frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 07 April 2026
DOI 10.3389/fsufs.2026.1765943

OPEN ACCESS

EDITED BY
Vijay Singh Meena,
ICAR - Mahatma Gandhi Integrated Farming Research Institute, India

REVIEWED BY
Iqtidar Hussain,
Gomal University, Pakistan
Isaac Mirahki,
University of Tennessee, Knoxville, United States
Haley Mosqueda,
North Dakota State University Press, United States

*CORRESPONDENCE
Francislene Angelotti
✉ francislene.angelotti@embrapa.br

RECEIVED 11 December 2025
REVISED 12 March 2026
ACCEPTED 16 March 2026
PUBLISHED 07 April 2026

CITATION
Nascimento LAd, de Oliveira AR, dos Santos CB, da Silva WO, Tardin FD, Morales MM and Angelotti F (2026) Sorghum biomass: productive potential and energy strategy for the semiarid region.
Front. Sustain. Food Syst. 10:1765943.
doi: 10.3389/fsufs.2026.1765943

Sorghum biomass: productive potential and energy strategy for the semiarid region

Layana Alves do Nascimento[1], Anderson Ramos de Oliveira[2], Camila Barbosa dos Santos[3], Weslley Oliveira da Silva[1], Flavio Dessaune Tardin[4], Marina Moura Morales[5] and Francislene Angelotti[2]*

[1]State University of Feira de Santana, Feira de Santana, Brazil, [2]Embrapa Semi-Arid, Brazilian Agricultural Research Corporation, Petrolina, Brazil, [3]University of Pernambuco, Petrolina, Brazil, [4]Embrapa Maize & Sorghum, Brazilian Agricultural Research Corporation, Sete Lagoas, Brazil, [5]Embrapa Forestry, Brazilian Agricultural Research Corporation, Colombo, Brazil

Biomass sorghum has emerged as a strategic crop in semi-arid regions and other areas with water limitations, providing a sustainable source of biomass for multiple uses, including bioenergy generation. This study evaluated the productive and energetic potential of biomass sorghum cultivars under sowing dates in brazilian semi-arid. Two experiments were conducted: the first assessed biometric and productive parameters of the cultivars Agri 002E and BRS 716, sown in two planting seasons (June and December). The first harvest was carried out when ≥50% of the panicles reached physiological maturity, and the regrowth was harvested 40 days later. The second experiment evaluated energy potential at phenological stages. Both experiments followed a randomized complete block design with three replications. Results showed that planting date significantly influenced sorghum development and biomass production. December sowing resulted in 57.97 t ha^{-1} of dry biomass at the first harvest and 26.69 t ha^{-1} during regrowth. June sowing produced 21.42 t ha^{-1} at the first harvest and 42.89 t ha^{-1} at regrowth. The optimal harvest time for energy production was 123 days after sowing, reaching 69.7 Gcal/ha. These findings demonstrate that biomass sorghum is a viable and sustainable alternative for bioenergy generation in semi-arid regions. The crop's capacity for regrowth, high biomass accumulation, and adaptability to environmental stress make it a promising strategy for reducing dependence on native forest biomass and promoting energy sustainability. Biomass sorghum contributes as a resilient and sustainable strategy for food and energy security.

KEYWORDS
bioenergy, biomass, regrowth, *Sorghum bicolor*, sustainability

1 Introduction

Sorghum (*Sorghum bicolor* (L.) Moench.) is an economically important cereal due to its versatility and efficiency, being suitable for grain production and high-quality biomass, with applications in forage, silage, and biofuel production (Choudhary et al., 2024; Ameen et al., 2024). An additional advantageous characteristic of sorghum is its regrowth potential. After cutting or harvesting, the root system remains active, enabling the regeneration of the aerial part and the continuation of productive cycles (Bhat et al., 2020).

This ability not only reduces replanting costs but also enhances the sustainability of the production system by maximizing soil and water resource use (Syuryawati and Aqil, 2021). Sorghum is also resilient to adverse conditions such as drought and low-fertility soils, making it a viable crop for regions with climatic and edaphic constraints (Alzahrani et al., 2024). Therefore, sorghum is considered strategic for both food and energy security, particularly under climate change scenarios (Alzahrani et al., 2024; Watson-Lazowski et al., 2024; Nascimento et al., 2023; Ndlovu et al., 2021).

Among the sorghum types cultivated, biomass sorghum stands out as a raw material for both second-generation ethanol and direct bioenergy generation through burning freshly harvested or densified biomass (Morales et al., 2024; Bakari et al., 2023). The use of biomass sorghum as an energy source is particularly notable when compared to eucalyptus wood. While eucalyptus requires a six-year cycle to reach optimal harvest and produces an average of ~22 t ha^{-1} of dry biomass per year (Binkley et al., 2017), biomass sorghum can produce over 80 t ha^{-1} of fresh biomass and approximately 40 t ha^{-1} of dry biomass within six months (Morales et al., 2024; Nascimento et al., 2023). Additionally, the energetic potential of biomass sorghum varies according to the cultivar, with higher heating values (HHV) ranging from 4,220 to 4,590 kcal/kg (Batista et al., 2018), althoguh eucalyptus average is (4,700 kcal/kg) (Moreira et al., 2012).

In the Brazilian semi-arid region, biomass consumption is high due to intensive energy demands, particularly from the gypsum industry, which produces 95% of Brazil's gypsum (Angelotti et al., 2022). This sector largely relies on wood from native Caatinga vegetation (Arcoverde et al., 2024), posing a serious threat to biodiversity and ecosystem conservation. Many studies address the first cycle of sorghum cultivation. However, there is a lack of information regarding whether regrowth after 40 days maintains significant energy potential. This information is important for predicting the cost of planting over two harvests. It also helps to indicate the best planting window for the Agri 002E and BRS 716 varieties, assisting in defining the zoning for each cultivar, and understanding the best harvest date to maximize energy generation. The experiment was conducted under irrigated conditions to ensure uniform crop development, enabling a consistent evaluation of the productive potential of the cultivars in semi-arid environments.

