

Short Communication

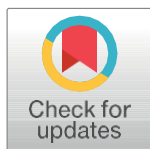
Agronomic phenotyping of *Setaria italica* cultivated at different sowing times

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Abstract

Setaria italica is a C4 grass with a short growth cycle, high water-use efficiency, and great potential for biomass production, forage, and soil cover. However, in Brazil, information on its agronomic performance under different sowing dates and on its interactions with environmental factors, pests, diseases, and soil physical conditions is still limited, which restricts the establishment of efficient management strategies. Therefore, the objective of this study was to evaluate the agronomic phenotyping of the cultivar URNRS24 of *Setaria italica* under different sowing dates and to analyze the occurrence of weeds, insect pests, and diseases under field conditions. The experiment was carried out in Ijuí, Rio Grande do Sul, Brazil, using a randomized block design with three sowing dates and five replications. Variables related to emergence, phenology, growth, yield components, soil penetration resistance, and meteorological data obtained from the National Aeronautics and Space Administration (NASA POWER database) (2025) were evaluated. In sequence, they were subjected to analysis of variance, correlation, and regression analyses. The results showed that sowing date significantly affected crop development and productivity. Early august sowing favored individual plant growth and grain weight per plant due to lower stand density and reduced intraspecific competition, whereas sowing in September promoted more uniform growth and better climatic adaptation, although with higher incidence of foliar diseases. Thus, the choice of sowing date is a key factor determining the agronomic performance of *Setaria italica* under subtropical conditions.

Keywords: Foxtail millet; subtropical environment; phenology; grain yield components; photosynthetic metabolism; hay; silage; soil cover crop.

Introduction

Setaria italica (L.) P. Beauv. is a small-grained cereal of the Poaceae family, classified as an annual grass with C4 photosynthetic metabolism and diploid ($2n = 18$) (Nani et al., 2015). The species exhibits rapid establishment and high biomass production, being widely used as forage, hay, silage, and soil cover crop, with the potential to contribute to nutrient cycling and the improvement of soil physical conditions (CODEX ALIMENTARIUS COMMISSION, 2023; Li et al., 2023). Global production of small grain cereals exceeds 89 million tons, cultivated on approximately 74 million hectares, with India standing out as the main producer. Average productivity varies between 1.2 and 1.5 t ha⁻¹, and can reach up to 4.0 t ha⁻¹ under proper management (Food and Agriculture Organization of the United Nations [FAO], 2022; Kalsi & Bhasin, 2023). However, in Brazil, there are still no consolidated official records of *Setaria italica* production, highlighting the need for studies that evaluate its agronomic potential as a forage alternative and soil cover crop.

Originating in East Asia, *Setaria italica* was domesticated from *Setaria viridis* approximately 11,000 years ago in northern China. Notable for its short growth cycle and high drought tolerance, the species has also been widely used as a model plant in studies related to C4 photosynthesis and adaptation to water stress (He et al., 2023; Gao et al., 2025). From an agronomic point of view, it presents a deep, fasciculated root system, favoring water and nutrient absorption and conferring greater hardiness and productive stability under water-restricted conditions (Kalsi & Bhasin, 2023). The high efficiency in water use and the species' natural tolerance to environments with low water availability are relevant characteristics for agricultural systems seeking greater productive sustainability (Oliveira, Schaaf, & Setta, 2024).

Biotic factors, such as weeds, pests, and diseases, also affect agronomic performance, soil cover, and nutrient cycling (Nadeem et al., 2020). However, studies that evaluate these components in an integrated way under field conditions, especially in systems focused on biomass production and soil cover, are still scarce. In this context, it becomes fundamental to generate information that allows us to understand the dynamics of weeds, pests, and diseases associated with *Setaria italica*, as well as their relationship with crop growth, soil cover, and nutrient cycling processes. Thus, the objective of this study was to evaluate the agronomic phenotyping of *Setaria italica* at different sowing times and to analyze the occurrence of weeds, insect pests, and diseases under field conditions.

Materials and Methods

The study was conducted in 2025 in Ijuí, Rio Grande do Sul (28°23'34'' S and 53°56'39'' W, altitude 328m) on the premises of the Regional University of the Northwest of the State of Rio Grande do Sul (UNIJUÍ). The soil is classified as a Typical Dystroferic Red Latosol (Santos, Jacomine, Anjos, Oliveira, & Lumberras, 2018), and the region's climate, according to the Köppen classification, is humid subtropical (Alvares, Stape, Sentelhas, Gonçalves, & Sparovek, 2014). Cultural practices included soil preparation, base fertilization (250 kg ha⁻¹ of NPK 5-20-20), topdressing fertilization according to soil analysis, manual weeding, and phytosanitary control as needed.

Soil analysis indicated a pH of 5.1 and a base saturation of 36.4%, with low levels of phosphorus (< 3.0 mg dm⁻³) and potassium (72 mg dm⁻³), while calcium (3.8 cmolc dm⁻³) and magnesium (1.5 cmolc dm⁻³) showed adequate levels. The *Setaria italica* cultivar used was URNRS24, developed by the Genetic Improvement Program - Grain and Cover Crop Line of UNIJUÍ, characterized by its suitability for biomass production and soil cover, with potential for forage, hay, silage, and ethanol production.

Table 1 presents the morphological descriptors of the URNRS24 cultivar, including semi-erect growth habit, low or absent anthocyanin pigmentation in leaves, sheaths, stems and reproductive structures, light green foliage color, short and dense conical panicle,

high number of grains per primary branch and grains of yellow color, medium oval shape, low thousand-grain weight and waxy endosperm.

Table 1. Morphological descriptors of the URNRS24 cultivar of *Setaria italica*.

Characteristic	Characteristic presented
1. First leaf: tip shape	Pointed
2. Plant: anthocyanin pigmentation of the basal leaf sheath	Absent or weak
3. Plant: intensity of the green color of the foliage	Light green
4. Plant: growth habit	Semi-erect
5. Plant: anthocyanin pigmentation of the leaf collar	Absent or weak
6. Cycle to emergency	-
7. Stem: anthocyanin pigmentation of the adventitious roots	Absent
8. Leaf: blade size	Semi-erect
9. Panicle: awn length	Medium
10. Panicle: anthocyanin pigmentation of the awn	Absent
11. Anther: color	White
12. Flag leaf: blade length	Medium
13. Flag leaf: blade width	Medium
14. Flag leaf: anthocyanin pigmentation of the leaf blade	Absent or very weak
15. Stem: length	Short
16. Stem: diameter	Medium
17. Glume: anthocyanin pigmentation	Absent
18. Plant: number of elongated internodes	Low
19. Panicle: size in relation to stem	Semi-erect
20. Plant: peduncle length	-
21. Panicle: shape	Conical
22. Panicle: length	Short
23. Panicle: density	Dense
24. Panicle: number of grains on the primary branch	High
25. Grain: weight of 1000 grains	Low
26. Grain: format	Medium-oval
27. Grain: color	Yellow
28. Peeled grain: color (unpolished)	Yellow
29. Endosperm: type	Waxy

Source: Authors

The experimental area measured 10 m × 3.4 m, composed of 20 rows spaced 0.17 m apart. Sowing was carried out manually, with a density of 50 kg ha⁻¹ of seeds. The crop was sown on three different dates: August 5th, August 21th, and September 24th, 2025. The experiment was conducted in a randomized block design, using inner strips as blocks, with five replications. Representative images of the crop under field conditions are shown in [Figure 1](#).

