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Articles

Energy quality of different biomasses from *Eucalyptus* sp. and *Myracrodruon urundeuva* All. species

Qualidade energética de diferentes biomassas das espécies de *Eucalyptus* sp. e *Myracrodruon urundeuva* All.

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ABSTRACT

This study aimed to analyze the energy quality of different biomasses from the species *Eucalyptus* sp. and *Myracrodruon urundeuva* (planted). Six trees of both species, at 13 years of age, were selected by using the simple random sampling method. Subsequently, the physical (moisture and apparent density), chemical (extractives, lignin, holocellulose, cold water solubility), and energetic properties (volatile matter, fixed carbon, ash, carbon, hydrogen, oxygen, calorific value, energy density, carbon stock, and fuel value index) of the biomasses (stem, bark, and branch) were determined. A significant difference, at the 5% level, was observed between the species and biomasses analyzed. The stem biomass of *Eucalyptus* sp. showed greater potential for energy production, given its high lignin content (20.71%), higher gross calorific value (4684.45 kcal/kg), high fixed carbon content (18.28%), better fuel value index (15.76), and low ash content (0.10%). The stem biomass of *Myracrodruon urundeuva* also proved promising for direct combustion.

Keywords: Planted forest; Properties; Quality; Stem; Higher heating value

RESUMO

Este estudo teve como objetivo analisar a qualidade energética de diferentes biomassas das espécies de *Eucalyptus* sp., e *Myracrodruon urundeuva (*plantada). Foram selecionadas seis árvores de ambas as espécies aos 13 anos de idade, pelo método aleatório simples. Posteriormente, foram avaliadas nas biomassas (fuste, casca e galho) as seguintes propriedades: teor de umidade, densidade aparente, teor de extrativos, lignina, holocelulose, solubilidade em água fria, matérias voláteis, carbono fixo, cinzas, composição elementar (carbono, hidrogênio e oxigênio), poder calorífico superior, densidade energética, estoque de carbono e índice de valor do combustível. Houve diferença significativa, a 5% de significância, entre as espécies e biomassas analisadas. A biomassa do fuste da espécie *Eucalyptus* sp. apresentou maior adequação para combustão direta, em função do elevado teor de lignina (20,71%), maior poder calorífico superior (4684,45 kcal/kg), alto teor de carbono fixo (18,28%), melhor índice de valor do combustível (15,76) e baixo teor de cinzas (0,10%). A biomassa do fuste da espécie de *Myracrodruon urundeuva* também se mostrou promissora para queima direta.

Palavras-chave: Floresta plantada; Propriedades; Qualidade; Fuste; Poder calorífico superior

1 INTRODUCTION

The growing scarcity of natural resources and rising fossil fuel prices have fueled global interest in renewable energy sources. Energy sources such as solar, wind, geothermal, hydroelectric and bioenergy have been utilized across various sectors, contributing to greater energy security (Mignogna et al., 2024). Among these alternatives, the biomass stands out for its wide availability and growth potential; it is considered an environmentally preferable option to fossil fuels, as well as helping to reduce greenhouse gas emissions and meet CO_2 mitigation targets (Mignogna et al., 2024).

In this context, biomass used in the form of solid fuels holds significant importance. According to Igwebuike et al. (2024), over 85% of the energy derived from this source is used for heating, cooking and lighting, with firewood and charcoal predominating; these ones feature as traditional bioenergy. This type of biomass remains essential in developing countries, where around 95% of national energy consumption depends on this source. Furthermore, biomass combustion is considered a carbon-neutral process, as the carbon dioxide released was previously absorbed by the plants, reinforcing its importance as a sustainable energy alternative (Igwebuike et al., 2024).

In Brazil, wood has historically played a central role in energy generation, whether through the direct burning of firewood or the production of charcoal, which is mainly used in the steel industry (Crisóstomo et al., 2021). The country stands out as the world's largest producer of charcoal, with 6.6 million tonnes in 2024, consolidating its importance as a raw material for various production chains (IBÁ, 2025).

