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Chemical and bioenergetic characterization of sorghum agronomic groups[1]

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ABSTRACT

The global demand and production of primary energy is expected to grow at a rate of 1.4 % per year by 2035. In the same period, the production of renewable energy is expected to grow at a rate of 6.6 % per year, rising from 3 % to 9 % of world primary energy. Therefore, the biofuels supply assumes a strategic role for world energy security. In this context, sorghum is a promising alternative in the bioenergetic sector, due to its agronomic characteristics and adaptability to limiting edaphoclimatic conditions. This study aimed at evaluating the productive potential of three sorghum agronomic groups (biomass, saccharin and forage), as well as chemically characterizing the biomass of these materials. For that, a field experiment was carried out using a randomized block design, where agronomic and chemical characteristics (cellulose, hemicellulose, lignin and ash), as well as moisture contents, were evaluated. The biomass sorghum cultivars presented a high yield (about 30 t ha^{-1} of dry stalk), being, for this reason, more suitable for the generation of solid biofuels, i.e., direct burning. On the other hand, the forage sorghum cultivars presented a lower lignin content in the stalks, in relation to the other cultivars, being indicated for the generation of liquid biofuels. It is also worth mentioning the possibility of producing second-generation bioethanol from saccharin sorghum bagasse. Therefore, sorghum presents different use potentials that may be exploited by the bioenergy sector according to the agronomic group and plant physical part.

KEYWORDS: *Sorghum bicolor*; bioenergy; biofuel.

RESUMO

Caracterização química e bioenergética de grupos agronômicos de sorgo

A demanda e produção mundial de energia primária deverá crescer à taxa de 1,4 % ao ano, até 2035. No mesmo período, a produção de energias renováveis deverá crescer à taxa de 6,6 % ao ano, passando de 3 % para 9 % de energia primária mundial. Logo, a oferta de biocombustíveis assume papel estratégico para a segurança energética mundial. Neste contexto, o sorgo é uma alternativa promissora no setor bioenergético, devido às suas características agronômicas e adaptabilidade às condições edafoclimáticas limitantes. Objetivou-se avaliar o potencial produtivo de três grupos agronômicos de sorgo (biomassa, sacarino e forrageiro), bem como caracterizar quimicamente a biomassa desses materiais. Para isso, conduziu-se um experimento utilizando-se delineamento em blocos casualizados, no qual foram realizadas avaliações agronômicas, químicas (celulose, hemicelulose, lignina e cinzas) e teores de umidade. As cultivares de sorgo biomassa apresentaram alta produtividade (cerca de 30 t ha^{-1} de colmo seco), sendo, por isso, mais indicadas para a geração de biocombustíveis sólidos, isto é, queima direta. Já as cultivares de sorgo forrageiro apresentaram menor teor de lignina nos colmos, em relação às demais cultivares, sendo indicadas para a geração de biocombustíveis líquidos. Destaca-se, ainda, a possibilidade de produção de bioetanol de segunda geração a partir do bagaço de sorgo sacarino. Logo, o sorgo apresenta diferentes potenciais de uso que podem ser explorados pelo setor de bioenergia de acordo com o grupo agronômico e a parte física da planta.

PALAVRAS-CHAVES: *Sorghum bicolor*; bioenergia; biocombustível.

INTRODUCTION

Brazil stands out as one of the world's largest bioenergy producers. In the specific case of ethanol, it is the second largest producer, only behind the USA. However, the Brazilian bioenergy sector has faced crises, given the oscillation in the price of ethanol, seasonality in production and climatic variations (Brasil 2014). In addition, the idleness of industrial units (four months per year) during the off-season of sugarcane (*Saccharum* spp.) results in a low competitiveness of the bioenergy sector.

