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Research Article

Agronomic strategies to mitigate abiotic stresses in tropical rainfed wheat[1]

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ABSTRACT

Wheat (*Triticum aestivum* L.) crop yield and performance are strongly influenced by abiotic stresses, particularly water deficit. This study evaluated the performance of wheat cultivars under different sowing dates and plant densities in rainfed conditions. Field experiments were conducted during the 2021 and 2022 growing seasons, using a randomized complete block design, with three replications. The treatments followed a factorial arrangement consisting of four cultivars, three sowing dates, and three plant populations. Agronomic and agrometeorological variables were monitored throughout the crop cycle. The plant density did not significantly affect grain yield, with no benefits observed from increasing seeding rates. The cultivars performance varied across sowing dates, with distinct genotypes performing better under early or normal sowing conditions. The normal sowing period was identified as the most suitable window, based on prevailing climatic patterns. The integration of agronomic and agroclimatic data indicated that late sowing substantially increases the risk of yield loss due to water limitations.

KEYWORDS: *Triticum aestivum* L., climatic variables, water deficit.

RESUMO

Estratégias agronômicas para mitigar estresses abióticos em trigo tropical de sequeiro

A produtividade e o desempenho da cultura do trigo (*Triticum aestivum* L.) são constantemente influenciados por estresses abióticos, especialmente o déficit hídrico. Objetivou-se avaliar o desempenho de cultivares de trigo em diferentes datas de semeadura e densidades de plantas, em condições de sequeiro. Os experimentos foram conduzidos nas safras de 2021 e 2022, utilizando-se delineamento em blocos ao acaso, com três repetições. Os tratamentos seguiram um arranjo fatorial composto por quatro cultivares, três datas de semeadura e três populações de plantas. Variáveis agronômicas e agrometeorológicas foram monitoradas ao longo do ciclo da cultura. A densidade de plantas não afetou significativamente a produtividade de grãos, não sendo observados benefícios do aumento na taxa de semeadura. O desempenho das cultivares variou entre as datas de semeadura, com genótipos distintos apresentando melhor performance em semeadura antecipada ou em época normal. A época normal de semeadura foi identificada como a janela mais adequada, considerando-se os padrões climáticos predominantes. A integração de dados agronômicos e agroclimáticos indicou que a semeadura tardia aumenta substancialmente o risco de perda de produtividade devido às limitações hídricas.

PALAVRAS-CHAVE: *Triticum aestivum* L., variáveis climáticas, déficit hídrico.

INTRODUCTION

Almost all wheat production in Brazil is concentrated in the Southern region (Conab 2025). However, increasing governmental incentives aimed at achieving self-sufficiency in grain production, particularly wheat, have stimulated research efforts to expand cultivation into the Central region of the country (Pasinato et al. 2018). This expansion depends on the development of cultivars adapted to local conditions, resilient to biotic and abiotic stresses, and aligned with national strategies for food security and sustainable production (Coelho et al. 2016).

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The expansion of wheat cultivation into new agricultural frontiers has been observed in several countries, with Australia standing out as one of the world's major producers, due to the adoption of highly adapted systems for low-rainfall environments (Collins & Chenu 2021). In south Australia, wheat is cultivated under restricted rainfall regimes using varieties genetically selected for drought tolerance and shorter growth cycles, enabling stable yields even under adverse edaphoclimatic conditions (Acuña et al. 2011). Similarly, other countries have expanded wheat production into tropical high-altitude or warm-climate regions, where breeding programs emphasize heat tolerance, drought resistance, and photoperiod adaptation, allowing wheat to advance into areas previously considered marginal (Braun et al. 2013).

Despite the prominence of the Minas Gerais state in emerging wheat-producing regions, its tropical climate poses significant challenges to yield, requiring information on cultivar adaptation, plant population, and sowing time to support decision-making (Condé et al. 2011, Pereira et al. 2019). Wheat expansion into tropical environments offers opportunities for breeding, but faces constraints such as high temperatures, irregular rainfall, and diseases such as wheat blast (*Pyricularia oryzae* pathotype *triticum*), which frequently reduce yield and grain quality (Bushuk 2001, Borém & Scheeren 2015, Maciel et al. 2024).

The Minas Gerais climate is predominantly subtropical humid, with well-defined dry and rainy seasons (Alvares et al. 2013). In the Vertentes region, rainfall is concentrated between October and March, followed by a pronounced dry period from April to September, limiting the water availability for rainfed crops such as wheat (Aparecido et al. 2023). This irregular rainfall distribution, combined with high interannual variability, directly affects soil moisture and, consequently, the optimal sowing window (Aparecido et al. 2023). In this context, studies that characterize local water availability are essential to refine the Agricultural Zoning of Climate Risk (ZARC). A specific ZARC is already available for rainfed wheat in the region (Pasinato et al. 2018), highlighting the importance of continuous research to improve its accuracy and support decision-making for sustainable wheat production under water-limited conditions.

