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Does Nitrogen Application Improve Elephant Grass Yield and Energetic Characteristics of Biofuels?

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Abstract

This study aimed to evaluate the effect of nitrogen (N) application in the biomass yield and energetic characteristics of biofuels (fresh and briquettes) of elephant grass grown in tropical conditions. The experiment was carried out during two consecutive harvests, and the following nitrogen fertilizer doses were evaluated: 0, 50, 100, 150, and 200 kg of N ha^{-1} $year^{-1}$. Biometric variables, biomass yield, total accumulated nitrogen, and C:N ratio and biomass energetic characterization were carried out. Briquettes were produced for the evaluation of the energetic, physical, and mechanical characteristics. Nitrogen application influenced the elephant grass yield growing in tropical conditions. The biomass yield reached 43 Mg ha^{-1} in the second harvest. The application of 100 kg ha^{-1} N promoted greater efficiency in the use of N and biomass yield. Thus, this is the recommended dose for cultivation of elephant grass for energy purposes in the edaphoclimatic conditions of the Cerrado biome (Brazilian Savannah). Elephant grass presented high heating value (17,196 kJ kg^{-1}), ash content (4.77%), and bulk and energy density (206.00 kg m^{-3} and 0.84 Gcal m^{-3}) that make it suitable for use as an energy resource in the fresh form. However, the production of briquettes improved its energetic characteristics. The application of N did not change the high heating value of biomass and the characteristics of briquettes.

Keywords *Cenchrus purpureus* · Briquettes · Bioenergy · Nitrogen use efficiency · Nitrogen accumulation

Introduction

The use of plant biomass appears as an alternative energy source, with the advantage of being renewable and clean, when compared to fossil fuels. Also, it has low production costs with minimal use of fossil sources and has high potential for carbon sequestration, since the emitted CO_2 is absorbed again during photosynthesis [1, 2]. Diversification of biomass sources for energy use as well as their viability [3] has currently been targeted in studies worldwide [4–6], and biomass densification has been widely used, with the increase in the production of pellets and briquettes in recent years [7, 8]. In this case, lignocellulosic biomass represents a promising alternative energy source, which uses wood and forest residues [9–11], as well as crops and agro-industrial residues [12, 13].

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The most common biomass energy sources in Brazil are sugarcane (*Saccharum* spp. L.) bagasse and reforested eucalyptus (*Eucalyptus* spp. L'Héritier), the former being the only source of sugar and ethanol and the latter currently the primary source of cellulose and charcoal [1]. As an alternative to traditional sources of biomass for bioenergy in Brazil, *Cenchrus purpureus* (Schumach.) Morrone (elephant grass) has great potential due to the photosynthetic efficiency attributed to the C4 carbon fixation mechanism, positive balance of biomass production, wide adaptability, and adequate energetic characteristics, with emphasis on the heating value [1, 14, 15].

Tropical soils are known to be highly weathered and feature as a characteristic of the predominance of low activity clay and low levels of organic matter [16]. For this reason, they are considered low fertility soils, with a wide variety of textures ranging from sandy to very clayey, favoring the processes of loss of nitrogen applied for fertilization purposes [17]. Nitrogen can be lost in the soil due to the processes of ammonia volatilization, nitrate leaching, denitrification, and runoff [16]. The use of crops adapted to tropical conditions favors the reduction of fertilizer costs, without presenting reductions in their productive potential [18].

Elephant grass has great potential for energy production. In native environments such as West Africa, it is grown on marginal soils, not very fertile and unsuitable for agricultural production, as it is considered an easily cultivated crop, with high biomass production and an excellent adaptation [19]. Its short life cycle and high growth rate make it an ideal biofuel [19]. In Brazil, elephant grass is a domesticated crop; however, to achieve a high growth rate in non-native environments, considerable amounts of nutrients, such as nitrogen, are still used, and it is essential to obtain an adequate evaluation that promotes their development satisfactory [19–21]. In the literature, it is possible to find several studies relating the productive characteristics of elephant grass according to the application of nitrogen [2, 14, 22–24]. Studies developed in Cerrado biome conditions (Brazilian Savannah) point out that elephant grass is highly responsible for nitrogen fertilization. Nitrogen doses above 50 kg ha^{-1} are able to favor the increase of fresh biomass, dry matter, and C:N ratio; even the increase of fertilization with up to 150 kg ha^{-1} does not cause the increase of ash content, favoring its use for energy purposes [14, 22, 25]. The high response potential of the productive attributes of elephant grass in function to the increase in nitrogen doses, makes it difficult to establish an ideal dose of the nutrient for the crop. The recommendations vary from 50 to 400 kg^{-1} ha^{-1} $year^{-1}$ of N [14, 25–27].

It is possible to find several studies related to the productive characteristics of elephant grass according to the application of nitrogen. However, few studies evaluate the use of nitrogen fertilizers to enhance the biomass energetic characteristics, especially in briquette form and for the edaphoclimatic conditions of the Cerrado biome. Thus, it was adopted the hypothesis that the proper management of nitrogen fertilization for the production of elephant grass can increase biomass production without affecting the quality of biofuels. In order to test the hypothesis, this study aimed to evaluate the effect of nitrogen application in the biomass yield and energetic characteristics of biofuels (fresh and briquettes) of elephant grass grown in tropical conditions during two consecutive harvests.

