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Scientific Article

Phenology and thermal accumulation of irrigated malting barley genotypes under nitrogen rates in the Cerrado

Fenologia e acúmulo térmico de genótipos de cevada cervejeira irrigada sob doses de nitrogênio no cerrado

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ABSTRACT - Barley cultivation in the Brazilian Cerrado has contributed to domestic malt production and adaptation to irrigated tropical environments, reducing imports. Understanding genotype × environment interactions is essential for optimizing crop performance, particularly through phenological characterization and thermal time dynamics. This study evaluated the phenological response of six malting barley genotypes to nitrogen rates under irrigation in the Cerrado in Central Brazil. The experiment was conducted at the experimental station of the Brazilian Agricultural Research Corporation (Embrapa Cerrados) in Planaltina, Federal District, in a randomized complete block design with split plots and three replications. Four nitrogen rates (0, 20, 40, and 80 kg ha^{-1}) and six genotypes (BRS Savanna, CEV 98074, Lacey, Prestige, BRS 180, and BRS 195) were evaluated. Phenological stages were monitored, and thermal accumulation was expressed as growing degree days (°C day^{-1}). Genotype, phenological stage, and their interaction significantly affected thermal requirements, whereas nitrogen rates did not affect thermal accumulation or phenological progression. BRS 195 had the longest cycle, requiring 1,562.83 °C day^{-1} up to heading, whereas Lacey and CEV 98074 were the earliest, requiring 1,119.93 and 1,190.28 °C day^{-1}, respectively. The 388.88 °C day^{-1} difference between the most contrasting genotypes corresponded to approximately 19 days in flowering, indicating high phenological variability. Thus, phenological development and thermal accumulation of irrigated malting barley were primarily determined by genotype rather than nitrogen rates under the evaluated environmental conditions.

Keywords: Growing degree days. Growth stages. *Hordeum vulgare* L. Irrigation. Nitrogen fertilization.

RESUMO – O cultivo de cevada no Cerrado brasileiro tem contribuído para a produção de malte e para a adaptação da cultura a ambientes irrigados, reduzindo a necessidade de importações. Compreender as interações genótipo × ambiente é essencial para otimizar o desempenho da cultura, especialmente pela caracterização fenológica e da dinâmica do tempo térmico. Este estudo avaliou a resposta fenológica de seis genótipos de cevada cervejeira a diferentes doses de nitrogênio sob irrigação no Cerrado do Planalto Central. O experimento foi conduzido na estação experimental da Embrapa Cerrados, em Planaltina, Distrito Federal, Brasil, em delineamento de blocos casualizados, com parcelas subdivididas e três repetições. Foram avaliadas quatro doses de nitrogênio (0, 20, 40 e 80 kg há$^{-1}$) e seis genótipos (BRS Savanna, CEV 98074, Lacey, Prestige, BRS 180 e BRS 195). Os estádios fenológicos foram monitorados, e o acúmulo térmico foi expresso em graus-dia. Genótipo, estádio fenológico e sua interação afetaram significativamente as exigências térmicas, enquanto as doses de nitrogênio não afetaram o acúmulo térmico nem a progressão fenológica. BRS 195 apresentou o ciclo mais longo, requerendo 1.562,83 °C dia^{-1} até o espigamento, enquanto Lacey e CEV 98074 foram os mais precoces, requerendo 1.119,93 e 1.190,28 °C dia^{-1}, respectivamente. A diferença de 388,88 °C dia^{-1} entre os genótipos mais contrastantes correspondeu a aproximadamente 19 dias na floração, indicando variabilidade fenológica. Assim, o desenvolvimento fenológico e o acúmulo térmico da cevada cervejeira irrigada foram determinados principalmente pelo genótipo, enquanto as doses de nitrogênio não tiveram efeito significativo, nas condições ambientais avaliadas.

Palavras-chave: Graus-dia. Estádios fenológicos. *Hordeum vulgare* L. Irrigação. Adubação nitrogenada.

Conflict of interest: The authors declare no conflict of interest related to the publication of this manuscript.

