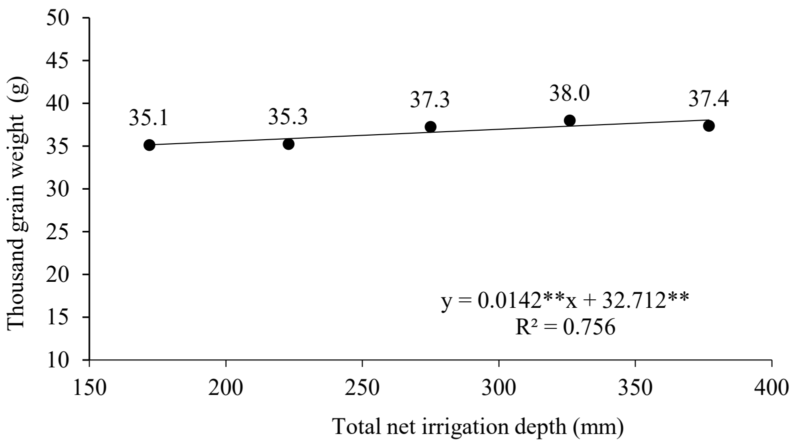


**Figure 7.** Regression of thousand grain weight of wheat cultivars as a function of total net irrigation depths in Sete Lagoas, MG, Brazil. **$p < 0.01$.

Y was adjusted to a linear regression model in relation to total net irrigation levels, showing an increasing trend and a coefficient of determination of 0.98 (Figure 8). Based on the linear regression model, each mm added to the total net irrigation depth resulted in an increase of 7.61 kg $ha^{-1}$ in Y.

The lowest Y value projected in the linear model was 3798.6 kg $ha^{-1}$, referring to the smallest irrigation depth (172 mm). This wheat crop yield was higher than that observed in Brazil between 2018 and 2023, equivalent to 2733 kg $ha^{-1}$.[32] The highest Y indicated in the linear regression model was 5357.9 kg $ha^{-1}$, obtained for the irrigation depth of 377 mm, which represents a gain of 29.1% in relation to the value obtained with the lowest irrigation depth. However, there was no indication of maximum achievable Y, inferring from the linear model that higher crop yield could be obtained with the application of higher irrigation depths. Based on the Agricultural Zoning of Climatic Risk for wheat crops, a potential crop yield of 7250 kg $ha^{-1}$ is expected for the ORS Feroz cultivar. Wheat yield gains resulting from higher irrigation levels have been reported for different experimental scenarios and cultivars.[22,23,29]

The effect of water scarcity on grain weight and productivity is directly related to the decrease in photosynthesis. The soil water content is important for defining the water status of the plant, which is crucial in the photosynthetic process. Under conditions of limited water availability, guard cells promote the closure of stomata to prevent water loss via transpiration. Stomatal closure imposes limitations on the photosynthetic process, which implies lower production of photoassimilates, resulting in lighter grains and, consequently, impacting productivity.[23]

A linear effect of total gross irrigation depth on irrigation water productivity was observed, with a coefficient of determination of 0.90 (Figure 9). The linear regression model indicated that there was a decrease of -2.96 g $m^{-3}$ in $W_{IRRI}$ per 1 mm increase in the total gross irrigation depth. The lowest $W_{IRRI}$ in the model was 1.240 kg $m^{-3}$, for the gross irrigation depth of 413 mm. Although the lower water inputs provided the lowest grain yields, they provided higher $W_{IRRI}$, like the results obtained by Ledesma-Ramírez et al.,[29] in which water productivity varied from 1.43 to 1.85 kg $m^{-3}$, also depending on the type of wheat. The grouped water productivity values obtained by Rao et al.[31] ranged from 1.09 to 1.28 kg $m^{-3}$, with the minimum value found for the maximum irrigation treatment. In simulations carried out with models calibrated by Kheir et al.[11] for wheat crops in Egypt, higher values of irrigation water productivity were also observed for lower irrigation levels, equivalent to 50% and 60% of ETc.

The results demonstrated that the deficit irrigation strategy improved the irrigation water productivity in wheat grain production. By reducing the gross irrigation depth from 413 mm ($W_{IRRI}$ = 1.240 kg $m^{-3}$ in regression model) to 196 mm ($W_{IRRI}$ = 1.881 kg $m^{-3}$ in regression model), there was an increase of approximately 51.7% in $W_{IRRI}$, which makes this management strategy feasible to be adopted when the focus is to prioritize water savings. Regarding the total net irrigation depth, this comparison is equivalent to a reduction from 377 mm to 172 mm (54.4%). The definition of the strategy regarding the level of irrigation deficit to be adopted should also be established based on economic analysis, considering restrictions on water resources, among others, that characterize the agricultural enterprise.