Material and Methods

Implantation and Conducting

The experiment was carried out in the experimental area of the Agronomy School of the Federal University of Goiás, in Goiânia, GO, Brazil (16° 35′ 53.5″ S and 49° 16′ 41.1″ W), from October 2015 to September 2017 [28]. The climate is classified as Aw, with hot and humid summer and dry winter [29]. Climatic data are shown in Fig. 1. The soil is classified as Ferralsol [30].

The experiment was carried out during two consecutive harvests. It was initiated in October 2015 (harvest 2015/16), at the beginning of the rainy season. The second harvest (2016/17) consisted of elephant grass regrowth, in September/2016, after cutting to standardize the plants. Forage cutting was performed at 180 days after sprouting, and nitrogen content and leaf, stem, and total biomass production were evaluated. *Cenchrus purpureus* (elephant grass) was chosen because it is a genotype adapted to the soil and climate conditions of the Brazilian Cerrado, being widely cultivated in this region for animal feeding purposes; however, with high energy generation capacity.

The soil was prepared according to the conventional tillage system with plowing and disking [31]. The chemical analysis of the soil layer was performed according to Soil Analysis Methods Manual [32]. Soil liming and fertilization was performed based on the soil analysis (Table 1) and according to the nutritional need of elephant grass. In total, 45 kg ha^{-1} of P_2O_5 and 40 kg ha^{-1} of K_2O were applied using simple superphosphate and potassium chloride as the source, respectively [33]. The fertilizer was distributed in furrows around 0.30 m deep, in which sowing was also carried out. Phytosanitary management was carried out during the experiment to provide conditions for the plants to express their

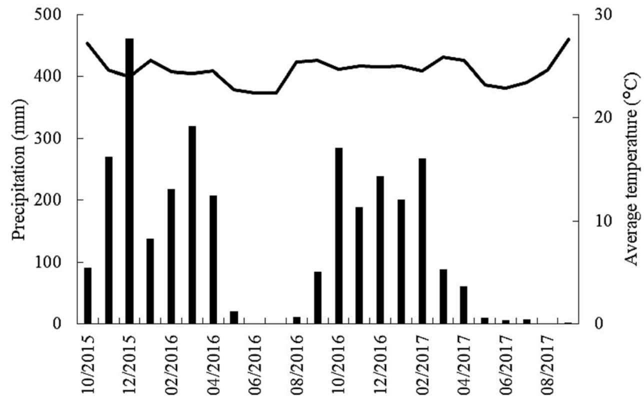

Fig. 1 Precipitation and average monthly temperature from October 2015 to September 2017, Goiânia, GO, Brazil. Source: (INMET. 2020) (Access on March 10, 2020)

Table 1 Background physicochemical characteristics of the surface (0–0.20 m) soil layer before treatment application

Soil layer	Clay	Silt	Sand	pH $CaCl_2$	OM[(a)]	P	K^+
m	kg dm^{-3}			–	g dm^{-3}	$cmol_c$ dm^{-3}	
0.00–0.20	320	250	430	5.10	5.00	0.03	0.09
	Ca^{2+}	Mg^{2+}	Al^{3+}	$H + Al^{3+}$	CEC[(b)]	BS[(c)]	m[(d)]
	$cmol_c$ dm^{-3}					%	
	1.20	0.60	0.00	3.50	5.40	35.00	0.00

[(a)] Organic matter

[(b)] Cation exchange capacity

[(c)] Base saturation

[(d)] Aluminum saturation

productive potential and ensure that the differences are only attributed to the nitrogen doses.

Experimental Design

Randomized complete block experimental design with four replications was used. Nitrogen fertilizer doses were evaluated at 0 (control), 50, 100, 150, and 200 kg ha^{-1} $year^{-1}$ of N. Urea was used as a nitrogen source, and it was distributed in the sowing furrows. Each experimental plot consisted of four rows of elephant grass with 5.0 m length, and 1.2 m row spacing, totaling 24.0 m^2 per plot.

Each plot was 2 m spacing between them, on all edges, to prevent possible contamination by runoff of nutrients. It should also be noted that the relief of the area was flat and that the application of mineral fertilizers was applied in the furrow of the sowing, which reduces the effects of losses by runoff. In the second year, the fertilization was carried out on surface after light scarifying the soil, considering the 0.20 m fertilization range from the center of the cultivation line, aiming to increase the utilization efficiency of the N-fertilizer applied and to avoid possible runoff losses.

Biometric Evaluations

Biometric evaluations were performed at each harvest before elephant grass cutting. The following biometric variables were evaluated:

i. *Leaf area*, evaluated in ten plants per plot using the middle portion of leaf +3 (third leaf with the sheath fully visible) [34] using the equation (1):

$$AF = C \times L \times 0.75 \times (N + 2) \tag{1}$$

where

C leaf +3 length;
L leaf +3 width;
N number of open leaves with at least 20% green area.

ii. *Plant height*, determined by measuring the distance from the base (ground level) until the apex of the tallest tiller, in ten plants per plot [35].
iii. *Number of tillers*, evaluated by counting the number of tillers within the two central rows of each plot that are at least 1 m tall [35].
iv. *Stem diameter*, measured in ten plants per plot with a digital caliper [35].
v. *Relative chlorophyll index* [36], determined from the middle portion of leaf +1 (first fully developed leaf) using a portable ClorofiLOG CFL 1030 FALKER® chlorophyll meter. Ten plants per plot were evaluated.

Dry Biomass Yield

The evaluations of elephant grass were performed close to the end of the rainy season each year to estimate biomass yield for each harvest, totaling approximately 180 days. Two meters of the two central lines of each plot were evaluated, totaling 4.8 m^2. The biomass (stems and leaves) of the plots were weighed immediately after cutting. Biomass subsamples were taken to the oven for drying at 65 °C until weight stabilization and then weighed to determine the dry matter fraction of the plants.