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INTRODUCTION

Barley is among the first plant species domesticated by humans and currently one of the most important cereal crops worldwide. According to projections of the United States Department of Agriculture (USDA) for the 2025/2026 crop season, Russia is the largest barley producing country, followed by Australia and Canada (USDA, 2026). Although barley production has traditionally been concentrated in temperate climate regions, the increasing demand from the malting industry has stimulated the expansion of cultivation into new production areas, including the Brazilian Cerrado, where breeding programs and the development of irrigated cultivars have contributed to increasing domestic production and reducing dependence on imported malt (THOMÉ et al., 2024).

In Brazil, barley cultivation has traditionally been concentrated in the Southern region, because of its adaptation to temperate climates. However, Zhao et al. (2022) reported that this region poses important constraints to barley cultivation, including high disease pressure favored by humid conditions, frosts that reduce grain yield, rainfall after physiological maturity that impairs grain quality, and competition with other winter crops, such as wheat.

The growing domestic demand for barley, driven mainly by the malting industry, has encouraged cultivation in new agricultural frontiers, particularly the Cerrado, where adapted genotypes have contributed to increased production and reduced dependence on imported malt (THOMÉ et al., 2024). In this context, barley emerges as a promising option for crop rotation, especially with common bean and soybean, showing agronomic and economic performance comparable to wheat in irrigated systems (AMABILE et al., 2017). The adaptation of barley to local environmental conditions is essential, but depends on a detailed understanding of phenology and appropriate crop management strategies (BORÉM; MIRANDA; FRITSCHE-NETO, 2017).

Despite these advances, information regarding barley development under tropical conditions remains limited, particularly concerning phenological responses and thermal requirements under different management strategies. This knowledge gap is especially relevant for irrigated production systems in the Brazilian Cerrado, where environmental conditions differ substantially from those traditionally associated with barley cultivation. Understanding these responses is essential to optimize crop management practices and support breeding programs aimed at improving adaptation to tropical environments (BORÉM; MIRANDA; FRITSCHE-NETO, 2017).

Growing degree days (thermal accumulation) and phenological stage assessments are fundamental tools for accurately characterizing barley development throughout the crop cycle. These parameters allow quantification of the progression of developmental phases in response to environmental conditions, particularly air temperature, the main factor affecting phenology (MKHABELA et al., 2016; OTERO; MIRALLES; BENECH-ARNOLD, 2020). The growing degree-day method described by Pereira, Angelocci, and Sentelhas (2002) enables a detailed analysis of the crop cycle and supports the interpretation of management and genetic background effects on barley growth and maturity (PEREIRA; ANGELOCCI; SENTELHAS, 2002; OTERO; MIRALLES; BENECH-ARNOLD, 2020).

From a physiological standpoint, barley development and grain yield are strongly conditioned by phenological dynamics. Nitrogen availability may influence crop development; however, its effects on phenology vary according to environmental conditions, water availability, soil fertility, and genotype. Although nitrogen fertilization affects biomass accumulation, yield components, and grain quality, its influence on the duration of phenological stages remains inconsistent across production environments (TAIZ et al., 2017).

Nitrogen availability also strongly influences barley development, grain yield, and malting quality. Nitrogen is an essential constituent of chlorophyll, amino acids, proteins, and enzymes, directly affecting photosynthetic capacity, tillering, biomass accumulation, and grain filling. Several studies have demonstrated that nitrogen fertilization can increase plant growth, grain yield, and seed quality, although the magnitude of these responses depends on genotype, environmental conditions, and crop management (BARBOSA et al., 2022; DAVIES; COULTER; PAGLIARI, 2020; GOVINDASAMY et al., 2023). In addition, barley cultivars may differ in their nitrogen requirements, indicating that fertilizer recommendations should consider genotype-specific responses (BARBOSA et al., 2022).

Despite the recognized importance of nitrogen fertilization for barley production, information on its influence on phenological development and thermal accumulation under irrigated tropical conditions remains limited. Most available studies have focused on grain yield and quality, whereas the interaction between nitrogen management and phenology has received considerably less attention, particularly for genotypes cultivated under the environmental conditions of the Brazilian Cerrado. Therefore, this study evaluated the effects of genotype and nitrogen rates on the phenology and thermal accumulation (growing degree days) of irrigated malting barley under Brazilian Cerrado conditions.