During the crop cycle, emergence, phenological, and reproductive variables were evaluated. Emergence variables included the emergence speed index (ESI), calculated from counts at 5, 10, 15, and 20 days after sowing (DAS), and the final plant stand, determined by counting in five 1 m segments per plot. The phenological and reproductive variables evaluated were the days to tillering, the days to flowering (visible emergence of panicles), and the total cycle duration, expressed in days to panicle harvest.

For the evaluation of productive performance, 25 panicles per plot were collected and used to determine the number of grains per panicle, grain weight per plant (g), plant

height (cm), and panicle insertion height (cm). The occurrence of insects, weeds, and diseases was evaluated using percentage scores (0-100%), assigned according to the intensity and severity observed in each plot.

Meteorological data, including maximum, mean, and minimum air temperatures (°C), precipitation (mm), and relative air humidity (%), were obtained from the NASA POWER database (2025). The physical condition of the soil was evaluated by penetration resistance, measured at depths of 5, 10, and 15 cm (kPa), using a Falker hand penetrometer, in addition to determining a general soil compaction index.

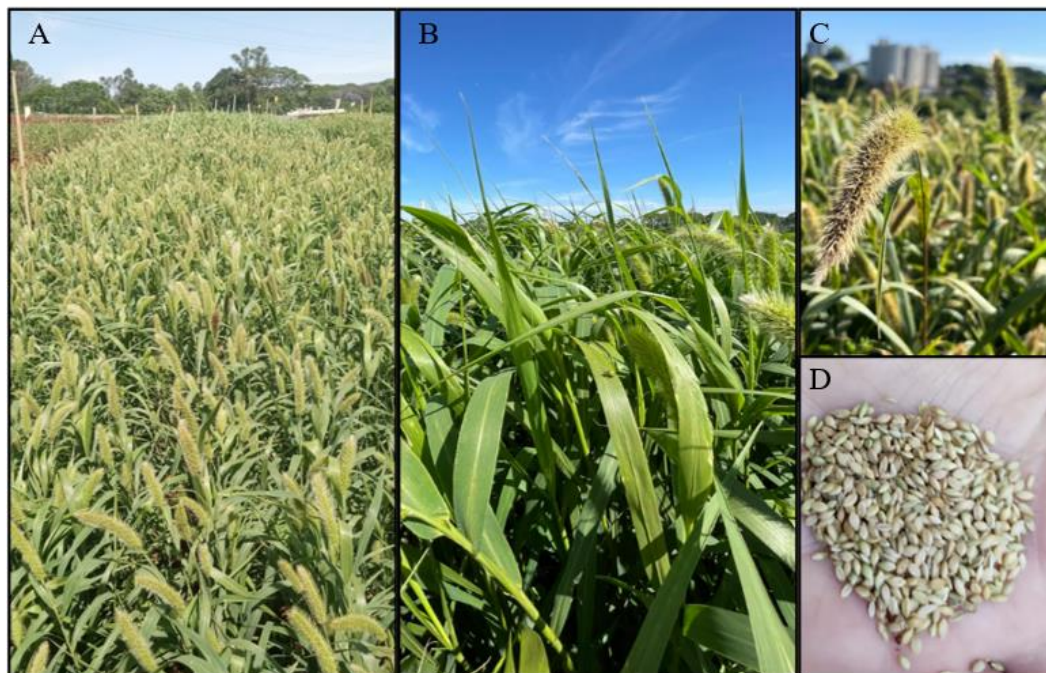


Figure 1. Agronomic characteristics of *Setaria italica* under field conditions in southern Brazil. (A) General field view at the reproductive stage; (B) Vegetative canopy architecture; and (C) Panicle at the grain filling stage; (D) Harvested seeds of *Setaria italica*.

Statistical analyses were performed using R software (R Core Team, 2025). Data normality and homogeneity of variances were verified using the Shapiro-Wilk and Bartlett tests, respectively. Variables that met the assumptions were subjected to analysis of variance (ANOVA), with mean comparisons using Tukey's test ($p \leq 0.05$). Relationships between variables were assessed using Pearson correlation and regression analyses.

Results and Discussion

Season 1 presented unfavorable water conditions, with an initial deficit and irregular rainfall distribution, characterized by prolonged periods of low precipitation interspersed with events exceeding 50-60 mm (Figure 2). This pattern compromised seedling emergence and uniformity. Between 22 and 70 days after sowing, high precipitation volumes increased canopy moisture, favoring foliar diseases such as *Bipolaris setariae* and *Helminthosporium* sp. Frequent minimum temperatures between 3-8 °C, combined with means below the optimum range and high thermal amplitude, resulted in delayed emergence and lower initial vigor (Figure 3).

In Season 2, precipitation distribution was good, with rain soon after sowing and larger volumes concentrated between 14 and 35 days, ensuring adequate water supply for vegetative growth. Minimum temperatures remained above 7-10 °C, with means between 15-20 °C and maximums between 23-28 °C, creating more favorable conditions for crop

development; however, prolonged periods of leaf wetness maintained an environment conducive to the development of pathogens (Figure 3).

Season 3 saw intense precipitation events concentrated in the first 10 days and between days 18 and 32, with volumes exceeding 40-60 mm, indicating a risk of surface waterlogging. After approximately 40 days, the reduction in precipitation led to alternating periods of excess and deficit of water. Thermal conditions were the most stable, with minimum temperatures between 8-12 °C, means between 16-21 °C, and maximums between 25-30 °C, favoring photosynthesis and biomass accumulation, despite the observed water fluctuations.