A key strategy for adapting wheat to tropical regions involves evaluating different sowing dates, once sowing time directly influences the alignment between crop development and climatic conditions, thereby affecting performance (Spink et al. 2000, Jarecki 2024). Early or late sowing may expose the crop to critical stresses such as high temperatures during flowering or drought during grain filling, leading to yield instability (Coelho et al. 2019, Pires & Cunha 2022). Determining the optimal sowing window is therefore essential to reduce climatic risk and ensure the full expression of the genetic potential of new cultivars.

In addition, the evaluation of different plant populations plays a fundamental role in breeding programs. Plant density influences light interception, tillering capacity, disease incidence, and resource-use efficiency (Zhang et al. 2023). Lower densities may favor tiller development, but excessive tillering under tropical stress conditions can compromise crop uniformity and final yield (Valério et al. 2009). Conversely, higher densities enhance ground cover and competitiveness with weeds, but may increase intraspecific competition, reducing grain size and quality (Caierão 2008). Therefore, research must identify the population levels at which new cultivars perform optimally under tropical conditions.

It is also essential to understand cultivar performance across varying sowing dates and their responses to climatic variability and extreme weather events, such as drought, heat stress, and excessive rainfall (Casadebaig et al. 2016, Ahmad et al. 2020). In this context, the development of more efficient agronomic strategies and resilient cropping systems represents a critical challenge for sustainable wheat production (Mohammadi 2018). This approach not only supports the identification of cultivars adapted to the Brazilian tropics, but also strengthens food security by enabling wheat expansion into non-traditional areas.

Given the scarcity of data on wheat performance in the mesoregion of Campo das Vertentes, many recommendations currently provided to farmers are derived from research conducted in other regions, making the present study pioneering. In this scenario, evaluating sowing times and plant populations is a necessary step in tropical wheat research programs, as it refines agronomic recommendations and accelerates the identification of cultivars that combine high yield potential, stability, and resistance to the biotic and abiotic stresses characteristic of tropical agriculture.

From this perspective, this study aimed to evaluate the agronomic performance of wheat cultivars under different sowing dates and plant densities under rainfed conditions in the Minas Gerais state, with the goal of identifying management-genotype combinations that enhance yield and adaptation to tropical environments.

MATERIAL AND METHODS

The study was conducted in Ijaci, southern Minas Gerais state, Brazil (21º9’51”S, 44º54’58”W and altitude of 833 m), where the soil is classified as Latossolo Vermelho-Amarelo (Santos et al. 2018) or Typic Hapludox (USDA 2022).

The regional climate, according to the Köppen classification, is Cwa (subtropical humid), characterized by hot and humid summers and cold, dry winters, with mean temperatures of 18-22 ºC and average annual rainfall of 1,650 mm (Aparecido et al. 2023). The dry season extends from May to September, whereas the rainy season typically lasts until late March or early April.

Meteorological data for maximum, minimum, and mean air temperatures, as well as rainfall, were obtained from a meteorological station of the National Institute of Meteorology (INMET-Brazil), located at approximately 5 km from the experimental area. The water balance was calculated on a ten-day scale to estimate water deficit and surplus during the wheat production cycle, in the 2021 and 2022 seasons (Figure 1). Calculation followed the Thornthwaite & Mather (1955) model, which integrates rainfall, soil water-holding capacity (set at 100 mm, based on the soil’s physical-hydraulic properties in the experimental area), and crop evapotranspiration (ETc), which was calculated as ETc = Kc × ETo, where Kc is the crop coefficient and ETo the reference evapotranspiration. The wheat ETo was estimated using the Thornthwaite (1948) method.

The thermal sum of the wheat crop was also calculated for the different sowing dates. Daily

