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Scientific Article

FIREWOOD QUALITY OF *Eucalyptus* spp. CLONES FOR AGROINDUSTRY SUPPLY IN MATO GROSSO, BRAZIL

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ABSTRACT

The use of renewable energy sources from biomass has been increasing in the agricultural sector, with a focus on wood produced from eucalyptus plantations. Given the economic significance of the state of Mato Grosso, Brazil, this study aimed to evaluate the energy potential of different eucalyptus clones planted in the state, with an emphasis on their use in agroindustry. Three trees were selected from each of eleven different eight-year-old genetic materials in a clonal test located in Tangará da Serra, MT. The bark percentage, basic density, higher heating value, and both elemental and structural chemical composition of the wood were determined. A cluster analysis was then performed. Additionally, a case study was conducted considering firewood consumption and costs for drying corn and soybeans. The bark percentage ranged from 5.00 to 11.04%. Basic density varied from 478 to 588 $kg.m^{-3}$, with significant differences among the three groups formed; the best-performing clones had values approximately 6% higher than the others. Higher heating values ranged from 4,609.33 to 4,743.67 $kcal.kg^{-1}$. Total lignin content also varied between clones, with one group standing out by ranging from 27.81% to 29.76%. Total extractive content ranged from 3.72 to 7.76%. The average energy density was 2.50 $Gcal.m^{-3}$, with no significant differences between the clones. Cluster analysis identified two main groups. The evaluated eucalyptus clones showed satisfactory characteristics for energy use, with clones 1, 4, and 10 standing out. The use of eucalyptus clones with superior energy properties can reduce wood consumption for drying grains such as soy and corn by up to 20%.

Keywords: Energy clones; Combustion; Renewable energy

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QUALIDADE DA LENHA DE CLONES DE *Eucalyptus* spp. PARA SUPRIMENTO DA AGROINDÚSTRIA EM MATO GROSSO, BRASIL

RESUMO O uso de fontes energéticas renováveis provenientes de biomassa tem aumentado no setor agrícola, com destaque para a madeira produzida em plantios de eucalipto. Dada a importância econômica do estado de Mato Grosso, Brasil, o objetivo deste trabalho foi avaliar o potencial energético de diferentes clones de eucalipto plantados no estado, visando sua utilização em agroindústrias. Três árvores foram selecionadas de cada um dos onze materiais genéticos distintos, com oito anos de idade, em um teste clonal localizado em Tangará da Serra, MT. Foram determinados o percentual de casca, a densidade básica, o poder calorífico superior e a composição química da madeira, tanto elementar quanto estrutural. Em seguida, realizou-se uma análise de agrupamento (cluster). Adicionalmente, foi conduzido um estudo de caso considerando o consumo e os custos da lenha utilizada na secagem de milho e soja. A porcentagem de casca variou de 5,00 a 11,04%. A densidade básica variou de 478 a 588 kg.m⁻³, com diferenças significativas entre os três grupos formados; os clones com melhor desempenho apresentaram valores aproximadamente 6% superiores aos demais. O poder calorífico superior foi de 4.609,33 a 4.743,67 kcal.kg-1. O teor de lignina total também apresentou variação entre os clones, destacando-se um grupo com valores entre 27,81% e 29,76%. O total de extrativos variou entre 3,72 e 7,76%. A densidade energética média foi igual a 2,50 Gcal.m⁻³, sem diferenças estatísticas entre os clones. A análise de agrupamento identificou dois grupos principais. Os clones de eucalipto avaliados apresentaram características satisfatórias para uso energético, com destaque para os clones 1, 4 e 10. O uso de clones de *Eucalyptus* com propriedades energéticas superiores pode reduzir o consumo de lenha para a secagem de grãos, como soja e milho, em até 20%.

Palavras-Chave: Clones energéticos; Combustão; Energia renovável

1. INTRODUCTION

The rapid growth of the world population and advances in civilization have resulted in a growing demand for energy, with fossil fuels, especially coal, oil, and their derivatives, being the main sources of energy (Olabi & Abdelkareem, 2022). However, during their combustion, these fuels release greenhouse gases, such as methane (CH_4) and carbon dioxide (CO_2). One of the strategies to reduce the emission of greenhouse gases is the replacement of fossil fuels by renewable sources, such as forest biomass, which mainly originates from forest plantations (Nogueira et al., 2024).

Eucalyptus plantations are established in several tropical countries because of their rapid growth and high adaptability, and productivity (Costa et al., 2020). Brazil stands out worldwide, with 7.83 million hectares planted with eucalyptus trees and an estimated productivity of 33.7 $m^3 \cdot ha^{-1} \cdot year^{-1}$, with an average age of 7.2 years (Ibá, 2024). These characteristics make eucalyptus an excellent raw material, allowing its wood to be used in several industrial segments, such as the production of panels, cellulosic pulp and paper, charcoal, and firewood.

The use of wood from eucalyptus plantations to generate thermal energy stands out in Brazil because of the relatively low costs of plantations and the characteristics of wood from different clones, such as density, chemical composition, and calorific value (Ribeiro et al., 2021; Massuque et al., 2022; Vieira et al., 2023). The growing trend in the use of renewable sources of forest biomass has been increasingly observed in the agro-industrial sector as a reflection of the increase in the production of grain, especially soybeans and corn, which stand out in national production. Moreover, the installation of new industries, such corn ethanol plants, which uses biomass as an energy source, has generated new opportunities for the forestry sector, especially in the state of Mato Grosso.