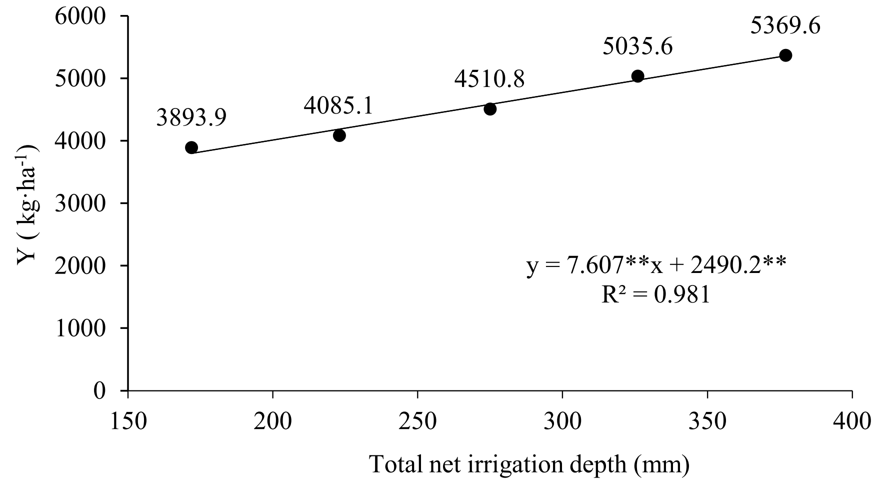


**Figure 8.** Regression for wheat grain yield (Y) as a function of total net irrigation depths in Sete Lagoas, MG, Brazil. **$p < 0.01$.

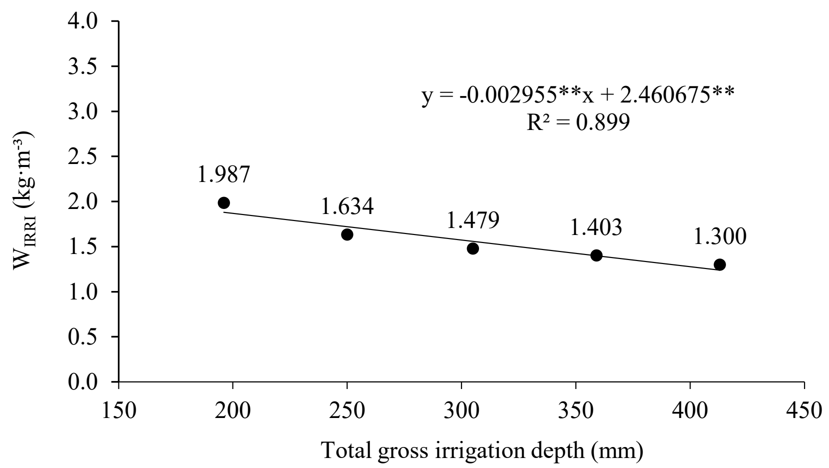


**Figure 9.** Regression for irrigation water productivity ($W_{IRRI}$) of wheat cultivars as a function of total gross irrigation depths in Sete Lagoas, MG, Brazil. **$p < 0.01$.

## CONCLUSION

No significant interaction was observed between cultivars and total irrigation depths. For the cultivar factor, no significant effect was observed for the variables number of grains per ear, crop yield, or irrigation water productivity. The results were significant for all variables – plant height, number of ears per $m^2$, number of grains per ear, thousand grain weight, crop yield, and irrigation water productivity – in response to irrigation depths.

The BRS 404 cultivar expressed higher values of plant height and thousand grain weight, while ORS Feroz presented a greater number of ears per $m^{-2}$.

Increases in crop yield were observed for both cultivars, with a linear response to the increase in irrigation depth. Even at the lowest level of irrigation (172 mm throughout the crop cycle), the average crop yield obtained exceeded the Brazilian averages between 2018 and 2023. However, the use of irrigation may have caused lodging in some experimental units of the BRS 404 cultivar, with plant height gain. The first-degree linear regression model indicated the possibility of achieving higher wheat grain crop yield with the application of higher total net irrigation depths.

A 54.4% reduction in the maximum total net irrigation depth caused a 29.1% reduction in wheat crop yield but provided a 51.7% increase in irrigation water productivity.

Under the experimental conditions, the use of deficit irrigation can provide significant water savings with some penalty to crop productivity. The analysis of the decision regarding deficit irrigation management should involve economic aspects and information on water availability.

## DATA AVAILABILITY

The entire dataset supporting the results of this study has been made available in SciELO Data and can be accessed at https://doi.org/10.48331/SCIELODATA.RMWLY5

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