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# Agronomic performance of wheat cultivars under different plant density and planting times[1]

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## ABSTRACT

Wheat plays a critical role in global food security and the agricultural economy. In Minas Gerais, Brazil, one of the major challenges for wheat production is the high variability of meteorological conditions. Therefore, studies that support wheat producers in defining more accurate sowing dates and plant densities according to cultivar requirements are essential, as they can contribute to increasing yield and enhancing agricultural resilience. The aim of this study was to evaluate the response of wheat cultivars, based on growth, micrometeorological, and yield-related traits, under different sowing times and plant densities. The experiment was conducted during the autumn–winter growing season of 2022 in an experimental area located in Ijaci, Minas Gerais, Brazil. Four wheat cultivars were evaluated under different sowing times and plant densities. Agronomic and agrometeorological variables were monitored throughout the field experiment. The results showed that wheat sown within the recommended sowing window exhibited superior performance, benefiting from greater soil water availability, higher growth rates, and increased radiation interception. Grain yield was, on average, 37.9% higher under normal sowing conditions compared with late sowing, confirming the strong influence of sowing time on crop performance. No significant differences were observed among cultivars or plant densities. These findings provide relevant guidance for producers and reinforce sowing time as a key factor for efficient wheat management.

**Keywords:** *Triticum aestivum* L., growth traits, agrometeorology, agricultural management practices.

## INTRODUCTION

Wheat plays a fundamental role in Brazil's agricultural economy, serving as a key component of food security and industrial processing. Although Brazil still imports a substantial share of its domestic wheat demand, national production has increased in recent years, particularly in regions such as the Southeast.[1] Minas Gerais, characterized by diverse climatic and soil conditions, has emerged as an important wheat-producing state, contributing to efforts aimed at increasing national self-sufficiency.[2]

The expansion of wheat cultivation in Minas Gerais has been driven by technological advances, the development of improved cultivars, and the adoption of sustainable management practices that enhance productivity and profitability.[3] Research focused on optimizing sowing time and planting density is essential to maximize yield and improve crop resilience to climatic variability, thereby strengthening the role of Minas Gerais as a strategic wheat-producing region in Brazil.

In tropical regions of Brazil, wheat cultivation frequently faces challenges associated with local weather conditions. Under rainfed systems, water deficits combined with high temperatures can impair crop growth, particularly by increasing the incidence of floral abortion, which is one of the main limiting factors for wheat production.[4,5] In addition, phytosanitary problems such as wheat blast, one of the most damaging diseases affecting the crop, are common and difficult to control.[6] In this context, adjustments in sowing date and plant density are essential to improve the use of solar radiation and, more importantly, water availability. These management strategies also contribute to establishing more favorable micrometeorological conditions for wheat growth and development.

The evaluation of solar radiation use efficiency and air temperature is crucial for understanding wheat crop responses under tropical conditions. Solar radiation directly affects photosynthesis, biomass accumulation, and grain filling, thereby influencing yield potential.[7] Likewise, air temperature plays a critical role in crop development by regulating the rates of physiological processes.[7] Variations in planting density modify canopy architecture, altering light interception and the microclimate within the crop canopy. Similarly, early or late sowing exposes plants to distinct thermal and radiative regimes, affecting growth dynamics and stress tolerance. Understanding these interactions is essential for developing adaptive management strategies that optimize yield and resource-use efficiency under variable environmental conditions.

One of the main challenges limiting the advancement of wheat cultivation in Minas Gerais is the selection of suitable cultivars in relation to sowing time and planting density. Studies that characterize local water availability are essential for refining the Agricultural Zoning of Climate Risk (ZARC), which recommends sowing periods with the lowest climatic risk, generally ranging from February to March.[8] Regarding plant density, the recommended range for rainfed wheat production varies from 350 to 450 viable seeds $m^{-2}$.[9]

Under well-managed soils with high fertility and adequate water availability, it is advisable to adopt planting densities closer to the lower end of the recommended range.[10-12] Higher plant densities can negatively affect tiller formation and plant architecture, which in turn influences the capacity of individual plants to intercept solar radiation. Moreover, increased planting densities can lead to a significant rise in production costs.[13]

Therefore, studies that assist wheat producers in defining more accurate sowing times and planting densities for major cultivars under specific meteorological conditions are essential, as they can contribute to yield improvement and support the expansion of wheat cultivation in Minas Gerais. Thus, the objective of this study was to evaluate the response of wheat cultivars in terms of growth, micrometeorological conditions, and yield-related traits under different sowing times and planting densities.

## MATERIAL AND METHODS

The experiment was conducted during the autumn–winter growing season of 2022 at the Center for Scientific and Technological Development of the Federal University of Lavras (Universidade Federal de Lavras–UFLA), located at 21°14'43" S and 44°59'59" W. The soil at the experimental site is classified as Latossolo Vermelho-Amarelo according to the Brazilian Soil Classification System[14] and as a Typic Hapludox according to Soil Taxonomy.[15]

The regional climate is classified as Cwa (humid subtropical with dry winters) under the Köppen climate classification, characterized by cold and dry winters and hot, humid summers. The mean annual air temperature is 20 °C, with an average annual rainfall of 1,460 mm and a potential evapotranspiration of 873 mm.[16]

The experimental design consisted of a randomized complete block design arranged in a triple factorial scheme (cultivar × plant density × sowing time), comprising 12 treatments with three replications. The treatments included the wheat cultivars BRS 264 (Brazilian Agricultural Research Corporation–Embrapa), Tbio Aton and Tbio Duque (Biotrigo Genética), and ORS Feroz (OR Genética de Sementes), evaluated at planting densities of 250, 350, and 450 viable seeds $m^{-2}$ under two sowing times.