Total (N-total) Accumulated Nitrogen and Carbon/Nitrogen Ratio (C:N)

After determining the dry matter yield, the samples were crushed in a Wiley mill (2-mm sieves) for N-total analysis. The nitrogen content was determined through wet digestion with sulfuric acid followed by distillation in the presence of NaOH, and titration with sulfuric acid (0.02 N) [37]. The carbon content (C) was determined by oxidation of the organic matter with sulfuric acid and potassium dichromate and subsequent titration for dosing, with a standard solution of ferrous ammonium sulfate [38]. The C:N ratio was estimated by the quotient between carbon content and total nitrogen content accumulated in the dry matter of elephant grass leaves and stems.

The nitrogen content in the soil was not measured, as its availability in agricultural systems is mediated by the addition of industrially available fertilizers [39]. About 50% of the nitrogen applied to the soil is lost [40]. These inefficiencies in relation to the use of N in the soil are attributed to the volatilization of ammonia, nitrate leaching, denitrification, and runoff [16]. Therefore, the measurement of nitrogen content does not make an alternative unfeasible under field conditions in tropical soils.

The nitrogen uptake in the elephant grass was made by multiplying by the nitrogen content (N-total) and the dry mass. The calculation of the nitrogen use efficiency (NUE) by elephant grass shows the plant's capacity to convert the absorbed nutrient into total dry matter [41] using Eq. (2):

$$\mathrm{NUE} = \mathrm{DMAP2}/\mathrm{NUAP} \tag{2}$$

where

NUE nitrogen use efficiency;
DMAP dry mass of aerial part;
NUAP nitrogen uptake of aerial part.

Biomass Characterization

The procedure for proximate analysis was based on ASTM standards (American Society for Testing and Materials), ASTM E872-82 [42], and ASTM D1102-84 [43], to determine the content of volatile, ash, and fixed carbon. The high heating value (HHV) was determined by a calorimeter, following the procedures recommended by ASTM D5865-13 [44]. Bulk density was determined according to the methodology established on ABNT standard (Brazilian Association of Technical Standards), ABNT NBR 11941 [45]: a quotient between the mass of the analyzed material and the known volume of a container. The biomass energy density was calculated by multiplying the HHV and the bulk density.

Briquette Production and Characterization

The compaction of the elephant grass biomass (leaves and stems) into briquettes was carried out in a laboratory scale with a temperature of 120 ± 5 °C, pressure of 140 kgf cm^{-2}, compaction time of 5 min, and cooling of 15 min with forced ventilation. The compaction conditions of the biomass were experimentally defined by preliminary tests and according to [2]. The biomass was adjusted to a moisture content of 8% dry basis, milled, and then mixed in order to create a composite sample. Ten briquettes were produced (0.04 m in length and 0.03 m in diameter) per treatment (nitrogen doses) and per harvest, totaling 100 briquettes (5 doses × 2 harvests). All the milled (< 4 mm) biomass was used to produce the briquettes; the material was not separated into granulometric fractions. Thus, all particle sizes were utilized.

Quality parameters evaluated:

i. *Apparent density*: determined by the stereometric method, using the volume and mass data of each briquette [46].
ii. *Energy density*: determined as the product of the apparent density and high heating value (HHV) of the biomass [47].
iii. *Durability*: determined from the sample mass loss, in which the briquettes were weighed to obtain the initial mass and later submitted to the orbital sieve shaker for 10 min [13].
iv. *Volumetric expansion*: determined by the briquette volume increment at two different times, immediately (zero hours) and 72 h after briquetting [6, 11].

Statistical Analysis

The data were submitted to analysis of variance and F test at 5% of probability using the AgroEstat software [48], and when significant, evaluated by the Scott-Knott test ($p \leq 0.05$) (qualitative data—harvest 1 and 2). Linear and quadratic mathematical models (polynomial regression) were tested for N doses (quantitative data), applying the models that obtained the best data adjustments. When significant, the maximum and minimum points were obtained by deriving the equations. The standard error of the mean was also shown in the tables and figures.

Results and Discussion

Biometric Characteristics and Production

After 2 years of evaluations, significant differences were observed for the following variables: plant height, number of plants per linear meter, relative chlorophyll index, and leaf area, with higher means observed in the second than the first harvest (Table 2). The nitrogen application did not influence the biometric variables, regardless of the harvest evaluated, except for plant height (Table 2).

The N doses applied in the first harvest promoted significant increases in plant height, with quadratic adjustments ($y = -0.004x^2 + 1.264x + 169.931$, $R^2 = 0.98$, $p = 0.003$**). The growth was up to 270 cm with the application of 158 kg ha^{-1} of N (Fig. 2). However, in the second crop, there was a reduction in height, from 318 cm (control) to 276 cm (200 kg ha^{-1} of N), with linear adjustment ($y = -0.191x + 314.100$, $R^2 = 0.86$, $p = 0.003$**) (Fig. 2).

The cultivation of elephant grass during two harvests evidenced the productive potential of the crop and the need for a long period for its establishment. However, there were no significant increases in biometric characteristics according to nitrogen fertilization in the second harvest, when it reached the average yield of 30 Mg ha^{-1} [14]. Low yields during the establishment of rhizomatous perennial grasses are expected during the first year, and this is a problem in biomass production systems [49], due to high energy requirements for root growth. In the second harvest, however, with the root system already established, the plant can then invest in its biomass production. This fact is corroborated by the increase in the number of plants and leaf area.