MATERIAL AND METHODS

The experiment was conducted at the experimental field of the Brazilian Agricultural Research Corporation (Embrapa Cerrados) in Planaltina, Federal District, Brazil (15°35'30" S, 47°42'30" W; altitude 1,007 m) from May to September 2022. The soil at the experimental site was classified as a Latossolo Vermelho Distrófico típico (Typic Hapludox), with a clay texture (SANTOS et al., 2025; SOIL SURVEY STAFF, 2022;). Soil analysis of the 0–10 and 10–20 cm layers showed the following results, respectively: 0.0 mmolc dm^{-3} Al for both layers, 31.6 and 30.5 mmolc dm^{-3} Ca, 9.9 and 9.3 mmolc dm^{-3} Mg, 37.67 and 30.87 mg kg^{-1} P, 2.6 and 1.6 mmolc dm^{-3} K, 25.6 and 23.2 g kg^{-1} organic matter, and pH in water of 6.27 and 6.35.

The regional climate, according to the Köppen classification, is tropical savanna (Aw), characterized by dry winters and rainy summers (ALVARES et al., 2023). The mean daily global solar radiation during the experimental period (May–September 2022) was 1,539.63 kJ m^{-2} day^{-1}, as recorded at the Ponte Alta meteorological station (A046) of the Instituto Nacional de Meteorologia (INMET), Federal District, Brazil. These environmental conditions, combined with irrigation management, provided conditions for evaluating barley phenological development under irrigation (ADÁMOLI et al., 1986; INMET, 2026).

The experimental design was a randomized complete block design in a split-plot arrangement, with three replications. Plots consisted of nitrogen rates, while subplots consisted of barley genotypes. Each plot consisted of 10 rows (4 m in length) spaced 20 cm apart, totaling a net area of 8 m^2. The barley genotypes evaluated comprised the experimental line CEV 98074, the foreign varieties Lacey (United States) and Prestige (France), and the Brazilian cultivars BRS Savanna, BRS 180, and BRS 195.

Four nitrogen rates (0, 20, 40, and 80 kg ha^{-1} of N) were evaluated based on the recommendations for barley cultivated under Cerrado conditions (BARBOSA et al., 2022). Urea (46% N) was used as the nitrogen source. Basal fertilization consisted of 20 kg ha^{-1} N, except for the 0 N treatment, which did not receive nitrogen fertilization. The 20 N treatment received nitrogen only at sowing, whereas the 40 N and 80 N treatments received 20 kg ha^{-1} N at sowing and two topdressing applications of 10 and 30 kg ha^{-1} N, respectively, on July 6 and July 22. Nitrogen was applied via fertigation using a sprinkler irrigation system with a circular wetting pattern. In addition, 100 kg ha^{-1} K_2O and 117 kg ha^{-1} P_2O_5 were applied at sowing to all plots, according to soil analysis recommendations.

Sprinkler irrigation was used whenever the volumetric soil water content reached the predefined value of 0.26%, corresponding to 50% depletion of the available water in the soil profile. Soil water content was measured by a Delta-T probe installed at 15 cm depth in the crop row. The water depth applied was calculated to restore soil moisture to field capacity. Measurements were taken daily from 8:00 h throughout the crop cycle.

Weed control was performed by hand hoeing. The daily mean air temperature (*Tm*) was calculated as the arithmetic mean of hourly air temperatures, according to the following Equation 1:

$$Tm = \frac{T_{1h} + T_{2h} + T_{3h} + \ldots + T_{24h}}{24} \quad (1)$$

where T_{1h}–$24h$: mean hourly air temperature (°C), for each hour.

The phenological stages of emergence, first node, booting, flag leaf emergence, flowering, and heading were monitored to calculate growing degree days during the crop cycle (GDi). The phenological stages were defined according to the criteria proposed by Zadoks, Chang, and Konzak (1974). Growing degree days were calculated following the thermal time approach widely adopted in crop phenology studies, as reported by Otero, Miralles, and Benech-Arnold (2020) (Equation 2):

$$GDi = \sum (Tmi - Tb) \quad (2)$$

where *Tmi*: mean daily air temperature (°C) on day *i*; *Tb*: base temperature (°C) for barley.