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Research has made significant advances in innovation and technology, in the conversion of raw materials to various biofuels (biodiesel, biokerosene, biogasoline, pellets, etc.) and biomaterials (biopolymers, bioplastics, etc.) (Goldenberg 2009). However, in practice, these advances suffer with the technical and economic feasibility of obtaining the final product (energy or biomaterial) at competitive prices. A promising strategy to leverage the bioenergy production and address the shortcomings of the sugar and ethanol industry would be the inclusion of other sources of raw material in the off-season of sugarcane, in order to reduce the idle production of industrial platforms and improve the competitiveness of the sector. Among the alternatives, sorghum (*Sorghum bicolor*) has stood out as a raw material for energy generation, given its high yield in a short time and high calorific power (Unica 2012).

Among the types of sorghum with energetic characteristics, it is possible to mention saccharine, biomass and forage sorghum. Saccharine sorghum is mainly used in the production of first generation ethanol, given the high concentration of sucrose in its stem. The biomass sorghum is generally used for direct burning and generation of bioelectricity, given its high lignin content and good performance in the combustion processes (May et al. 2013). The forage sorghum is used for silage production, given the high digestibility of its fibrous fractions, due to its low lignin content.

Although these three agricultural groups have a high potential for biomass production, the variations in the structural and chemical composition of the plant parts, notably cellulose and hemicellulose (Neumann et al. 2002), may result in their indication for different purposes (direct burning, solid or liquid biofuels, biopolymers, etc.).

Thus, this study aimed at evaluating the productive potential of three sorghum agronomic groups (biomass, saccharine and forage), as well as characterizing the biomass of these materials, in order to guide the productive sector in the choice of the most promising material, according to its use.

MATERIAL AND METHODS

The experiment was carried out in a single experimental field at the Universidade Federal de Viçosa, in Coimbra, Minas Gerais state, Brazil (20º51'S, 42º46'W and 720 m of altitude), from December 2014 to April 2015. Sowing was performed on 04 December 2014, adopting the manual system, in a flat area of 861 m², with density of 12 seeds m^{-1}. At 20 days after sowing, manual thinning was performed, leaving 9 plants m^{-1}. The environmental conditions during the experiment are described in Figure 1.

The design used for the phytotechnical evaluations was randomized blocks, with six replicates. Two cultivars of each sorghum agronomic group were used for the characterization, in order to allow a general inference about the performance of these materials. The selected cultivars may be considered a good representation of the groups, because they are among the most planted ones in Brazil. Thus, six cultivars were evaluated, divided into three groups: biomass sorghum (BD 7607 and BRS 716 hybrids), saccharine sorghum (BD 5404 and BRS 511 hybrids) and forage sorghum (BD 1615 and BRS 655 hybrids). The experimental plots consisted of four lines of 6 m each, spaced 0.70 m apart. For evaluations, the useful area consisted of the two central lines of the plot, eliminating 1.0 m from each end. Harvest was carried out between April and May 2016. Therefore, the experimental period was five months.

Ten plants from the useful area of each plot were randomly sampled. These were harvested during the grain physiological maturity of each cultivar, in order to evaluate the plant height and total fresh mass production (kg $plot^{-1}$), by weighing the ten complete plants. Afterwards, the plants were sectioned in stalk, leaves and panicle, to weigh the fresh matter of each

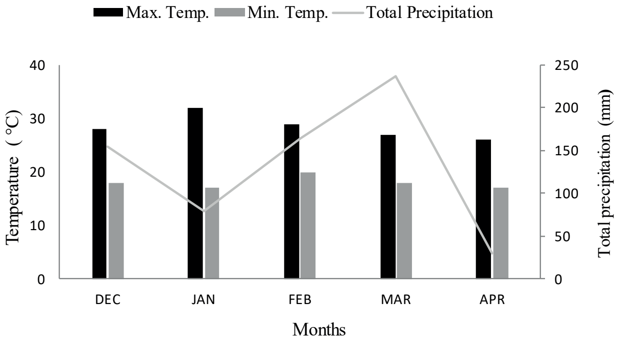

Figure 1. Monthly average cumulative precipitation (mm) and temperatures (ºC), from December 2014 to April 2015. The data were obtained from the meteorological station of the Department of Agricultural Engineering of the Universidade Federal de Viçosa, in Coimbra, Minas Gerais state, Brazil.

part, evaluating later the total dry mass production, determined by the weight difference between the samples of fresh and dried material. The fresh and dry matter yields were also estimated by multiplying the average weight obtained in the ten plants by 128,571 (expected stand).