The experiment was conducted during two distinct sowing periods within the recommended wheat planting window. The first period was defined as the normal (recommended) sowing time, while the second corresponded to late sowing. The first sowing was performed on March 9, 2022, with harvest on July 29, 2022, whereas the second sowing occurred on March 30, 2022, with harvest on August 19, 2022.

Each experimental plot measured 5 m in length and 1 m in width, totaling 5 $m^2$, with an inter-row spacing of 0.20 m. Crop management practices followed the recommendations of the Brazilian Commission for Wheat and Triticale Research.[9]

Meteorological data were obtained from a weather station installed near the experimental area. Data on incident solar radiation (MJ $m^{-2}$), air temperature (°C), and precipitation (mm) were recorded throughout the growing season. The water balance was calculated on a ten-day scale to determine periods of water deficit and surplus during the wheat production cycle in 2022. Calculations followed the Thornthwaite and Mather model,[17] which accounts for soil–plant–climate interactions using precipitation, soil water holding capacity (AWC), and crop evapotranspiration (ETc).

According to the water balance (Figure 1), an initial period of water surplus was observed, followed by water deficit throughout most of the crop cycle, resulting in a total accumulated deficit of 364.7 mm, particularly from early May onward. These results indicate that the water demand of the wheat crop was not fully met during the growing season.

Destructive sampling was performed during the wheat growth cycle to evaluate plant development. Five representative plants were collected per plot, and four evaluations were conducted at approximately 15-day intervals. For the first sowing time, evaluations took place on April 11, April 29, May 13, and June 2, 2022; for the second sowing time, evaluations were conducted on April 29, May 13, June 2, and June 19, 2022.

The collected samples were used to determine leaf area index (LAI), specific leaf area (SLA), and plant dry matter. Leaf area was measured using a LI-3000C leaf area integrator. Specific leaf area (SLA) was calculated as the ratio between leaf area and leaf dry matter. The leaf area index (LAI) was calculated based on the leaf area of each plant and the soil area it occupies, according to Equation (1):

$$LAI = LA/SA \quad (1)$$

Where: LAI = Leaf Area Index; LA = Total leaf area of the plant ($cm^2$); SA = Explored soil area by the plant ($cm^2$).

For dry matter determination, the collected plants were oven-dried at 65 °C in a forced-air circulation oven until constant weight and subsequently weighed using an analytical balance.

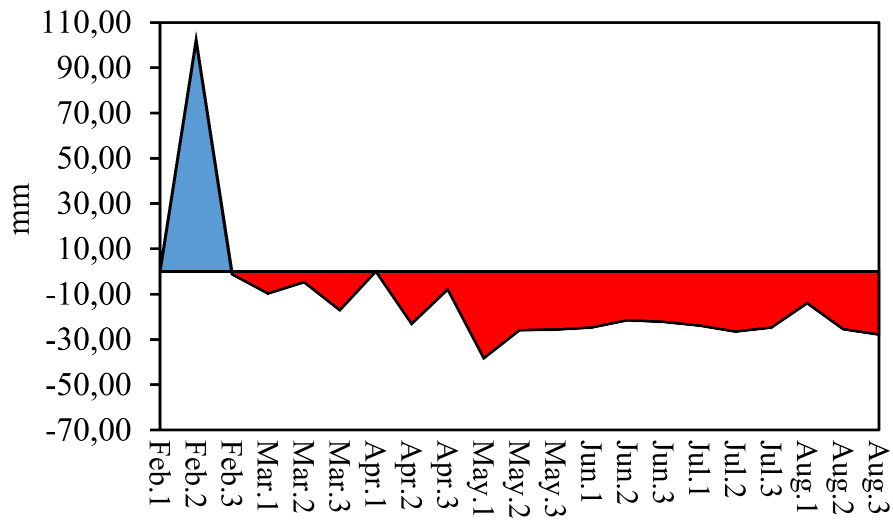


**Figure 1.** Sequential water balance of wheat crop on a ten-day scale during the crop cycle.

Wheat yield was evaluated by harvesting a 3 $m^2$ area from each plot. Grain yield was determined by weighing the total grain mass obtained per plot, correcting the values to 13% moisture content, and extrapolating the data to kg $ha^{-1}$.

Radiation use efficiency (RUE) was estimated using total plant dry matter and meteorological data. Biomass production was calculated based on the model proposed by Monteith,[18] in which dry biomass is considered dependent on the amount of intercepted photosynthetically active radiation (PAR) multiplied by the efficiency of conversion into dry matter.

Thus, radiation use efficiency was calculated as the ratio between accumulated dry biomass production and intercepted photosynthetically active radiation (IPAR), as described in Equation (2):

$$BP = \varepsilon b * IPAR \quad (2)$$

where BP is dry biomass production (g $m^{-2}$), IPAR is intercepted photosynthetically active radiation (MJ $m^{-2}$), and εb is radiation use efficiency, representing the efficiency of IPAR conversion into dry biomass (g $MJ^{-1}$). The slope of this relationship represents the amount of accumulated biomass produced per unit of intercepted energy.