A base temperature (*Tb*) of 0 °C was adopted for the calculation of thermal accumulation, according to recommendations commonly used for barley phenological studies (PAREDES et al., 2025).

Phenological evaluations were performed visually at 3- to 8-day intervals, from emergence to heading, following the Zadoks scale (ZADOKS; CHANG; KONZAK, 1974). The duration of each developmental stage was subsequently converted into growing degree days to characterize thermal accumulation throughout the crop cycle.

Data were analyzed descriptively, and mean values were used to summarize barley genotype responses at the different phenological stages to the nitrogen rates evaluated.

Subsequently, an analysis of variance (ANOVA) was performed to evaluate the effects of genotype and phenological stage, as well as their interaction. Because nitrogen rate was a quantitative factor, the possibility of fitting regression models was initially evaluated. However, no significant effect was detected by ANOVA ($p > 0.05$); therefore, regression models were not fitted, and the results were interpreted based on the ANOVA. Means were compared using Tukey's test at the 5% significance level ($p \leq 0.05$). Statistical assumptions were verified prior to analysis, and all analyses were performed using R software (R CORE TEAM, 2024).

RESULTS AND DISCUSSION

Figures 1, 2 and 3 illustrate the phenological responses of six malting barley genotypes cultivated under irrigation in the Brazilian Cerrado to four nitrogen rates. The analysis of variance (ANOVA) showed significant effects of genotype ($p < 0.001$) and phenological stage ($p < 0.001$), as well as a significant genotype × phenological stage interaction ($p = 0.002$) (Table 1). In contrast, nitrogen rates did not significantly affect thermal accumulation or phenological progression under the experimental conditions evaluated.

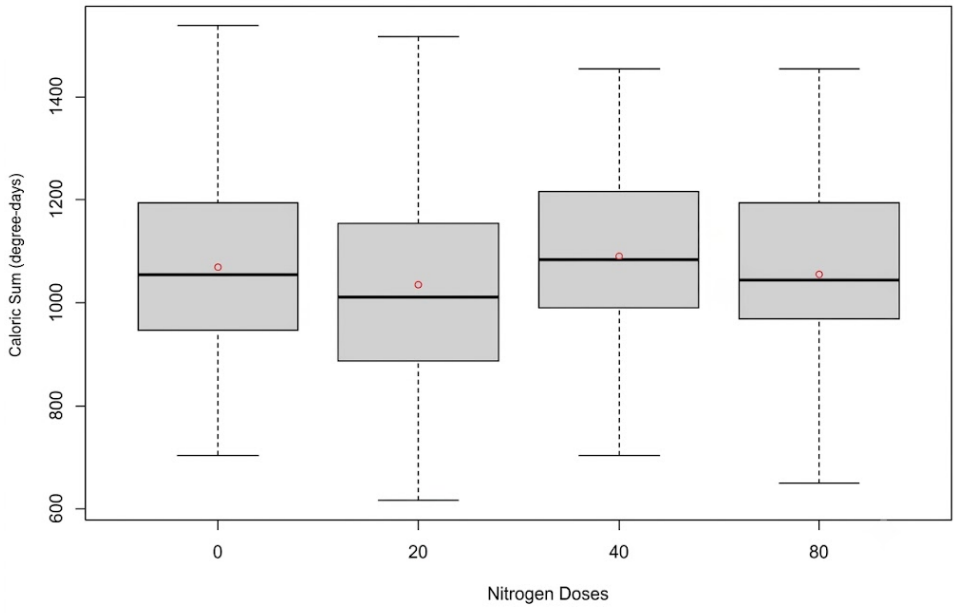


Figure 1. Boxplot showing the overall distribution of thermal accumulation (growing degree days, °C day^{-1}) of six malting barley (*Hordeum vulgare* L.) genotypes cultivated under irrigation and four nitrogen rates in the Brazilian Cerrado, Federal District.

