

## Article

# Energy Potential and Age-Related Variation in Wood Properties of *Eucalyptus* Clones Grown in Mato Grosso, Brazil

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## Abstract

The growing demand for energy in agro-industrial systems has increased the need for forest biomass in regions of expanding commercial forestry, such as Mato Grosso State, Brazil. However, information on how genetic material and harvest age influence the energy properties of eucalyptus wood under local edaphoclimatic conditions remains limited. This study evaluated the energy potential of wood from different eucalyptus clones and harvest ages intended for industrial combustion in Mato Grosso. Clones H13, VM01, and H15 were assessed at 54 months of age. To investigate the effect of harvest age, clone VM01 was also evaluated at 54, 108, and 144 months. All samples were collected from a commercial plantation located in Brasnorte, Mato Grosso, Brazil. Morphological, physical, chemical, and energy-related wood properties were determined. Among the evaluated clones, VM01 showed the highest energy potential, with energy production reaching 674.62 Gcal ha<sup>-1</sup>, approximately 53% higher than H15. Clone H13 presented the highest lignin and fixed carbon contents, while H15 exhibited the highest extractives content. Regarding harvest age, wood maturation led to increases in basic density (15.9%), extractives content, and fixed carbon content, along with reductions in ash content, volatile matter, and the elemental ratios H/C, N/C, and O/C, indicating a gradual improvement in biomass energy quality with increasing harvest age. These results provide technical support for clone selection and harvest age optimization, contributing to more efficient use of eucalyptus wood as a renewable energy source in tropical regions where commercial forestry is expanding.

**Keywords:** forest biomass; bioenergy production; basic density; wood chemical composition; fast-growing plantations



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## 1. Introduction

The search for renewable energy sources has intensified due to the need to ensure energy security and mitigate the impacts of climate change. In this context, diversification

of the energy matrix has become essential, given the vulnerability of sources such as hydropower, wind, and solar energy to climatic variability [1]. Forest biomass stands out because of its supply predictability, storability, and management flexibility, making it a reliable alternative for continuous energy generation [2]. Biomass currently accounts for approximately 14% of global energy consumption, reaching 38% in developing countries and 49.1% in Brazil, where its use is concentrated mainly in the industrial sector [3].

Fast-growing forest plantations play a prominent role in biomass production, particularly those of the genus *Eucalyptus* L., which are widely established due to their high productivity, adaptability to diverse edaphoclimatic conditions, and multiple end uses [4,5]. In Brazil, eucalyptus plantations cover approximately 8.1 million hectares, representing nearly 77% of the total planted forest area, with continuous expansion over recent decades [6]. Their use for energy purposes occurs mainly through direct combustion of firewood and charcoal production, accounting for a substantial share of the country's wood consumption.

*Eucalyptus* stands out for its high productivity, reaching up to  $41.3 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ , as well as its short rotation cycles, averaging approximately 7.2 years, factors that enhance its competitiveness as a biomass feedstock for energy production [6]. In addition to productivity, wood technological properties, particularly density, are commonly used as criteria for selecting species and clones for energy applications [7]. Previous studies have reported basic density values ranging from  $0.41$  to  $0.56 \text{ g cm}^{-3}$  under different growing conditions and harvest ages [7–10].

Other attributes should also be considered, including higher heating value (HHV), chemical composition (lignin, holocellulose, and extractives contents), and proximate analysis (fixed carbon, volatile matter, and ash contents), aiming at the selection of genotypes with superior energy performance [11–13]. However, genetic and environmental factors influence these properties, resulting in significant variations among clones, harvest ages, and cultivation conditions [10,13,14].

The interaction between genotype and environment is a key factor influencing forest productivity and wood quality, particularly in frontier forestry regions such as the Brazilian Midwest, where edaphoclimatic conditions differ substantially from those of traditional eucalyptus-growing areas [15,16]. The region is predominantly characterized by a tropical savanna climate (Aw), with rainfall concentrated during the summer and a pronounced dry season during winter, resulting in extended periods of water deficit despite relatively high annual precipitation. In addition, the predominant soils are generally acidic and exhibit low natural fertility, particularly with respect to phosphorus and exchangeable base cations [17–19], which may constrain forest growth and biomass production.

In this context, the state of Mato Grosso has experienced increasing demand for forest biomass, driven by the agribusiness sector and the growing need for thermal energy in industrial processes such as grain drying and corn ethanol production. Mato Grosso plays a strategic role in both the Brazilian economy and global food security, having established itself as one of the country's leading agricultural commodity-producing regions. As Brazil's largest grain-producing state, particularly for soybean, corn, and cotton, Mato Grosso accounts for approximately 28% of the national grain production [20,21] and contributes significantly to Brazil's position as the world's leading soybean producer [22]. This prominent role increases the demand for renewable and competitive energy sources to supply regional agro-industries, reinforcing the importance of forest biomass as a sustainable alternative for the energy needs of the sector.

In this context, the availability of forest biomass becomes strategic to meet the energy demand associated with agribusiness and industrial activities in the state. Although Mato Grosso still has a smaller planted forest area than the Southern and Southeastern regions of Brazil, it holds considerable potential for forest biomass production. In 2024,

the state accounted for more than 230 thousand hectares of eucalyptus plantations, most of which were dedicated to bioenergy production [6]. However, the expansion of forest plantations has often relied on clones developed for other regions, reinforcing the need for evaluations under local growing conditions. Previous studies have shown that genetic materials exhibiting superior performance in specific environments may respond differently when cultivated under new conditions, highlighting the importance of regional research to support the recommendation of better-adapted clones [23].

In addition to genetic factors, harvesting age directly influences wood properties. Anatomical, physical, and chemical changes occur throughout tree development, affecting characteristics such as wood density, lignin content, and HHV [24,25]. Nevertheless, harvest age is still frequently determined based on maximizing wood volume, often disregarding wood quality attributes. In Mato Grosso, this issue is particularly relevant, as the growing demand for biomass has led both to the premature harvesting of forest stands and to the maintenance of plantations beyond the optimal rotation age, driven by operational and market-related factors [26]. However, the impact of extending the rotation cycle beyond 100 months on the chemical and energy properties of clones cultivated under the specific conditions of the Mato Grosso Cerrado remains poorly understood. This knowledge gap limits the optimization of industrial processes that require high thermal stability and predictable biomass quality.

A comprehensive assessment of genetic material and harvesting age is essential to understand how the energy performance of eucalyptus wood varies under specific growing conditions. Evaluating these factors simultaneously allows the estimation of energy yield per unit area and supports the optimization of forest management and industrial biomass utilization, contributing to greater efficiency throughout the production chain. Given the need to identify genetic materials adapted to local edaphoclimatic conditions and to understand the dynamics of wood maturation over time, this study focused on three commercial eucalyptus clones that represent the genetic materials most widely planted and commercialized in the state of Mato Grosso. Their selection was based not only on their commercial relevance but also on the availability of commercial-scale plantations provided by the partner forestry company, enabling the evaluation of materials currently used by the regional forest-based industry. Considering that the objective of this study was to generate information applicable to commercial forestry, prioritizing the evaluation of commercially deployed genetic materials provides results with greater practical relevance than studies restricted to experimental genotypes. Accordingly, the study evaluated the energy potential of the commercial eucalyptus clones *Eucalyptus grandis* W.Hill ex Maiden  $\times$  *Eucalyptus urophylla* S.T.Blake (H13), *Eucalyptus urophylla*  $\times$  *Eucalyptus camaldulensis* Dehnh. (VM01), and *Eucalyptus grandis*  $\times$  *Eucalyptus urophylla* (H15) at 54 months of age, considering their wood quality and energy-related properties for industrial combustion applications in Mato Grosso, Brazil. In addition, the effect of age on the energy-related properties of *Eucalyptus urophylla*  $\times$  *Eucalyptus camaldulensis* (VM01) wood was assessed by comparing trees at 54, 108, and 144 months of age.

## 2. Materials and Methods

### 2.1. Study Site and Material Collection

Three eucalyptus clones were evaluated at 54 months of age: *Eucalyptus grandis*  $\times$  *Eucalyptus urophylla* (H13), *Eucalyptus urophylla*  $\times$  *Eucalyptus camaldulensis* (VM01), and *Eucalyptus grandis*  $\times$  *Eucalyptus urophylla* (H15). Additionally, age effects were assessed for the *Eucalyptus urophylla*  $\times$  *Eucalyptus camaldulensis* (VM01) clone at 54, 108, and 144 months. These clones were selected because they are among the most widely planted genetic materials in the state of Mato Grosso [22].

The study was carried out in commercial eucalyptus plantations owned by Grupo Mônica (Figure 1), established at a spacing of  $3.5 \times 2.5$  m and located in the municipality of Brasnorte, Mato Grosso State, Brazil ( $13^{\circ}11'29.89''$  S;  $57^{\circ}59'9.63''$  W). According to the Köppen climate classification, the region has an Aw climate (tropical savanna climate), characterized by a rainy summer season and a dry winter season. The mean annual temperature is  $26.1^{\circ}\text{C}$ . The warmest months are September and October, with an average temperature of  $28.6^{\circ}\text{C}$ , whereas the coolest months are June ( $24.9^{\circ}\text{C}$ ) and July ( $24.7^{\circ}\text{C}$ ). Mean annual precipitation is 1991.6 mm, concentrated mainly between December and March, with February being the wettest month (375.9 mm). In contrast, the driest period occurs between June and August, with July presenting the lowest precipitation (3.6 mm) [27].