A similar result was found previously [49], in which elephant grass productivity from the second harvest, with fertilization with 100 kg ha^{-1} [2], which found yields ranging from 26 to 54 Mg ha^{-1}, according to the elephant grass genotype. When comparing with previous studies [23], we found a larger stem diameter and a higher yield during the second harvest, but shorter plants. The influence of nitrogen on elephant grass yield is still divergent in the literature. Some studies [14, 24] also did not show an increase in the elephant grass yield due to the application of nitrogen. However, studies show that there are gains in the production of biomass with the increase of N doses, with a consequent increase in the demand of N for forage [22, 50].

Table 2 Biometric variables and relative chlorophyll index (RCI) of elephant grass at different harvests and nitrogen doses

Treatments	Height cm	Stem diameter mm	Number of plants m^1	RCI µg cm^{-2}	Leaf area cm^2
Harvest (H)					
2015/16	235.79 ± 22.66 b	21.14 ± 0.68	22.38 ± 1.42 b	42.27 ± 1.60 b	6966.11 ± 1227.08 b
2016/17	295.00 ± 20.70 a	21.31 ± 0.50	68.25 ± 13.27 a	55.34 ± 1.38 a	13,311.08 ± 380.50 a
Pr(> F)	0.00**	0.65^{ns}	0.00**	0.00**	0.00**
N doses (D) (kg ha^{-1})					
0	238.22 ± 39.99	21.04 ± 0.56	48.77 ± 22.70	48.01 ± 4.12	9361.91 ± 1247.31
50	272.64 ± 24.69	20.73 ± 0.67	43.37 ± 15.80	49.26 ± 4.29	9829.09 ± 1674.26
100	271.78 ± 14.18	20.75 ± 0.64	41.37 ± 10.00	48.81 ± 3.75	10,243.41 ± 1794.21
150	273.10 ± 22.79	21.40 ± 0.46	47.93 ± 14.53	48.94 ± 3.43	10,164.47 ± 22.18
200	271.22 ± 24.80	22.19 ± 0.38	45.12 ± 12.17	49.01 ± 3.43	11,094.09 ± 2393.77
Pr(> F)	0.27^{ns}	0.11^{ns}	0.93^{ns}	0.95^{ns}	0.41^{ns}
H × D					
Pr(> F)	0.01**	0.86^{ns}	0.82^{ns}	0.53^{ns}	0.19^{ns}
CV (%)	13.79	5.45	45.39	6.47	17.21

ns not significant at 5% probability by the Scott-Knott test, *CV* coefficient of variation (%)

**Significant at 5% of probability by the Scott-Knott test

During the second harvest, the nitrogen content increased significantly by 14%, N accumulation by 448%, and N use efficiency by 327%. Consequently, the biomass yield exceeded that of the first harvest about 35 Mg ha^{-1}. However, the C:N ratio was lower in the second harvest, which was expected due to the increase in biomass nitrogen content. Since N dose influenced nitrogen accumulation, use efficiency, and biomass yield, there was an interaction between the harvests and nitrogen doses (Table 3).

Nitrogen uptake during the first harvest increased linearly with the N dose ($y = 0.541x + 0.088$, $R^2 = 0.88$, $p = 0.090$**). The increase was 112.90% as the nitrogen dose increased from 0 to 200 kg ha^{-1} (Fig. 3a). The N uptake was higher in the second harvest than the first. Unlike the first harvest, the results were consistent with the second-degree polynomial function ($y = -0.013x^2 + 3.115x + 0.672$; $R^2 = 0.57$, $p = 0.001$**), in which the highest nitrogen accumulation (0.852 Mg ha^{-1}) occurred at 115.37 kg ha^{-1} of nitrogen (Fig. 3a).

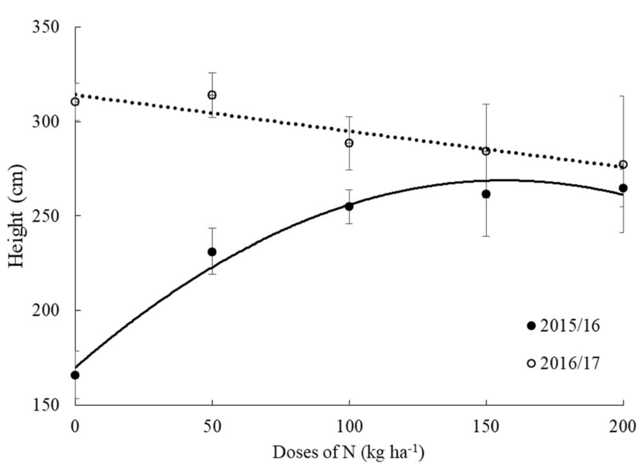

Fig. 2 Plant height of elephant grass as a function of the nitrogen dose in 2015/16 and 2016/17 harvests

The higher nitrogen accumulation during the second harvest is positively correlated with the higher relative chlorophyll index (RCI) (Table 2) also observed in the same period. Studies indicate that RCI correlate well with the N content in the leaf [51, 52]. This relationship can be explained by the fact that the main function of N in the plant is structural, being a constituent of organic compounds such as chlorophyll. Studies that evaluate the effects of N applied on plants most often point to an increase in leaf area and plant biomass, which are attributed to the increase in the photosynthetic capacity of the plant, by maintaining the green leaf for longer [41, 53].