The intercepted photosynthetically active radiation (IPAR) was estimated according to the model proposed by Varlet-Grancher,[19] as shown in Equation (3):

$$IPAR = 0.95 * (PARinc) * (1 - e^{(-K*LAI)}) \quad (3)$$

Where: IPAR = Intercepted photosynthetically active radiation (MJ $m^{-2}$); PARinc = Incident photosynthetically active radiation (MJ $m^{-2}$); K = Extinction coefficient, which depends on the optical properties of the leaves and the canopy geometry (dimensionless); LAI = Leaf area index (dimensionless).

In parallel with growth assessments, micrometeorological measurements were performed for each treatment. Incident solar radiation within and above the crop canopy was measured using a portable pyranometer. Air temperature was recorded using an infrared thermometer at three positions: within the canopy, near the soil surface, and above the canopy. Measurements were conducted between 10:00 and 12:00 h. Solar radiation interception (SRI) was calculated using the equation proposed by Caron,[20] as shown in Equation (4):

$$\%interception = [100 - ( Rn \times \frac{100}{Rt} )] \quad (4)$$

Where: Rn = Incident solar radiation within the canopy; Rt = Total incident solar radiation above the canopy.

Statistical analyses were performed using SISVAR software.[21] Data related to plant growth and micrometeorological variables were analyzed using descriptive statistics to characterize cultivar responses throughout the production cycle under different sowing times and plant densities. Grain yield and radiation use efficiency data were subjected to analysis of variance (ANOVA), and treatment means were compared using Tukey's test, with statistical significance considered at $p<0.05$.

## RESULTS AND DISCUSSION

### *Wheat growth traits during the crop cycle*

Based on the results, a similar response pattern was observed among the studied cultivars during the normal sowing season (Figure 2). The highest leaf area index values were recorded 51 days after sowing, followed by a gradual decline toward the end of the crop cycle. Specific leaf area exhibited its highest values during the initial stages of plant growth, with a subsequent decrease as development progressed.

The leaf area index directly influences solar radiation interception and carbon assimilation.[22,23] During the vegetative phase, LAI increases progressively and reaches its maximum near flowering, when the crop's photosynthetic capacity is highest. Specific leaf area, which expresses the ratio between leaf area and leaf biomass, serves as an indicator of leaf thickness and structural efficiency. High SLA values during early growth stages reflect thinner leaves, whereas the decline observed during the reproductive phase indicates thicker leaves and greater reserve accumulation. The combined analysis of these variables helps elucidate canopy dynamics and their interaction with the wheat micrometeorological environment, which directly influences crop productivity.

The results for leaf area index and specific leaf area during the late sowing season are shown in Figure 3. The response pattern of these growth variables differed markedly from that observed under normal sowing conditions (Figure 2). The highest LAI and SLA values were recorded 33 days after sowing, followed by a sharp decline throughout the crop cycle. This behavior is associated with reduced rainfall and the water deficit observed in Figure 1.

It is important to note that LAI values during late sowing were consistently lower than those observed during the normal sowing season, indicating less favorable conditions for plant development, particularly in terms of water