In this context, the *Eucalyptus* genus occupies a strategic position, providing raw materials for pulp, paper, sawn timber, firewood and, in particular, charcoal (Teixeira et al., 2020). In 2024, of the 10.52 million hectares of planted trees in Brazil, approximately 8.1 million were *Eucalyptus* (IBÁ, 2025).

Despite the importance of plantations of exotic species, there is growing interest in native alternatives, driven by the search for greater diversity, ecological adaptation and sustainability. Native species offer productive and energy potential, but their overexploitation, without proper management, has led many of them to the brink of extinction. Among these, *Myracrodruon urundeuva* Allemão (aroeira) excels, being widely used for timber purposes as well as medicinal applications (Pareyn et al., 2018). Its wide distribution across biomes such as the Caatinga, Cerrado and Atlantic Forest, combined with its drought tolerance, reinforces its ecological and economic importance. However, intensive exploitation led to the species being included on the list of endangered species in 1992 by IBAMA, highlighting the need for sustainable practices (Pareyn et al., 2018).

The aroeira tree, in addition to its ecological and historical significance, possesses excellent physical and mechanical properties, which are widely recognized in applications such as stakes, slats, rafters, flooring, firewood and charcoal (Pareyn et al., 2018). These features, combined with the high density and quality of the biomass, reinforce its potential for bioenergy systems. Investigating threatened species with technological attributes helps to encourage sustainable management and the planting of native species, expanding alternatives for use and reducing pressure on natural populations.

In this context, it is important to emphasize that there are no wood species that cannot be employed in energy production (Brun et al., 2018). However, when considering the use of forest biomass for energy purposes, it is essential to evaluate its physical and chemical aspects, since these properties determine the quality of the material and directly influence their energy performance and efficiency (Lopes et al., 2023). For energy generation, priority is given to woods with high calorific value, as they are directly related to the energy yield of biomass (Teixeira et al., 2020).

Despite its broad potential, the use of timber inputs as an energy source often occurs without access to essential information needed to quantify and qualify the final product. In this regard, understanding the energy potential of biomass emerges as a study of significant importance. Furthermore, the use of biomass for energy generation does not present restrictive characteristics, since different parts of the wood (stem, branches, bark, and roots) can be utilized without limitations (Reis et al., 2023).

Given the above, the present study aimed to evaluate the energy quality and compare the potential derived from the different biomass components (stem, branch, and bark), focusing on the species *Eucalyptus* sp. and *Myracrodruon urundeuva* Allemão (aroeira).

2 MATERIALS AND METHODS

2.1 Location and collection

The research was conducted at the Laboratory of Forest Product Technology and Utilization I, at the Federal University of Tocantins, Gurupi campus. Six trees of the genus *Eucalyptus* and six of *Myracrodruon urundeuva* Allemão (aroeira) were selected, all being at 13 years old. The average diameters were 21 cm (8,26 in) for the *Eucalyptus* and 9.7 cm (3,82 in) for the aroeira. The selection followed the simple random sampling method described by Wastowski (2018).

The *Eucalyptus* sp. originated from a forest stand located at the Água Franca Farm (UFT experimental farm) in Gurupi, TO (Latitude: 11°46’20.76” S; Longitude: 49°2’51.22” W). The aroeira was obtained from a plantation belonging to the company TETO – Telhados Tocantins, also in Gurupi, TO (Latitude: 11°41’34.04” S; Longitude: 49°2’28.58” W). Four discs were taken at DBH (Diameter at Breast Height), as well as bark and small discs from the branches.

2.2 Sample preparation

The trunk, branch and bark samples were transported to the laboratory, where they were chopped into chips and sticks, shredded and ground (Figure 1). The particles were then sieved using 40-mesh and 60-mesh sieves. For the analyses, the fraction retained on the 60-mesh sieve was used, as per Klock et al. (2012).