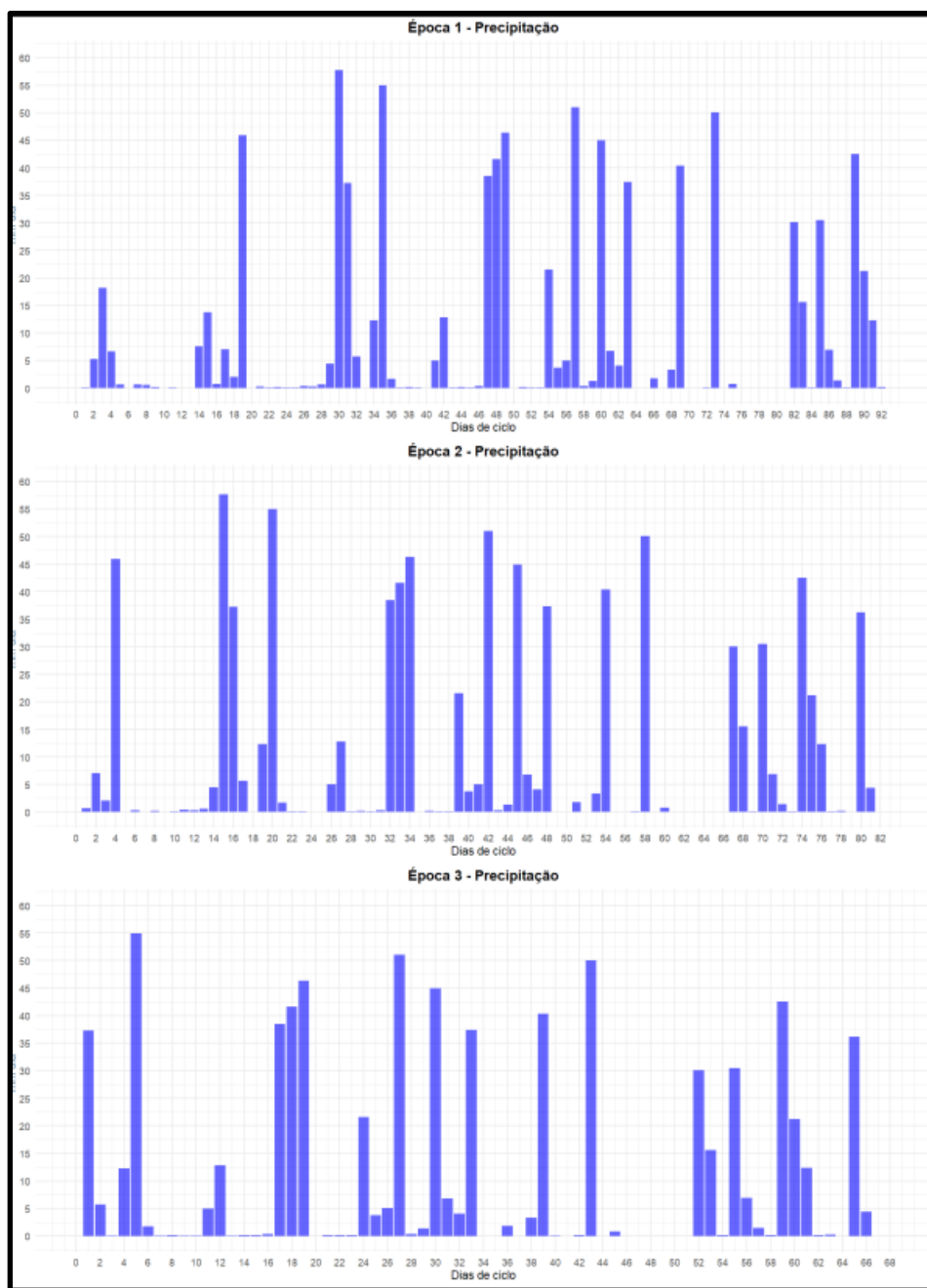


Figure 2. Distribution of precipitation (mm) throughout the *Setaria italica* cycle at different sowing times.

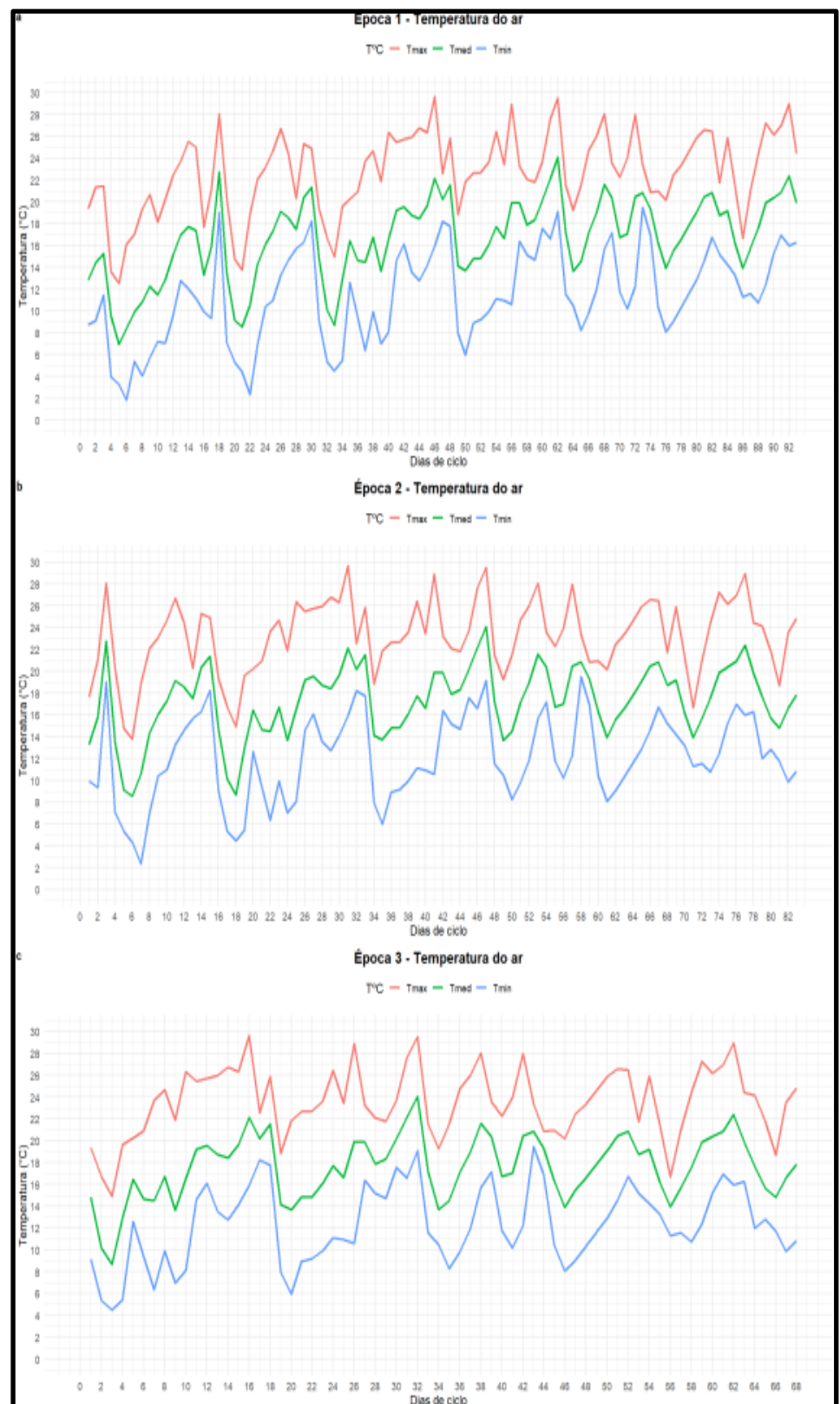


Figure 3. Minimum, mean, and maximum air temperatures (°C) throughout the *Setaria italica* cycle during the three sowing seasons. T°C - Temperature in degrees Celsius; Tmax - Maximum temperature; Tmean - mean temperature; Tmin - Minimum temperature.