Samples of the plant physical components (panicle, leaf and stalk) were used for evaluating the moisture content. The wet samples were weighed and then fed into a forced ventilation oven at 65 ± 5 ºC, until reaching a constant weight. For that, the following equation was used: moisture content = [(initial mass - final mass/ initial mass)] x 100.

After determining the moisture content of the samples, they were ground to reduce particle size and to standardize the specific surface, using a Wiley mill with 1 mm sieves. Subsequently, the samples were packaged in Kraft paper, properly identified and stored for later use in chemical and energy determinations.

The chemical analyses were carried out with the dried and ground samples, according to Detmann et al. (2012). The contents of cellulose and hemicellulose were determined by acid detergent fiber and neutral detergent fiber contents, while the lignin determination was performed by the acid detergent lignin method. The lignin content was calculated by the weight loss after burning in the muffle. The cellulose content was estimated by the difference between the acid detergent fiber content minus the lignin and ash contents. Hemicellulose was determined by the difference between neutral detergent fiber and acid detergent fiber. For ash determination, 2 g of the sample were weighed in a porcelain crucible (weight already recorded) and placed in a muffle at 575 ± 25 ºC, for 3 h. The crucible was cooled in a desiccator to reach equilibrium at room temperature and the final weight was recorded. The ash content is equal to the final weight of the carbonized sample divided by the weight of the initial sample.

Data were submitted to analysis of variance by the F-test, at 1 % and 5 %. The Tukey test was applied to compare the cultivars at 5 %, for the variables that presented significance.

RESULTS AND DISCUSSION

The BD 7607 and BRS 711 cultivars, belonging to the agronomic group of biomass sorghum, presented a higher height, with averages of 5.15 m and 4.97 m, respectively, significantly differing from the other cultivars (Figure 2). The forage sorghum BRS 655 presented the lowest height (2.62 m). Height is highly influenced by genetic constitution, being controlled by several genes that act independently (Magalhães et al. 2014).

In terms of total fresh mass, the biomass sorghum cultivars presented a higher production, being significantly superior to the other ones, with an average of 110 $t\ ha^{-1}$ and 108 $t\ ha^{-1}$, respectively. In addition, the total dry mass production followed the same trend as the total fresh mass production. The BD 7607 (biomass sorghum) cultivar presented the highest total dry mass production (43 $t\ ha^{-1}$), being significantly higher than the other ones. The BRS 655 cultivar had the lowest production: 16 $t\ ha^{-1}$ (Figure 2).