2 Materials and methods

2.1 Experimental site

The study was conducted at the Caatinga Experimental Field, belonging to Embrapa Semi-arid, located in Petrolina, Pernambuco, Brazil (latitude 9° 8′8.9″ S, longitude 40° 18′33.6″ W, altitude 373 m). The soil in the experimental area is classified as Red-Yellow Argisol, with medium texture and flat relief. The climate is semi-arid (BSwh'), according to Köppen's classification, with a well-defined rainy period from November to April and an average annual precipitation of approximately 500 mm (Dubreuil et al., 2019).

2.2 Experimental design

The experimental design used was a randomized complete block design with three replications. In the first trial, to determine productive potential, the experimental treatments consisted of two biomass sorghum cultivars, BRS 716 and Agri 002E. BRS 716, developed by the Brazilian Agricultural Research Corporation (Embrapa), is a biomass-type sorghum widely used for bioenergy production due to its tall plant stature, high vegetative growth, and high dry matter yield, particularly under tropical and semi-arid conditions (May et al., 2016). The cultivar AGRI-002E is a forage sorghum genotype with Bolivian genetic background developed and commercialized by Tropigene/Latina Seeds, registered in Brazil in 2011. It was bred to maximize vegetative growth and biomass production, presenting vigorous growth, deep root system, high regrowth capacity, and high fresh and dry matter yields, characteristics that make it suitable for silage production and forage supply in tropical environments (Pucetti et al., 2024). Due to its high biomass accumulation and adaptability to warm climates, these cultivars have been widely used in studies evaluating biomass productivity and forage systems. These cultivars were tested under two sowing dates: June and December Sowing in June corresponds to the onset of winter in the southern hemisphere, while sowing in December corresponds to the onset of summer. During the experimental period, climatic data were monitored via an automatic meteorological monitoring station (Figure 1).

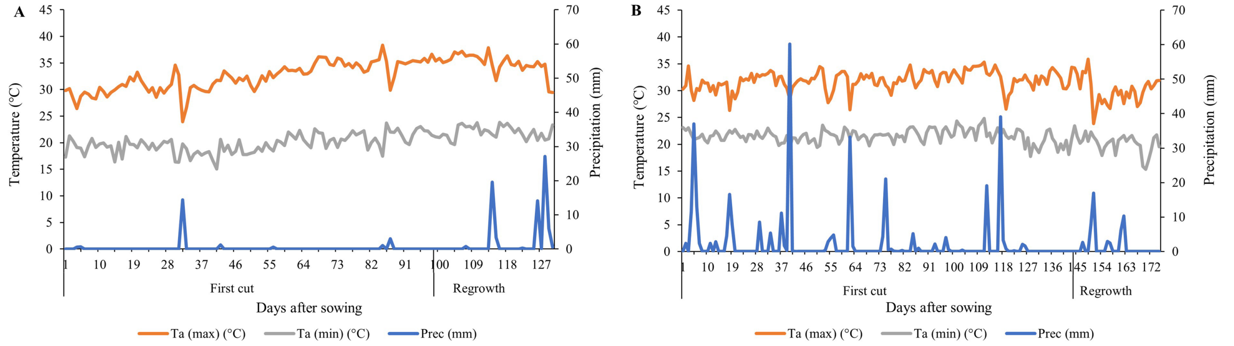

FIGURE 1
(A) Winter—June to September 2021. **(B)** Summer—December to May 2022. Maximum temperature [Ta (max) (°C)], minimum temperature [Ta (min) (°C)], precipitation [Prec (mm)], and sorghum biomass cycle (sowing to harvest) of two sowing seasons, from June to September 2021 and December to May 2022.

2.3 Treatments and agronomic management

Soil preparation was performed via harrowing. The area was then divided into plots composed of eight rows, each measuring 3.0 m in length and spaced 0.70 m apart, totaling a plot area of 16.80 m^2 (3.0 m × 5.6 m). Seeds with 90% germination rate were manually sown on June 30, 2021 (season 1) and December 21, 2021 (season 2). Fourteen seeds were deposited per linear meter at a depth of 3–5 cm, spaced 15 cm between furrows. Seedlings were thinned 20 days after sowing, maintaining seven plants per linear meter.

Fertilization was based on soil chemical analysis (Table 1) and followed recommendations from Santos et al. (2015). At sowing, 28 kg/ha of N, 98 kg/ha of P_2O_2, and 56 kg/ha of K_2O were applied. Topdressing fertilization consisted of 110 and 50 kg/ha of N applied at 20 and 30 days after sowing, respectively. For regrowth, 150 kg/ha of N was applied in two split applications 15 days after the first harvest. Irrigation was carried out via drip irrigation according to crop water demand (Santos et al., 2015).

2.4 Data collection and measurements

At the time of the first harvest (first cut), 10 plants were sectioned and cut 10 cm above ground level for assessment. For analysis, data from the four meters of the central planting rows were considered to ensure sample representativeness. Harvesting was performed when 50% or more of the panicles exhibited grains at physiological maturity, with a moisture content of approximately 15%. To assess regrowth capacity, the plants were cut again 40 days after the first cut.

The characteristics evaluated in the first cut were: plant height (PH), measured from the base, at soil level, to the last fully expanded leaf, using a graduated measuring tape (m); number of leaves (NL), determined through simple counting, considering all leaves with visible and fully developed ligules; stem diameter (SD), measured with a digital caliper by taking two readings between the second and third internodes and calculating the average value (mm); and leaf area (LA), which was calculated based on the dimensions of the third leaf with an open ligule by measuring its length (L) and width (W) with a graduated measuring tape.

To determine fresh matter yield (kg), plant components (leaf, stem, and total) were separated and weighed using an analytical scale. Dry biomass was determined after drying the samples in a forced-air circulation oven maintained at 60 °C until constant weight was reached (approximately 72 h). The same variables were evaluated during the regrowth harvest, following the same methodological procedures used in the first cut.

Fresh matter production (FMP) per hectare was obtained as the product of production per linear meter cultivated and the total linear meters cultivated per hectare. Dry matter production (DMP) was estimated as the product of FMP and DMP content, and subsequently converted to DMP per hectare.

2.5 Energy potential assessment (second experiment)

In the second experiment, conducted under the same conditions, the cultivar BRS 716 was sown in July to determine energy potential at five harvest times: 62, 73, 101, 108, and 113 days after sowing. July was selected to evaluate energy potential under intermediate photoperiod and temperature conditions.