The nitrogen use efficiency (NUE) was higher in the second harvest than the first (Fig. 3b). NUE were adjusted to a linear function in 2015/16 harvests ($y = 12.407x + 4447.500$; $R^2 = 0.84$, $p = 0.002$**) and quadratic function in 2016/17 ($y = -0.529x^2 + 111.612x + 21{,}071$; $R^2 = 0.85$, $p = 0.000$**). In the second harvest, the highest efficiency (26,951.28) was estimated at 105.37 kg ha^{-1} of N, and in the first harvest, the application of the highest dose (200 kg ha^{-1}) was observed, and even so, the efficiency was lower than that for the previous year (Fig. 3b).

The nitrogen accumulation and nitrogen use efficiency correlated positively with the biomass yield, and the relationships were best described with a linear (2015/16: $y = 0.027x + 6.218$; $R^2 = 0.86$, $p = 0.000$**) and quadratic model

Table 3 Nitrogen content and uptake, nitrogen use efficiency (NUE), C:N ratio, and biomass yield of elephant grass at different harvests and nitrogen doses

Treatments	N content g kg^{-1}	N uptake Mg ha^{-1}	NUE kg^2 kg^{-1}	C:N ratio –	Biomass yield Mg ha^{-1}
Harvest (H)					
2015/16	15.76 ± 1.08 b	0.14 ± 0.02 b	5688.17 ± 624.54 b	32.34 ± 2.39 a	8.93 ± 1.08 b
2016/17	17.95 ± 0.49 a	0.78 ± 0.05 a	24,288.56 ± 1,518.72 a	27.94 ± 0.79 b	43.51 ± 2.69 a
Pr(> F)	0.00**	0.00**	0.00**	0.00**	0.00**
N doses (D) (kg ha^{-1})					
0	15.64 ± 1.20	0.35 ± 0.14	12,495.21 ± 4274.79	32.68 ± 2.63	20.97 ± 8.00
50	16.84 ± 1.41	0.49 ± 0.21	15,560.03 ± 5960.27	30.58 ± 3.04	27.64 ± 11.27
100	16.85 ± 0.44	0.48 ± 0.17	16,573.81 ± 5642.96	29.75 ± 0.80	28.44 ± 9.94
150	17.37 ± 0.82	0.48 ± 0.16	15,521.30 ± 4828.28	29.03 ± 1.54	27.36 ± 8.85
200	17.58 ± 0.77	0.48 ± 0.16	14,782.47 ± 4386.80	28.67 ± 1.42	26.70 ± 8.48
Pr(> F)	0.17^{ns}	0.00**	0.00**	0.15^{ns}	0.00**
H × D					
Pr(> F)	0.39^{ns}	0.01**	0.00**	0.28^{ns}	0.00**
CV (%)	9.61	13,14	8.91	11.10	8.40

ns not significant at 5% probability by the Scott-Knott test, *CV* coefficient of variation (%)

**Significant at 5% of probability by the Scott-Knott test

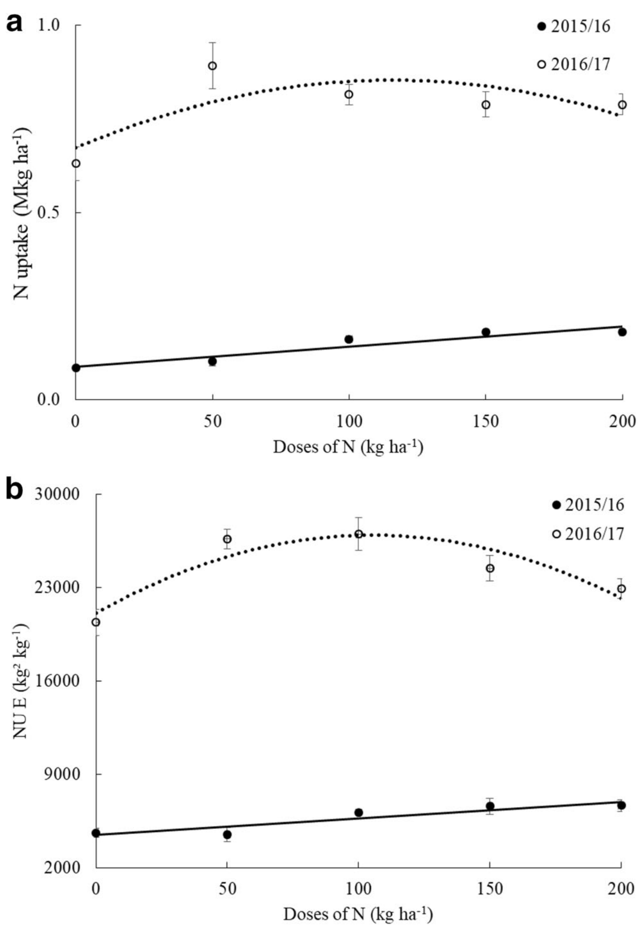

Fig. 3 Nitrogen accumulation (**a**) and nitrogen use efficiency (NUE) (**b**) of elephant grass according to the nitrogen dose in 2015/16 and 2016/17 harvests

(2016/17: $y = -0.001x^2 + 0.186x + 37.576$; $R^2 = 0.72$, $p = 0.007$**) (Fig. 4). In the 2015/16 harvest, the biomass yield at 200 kg ha^{-1} of N (10.92 Mg ha^{-1}) was 74.93% higher than the control treatment (6.24 Mg ha^{-1}). In the 2016/17 harvest, the dose with the highest biomass production was 116.81 kg ha^{-1} of N (Fig. 4), practically the same dose that resulted in a higher accumulation of N in the plant.