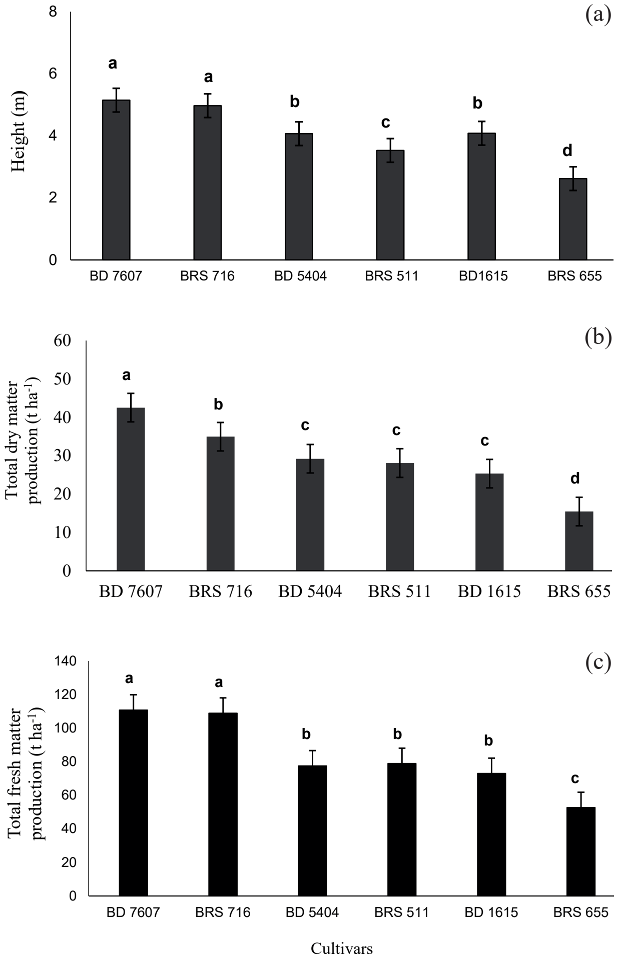

Figure 2. Average height (a), total dry matter production (b) and total fresh matter production (c) of six sorghum cultivars. Letters above the bars indicate the results of a Tukey test at 5 %

When compared to other bioenergy crops, sorghum stands out because it has a short cycle and high potential for the production of dry matter. Eucalyptus, for example, the most common plant in Brazil for the production of cellulose and charcoal, produces up to 20 t ha^{-1} of dry biomass per year, on average; however, it takes five years to reach an adequate size for cutting (Silva 2010). On the other hand, the biomass sorghum cultivars evaluated in this study produced an average of 40 t ha^{-1} of dry mass in approximately five months.

In view of the high yield levels achieved, the biomass sorghum cultivars are a promising alternative in the supply of raw material for the bioenergy sector. This biomass may be used for direct burning in the steam generation (energy production) and/or for animal feed production, papermaking and hydrolysis to generate alcohol, among others. In addition, because it is harvested between March and April, sorghum may complement the supply of raw material in the off-season of sugarcane, when there is no more sugarcane bagasse for burning and generating energy in mills (Unica 2012).

The percentage of panicles in the total dry matter was inferior to the other plant components for the cultivars BRS 716, BD 5404, BRS 511 and BD 1615. For the cultivars BD 7607 and BRS 655, the participation of the panicle did not differ statistically from the leaf (Table 1). For the cultivars that have a succulent stalk (BD 5404, BRS 511 and BD 1615), the lower participation of panicles is advantageous for a good broth yield, in order to produce ethanol. The translocation of photoassimilates stored in the stalk (sucrose) to fill the grains at the end of the cycle is disadvantageous for saccharine sorghum (Ribas 2014). According to May et al. (2013), in order to enable the production of ethanol from saccharine sorghum, a higher concentration of sugars in the broth is important.

Among the factors that affect the panicle ratio, the sorghum agronomic group is one of the variables that should be considered. The forage genotypes, such as the BRS 655 cultivar, are able to reconcile mass and grain production, justifying their superiority in the panicle production (Botelho et al. 2010). In addition, the higher percentage of panicles contributes to increase the quality of the silage and has a great participation in the increase of the dry matter percentage of the ensiled mass, given its lower water content (Corrêa et al. 1996). Thus, these materials could be better used in the bioenergy sector for the production of second-generation ethanol (biomass) and also for producing ethanol from grain starch.

The stalk was the plant physical component with the highest percentage participation for all the cultivars, being statistically superior to the other components. This shows that the stalk is the portion of the sorghum plant that most influences the productive yield of the cultivars, besides being the plant physical component that will contribute the most with the cogeneration of solid or liquid biofuels.

There was a significant difference, in relation to the moisture percentage, between the plant parts evaluated in the same cultivar. The moisture content in the stalk was significantly higher than in the other plant components, for all cultivars, ranging from 65.10 % (BD 1615) to 77.43 % (BRS 655). However, the BRS 511 cultivar did not present a significant difference between the moisture content for stalk and leaf, which were significantly superior to the other parts.

Moisture content is influenced by the type of sample and the time it was collected. The sorghum samples had a moisture content ranging 30-70 %, considering all the plant components (Table 2). The average moisture contents found in the sorghum bagasse for the cultivars BD 1615, BRS 511 and BD 5404 were 47 %, 56.62 % and 46.50 %,

Table 1. Percentage of panicle, leaf and stalk in the plant dry matter of six sorghum cultivars.