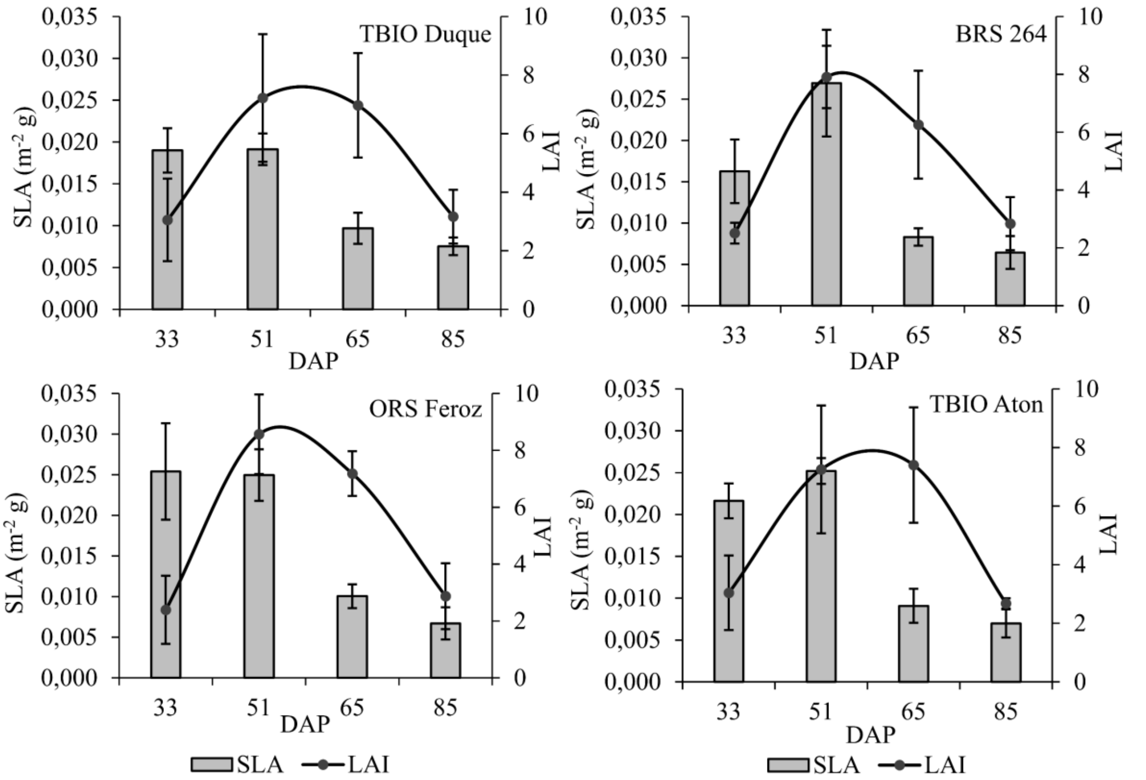


**Figure 2.** Specific leaf area and leaf area index during the crop cycle of different wheat cultivars in the normal planting season.

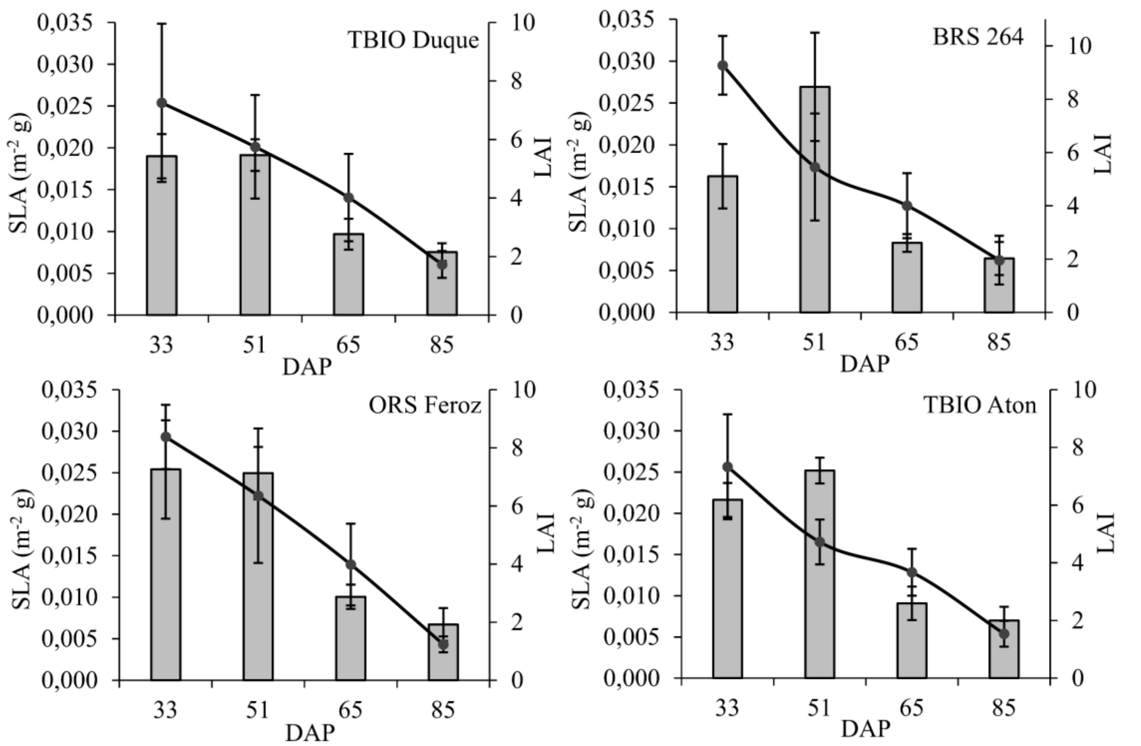


**Figure 3.** Specific leaf area and leaf area index during the crop cycle of different wheat cultivars in the late planting season.

availability. In this context, special attention should be given to the challenges faced by wheat crops sown at the end of March. Rainfall reduction and the resulting water deficit become more pronounced from April onward in the Campo das Vertentes mesoregion.[24] This aspect is critical when selecting sowing dates, as it directly affects water availability throughout the production cycle. Wheat sown at the end of March (late sowing) may therefore experience significant constraints during both establishment and development due to water scarcity from April onward.

Leaf area index and specific leaf area are key variables for assessing wheat photosynthetic efficiency and growth.[22,25] These growth-related traits determine both the amount of solar radiation intercepted by the canopy and the plant's capacity to convert intercepted radiation into dry matter and, ultimately, grain yield.

### *Micrometeorology in different wheat cultivars*

A similar response pattern was observed for temperature inside and above the canopy among the wheat cultivars throughout the production cycle, for both the normal sowing season (Figure 4) and the late sowing season (Figure 5). The highest temperatures occurred at the beginning of the crop cycle, when leaf area was still limited, whereas the lowest temperatures were recorded approximately 65 days after sowing. This period coincided with the maximum leaf area values (Figures 2 and 3), which contributed to reducing temperature fluctuations within the canopy. As leaf senescence progressed, canopy temperatures increased again due to greater soil exposure to solar radiation.

When comparing planting seasons, maximum temperatures inside the canopy were higher during the normal planting period than during late planting, particularly at the beginning of the crop cycle. This difference is attributed to the higher average air temperatures prevailing during the normal sowing period. The highest temperatures recorded in the experiment occurred inside the canopy, with mean values exceeding 40 °C.