The analysis of variance (Table 2) indicated that the sowing time significantly influenced most of the variables evaluated, including soil resistance to penetration at 5 and 10 cm, days to tillering and flowering, plant height, panicle insertion height, panicle length, cycle, and grain weight per plant. Only soil resistance at 15 cm and the number of grains per panicle did not show statistical significance. The block effect was not very relevant, except for grain weight per plant, suggesting general homogeneity of the experimental area.

Table 2. Analysis of variance (ANOVA) for phenological, morphological, productive variables and physical soil attributes in *Setaria italica* cultivated at different sowing times.

VF ¹	DF	Probability at 5% using the f-test.					
		P5	P10	P15	DT	DF	CYC
		kPa	kPa	kPa	days	days	days
Treatment	2	0.0392*	0.0326*	0.2274	0.001*	0.001*	0.001*
Block	4	0.4457	0.1104	0.7406	0.4609	0.4609	0.4609
Error	9	33663	7903	48137	0.001*	0.001*	0.001*
CV	-	28.07	10.63	24.96	1	1	1
Mean	-	653.6	836.27	879.07	54.67	67.67	81.33
FV	DF	PH	PanH	PanL	NGP	GWP	-
		cm	cm	cm	g	g	-
		cm	cm	cm	g	g	-
Treatment	2	0.0333*	0.011*	0.001*	0.0621	0.001*	-
Block	4	0.3049	0.5891	0.0589	0.3699	0.0456*	-
Error	9	18.22	9.47	0.678	16248	0.001	-
CV	-	6.44	12.38	9.53	22.65	15.91	-
Mean	-	66.29	24.85	8.64	562.83	0.2643	-

¹VF: Source of variation; DF: degrees of freedom; MS: mean square; CV: coefficient of variation; * significant at $p \leq 0.05$; ** significant at $p \leq 0.01$. P5: Penetrometer at 5 centimeters. P10: Penetrometer at 10 centimeters. P15: Penetrometer at 15 centimeters. DP: Days to tillering. DF: Days to flowering. CYC: Cycle. PH: Plant height. PanH: Panicle insertion height. PanL: Panicle length. NGP: Number of grains per plant. GWP: Grain weight per panicle. kPa: Kilopascal. days: Number of days. cm: Centimeters. g: Grams. *: Significant factor.

The block factor showed little effect on most variables, indicating good experimental homogeneity. Only grain weight per plant showed significance for blocks, which may indicate some spatial variation for this characteristic. Overall, the results indicate that the sowing time modified aspects related to vegetative growth, reproductive development, and productive performance of *Setaria italica*.

The means of the variables (Table 3) indicate that Period 1 presented greater soil resistance at 5 and 10 cm, a greater number of days for tillering and flowering, and a longer cycle, reflecting more adverse initial conditions. Plant height and panicle insertion height were significantly greater in Period 1 compared to Period 2, while Period 3 showed intermediate values. This pattern suggests that, even with less favorable initial temperature and water regime conditions, the lower plant stand in Period 1 favored greater individual growth, reflected in the mean height and higher panicle position, potentially increasing the accumulation of reproductive biomass.

Panicle length was greater in Period 3, differing from the other periods, while Periods 1 and 2 showed no significant difference. The number of grains per panicle did not vary between periods, but the grain weight per plant was greater in Period 1, evidencing a direct effect of sowing time on individual yield potential.

Figure 4 shows the relationship between the number of tillers and days after sowing (DAS). The regression lines show that Period 1 had the highest tillering rate (slope = 0.08), while Periods 2 and 3 showed a slower increase (0.02), possibly due to greater

intraspecific competition or differences in initial environmental conditions. The low coefficients of determination (R^2) suggest that the number of tillers is influenced by factors beyond time, including water regime, soil compaction, and nutrient availability.

Table 3. Mean values of phenological, morphological, productive variables and physical soil attributes of *Setaria italica* as a function of sowing dates.

Season	P5 kPa	P10 kPa	DT dias	DF dias	PH cm	PanH cm	PanL cm	CYC dias	GWP g
Season 1	774.8a	908.6a	69a	76a	71.16a	28.96a	8.36b	93a	0.3446a
Season 2	442.8b	732.0b	53b	62c	62.52b	21.04b	7.37b	83b	0.1908b
Season 3	743.2ab	868.2ab	42c	65b	65.20ab	24.56ab	10.20a	68c	0.2576b

*Means followed by the same letter in the column do not differ from each other by Tukey's test ($p \leq 0.05$). P5: Penetrometer at 5 centimeters. P10: Penetrometer at 10 centimeters. DT: Days to tillering. DF: Days to flowering. CYC: Cycle. PH: Plant height. PanH: Panicle insertion height. PanL: Panicle length. GWP: Grain weight per panicle. kPa: Kilopascal. days: Number of days. cm: Centimeters. g: Grams. *: Significant factor.