Despite the increased demand for forestry biomass, Mato Grosso has an area of only 129,000 planted hectares of *Eucalyptus*, which represents approximately 1.6% of the total Brazilian area (Imea, 2022; Ibá, 2024). To ensure the sustainable growth of the forestry sector in the state, it is essential to expand the production of forest plantations, aiming not only to reduce environmental pressures on native areas but also to improve the efficiency and sustainability of agro-industrial projects. In addition, it is necessary to evaluate the characteristics of clones and hybrids under the specific soil and climate conditions of Mato Grosso, since many of these clones were developed and evaluated in other regions of Brazil, which may influence their performance and adaptability in the state.

Conducting studies on the firewood quality from *Eucalyptus* plantations is essential to support the selection and recommendation of the best clones for planting, as well as to assess the efficiency of this biomass in thermal energy conversion. Thus, this study aimed to evaluate the energy potential of different clones from a clonal test in Mato Grosso, Brazil, for their use in agro-industries. This was done by determining the physical, chemical, and energy properties of the firewood. Additionally, the study sought to identify the most suitable clones for thermal energy generation through combustion, contributing to the selection and expansion of the genetic base of clonal materials cultivated in the state. Furthermore, it aimed to estimate the cost of using *Eucalyptus* wood from these clones for drying corn and soybean grains.

2. MATERIAL AND METHODS

2.1 Study site and material collection

The study material was firewood from eleven eucalyptus clones (Table 1) from a clonal test, aged eight years (96 months), with a spacing of 3 × 2 m, belonging to a forestry company, located in the municipality of Tangará da Serra, Mato Grosso, Brazil, at the geographical coordinates 14°15'03"S latitude and 57°41'59"W longitude. The municipality is located at an elevation of 393 m above sea level and has an Aw climate (tropical rainy climate with dry winters), according to the Köppen and Geiger classification. The mean annual temperature is 24.9 °C, and the mean annual rainfall is 1499 mm (Zepner et al., 2020).

For each clone (Table 1), three trees representative of the average diameter and in adequate health conditions, without visual defects, were selected. Trees affected by border effects were excluded. From each selected tree, five disks measuring 10 cm in thickness were removed at positions corresponding to 0, 25, 50, 75, and 100% of the commercial trunk height, which was defined as the point where the diameter reached 7 cm. The discs were sectioned into four wedges, which passed through the pith. Two opposing wedges were used to determine the basic density, while the other two were used for the remaining analyses. These wedges were processed into sawdust using a Wiley-type mill, resulting in a

Table 1. Identification of clones from the *Eucalyptus* spp. clonal test established in Tangará da Serra, Mato Grosso, Brazil
Tabela 1. Identificação dos clones do teste clonal de *Eucalyptus* spp. estabelecido em Tangará da Serra, Mato Grosso, Brasil

Clone	Commercial identification	Species/Hybrid
1	0410	*Eucalyptus* sp.
2	102	*Eucalyptus* sp.
3	02	*E. urophylla*
4	401053	*E. urophylla*
5	0109	*E. urophylla*
6	0105	*E. urophylla* x *E. grandis*
7	I042	*E. Urophylla* x *E. grandis*
8	01	*E. urophylla* x *E. grandis*
9	0106	*E. urophylla* x *E. grandis*
10	0400104	*E. urophylla* x *E. camaldulensis*
11	0115	*E. urophylla* x *E. camaldulensis*

composite sample for each tree. The sawdust was then classified through sieves of 40 and 60 mesh, corresponding to particle sizes of 0.40 mm and 0.25 mm, respectively.

2.2 Properties of eucalyptus wood

Initially, the circumference of each disk with bark was measured using a measuring tape, with a precision of 0.1 cm. After manually debarking the disks, the circumference was measured again with the same measuring tape. The bark percentage for each disk was then calculated based on the ratio between the circumferences with and without bark, and the arithmetic mean was determined for each tree.

The basic density of the wood was determined using the water immersion method, as described in NBR 11941 (ABNT, 2003), by calculating the ratio between the dry mass and the saturated volume of the samples.

To determine the higher heating value (HHV), the procedures outlined in ASTM E711-87 (ASTM, 2004) were followed, using an IKA C-200 adiabatic bomb calorimeter. The net caloric value was calculated by considering a moisture content of 30% on a wet basis, as shown in Equation 1.

$$NCV=LHV\times(100-U\times100)-6\times H \quad \text{(Eq. 1)}$$

Where NCV is the net calorific value, in kcal·kg^{-1}; LHV is the lower heating value, in kcal·kg^{-1} (LCV = HHV - (600 × 9H100)); U is the moisture content, which is equal to 30%; and H is the percentage of hydrogen.

The energy density (ED) was calculated by multiplying the basic density (kg·m^{-3}) by the higher heating value (HHV, kcal·kg^{-1}). Proximate analysis was performed according to ASTM standards E872-82 (Astm, 2013e) for volatile matter (VM) and D1102-84 (Astm, 2013a) for ash content. The fixed carbon (FC) content was calculated by subtracting the sum of the volatile matter and ash contents from 100.

For the elemental analysis, a CHN analyzer (LECO®) was used. The percentages of carbon (C), hydrogen (H), and nitrogen (N) were determined via the TruSpec CHN Micro module. The oxygen (O) composition was calculated by subtracting the sum of the percentages of C, H, N, and ash from 100. The H/C, O/C, and N/C ratios were determined by dividing the percentages of the chemical elements by their respective molecular weights.