Canopy temperature is closely linked to local microclimatic conditions and is influenced by factors such as leaf area and canopy architecture. Moreover, canopy temperature relative to ambient air temperature can be an indicator of plant water stress.[26,27]

In most cases, canopy temperature was higher than the external air temperature, which may be associated with water deficit and the consequent increase in soil temperature. Photosynthetic activity and the rate of biochemical reactions in plants are strongly influenced by canopy temperature.

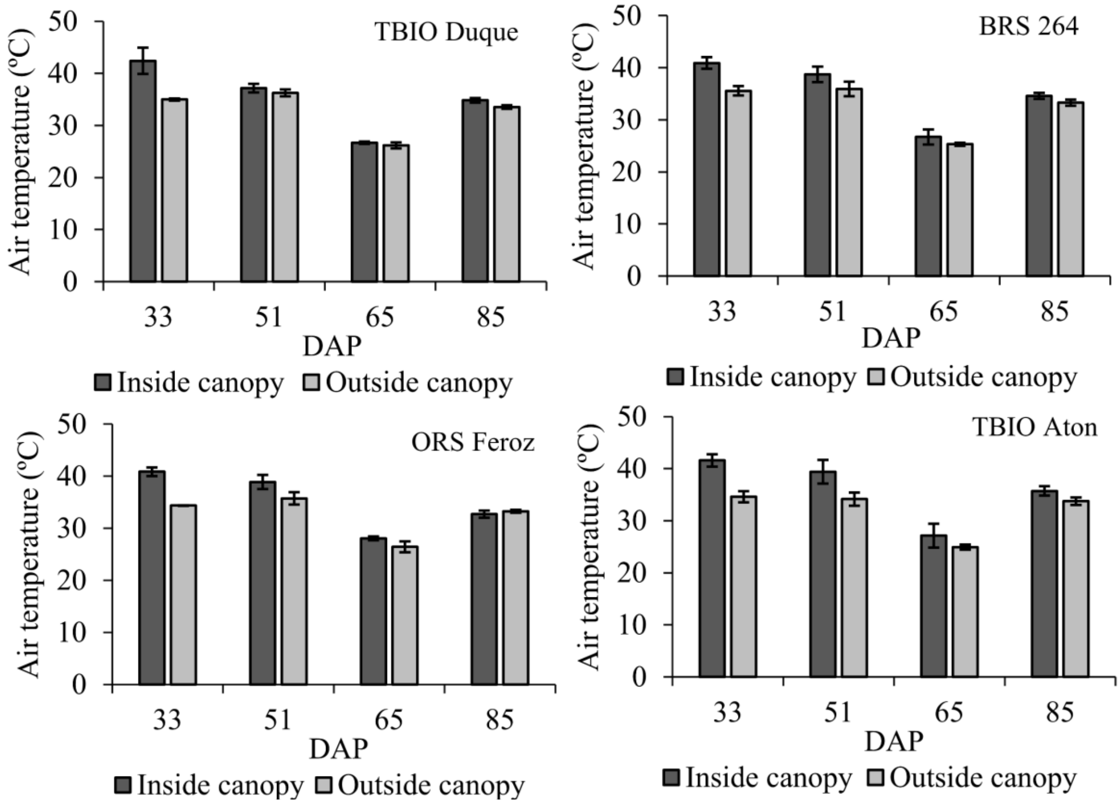


**Figure 4.** Air temperature inside and outside wheat canopy during the cycle of different cultivars in the normal planting season.