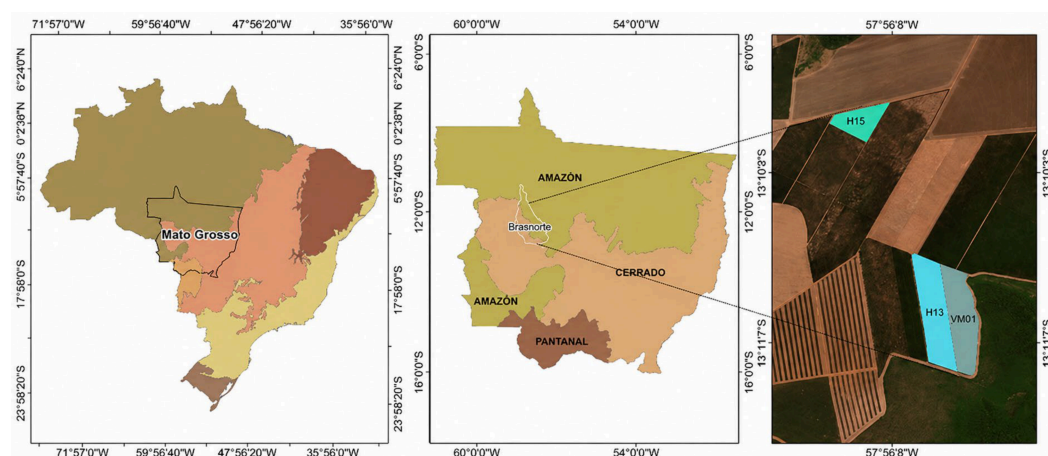


**Figure 1.** Geographic location of the study area and the commercial eucalyptus plantation stands where trees were sampled in Brasnorte, Mato Grosso State, Brazil.

A total of five trees per treatment (clone and/or age) were randomly selected within each stand, excluding border trees and individuals showing signs of diseases, pest attack, or visible defects. Prior to felling, diameter at breast height (DBH) was measured for all selected trees. After harvesting, total height and commercial height were determined (Table 1). Subsequently, wood discs approximately 5 cm thick were collected along the stem at 0, 25, 50, 75, and 100% of the commercial height, the latter corresponding to a stem diameter of 5 cm.

**Table 1.** Mean values of the dendrometric variables of selected trees from three *Eucalyptus* clones at 54 months of age and of clone VM01 at 54, 108, and 144 months in Brasnorte, Mato Grosso, Brazil.

| <i>Eucalyptus</i> clones at 54 months of age               |              |              |              |
|------------------------------------------------------------|--------------|--------------|--------------|
| Clones                                                     | DBH (cm)     | TH (m)       | CH (m)       |
| <i>E. grandis</i> × <i>E. urophylla</i> (H13 clone)        | 16.87 (0.93) | 20.14 (0.68) | 18.10 (0.49) |
| <i>E. urophylla</i> × <i>E. camaldulensis</i> (VM01 clone) | 19.93 (2.20) | 21.84 (1.07) | 20.01 (0.80) |
| <i>E. urophylla</i> × <i>E. grandis</i> (H15 clone)        | 17.70 (1.39) | 18.42 (0.36) | 16.76 (0.49) |
| Clone VM01 at different ages                               |              |              |              |
| Age (months)                                               | DBH (cm)     | TH (m)       | CH (m)       |
| 54                                                         | 19.93 (2.20) | 21.84 (1.07) | 20.01 (0.80) |
| 108                                                        | 25.78 (2.17) | 26.50 (0.99) | 24.84 (1.04) |
| 144                                                        | 32.59 (1.85) | 30.08 (1.13) | 28.20 (1.36) |

DBH: diameter at breast height; TH: total height; CH: commercial height; values in parentheses indicate the standard deviation (SD).

## 2.2. Sample Preparation

After air-drying under ambient conditions (approximately 25 °C and 60% relative humidity), the discs were sanded using a belt sander fitted with 80-grit sandpaper to improve the visualization of the bark, sapwood, and heartwood boundaries. The disc surfaces were then brushed twice with a 0.4% (*w/v*) methyl yellow ( $C_{14}H_{15}N_3$ ; Sigma-Aldrich, St. Louis, MO, USA) solution prepared in absolute ethanol (100%). The stain was allowed to react for 24 h under ambient conditions before image acquisition. Due to the pH differences between heartwood and sapwood, the heartwood exhibited a pink coloration, whereas the sapwood turned yellow. Subsequently, all discs were photographed under standardized conditions using the same camera, fixed shooting distance, and uniform lighting. A 0.5-cm scale bar was included in each image to allow calibration and ensure accurate measurements of bark, sapwood, and heartwood proportions.

For each disc, a diametrical strip 3 cm wide encompassing the entire diameter (bark–pith–bark) was delineated. Two parallel lines were drawn equidistant from the pith, 1.5 cm on either side of the center. This strip was subsequently divided into radial subsamples corresponding to 0%–33%, 34%–66%, and 67%–100% of the radius in the pith-to-bark direction, as illustrated in Figure 2. These subsamples were used for basic density determination.

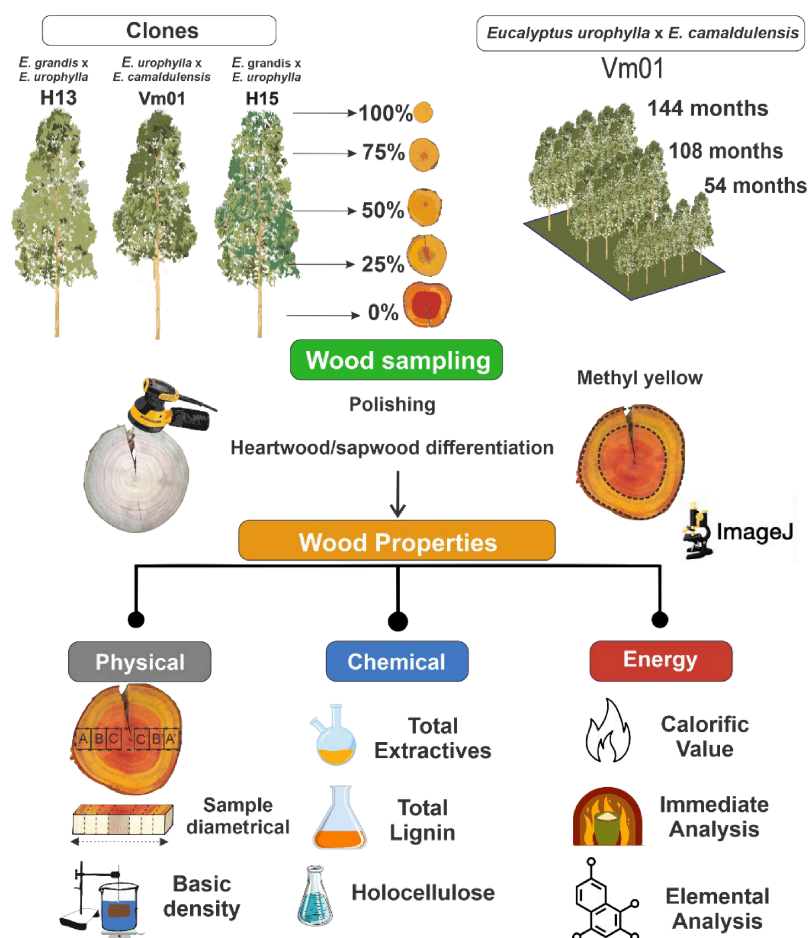


**Figure 2.** Flowchart of the experimental procedures used to evaluate the wood properties of three *Eucalyptus* clones at 54 months of age and of clone VM01 (54, 108, and 144 months), in Brasnorte, Mato Grosso, Brazil. (Note: the explicit radial sampling in the pith-to-bark direction: 0%–33%, 34%–66%, and 67%–100%).

For the remaining analyses, wood shavings were obtained by drilling the discs with a bench drill press in regions outside the diametrical strip. The resulting material was

milled in a Wiley mill (MA680, Marconi, Piracicaba, SP, Brazil) and sieved. The fraction retained between the 40- and 60-mesh sieves (corresponding to particle sizes between 0.40 and 0.25 mm) was used for chemical composition analysis, proximate analysis, and HHV determination. The fraction passing through the 60-mesh sieve was used for ultimate analysis. For all analyses, a composite sample was prepared from each tree.

### 2.3. Wood Properties

The percentages of bark, sapwood, and heartwood in each disc were determined from digital images using ImageJ software, version 1.54k [28]. Total cross-sectional area, area without bark, and heartwood area were measured. The proportions of bark, sapwood, and heartwood were calculated based on the relationships among these areas, and weighted mean values were subsequently obtained for each tree.

Basic wood density was determined using samples collected from the diametrical strip along the pith-to-bark direction. Six specimens were obtained from each disc, corresponding to three samples per radius (Figure 2). Density was determined by the water displacement method according to ABNT NBR 11941 [29]. Radial and longitudinal variations in basic density were also evaluated.

Higher heating value (HHV) was determined according to ASTM E711-23 [30] using an adiabatic bomb calorimeter (C-200, IKA, Staufen, Baden-Württemberg, Germany).

Proximate analysis was performed according to ASTM E872-19 [31] for volatile matter and ASTM D1102-84 [32] for ash content. Fixed carbon content was calculated by difference.

Ultimate analysis was conducted using a CHN elemental analyzer (TruSpec Micro, LECO Corporation, St. Joseph, MI, USA) to determine carbon, hydrogen, nitrogen, and sulfur contents. Oxygen content was calculated by difference, and the H/C, O/C, and N/C atomic ratios were calculated based on the molecular weights of the respective elements.

Structural chemical composition was determined through the quantification of total extractives (ASTM D1105-21, ASTM D1107-21, and ASTM D1110-21) [33–35], insoluble lignin (modified Klason method), and soluble lignin (spectrophotometric method). Holocellulose content was calculated by difference.

### 2.4. Estimation of Wood Volume and Energy Density

Estimates of wood volume, energy density, energy yield per hectare, and equivalence with fossil fuels were performed exclusively for the clone comparison experiment conducted at 54 months of age.

Individual tree volume was estimated using the Smalian method, considering four sections along the commercial stem height divided into 25% intervals (0%–25%, 25%–50%, 50%–75%, and 75%–100%). The cross-sectional areas at the ends of each section were calculated from stem diameters measured at 0%, 25%, 50%, 75%, and 100% of the commercial height and converted into disk area ( $\text{m}^2$ ). The volume of each section was obtained by multiplying the mean cross-sectional area of the two ends by the corresponding section length (one-fourth of the commercial height). Total tree volume was calculated as the sum of the volumes of the four sections. Wood volume per hectare was estimated by multiplying the mean tree volume by the planting density ( $1142.85 \text{ trees ha}^{-1}$ ).