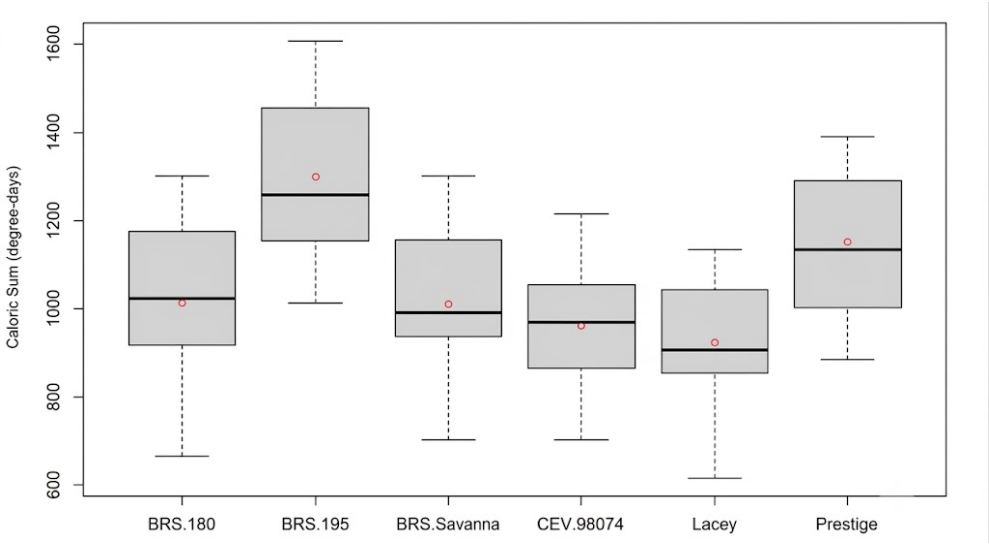


Figure 2. Boxplot of total thermal accumulation (growing degree days, °C day^{-1}) up to heading of six malting barley (*Hordeum vulgare* L.) genotypes cultivated under irrigation in the Brazilian Cerrado, considering all applied nitrogen rates.

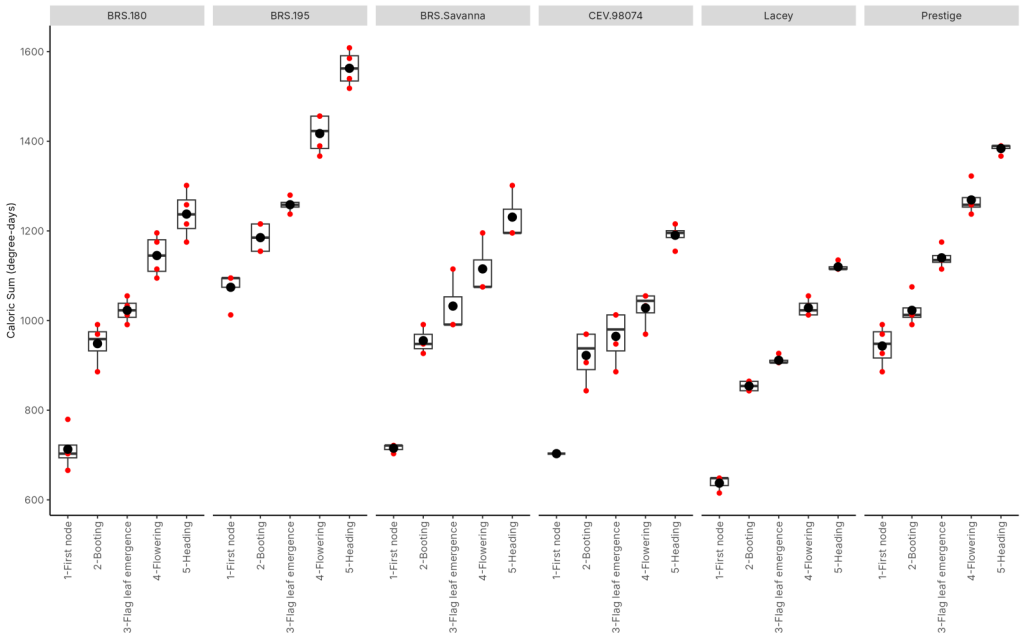


Figure 3. Boxplot of thermal accumulation (growing degree days, °C day^{-1}) at different phenological stages (first node, booting, flag leaf emergence, flowering and heading) of six malting barley (*Hordeum vulgare* L.) genotypes under irrigated cultivation in the Brazilian Cerrado. Red dots represent individual observations obtained under the applied nitrogen rates.