The following variables were evaluated: biomass yield (t ha^{-1}), higher heating value (HHV)—estimated using a bomb calorimeter adapted from ASTM D5865 (ASTM – American Society for Testing and Materials, 2013), ash content (%)—analyzed using NBR 8112 (ABNT – Brazilian Association of Technical Standards, 1986).

$$\text{Energy productivity Gcal/ha} = \text{HHV Kcal/kg} \times \text{Productivity t ha}^{1}\ 1{,}000$$

where:
HHV (kcal/kg) = Higher Heating Value of the biomass
Biomass Yield (t ha^{-1}) = Total dry biomass production per hectare
1,000 = conversion factor from kcal to Gcal.

The optimal harvest time of 123 days was determined a mathematical approach based on the growth trend observed in our data. We fitted a second-order polynomial regression model ($y = -0.0077x^2 + 1.8929x - 46.631$; $R^2 = 0.8314$) to the Energy Productivity dataset. To identify the theoretical maximum of the energy accumulation curve, we calculated the first derivative of the regression function ($dy/dx = 2ax + b$) and set it to zero ($dy/dx = 0$). Solving for x gave us the stationary point, which corresponds to the maximum energy productivity.

2.6 Statistical analysis

Statistical analyses were performed using analysis of variance (ANOVA). When significant effects were detected, treatment means were compared using Tukey's test at a 95% confidence level ($p < 0.05$), with analyses carried out in Sisvar software version 5.6 (Ferreira, 2011).

For the second experiment, data were analyzed using a General Linear Model (GLM). Mean comparisons were also performed using Tukey's test ($p < 0.05$), in Jamovi software version 2.6 (Jamovi Project, 2025).

3 Results and discussion

3.1 Productive potential

The duration of the biomass sorghum cycle, from planting to grain physiological maturity, varied significantly with the planting season. In the June planting, the first cut occurred at 90 days, during which

TABLE 1 Soil chemical analysis (0–20 cm deep) during two sowing seasons (June to September 2021 and December 2021 to May 2022).

Season	M.O	pH H_2O	P	S-SO^{-4}	Ca^{2+}	Mg^{2+}	K^{+}	H + Al	V
	g kg^{-1}	mg dm^{-3}			cmolc dm^{-3}			%	
Season 1	21.8	5.7	1.3	2.4	1.87	1.05	0.31	0.97	76.84
Season 2	4.3	6.8	11.6	6.7	1.72	0.45	0.32	1.11	69.57

temperatures ranged from 15 to 38 °C and total rainfall was 21 mm. Regrowth occurred between 29 September and 8 November, with temperatures from 19 to 37 °C and total rainfall of 71 mm. The second cut, following December planting, occurred 135 days after planting, with temperatures ranging from 17 to 35 °C and total rainfall of 340 mm. Regrowth occurred from 5 May, with harvesting on 14 June, with temperatures between 15 and 35 °C and total rainfall of 50 mm (Figure 1).

3.2 Influence of temperature and photoperiod

The productivity of fresh mass (FMY) and total dry mass (DMY) of biomass sorghum was influenced by planting season ($p > 0.05$) (Tables 2, 3). In the first harvest, plants produced more biomasswhen sown in December (Table 2).

In contrast, during the regrowth stage, fresh and dry matter production was higher in plants sown in June (Table 3).

Planting time is a determining factor in the productivity of biomass sorghum, as it directly affects vegetative development. Photoperiod-sensitive sorghum cultivars, such as those used in this study (Agri 002E and BRS 716), exhibit characteristic phenological behavior: under long-day conditions, flowering is delayed, extending the vegetative phase and promoting biomass accumulation (Wolabu and Tadege, 2016). Casto et al. (2019) reported that this photoperiod sensitivity is associated with the Maturity2 (Ma2) locus, which promotes selective upregulation of the SbPRR37 and SbCO genes. These genes act as co-repressors of the florigen SbCN12, thereby delaying flowering. This molecular mechanism can be advantageous for cultivars adapted to specific photoperiods, as it enables greater biomass accumulation before the onset of the reproductive stage.

In addition to photoperiod, temperature is a crucial element that directly affects plant growth and development. The optimal temperature range for sorghum development varies between 21 and 38 °C (Chadalavada et al., 2021; Silva et al., 2024; Nascimento et al., 2023, 2025). In the present study, biomass sorghum sown in June experienced minimum temperatures of 15.04 °C and maximum temperatures of 38.33 °C, with values below 20 °C recorded for 56 days (Figure 1). These conditions may have contributed to the reduction in biomass production of Agri 002E and BRS 716 cultivars. Previous studies indicate that the biometric and productive performance of sorghum cultivars is significantly reduced at temperatures between 20 and 33 °C, compared to higher thermal ranges between 24.8 and 39.3 °C (Simpson et al., 2020). This response is associated with sorghum's C4 photosynthetic metabolism, which is highly efficient under high-temperature and high-light conditions. The C4 pathway significantly reduces photorespiration and optimizes carbon fixation, conferring greater thermotolerance compared to C3 species (Opoku et al., 2024). As a result, accelerated growth and higher biomass production are favored (Monteiro et al., 2012; Simpson et al., 2020).

Furthermore, temperatures below the ideal range for sorghum development may significantly compromise physiological and productive performance. Under such conditions, enzymatic activity and carbon assimilation become limited, reducing photosynthetic efficiency and, consequently, yield potential (Meki et al., 2017). Thermal stress directly affects plant growth and development, causing delays in panicle initiation, reductions in inflorescence size, and lower grain yield—especially in early and intermediate planting dates when the crop is exposed to suboptimal temperatures (Emendack et al., 2021). Therefore, the interaction between photoperiod and temperature is crucial for maximizing sorghum productivity, particularly in cultivars sensitive to environmental variability. The choice of planting season must consider not only day length but also thermal fluctuations throughout the crop cycle to ensure optimal development conditions.