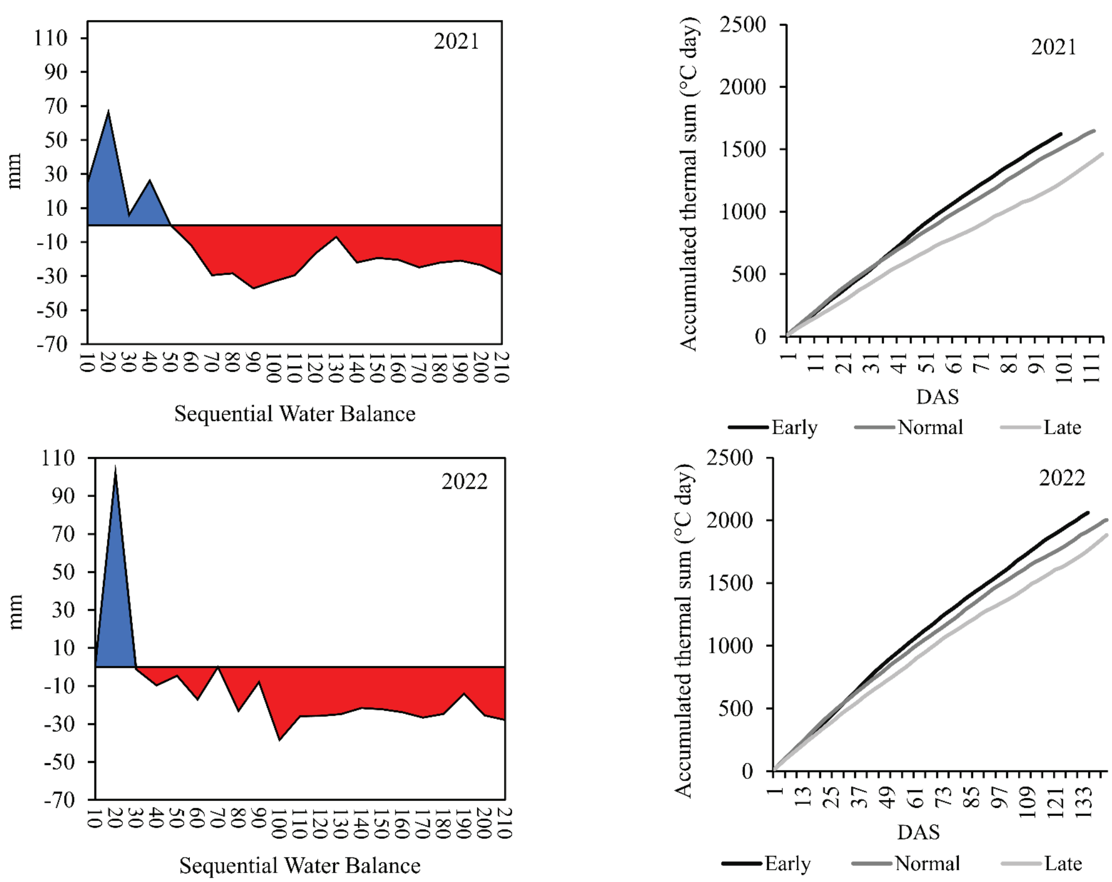

Figure 1. Sequential water balance of wheat crop on a ten-day scale and accumulated thermal sum for the 2021 and 2022 crops. DAS: days after sowing.

thermal sums (DTS; ºC day) were estimated using the Gilmore & Rogers (1958) method: DTS = Tmean - Tb, where Tmean is the daily mean air temperature and Tb the base temperature, set at 5 ºC. The accumulated thermal sum (ATS; ºC day) was obtained by summing daily values from emergence to harvest (ATS = ∑ DTS) (Figure 1).

The experiments were carried out during the 2021 and 2022 crop seasons, in a randomized block design arranged in a 4 × 3 × 3 factorial scheme, with three replications. Four wheat cultivars were evaluated: BRS 264 (Embrapa), TBIO Aton and TBIO Duque (Biotrigo Genética), and ORS Feroz (OR Genética de Sementes). Three sowing densities were tested: 250, 350, and 450 plants m^{-2}; as well as three sowing dates within the recommended planting window for the region: early, normal, and late. In 2021, sowing occurred on February 9, March 11, and April 4, respectively. In 2022, early sowing was carried out on February 16, normal on March 9, and late on April 10.

Plots measured 5 m² and consisted of five rows, each 5 m long and spaced 0.20 m apart. Pests and diseases were monitored and managed according to the crop requirements. At sowing, 300 kg ha^{-1} of NPK fertilizer (08 % of N, 28 % of P_2O_5 and 16 % of K_2O) were applied, and 30 kg ha^{-1} of N were applied as topdressing at the tillering stage.

The evaluated agronomic traits included plant height, flag leaf height, grain yield, 1,000-kernel weight, and number of grains per ear. Plant and flag leaf heights were measured using a ruler on three randomly selected plants from the central rows of each plot after flowering (stage 71 of Zadoks et al. 1974), and mean values were calculated. Plant height was measured from the plant base to the tip of the spike, and flag leaf height from the plant base to the insertion of the last leaf. Grain yield was obtained from a 5-m² useful area per plot, converted to kg ha^{-1}, and standardized to 13 % of moisture. One thousand kernel weight was determined by averaging three subsamples of 1,000 grains per plot. For number of grains per ear, three plants were collected before harvest, the grains of each ear were counted, and the average was used as the plot value.