Volumetric energy density ( $\text{Gcal m}^{-3}$ ) was calculated as the product of higher heating value ( $\text{kcal kg}^{-1}$ ) and basic wood density ( $\text{kg m}^{-3}$ ). Energy yield per hectare ( $\text{Gcal ha}^{-1}$ ) was obtained by multiplying volumetric energy density by wood volume per hectare ( $\text{m}^3 \text{ ha}^{-1}$ ) for each clone.

The energy equivalence between wood and fossil fuels (diesel oil, natural gas, liquefied petroleum gas (LPG), and coal) was estimated by dividing the energy contained in  $1 \text{ m}^3$  of wood ( $\text{kcal m}^{-3}$ ) by the higher heating value of each fuel. HHVs obtained from official

sources were adopted: diesel oil ( $10,750 \text{ kcal kg}^{-1}$ ), natural gas ( $9400 \text{ kcal m}^{-3}$ ), LPG ( $11,750 \text{ kcal kg}^{-1}$ ), and coal ( $6000 \text{ kcal kg}^{-1}$ ) [3].

### 2.5. Statistical Analysis

Experiment I, designed to evaluate the three eucalyptus clones (H13, VM01, and H15) at 54 months of age, was conducted in a completely randomized design (CRD), with three treatments (clones) and five replicates (trees). Experiment II, aimed at evaluating the effect of age on clone VM01, was also conducted in a CRD, with three treatments (54, 108, and 144 months) and five replicates (trees).

The tree was considered the experimental unit in both experiments. For morphological characterization, five discs were collected from each tree at different longitudinal positions along the stem, allowing the assessment of longitudinal variation. For basic wood density determination, six samples were obtained from each disc, representing radial and longitudinal positions within the stem.

Proximate analysis was performed in triplicate, and structural chemical analyses were conducted in duplicate for each tree. HHV and ultimate analysis were determined for four trees per treatment, with analytical replicates performed for each sample.

The tree was considered the experimental unit for all statistical analyses. Model assumptions were considered satisfied when  $p > 0.05$ . For both experiments, data were analyzed using one-way analysis of variance (ANOVA), considering clone (Experiment I) or tree age (Experiment II) as fixed effects. The ANOVA model included treatment and residual error, with degrees of freedom of 2 and 12, respectively. Treatment means were compared using Tukey's test at  $p \leq 0.05$ . For Experiment II, linear regression models were additionally fitted using the mean values of the three sampling ages (54, 108, and 144 months) to describe age-related trends in wood properties. Because only three sampling ages were available, the fitted equations and coefficients of determination ( $R^2$ ) were used as descriptive indicators of these trends rather than predictive models, and formal residual diagnostics were not emphasized due to the limited residual degrees of freedom. All statistical analyses were performed using R software version 4.5.2 [36].

## 3. Results and Discussion

### 3.1. Experiment I: Wood Properties Among Eucalyptus Clones at 54 Months of Age

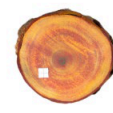
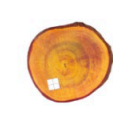
Visual assessment of the stem discs showed that sapwood corresponded to the lighter-colored region of the radial section, whereas heartwood exhibited a darker coloration and greater contrast in discs collected below 50% of the commercial stem height (Table 2). The mean percentages of bark (10.7%), sapwood (66.1%), and heartwood (34.5%) did not differ significantly among the evaluated clones ( $p > 0.05$ ).

The bark proportion exhibited a similar longitudinal distribution among the three clones, with higher values at the stem base, a reduction at 25% of the commercial height, and a gradual increase toward the top of the stem. This pattern is consistent with the protective role of bark at the stem base against biotic and abiotic stresses and with the greater relative contribution of bark in the upper stem, where xylem development is less advanced and juvenile wood predominates [37]. The bark proportions observed in the present study are consistent with values reported for different *Eucalyptus* species and clones under a range of ages and growing conditions [38,39].

Although no significant differences were detected among clones, VM01 exhibited the lowest bark proportions throughout the stem. This characteristic may be related to its greater tree growth, as larger trees generally display a lower relative bark proportion due to increased secondary xylem production [37]. For biomass energy production, this characteristic is advantageous because bark generally presents higher ash content and

lower HHV than wood [40]. Therefore, the bark proportions observed in the evaluated clones do not represent a limitation for energy use.

**Table 2.** Longitudinal variation in bark, heartwood, and sapwood proportions along the commercial stem of eucalyptus clones at 54 months of age in Brasnorte, Mato Grosso, Brazil.

| Clone | Parameter | Longitudinal Position                                                               |                                                                                      |                                                                                       |                                                                                       |                                                                                       |
|-------|-----------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
|       |           | 0%                                                                                  | 25%                                                                                  | 50%                                                                                   | 75%                                                                                   | 100%                                                                                  |
| H13   | Bark      | 13.1 (0.78)                                                                         | 8.4 (0.84)                                                                           | 10.9 (1.03)                                                                           | 13.6 (2.21)                                                                           | 15.3 (0.74)                                                                           |
|       | SW        | 54.9 (3.36)                                                                         | 66.7 (4.29)                                                                          | 92.0 (10.90)                                                                          | 100.0 (0.00)                                                                          | 100.0 (0.00)                                                                          |
|       | HW        | 45.1 (3.36)                                                                         | 33.3 (4.29)                                                                          | 8.0 (10.90)                                                                           | 0.0 (0.00)                                                                            | 0.0 (0.00)                                                                            |
|       | Photo     |    |    |    |    |    |
|       |           |                                                                                     |                                                                                      |                                                                                       |                                                                                       |                                                                                       |
| VM01  | Bark      | 11.0 (0.50)                                                                         | 8.0 (0.73)                                                                           | 9.9 (1.83)                                                                            | 12.4 (0.76)                                                                           | 12.1 (0.99)                                                                           |
|       | SW        | 54.7 (1.67)                                                                         | 68.8 (3.44)                                                                          | 82.7 (9.52)                                                                           | 89.8 (20.35)                                                                          | 97.9 (4.12)                                                                           |
|       | HW        | 45.3 (1.67)                                                                         | 31.2 (3.44)                                                                          | 17.3 (9.52)                                                                           | 10.2 (20.35)                                                                          | 2.1 (4.12)                                                                            |
|       | Photo     |    |    |    |    |    |
|       |           |                                                                                     |                                                                                      |                                                                                       |                                                                                       |                                                                                       |
| H15   | Bark      | 11.5 (0.94)                                                                         | 8.6 (0.18)                                                                           | 10.5 (0.57)                                                                           | 13.6 (1.35)                                                                           | 15.0 (1.15)                                                                           |
|       | SW        | 51.5 (2.17)                                                                         | 61.9 (3.84)                                                                          | 90.2 (8.54)                                                                           | 100.0 (0.00)                                                                          | 100.0 (0.00)                                                                          |
|       | HW        | 48.5 (2.17)                                                                         | 38.1 (3.84)                                                                          | 9.8 (8.54)                                                                            | 0.0 (0.00)                                                                            | 0.0 (0.00)                                                                            |
|       | Photo     |  |  |  |  |  |
|       |           |                                                                                     |                                                                                      |                                                                                       |                                                                                       |                                                                                       |

SW = Sapwood; HW = Heartwood; values in parentheses indicate the standard deviation (SD).

Sapwood proportion increased toward the top of the stem, whereas heartwood showed the opposite trend, reflecting the progressive reduction in heartwood formation with increasing stem height. VM01 was the only clone in which heartwood was detected at 75% and 100% of the commercial height (Table 2), suggesting greater longitudinal extension of heartwood compared with H13 and H15. Although heartwood formation is influenced by tree age, genetic differences in growth rate and cambial activity may also affect its onset and distribution within the stem [41].

The heartwood-to-sapwood ratio (H/S) averaged 0.6 and approached zero in the upper portions of the stem, confirming the predominance of sapwood in these young trees [42]. The slightly greater heartwood occurrence observed in VM01 is consistent with its wider longitudinal heartwood distribution, whereas H13 and H15 remained predominantly composed of sapwood. For energy applications, low H/S ratios are considered favorable because sapwood exhibits higher permeability, facilitating wood drying, reducing moisture content, and improving combustion efficiency [43]. Therefore, the predominance of sapwood observed in all evaluated clones indicates favorable potential for biomass production under short-rotation management systems.

Mean basic wood density differed significantly among clones ( $p \leq 0.05$ ) (Figure 3A), with H13 and H15 exhibiting higher values than VM01. The densities observed fall within the range commonly reported for *Eucalyptus* clones grown under different environmental conditions and ages [44,45].