Table 1. Analysis of variance (ANOVA) for thermal accumulation of malting barley genotypes cultivated under irrigation in the Brazilian Cerrado.

Source of variation	Degrees of freedom	*p*-value
Genotype (G)	5	< 0.001
Phenological stage (PS)	4	< 0.001
G × PS interaction	20	0.002
Residual	84	-

Phenological characterization of barley is essential to quantify the available genetic variability and to support breeding programs. In this context, previous studies have shown that phenological differences among genotypes enable assessment of genetic diversity and its use in the development of more productive cultivars adapted to different environments. In addition, phenological traits have been used as indicators to monitor the impacts of breeding over time (HILL et al., 2019).

Nitrogen rates did not significantly affect thermal accumulation up to heading (Figure 1). This result indicates that the nitrogen rates evaluated were not associated with detectable changes in phenological cycle duration under the experimental conditions.

The absence of a phenological response may be partially explained by the relatively high organic matter content in the 0–10 cm soil layer (25.6 g kg^{-1}), which may have contributed to nitrogen availability through mineralization during crop development. Under these conditions, additional nitrogen inputs may have had a limited effect on developmental timing.

Although nitrogen is essential for plant growth and yield, its influence on crop phenology is highly dependent on environmental conditions and crop management. Plant phenology responses to nitrogen addition often are more pronounced under water-limited 7environments or low soil fertility conditions (HE et al., 2025). Under irrigated conditions in the Brazilian Cerrado, where water supply was not limiting, temperature and genetic background appeared to exert a stronger influence on phenological progression than nitrogen availability.

This finding contrasts with previous studies reporting changes in pre-heading development and reproductive growth under different nitrogen supplies (ARISNABARRETA; MIRALLES, 2010; KAMAL; MUQADDASI; SCHNURBUSCH, 2022). However, those studies were conducted under different environmental conditions and assessed agronomic traits in addition to phenology.

Because the nitrogen rates evaluated did not significantly affect phenological development, their effects should be interpreted cautiously in the context of this study. Nitrogen is essential for processes such as photosynthesis, protein synthesis, tillering, and grain production (SOUSA; LOBATO, 2004), none of which were evaluated in this experiment. The relatively high soil organic matter content (25.6 g kg^{-1}) may also have contributed to crop nitrogen supply through mineralization, thereby reducing the response to the applied nitrogen rates. Soil nitrogen availability may therefore have been sufficient to meet crop demand during the phenological stages evaluated. Consequently, potential effects of nitrogen fertilization on biomass accumulation, grain quality, and grain yield remain speculative and require further investigation.

The lack of a phenological response to nitrogen is consistent with Brazilian fertilization recommendations, which indicate that barley nitrogen requirements may be lower in production systems following legume crops because of residual soil nitrogen (SOUSA; LOBATO, 2004).

The genotypes differed significantly in thermal accumulation up to heading (Figure 2). BRS 195 had the latest cycle, accumulating 1562.83 °C day^{-1} up to heading, whereas Lacey and CEV 98074 were the earliest, requiring 1119.93 and 1190.28 day^{-1}, respectively. Prestige showed an intermediate-to-late development.

The wide variation in thermal time to heading among genotypes reflects differences in genetic control of phenological development. The genotypes Lacey (United States) and CEV 98074 (France) required less thermal accumulation to reach heading, indicating earlier development under Cerrado conditions. This variation may be associated with differences in photoperiod sensitivity, temperature response, and flowering-related genes, which influence barley cycle duration (ALZUETA et al., 2014). Previous studies have demonstrated substantial genetic variability among barley genotypes in flowering regulation, resulting from the interaction between developmental genes and environmental factors such as temperature and photoperiod (SATO et al., 2020). In contrast, the Brazilian cultivars BRS 195 and Prestige accumulated more growing degree days up to heading, indicating their selection in breeding programs targeting irrigated crops under Cerrado conditions, where a longer vegetative phase favors greater biomass accumulation and may contribute to higher yield potential (ALZUETA et al., 2014). Therefore, the differences among genotypes reflect not only their geographic origin but, more importantly, variation in genetic constitution, phenological regulation, and the breeding objectives for distinct production environments.