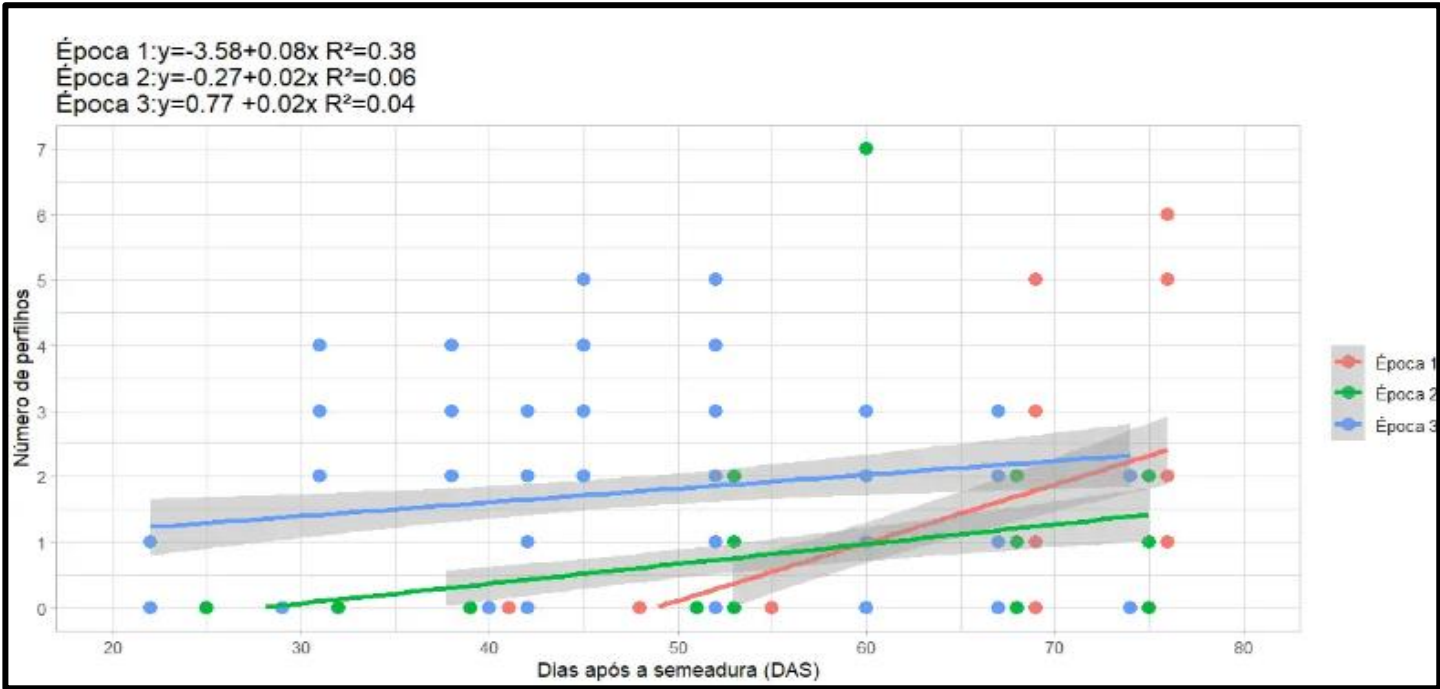


Figure 4. Growth trend for the number of offshoots in all three periods.

In [Figure 5](#), the evolution of the number of nodes per plant throughout the cycle shows gradual growth in all periods, with differences in intensity. Period 1 presented a slope of 0.05 nodes/day, reflecting slower growth and low explanation by time ($R^2 = 0.05$), possibly due to external factors such as partial shading. Period 2 showed similar behavior (0.04 nodes/day; $R^2 = 0.04$), while Period 3 showed a higher rate of node formation (0.07 nodes/day; $R^2 = 0.14$), indicating more consistent development and less relative variability.

Leaf emergence ([Figure 6](#)) was initially later in Period 1, but throughout the cycle, leaf development surpassed that of Period 2, resulting in a higher final number of leaves. Period 3 stood out for its early leaf emergence and the highest total values throughout the period. Regarding regressions, Period 1 showed the highest slope coefficient (0.36 leaves/day), followed by Period 3 (0.18), while Period 2 showed the lowest leaf increment rate. The higher R^2 in Period 1 indicates a moderate fit and a relatively strong association between the number of leaves and days after sowing.

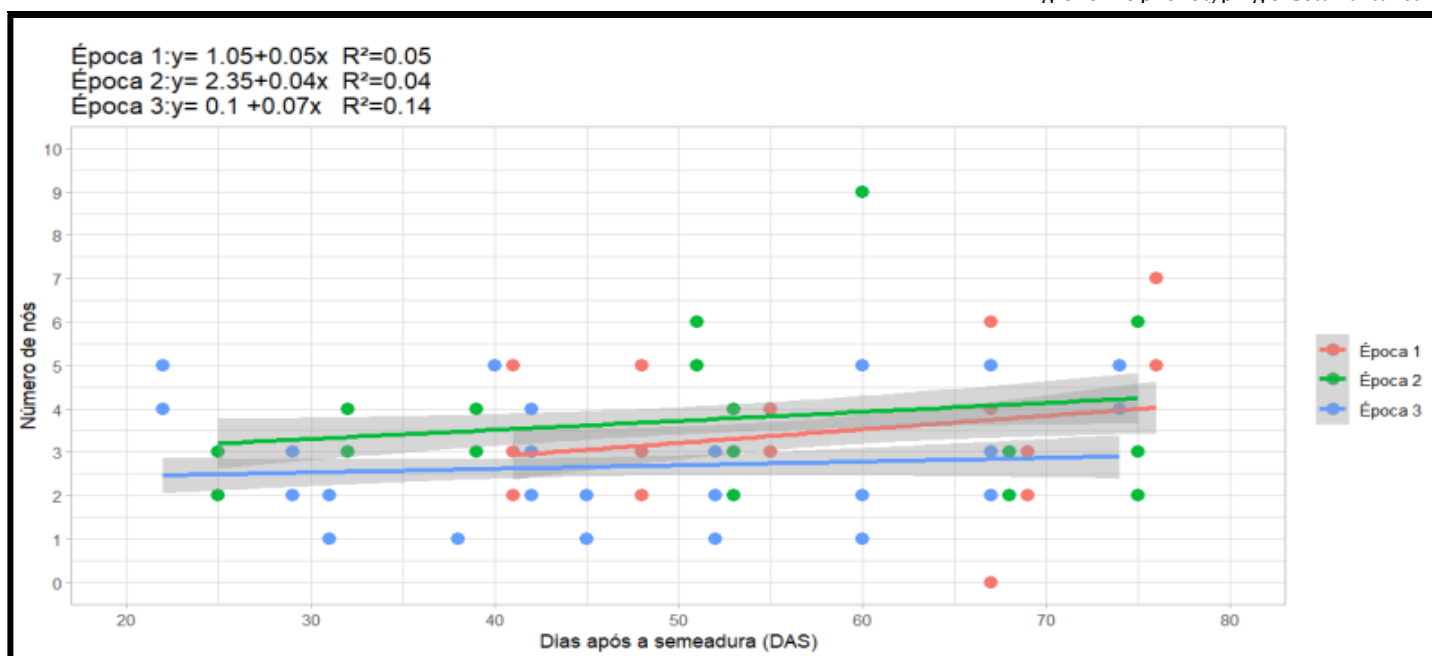


Figure 5. Trend of increasing number of nodes throughout the *Setaria italica* cycle in the three sowing seasons.