After testing normality and homoscedasticity, analysis of variance (Anova) was performed for the 2021 and 2022 seasons, considering the factors season, cultivar, and sowing density (4 × 3 × 3). The used model was: $\gamma_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_k + a_{ij} + b_{ik} + c_{jk} + d_{ijk} + r_l + \varepsilon_{ijkl}$, where: $\gamma_{(ijkl)}$ is the value corresponding to the i-th level of the season factor combined with the j-th level of the cultivar factor and the k-th level of the sowing-density factor, in block l; μ the constant associated with all observations; α_i the effect of the i-th level of the season factor; β_j the effect of the j-th level of the cultivar factor; γ_k the effect of the k-th level of the sowing-density factor; r_l the effect of block l; a_{ij} the interaction effect between the i-th level of the season factor and the j-th level of the cultivar factor; b_{ik} the interaction effect between the i-th level of the season factor and the k-th level of the sowing-density factor; c_{jk} the interaction effect between the j-th level of the cultivar factor and the k-th level of the sowing-density factor; d_{ijk} the three-way interaction effect among the i-th level of the season factor, the j-th level of the cultivar factor, and the k-th level of the sowing-density factor; and $\varepsilon_{(ijkl)}$ the experimental error associated with observation $\gamma_{(ijkl)}$, assumed to be an independent and identically distributed random variable with zero mean and constant variance.

The Tukey test was applied when Anova indicated significant differences. Statistical analyses were performed using the R software, version 4.2.1 (R Core Team 2024).

To assist the interpretation of trait interactions, a principal component analysis (PCA) was conducted to identify major patterns of variation and ordination of yield-related traits. PCA and biplots were generated using the R software, version 4.2.1 (R Core Team 2024). Data were standardized by subtracting the mean and dividing by the standard deviation for each variable. Two principal components were retained for interpretation, and variables exhibiting apparent collinearity were excluded from the PCA.

RESULTS AND DISCUSSION

Pronounced water deficit and substantial temperature variation were observed during the wheat production cycle in both crop years (Figure 1). During the early stages of crop establishment, periods of water surplus occurred in both seasons. However, water deficit was recorded from the second half of February 2022 onward. Accumulated rainfall differed markedly among the sowing periods: in both years, the earliest sowing period received approximately 50 % more rainfall than the latest one. Although the rainfall occurred during February 2022 and February and March 2021, it declined sharply as the crop developed, resulting in a negative water balance during most of the remaining cycle.

Thermal accumulation patterns indicated that early and normal sowing dates presented similar accumulated degree-days, reaching approximately 1,660 ºC in 2021 and 2,060 ºC in 2022 (Figure 1). In contrast, late sowing resulted in a reduction of 12 and 9 % in accumulated thermal sum in 2021 and 2022, respectively. This reduction is associated with the intense water deficit observed in the later sowing windows, which accelerated plant maturation and shortened the crop cycle.

Water availability is one of the primary factors determining wheat performance, and the Campo das Vertentes mesoregion typically experiences reduced rainfall after March (Aparecido et al. 2023). Thus, sowing date directly influences the amount of water available during the production cycle. Sowing in February (early period) may benefit the crop establishment due to higher rainfall. Conversely, sowing after late March (late period) may compromise the establishment and development due to water deficiency starting in April (Figure 1).

The Anova results indicated that sowing density had no significant effect, either individually or through interactions, with other factors (Table 1).

These findings are supported by the yield performance of cultivars at different sowing densities across the crop seasons (Figure 2). No consistent pattern of increased yield with higher sowing densities was observed in either 2021 or 2022. Only the BRS 264 cultivar exhibited a numerically higher mean yield at the higher density (Figure 2A).

In this study, density did not increase grain yield (Table 1; Figures 2 and 3). Across all analyses, the sowing density did not differ significantly. These results are particularly relevant when compared with seed company recommendations for the study region, which range from 300 to 450 viable seeds m^{-2} (Cunha & Caierão 2023). It is important to emphasize that seeding density directly influences the yield component number of spikes per area, which is a phenotypic expression resulting from genotype-environment interactions.

Plant population directly influences competition for water, nutrients, and solar radiation (Zhang et al. 2023). Wheat has a natural tillering

Table 1. Analysis of variance considering the factors season, cultivar, and sowing density for the years 2021 and 2022.