Phenological differences remained consistent throughout all developmental stages, especially between the most contrasting genotypes, BRS 195 and Lacey (Table 2).

Table 2. Thermal accumulation (growing degree days, °C day^{-1}) at each phenological stage of malting barley genotypes cultivated under irrigation in the Brazilian Cerrado.

Genotypes	Phenological stages				
	First node	Booting	Flag leaf	Flowering	Heading
BRS Savanna	715.23 Dc*	955.17 Cbc	1032.30 BCc	1115.23 Bc	1230.80 Ac
BRS 195	1074.25 Da	1185.05 Ca	1258.48 Ca	1417.18 Ba	1562.83 Aa
BRS 180	712.90 Dc	948.55 Cbc	1022.90 Cc	1145.08 Bc	1237.58 Ac
CEV 98074	703.10 Dc	922.23 Ccd	964.70 BCcd	1028.13 Bd	1190.28 Acd
Lacey	637.33 Dc	853.95 Cd	911.40 Cd	1028.30 Bd	1119.93 Ad
Prestige	943.28 Eb	1022.83 Db	1140.00 Cb	1269.13 Bb	1383.93 Ab

*Means followed by the same lowercase letters within a column, or the same uppercase letters within a row, do not differ by Tukey's test at the 5% probability level.

These results reinforce the predominance of genetic control over phenological development under irrigated conditions in the Cerrado. Traits related to photoperiod sensitivity and intrinsic developmental rate are known to influence flowering and heading timing in barley (FERNÁNDEZ-CALLEJA; CASAS; IGARTUA, 2021; CAMMARANO et al., 2021).

Prestige differed significantly across phenological stages, indicating a gradual and consistent developmental pattern, which may favor greater predictability in irrigation and other crop management operations.

Greater variation at the first node stage was observed in the later genotypes, particularly Prestige and BRS 195 (Figure 3), indicating greater variability in thermal accumulation during early development. In contrast, Lacey and CEV 98074 showed a more consistent developmental pattern throughout the cycle.

BRS Savanna and BRS 180 showed intermediate thermal accumulation patterns. This may indicate potential suitability for environments with shorter growing seasons or greater risk of heat stress during late developmental stages.

The flowering stage occurred at 1028.30 °C day^{-1} for Lacey and 1417.18 °C day^{-1} for BRS 195, corresponding to a difference of 388.88 °C day^{-1}. Considering a mean air temperature of 19.9 °C, this difference represents approximately 19 days.

This variation indicates phenological plasticity among genotypes and supports genotype-specific management. Irrigation and nitrogen applications could be adjusted according to genotype-specific thermal requirements, as water and nutrient demands vary throughout the crop cycle (YIĞIT; CHMIELEWSKI, 2024).

The earliness of Lacey and CEV 98074 suggests potential use in breeding programs targeting regions with shorter planting windows or greater exposure to heat and water stress during reproductive stages. In contrast, the longer cycle of BRS 195 may favor biomass accumulation and yield potential under irrigated conditions. These assumptions, however, require confirmation through additional studies evaluating yield and grain quality. Under the conditions tested, nitrogen management did not modify the duration of the phenological cycle; effects on yield and grain quality were not evaluated in this study.

These findings should be interpreted within the scope of a single growing season. Multi-year and multi-environment studies are needed to validate the results and assess their applicability to other production systems. Overall, under the evaluated conditions, phenology and thermal accumulation of irrigated malting barley in the Cerrado were primarily determined by genotype rather than nitrogen rates. These findings may support breeding programs, agricultural zoning, and improved management of barley cultivation in Central Brazil.

CONCLUSION

Under the conditions evaluated, the phenology and thermal accumulation of malting barley genotypes under irrigation in the Brazilian Cerrado were determined predominantly by genotype rather than nitrogen fertilization. The nitrogen rates tested did not significantly affect phenological development or growing degree-day accumulation throughout the crop cycle.

BRS 195 had the longest cycle and the highest growing degree-day requirement, whereas Lacey and CEV 98074 had shorter cycles, suggesting potential suitability for environments with shorter growing windows or greater exposure to heat stress.

These findings should be interpreted with caution because the study was conducted during a single growing season. Multi-year and multi-environment experiments are needed to validate the results and assess their applicability to other production conditions.

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