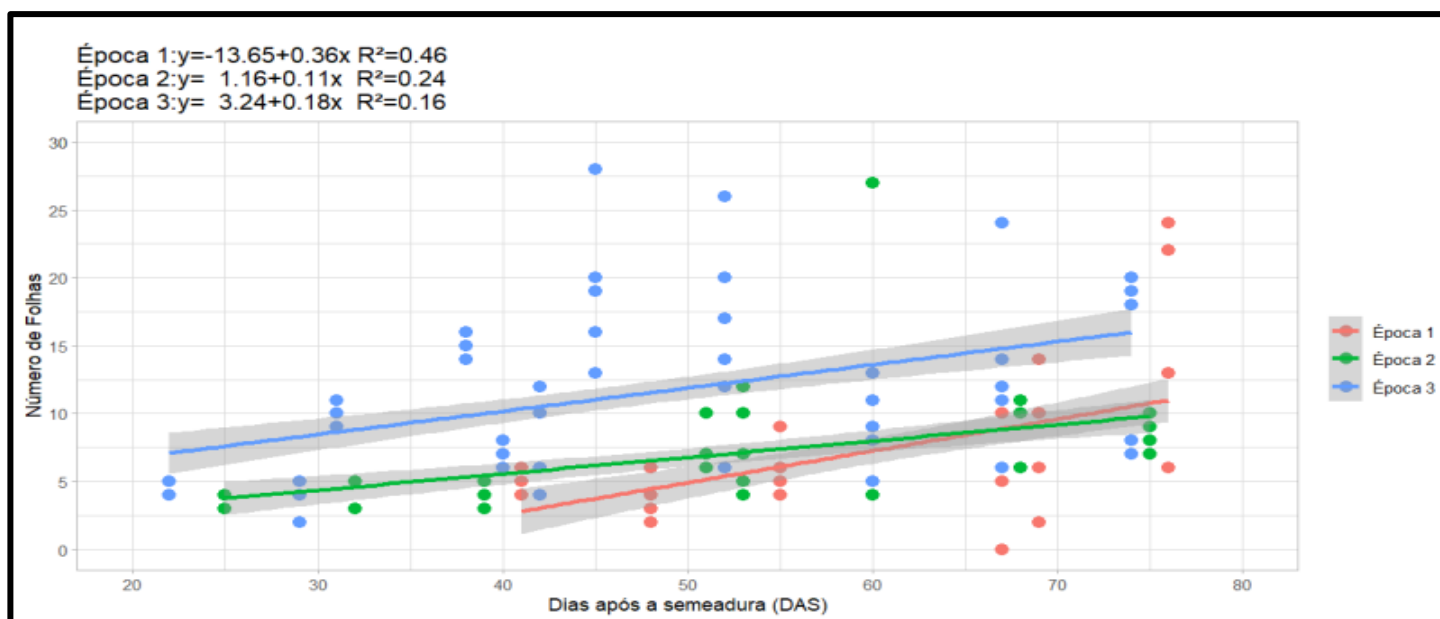


Figure 6. Number of leaves throughout the *Setaria italica* cycle in the three sowing seasons.

The height of the plants throughout the cycle (Figure 7) showed clear differences in the growth rate. Period 1 showed slower growth (0.78 cm/day; $R^2 = 0.51$), suggesting the influence of external factors such as shading and prolonged water stress in the initial stages. Period 2 showed more uniform growth (1.11 cm/day; $R^2 = 0.90$), while Period 3 exhibited the highest rate of increase (1.24 cm/day; $R^2 = 0.83$), evidencing more favorable environmental conditions, including greater thermal stability and regular rainfall, which favored stem elongation and continuous growth.

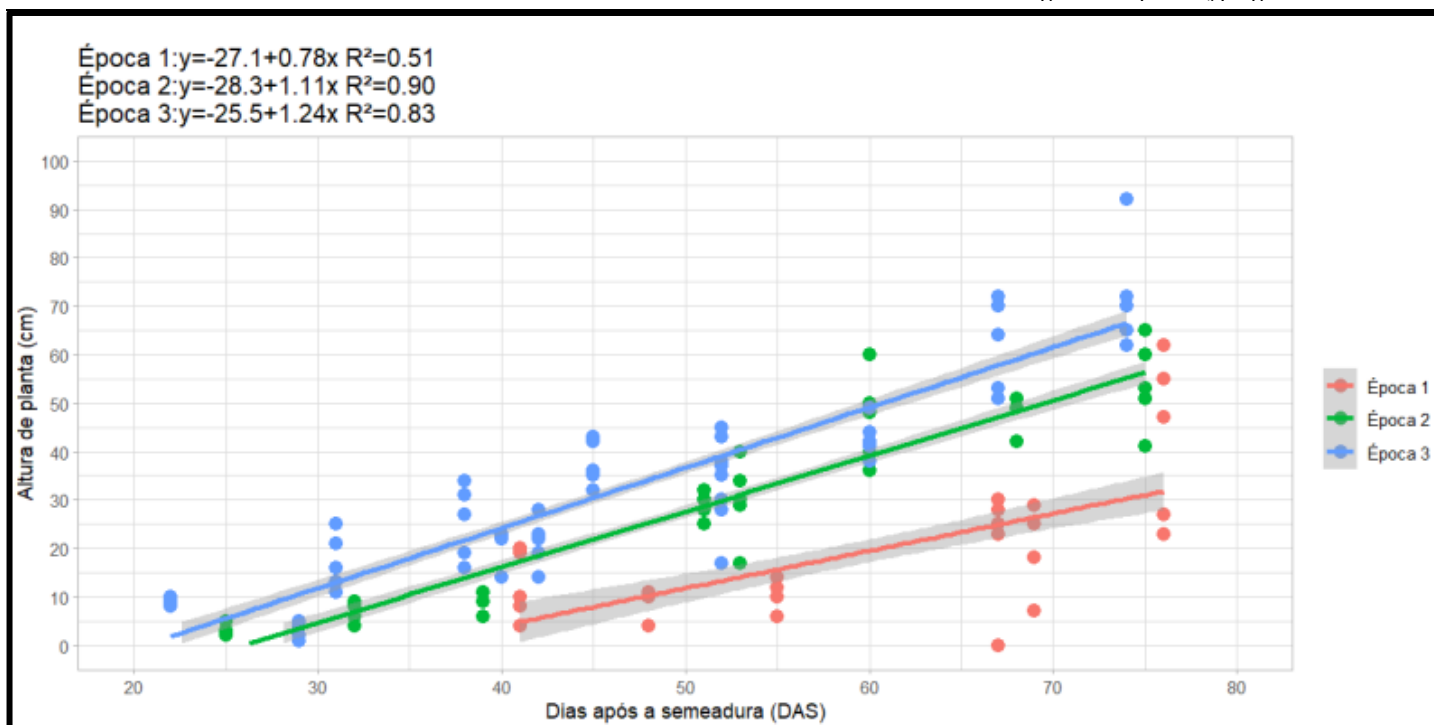


Figure 7. Trend in plant height growth throughout the *Setaria italica* cycle in the three sowing seasons.

Pearson's correlation matrix (Figure 8) allowed for the evaluation of interactions between environmental, morphological, productive, and physical soil variables in the development of *Setaria italica*. Morphological and productive variables, such as plant height, panicle insertion height, grain weight and number per panicle, cycle duration, and days until flowering and tillering, showed a strong positive correlation with each other. This pattern is physiologically expected, as plants with greater vegetative growth tend to accumulate more biomass and invest more in reproductive structures, reflecting higher productive performance. Thus, these variables form a cohesive block, indicating a direct dependence of yield on structural expansion and cycle duration.

In contrast, climatic variables, especially maximum temperature, followed by mean and minimum temperature, showed moderate to strong negative correlations with most morphological and productive characteristics, suggesting that high temperatures act as a limiting factor, reducing plant height, yield components, and crop cycle duration. Variables related to emergence, such as emergence speed index and final stand, showed a positive correlation with each other, but a negative correlation with productive attributes, indicating that a higher stand or faster emergence does not necessarily result in higher production per plant, possibly due to greater intraspecific competition.

Soil resistance to penetration (5 and 15 cm) showed a strong positive correlation with each other ($r = 0.75$), demonstrating consistency of compaction in the evaluated profile. Both resistance levels showed a negative correlation with plant height, number of tillers, and biomass, evidencing that compaction limits root growth and compromises the morphophysiological performance of the crop.