3.3 Biometric variables

For the productive variables, in addition to the significant interaction with planting season, significant differences were observed between cultivars, both in the first cut and in regrowth. The cultivar Agri 002E produced higher fresh mass yield (FMY), dry mass yield (DMY), dry leaf mass (DLM), and fresh (FSM) and dry stem mass (DSM) (Figure 2), regardless of planting season. For fresh leaf mass (FLM), cultivar Agri 002E differed significantly from BRS 716 only in the December planting during the first cut, and in regrowth from the June planting (Figure 3).

Individually, planting season affected the development of biomass sorghum plants, resulting in differences in biometric traits. Plant height (PH) and number of leaves (NL) were lower for plants sown in June (Figures 4A,C). In regrowth, the effect of planting time was reversed, with higher height, number of leaves, stem diameter, and leaf area index in plants sown in June (Figures 4B,D,E,F).

Biometric traits play a fundamental role in biomass sorghum production, as they are directly linked to growth, development, and productivity. Taller plants tend to produce more dry mass, as the longer vegetative period enables greater biomass accumulation (Bera et al., 2026). This occurs because photoperiod-sensitive hybrids have an extended vegetative cycle, which favors green mass production. Alongside plant height, the number of leaves directly influences sorghum productivity, as leaves are essential for photosynthetic efficiency (Chavez et al., 2022). Thus, a higher number of healthy and well-developed leaves is associated with greater photosynthetic capacity and, consequently, increased biomass production. Similarly, stem diameter is another variable that directly influences biomass yield, as it relates to structural support capacity and storage of photoassimilates. As highlighted by Souza et al. (2024), stem diameter is proportional to plant weight and, therefore, forage mass production. Additionally, Andrade Júnior et al. (2020) noted that the stem is an important storage organ for carbohydrates and other reserve substances, and that greater stem diameter is associated with higher storage capacity of photoassimilates, contributing to greater fresh and dry mass production.

In the Brazilian Semi-arid region, biomass sorghum demonstrated remarkable productive potential, with 173.05 t ha^{-1} of fresh mass yield (FMY) and 57.97 t ha^{-1} of dry mass yield (DMY) in the first cut from the December planting (Table 4).

Additionally, in regrowth harvested 40 days after the first cut in the June planting, the crop reached 233.6 t ha^{-1} (FMY) and 42.89 t ha^{-1} (DMY) (Table 5). These results illustrate the high potential of sorghum for biomass production under semi-arid conditions.

These irrigated yields exceed rainfed systems (e.g., Girotto et al., 2021 reported 69.49 t ha^{-1} of FMY in the first cut and 28.46 t ha^{-1} and 28.46 t/ha in regrowth), underscoring water's influence. However, studies by Girotto et al., 2021 demonstrate the viability of biomass sorghum in rainfall-dependent production systems, reinforcing its adaptability to different environmental conditions. Furthermore, these data reinforce the importance of biomass sorghum as a strategic crop for semi-arid regions, where water scarcity and adverse climatic conditions limit the cultivation of other species. Biomass sorghum not only adapts well to these conditions but also offers a viable source of biomass for multiple

TABLE 2 Summary of the analysis of variance (mean square values) for plant height (PH), number of leaves (NL), stem diameter (SD), leaf area (LA), fresh leaf mass (FLM), dry leaf mass (DLM), fresh stem mass (FSM), dry stem mass (DSM), fresh matter yield (FMY), and dry matter yield (DMY) of biomass sorghum cultivars Agri-002E and BRS 716 evaluated at the first cut under two planting times: Season 1 (sowing in June 2021) and Season 2 (sowing in December 2021).

Source of variation	DF	PH (cm)	NL (unit)	SD (mm)	LA (cm^2)	FLM	DLM	FSM	DSM	FMY	DMY
						t ha^{-1}					
Block	2	56,327.25^{ns}	0.11^{ns}	0.99^{ns}	7.06^{ns}	56,483.84^{ns}	38,086,684.90^{ns}	13,983,849.96^{ns}	1.98^{ns}	56,483.84^{ns}	38,086,684.90^{ns}
Planting time	1	16,019,852.08**	272.65**	391.93**	204.68*	911,047,835.43**	28,967,551,140.00**	2,040,105,540.00**	391.93**	911,047,835.43**	28,967,551,140.00**
Cultivar	1	30,300.75^{ns}	0.21^{ns}	16.85*	539.48*	182,289,426.87**	1,235,010,909.00*	271,021,007.78**	16.85*	182,289,426.87**	1,235,010,909.00*
PT × C	1	1,800.75^{ns}	1.92^{ns}	7.58^{ns}	75.20^{ns}	31,885,831.87^{ns}	36,195,328.87^{ns}	1,313,090.75^{ns}	7.58^{ns}	31,885,831.87^{ns}	36,195,328.87^{ns}
Error	4	10,770.67	0.24	0.56	24.91	7,096,236.53	73,496,695.27	8,250,924.57	0.56	7,096,236.53	73,496,695.27
CV (%)	–	3.80	4.00	3.27	6.11	16.44	11.28	10.94	10.74	10.94	11.28

ns, not significant; *$p \leq 0.05$; **$p \leq 0.01$ (*F* test).

TABLE 3 Summary of the analysis of variance (mean square values) for plant height (PH), number of leaves (NL), stem diameter (SD), leaf area (LA), fresh leaf mass (FLM), dry leaf mass (DLM), fresh stem mass (FSM), dry stem mass (DSM), fresh matter yield (FMY), and dry matter yield (DMY) of biomass sorghum cultivars Agri-002E and BRS 716 evaluated during regrowth under two planting times: Season 1 (sowing in June 2021) and Season 2 (sowing in December 2021).