Figure 1 – Preparation of samples for analysis

Source: Authors (2023)

2. 3 Analysis of properties

The bulk density (BD) was determined by using the mercury immersion method (Vital, 1984) and employing wood chips that had been dried in an oven to constant weight. The moisture content (MC), total extractives, total lignin, holocellulose and cold-water solubility were determined according to Wastowski (2018).

To determine total extractives, the samples underwent sequential Soxhlet extraction with ethanol-toluene (1:2) for 8 hours and 95% ethanol for 6 hours, followed by a water bath for 1 hour. After the removal of the extractives, the Klason lignin was quantified: the samples were treated with 3 mL of 72% H_2SO_4 for 1 h, diluted in 84 mL of hot water and autoclaved at 118 °C for 1 h. The insoluble material was filtered and dried in an oven. The filtrate was analyzed on a spectrophotometer at 205 nm to calculate the soluble lignin. Holocellulose was determined by the equation: 100 – (total extractives + total lignin).

The contents of volatile matter (VM), fixed carbon (FC) and ash (AZ) were determined in accordance with standard NBR 8112 (1986). The higher heating value (HHV) was estimated using the method described by Channiwala et al. (2002), Equation (1). The energy density (ED) was calculated according to Jesus et al. (2017), using the bulk density, Equation (2).

$$HHV = (84{,}51 * FC) + (37{,}26 * VM) + (1{,}86 * AZ) \quad (1)$$

$$ED = Bd * HHV \quad (2)$$

In where: HHV = higher heating value (kcal/kg); FC = fixed carbon content (%); VM = volatile matter (%); AZ = ash content (%); ED = Energy density (kcal/cm³); Bd = bulk density (g/cm³).

To determine the elemental composition of the biomass (C, H, O), the methodology described by Parikh et al. (2007) was used for estimation, in accordance with equations (3), (4) and (5).

$$C = (0{,}637 * FC) + (0{,}455 * VM) \quad (3)$$

$$H = (0{,}052 * FC) + (0{,}062 * VM) \quad (4)$$

$$O = (0{,}304 * FC) + (0{,}476 * VM) \quad (5)$$

In where: C = elemental carbon (%); H = elemental hydrogen (%); O = elemental oxygen (%); FC = fixed carbon (%); VM = volatile matter (%).

The carbon stock (CS) was calculated according to Protásio et al. (2015), using the elemental carbon content. The calorific value index (CVI) was obtained in accordance with Corradi (2021), taking into account HHV, BD, AZ and MC, Equation (6).

$$CVI = \frac{HHV * BD}{AZ * MC} \quad (1)$$

In where: CVI = calorific value index; HHV = higher heating value (kcal/kg); BD = bulk density (g/cm³); AZ = ash content (%); MC = moisture content (%).

2.4 Statistical analysis

The experiment was conducted using a completely randomized design (CRD), considering the trunk, branches and bark of the two species. Normality tests, analysis of variance (ANOVA) and Tukey's test were performed to compare the means at a 5% significance level, using the Sisvar statistical software. Pearson's correlation analysis was performed in Excel to identify relationships between the evaluated parameters.

3 RESULTS AND DISCUSSION

Table 1 presents the mean values of the physical and chemical properties of the bark, twigs and trunk of *Eucalyptus* sp. and *M. urundeuva*. The results show that the effect of the species × biomass interaction (bark, twigs and trunk) was significant at the 5% probability level for all parameters analyzed.

The bulk density (BD) of the biomasses studied ranged from 540.28 to 1033.37 kg/m³, revealing significant differences between the species and types of biomasses (bark, twigs and trunk). The species *M. urundeuva* performed best in all components, with mean values of 1033.37 kg/m³ for bark, 832.06 kg/m³ for trunk and 788.84 kg/m³ for branches, thus characterizing it as high-density. This pattern indicates greater energy potential, as denser woods have a higher mass per unit volume, resulting in higher calorific value and combustion efficiency. In contrast, the trunk and branches of *Eucalyptus* sp. recorded the lowest densities (540.28 and 594.87 kg/m³, respectively), classifying them as medium density and suggesting lower energy yield.