The increase in N uptake in the shoot followed mainly the production of dry matter and directly influenced the efficiency of nitrogen use. Despite this increase in N, there was no reduction in the C:N ratio; that is a desirable feature when working with economically efficient crops. The higher the C:N ratio, the more fibrous and lignified the material is, providing

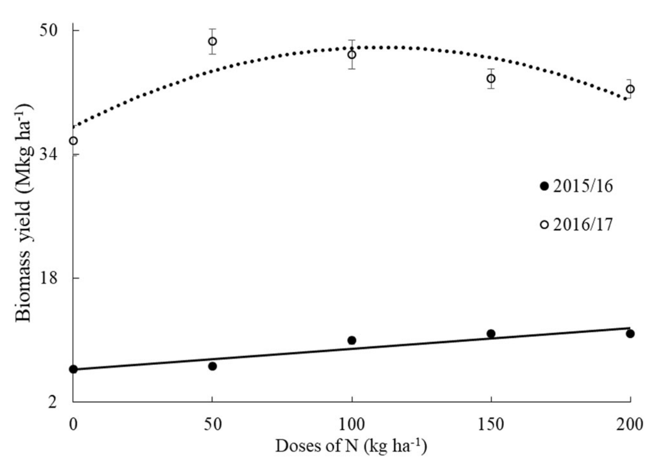

Fig. 4 Biomass yield of elephant grass according to the nitrogen dose in 2015/16 and 2016/17 harvests

better conditions for energy use and indicating a higher production capacity with less accumulated nitrogen [14]. The lack of response of some variables, to the use of fertilizer, may be indicative of the efficiency of elephant grass in the absorption and use of nitrogen, directly from the soil or by the contribution of diazotrophic bacteria associated with the plant [20], since the species can fix nitrogen.

Biomass Characterization

All the energetic and physical characteristics of the elephant grass biomass evaluated were influenced by the harvests. The ash content, volatile content, and bulk density were 36.0%, 5.8%, and 5.0%, higher in 2016/17 than 2015/16, respectively. In contrast, the fixed carbon content, high heating value, and energy density were 53.5%, 8.0%, and 2.4% lower in the second harvest than in the first (Table 4). Nitrogen doses also influenced these physical and energetic variables, except for the high heating value. The interaction effects of nitrogen doses and harvests on bulk density, high heating value, and energy density were not obvious (Table 4).

The ash content showed a quadratic behavior in the two harvests (2015/16: $y = 0.001x^2 - 0.005x + 4.070$; $R^2 = 0.69$, $p = 0.048^{**}$; 2016/17: $y = -0.001x^2 + 0.013x + 4.934$; $R^2 = 0.83$, $p = 0.002^{**}$). There was an increase in the second harvest with N application up to about 140 kg ha^{-1}, from where the ash content gradually decreased (Fig. 5a). The fixed carbon content followed a linear behavior (2015/16: $y = -0.003x + 17.627$; $R^2 = 0.52$, $p = 0.556^{ns}$), without nitrogen fertilization effect for the first harvest. In the 2016/17 harvest, the data were adjusted to a positive quadratic function (2016/17: $y = 0.001x^2 - 0.047x + 12.608$; $R^2 = 0.75$, $p = 0.002^{**}$), with the highest fixed carbon content estimated in control treatment (without nitrogen application) and with 200 kg ha^{-1} of N (Fig. 5b). In the first harvest, volatile content showed a linear behavior (2015/16: $y = 0.002x + 78.468$; $R^2 = 0.32$, $p = 0.771^{ns}$), without effect of N application, unlike the second harvest (2016/17: $y = -0.001x^2 + 0.033x + 82.457$; $R^2 = 0.60$, $p = 0.000^{**}$), with a maximum value estimated at 100 kg ha^{-1} of N (Fig. 5c).

The average ash content obtained in this study (4.7%) was lower than in other studies that evaluated the elephant grass [23, 36] and other grasses like sugar cane [54]. The low ash values show the potential of elephant grass for energy purposes. Materials with higher ash content release a higher amount of volatile substances at higher temperatures [14]. Also, higher ash contents reduce the energy available in the material and therefore reduce conversion efficiency [23, 55]. Ashes result from the accumulation of minerals in the tissues of the plant. The content as well as the composition vary according to the biomass source, and the main ash-forming compounds are CaO, SiO_2, K_2O, MgO, P_2O_5, and Al_2O_3 [50].

The increase in ash content with nitrogen dose in the second harvest decreased the fixed carbon and increased in volatile compounds produced by burning elephant grass (Fig. 5). Volatile content expresses the ease of burning of the material; the higher its content, the greater the reactivity and, consequently, the ignition [2]. The volatile materials are originating from polysaccharides, such as hemicellulose and cellulose,

Table 4 Energetic and physical characteristics of elephant grass biomass at different harvests and nitrogen doses