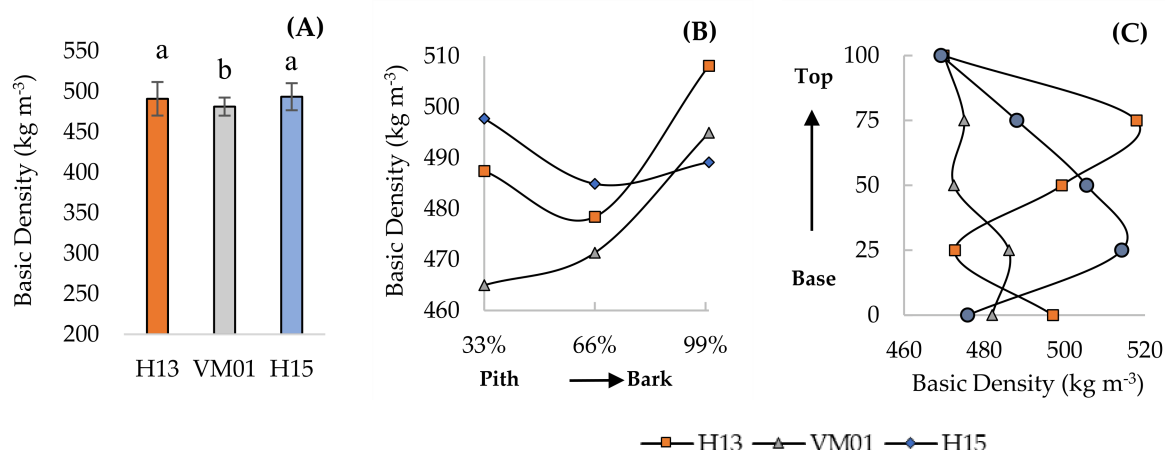


**Figure 3.** Basic wood density of the H13, VM01, and H15 eucalyptus clones at 54 months of age in Brasnorte, Mato Grosso, Brazil: (A) weighted mean basic density; (B) radial variation (33%, 66%, and 99% of the radius); and (C) longitudinal variation (0%, 25%, 50%, 75%, and 100% of commercial stem height). In panel A, means followed by the same letter do not differ significantly according to Tukey's test ( $p \leq 0.05$ ). Error bars represent standard deviation.

The observed values are consistent with the age of the stand (54 months of age), although they remain below the values generally recommended for energy applications. It should be noted that basic density tends to increase during the early years of growth due to anatomical changes associated with the transition from juvenile to mature wood [46,47]. Therefore, the values observed mainly reflect the physiological stage of tree development.

The clones exhibited distinct radial and longitudinal patterns of basic density variation (Figure 3B,C), highlighting the combined influence of genetic, anatomical, and environmental factors on wood formation [48]. In the radial direction, H13 and VM01 showed an increasing trend in density from pith to bark, whereas H15 exhibited an initial decrease followed by stabilization toward the bark. Along the longitudinal direction, the three clones displayed different patterns of basic density variation from the base to the top of the commercial stem.

Because the trees were only 54 months old, the wood evaluated was predominantly juvenile, indicating that these differences are more likely associated with genotype-dependent xylem development during early growth than with the transition from juvenile to mature wood. Variations in fiber wall thickness, fiber lumen diameter, and vessel proportion affect the amount of cell-wall material per unit volume and are recognized as major determinants of basic wood density in *Eucalyptus* [49,50]. Accordingly, the increasing density observed in H13 and VM01 may reflect progressive anatomical changes during juvenile xylem formation, whereas the behavior of H15 suggests a distinct genotype-specific developmental trajectory. Although anatomical traits were not directly measured in this study, previous research supports the interpretation that genetic differences in xylem anatomy contribute substantially to density variation among juvenile *Eucalyptus* clones.

Basic density is one of the most important properties for the energetic utilization of wood because it is directly related to the amount of energy stored per unit volume and to biomass transportation and storage efficiency. Consequently, forest breeding programs aimed at industrial applications generally seek materials with basic density values above  $0.500 \text{ g cm}^{-3}$ , while values exceeding  $0.540 \text{ g cm}^{-3}$  are considered desirable for energy purposes [51]. Although the values observed in the present study were below this threshold, they are consistent with the age of the stand and are expected to increase as the trees mature. Clones H13 and H15 showed an advantage over VM01 due to their higher mean

density. Conversely, VM01 exhibited lower longitudinal variation, a characteristic that may contribute to greater wood uniformity and improved industrial processing performance.

Carbon, hydrogen, and oxygen contents, as well as the H/C and O/C ratios, did not differ among the evaluated clones ( $p \geq 0.05$ ) (Table 3). Significant differences were observed only for nitrogen and sulfur contents ( $p \leq 0.05$ ), with clone H15 presenting the lowest nitrogen content and H13 the lowest sulfur content.

**Table 3.** Elemental composition, structural chemical composition, proximate analysis, and higher heating value of wood from eucalyptus clones at 54 months of age in Brasnorte, Mato Grosso, Brazil.

| Parameter                    | Clones                     |                            |                            | Mean                     |
|------------------------------|----------------------------|----------------------------|----------------------------|--------------------------|
|                              | H13                        | VM01                       | H15                        |                          |
| C (%)                        | 50.70 a <sup>(0.18)</sup>  | 50.55 a <sup>(0.21)</sup>  | 50.60 a <sup>(0.14)</sup>  | 50.62 <sup>(0.08)</sup>  |
| H (%)                        | 6.51 a <sup>(0.03)</sup>   | 6.47 a <sup>(0.06)</sup>   | 6.54 a <sup>(0.15)</sup>   | 6.51 <sup>(0.04)</sup>   |
| N (%)                        | 0.05 a <sup>(0.01)</sup>   | 0.06 a <sup>(0.00)</sup>   | 0.02 b <sup>(0.00)</sup>   | -                        |
| S (%)                        | 0.05 b <sup>(0.01)</sup>   | 0.07 a <sup>(0.01)</sup>   | 0.08 a <sup>(0.01)</sup>   | -                        |
| O (%)                        | 42.36 a <sup>(0.21)</sup>  | 42.46 a <sup>(0.26)</sup>  | 42.38 a <sup>(0.22)</sup>  | 42.40 <sup>(0.05)</sup>  |
| H/C                          | 1.5396 a <sup>(0.00)</sup> | 1.5365 a <sup>(0.01)</sup> | 1.5516 a <sup>(0.04)</sup> | 1.5426 <sup>(0.01)</sup> |
| N/C                          | 0.0008 a <sup>(0.00)</sup> | 0.0010 a <sup>(0.00)</sup> | 0.0004 b <sup>(0.00)</sup> | 0.0007 <sup>(0.00)</sup> |
| O/C                          | 0.6266 a <sup>(0.01)</sup> | 0.6299 a <sup>(0.01)</sup> | 0.6281 a <sup>(0.00)</sup> | 0.6282 <sup>(0.00)</sup> |
| Total extractives (%)        | 4.68 b <sup>(0.40)</sup>   | 2.39 c <sup>(0.47)</sup>   | 5.44 a <sup>(0.99)</sup>   | -                        |
| Total lignin (%)             | 36.21 a <sup>(0.89)</sup>  | 33.40 b <sup>(0.44)</sup>  | 32.42 b <sup>(1.11)</sup>  | -                        |
| Holocellulose (%)            | 58.68 b <sup>(1.27)</sup>  | 63.81 a <sup>(0.73)</sup>  | 61.75 a <sup>(1.74)</sup>  | -                        |
| Volatile matter (%)          | 83.44 a <sup>(0.79)</sup>  | 83.94 a <sup>(0.75)</sup>  | 84.10 a <sup>(0.84)</sup>  | 83.83 <sup>(0.35)</sup>  |
| Ash (%)                      | 0.40 a <sup>(0.09)</sup>   | 0.38 a <sup>(0.09)</sup>   | 0.39 a <sup>(0.04)</sup>   | 0.39 <sup>(0.01)</sup>   |
| Fixed carbon (%)             | 16.22 a <sup>(0.69)</sup>  | 15.68 ab <sup>(0.74)</sup> | 15.51 b <sup>(0.86)</sup>  | -                        |
| HHV (kcal kg <sup>-1</sup> ) | 4717 b <sup>(53.27)</sup>  | 4828 a <sup>(69.16)</sup>  | 4795 ab <sup>(62.67)</sup> | -                        |

HHV = Higher heating value. Means followed by the same letter within a row are not significantly different according to Tukey's test ( $p \leq 0.05$ ). Values in parentheses indicate the standard deviation (SD).

Overall, the values obtained were similar to those reported for *Eucalyptus* clones grown under different ages and cultivation conditions [44,52,53]. The low variation observed among clones was expected, since the wood ultimate composition tends to remain relatively stable among genetic materials of the same species and age [24].

The carbon and hydrogen contents are directly associated with the energy potential of biomass, whereas low nitrogen and sulfur contents are desirable because they reduce the formation of nitrogen oxides (NO<sub>x</sub>) and sulfur dioxide (SO<sub>2</sub>) during combustion [44,54]. In this regard, all clones exhibited N and S concentrations below the limits generally considered suitable for energy biomass, indicating a low potential for pollutant emissions and reinforcing the suitability of the wood for energy applications.

The elemental ratios showed a similar pattern among the clones, except for the N/C ratio (Table 3), and were within the range reported for *Eucalyptus* wood used for bioenergy production [53]. Lower H/C and O/C ratios are generally associated with a higher degree of carbon condensation and lower oxygen availability in the fuel, resulting in greater thermal stability, higher energy density, and improved combustion performance [55]. During thermal conversion, biomass with lower O/C ratios tends to release fewer oxygenated volatile compounds during the initial stages of decomposition, reducing energy losses associated with devolatilization. Likewise, lower H/C ratios indicate a greater proportion of condensed carbon structures, which contribute to a more sustained heat release during the oxidation of fixed carbon, improving combustion efficiency and fuel stability [55]. Although thermogravimetric analyses were not performed in the present study, previous investigations have demonstrated that fuels with lower H/C and O/C ratios generally ex-

hibit slower devolatilization, higher char yields, and a greater contribution of fixed-carbon combustion to the total energy released [55]. In addition, the low N/C ratios observed for all clones indicate a reduced potential for NO<sub>x</sub> formation during combustion. Together with the low sulfur contents, these characteristics reinforce the suitability of the evaluated genetic materials for bioenergy production.

The contents of extractives, lignin, and holocellulose differed among the evaluated clones (Table 3). Clone H15 exhibited the highest extractives content, whereas H13 was characterized by the highest lignin content and the lowest holocellulose content. In contrast, VM01 showed the lowest extractives content and intermediate values for the other components. The values observed were similar to those reported for different *Eucalyptus* clones and hybrids cultivated in Brazil [56,57].

The wood chemical composition strongly influences its energy potential. Lignin has a higher HHV than holocellulose and is associated with increased fixed carbon content, both of which are desirable characteristics for energy production [58,59]. Conversely, higher holocellulose contents promote thermal degradation and volatile release during combustion, facilitating biomass ignition. However, due to the high oxygen content of these components, their contribution to the heating value is lower than that of lignin [60,61].