Table 1 – Physical and chemical properties of biomass from *Eucalyptus* sp. and *M. urundeuva*

Properties	**Biomass**	***Eucalyptus* sp.**	***M. urundeuva***	**Pr>Fc interaction**
Bulk density (Bd) (kg/m³)	Bark	716,38 bA (14,53)	1033,37 aA (8,47)	*
	Twig	594,87 bB (15,43)	788,84 aC (4,52)	
	Trunk	540,28 bB (9,80)	832,06 aB (16,80)	
Moisture content (MC) (%)	Bark	8,09 bA (1,80)	9,61 aA (2,37)	*
	Twig	6,92 aB (2,04)	6,22 aC (4,39)	
	Trunk	6,48 bB (3,06)	8,03 aB (2,68)	
Total extractives (%)	Bark	15,19 bA (3,55)	27,89 aA (0,83)	*
	Twig	4,02 bC (3,06)	6,97 aC (1,24)	
	Trunk	7,93 bB (0,81)	8,21 bB (2,22)	
Total Lignin (%)	Bark	17,26 aB (18,62)	12,91 bB (6,65)	*
	Twig	20,19 aA (27,64)	14,01 bA (0,48)	
	Trunk	20,71 aA (3,00)	14,19 bA (1,09)	
Holocellulose (%)	Bark	67,55 aC (4,00)	59,20 bC (1,81)	*
	Twig	75,78 bA (7,24)	79,03 aA (0,05)	
	Trunk	71,37 bB (0,79)	77,60 aB (0,43)	
Solubility in cold water (%)	Bark	12,26 bA (3,68)	19,20 aA (1,53)	*
	Twig	3,43 bC (11,74)	5,29 aB (7,76)	
	Trunk	5,43 aB (2,85)	4,22 bC (11,60)	

Source: Authors (2023)

In where: Mean values followed by the same lower-case letter in the row and the same upper-case letter in the column do not differ from one another according to Tukey's test at a 5% significance level.

Despite the higher apparent density of the *M. urundeuva* stem, *Eucalyptus* sp. had a larger DAP, resulting in greater accumulated biomass. This performance indicates that the average annual growth of *Eucalyptus* tends to exceed that of *M. urundeuva* in stands of the same age and area, highlighting its greater productive capacity. Effectively, this means that *Eucalyptus* offers a greater volume of biomass in a shorter time, making it more efficient for large-scale energy generation.

In addition to density, moisture content (MC) is a key parameter for the energy utilization of biomass. The higher the MC, the lower the gross calorific value, as the water present in the wood consumes part of the energy released during combustion through evaporation, thereby reducing energy efficiency (Halim; Muhammad, 2025). Considering this, it is essential to use biomass with a low moisture content to achieve better performance.

Table 1 presents the MC values of the species following a period of air drying. Among the species, *M. urundeuva* had the highest moisture content in its biomass, which reduced the gross calorific value, as shown in Table 2.

As for the total extractives, the bark of *M. urundeuva* had the highest average, at 27.89%, followed by the bark of *Eucalyptus* sp., at 15.19%. This result stresses the physiological role of the bark, which acts as the main physicochemical barrier against biotic and abiotic environmental influences, favoring the concentration of extractives that work as a natural protection against xylophagous organisms (Gunnarsdottir et al., 2023). In contrast, the branch of *Eucalyptus* sp. had the lowest extractive content, with an average of 4.02%. Biomass with a high concentration of extractives increases energy efficiency, as it enhances the calorific value (Esteves et al., 2023). According to Esteves et al. (2023), extractives rich in terpenoid hydrocarbons and lipids oxidize less and therefore release more energy, whilst extractives with a higher concentration of phenolic compounds oxidize more intensely and consequently produce less energy.