Treatments	Ashes %	FC %	Volatile %	BD kg m^{-3}	HHV kJ kg^{-1}	ED Gcal m^{-3}
Harvest (H)						
2015/16	4.04 ± 0.19 b	17.28 ± 0.41 a	78.68 ± 0.40 b	200.00 ± 5.38 b	17,847 ± 652 a	0.86 ± 0.02 a
2016/17	5.51 ± 0.19 a	11.26 ± 0.70 b	83.22 ± 0.62 a	210.00 ± 9.08 a	16,546 ± 319 b	0.84 ± 0.04 b
Pr(> F)	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**
N doses (D) (kg ha^{-1})						
0	4.46 ± 0.33	15.05 ± 1.45	80.48 ± 1.24	190.00 ± 4.81	17,190 ± 440	0.78 ± 0.01
50	4.80 ± 0.47	14.34 ± 1.58	80.85 ± 1.15	200.00 ± 2.26	17,025 ± 426	0.82 ± 0.03
100	4.76 ± 0.56	13.45 ± 2.28	81.78 ± 1.74	200.00 ± 1.51	17,770 ± 104	0.84 ± 0.02
150	4.89 ± 0.38	13.97 ± 1.64	81.13 ± 1.27	220.00 ± 4.78	17,083 ± 570	0.91 ± 0.05
200	4.97 ± 0.38	14.52 ± 1.34	80.50 ± 1.00	221.00 ± 2.74	16,914 ± 411	0.87 ± 0.01
Pr(> F)	0.01**	0.01*	0.02*	0.00**	0.59^{ns}	0.00**
H × D						
Pr(> F)	0.00**	0.00**	0.02**	0.00**	0.80^{ns}	0.00**
CV (%)	5.68	6.10	1.06	2.42	6.31	2.45

ns not significant at 5% probability by the Scott-Knott test, *CV* coefficient of variation (%), *FC* fixed carbon, *BD* bulk density, *HHV* high heating value, *ED* energy density

*Significant at 5% of probability by the Scott-Knott test

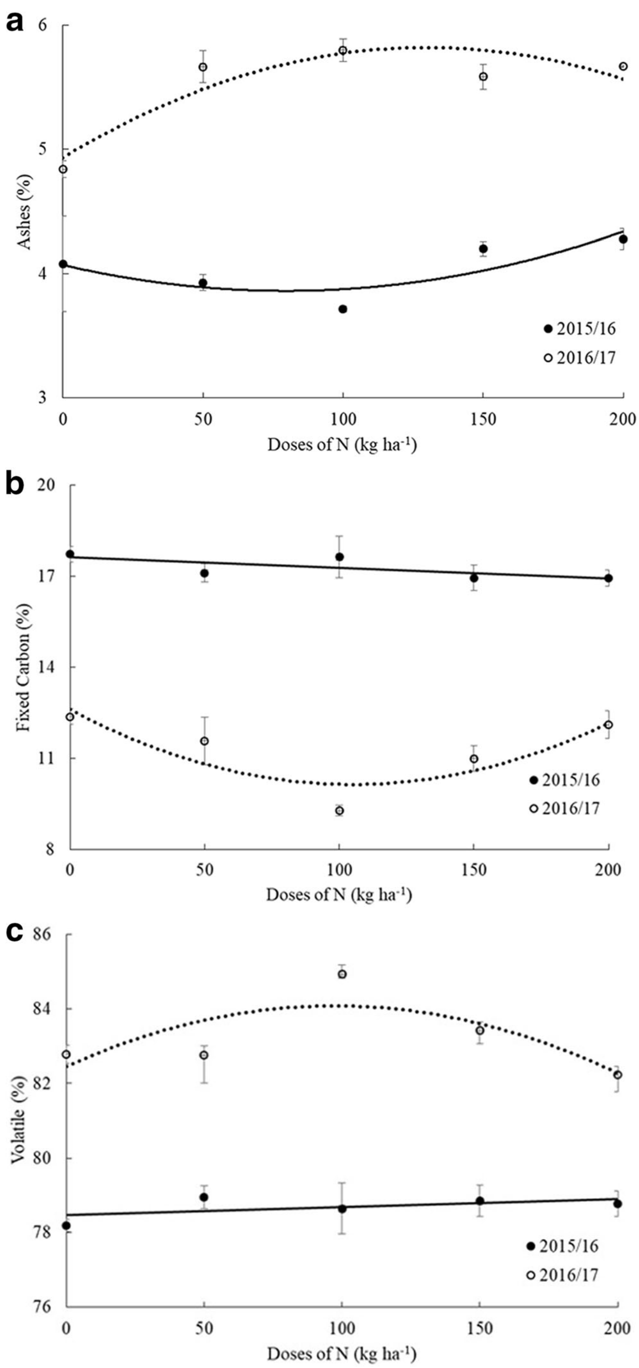

Fig. 5 Ash content (**a**), fixed carbon content (**b**), and volatile content (**c**) of elephant grass according to the nitrogen dose in 2015/16 and 2016/17 harvests

with higher content in the second harvest, also influenced by nitrogen application (Table 4). The increase in the content of the volatile material may have been influenced by the better nutritional environment in the second harvest due to the higher nutrient input in soil, as well as the optimal amount of nitrogen supplied in the fertilization. Such factors favor photoassimilate production, which results in the polymerization of these compounds.

Consistent with the ash and volatile content, which increased in the second crop, the fixed carbon content decreased since its determination is indirect, excluding ash and volatile from the total sample. The fixed carbon content establishes the amount of heat generated in the combustion, and the speed of burning of a material; the lower the value, the faster the material will burn [2]. Therefore, when associated with lower ash and higher fixed carbon contents, it is possible to verify the high energetic capacity of elephant grass biomass, especially in the harvest of 2015/16, with higher HHV, of about 1300 kJ kg^{-1}, than in the harvest of 2016/17 (Table 4). Fixed carbon and ash content are also related to the HHV, i.e., higher carbon content and lower ash content reflect a higher HHV [23, 56], as verified in this study. The use of nitrogen fertilizers does not affect the high heating value of elephant grass biomass, which remains at high levels [14]. The energy density represents the amount of energy per volume of material; thus, the higher the energy density, the better the biomass performance as fuel [6, 36]. The energy density was 2.4% higher in the first harvest than the second, and this difference is associated with the higher HHV values which was also observed (Table 4).