Crop season	Source of variation	DF	p-values				
			Plant height	Flag leaf height	Number of grains per ear	1000-kernel weight	Grain yield
2021	Blocks	8	0.80	0.82	0.06	0.27	0.37
	Season	2	0.00**	0.00**	0.09	0.05	0.00**
	Cultivar	3	0.00**	0.00**	0.03**	0.00**	0.03**
	Sowing density (SD)	2	0.33	0.61	0.06	0.37	0.46
	Season *vs.* cultivar	6	0.91	0.47	0.00**	0.06	0.40
	Season *vs.* SD	4	0.26	0.28	0.06	0.15	0.28
	Cultivar *vs.* SD	6	0.41	0.22	0.69	0.27	0.31
	Season *vs.* cultivar *vs.* SD	12	0.25	0.42	0.94	0.11	0.15
	Error	58	-	-	-	-	-
	CV (%)	-	7.87	9.64	20.27	6.57	15.39
	Average	-	54.59	40.67	29.00	34.61	1,034.00
2022	Blocks	8	0.02**	0.04**	0.72	0.22	0.00**
	Season	2	0.00**	0.00**	0.00**	0.00**	0.00**
	Cultivar	3	0.03**	0.01**	0.13	0.00**	0.06
	Sowing density (SD)	2	0.99	0.59	0.16	0.28	0.39
	Season *vs.* cultivar	6	0.25	0.23	0.18	0.00**	0.00**
	Season *vs.* SD	4	0.78	0.86	0.98	0.98	0.86
	Cultivar *vs.* SD	6	0.43	0.44	0.73	0.07	0.54
	Season *vs.* cultivar *vs.* SD	12	0.73	0.85	0.29	0.13	0.71
	Error	70	-	-	-	-	-
	CV (%)	-	12.70	12.55	22.13	7.13	19.56
	Average	-	46.90	33.90	21.56	35.58	992.86

** Statistically significant at 0.05 of probability.

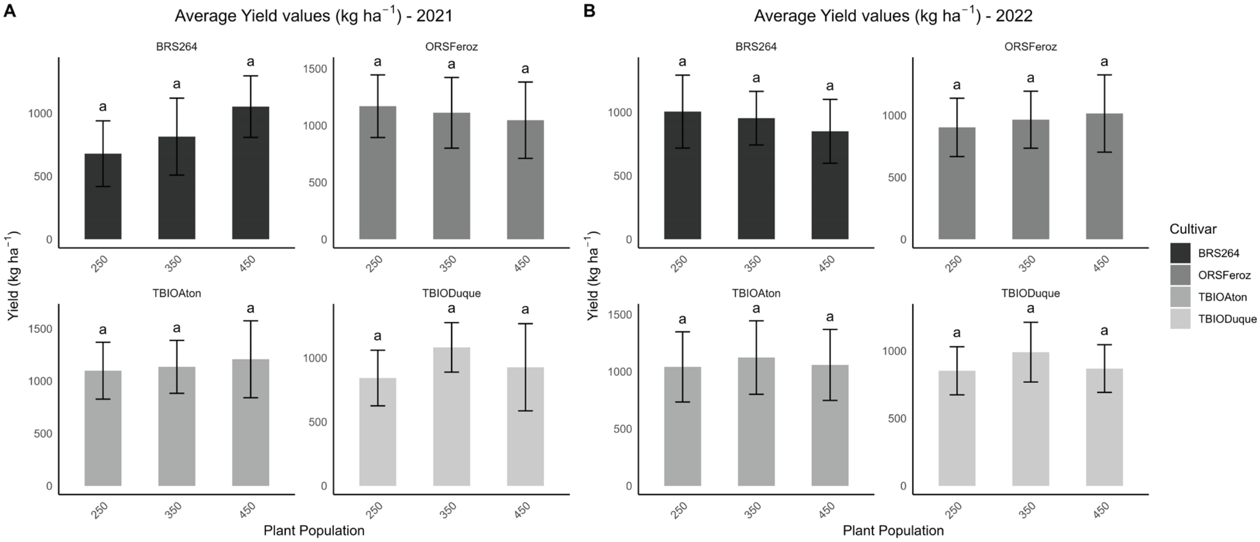

Figure 2. Average yield of wheat cultivars under different plant densities in 2021 (A) and 2022 (B).