The total extractive content was determined following the methodologies described in the technical standards D1105-96 (Astm, 2013b), D1107-96 (Astm, 2013c) and D1110-84 (Astm, 2013d). The process involved extraction using ethanol-toluene (2:1) and ethanol in a Soxhlet apparatus, followed by hot water extraction in a water bath. The total lignin content was calculated as the sum of insoluble lignin (Klason lignin) and soluble lignin, determined according to the methodologies proposed by Gomide & Demuner (1986) and Goldschimid et al. (1971), respectively. The Klason lignin percentage was calculated as the ratio between the mass of insoluble material and the initial wood mass. The soluble lignin content was determined through ultraviolet (UV) spectrometry using the diluted filtrate from the previous procedure. The total lignin content was determined by summing the soluble lignin and Klason lignin contents. The holocellulose content was calculated by subtracting the total extractives and lignin contents from 100.

For the syringyl/guaiacyl (S/G) ratio, we performed pyrolysis via a microfurnace pyrolyzer connected to a GC–MS device (Model QP2020) equipped with an Ultra-ALLOY® capillary column. The analysis followed a methodology adapted from (Barbosa et al., 2008). By determining the percentages of syringyl and guaiacyl, we calculated the ratio between these two types of lignin.

2.3 Statistical analysis

The experiment was set up in a completely randomized design with 11 treatments (clones) and three replications (trees). The results of the measured properties were subjected to analysis of variance (ANOVA), and when significant differences were found, the Scott–Knott test was performed (p-value < 0.05).

A multivariate cluster analysis was conducted to group clones with similar properties, considering the following variables: bark percentage, basic density, total lignin, extractives, ash content, and HHV. The resulting grouping was represented by a dendrogram of similarity. The Euclidean distance was used to standardize the data and adjust the correlations between the variables. The definition of two groups (k = 2) was adopted as the stopping criterion to identify similarities among the clones. The consistency of the dendrogram was verified through the cophenetic correlation coefficient, which reported the calculated Euclidean distances to the original distances between the eucalyptus clones.

All analyses were performed with the aid of R software version 4.4.2.(R Core Team, 2023).

2.4 Case study

To evaluate the influence of energy quality on the costs associated with the use of wood from these eucalyptus clones in grain drying, a case study was conducted focusing on soybean and corn agricultural activities in the state of Mato Grosso.

To estimate the wood volume and firewood cost in agro-industrial processes, the 2022 harvest in Mato Grosso for soybeans and corn was considered, analyzing the factors involved in drying the harvested grains. In the 2022 season, soybean and corn production in the state reached 38,331,222 tons and 38,025,387 tons, respectively, with a cultivated area of 10,924,622 hectares for soybeans and 6,414,777 hectares for corn IBGE data (2024).

The energy required to dry one ton of each grain (EDG) was based on the values established by Bell (2012). For soybeans, the initial moisture content was 22%, the final moisture content 13%, the drying thermal efficiency (DTE) 40%, resulting in an EDG of 757,810 $kJ.kg^{-1}$. For corn, the initial moisture content was 26%, the final moisture content 13%, the DTE was 40%, and the EDG was 1,094,614 $kJ.kg^{-1}$.

The amount of firewood required for drying one ton of each grain type (FDT) for each eucalyptus clone was performed by dividing the EDG by the NCV, considering a moisture content of 30% on a wet basis.

The eucalyptus firewood volume required to dry one ton of soybeans or corn (VFD) was calculated as the relationship between the amount of firewood (FDT) and the basic wood density of each clone evaluated (Table 1).

The total firewood volume required for drying the grains of the 2022 harvest (TVF), in m^3, was determined by dividing the total grain quantity by VFD.

Finally, the overall cost of firewood was calculated by multiplying the total volume (TVF) by the average price of R$133.08 per cubic meter of eucalyptus firewood in Mato Grosso, Brazil (Famasul, 2023), which corresponds to approximately $26.51 USD.

3. RESULTS

3.1 Wood properties of eucalyptus clones

The average bark percentage in the different eucalyptus clones ranged from 5% to 11.04%, with significant differences between them, resulting in the formation of two distinct groups (Figure 1A). The values of basic wood density ranged from 478 to 588 $kg.m^{-3}$, which was also significantly different, and the values were grouped into three groups (Figure 1B).

The clones with the highest values had bark percentages ranging between 7.97% and 11.04%, whereas the other clones had values between 5.00% and 7.32% (Figure 1A). The clones with the highest wood basic density had an average value of 560 $kg.m^{-3}$, which was 6% greater than the average value of the intermediate clones (526 $kg.m^{-3}$). On the other hand, clone 8 presented the lowest basic density (Figure 1B), with an average value of 478 $kg.m^{-3}$, which represents a reduction of 15% compared with that of clones with higher basic density.

There were significant differences in ash content and HHV in the wood of the eucalyptus clones evaluated, while the mean values of MV, FC, and ED were statistically equal (Table 2).

The volatile matter content (VM) was equal to 84.26%, with values ranging from 83.19% to 87.00% (Table 2). The fixed carbon content (FC) had an average value of