The volatile and fixed carbon contents found in this study are close to those found in the previous [2, 36, 57]. The HHV of elephant grass biomass is very close to the sugarcane biomass, which evidences its high energy potential [2]. The results obtained in this work indicate that it is possible to use the elephant grass biomass as an energy resource in the fresh form.

Energetic, Physical, and Mechanical Characteristics of Briquettes

The time of harvest and N application had little effects on the quality of briquettes of elephant grass, except for the energy density (Table 5). The energy density was significantly higher in the 2015/16 harvest by 9% compared to the 2016/17 harvest, as a function of the highest HHV of the biomass observed for the first period of evaluation (Table 4).

In general, the nitrogen fertilizers and the harvests did not influence the variables evaluated for the briquettes. The homogeneity of the briquette characteristics is related to the briquetting process conditions (pressure and temperature), which tend to influence the physical and mechanical characteristics of the densified materials in a more significant way [58], making the average values homogeneous.

Results show that the densification of the biomass, through the briquetting process, increases the bulk and energy densities, with increments in the order of six times (from 205.00 to 1256 kg m^{-3} and from 0.85 to 5.14 Gcal m^{-3}). Apparent density is one of the most important characteristics of densified materials because it influences the behavior of the material during combustion since the absence of voids restricts the movement of oxygen and prolongs the burning time [59]. The

Table 5 Energetic, physical, and mechanical characteristics of elephant grass briquettes at different harvests and nitrogen doses

Treatments	AD kg m^{-3}	ED Gcal m^{-3}	VE %	Durability %
Harvest (H)				
2015/16	1267.96 ± 8.85	5.43 ± 0.04 a	2.71 ± 0.09	99.75 ± 0.03
2016/17	1250.95 ± 19.18	4.94 ± 0.24 b	3.32 ± 0.11	99.71 ± 0.13
Pr(> F)	0.12 ^{ns}	0.00**	0.07^{ns}	0.44^{ns}
N doses (D) (kg ha^{-1})				
0	1,259.18 ± 15.37	5.13 ± 0.10	3.32 ± 0.21	99.79 ± 0.07
50	1260.32 ± 11.90	5.07 ± 0.09	2.35 ± 0.12	99.71 ± 0.10
100	1255.32 ± 30.69	5.30 ± 0.36	4.03 ± 0.32	99.58 ± 0.09
150	1251.43 ± 12.17	5.10 ± 0.15	2.58 ± 0.11	99.82 ± 0.09
200	1256.89 ± 16.43	5.02 ± 0.07	3.54 ± 0.18	99.72 ± 0.07
Pr(> F)	0.64^{ns}	0.96^{ns}	0.18^{ns}	0.07^{ns}
H × D				
Pr(> F)	0.97^{ns}	0.82^{ns}	0.19^{ns}	0.10^{ns}
CV (%)	1.73	8.10	11.4	0.16

ns not significant at 5% probability by the Scott-Knott test, *CV* coefficient of variation (%), *AD* apparent density, *ED* energy density, *VE* volumetric expansion

**Significant at 5% of probability by the Scott-Knott test

higher density of briquettes reduces transport costs, increasing their profitability, and it is a considerable advantage over the other most common types of biomass [1]. Similarly, the energy density is an important parameter for solid biofuels since it evaluates the amount of energy stored in each volume of material [11].

The volumetric expansion and durability did not undergo significant variations due to the harvests or nitrogen application. These parameters are important since they indicate the dimensional stability of the briquettes and the impact of resistance during storage and transport [60]. The average volumetric expansion (3.0%) was higher than that observed in *Eucalyptus urophylla* S.T. Blake x *Eucalyptus grandis* Hill ex Maiden (called urograndis) briquettes (1.03%) [11]. This difference can be due to the lignin content since their viscoelastic property is responsible for the union of the particles during the densification process of the lignocellulosic biomass, generating products with low volumetric expansion index. Some factors influence the cohesion capacity of the aggregates of biomass particles, such as moisture and chemical composition of the biomass [61]. Elephant grass has around 9.0% lignin content [62], while forest species such as urograndis and *E. grandis* Hill ex Maiden have 23.2% and 21.9% in the wood, respectively [63].

The cohesive capacity of the particles also influences the durability of the briquette (99.7%), close to those obtained for *Phyllostachys aurea* Carrière (99.8%) briquettes [47]. It has been a suggested claim that briquetting the elephant grass biomass is beneficial, being capable of transforming the fresh biomass into biofuel with higher quality and uniformity [2], as observed in this study.

Conclusions

Nitrogen application influenced the elephant grass yield growing in tropical conditions. The biomass yield reached 43 Mg ha^{-1} in the second harvest. The application of 100 kg ha^{-1} N promoted greater efficiency in the use of N and biomass yield. Thus, this is the recommended dose for cultivation of elephant grass for energy purposes in the edaphoclimatic conditions of the Cerrado biome (Brazilian Savannah).

Elephant grass presented high heating value, ash content, and bulk and energy density that make it suitable for use as an energy resource in the fresh form. However, the production of briquettes improved its energetic characteristics. The application of N doses did not change the high heating value of biomass and energetic, physical, and mechanical characteristics of the briquettes.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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