Extractives also contribute to the heating value of biomass, particularly when composed of carbon-rich phenolic compounds [25,62]. Although heartwood and sapwood proportions were similar among the clones (Table 2), genetic differences may explain the variation observed in extractives content.

Overall, the differences observed among the clones reflect distinct combinations of chemical constituents that influence the energy performance of wood. Clone H13 exhibited the chemical composition most favorable for energy applications, characterized by the highest lignin content, the lowest holocellulose content, and intermediate extractives levels.

The volatile matter and ash contents did not differ among the evaluated clones ( $p > 0.05$ ), whereas fixed carbon content and HHV showed significant differences ( $p \leq 0.05$ ) (Table 3). The proximate analysis results were similar to those reported for different *Eucalyptus* clones intended for energy production [12,44], indicating that the evaluated materials exhibit characteristics suitable for wood-based energy applications.

Volatile matter contents, averaging approximately 84%, were within the range considered adequate for combustion, favoring ignition and energy release during the initial stages of burning [63,64]. Likewise, the low ash contents observed in all clones meet the requirements generally recommended for energy biomass, reducing potential operational problems associated with the accumulation of inorganic residues during combustion [65].

Fixed carbon content was influenced by genetic material, with clone H13 exhibiting the highest mean value (Table 3). This characteristic is desirable for energy applications because it is associated with sustained combustion and the gradual release of energy [66]. The higher fixed carbon content observed in H13 is consistent with its elevated lignin content, as lignin-rich biomass generally produces greater amounts of carbonaceous residue during thermal degradation [58,59]. This result reinforces the favorable energy profile of H13, previously evidenced by its chemical composition.

The HHVs observed were consistent with those reported for *Eucalyptus* wood of similar ages [47,57]. Among the evaluated materials, clone VM01 exhibited the highest HHV, indicating a greater energy yield on a mass basis. HHV is one of the main indicators of biomass fuel quality, as it represents the maximum amount of energy released during complete combustion [64].

Although clone H13 exhibited higher lignin and fixed carbon contents, the highest HHV was observed in VM01. This result indicates that the energy performance of wood is not governed by a single property, but rather by the interaction among elemental com-

position, structural chemical constituents, and other wood characteristics that influence heat release during combustion. Similar relationships have been reported for *Eucalyptus* biomass, where HHV reflects the combined influence of multiple fuel properties rather than lignin content alone [44,67]. As highlighted by Bonfatti Júnior et al. [67], the heating value is complexly governed by the qualitative nature of extractives; lipophilic fractions and low-molecular-weight phenolic compounds can expressively increase the HHV even in genotypes with lower total lignin content.

Therefore, the results highlight the importance of an integrated evaluation of wood properties when selecting genetic materials for bioenergy production. While lignin and fixed carbon are important indicators of fuel quality, they may not fully explain the overall energy performance of the biomass. In this context, the superior HHV observed for VM01 suggests a favorable energy profile that, when combined with growth performance, may enhance energy production at the plantation scale.

Table 4 presents the mean values of wood volume per tree, wood volume yield per hectare, volumetric energy density, and energy yield per hectare for the evaluated clones.

**Table 4.** Mean wood volume per tree, wood volume yield per hectare, volumetric energy density, and energy yield per hectare of eucalyptus clones at 54 months of age in Brasnorte, Mato Grosso, Brazil.

| Clone | Volume per Tree (m <sup>3</sup> ) | Wood Volume (m <sup>3</sup> ha <sup>-1</sup> ) | Volumetric Energy Density (Gcal m <sup>-3</sup> ) | Energy Yield per Hectare (Gcal ha <sup>-1</sup> ) |
|-------|-----------------------------------|------------------------------------------------|---------------------------------------------------|---------------------------------------------------|
| H13   | 0.17                              | 204.86                                         | 2.32                                              | 474.76                                            |
| VM01  | 0.25                              | 293.06                                         | 2.30                                              | 674.62                                            |
| H15   | 0.16                              | 192.01                                         | 2.29                                              | 439.76                                            |

The total wood volume per hectare of the three clones was within the range expected for eucalyptus plantations in Mato Grosso, Brazil. According to Michetti et al. [22], genetic materials adapted to the state typically exhibit a Mean Annual Increment (MAI) ranging from 30 to 60 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup>, corresponding to wood volumes between 135 and 270 m<sup>3</sup> ha<sup>-1</sup> at 54 months of age. In this context, clone VM01 stood out, with productivity exceeding the upper limit of this range (Table 4). Similar results were reported by Serenini et al. [68], who observed wood volumes ranging from 108.34 to 370.81 m<sup>3</sup> ha<sup>-1</sup> for eucalyptus clones at 60 months of age in northern Mato Grosso, Brazil.

The volumetric energy density values were similar to those reported for older eucalyptus clones cultivated for energy production. Vieira [69] reported a mean value of 2.37 Gcal m<sup>-3</sup> for *Eucalyptus* hybrids at 72 months of age, whereas Magalhães et al. [70] found values ranging from 2.18 to 2.92 Gcal m<sup>-3</sup> for clones at 84 months of age. These findings indicate that the evaluated materials exhibit suitable energy-related characteristics even at 54 months of age.

Although the clones showed similar volumetric energy densities (Table 4), substantial differences were observed in energy yield per hectare, primarily due to differences in wood volume productivity. Clone VM01 exhibited the highest energy yield (674.62 Gcal ha<sup>-1</sup>), followed by H13 and H15. When expressed on a volumetric basis, energy values ranged from 2662 to 2674 kWh m<sup>-3</sup>, remaining within the range reported by Carneiro et al. [71] for *Eucalyptus* clones at 48 months of age. These results demonstrate that wood volume productivity exerted a greater influence on total energy production than volumetric energy density.

The analysis of equivalence with fossil fuels further reinforces this finding. Clone VM01 showed the potential to replace approximately 75,362 L of diesel fuel, 57,365 kg of liquefied petroleum gas (LPG), 71,706 m<sup>3</sup> of natural gas, or 112,340 kg of coal per hectare. For H13, the corresponding values were 52,681 L of diesel fuel, 40,100 kg of LPG, 50,125 m<sup>3</sup> of natural gas, and 78,530 kg of coal, whereas H15 exhibited the lowest replacement

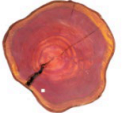
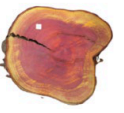
potential, corresponding to 49,376 L of diesel fuel, 37,585 kg of LPG, 46,981 m<sup>3</sup> of natural gas, and 73,604 kg of coal per hectare.

Therefore, despite the small differences in volumetric energy density among the evaluated materials, wood volume productivity was the main determinant of bioenergy potential, providing a clear advantage to clone VM01. Beyond the economic benefits associated with greater energy production, eucalyptus biomass represents a renewable energy source capable of reducing dependence on fossil fuels and contributing to the mitigation of net greenhouse gas emissions. These findings reinforce the potential of the evaluated clones for bioenergy applications, particularly in production systems aimed at supporting the transition toward lower-carbon energy systems.

### 3.2. Experiment II: Effect of Age on the Wood Properties of Clone VM01

The highest heartwood proportions were observed at the stem base across all evaluated ages, followed by a progressive reduction toward the upper stem sections, where heartwood was absent or occurred only residually (Table 5). In contrast, the sapwood proportion increased along the stem, becoming the predominant tissue in the upper portions of the trunk. Bark proportion showed lower values at 25% of commercial stem height, followed by a gradual increase toward the top.

**Table 5.** Longitudinal variation in bark, heartwood, and sapwood proportions along the commercial stem height of clone VM01 at 54, 108, and 144 months of age in Brasnorte, Mato Grosso, Brazil.

| Age<br>(Months) | Parameter | Longitudinal Position                                                               |                                                                                      |                                                                                       |                                                                                       |                                                                                       |
|-----------------|-----------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
|                 |           | 0%                                                                                  | 25%                                                                                  | 50%                                                                                   | 75%                                                                                   | 100%                                                                                  |
| 54              | Bark      | 11.0 (0.99)                                                                         | 8.0 (0.76)                                                                           | 9.9 (1.83)                                                                            | 12.4 (0.73)                                                                           | 12.1 (0.50)                                                                           |
|                 | SW        | 54.7 (1.67)                                                                         | 68.8 (3.44)                                                                          | 82.7 (9.52)                                                                           | 89.8 (20.35)                                                                          | 97.9 (4.12)                                                                           |
|                 | HW        | 45.3 (1.67)                                                                         | 31.2 (3.44)                                                                          | 17.3 (9.52)                                                                           | 10.2 (20.35)                                                                          | 2.1 (4.13)                                                                            |
|                 | Photo     |  |  |  |  |  |
|                 |           |                                                                                     |                                                                                      |                                                                                       |                                                                                       |                                                                                       |
| 108             | Bark      | 9.6 (0.85)                                                                          | 7.9 (0.54)                                                                           | 8.6 (1.16)                                                                            | 9.7 (1.45)                                                                            | 15.1 (1.42)                                                                           |
|                 | SW        | 29.0 (1.57)                                                                         | 45.1 (1.21)                                                                          | 58.1 (2.73)                                                                           | 95.5 (2.84)                                                                           | 100.0 (0.00)                                                                          |
|                 | HW        | 71.0 (1.57)                                                                         | 54.9 (1.21)                                                                          | 41.9 (2.73)                                                                           | 4.5 (2.84)                                                                            | 0.0 (0.00)                                                                            |
|                 | Photo     |  |  |  |  |  |
|                 |           |                                                                                     |                                                                                      |                                                                                       |                                                                                       |                                                                                       |
| 144             | Bark      | 8.6 (0.44)                                                                          | 7.8 (0.16)                                                                           | 8.4 (1.40)                                                                            | 10.4 (1.59)                                                                           | 14.4 (1.51)                                                                           |
|                 | SW        | 21.6 (1.55)                                                                         | 34.9 (3.16)                                                                          | 47.3 (4.89)                                                                           | 88.2 (11.20)                                                                          | 100.0 (0.00)                                                                          |
|                 | HW        | 78.4 (1.55)                                                                         | 65.1 (3.16)                                                                          | 52.7 (4.89)                                                                           | 11.8 (11.20)                                                                          | 0.0 (0.00)                                                                            |
|                 | Photo     |  |  |  |  |  |
|                 |           |                                                                                     |                                                                                      |                                                                                       |                                                                                       |                                                                                       |

SW = Sapwood; HW = Heartwood; Values in parentheses indicate the standard deviation (SD).