However, when the extractive content increases in relation to the total biomass mass, the other chemical constituents appear in relatively smaller proportions. This pattern is confirmed in the total lignin content of the bark of *Eucalyptus* sp. and *M. urundeuva* (17.26% and 12.91%, respectively) as well as in the holocellulose content (67.55% and 59.20%, respectively), as the bark of these species contained higher levels of extractives. Conversely, the branches and stems of the same species recorded higher lignin and holocellulose contents, a result which is directly associated with the low concentration of extractives in these biomasses.

In general terms, forest biomass intended for energy production should have a high lignin content, as the higher the lignin content, the higher the calorific value (Esteves et al., 2023). The biomass from the species *Eucalyptus* sp. had higher lignin contents than that of *M. urundeuva*, with averages of 20.71% (stem), 20.19% (branch) and 17.26% (bark). Considering this, it is expected that the fixed and elemental carbon content will be higher in *Eucalyptus*, as lignin concentrates a greater amount of carbon within its structure. Furthermore, as noted by Saraiva et al. (2025), the lignin present in wood exhibits greater resistance to deterioration when subjected to high temperatures, resulting in slower combustion and the prolonged release of energy.

About the solubility in cold water, mean values ranging from 3.43% to 19.20% were found, with statistically significant differences between species and biomass types. It was observed that *Eucalyptus* sp. twigs had the lowest mean solubility value (3.43%), indicating greater resistance to weathering. In contrast, the bark of *M. urundeuva* recorded the highest value (19.20%), indicating greater susceptibility to leaching and, consequently, lower efficiency when stored under uncontrolled conditions. These results reinforce the importance of considering solubility as a criterion for selecting species for energy purposes, since the durability of biomass against weather conditions such as rain directly influences its quality.

Table 2 presents the mean values of the energy properties of the biomass. Analysis of variance indicated significant differences at the 5% probability level and revealed interaction between the factors for the parameters VM, FC, AZ, C, O, HHV, ED, CS and CVI. Regarding the hydrogen (H) content, the means did not differ statistically between species and biomass types, demonstrating the uniformity of this element in the materials evaluated.

The mean volatile matter (VM) content ranged from 81.62% to 88.97%, with statistically significant differences between species and types of biomasses. The *Eucalyptus* sp. stem recorded the lowest value (81.62%), whilst the *M. urundeuva* branch had the highest mean (88.97%), showing no statistical difference from the *Eucalyptus* sp. branch (88.48%). An inverse relationship was observed between VM and fixed carbon (FC), evident in the *Eucalyptus* sp. stem, which had lower VM and, consequently, higher FC (18.28%). Ferreira et al. (2024) highlights that high DM contents favor rapid ignition and initial combustion of biomass, although they generate energy for a shorter duration due to their volatile nature.