Cultivar	Plant component			Dry matter (t ha^{-1})
	Panicle (%)	Leaf (%)	Stalk (%)	
BD 7607	15.80 bA*	13.09 bC	72.94 aB	43.63
BRS 716	5.22 cB	18.27 bB	77.10 aA	41.04
BD 5404	6.14 cB	19.79 bB	74.38 aB	24.36
BRS 511	0.99 cC	17.78 bB	81.23 aA	26.23
BD 1615	5.92 cB	14.15 bC	79.94 aA	22.95
BRS 655	18.87 bA	25.55 bA	53.58 ac	19.80

* Averages followed by the same lowercase letter in the row and uppercase letter in the column do not differ statistically from each other at 5 %, using the Tukey test.

Table 2. Moisture content of the panicle, leaf, stem and bagasse of six sorghum cultivars.

Plant component	Moisture (%)					
	BD 7607	BRS 716	BD 5404	BRS 511	BD 1615	BRS 655
Panicle	50.90 b*	54.69 b	42.15 c	30.71 c	60.65 b	38.95 c
Leaf	44.03 b	51.77 b	59.29 b	61.87 a	55.80 c	65.10 b
Stalk	61.87 a	70.57 a	65.85 a	66.95 a	65.10 a	77.43 a
Bagasse	-	-	47.00 c	56.62 b	46.50 d	-
Average	53.17	59.01	55.76	53.17	57.01	60.49
CV (%)	8.61	7.22	4.19	6.12	3.87	5.43

* Averages followed by the same letter do not differ among themselves at 5 %, by the Tukey test.

respectively. These values were close to that found by Silva & Morais (2008) for sugarcane bagasse (approximately 50 % of moisture). The sorghum stalk has a greater moisture content and, therefore, needs to be dried before the beginning of the combustion process, so that it can release sufficient energy from the burning process.

According to Demirbas (2004), a high moisture content reduces the efficiency of the process to convert biomass into fuel, because the energy needed to evaporate the water and to maintain the operating temperature is obtained by feeding more fuel and oxidant. In this way, moisture is a limiting factor in the fuel choice (biomass). Values of moisture content above 50 % are generally not allowed, because insufficient energy is released from combustion and, consequently, the production of heat is impaired (Vieira 2012).

By analyzing the chemical characteristics of the plants parts, it was possible to verify that, except for the BD 7607 cultivar, which presented the highest hemicellulose content in the leaves, the other cultivars had a higher hemicellulose content in the panicle (28-45 %). These values are higher than those found in the leaf and stem components (Table 3). The BD 5404 and BD 1615 cultivars presented the highest hemicellulose levels in the panicle and also in the leaves. In addition, there were no significant differences between these parts of the plant for this variable. Hemicellulose is a heterogeneous polymer formed by monomers (Jenkins et al. 1998). Xylose is the most abundant pentose in the hemicellulose of cellulosic materials (Godin et al. 2011). This sugar has been used in the production of furfural, a selective solvent used in large scale in the purification of mineral, vegetable and animal oils (Lange et al. 2012). In addition, xylose may be used for other purposes, such as the production of xylitol, a product of higher added value, widely used in the food industry as a sweetener, as it is as sweet as sucrose, but approximately 40 % less caloric (Santos 2012).

Panicle was the component that presented the lowest average cellulose values, if compared to the other plant components, varying from 7.59 % (BRS 655) to 20.31 % (BRS 511). On the other hand, the leaf, stalk and bagasse components (for the BD 1615, BRS 511 and BD 5404 cultivars) presented the highest cellulose levels, not statistically different from each other, with an average of 27 %.