This distribution pattern was consistent across all ages and similar to that observed among the evaluated clones at 54 months of age, reflecting the progressive reduction in heartwood formation toward the upper stem sections. A comparable longitudinal pattern of heartwood distribution has been reported for *Eucalyptus grandis*, *Eucalyptus grandis* × *E. urophylla*, and *Eucalyptus globulus* [72–74].

In addition to the longitudinal variation, an increase in heartwood proportion was observed with advancing age (Table 5). Previous studies have shown that heartwood formation is positively correlated with DBH and tree height, indicating that larger trees tend to exhibit greater proportions of this anatomical region [72,73]. A similar pattern was observed in the present study, as trees at 144 months of age, which exhibited the largest dendrometric dimensions, also showed the highest heartwood proportions.

The mean proportions of bark, heartwood, and sapwood at the different ages evaluated are presented in Figure 4. Bark proportion showed a slight decrease with increasing age, declining from 10.7% at 54 months to 9.9% at 144 months of age (Figure 4A). This limited variation is consistent with values reported for *Eucalyptus* spp. clones, in which bark proportions ranged from 9.8% to 12.3% in trees between 36 and 60 months of age [73,74]. In general, bark proportion tends to remain relatively stable throughout tree development, since diameter growth occurs predominantly through wood formation rather than bark accumulation [38].

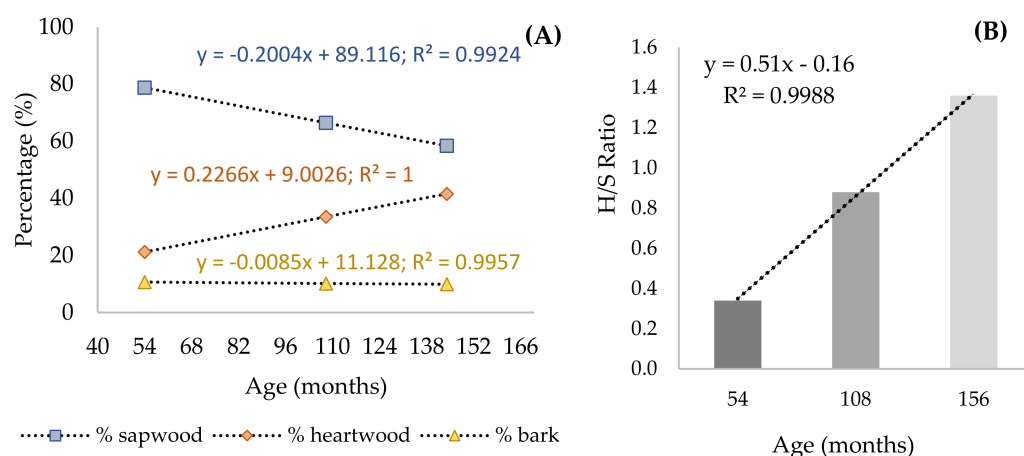


**Figure 4.** Mean proportions of bark, heartwood, and sapwood (A) and heartwood-to-sapwood (H/S) ratio (B) of clone VM01 at 54, 108, and 144 months of age in Brasnorte, Mato Grosso, Brazil. The dotted line indicates the regression model fitted to the age data.

Sapwood proportion progressively decreased with age, whereas heartwood increased proportionally (Figure 4A), resulting in a continuous increase in the H/S ratio (Figure 4B). Between 54 and 144 months of age, the relative proportion of sapwood decreased by approximately one-third, while the heartwood proportion nearly doubled. This pattern is associated with the natural process of heartwood formation, whereby older sapwood tissues cease to perform conductive functions and are gradually transformed into heartwood through the deposition of extractives and the formation of tyloses [43].

Similar trends have been reported by dos Santos et al. [73] and Santos et al. [74], who observed an increase in heartwood proportion with age in *Eucalyptus urophylla* hybrids, as well as by Golçalves [75] and Evangelista [42], who reported a reduction in sapwood proportion and a corresponding increase in heartwood in older trees.

From an energy perspective, the increase in heartwood may present both advantages and limitations. On the one hand, it is associated with greater wood accumulation per tree. On the other hand, the lower permeability of heartwood, resulting from the presence of tyloses and extractives, restricts moisture movement and may increase the time required for wood drying [4,76]. Therefore, age-related changes in heartwood proportion should be considered when planning the energy utilization of forest biomass.

Basic wood density of clone VM01 increased significantly with age ( $p \leq 0.05$ ), exhibiting a positive linear relationship with age ( $R^2 = 0.9623$ ) (Figure 5A).

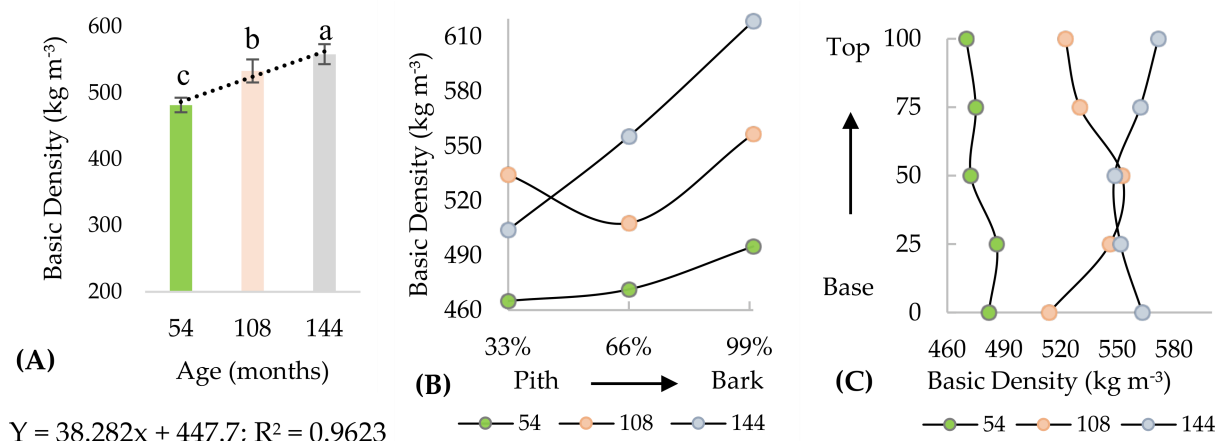


**Figure 5.** Mean basic wood density (A) and radial (B) and longitudinal (C) variation in basic wood density of clone VM01 at 54, 108, and 144 months of age in Brasnorte, Mato Grosso, Brazil. In panel (A): the dotted line indicates the regression model fitted to the age data, means followed by the same letter do not differ significantly according to Tukey's test ( $p \leq 0.05$ ), and error bars represent the standard deviation (SD).

Basic wood density increased with age (Figure 5A), with increments of 10.67% between 54 and 108 months of age, 4.72% between 108 and 144 months of age, and 15.89% over the entire evaluation period. Similar results were reported by Sette et al. [46], who observed an approximately 7% increase in the wood density of *Eucalyptus grandis* between 2 and 6 years of age, whereas Santana et al. [77] found a 15.5% increase between 34 and 48 months of age for the hybrid *Eucalyptus grandis*  $\times$  *Eucalyptus urophylla*.

The increase in basic wood density is associated with the gradual transition from juvenile to mature wood, which is characterized by changes in wood anatomical structure [46,47]. Although some studies have reported density stabilization or even reductions at more advanced ages, this pattern was not observed for clone VM01.

Higher basic wood density is desirable because it increases volumetric energy density and enhances biomass transportation and storage efficiency. However, the definition of the optimal harvest age should balance the technological gains associated with denser wood against the costs of maintaining stands under longer rotations, particularly considering the reduced growth increment observed after 108 months of age (Table 1).

Radial variation in basic wood density exhibited distinct patterns among the evaluated ages (Figure 5B). At 54 months of age, density increased gradually from pith to bark, a pattern typically associated with juvenile wood. At 108 months of age, density initially decreased until approximately one-third of the radius, followed by a continuous increase toward the bark. At 144 months of age, a pronounced increase was observed throughout the radial profile, indicating a greater degree of wood maturation. The increase in density from pith to bark has been widely reported for *Eucalyptus* species [42,51,78] and is associated with anatomical changes resulting from cambial maturation, including fiber wall thickening and changes in vessel frequency and diameter [79]. These results indicate that the radial density gradient became more pronounced with advancing age, reflecting the progressive formation of mature wood.

Regarding longitudinal variation (Figure 5C), at 54 months of age, density increased slightly up to 25% of commercial stem height and then decreased toward the top of the stem. At 108 months of age, the density profile was more uniform along the stem. In contrast, at 144 months of age, density decreased up to approximately 50% of commercial stem height and subsequently increased toward the upper stem sections. According to [46], such

longitudinal variations may be associated with the mechanical requirements for supporting both the stem and the crown.

Overall, increasing age promoted higher basic wood density and intensified the radial gradient of this property, reflecting the wood maturation process. From an energy standpoint, this behavior is advantageous because denser wood concentrates a greater amount of energy per unit volume, thereby increasing the efficiency of forest biomass transportation, storage, and utilization.

Age significantly affected the volatile matter, ash, fixed carbon, and HHV of clone VM01 wood (Figure 6).