During the development of *Setaria italica*, several pests were recorded that influenced the growth and yield of the crop. The most frequent species was the green-yellow beetle (*Diabrotica speciosa*), responsible for defoliation and reduction of the photosynthetic area. Infestations of *Rhopalosiphum maidis* (corn aphid), characterized by sap-sucking and potential transmission of viruses; *Euchroma* spp. (metalops), causing leaf scraping; *Dichelops furcatus* (green stink bug), associated with damage to vegetative and reproductive tissues; and the golden-green beetle (*Chrysochus auratus*), whose leaf

feeding contributed to the reduction of the photosynthetic area, especially in the initial stages of the crop, were also observed.

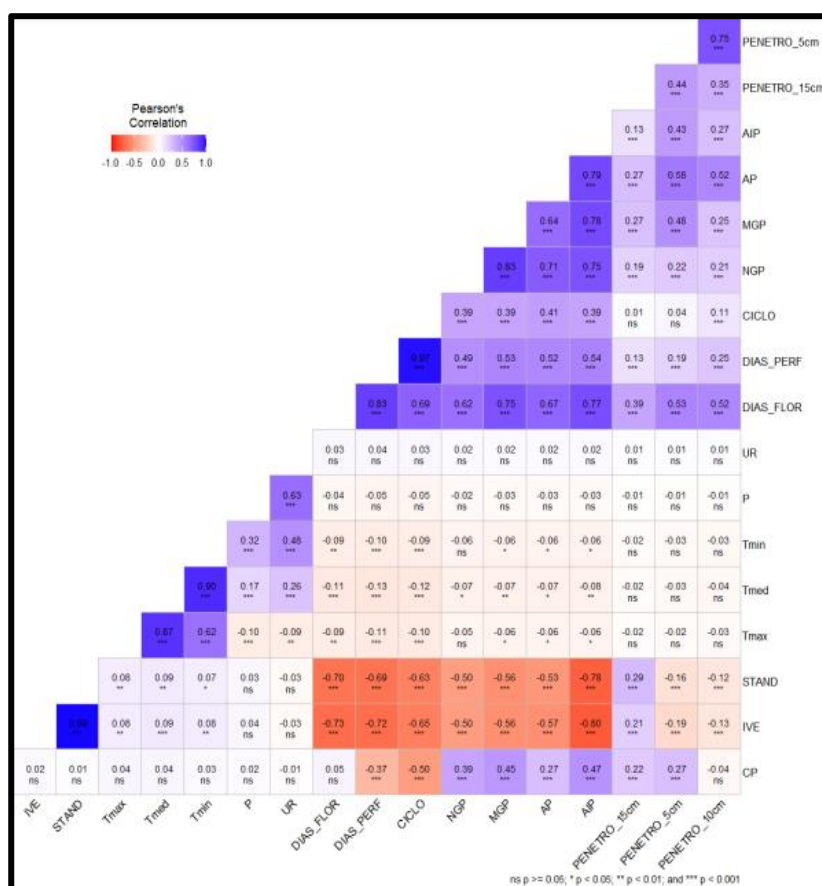


Figure 8. Pearson correlation matrix between phenological, morphological, productive variables and physical soil attributes in *Setaria italica*. The correlation coefficients are represented by the color intensity, according to the scale shown in the figure. ESI - Emergence Speed Index; STAND - Final stand (plants per area); Tmax - Maximum temperature; Tmean - Mean temperature; Tmin - Minimum temperature; P - Precipitation; RH - Relative humidity; DAYS_FLOW - Days until flowering; DAYS_TILL - Days until reproductive tillering; CYCLE - Total duration of the crop cycle; NGP - Number of grains per panicle; GWP - Grain weight per plant; PH - Plant height; PanH - Panicle insertion height; PENETRO_5cm - Soil resistance to penetration at a depth of 5 cm; PENETRO_15cm - Soil resistance to penetration at a depth of 15 cm; SC - Soil compaction.

Among the diseases, leaf spot caused by *Bipolaris* sp. stood out, with its incidence being more pronounced during periods characterized by higher humidity and prolonged leaf wetness. The occurrence of the pathogen resulted in a reduction in functional leaf area, accelerated senescence, and compromised productive performance, especially in later sowing periods.

The combined pressure from insect pests and diseases helped explain the differences observed between sowing times. Despite more favorable thermal and water conditions for vegetative growth in later sowing periods, higher canopy moisture favored the intensification of leaf spot caused by *Bipolaris* sp. and increased the occurrence of sucking insects, which limited yield. In contrast, the first sowing period showed lower pathogen and pest pressure, associated with lower initial moisture and lower plant stand, favoring tillering and production components.

In general, sowing dates significantly influenced the agronomic performance of *Setaria italica*, reflecting the combined effects of water regime, temperature, and soil mechanical resistance. The first sowing date, although showing an initial delay in leaf emergence and greater thermal stress, stood out for greater tillering, greater plant and panicle height, and greater grain weight per plant, a result associated with less intraspecific competition due to the lower plant stand.

The second growing season presented more favorable conditions for emergence and initial establishment; however, these advantages did not translate into higher yields, resulting in lower grain weight per panicle. The third growing season, despite exhibiting greater thermal stability and good vegetative development, was negatively affected by higher canopy humidity, which favored the occurrence of fungal diseases, especially *Bipolaris* sp., limiting reproductive performance.

The occurrence of insect pests and diseases was directly associated with the microclimatic conditions imposed by the plant stand and canopy architecture. In the second and third sowing seasons, the higher density promoted greater moisture retention and prolonged leaf wetness, favoring the development of necrotrophic pathogens, such as *Bipolaris* sp., a pattern widely described for C4 grasses in subtropical and tropical environments (European and Mediterranean Plant Protection Organization [EPPO], 2025; Peng & Zhang, 2021). Similarly, the greater availability of young and succulent tissues may have intensified the occurrence of sucking insects, such as *Rhopalosiphum maidis*, resulting in negative impacts on reproductive performance, as reported for cereal systems in different regions of the world (Huang et al., 2023; Khariani et al., 2021). In contrast, the lower stand observed in the first sowing season provided greater canopy aeration and lower leaf moisture, reducing pest and disease pressure, even under less favorable initial temperature and water availability conditions (Pant, Irigoyen, Doust, Scholthof, & Mandadi, 2016; Wang et al., 2024).

In an integrated manner, the results indicate that the differences between the sowing times of *Setaria italica* are not only due to climatic conditions, but also to variations in plant stand, which influenced intraspecific competition and individual performance. The first sowing time presented a lower plant population, favoring individual growth, reflected in greater plant height, greater panicle insertion height, and greater grain weight per plant, even in the face of less favorable initial conditions of temperature, irregular water regime, and greater soil resistance (Sun et al., 2022; Peng & Zhang, 2021).

In contrast, the second and third seasons presented better thermal and water conditions for emergence and initial vegetative growth, resulting in higher plant stands and better collective performance in variables such as tillering, number of nodes, and leaf emission (Huang et al., 2023; Zhang et al., 2025). The third season (September) stood out for presenting more balanced climatic conditions, favoring uniform vegetative development; however, higher plant stands and higher canopy humidity increased intraspecific competition and favored the incidence of foliar diseases, limiting individual reproductive performance (EPPO, 2025; Khariani et al., 2021; Sravani, Subramanyam, Nagavani, Umahesh, & Sagar, 2021).