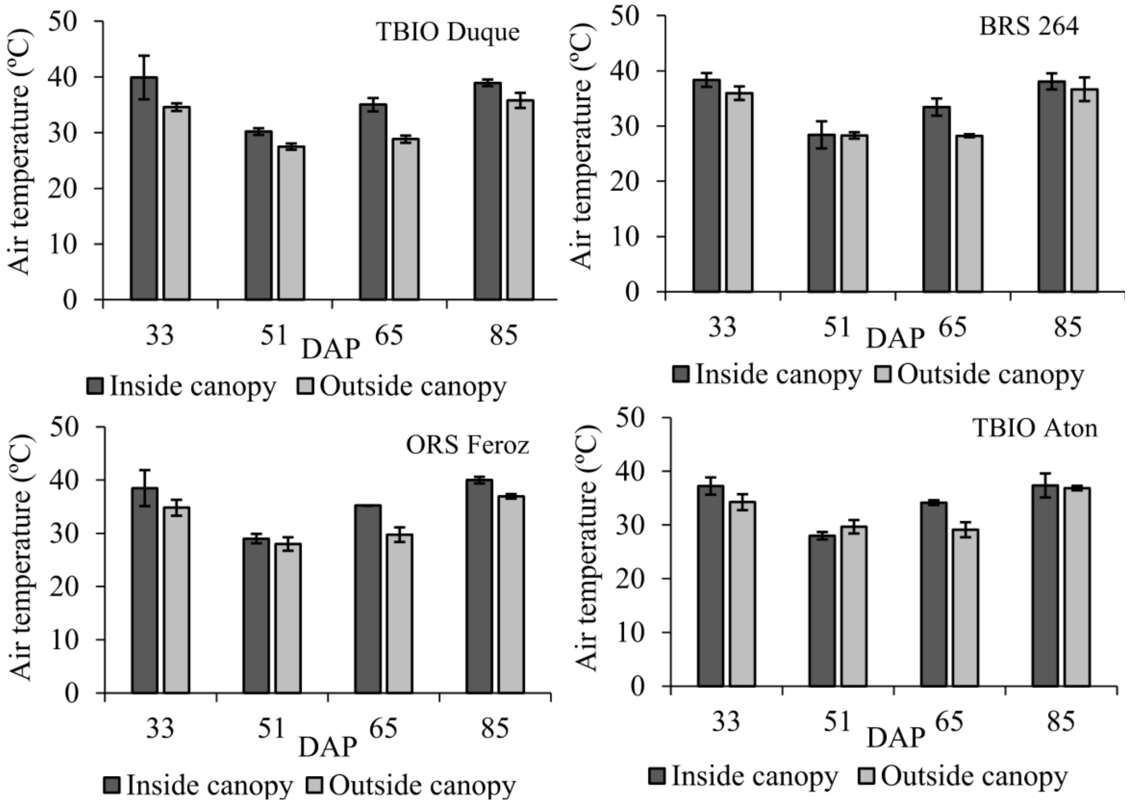


**Figure 5.** Air temperature inside and outside wheat canopy during the cycle of different cultivars in the late planting season.

Under heat stress conditions, plant metabolism is impaired, leading to a reduction in yield potential.[28,29]

During the normal planting season, cultivars exhibited similar patterns of solar radiation interception, with maximum values occurring 51 days after planting (Figure 6), coinciding with peak LAI. Plant density did not significantly affect solar radiation interception. In some cases, such as for the BRS 264 cultivar, increasing plant density resulted in lower radiation interception. This suggests that higher plant densities intensify competition for resources, negatively affecting canopy radiation interception.

Solar radiation interception is a fundamental micrometeorological variable, as it reflects the canopy's capacity to capture and use solar energy for photosynthesis. Low interception values indicate poor soil coverage and reduced photosynthetic capacity.[25]

During the late sowing season, solar radiation interception did not follow a consistent pattern with respect to plant density (Figure 7). The TBIO Duque and TBIO Aton cultivars exhibited higher interception at a density of 250 plants $m^{-2}$, whereas BRS 264 showed better performance at 350 plants $m^{-2}$. A pronounced reduction in radiation interception was observed 65 days after sowing, associated with decreased leaf area during this period (Figure 3). This reduction is likely related to the shortened crop cycle and accelerated maturation caused by water deficit during the growing season.

### *Radiation use efficiency and wheat yield*

Based on the Anova results, a significant effect of plant density was observed for radiation use efficiency (RUE), whereas wheat yield was significantly affected only by sowing time. Overall, RUE increased with higher plant densities, indicating greater biomass accumulation per unit of intercepted radiation (Figure 8). However, higher radiation use efficiency did not necessarily result in increased grain yield. According to Molero,[30] radiation use efficiency is a key physiological trait, as it can explain approximately 40% of yield variability. Furthermore, RUE provides insight into light capture processes and the biochemical mechanisms in leaves that drive biomass accumulation and yield formation.[25,31]

The RUE results highlight the effects of plant competition for natural resources, particularly water. Although higher plant populations resulted in greater dry matter accumulation per unit area, individual plant productivity may have been reduced, which in some cases did not translate into higher grain yield. The RUE values observed in this study are consistent with those reported in the literature for wheat.[22,30,31]

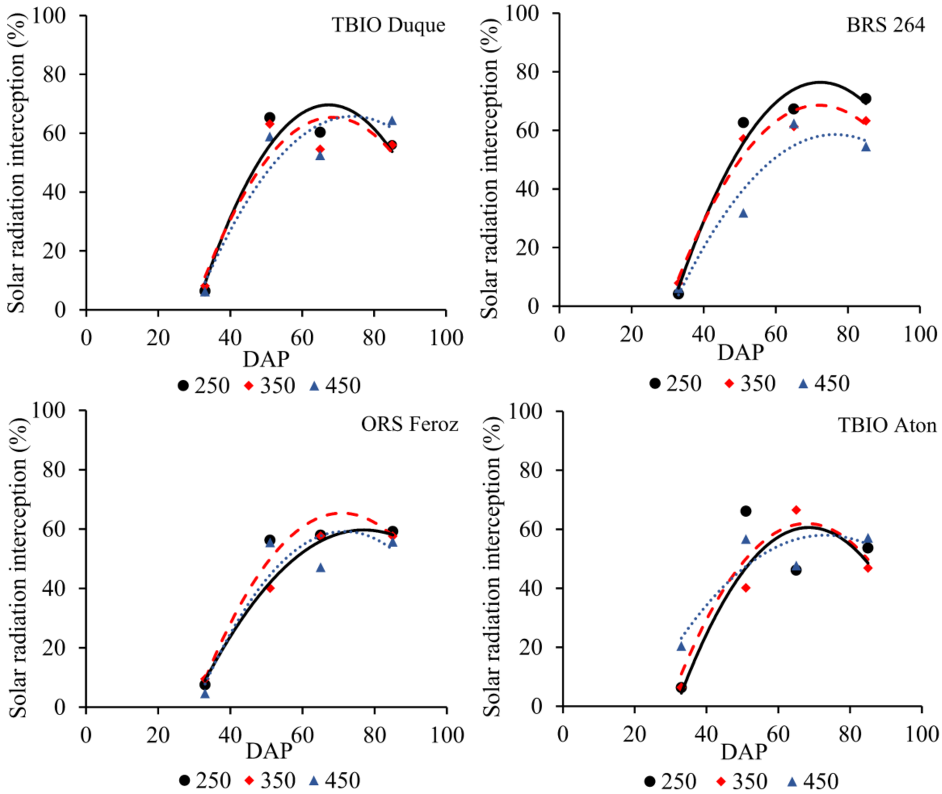


**Figure 6.** Interception of solar radiation during the crop cycle of different wheat cultivars as a function of three plant densities in the normal planting season.