Source of variation	DF	PH (cm)	NL (unit)	SD (mm)	LA (cm^2)	FLM	DLM	FSM	DSM	FMY	DMY
						t ha^{-1}					
Block	2	136,958.84^{ns}	1.79^{ns}	0.32^{ns}	10.49^{ns}	171.85^{ns}	343.70^{ns}	19,043,342.45^{ns}	7,900,000.00^{ns}	19,043,342.45^{ns}	1,427,285,855.00^{ns}
Planting time	1	19,801,081.34**	5.88*	33.20**	18.55*	819.23*	3,080.00**	28,967,551,140.00**	1,120,000,000.00**	28,967,551,140.00**	2,350,755,285.0*
Cultivar	1	17,862.54^{ns}	0.16^{ns}	2.31^{ns}	5.71^{ns}	20.67^{ns}	554.00*	1,235,010,909.00*	465,000,000.00*	1,235,010,909.00*	1,180,000,000.0*
PT × C	1	17,865.63^{ns}	0.00^{ns}	0.11^{ns}	0.16^{ns}	494.73^{ns}	75.20^{ns}	36,195,328.87^{ns}	2,350,755,285.00^{ns}	36,195,328.87^{ns}	2,350,755,285.0^{ns}
Error	4	75,797.96	0.64	0.52	0.22	102.81	679.00	73,496,695.27	285,000,000.00	73,496,695.27	356,821,463.74
CV (%)	—	21.40	10.25	4.62	4.87	10.74	11.28	10.94	11.28	10.94	11.28

CV = coefficients of variation; ns, not significant; *$p \leq 0.05$; **$p \leq 0.01$ (*F* test).

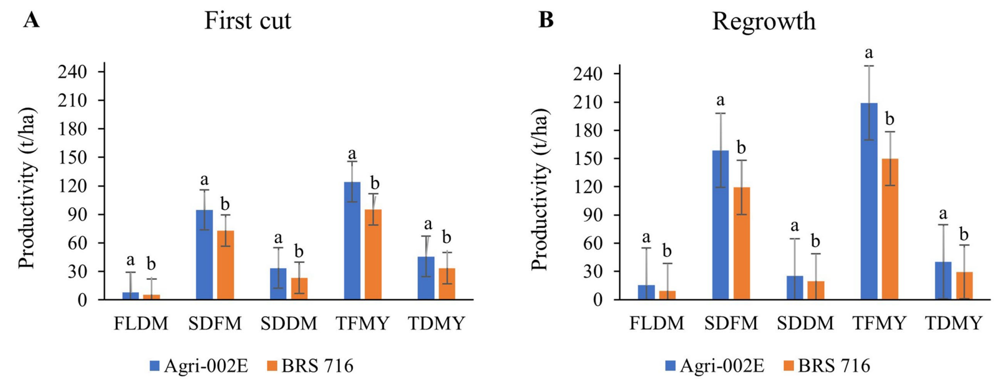

FIGURE 2
Mean values of productive variables of biomass sorghum cultivars Agri-002E and BRS 716 evaluated at two sowing seasons: Season 1 (June 2021) and Season 2 (December 2021). **(A)** First cut. **(B)** Regrowth. Error bars represent the standard error of the mean. Different lowercase letters indicate significant differences between cultivars within each variable according to the F test ($p < 0.05$). FLM, fresh leaf mass; DLM, dry leaf mass; FSM, fresh stem mass; DSM, dry stem mass; TFMY, total fresh matter yield; TDMY, total dry matter yield.

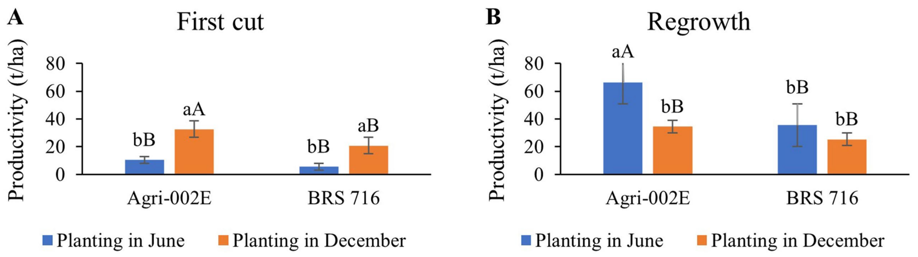

FIGURE 3
Mean fresh leaf mass (FLM) of biomass sorghum cultivars Agri 002E and BRS 716 in the first cut and regrowth at two planting times: Season 1—sown in June 2021 and Season 2—sown in December 2021. **(A)** First cut. **(B)** Regrowth. Lowercase letters indicate significant differences ($p < 0.05$) between planting times, and uppercase letters indicate significant differences ($p < 0.05$) between cultivars within each planting time.

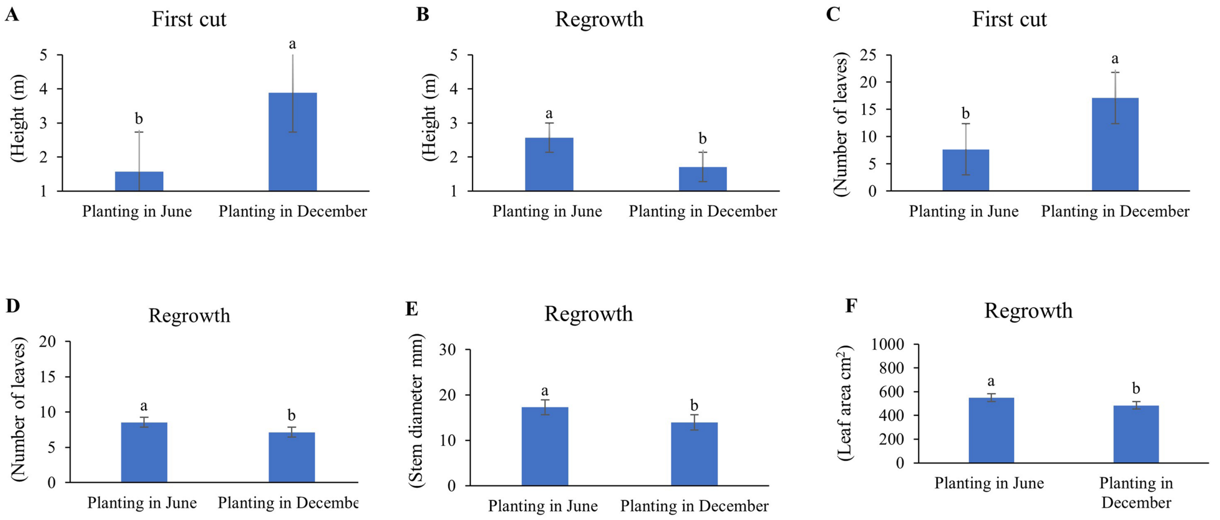

FIGURE 4
Mean biometric variables of biomass sorghum in the first cut and regrowth at two planting times: Season 1—sown in June 2021 and Season 2—sown in December 2021. **(A, B)** Plant height (PH); **(C, D)** number of leaves (NL); **(E, F)** stem diameter (SD). Lowercase letters between columns indicate significant differences ($p < 0.05$) between planting times.

uses such as forage, silage, and bioenergy production, contributing to food security and agricultural sustainability in these regions (Figure 5).