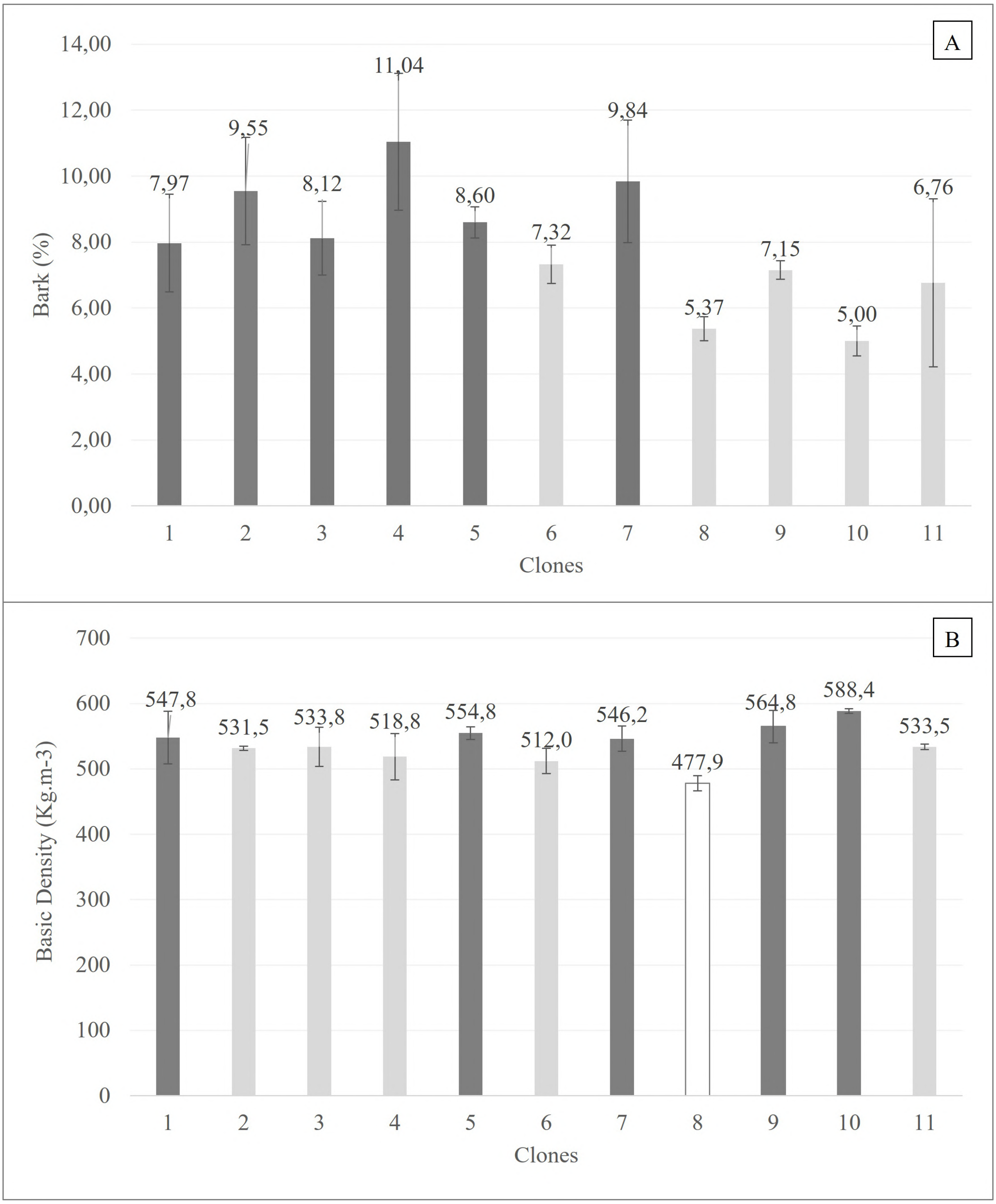

Figure 1. (A) Bark percentage (B) Wood basic density of eucalyptus clones from a clonal test in Mato Grosso, Brazil**.** The different colors represent the groups formed by the Scott–Knott test ($p \leq 0.05$). The error bars indicate the standard deviation.

Figura 1. (A) Percentagem de casca (B) Densidade básica da madeira dos clones de eucalipto de um teste clonal em Mato Grosso, Brasil. As diferentes cores representam os grupos formados pelo teste de Scott–Knott ($p \leq 0,05$). As barras de erro indicam o desvio padrão.

15.62%, with average values between 14.71% and 16.51% (Table 2). There was a significant effect of the clone on the ash content, resulting in the formation of three groups (Table 2). The group represented by clones 4, 5, 6, 7, 9, 10 and 11 presented variations between 0.22 and 0.40%, and these eucalyptus clones having a lower ash

Table 2. Energy characteristics of the wood of the eucalyptus clones of a clonal test in Mato Grosso, Brazil
Tabela 2. Características energéticas da madeira dos clones de eucalipto de um teste clonal em Mato Grosso, Brasil

Clone	MV (%)	FC (%)	Ash (%)	HHV ($kcal.kg^{-1}$)	ED ($Gcal.m^{-3}$)
1	84.09 $^{(1.06)}$ a	15.40 $^{(0.80)}$ a	0.51 $^{(0.27)}$ b	4696.33 $^{(10.75)}$ a	2,57 $^{(0,18)}$ a
2	84.84 $^{(0.69)}$ a	14.71 $^{(0.56)}$ a	0.45 $^{(0.14)}$ b	4639.33 $^{(34.05)}$ b	2.47 $^{(0.01)}$ a
3	83.90 $^{(0.32)}$ a	15.35 $^{(0.28)}$ a	0.74 $^{(0.15)}$ c	4641.67 $^{(28.37)}$ b	2.48 $^{(0.12)}$ a
4	83.64 $^{(0.35)}$ a	15.95 $^{(0.46)}$ a	0.40 $^{(0.11)}$ a	4712.33 $^{(4.54)}$ a	2.44 $^{(0.16)}$ a
5	87.00 $^{(4.02)}$ a	15.25 $^{(0.23)}$ a	0.22 $^{(0.06)}$ a	4609.33 $^{(37.00)}$ b	2.56 $^{(0.06)}$ a
6	84.02 $^{(0.14)}$ a	15.90 $^{(0.11)}$ a	0.26 $^{(0.03)}$ a	4620.83 $^{(7.42)}$ b	2.37 $^{(0.08)}$ a
7	84.67 $^{(0.97)}$ a	15.32 $^{(0.90)}$ a	0.24 $^{(0.11)}$ a	4616.33 $^{(34.27)}$ b	2.52 $^{(0.07)}$ a
8	83.19 $^{(0.96)}$ a	16.35 $^{(0.65)}$ a	0.52 $^{(0.23)}$ b	4661.17 $^{(8.10)}$ b	2.23 $^{(0.05)}$ a
9	83.90 $^{(1.35)}$ a	15.80 $^{(1.36)}$ a	0.30 $^{(0.05)}$ a	4653.00 $^{(18.66)}$ b	2.63 $^{(0.09)}$ a
10	83.20 $^{(0.81)}$ a	16.51 $^{(0.82)}$ a	0.29 $^{(0.04)}$ a	4743.67 $^{(5.97)}$ a	2.79 $^{(0.01)}$ a
11	84.43 $^{(1.34)}$ a	15.24 $^{(1.23)}$ a	0.39 $^{(0.09)}$ a	4652.50 $^{(24.39)}$ b	2.48 $^{(0.02)}$ a
Mean	84.26	15.62	-	-	2.50