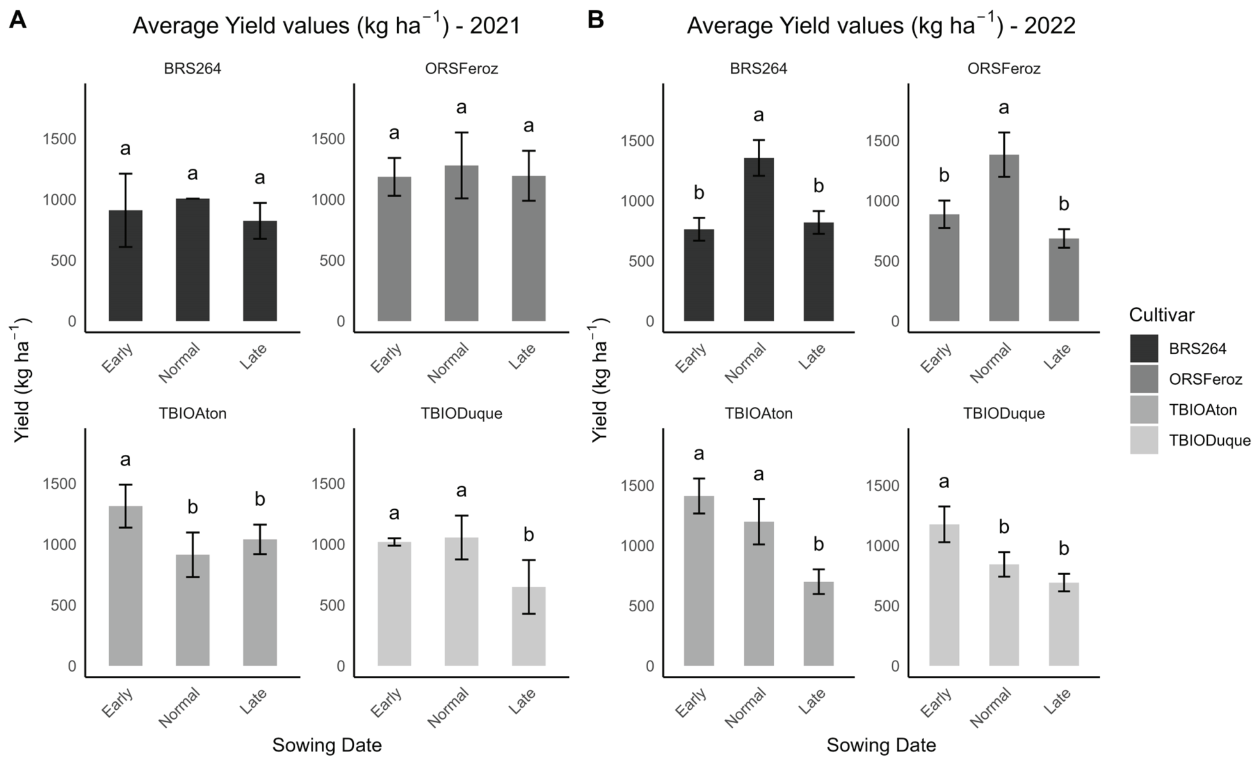

Figure 3. Average yield of wheat cultivars sown in different seasons in 2021 (A) and 2022 (B).

capacity, and under lower plant densities, the tiller production tends to increase (Caierão 2008). The main factors affecting tillering are water, nutrients, and temperature (Valério et al. 2009); thus, at least two of these factors are closely linked to plant population, with water availability and nutrient supply being the most influential (Valério et al. 2009). Under Brazilian tropical conditions, agrometeorological variability strongly affects tillering, emphasizing that recommendations from other regions are not necessarily suitable for local application (Ruiz-Cardozo et al. 2025).

In the factorial interaction analysis, the cultivar performance varied across seasons and years (Table 1). This is evident, for example, in the early sowing season of 2022, when ORS Feroz exhibited the lowest grain yield; whereas, in 2021, it ranked among the most productive (Figures 3A and 3B). Numerous factors influencing crop development have been widely documented (Havlin et al. 2013). In the region where this study was conducted, producers have progressively extended the sowing window, primarily in response to water deficit (Aparecido et al. 2023). However, this practice increases production risks and reduces grain yield and profitability (Pires & Cunha 2022). The present results clearly indicate that such an extension of the sowing window compromises the viability of wheat cultivation under these conditions. Wheat yields were consistently higher in the normal sowing season, when compared to the other seasons (Figure 3). These findings demonstrate that sowing season, cultivar, and year - along with their interactions - significantly influenced grain yield (Table 1).

Differences in plant population were expected to affect key yield components and plant height. As previously indicated (Table 1), most traits showed significant effects of season and cultivar. To illustrate these patterns more clearly, Figure 4 presents the mean values of each trait evaluated in the 2021 and 2022 growing seasons. Overall, the observed variation was largely attributable to differences between cropping seasons and among cultivars. One thousand kernel weight was the most stable trait across years and sowing densities, reflecting a high experimental precision. The number of grains per ear also warrants attention, as it appears directly influenced by plant population. In 2021, most traits showed a higher magnitude and variability, suggesting a greater environmental responsiveness under that season's conditions. Plant height and flag leaf height were expected to vary with plant population, given that denser stands typically reduce light penetration and induce morphological plasticity toward taller phenotypes (Wu et al. 2022). However, such responses were not observed, likely due to the specific climatic conditions during the experimental years in this region.