Table 2 – Energy properties of biomass from *Eucalyptus* sp. and *M. urundeuva*

Properties	**Biomass**	***Eucalyptus* sp.**	***M. urundeuva***	**Pr>Fc interaction**
VM (%)	Bark	86,33 aB (3,41)	86,12 aC (3,74)	*
	Twig	88,48 aA (1,52)	88,97 aA (1,64)	
	Trunk	81,62 bC (2,14)	87,71 aB (1,27)	
FC (%)	Bark	10,97 aB (23,29)	9,31 aB (35,23)	*
	Twig	11,19 aB (11,70)	10,31 aAB (11,77)	
	Trunk	18,28 aA (9,58)	11,92 bA (11,87)	
AZ (%)	Bark	2,70 bA (31,20)	4,57 aA (1,56)	*
	Twig	0,32 bB (18,29)	0,91 aB (2,70)	
	Trunk	0,10 bC (44,80)	0,61 aB (2,01)	
C (%)	Bark	46,27 aC (1,06)	45,11 bB (1,38)	*
	Twig	47,05 aB (0,48)	47,39 aA (0,44)	
	Trunk	48,79 aA (0,66)	47,35 bA (0,43)	
H (%)	Bark	5,92 aA (1,11)	5,82 aA (0,51)	ns
	Twig	6,07 aA (0,25)	6,05 aA (0,54)	
	Trunk	6,01 aA (0,29)	6,04 aA (0,18)	
O (%)	Bark	44,43 aB (1,55)	43,82 bB (1,23)	*
	Twig	45,52 aA (0,53)	45,48 aA (0,76)	
	Trunk	44,41 bB (0,67)	45,30 aA (0,42)	
HHV (Kcal/kg)	Bark	4409,37 aC (1,22)	4283,38 bC (1,59)	*
	Twig	4531,78 aB (0,54)	4494,40 bB (0,50)	
	Trunk	4684,45 aA (0,75)	4527,34 bA (0,49)	
ED (Kcal/cm³)	Bark	3179,97 bA (1,21)	4426,30 aA (1,59)	*
	Twig	2695,80 bB (0,54)	3545,34 aC (0,50)	
	Trunk	2530,93 bB (0,75)	3767,02 aB (0,49)	
CS (Kg/m³)	Bark	331,45 bA (1,06)	466,19 aA (1,38)	*
	Twig	281,89 bB (0,48)	371,11 aC (0,44)	
	Trunk	263,58 bC (0,66)	393,96 aB (0,43)	
CVI	Bark	0,53 aC (4,63)	0,43 aC (3,03)	*
	Twig	5,22 aB (18,70)	2,58 bB (2,07)	
	Trunk	15,76 aA (25,12)	3,71 bA (2,13)	

Source: Authors (2023)

In where: VM (volatile matter), FC (fixed carbon), AZ (ash), C (carbon), H (hydrogen), O (oxygen), HHV (Higher heating value), ED (energy density), CS (carbon stock) and CVI (calorific value index). Mean values followed by the same lower-case letter in the row and upper-case letter in the column do not differ from one another according to Tukey's test at a 5% probability level.

In this study, the dry matter (DM) content for *Eucalyptus* sp. was 88.48% in the branches and 81.62% in the trunk, figures close to those reported by Reis et al. (2024), who found 85.02% and 85.03%, respectively. This similarity suggests consistency between the studies and confirms the high proportion of volatiles in *Eucalyptus*. The bark of *M. urundeuva* had the lowest fixed carbon content (9.31%) compared to the other biomass types of the species, whilst the trunk of both species recorded high FC values. Biomass with a higher concentration of fixed carbon, as highlighted by Ferreira et al. (2024), prolongs the combustion process and thus increases energy efficiency. Thus, the higher the concentration of fixed carbon, the better the biomass becomes for energy generation, whether through direct burning or the production of charcoal, since carbon represents one of the most relevant elements in energy generation.

The *Eucalyptus* sp. stem had the lowest ash content (AC), at 0.10%, a figure consistent with typical values for the species, which are generally below 1%. In contrast, the bark of both species had higher ash contents than those observed in the twigs and stems. The ash content corresponds to inorganic substances that do not participate in combustion and are therefore undesirable for energy purposes. In addition to not contributing to energy generation, ash reduces the calorific value of biomass, as it occupies the fraction that could otherwise be composed of combustible material. Thus, an increase in ash content compromises combustion efficiency and limits the energy utilization of biomass (Reis et al., 2025).

According to Reis et al. (2012), the use of wood as an energy source requires its elemental characterization, as the biomass intended for this purpose must have a low oxygen content and high carbon and hydrogen contents. These chemical elements are directly related to the calorific value of the biomass. The *Eucalyptus* sp. stem recorded the highest carbon content, with an average of 48.79%, whilst the *M. urundeuva* bark had the lowest value, 45.11%, highlighting significant differences between those species. For hydrogen content, there was no statistically significant difference between the biomasses evaluated. Regarding the oxygen, the bark of *M. urundeuva* had the lowest content, with an average of 43.82%, and the branches of *Eucalyptus* sp. recorded the highest percentage, 45.52%, although this did not differ statistically from the branches of *M. urundeuva*.