VM: volatile matter; FC: fixed carbon; HHV: higher heating value. ED: energy density. Means followed by the same letter in the same column do not differ from each other according to the Scott–Knott test ($p \leq 0.05$); (...): Standard deviation.
VM: materiais voláteis; FC: carbono fixo; HHV: poder calorífico superior. ED: densidade energética. Médias seguidas pela mesma letra na mesma coluna não diferem entre si, de acordo com o teste de Scott–Knott ($p \leq 0,05$); (...): Desvio padrão.

content than the others (Table 2). Clone 3, *E. urophylla*, presented the highest mean ash content (0.70%).

For HHV, most clones presented values below 4680 $kcal.kg^{-1}$, which is approximately 2% lower than the values observed for clones with HHVs between 4696 and 4743 $kcal.kg^{-1}$ (Table 2).

Regarding energy density (ED), no significant differences were observed among the eucalyptus clones evaluated in this study, with values between 2.23 and 2.79 $Gcal.m^{-3}$ and an overall mean of 2.50 $Gcal.m^{-3}$ (Table 2). These values did not follow the variations observed in the basic density (Figure 1B) or in the HHV (Table 2).

There was no significant effect on the elemental composition of the eucalyptus clones, whose mean values were 49.84% C (sd = 0.695), 6.16% H (sd = 0.217), 43.83% O (sd = 0.775) and 0.18% N (sd = 0.098). The H/C, O/C and N/C ratios were statistically equal ($p \leq 0.05$), since the isolated elements also presented similar values. The mean H/C, O/C and N/C ratios were 1.48, 0.66 and 0.0022, respectively.

The holocellulose content ranged between 64.37% and 70.90%, with a significant difference between the clones evaluated. Clones 7, 10 and 11 presented values higher than 69%, whereas the other clones presented an average value of 65.8% (Table 3).

The total extractive content ranged between 3.72% and 7.76%, whereas the total lignin content ranged between 24.32% and 29.76%, both with significant differences between the clones evaluated (Table 3). However, in the eucalyptus clones evaluated, the S/G ratio did not significantly differ, ranging from 1.94 to 3.26, with an overall mean of 2.74 (Table 3).

Figure 2 presents the cluster dendrogram generated for the eucalyptus clones evaluated, considering the main energy characteristics. The cophenetic correlation coefficient was 0.843, which was significant ($p < 0.05$) according to the t test. This finding indicates that the dendrogram obtained is satisfactory and consistent for representing the grouping of the different eucalyptus clones evaluated.

The clones of Group 1 (clones 2, 3, 5, 6, 7, 8, 9 and 11) presented lower or

Table 3. Holocellulose, total extractives, and total lignin contents, and S/G ratio of the woods of eucalyptus clones from a clonal test in Mato Grosso, Brazil
Tabela 3. Teores de holocelulose, extrativos totais e de lignina total e relação S/G das madeiras dos clones de eucalipto de um teste clonal em Mato Grosso, Brasil

Clone	Holocellulose (%)	Total extractives (%)	Total lignin (%)	S/G Ratio
1	65.11 (2.84) b	5.37 (0.43) b	29.50 (3.28) a	2.73 (0.22) a
2	65.88 (3.35) b	4.53 (0.84) b	28.85 (3.76) a	3.13 (0.58) a
3	66.87 (1.03) b	3.73 (0.01) b	29.40 (1.03) a	2.83 (0.39) a
4	66.51 (1.09) b	3.73 (0.81) b	29.76 (1.58) a	2.41 (0.29) a
5	64.37 (2.63) b	6.27 (1.62) a	29.36 (1.06) a	2.60 (0.24) a
6	64.86 (2.07) b	6.44 (0.82) a	28.70 (1.72) a	3.17 (0.08) a
7	69.12 (0.58) a	4.18 (1.35) b	26.71 (1.91) b	3.26 (0.66) a
8	67.40 (2.58) b	4.79 (1.73) b	27.81 (0.85) a	2.68 (0.08) a
9	65.40 (1.00) b	7.76 (1.66) a	26.84 (0.98) b	1.94 (0.61) a
10	69.60 (2.87) a	5.75 (1.52) a	24.64 (3.86) b	2.59 (0.19) a
11	70.90 (3.10) a	4.78 (1.49) b	24.32 (2.15) b	2.84 (0.33) a
Mean	-	-	-	2.74

Means followed by the same letter in a column do not differ from each other, according to the Scott–Knott test ($p \leq 0.05$); (...): Standard deviation of the mean of the different clones evaluated.
Médias seguidas pela mesma letra em uma coluna não diferem entre si, de acordo com o teste de Scott–Knott ($p \leq 0,05$); (...): Desvio padrão da média dos diferentes clones avaliados.

intermediate values for most of the properties evaluated. On the other hand, Group 2 (clones 1, 4 and 10) stood out, in general, in terms of the bark percentage, basic density, HHV, ash content and total lignin properties.