For the TBIO Aton cultivar, earlier sowing dates resulted in superior performance in both years (Figure 3). The BRS 264 cultivar had the lowest yields in both years under early sowing, but ranked among the most productive in the normal season and

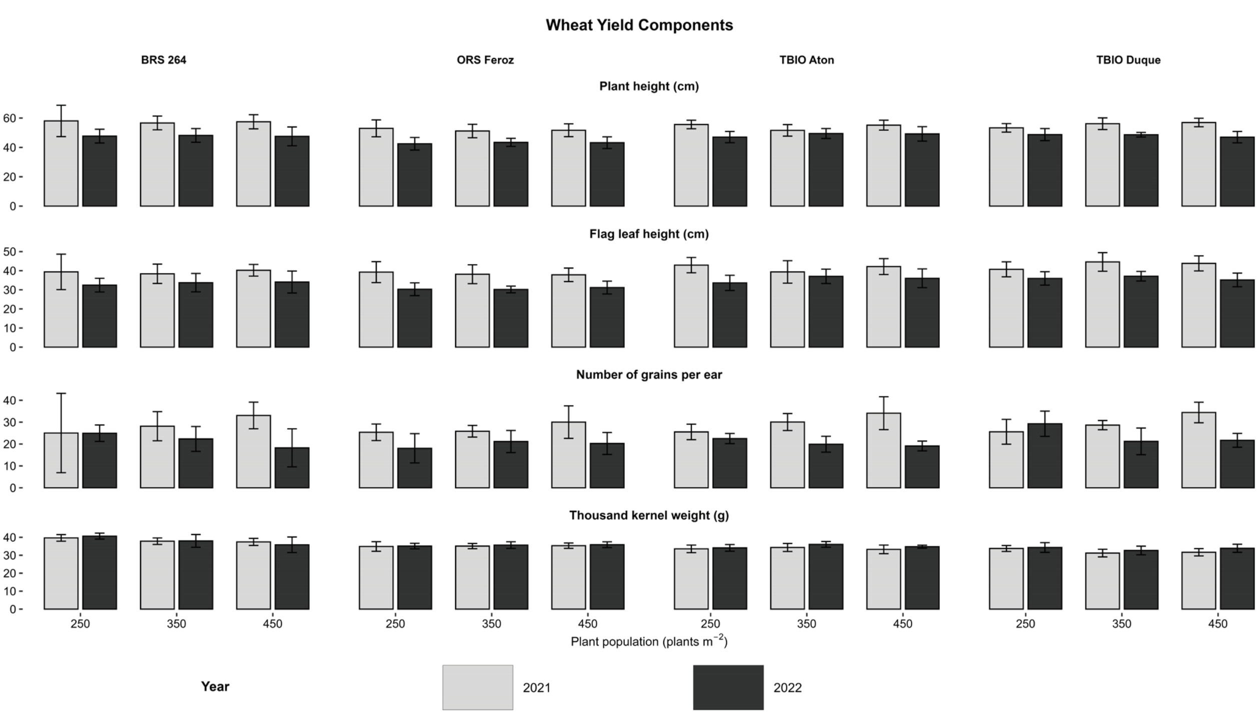

Figure 4. Yield components considering the factors year and sowing density for each cultivar. Gray bars: season 2021; dark bars: season 2022.

showed intermediate performance in the late season of 2021. For TBIO Duque, the early sowing season was the most favorable, with yields approximately 20 % higher than in the other seasons. For BRS 264 and ORS Feroz, the normal season provided the best performance. Within each season, TBIO Aton and TBIO Duque stood out in the early season, whereas ORS Feroz and BRS 264 were superior in the normal season. In the late season, ORS Feroz and TBIO Aton performed better in 2021, whereas no significant cultivar differences were observed in 2022.

In general, sowing wheat outside the recommended climatic zoning window may lead to substantial yield losses, compromising crop planning and decision-making in annual production systems (Pasinato et al. 2018). Wheat requires mild temperatures and adequate water availability for optimal growth and yield (Aparecido et al. 2023). In late sowing, drought tolerance becomes a decisive factor enabling viable wheat cultivation in the region (Pereira et al. 2019). Therefore, identifying cultivars with enhanced drought tolerance remains one of the primary challenges for breeding and agronomic research.