The biomasses analyzed had average higher heating value (HHV) ranging from 4283.38 to 4684.45 kcal/kg, with statistically significant differences between species and types of biomasses. *Eucalyptus* sp. stems recorded the highest HHV, with an average of 4684.45 kcal/kg. This performance results from high fixed carbon and elemental carbon contents, which increase energy potential by providing more combustible material and prolonging combustion. Furthermore, the low ash content reduced the non-combustible inorganic fraction, allowing a higher proportion of mass to be effectively converted into energy. The combination of these factors ensured greater efficiency and calorific value for the *Eucalyptus* sp. trunk. The *M. urundeuva* bark biomass had the lowest Higher heating value (HHV), with an average of 4283.38 kcal/kg. Contrasted, the *Eucalyptus* sp. twig recorded the highest SC among the secondary biomass types, reaching 4531.78 kcal/kg.

In this study, the energy content of *Eucalyptus* sp. was 4,531.78 kcal/kg in the branches and 4,684.45 kcal/kg in the trunk. These values exceed those reported by Reis et al. (2024), who found 4,286.40 kcal/kg in the branches and 4,296.34 kcal/kg in the trunk. The comparison shows that, although both studies confirm the high energy potential of *Eucalyptus*, the results obtained here indicate a greater capacity for energy generation, particularly in the trunk.

Energy density (ED) corresponds to the amount of energy available in each volume of wood and is directly related to bulk density (BD). The higher the BD, the higher the ED tends to be, making the biomass more efficient for direct energy generation (Protásio et al., 2013). In this regard, *M. urundeuva* biomass performed better than that of *Eucalyptus* sp., with averages of 4426.30 kcal/kg (bark), 3767.02 kcal/kg (stem) and 3545.34 kcal/kg (twigs), representing statistically significant differences. These values reinforce the species' potential for energy applications, as higher energy density implies a greater amount of heat released per unit volume of biomass, favoring processes such as direct combustion and charcoal production.

In contrast, the stem of *Eucalyptus* sp. had the lowest energy density, with an average of 2,530.93 kcal/kg, which limits its efficiency and highlights the comparative advantage of *M. urundeuva* in the context of bioenergy. However, in this study, the biomass values for the stems and branches of *Eucalyptus* sp. were higher than those reported by Reis et al. (2024), who obtained 2,117.58 kcal/cm³ for branches and 2,442.45 kcal/cm³ for stems. This comparison shows that, even with a lower density than *M. urundeuva*, *Eucalyptus* maintains high and consistent energy performance, reinforcing its suitability for energy generation systems.

Average carbon stock (CS) values ranged from 263.58 to 466.19 kg/m³, with statistically significant differences between species and biomass types. The biomass values for *M. urundeuva* were higher than those for *Eucalyptus* sp., recording 466.19 kg/m³ (bark), 393.96 kg/m³ (stem) and 371.11 kg/m³ (twigs). Opposed to it, the stem of *Eucalyptus* sp. had the lowest EC, with an average of 263.58 kg/m³. These results reinforce the importance of EC for bioenergy purposes, as higher carbon stocks are directly related to higher wood density, whilst also reflecting the trees' capacity to fix and store atmospheric CO_2 through photosynthesis. Thus, in addition to indicating energy efficiency, EC enhances the potential for mitigating greenhouse gas emissions and reinforces the relevance of biomass in the context of renewable energy, which is considered a viable alternative with a smaller ecological footprint compared to conventional sources (Gheorghe et al., 2023).

According to Corradi (2021), the Calorific Value Index (CVI) is an essential parameter for assessing the quality of a fuel, as it incorporates desirable characteristics such as high calorific value, high wood density, low ash content (AC) and low moisture content (MC). Biomass from the stems of *Eucalyptus* sp. exhibited the best HVI, with an average of 15.76, a result associated with low AS and MC content, which increase combustion efficiency and reduce energy losses. In contrast, the bark of both species recorded the lowest CVI values, a consequence of the high ash and moisture contents, which reduce the proportion of effectively combustible material and compromise the energy quality of the biomass.