3.2 Case study: Use of eucalyptus firewood for drying grains in Mato Grosso, Brazil

To dry one ton of soybeans, considering firewood with 30% moisture content, between 0.1009 m³ (clone 10) and 0.1267 m³

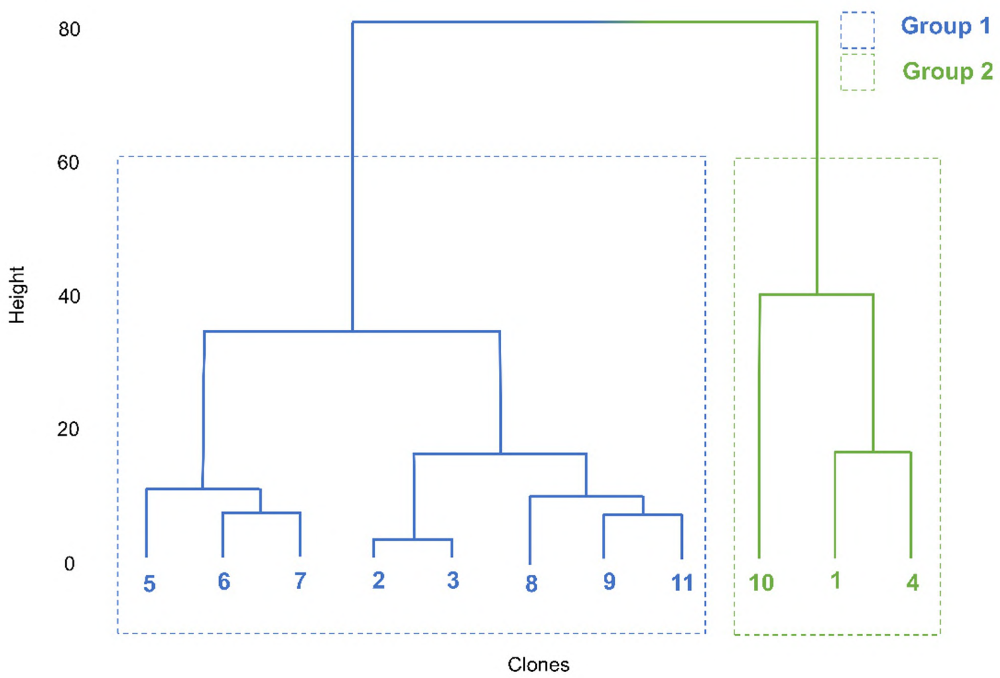

Figure 3. Cluster dendrogram of eucalyptus clones from a clonal test in Mato Grosso, Brazil
Figura 3. Dendrograma de agrupamento dos clones de eucalipto de um teste clonal em Mato Grosso, Brasil

(clone 8) would be required. For the 2022 soybean harvest in Mato Grosso, eucalyptus firewood costs would range from US$ 102.6 million to US$ 128.7 million (Table 4). For drying one ton of corn, the required firewood volume would range from 0.1458 m³ (clone 10) to 0.1830 m³ (clone 8), with estimated costs between US$ 146.9 million and US$ 184.4 million, respectively (Table 4).

Table 4. Wood volume from *Eucalyptus* clones required for drying soybean and corn grains produced in the 2022 harvest in Mato Grosso, Brazil and the total cost value of the firewood, expressed in US$
Tabela 4. Volume de madeira dos clones de *Eucalyptus* necessário para a secagem de grãos de soja e milho produzidos na safra de 2022 em Mato Grosso, Brasil e o valor total do custo da lenha, expresso em US$

Clone	Soybean			Corn		
	VFD (m³)	TVF (m³)	Total cost (US$.million)	VFD (m³)	TVF (m³)	Total cost (US$.million)
1	0.1096	4,201,623	111.4	0.1583	6,020,586	159.6
2	0.1134	4,346,326	115.2	0.1638	6,227,934	165.1
3	0.1138	4,361,930	115.6	0.1644	6,250,293	165.7
4	0.1153	4,420,907	117.2	0.1666	6,334,802	167.9
5	0.1104	4,230,434	112.1	0.1594	6,061,869	160.7
6	0.1190	4,562,420	120,9	0.1719	6,537,579	173.3
7	0.1119	4,290,127	113.7	0.1617	6,147,405	162.9
8	0.1267	4,855,812	128.7	0.1830	6,957,985	184.4
9	0.1075	4,120,548	109.2	0.1553	5,904,411	156.5
10	0.1009	3,869,368	102.6	0.1458	5,544,491	146.9
11	0.1140	4,370,599	115.9	0.1647	6,262,715	166.0
Mean	0.1129	4,330,009	114.8	0.163173	6,204,551	164.5

VFD: volume of firewood required for drying one ton of each grain; TVF: total volume of firewood required for drying the grains of the 2022 harvest in Mato Grosso, Brazil.
VFD: volume de lenha necessário para secar uma tonelada de cada grão; TVF: volume total de lenha necessário para a secagem dos grãos da safra de 2022 em Mato Grosso, Brasil.