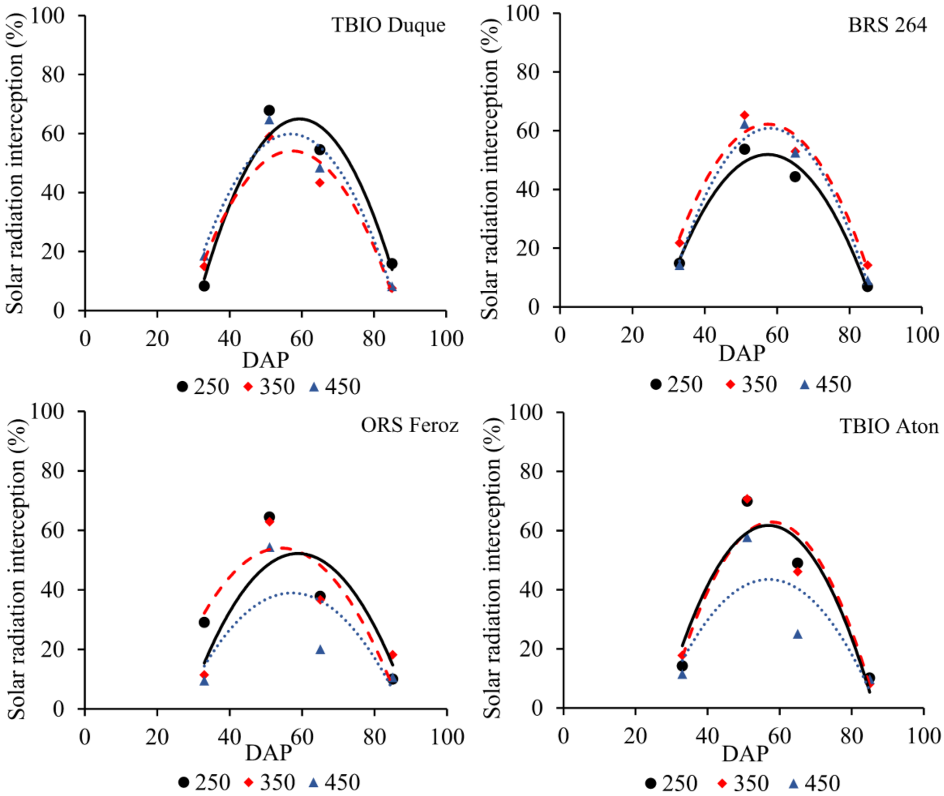


**Figure 7.** Interception of solar radiation during the crop cycle of different wheat cultivars as a function of three plant densities in the late planting season.

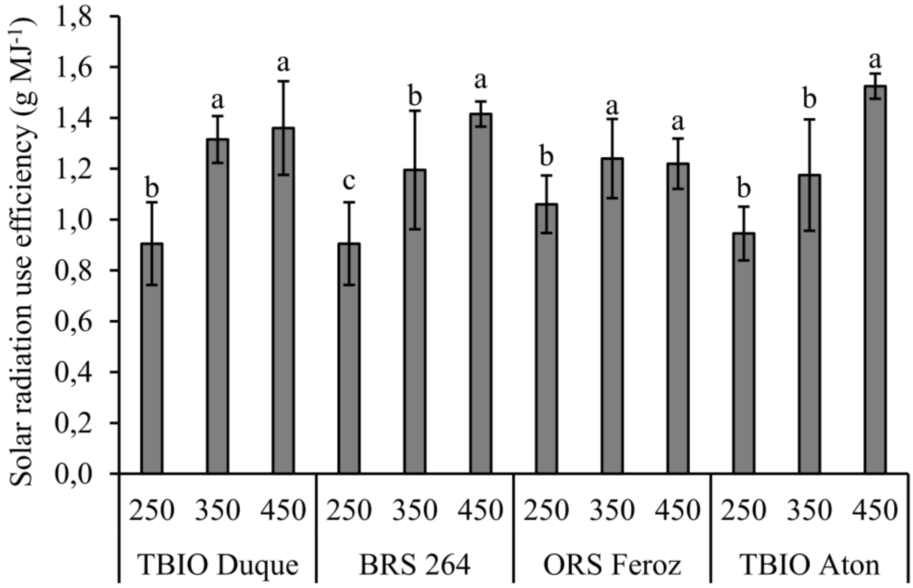


**Figure 8.** Solar radiation use efficiency for different wheat cultivars and plant densities under normal and late planting times. *Different lowercase letters indicate a statistical difference according to the Tukey test ($p<0.05$).