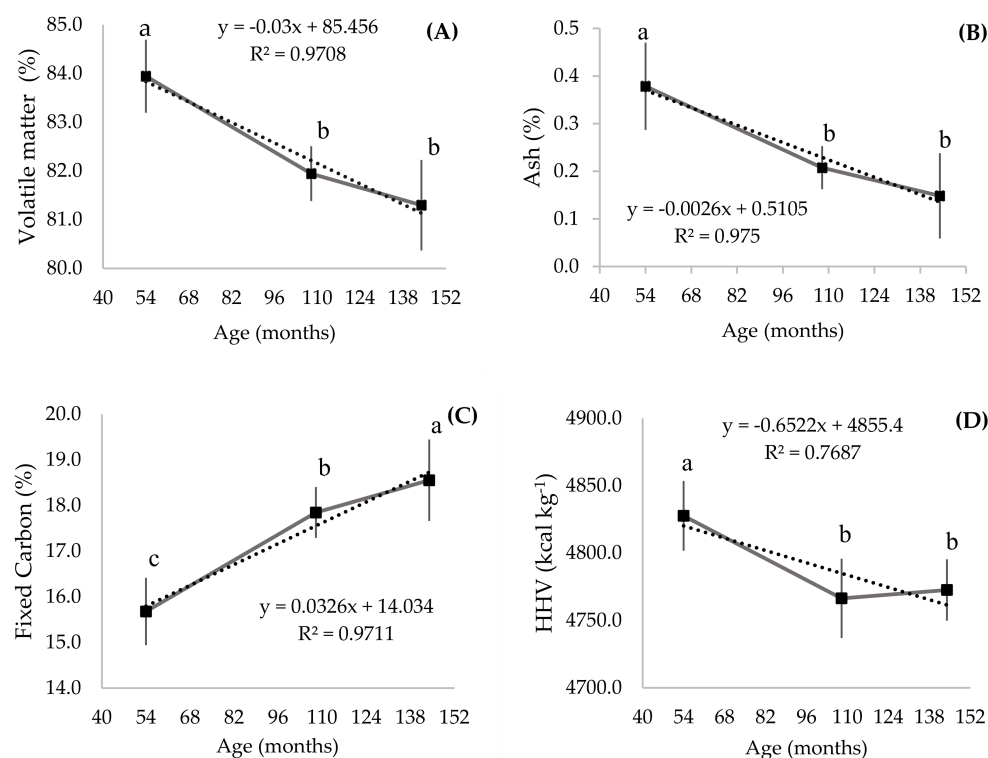


**Figure 6.** Mean values of volatile matter (A), ash content (B), fixed carbon (C), and higher heating value (HHV) (D) for clone VM01 at 54, 108, and 144 months of age, grown in Brasnorte, Mato Grosso, Brazil. The dotted lines represent the regression models fitted for each variable; the corresponding equations and coefficients of determination ( $R^2$ ) are shown in the respective panels. Means followed by the same letter do not differ significantly according to Tukey's test ( $p \leq 0.05$ ). Error bars represent the standard deviation (SD).

Volatile matter content decreased with increasing age, from 83.94% to 81.30%, with no significant difference between 108 and 144 months of age (Figure 6A). Similar results were reported by Kumar et al. [80], who observed a reduction from 81.15% to 79.29% in *Eucalyptus* hybrids between 2 and 20 years of age. This trend is associated with wood maturation and the gradual changes in wood structure and chemical composition that occur during tree development. Although lower volatile matter content may reduce combustion intensity during the initial stages of burning, the higher wood density and greater wood production observed at older ages contribute to improved energy yield per unit volume [81].

Ash content decreased significantly with age, from 0.38% to 0.15% (Figure 6B), decreasing by a factor of approximately 2.5. Similar results were reported by Carvalho et al. [82] for *Eucalyptus grandis* × *E. urophylla* hybrids. The higher mineral concentration observed in younger trees is associated with their elevated metabolic activity and greater nutrient demand during the early stages of growth [7]. For bioenergy, lower ash contents are desirable because they reduce operational problems such as fouling, slagging, and thermal wear of

combustion equipment, while increasing the effective energy utilization of biomass [47]. Furthermore, the sharp decrease in ash content at 144 months can be attributed to both a biological dilution effect—where the rapid accumulation of secondary xylem volumes outpaces mineral uptake—and the heartwood maturation process, which involves the dynamic retranslocation of mobile nutrients (such as potassium and phosphorus) from the dying inner cells toward the active outer sapwood.

In contrast, fixed carbon content increased progressively with age, rising from 15.68% to 18.55%, with significant differences among all evaluated ages (Figure 6C). A similar trend was reported by Resquin et al. [53] for *Eucalyptus* clones. Although lignin content did not vary significantly with age, fixed carbon increased throughout the evaluation period, suggesting that age-related changes in wood composition and structure may influence biomass behavior during thermal degradation.

HHV showed a slight reduction of approximately 1% between 54 and 144 months of age (Figure 6D). This behavior is consistent with studies reporting an initial increase in HHV during the first years of growth, followed by stabilization or a slight decline at more advanced ages [8,77]. The decrease in HHV may be associated with gradual changes in wood chemical composition during the maturation process [73,79,83]. Nevertheless, the magnitude of this reduction was small and was offset by the substantial increases in wood density and volume production observed with age, resulting in an overall improvement in the energy performance of the biomass.

The results of the ultimate analysis and atomic ratios were affected by age, with significant differences ( $p < 0.05$ ) observed for carbon, hydrogen, nitrogen, sulfur, and the H/C and N/C ratios, whereas oxygen content remained stable across the evaluated ages (Figure 7).

Carbon content increased from 50.55% at 54 months of age to 51.15% at 108 months of age and 51.33% at 144 months of age (Figure 7A). Similar values have been reported for eucalyptus wood, in which carbon content is typically around 50% [71]. Although Soares et al. [84] observed a decrease in carbon content with increasing age, the present results agree with those reported by Carneiro et al. [71], who found an increase in carbon content in *Eucalyptus urophylla* × *E. grandis* clones. From an energy perspective, higher carbon contents are desirable because carbon is the primary element responsible for heat release during combustion.

In contrast, hydrogen content decreased from 6.47% to 6.20% between 54 and 144 months of age (Figure 7B). A similar trend was reported by Soares et al. [84], whereas Carneiro et al. [71] found no significant effect of age on this variable. Despite this reduction, hydrogen content remained close to, or slightly above, the values commonly reported for eucalyptus wood (approximately 6%). Hydrogen contributes substantially to the energy content of biomass, releasing considerably more energy per unit mass than carbon during combustion [81]. Therefore, reductions in hydrogen content may contribute to the slight decrease in HHV observed with increasing age. Nevertheless, the changes observed in both carbon and hydrogen contents were relatively small, which is consistent with the modest reduction in HHV (approximately 1%) between 54 and 144 months of age.

Nitrogen content decreased significantly with increasing age, from 0.06% to 0.02% (Figure 7C). Similar results were reported by Protásio et al. [8], who also observed a decline in nitrogen content with age. The values obtained in the present study were lower than the average value of approximately 0.15% commonly reported for eucalyptus wood [71]. From both environmental and energy perspectives, this reduction is desirable because lower nitrogen concentrations decrease the formation of nitrogen oxides ( $\text{NO}_x$ ) during combustion, thereby reducing environmental impacts and potential risks to human health [60,85].