4. DISCUSSION

4.1 Wood properties of eucalyptus clones

A lower bark percentage is desirable for direct combustion, as bark contains a higher concentration of minerals compared to wood (Juizo et al., 2017; Neiva et al., 2018). Since inorganic materials contribute to ash and residue formation after combustion, this can affect the operation of the combustion system if residue removal is not properly performed. Clones with lower bark percentages are more suitable for this purpose. Thus, clones 6, 8, 9, 10 and 11, which presented the lowest bark percentage (Figure 1A), stand out for the use of wood in furnaces and dryers in agroindustry.

Pereira et al. (2013) evaluated different 7.5-year-old eucalyptus clones and reported bark percentages between 9% and 17%, whereas Costa et al. (2017) reported values between 15% and 17% for *Eucalyptus camaldulensis* clones of the same age. The higher percentages observed in these studies, compared with the results of the present study (Figure 1A), may be related to the characteristics of the genetic material, as well as to the differences in the edaphic and climatic conditions of the planting sites.

Considering the classification proposed by Csanády et al. (2015), the wood of all eucalyptus clones evaluated in this study falls into the medium-density class (500–750 kg.m^{-3}) (Figure 1B), similar to that normally observed for eucalyptus wood from Brazilian plantations (Ribeiro et al., 2021; Nogueira et al., 2024; Vieira et al., 2024). Protásio et al. (2019), when evaluating eucalyptus clones approximately 7 years old, found values

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ranging from 455 to 570 kg.m -3 were found. The authors state that, in general, clones from crosses with *E. camaldulensis* tend to have higher basic density and, consequently, better energy performance. This relationship was also observed in the present study, especially for Clone 10, a hybrid of *E. urophylla* × *E. camaldulensis*, which presented the highest basic density (Figure 1B).

When density is considered the primary indicator of energy potential in eucalyptus wood, clones with densities ranging from 546 to 588 kg.m³ (Figure 1B) can be regarded as superior. This is because a higher wood density results in a greater amount of energy stored per unit volume (Carneiro et al., 2014). In addition, density directly influences transportation costs, as denser materials reduce the need for greater volume for the same transported weight. Likewise, woods with higher density tend to be more efficient in energy conversion in equipment such as furnaces and boilers (Protásio et al., 2019). Furthermore, determining density is important for logistics planning and wood stock management in agroindustrial combustion systems, as it influences the volume of wood required and the specific wood consumption for energy generation (Leonello et al., 2024).

The clones evaluated exhibited similar trends for volatile matter (VM) and fixed carbon (FC) contents. This absence of significant differences may suggest homogeneous behavior during firing. Notably, VM involves the burning of a material in its gaseous state, and compounds such as hydrogen, hydrocarbons and CO are the main compounds involved in the ignition process of the combustible material (Santos et al. (2011). In practical terms, materials with higher volatile matter (VM) content accelerate the energy release process from biomass, leading to faster ignition. This, in turn, accelerates the oxidation of the combustible material and enhances the intensity of the combustion process. Higher FC values are associated with slower burning, which implies a longer residence time of the biofuel material in the burning equipment, resulting in a longer thermal degradation process.

The average ash values were lower than 0.8% (Table 2), which is in line with the values commonly reported for eucalyptus wood, which are lower than 1% (Juizo et al., 2017; Protásio et al., 2019; Gmach et al., 2023). Thus, the ash content was not considered a limiting factor for burning. This low ash content is advantageous for firing systems, such as those with fixed, fluidized and pulverized feed, which ensure high efficiency in thermal conversion and reduce technical problems related to the formation of scale and corrosion in boilers (Protásio et al., 2019). Materials with lower ash contents are preferable for energy use via combustion because the minerals present in the ash do not contribute to the combustion process, decreasing the energy potential and potentially causing damage to equipment (Soteli et al., 2023).

The HHV represents the maximum amount of energy available in the wood that can be released during combustion (Carneiro et al., 2014). It indicates the energy potential of the clones and, together with moisture content, is an important property for determining the amount of biomass required for thermal processes (Leonello et al., 2024). Clones with higher average HHV values, such as clones 1, 4 and 10 (Table 2), have a greater ability to release energy, making them more advantageous for thermal processes. In addition, these clones directly impact operating costs because, by using materials with higher HHVs, it is possible to reduce wood consumption to generate the same amount of energy. The values observed are in accordance with those normally found for eucalyptus wood (Protásio et al., 2019; Vieira et al., 2023).

Energy density (ED) refers to the amount of energy contained in a specific volume of wood, indicating its energy potential. The higher the ED, the greater the energy released per unit volume of fuel (Jesus et al., 2017). Although no significant differences were found between the clones regarding ED, higher values lead to greater energy production for the same volume of wood. This can directly impact forestry and industrial planning, particularly in relation to biomass stock and consumption by agro-industries.

The elemental composition values are within the ranges reported for eucalyptus wood, indicating a homogeneous pattern in its empirical formula (Neiva et al., 2018; Protásio et al., 2019). Thus, it is not possible to define superior clones for energy use on the basis of only these parameters. However, the elemental composition directly influences the HHV and the gases generated during combustion, which is a relevant factor in the design of combustion systems. For thermal energy generation, clones with higher C and H contents and lower N and O contents are preferable because these elements are positively correlated with HHV (Pereira et al., 2013). Protásio et al. (2011) established that the levels of C and H are positively correlated with VHV. Notably, despite the positive contribution to the HHV, the low percentage of N, equal to 0.18%, has little effect on this property.