Grain yield was strongly influenced by sowing time (Figure 9). The highest yields were obtained during the sowing period considered normal, corresponding to the window recommended by the Agricultural Zoning of Climatic Risk (ZARC).(8) The yield difference between sowing periods was approximately 38%. Higher yields under normal sowing conditions were associated with greater water availability at the beginning of the crop cycle, higher growth rates, and increased solar radiation interception. Therefore, selecting the optimal sowing period, combined with appropriate cultivar placement within this window, enhances yield potential and profitability. This principle applies not only to wheat(12) but also to other major crops, such as maize(32) and soybean.(33)

Planting wheat outside the recommended zoning window can result in substantial yield losses in agricultural production systems. Wheat requires mild temperatures and adequate water availability to achieve its full yield potential.(24) Under late sowing conditions, the drought tolerance of wheat cultivars may partially support commercial production in the region; however, the primary research challenge lies in identifying and developing cultivars with enhanced drought tolerance.(3)

No significant differences in yield were observed among cultivars or planting densities. This response may be attributed to the compensatory ability of wheat through tillering, which allows plants to offset lower plant populations by producing additional tillers. In a study evaluating different planting densities for the wheat cultivar BRS Belajoia, no significant differences in grain yield were observed for densities ranging from 200 to 500 viable seeds $m^{-2}$ under most conditions.(34)

The information generated in this study provides valuable support for wheat producers in agricultural planning and decision-making, particularly in identifying optimal combinations of cultivars and sowing times. Wheat sown in early March benefits from greater water availability, ensuring adequate crop establishment. In contrast, sowing at the end of March (late period) may result in severe constraints on establishment and development due to water deficits occurring from April onward.

## CONCLUSIONS

This study demonstrated that wheat cultivars responded primarily to variations in sowing time, with planting within the recommended window providing clear advantages in terms of growth, micrometeorological conditions, and productivity. Favorable water availability, higher growth rates, and greater radiation interception during this period supported improved crop performance. On average, grain yield under the recommended sowing window was 37.9% higher than under late sowing, highlighting the substantial productivity gains associated with optimal sowing time. In contrast, late sowing exposed plants to water deficit, reducing leaf area, limiting radiation interception, shortening the crop cycle, and ultimately decreasing yield.

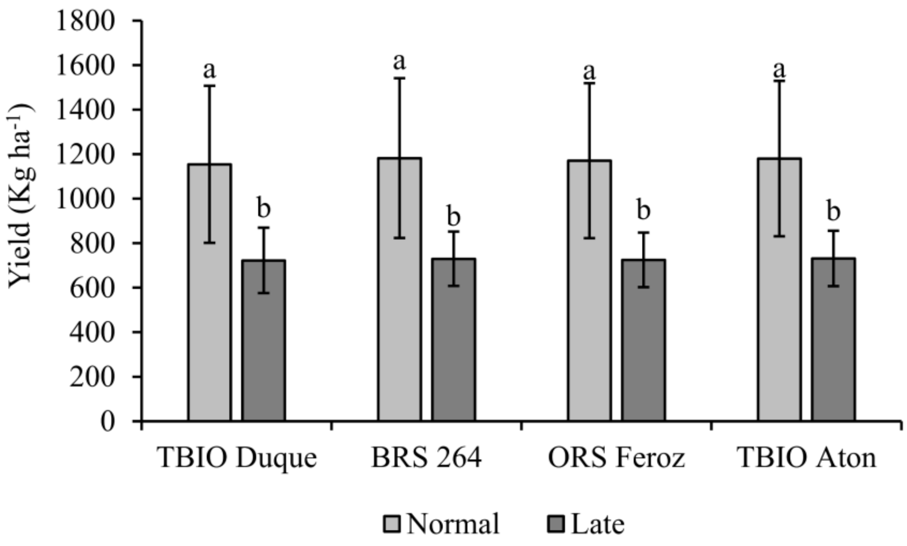


**Figure 9.** Grain yield for different wheat cultivars under normal and late planting times. *Different lowercase letters indicate a statistical difference according to the Tukey test ($p<0.05$).

No significant differences were observed among cultivars or planting densities, indicating that these factors played a secondary role under the environmental conditions of this study. Overall, the results confirm sowing time as the dominant driver of wheat responses across growth, micrometeorological, and productivity traits, emphasizing its critical importance for management decisions and for the expansion of wheat cultivation in cropping systems in Minas Gerais.

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## DATA AVAILABILITY STATEMENT

All data supporting the results of this study are contained within this article.

## AUTHOR CONTRIBUTIONS

**Conceptualization:** Felipe Schwerz, José Maria Villela Pádua.

**Data curation:** Gabriel Lasmar Soares, Lara Eduarda Silva Viol.

**Formal analysis:** Gabriel Lasmar Soares, Adilson Júnior Soares Alves.

**Funding acquisition:** Felipe Schwerz.

**Investigation:** Adilson Júnior Soares Alves, José Maria Villela Pádua.

**Methodology:** Gabriel Lasmar Soares, Lara Eduarda Silva Viol.

**Project administration:** Felipe Schwerz, José Maria Villela Pádua.

**Resources:** Fábio Aurélio Dias Martins.

**Supervision:** Felipe Schwerz, José Maria Villela Pádua.

**Validation:** Fábio Aurélio Dias Martins.

**Visualization:** José Maria Villela Pádua.

**Writing – original draft:** Gabriel Lasmar Soares.

**Writing – review & editing:** Felipe Schwerz, Lara Eduarda Silva Viol, Fábio Aurélio Dias Martins.

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