Conversely, although early wheat sowing may appear to be the most advantageous option due to the greater water availability during early crop development, it poses a major challenge for farmers. Early sowing favors the incidence of wheat head blast, a disease caused by the *Pyricularia oryzae* pathotype *triticum*, which has gained increasing attention in the Brazilian Cerrado due to its high severity under favorable conditions of high relative humidity and temperature (Ascari et al. 2021, Torres et al. 2022). To mitigate this issue, the adoption of cultivars with resistance to the pathogen is essential. In this regard, it is noteworthy that the present study included cultivars with documented resistance (Maciel et al. 2024).

In the principal component analysis (PCA), the variable that best explained wheat yield was the number of grains per ear, followed by 1,000-kernel weight (Figure 5). This pattern is reflected in the proximity of their loadings on the axes, indicating a strong interaction between these variables. Such relationships are expected in studies assessing the effects of cultivar, sowing season, and plant density, as these factors directly affect yield components (Zhai et al. 2021). As anticipated, plant height and flag leaf height exhibited a high, positive correlation with each other and only weak associations with the remaining variables.

Plant density may also influence other performance-related traits (Kiss et al. 2018). As observed, the number of grains per ear and 1,000-kernel weight displayed a strong relationship with grain yield (Figure 5), being consistent with findings from path analyses of wheat yield components (Abdurezake et al. 2024, Bhandari & Poudel 2024). Similarly, plant height and flag leaf height again showed a strong positive correlation. Plant height in wheat has been extensively studied worldwide, and reductions in height are often associated with increased grain yield (Jobson et al. 2019). For instance, analysis of barley cultivars released between 1920 and 1984 across multiple environments revealed that increased grain yield was associated - among other traits - with reduced plant height (Boukerrou & Rasmusson 1990).

Overall, the results indicate that the most favorable yield responses occur under normal sowing dates, primarily due to the combination of higher water accumulation and milder temperatures during this period. However, grain yield also depends strongly on the soil water balance of each year, which has become a growing concern for wheat producers, as extreme drought and heat

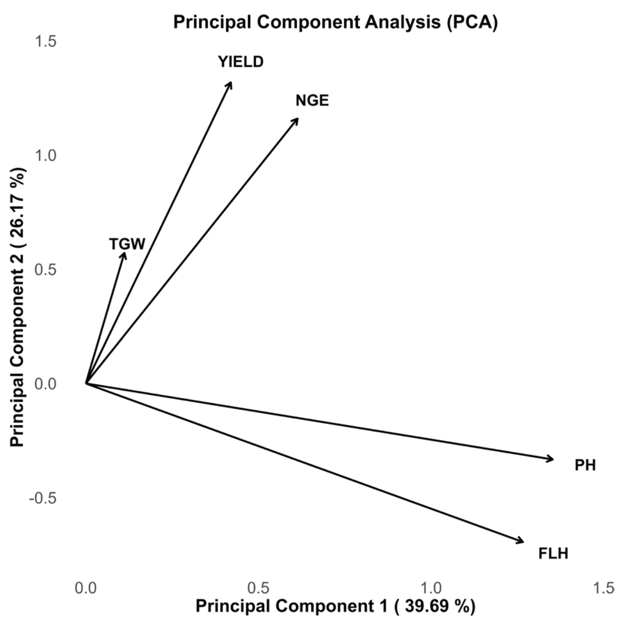

Figure 5. Principal component analysis for evaluated agronomic characteristics. YIELD: grain yield; NGE: number of grains per ear; PH: plant height; TKW: 1,000-kernel weight; FLH: flag leaf height.

events become increasingly frequent. Although the conclusions presented here are based on two growing seasons, the generated evidence demonstrates that optimizing the combination of sowing time and cultivar selection may be essential for sustaining the wheat production in the region. These results support improved agricultural planning and decision-making and reinforce the potential for maintaining and expanding wheat cultivation under tropical conditions.

CONCLUSIONS

1. Early and normal sowing dates are recommended for the cultivars BRS 264, TBIO Aton, TBIO Duque and ORS Feroz, as they are associated with higher yields and greater water availability throughout the crop cycle;
2. Plant density did not significantly influence wheat yield, and a satisfactory yield was obtained at 250 viable seeds m^{-2}. It is important to note that, in years with adequate water availability throughout the entire growing period, the interactions among cultivar, sowing time, and plant density may differ, potentially modifying yield responses under more favorable environmental conditions;
3. Variability in meteorological conditions during the 2021 and 2022 seasons affected the wheat yield, particularly under late sowing. Severe water deficits during flowering and grain filling negatively affected plant performance and reduced yield, highlighting the importance of appropriate sowing time and adequate water management strategies to mitigate such impacts.

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