The mean values of the H/C, O/C and N/C ratios are in agreement with previous studies on eucalyptus wood for energy purposes (Pereira et al., 2013; Protásio et al., 2019). This finding indicates that, among the clones evaluated in this study, the behavior and combustion products tend to be similar, despite their genetic differences. Lower atomic ratios are desirable for biomass intended for energy generation because they reflect greater efficiency in energy release and lower emission of pollutant gases during combustion (Lima et al., 2020). This contributes to the mitigation of climate impacts.

For energy use, wood with higher lignin content and a lower presence of holocellulose should be prioritized because it has a high oxygen content, which reduces the HHV of the material and generates instability at high temperatures (Vieira et al., 2023). However, holocellulose also influences the ignition and combustion of biomass because of its faster thermal decomposition and the formation of gaseous products during the process (Wang et al., 2020).

Clones 5, 6, 9 and 10 presented relatively high values of total extractives. For the use of biomass as an energy source, materials with a greater presence of extractives are preferable because the thermal degradation of these compounds occurs at high temperatures (250–550 °C) (Protásio et al., 2019). In addition, extractives contain carbon in their composition, which positively contributes to energy yield (Vieira et al., 2023). The clones with the highest mean values of lignin content ranged from 27.81 to 29.76% (Table 3), whereas clones 7, 9, 10 and 11 presented values lower than 27%. A higher lignin content is desirable for wood intended for energy use because lignin contains a higher percentage of carbon in its composition, which contributes to a higher HHV and higher thermal energy yield. In addition to the total amount of lignin, its composition can also influence wood combustion and the duration of its various stages (Protásio et al., 2019). The extractive values observed are similar to those reported for eucalyptus wood (Massuque et al., 2022), as are the total lignin values (Protásio et al., 2019; Massuque et al., 2022; Vieira et al., 2023).

After the global analysis of the firewood properties, cluster grouping revealed that the clones in Group 1 presented lower energy characteristics than those in Group 2 did. However, the clones of Group 1 should not be rejected for energy use, especially in agro-industries that demand greater versatility in the use of biomass. On the other hand, the clones of Group 2, with their superior characteristics, are more suitable for firing systems, offering higher thermal yield. Thus, these clones are more suitable for new forest plantations or breeding programs in Mato Grosso, Brazil, with the aim of optimizing the energy use of wood.

The results obtained in this study demonstrate that the wood of the eucalyptus clones planted under the edaphoclimatic conditions of Mato Grosso exhibits satisfactory properties. These characteristics are comparable to those of genetic materials developed in states with larger eucalyptus plantation areas and, consequently, more extensive research. This finding supports the rational use of biomass and enables the full energy potential of these clones to be harnessed in agro-industrial applications, such as grain dryers and boilers.

4.2 Case study: Use of eucalyptus firewood for drying grains in Mato Grosso, Brazil

The variation in the volumes of firewood required for drying of soybean and corn, as well as the associated costs, stems from differences in the wood properties of the clones, particularly basic density (Figure 1B), which had the greatest influence on the results. Clone 10 showed higher basic density and energy density (ED), resulting in a 20% reduction in firewood consumption for grain drying. This translates into substantial savings, with a cost reduction of up to US$12.2 million for soybean drying and US$17.6 million for corn drying, based on the total 2022 harvest. The savings achieved through the use of superior clones can be reinvested in improvements in both the forestry and agricultural sectors, including plantations and processing facilities.

These results highlight the importance of selecting *Eucalyptus* clones with superior energetic characteristics, such as higher basic density, to optimize thermal yield and reduce operational costs for agro-industries. Furthermore, the analysis of overall firewood expenses, ranging from US$ 102.6 million to US$ 128.7 million for soybean and from US$ 146.9 million to US$ 184.4 million for corn, further emphasizes the economic impact of clone selection.

In addition to reducing the cost of firewood purchase (Table 4), the use of superior clones also lowers transportation expenses, since lower consumption means less wood needs to be transported from the forest to the industry. This benefits the forestry sector, as factors such as wood price, productivity, and harvesting costs, including cutting and transportation, directly affect the profitability of eucalyptus plantations (Moreira et al., 2017).

Beyond the economic aspect, wood from superior clones offers higher energy yield, lower greenhouse gas emissions, and more efficient drying of corn and soybean grains during the first pass through the dryer. However, to fully harness this energy potential, producers must use properly dried firewood, either logs or chips, that are compatible with the combustion system, and adopt operational practices that ensure efficient burning.

5. CONCLUSION

The evaluated *Eucalyptus* clones exhibited characteristics suitable for energy use, with the clone significantly influencing wood properties such as bark percentage, basic density, ash content, higher heating value, and lignin content.

Clones 1, 4 and 10 stand out for their superior energy properties and are recommended for energy use in agro-industry and for new plantations in the state of Mato Grosso.

The use of *Eucalyptus* clones with superior energetic properties can reduce firewood consumption by up to 20% in the drying of corn and soybean grains, resulting in a significant reduction in the operating costs of agribusinesses.

The present study contributes to the selection of clones best suited to the soil and climate characteristics of the state of Mato Grosso, Brazil, and to the expansion of the genetic base of *Eucalyptus* in the state, with a focus on the supply of firewood for agroindustry.

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AUTHOR CONTRIBUTIONS

VTJ: Conceptualization, methodology, investigation, formal analysis, Writing – original draft; CNA: Methodology, investigation, formal analysis; CMC: Methodology, investigation, formal analysis; LLR: Methodology, investigation, formal analysis; ACOC: Methodology, investigation, validation, Writing – review & editing; AMMLC: Methodology, investigation, validation; ACO: Conceptualization, Supervision, Writing – review & editing; BLCP: Conceptualization, Supervision, Resources, Data Curation, Writing – review & editing.

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