In summary, the choice of planting season must be strategic and aligned with the objectives of the production system. For systems prioritizing initial biomass production, sowing biomass sorghum in December is more suitable. On the other hand, for systems relying on regrowth, June planting is more efficient. Additionally, it is essential to consider local climatic conditions, cultivar cycle, and

TABLE 4 Mean biomass sorghum yield in the first cut at two planting times (June and December 2021).

Planting time	FMY (t ha^{-1})	DMY (t ha^{-1})
June	46.4 b	21.42 b
December	173.05 a	57.97 a
CV%	12.54	14.02

Lowercase letters indicate significant differences between planting times according to Tukey's test ($p < 0.05$). FMY = total fresh mass yield; DMY = total dry mass yield; CV = coefficients of variation.

TABLE 5 Mean biomass sorghum yield from regrowth at two planting times (June and December 2021).

Planting time	FMY (t ha^{-1})	DMY (t ha^{-1})
June	233.6 a	42.89 a
December	125.1 b	26.69 b
CV%	15.16	11.49

Lowercase letters indicate significant differences between planting times according to Tukey's test ($p < 0.05$). FMY = total fresh mass yield; DMY = total dry mass yield; CV = coefficients of variation.

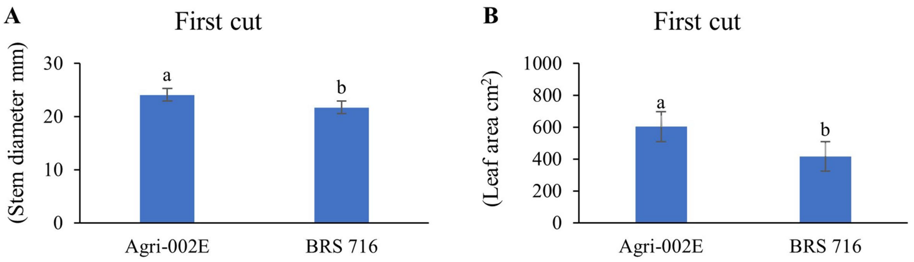

FIGURE 5
Mean stem diameter and leaf area index of biomass sorghum cultivars Agri 002E and BRS 716 in the first cut at two planting times: Season 1—sown in June 2021 and Season 2—sown in December 2021. **(A)** Stem diameter (SD); **(B)** leaf area (LA). Lowercase letters between columns indicate significant differences ($p < 0.05$) between cultivars.

resource availability to maximize productivity and ensure system sustainability.

3.4 Energy productivity of biomass

The energy productivity of biomass sorghum is directly correlated with dry biomass yield ($r = 0.998$, $p < 0.01$). The energy productivity peaked at an estimated 123 days after planting (DAP), resulting in 69.7 Gcal ha^{-1} (Figure 6). Although our field measurements concluded at 113 DAP, the data showed a consistent upward trend in energy accumulation. Extrapolated using quadratic regression (equation provided in Figure 6), this estimate identifies the theoretical biological peak. This mathematical projection suggests that the energy productivity reaches its maximum (123 DAP) before initiating a potential decline, offering a precise target for optimizing the harvest window.

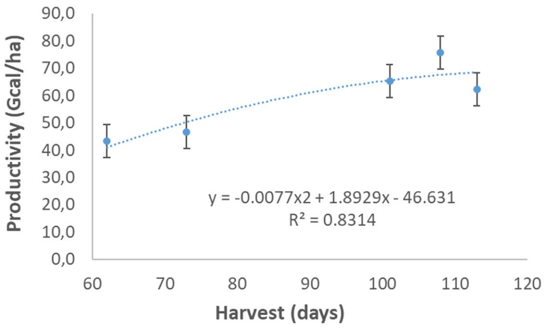

FIGURE 6
Relationship between biomass sorghum energy productivity and harvest time.

In comparison, in the Northeastern region of Brazil, several industrial sectors—such as the ceramic, gypsum, and steel industries—use biomass as a thermal energy source, historically depending on firewood. Firewood production derived from Caatinga vegetation extraction in the Northeast is ~8.4 million tons, considering an average wood density of 709.6 kg m^{-3} (Brazilian Institute of Geography and Statistics (IBGE), 2024; Santos et al., 2020), equivalent to ~39.6 million Gcal per year, using an average higher heating value of 4,730.8 kcal kg^{-1} (Santos et al., 2020). Therefore, to supply one year of firewood demand extracted from vegetation, 569,000 ha of sorghum would be required—produced in only 123 days. It is worth noting that the average yield obtained in this trial was 15.7 t ha^{-1}, with planting carried out in July, and the limiting factor being cultivar sensitivity to photoperiod (Wolabu and Tadege, 2016). However, as previously discussed, selecting the optimal planting season and utilizing regrowth could enable higher yields.

It is important to highlight that, compared with Caatinga firewood, which contains ~1.6% ash (Santos et al., 2020), biomass sorghum has 3.5 times more ash (5.72%; CV = 12.4). Therefore, during biomass combustion, ash management must be considered in the furnace system to prevent abrasion and incrustation. This issue may be mitigated by the addition of anti-scaling agents during combustion.

4 Conclusion

Planting season is a determining factor in the productive performance of biomass sorghum in the Brazilian Semi-arid region, influencing both the first cut and regrowth. Sowing in December results in higher productivity during the first harvest, whereas June planting is more advantageous for regrowth. The interaction between specific environmental conditions of each season and the characteristics of the cultivars evaluated plays a key role in biomass sorghum performance.