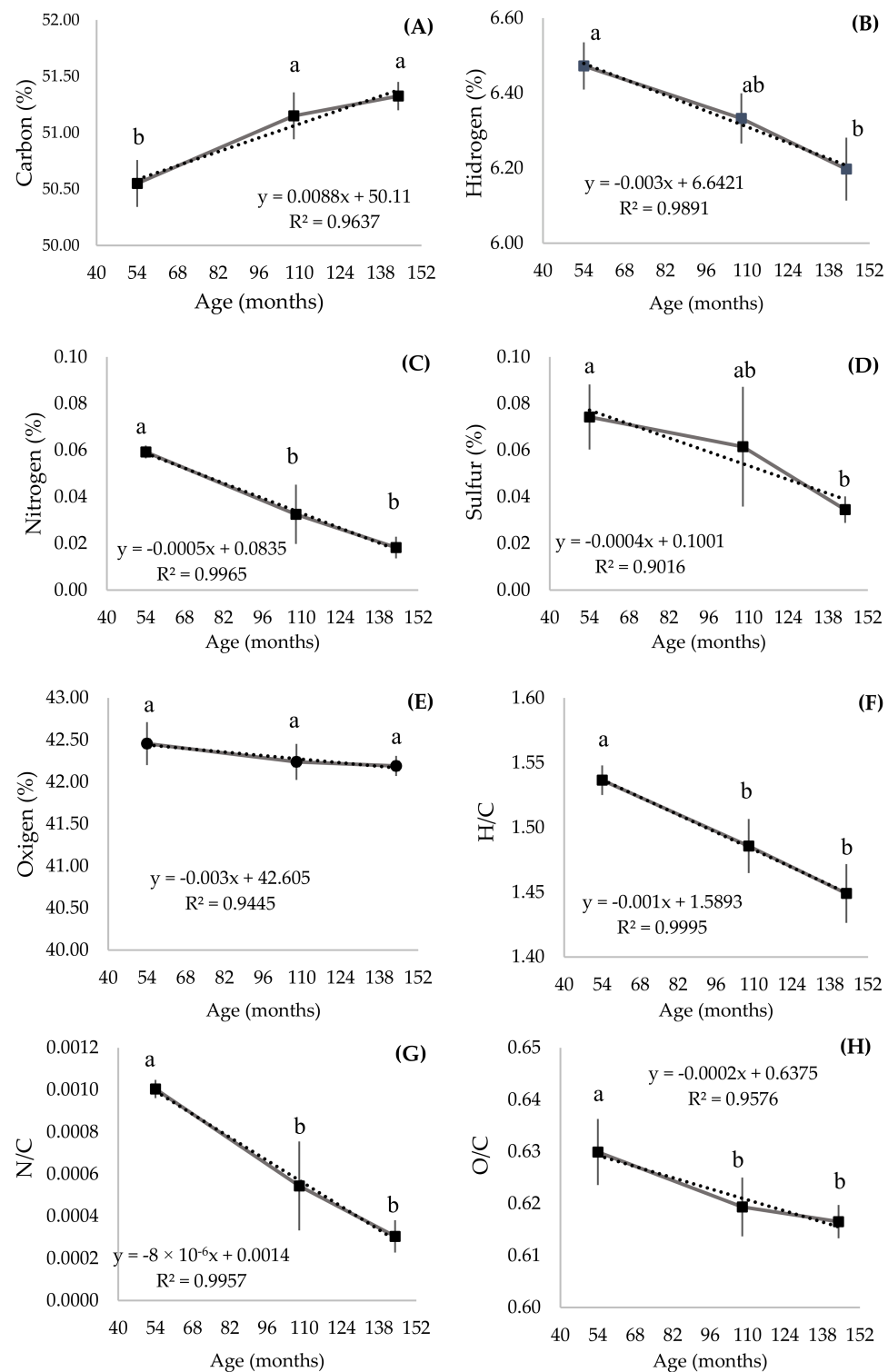


**Figure 7.** Mean values of the elemental composition of clone VM01 wood at 54, 108, and 144 months of age in Brasnorte, Mato Grosso, Brazil: (A) carbon (C), (B) hydrogen (H), (C) nitrogen (N), (D) sulfur (S), and (E) oxygen (O), and atomic ratios (F) H/C, (G) N/C, and (H) O/C. The dotted lines represent the regression models fitted as a function of age, whose equations and coefficients of determination ( $R^2$ ) are presented in the respective graphs. Means followed by the same letter do not differ significantly according to Tukey's test ( $p \leq 0.05$ ). Error bars represent the standard deviation (SD).

A similar pattern was observed for sulfur, whose content decreased from 0.07% to 0.03% (Figure 7D). The values obtained were consistent with those reported by

Carneiro et al. [71] for eucalyptus clones. Low sulfur contents represent an important environmental advantage because sulfur combustion generates sulfur dioxide ( $\text{SO}_2$ ), a precursor of acid rain [11]. Therefore, the reduction observed with increasing age further reinforces the suitability of this biomass for environmentally sustainable energy applications.

Unlike the other elements, oxygen content did not vary significantly with age, averaging 42.29% (Figure 7E). This value is slightly lower than the 43%–44% commonly reported for eucalyptus wood [71]. Because oxygen is already partially oxidized, higher oxygen contents are generally associated with lower energy density in biomass [8]. Thus, the relatively low and stable oxygen contents observed in the present study indicate energy properties comparable to those reported for woody biomass used for energy generation.

The atomic ratios were also influenced by age (Figure 7F–H). The H/C ratio decreased from 1.54 to 1.45 (Figure 7F), reflecting the proportional reduction in hydrogen relative to carbon. This trend is consistent with the changes observed in elemental composition during wood maturation and may partially explain the slight reduction in HHV with increasing age. The N/C ratio decreased markedly, from 0.0010 to 0.0003 (Figure 7G), directly reflecting the decline in nitrogen content. This behavior is environmentally favorable because it indicates a lower potential for  $\text{NO}_x$  emissions during combustion. The O/C ratio showed a slight decrease, from 0.63 to 0.62 (Figure 7H). Although small, lower O/C ratios are generally associated with fuels of higher energy quality because they indicate a lower proportion of oxygen in the biomass. Overall, the observed changes in the atomic ratios suggest a gradual improvement in the environmental performance of the biomass with age, while maintaining its energy quality.

Wood structural composition was influenced by age, with significant variations ( $p < 0.05$ ) observed in extractives and holocellulose contents, whereas lignin content remained stable throughout the evaluation period (Figure 8).

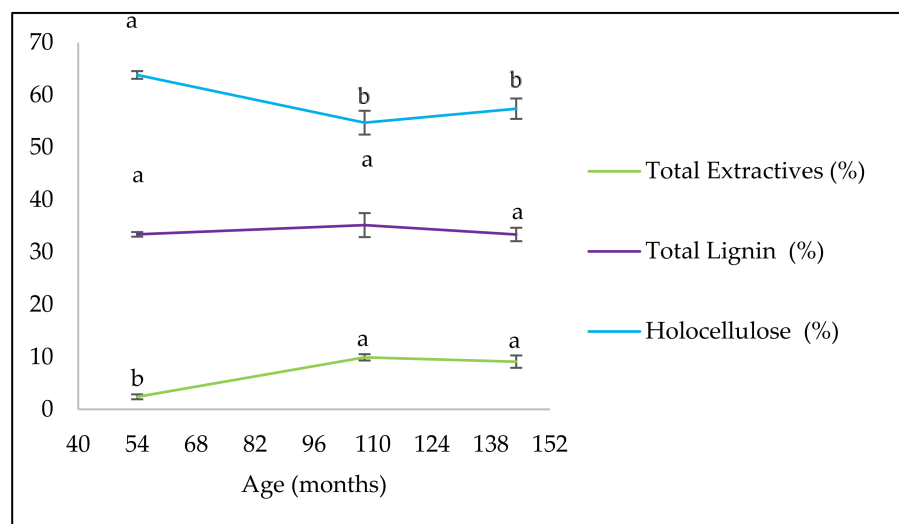


**Figure 8.** Mean values of total extractives, total lignin, and holocellulose for clone VM01 at 54, 108, and 144 months of age. Means followed by the same letter within a parameter do not differ significantly according to Tukey's test ( $p \leq 0.05$ ). Error bars represent the standard deviation (SD).

Extractives content increased significantly with age, showing an approximately threefold increase between 54 and 144 months of age (Figure 8). A similar trend was reported by dos Santos et al. [73] for *Eucalyptus urophylla* clones and *Eucalyptus* hybrids, as well as by Ramos et al. [26] for *Eucalyptus* trees older than nine years. The accumulation of extractives is associated with the heartwood formation process, during which phenolic

compounds, resins, tannins, and other low-molecular-weight substances are deposited within cell lumina and cell walls [38].

Extractives generally exhibit higher heating values than the structural polysaccharides of wood due to their relatively high carbon content. Depending on their chemical composition, these compounds may present heating values ranging from 25 to 30 MJ kg<sup>-1</sup>, thereby contributing to the overall energy content of the biomass [52,56]. The increase in extractives content observed in clone VM01 is also consistent with the reduction in the O/C ratio previously observed (Figure 7), indicating gradual changes in wood chemical composition during maturation.

Lignin content did not differ among the evaluated ages, remaining at an average of 33.89% (Figure 8). Similar stability was reported by dos Santos et al. [73], although lower lignin contents were observed by those authors. Lignin is a structural component primarily deposited during secondary cell wall formation and generally exhibits limited variation after wood maturation [38]. Although some studies have reported age-related changes in lignin content [86], the absence of significant variation in the present study may be associated with the age range evaluated, since the largest changes often occur during the early stages of tree development. The consistently high lignin content observed in clone VM01 may have contributed to maintaining favorable energy characteristics throughout the evaluated period, given the important role of lignin in the energy value of woody biomass.

In contrast, holocellulose content decreased significantly with increasing age (Figure 8). Similar results have been reported by Silva et al. [87] and Ramos et al. [26]. This reduction reflects a proportional effect resulting from the accumulation of extractives, since lignin content remained unchanged throughout the evaluated period. From an energy perspective, a lower relative proportion of holocelluloses may be advantageous because cellulose and hemicelluloses are less thermally stable than lignin and extractives and tend to degrade at lower temperatures during thermal conversion processes [54].

This study provides important information for selecting eucalyptus genetic materials and harvest ages for energy production under the edaphoclimatic conditions of Mato Grosso. However, some limitations should be acknowledged. The evaluation of harvest age was restricted to clone VM01, and the experiments were conducted in a single commercial plantation, which limits the extrapolation of the results to other genetic materials and growing environments. Future studies should investigate age-related changes in additional eucalyptus clones across different site conditions and integrate wood quality with silvicultural performance and techno-economic analyses to support optimized biomass production systems.

#### 4. Conclusions

The results confirmed the energy potential of clones H13, H15, and VM01 for bioenergy production through direct combustion in the state of Mato Grosso, Brazil. At 54 months of age, all evaluated materials exhibited characteristics compatible with bioenergy applications, demonstrating their suitability as biomass sources for industrial energy supply.

Among the evaluated clones, VM01 stood out for its higher wood volume yield per hectare, greater energy yield per hectare, and higher potential for fossil fuel replacement, demonstrating that wood volume productivity is a key determinant of the overall energy performance of eucalyptus plantations. Although the three clones exhibited similar volumetric energy densities, the superior growth of VM01 resulted in greater energy yield per unit area.

Increasing age promoted changes in the wood properties of clone VM01 that generally enhanced its energy performance. These changes included increases in basic wood density, extractives content, and carbon content, which was characteristically fixed carbon content,

accompanied by reductions in components considered less desirable for combustion, such as ash, nitrogen, and sulfur.

The findings contribute to a better understanding of the technological and energy-related performance of eucalyptus clones cultivated under the edaphoclimatic conditions of the Brazilian Midwest, providing valuable information for tree breeding programs, forest planning, and management strategies aimed at biomass production for industrial bioenergy applications.

Overall, clone VM01 (*Eucalyptus urophylla* × *E. camaldulensis*) exhibited the most favorable combination of traits for energy-oriented forest plantations, integrating high wood volume productivity with suitable energy-related wood properties, particularly at more advanced ages. Its superior energy yield per hectare and fossil fuel replacement potential highlight its suitability for meeting the growing demand for woody biomass used in thermal energy generation by agro-industrial facilities in Mato Grosso, Brazil.

The results indicate that 54-month-old plantations are suitable for supplying biomass to agro-industrial facilities operating under short-rotation harvest systems and requiring a continuous feedstock supply. Conversely, harvesting at 108–144 months may be more appropriate for large-scale bioenergy industries, where the higher wood density, fixed carbon content, and energy density of older trees can improve fuel quality and overall energy yield. Regardless of the production system, the optimal harvest age should be defined by integrating wood properties with silvicultural, operational, and economic criteria.

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