Among the biomasses studied, those from *M. urundeuva* showed lower CVI values compared to those from *Eucalyptus* sp. Although they recorded higher bulk density, the lower CVI performance due to higher concentrations of ash and moisture. These factors reduce effectively the combustible fraction and increase energy losses, resulting in a decrease in the index.

3.1 Pearson's correlation between physical, chemical and energy properties

Table 3 shows the presence of positive and negative correlations between the parameters analyzed, revealing interactions that directly influence the energy quality of the biomass. Positive correlations indicate that an increase in one variable is associated with an increase in another, as in the case of lignin, which showed a direct correlation with fixed carbon (0.53), carbon (0.54), HHV (0.54) and CVI (0.48). This means that higher lignin contents increase the energy potential of the biomass.

Table 3 – Pearson's correlation between the physical, chemical and energy properties of the species

Parameters	TE (%)	TL (%)	FC (%)	AZ (%)	C (%)	HHV (Kcal/ Kg)	ED (Kcal/cm³)	CVI	BD (Kg/ m³)
TE (%)	1								
TL (%)	-0,41	1							
FC (%)	-0,34	0,53	1						
AZ (%)		-0,40	-0,45	1					
C (%)	-0,79	0,54	0,82	-0,88	1				
HHV (Kcal/ Kg)		0,54	0,82	-0,88	1	1			
ED(Kcal/cm³)									
CVI		0,48	0,69	-0,47	0,67	0,67		1	
BD (Kg/m³)	0,76						0,92		1

Source: Authors (2023)

In where: total extractives (TE), total lignin (TL), fixed carbon (FC), ash (As), carbon (C), higher heating value (HHV), energy density (ED), Calorific Value Index (CVI) and bulk density (BD).

Negative correlations, on the other hand, show that an increase in one variable reduces the other, as observed between ash content and carbon (-0.88), HHV (-0.88) and CVI (-0.47). In this case, higher ash contents decrease the combustible fraction and reduce energy efficiency. Similarly, the negative correlation between extractives and lignin (-0.41) indicates that higher extractive contents reduce the proportion of lignin in the biomass, which was also reflected in negative correlations with fixed carbon (-0.34) and elemental carbon (-0.79).

Fixed carbon reinforced this pattern, correlating positively with carbon (0.82), HHV (0.82) and CVI (0.69), whilst showing a negative correlation with ash (-0.45). Energy density (ED), in turn, showed a strong positive correlation with bulk density (0.92), demonstrating that the physical structure of wood directly influences its capacity to generate energy.

These correlations demonstrate that it is not only the individual properties that must be considered, but also their interactions, since energy performance results from a combination of multiple factors. Correlation analysis therefore helps to understand which characteristics are decisive in selecting the most suitable species and biomass components for energy-intensive systems.

4 CONCLUSIONS

The results showed that *Eucalyptus* sp. exhibited greater energy potential, as evidenced by its high lignin and fixed carbon contents, higher calorific value and fuel value index, as well as lower ash content. Among the different components of the *Eucalyptus* sp. biomass studied, the stem stood out as the most suitable for direct combustion, confirming its suitability for use in energy systems.

The species *M. urundeuva* also exhibited favorable features for energy purposes, standing out for its higher bulk density and energy density in the biomass studied compared to *Eucalyptus* sp., properties that are desirable in materials intended for energy generation through direct combustion. However, it exhibited a lower average annual increment than that observed in *Eucalyptus* sp. At 13 years, both species exhibited distinct diameters (9.7 cm for *M. urundeuva* and 21 cm for *Eucalyptus* sp.), reinforcing the superiority of *Eucalyptus* growth in intensive production systems.

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