Biomass sorghum has the potential to fully replace the annual demand for firewood extracted from the Caatinga vegetation in Northeastern Brazil—requiring only 569,000 ha in 123 days—representing a real gain in the mitigation of native forest suppression. This requires the implementation of favorable policies, economic viability, and widespread adoption.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

LN: Investigation, Data curation, Methodology, Writing – original draft, Validation. AO: Project administration, Conceptualization, Supervision, Writing – review & editing. CS: Writing – original draft, Formal analysis, Methodology. WS: Writing – original draft, Methodology, Formal analysis. FT: Writing – review & editing, Formal analysis. MM: Formal analysis, Methodology, Writing – review & editing. FA: Project administration, Conceptualization, Supervision, Writing – review & editing.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

References

ABNT – Brazilian Association of Technical Standards (1986). *NBR 8112: Charcoal – Determination of ash content*. Rio de Janeiro: ABNT.

Alzahrani, Y., Abdulbaki, A. S., and Alsamadany, H. (2024). Genotypic variability in stress responses of *Sorghum bicolor* under drought and salinity conditions. *Front. Genet.* 15:1502900. doi: 10.3389/fgene.2024.1502900

Ameen, M. A., Mahmood, T., Shahzad, A. N., Zia, M. A., and Javaid, M. M. (2024). Sorghum's potential unleashed: a comprehensive exploration of bio-energy production strategies and innovations. *Bioresour. Technol. Rep.* 27:101906. doi: 10.1016/j.biteb.2024.101906

Andrade Júnior, I. O., Santos, S. R., Kondo, M. K., Oliveira, P. M., and Rocha Júnior, V. R. (2020). Response of forage sorghum to water availability in a typic quartzipsamment. *Rev. Caatinga* 32:1015–26. doi: 10.1590/1983-21252019v32n418rc

Angelotti, F., Oliveira, A. R., Giongo, V., Barros, J. R. A., and Guimarães, M. J. M. (2022). "Sustainable agriculture as an adaptation measure for Araripe plaster pole," in *Public Policies for Adapting Agriculture to Climate Change in Semi-Arid Northeast Brazil*, eds. E. Sabourin, L. M. R. Oliveira, F. Goulet and E. S. Martins (Rio de Janeiro, Brazil: E-papers), 61–76.

Arcoverde, G. F. B., Silva, A. R., Pinto, R. A., Dias, F. G., Pereira, J. A., Bezerra, U. A., et al. (2024). "Patterns of natural vegetation removal in the Caatinga biome in Prodes project scope," in The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. XLVIII-3 Göttingen, Germany: Copernicus Publications on behalf of the International Society for Photogrammetry and Remote Sensing (ISPRS). 9–15. doi: 10.5194/isprs-archives-XLVIII-3-2024-9-2024

ASTM – American Society for Testing and Materials (2013). *ASTM D5865: Standard Test Method for Gross Calorific Value of Coal*. West Conshohocken, PA.

Bakari, H., Djomdi, R. Z. F., Roger, D. D., Cedric, D., Guillaume, P., Pascal, D., et al. (2023). *Sorghum bicolor* and its main parts as promising sustainable sources of value-added ingredients. *Waste Biomass Valoriz.* 14, 1023–1044. doi: 10.1007/s12649-022-01992-7

Batista, V. A. P., Batista, V. Z. P., Moreira, T. S., Barros, A. F., and Pimentel, L. D. (2018). Agronomic and energetic potential of sorghum evaluated in two consecutive crops. *J. Exp. Agric. Int.* 22, 1–9. doi: 10.9734/JEAI/2018/41082

Bera, T., Yang, Y., Wilson, L. T., Dou, F., Knoll, J. E., Araji, H., et al. (2026). Seasonal growth dynamics and yield potential of biomass sorghum in the southeastern US. *BMC Plant Biol.* 26:248. doi: 10.1186/s12870-025-08032-1

Bhat, B. V., Venkateswarlu, R., and Tonapi, V. A. (2020). "Breeding sorghum for forage and feed: status and approaches," in *Sorghum in the 21st Century: Food – Fodder – Feed – Fuel for a Rapidly Changing World*, eds. V. A. Tonapi, H. S. Talwar, A. K. Are, B. V. Bhat, C. R. Reddy and T. J. Dalton (Singapore: Springer). doi: 10.1007/978-981-15-8249-3_17

Binkley, D., Campo, O. C., Alvares, C., Carneiro, R. L., Cegatta, I., and Stape, J. L. (2017). The interactions of climate, spacing and genetics on clonal eucalyptus plantations across Brazil and Uruguay. *For. Ecol. Manag.* 405, 271–283. doi: 10.1016/j.foreco.2017.09.050

Brazilian Institute of Geography and Statistics (IBGE). (2024). Production of plant extraction and silviculture. Rio de Janeiro, Brazil: Brazilian Institute of Geography and Statistics (IBGE). Available online at: https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/9105-producao-da-extracao-vegetal-e-da-silvicultura.html (Accessed November 29, 2025).

Casto, A. L., Mattison, A. J., Olson, S. N., Thakran, M., Rooney, W. L., and Mullet, J. E. (2019). Maturity2, a novel regulator of flowering time in *Sorghum bicolor*, increases expression of SbPRR37 and SbCO in long days delaying flowering. *PLoS One* 14:e0212154. doi: 10.1371/journal.pone.0212154

Chadalavada, K., Kumari, B. D. R., and Kumar, T. S. (2021). Sorghum mitigates climate variability and change on crop yield and quality. *Planta* 253:113. doi: 10.1007/s00425-021-03631-2

Chavez, J. C., Ganjegunte, G. K., Jeong, J., Rajan, N., Zapata, S. D., Ruiz-Alvarez, O., et al. (2022). Radiation use efficiency and agronomic performance of biomass sorghum under different sowing dates. *Agron.* 12:1252. doi: 10.3390/agronomy12061252

Choudhary, S., Singh, K., Chadha, M., and Shukla, R. (2024). "Sorghum: biology, functional potential and sustainable utilization," in *Millets: The Multi-Cereal Paradigm for Food Sustainability*, ed. M. Thakur (Cham: Springer). doi: 10.1007/978-3-031-64237-1_6

Dubreuil, V., Fante, K. P., Planchon, O., and Sant'Anna Neto, J. L. (2019). Climate change evidence in Brazil from Köppen's climate annual types frequency. *Int. J. Climatol.* 39, 1446–1456. doi: 10.1002/joc.5893

Emendack, Y., Sanchez, J., Hayes, C., Nesbitt, M., Laza, H., and Burke, J. J. (2021). Seed-to-seed early-season cold resiliency in sorghum. *Sci. Rep.* 11:7801. doi: 10.1038/s41598-021-87450-1

Ferreira, D. F. (2011). Sisvar: a computer statistical analysis system. *Ciênc. Agrotecnol.* 35, 1039–1042. doi: 10.1590/S1413-70542011000600001

Girotto, H. C., Rodovalho, W. M. A., and Nakao, A. H. (2021). Agronomic parameters of forage sorghum cultivars in first cut harvest and regrowth as a result of seeding density in sandy soils. *Unifunec Ciência Multidisciplinar* 10:1–16. doi: 10.24980/ucm.v10i12.4140

Jamovi Project. (2025). Jamovi (version 2.6) [computer software]. Available online at: https://www.jamovi.org. (Accessed November 29, 2025).