These results highlight the relationship between population and individual performance: while the first sowing season favored more vigorous isolated plants, seasons 2 and 3 provided greater structural uniformity and collective vigor, although with lower yield per plant. In practical terms, the third sowing season presents better agronomic suitability, combining uniform establishment, lower risk of thermal and water stress, and greater compatibility with the regional agricultural calendar, demonstrating that the choice of sowing season should consider both individual yield and population performance and the stability of the production system (Pant et al., 2016; Wang et al., 2024).

Conclusions

Water availability, temperatures, and soil physical conditions influenced the performance of *Setaria italica*. The first sowing period early August favored individual growth and greater grain weight per plant due to the lower plant stand. The third period September provided better establishment, uniform growth, and a lower risk of stress, making it the most suitable for recommendation.

References

- Alvares, C. A., Stape, J. L., Sentelhas, P. C., Gonçalves, J. L. M., & Sparovek, G. (2014). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*, 23(6), 711–728. <https://doi.org/10.1127/0941-2948/2013/0507>
- CODEX ALIMENTARIUS COMMISSION. (2023). *Proposal for standardization of millets: Comments of India*. FAO/WHO. Available at: <https://www.fao.org/fao-who-codexalimentarius/>
- EPPO - European and Mediterranean Plant Protection Organization.) (2025). *EPPO Global Database: Setaria italica pests*. Retrieved February 16th, 2026. From: <https://gd.eppo.int>
- FAO - Food and Agriculture Organization of the United Nations. (2022). *FAOSTAT: Production – Crops and livestock products*. Available at: <https://www.fao.org/faostat/>
- Gao, L., Zhu, Q., Li, H., Wang, S., Fan, J., Wang, T., Yang, L., Zhao, Y., Ma, Y., Chen, L., Li, X., Dong, S., Chu, X., Diao, X., Yuan, X., Wang, J., & Yang, G. (2025). Construction of a genetic linkage map and QTL mapping of the agronomic traits in foxtail millet (*Setaria italica*). *BMC Genomics*, 26(1), 152. <https://doi.org/10.1186/s12864-024-11169-2>
- He, Q., Tang, S., Zhi, H., Chen, J., Zhang, J., Liang, H., Alam, O., Li, H., Zhang, H., Xing, L., Li, X., Zhang, W., Wang, H., Shi, J., Du, H., Wu, H., Wang, L., Yang, P., Yan, H., ... Diao, X. (2023). A graph-based genome and pan-genome variation of the model plant *Setaria*. *Nature Genetics*, 55(7), 1232–1242. <https://doi.org/10.1038/s41588-023-01423-w>
- Huang, Y. C., Wang, Y. T., Choong, Y. C., Huang, H. Y., Chen, Y. R., Hsieh, T. F., & Lin, Y. R. (2023). How ambient temperature affects the heading date of foxtail millet (*Setaria italica*). *Frontiers in Plant Science*, 14, 1147756. <https://doi.org/10.3389/fpls.2023.1147756>
- Kalsi, R., & Bhasin, J. K. (2023). Nutritional exploration of foxtail millet (*Setaria italica*) in addressing food security and its utilization trends in food system. *eFood*, 4(5), e111. <https://doi.org/10.1002/efd2.111>
- Li, X., Hou, S., Feng, M., Xia, R., Li, J., Tang, S., Han, Y., Gao, J., & Wang, X. (2023). MDSi: Multi-omics database for *Setaria italica*. *BMC Plant Biology*, 23, 223. <https://doi.org/10.1186/s12870-023-04238-3>
- Nadeem, F., Ahmad, Z., Ul Hassan, M., Wang, R., Diao, X., & Li, X. (2020). Adaptation of foxtail millet (*Setaria italica* L.) to abiotic stresses: a special perspective of responses to nitrogen and phosphate limitations. *Frontiers in plant science*, 11, 187. <https://doi.org/10.3389/fpls.2020.00187>
- NASA - National Aeronautics and Space Administration. (2025). *NASA Prediction of Worldwide Energy Resources (POWER) project: Surface meteorology and solar energy – Daily data*. Langley Research Center. Retrieved February 16th, 2026. From: <https://power.larc.nasa.gov/>

- Oliveira, I. P., Schaaf, C., & Setta, N. (2024). Drought Responses in Poaceae: Exploring the Core Components of the ABA Signaling Pathway in *Setaria italica* and *Setaria viridis*. *MDPI: Plants*, 13(11), 1451. <https://doi.org/10.3390/plants13111451>
- Pant, S. R., Irigoyen, S., Doust, A. N., Scholthof, K.-B. G., & Mandadi, K. K. (2016). Setaria: A food crop and translational research model for C4 grasses. *Frontiers in Plant Science*, 7, 1885. <https://doi.org/10.3389/fpls.2016.01885>
- Peng, R., & Zhang, B. (2021). Foxtail millet: A new model for C4 plants. *Trends in Plant Science*, 26(3), 199–201. <https://doi.org/10.1016/j.tplants.2020.12.003>
- R Core Team. (2025). *R: A language and environment for statistical computing*. Viena, Austria: R Foundation for Statistical Computing. Available at: <https://www.r-project.org/>
- Santos, H. G., Jacomine, P. K. T., Anjos, L. H. C., Oliveira, V. A., & Lumberras, J. F. (2018). *Sistema brasileiro de classificação de solos* (5th ed.). Rio de Janeiro, RJ, Brazil: Embrapa Solos.
- Sun, M. J., Chao, Y., He, W., Kang, X. R., Yang, Q. G., Wang, H., Pan, H., Lou, Y.H., & Zhuge, Y. P. (2022). Changes in foxtail millet (*Setaria italica* L.) yield, quality, and soil microbiome after replacing chemical nitrogen fertilizers with organic fertilizers. *MDPI: Sustainability*, 14(24), 16412. <https://doi.org/10.3390/su142416412>
- Stravani, P., Subramanyam, D., Nagavani, A. V., Umahesh, V., & Sagar, G. K. (2021). Weed management effect on weed growth and yield of foxtail millet (*Setaria italica* L. Beauv.). *Indian Journal of Weed Science*, 53(4), 430–432. <https://doi.org/10.5958/0974-8164.2021.00079.4>
- Wang, Z., Hao, J., Shi, X., Wang, Q., Zhang, W., Li, F., Mur, L. A. J., Han, Y., Hou, S., Han, J., & Sun, Z. (2024). Integrating dynamic high-throughput phenotyping and genetic analysis to monitor growth variation in foxtail millet. *Plant Methods*, 20(1), 168. <https://doi.org/10.1186/s13007-024-01295-z>
- Zhang, W., Wang, B., Liu, B., Chen, Z., Lu, G., Bai, C., & Ge, Y. (2025). Response of Summer Foxtail Millet Yield and Water Productivity to Water Supply in the North China Plain. *MDPI: Agronomy*, 15(11), 2468. <https://doi.org/10.3390/agronomy15112468>