Cellulose is a biodegradable polymer of great commercial importance, given its wide application in the industries of paper, textile, filter, pigment, transparent photographic films, plastic materials and capsules for the pharmaceutical industry, among others (Braz & Ascheri 2015). During the sorghum processing by industries, only the stalk is used to manufacture products such as ethanol (first and second generation), bioelectricity and direct burning (Braz & Ascheri 2015). The other parts (panicle and leaves) are discarded as agro-industrial waste, being used for the production of animal feed or as an energy source for the industry itself, by pyrolysis (Oliveira et al. 2009). However, these materials may be used as an alternative source of hemicellulose and cellulose.

The cellulose production from eucalyptus has a high industrial cost, given the high lignin content of the material, but has the advantage of a continuous supply to the industry throughout the year, regardless of the harvest season. However, the forest cycle for cutting is seven years, on average, what does not allow the sector to respond to the increase in demand in the short term. In this context, the use of sorghum could be a complementary alternative for the sector, since it can be produced in specific demands and in a short time, to supply an increased demand. In addition, it would have the advantage of a lower industrial cost, because it has less lignin than wood. Therefore, the use of sorghum would be

Table 3. Average contents of hemicellulose, cellulose, lignin and ashes of the different plant parts, according to the sorghum cultivar.

Plant component	Hemicellulose (%)		Cellulose (%)		Lignin (%)		Ash (%)		Extractive content (%)**	
	Biomass sorghum									
	BD 7607	BRS 716	BD 7607	BRS 716	BD 7607	BRS 716	BD 7607	BRS 716	BD 7607	BRS 716
Panicle	28.59 b	46.16 a	8.38 b	18.54 b	6.22 b	7.60 ab	1.98 b	6.71 a	54.83	20.99
Leaf	34.45 a	35.08 b	23.36 a	27.09 a	5.60 b	5.43 b	5.51 a	7.10 a	31.08	25.30
Stalk	28.68 b	28.86 b	29.14 a	29.14 a	8.48 a	10.21 a	3.88 a	5.67 a	29.82	26.12
Average	30.57	35.65	20.44	22.10	6.70	7.91	3.79	6.50	-	-
CV (%)	8.01	13.66	19.03	24.18	12.26	18.86	21.82	12.56	-	-
	Saccharine sorghum									
	BD 5404	BRS 511	BD 5404	BRS 511	BD 5404	BRS 511	BD 5404	BRS 511	BD 5404	BRS 511
Panicle	38.44 a	41.19 a	11.00 c	20.31 b	4.91 b	5.06 b	7.08 b	8.63 a	38.57	24.81
Leaf	35.08 ab	32.98 b	21.93 b	20.04 b	6.15 b	3.50 b	10.47 a	8.41 a	26.37	35.07
Stalk	28.86 b	25.55 c	25.33 b	31.13 a	7.41 b	9.16 a	3.73 c	5.03 b	34.67	29.13
Bagasse	30.46 b	28.14 bc	33.74 a	29.61 a	10.08 a	8.56 a	3.67 c	3.16 b	22.05	30.53
Average	32.93	31.96	23.12	25.98	7.89	6.70	6.23	6.31	-	-
CV (%)	9.68	8.32	14.88	9.89	19.69	12.70	13.03	18.22	-	-
	Forage sorghum									
	BD 1615	BRS 655	BD 1615	BRS 655	BD 1615	BRS 655	BD 1615	BRS 655	BD 1615	BRS 655
Panicle	37.46 a	45.58 a	19.05 b	7.59 b	5.29 a	6.25 a	2.82 c	5.56 a	35.38	35.02
Leaf	34.70 ab	33.90 b	26.43 a	27.38 a	6.86 a	5.71 a	10.68 a	7.77 a	21.33	25.24
Stalk	31.89 b	32.62 b	28.68 a	22.44 a	6.07 a	5.43 a	6.80 b	7.59 a	26.56	31.92
Average	34.61	37.37	24.46	19.13	6.11	5.79	6.49	6.97	-	-
CV (%)	5.24	3.29	10.74	15.24	17.32	15.58	14.44	18.12	-	

* Averages followed by the same lowercase letter in the columns do not differ among themselves at 5 %, by the Tukey test; ** The extractive content was not evaluated in this study.

a complementary strategy to the eucalyptus-based bioenergy industry.