May, A., Parrella, R. A. C., Damasceno, C. M. B., Simeone, M. L. F., and Schaffert, R. E. (2016). Sorghum biomass for energy production in Brazil. *Pesq. Agrop. Brasileira* 51, 1412–1421. doi: 10.1590/S0100-204X2016000900041

Meki, M. N., Ogoshi, R., Kiniry, J. R., Crow, S. E., Youkhana, A. H., Nakahata, M. H., et al. (2017). Performance evaluation of biomass sorghum in Hawaii and Texas. *Ind. Crop. Prod.* 103, 257–266. doi: 10.1016/j.indcrop.2017.04.014

Monteiro, J. S., Havrland, B., and Ivanova, T. (2012). Sweet sorghum bioenergy value – importance for Portugal. *Agric. Trop. Subtrop.* 45. doi: 10.2478/v10295-012-0002-y

Morales, M. M., Hoshide, A. K., Carvalho, L. M. P., and Tardin, F. D. (2024). Sorghum biomass as an alternative source for bioenergy. *Biomass* 4, 1017–1030. doi: 10.3390/biomass4030057

Moreira, J. M. M. A. P., de Lima, E. A., and Goulart, I. C. G. d. R. (2012). *Impacto do teor de umidade e da espécie florestal no custo da energia útil obtida a partir da queima da lenha*. Colombo: Embrapa Florestas. Comunicado técnico, 293, 5.

Nascimento, G. S. G., Guimarães, M. J. M., Falcao, H. M., Silva, E. G. F., Barros, J. R. A., Oliveira, A. R., et al. (2025). Vegetative growth of sorghum cultivars under increasing air temperature. *Acta Biol. Colomb.* 30, 1–38. doi: 10.15446/abc.v30n2.109430

Nascimento, G. S. G., Oliveira, G. M., Silva, E. G. F., Barros, J. R. A., and Guimarães, M. J. M. (2023). The increase in air temperature and its interference in the emergence and initial growth of sorghum cultivars. *GJSFR-D Agric. Vet.* 23:2249–4626.

Ndlovu, E., Van Staden, J., and Maphosa, M. (2021). Morpho-physiological effects of moisture, heat and combined stresses on *Sorghum bicolor* and its acclimation mechanisms. *Plant Stress* 2:100018. doi: 10.1016/j.stress.2021.100018

Opoku, E., Sahu, P. P., Findurová, H., Holub, P., Urban, O., and Klem, K. (2024). Differential physiological and production responses of C3 and C4 crops to climate factor interactions. *Front. Plant Sci.* 15:1345462. doi: 10.3389/fpls.2024.1345462

Pucetti, P., Valadares Filho, S. C., Silva, J. T., Oliveira, K. R., Souza, G. A. P., Cidrini, F. A., et al. (2024). Effects of different concentrate levels in AGRI-002E sorghum silage-based diets on nutrient intake and digestibility in beef cattle. *Anim. Feed Sci. Technol.* doi: 10.1016/j.anifeedsci.2024.115xxx

Santos, F. C., Resende, A. V., and Coelho, A. M. (2015). "Nutritional requirements and fertilization," in *Sorghum: The Producer Asks*, eds. I. A. Pereira Filho and J. A. S. Rodrigues (Brasília, DF: Embrapa), 81–97.

Santos, C. P. S., Santos, R. C., Carvalho, A. J. E., Castro, R. V. O., Costa, S. E. L., Lopes, L. I., et al. (2020). Energy stock of wood in forest management areas in Rio Grande do Norte. *Sci. For.* 48:e3080. doi: 10.18671/scifor.v48n126.06

Silva, W. O., Barros, J. R. A., Simões, W. L., Oliveira, A. R., Nascimento, L. A., and Angelotti, F. (2024). Water availability and growing season temperature on the performance of sorghum cultivars. *Rev. Bras. Cienc. Agrar.* 19:e3665. doi: 10.5039/agraria.v19i2a3665

Simpson, K. J., Bennett, C., Atkinson, R. R. L., Mockford, E. J., McKenzie, S., Freckleton, R. P., et al. (2020). C4 photosynthesis and the economic spectra of leaf and root traits independently influence growth rates in grasses. *J. Ecol.* 108:1899–909. doi: 10.1111/1365-2745.13412

Souza, H., Tonani, F. L., Santos, D. B. R., and Souza, A. C. S. A. (2024). Agronomic characteristics and bioenergetic potential of sweet sorghum cultivars and biomass. *Rev. Desafios* 11, 2359–3652. doi: 10.20873/Agroenergia_2024_v11_n7_11

Syuryawati, F., and Aqil, M. (2021). "Ratoon cultivation increases sorghum production," in IOP Conference Series: Earth and Environmental Science, vol. 911:012077. Bristol, United Kingdom: IOP Publishing.

Watson-Lazowski, A., Cano, F. J., Kim, M., Benning, U., Koller, F., George-Jaeggli, B., et al. (2024). Multi-omic profiles of Sorghum genotypes with contrasting heat tolerance connect pathways related to thermotolerance. *J. Exp. Bot.* 19:506. doi: 10.1093/jxb/erae506

Wolabu, T. W., and Tadege, M. (2016). Photoperiod response and floral transition in sorghum. *Plant Signal. Behav.* 11:e1261232. doi: 10.1080/15592324.2016.1261232