The bagasse of the cultivars under study presented a good cellulose content: approximately 30 % (Table 3). This value is close to the cellulose content found in agro-industrial waste, such as wheat straw (34 %), sugarcane bagasse (40 %), corn cob (32 %) and sorghum straw (34 %) (Silva 2010). However, it is lower than the cellulose content found in *Eucalyptus globulus* wood, which is approximately 46 % (Silva 2010).

The bagasse of the cultivars BD 5404, BRS 511 and BD 1615 originated from their stalk, and this was the component that presented the greatest participation in the total biomass (Table 3). In this way, sorghum bagasse has a high yield per hectare and reduced production costs, when compared to other crops, and it may be used for the extraction of cellulose and generation of biomaterials. The use of this bagasse for this purpose would reduce the environmental degradation and deforestation of large planted areas (Quilho 2011).

It is also worth mentioning the possibility of producing second-generation bioethanol from sorghum bagasse. The process occurs from the enzymatic or acidic hydrolysis of cellulose, in which the bagasse is subjected to the process of extraction of sugars with the addition of sulfuric acid at high temperatures or with the use of specific enzymes. The sugars obtained are in the fermentable form (Gnansounou & Dauriat 2005).

Lignin has a much more complex structure than cellulose and hemicellulose, given the presence of several precursor units (Saidur et al. 2011). Lignin is non-fermentable and its structure may influence the thermal degradation of the biomass, raising its upper calorific value (Jenkins et al. 1998). Thus, as the stalk and bagasse components presented a higher lignin content, in relation to the other ones, both have a potential for the generation of bioelectricity and heat from direct burning.

The biomass sorghum cultivars showed a high lignin content in the stalk. In addition, these cultivars showed a high yield (approximately 30 t ha^{-1} of dry stalk). Therefore, they are best indicated for the generation of solid biofuels, i.e., direct burning for the generation of steam/energy. On the other hand, the forage sorghum cultivars presented a lower lignin content in the stalks, in relation to the other cultivars, so this material will probably be more susceptible to hydrolysis and, consequently, generate more sugars for the production of second-generation ethanol, being indicated for the generation of liquid biofuels.

The values found for ash content ranged from 1.98 % to 10.68 % (Table 3). These values are close to those obtained by other energy crops, such as corn cob and sugarcane bagasse, which presented values of 1.1 % and 11.3 %, respectively (Demirbas 2004). Higher ash contents were found in the leaves of the cultivars, with values varying from 5.51 % (BD 7607) to 10.68 % (BD 1615).

Plant ash, which is a solid waste from the burning of plant biomass, presents reasonable amounts of macronutrients and micronutrients in its composition. This waste is efficient in reducing acidity and improving soil fertility. It can reduce the content of H + Al and increase the pH and the contents of magnesium, phosphorus and potassium, thus having the potential to be used as a fertilizer and as a corrective treatment (Bonfim-Silva et al. 2013). However, ash is undesirable in the pyrolysis-based bioenergy industries, as it is a waste that needs to be constantly removed from the furnace.

The participation of leaves in total biomass varied from 13 % (BD 7607) to 25 % (BRS 655) (Table 3), producing from 6 t ha^{-1} to 4 t ha^{-1} of leaves, respectively, on average. Thus, in addition to being generally used for animal silage, the leaves produced by these cultivars may be used in direct burning and later as fertilizer.

CONCLUSIONS

1. The BD 7607 and BRS 716 cultivars (biomass sorghum group) present a higher productive potential, with characteristics that enable their use in direct combustion and energy cogeneration;
2. The plant physical components present different potentials of use, given their chemical composition and proportion in total biomass. The stalk is the part with the highest participation, with approximately 70 % of the total biomass, being the most indicated for bioenergetic purposes;
3. The moisture content is a limiting factor, as it is found at high levels in all parts of the sorghum plants, especially in the stalk. However, moisture could be removed with specific agronomic management, such as the application of desiccants and/or growth regulators (commonly used in the sugar and ethanol industry for sugarcane).

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