

BIOMASS YIELD AND BIOENERGY POTENTIAL OF STEM AND FOREST BY-PRODUCTS IN THREE *Eucalyptus* SPECIES

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ABSTRACT

Forest biomass is widely used as a biofuel for energy generation due to its renewable nature and favorable technological properties. However, information regarding the contribution of different tree components to biomass production and energy stock remains limited, particularly for fast-growing *Eucalyptus* species used in bioenergy systems. Therefore, this research aimed to evaluate the performance and energy stock of the stem and forest by-products in three *Eucalyptus* species. The data were collected from *Eucalyptus benthamii* (camden white gum), *Eucalyptus dunnii* (white gum), and *Eucalyptus saligna* (blue gum) trees at six-years-old, cultivated in the south of Brazil. The wood basic density, the wood calorific value and the dry biomass of the tree stems were determined, the dry biomass and the calorific value of the co-products (bark, leaves, and branches) were also determined. Finally, the biomass stock and energy yield of wood and by-products of the species used were determined. The stem contributed 66 % to 81 % in total biomass while the by-products 19 % to 34 %. The energy stock was over 360 GJ ha⁻¹ and 81 GJ ha⁻¹ for the stem and by-products, respectively. The stem showed the highest biomass stock and energy yield; however, forest by-products, particularly bark and branches, also presented substantial energy potential. These findings improve the understanding of biomass allocation and energy stock distribution among *Eucalyptus* tree components and demonstrate the

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Received: 02.06.2024 Accepted: 15.06.2026

importance of considering forest by-products as complementary feedstocks for bioenergy systems. Among the species evaluated, *Eucalyptus benthamii* showed the best overall performance, combining high biomass yield, favorable energy properties, and superior energy stock.

Keywords: Bioenergy, Forest biomass, forest by-products, energy stock, biomass allocation, *Eucalyptus*.

INTRODUCTION

Fossil fuels, with emphasis on the use of mineral coal converted into a driving force after the invention of thermal machines in the 18th century, were the main sources of energy that promoted the progress of industry worldwide and to this day continue to exert a strong influence on the global economy (Smil 2018, Yang *et al.* 2021). However, in recent decades the environmental impact caused using these non-renewable raw materials has been highlighted since they are the main providers in increasing the concentration of greenhouse gases (Soeder 2021, Osman *et al.* 2023a, Chen *et al.* 2023). Although non-renewable fuels still dominate primary energy generation, interest in lignocellulosic biomass as a biofuel has been gaining recognition due to increased global energy consumption and its attractive industrial-scale costs (Osman *et al.* 2023b). In addition, as a renewable source, lignocellulosic biomass offers environmental benefits by contributing to energy generation with low environmental impact (Lisý *et al.* 2020).

In 2021, about 50 % of global energy production was consumed in the form of heat, half of which was used in industrial processes (International Energy Agency 2022). In the global industry, 86 % of the energy consumed comes from renewable sources, with emphasis on the forestry and agricultural sectors (International Energy Agency 2022). Brazil stands out as the world's largest producer and consumer of renewable energy, accounting for 45 % - 49 % of its primary energy generation (Osman *et al.* 2023a). In 2022, the country's domestic energy supply reached 5,5 EJ, of which 36,8 % originated from lignocellulosic biomass. This energy was consumed mainly by the industrial sector, and the surplus was marketed to the electric power industry (Empresa de Pesquisa Energética 2023).

The planted tree sector in Brazil has a prominent position in the forest economy with a total of 10,52 million hectares of forest plantations of which about 8,10 million hectares are of genus *Eucalyptus* (Indústria Brasileira de Árvores 2025). *Eucalypts* are, therefore, the main source of raw material for the forest industries; they supply fuel that feeds primary energy generation from the biomass of timber or forest by-products, originating from the manufacturing processes and harvesting, respectively.

It is considered forest or timber by-products the resulting material from the harvesting process or the industrial processing of the logs, respectively, which until mid-2010 were considered as waste because they did not present any value to the commercial chain. However, this concept lost notoriety due to the use of these materials for energy purposes, conferring an economic, social, and environmental function (Spinelli *et al.* 2019).

The rising demand for the use of renewable energy has caused part of the forest by-products to be collected, and then consumed as fuel in the industrial units for heat generation, rather than leaving them in the forest to ensure nutrient cycling into the soil (Sahoo *et al.* 2022). Information about the contribution of tree components to total biomass production has been little explored in silvicultural and wood technology research, as studies have traditionally focused on the industrial use of the stem. However, by-products are important for energy production and make a great contribution to the total dry mass of the tree (Sette Júnior *et al.* 2020a). This knowledge gap limits the accurate assessment of biomass availability and energy stocks at the plantation level, which are essential parameters for bioenergy planning and the design of integrated forest biorefineries. Furthermore, insufficient information regarding the distribution of biomass among tree components hinders decision-making related to residue recovery, nutrient management, and the optimization of biomass utilization strategies in planted forests.

Therefore, concerning technology and the utilization of forest by-products, the bark component has stood out in research especially investigating its potential for use in biorefineries (Neiva *et al.* 2016, Neiva *et al.* 2018) and the production of pellets and briquettes for energy purposes (Sette Júnior *et al.* 2020b). It should be noted that the forest-based industry has been searching to optimize the usage of biomass from planted trees,

attempting to increase the efficiency in its use, which includes the utilization of other tree morphological components (Velvizhi *et al.* 2022).

In this sense, as the stem and forest by-products are potential biofuels for energy generation in the industrial sector (Flores *et al.* 2023), this research investigated if the stem, bark, branch, and leaf components present differences in energy. The general aim of this paper was to evaluate the performance and energy stock of the forest by-products and stem biomass in three species of *Eucalyptus*; the specific objectives were: (i) quantify the participation of each component in the total biomass; (ii) quantify the biomass production per component; and (iii) quantify the potential energy stock.

MATERIAL AND METHODS

Sample collection

Data were collected in an experimental plantation installed in the municipality of Canoinhas, state of Santa Catarina, Brazil; at a latitude of 26°07'37 "S, the longitude of 050°23'41 "W and altitude of 780 meters above sea level. The region's climate is "Cfb" according to the Köppen climate classification, with no dry season, fresh summers, and frequent frosts in June, July, and August; it has an average temperature of 17 °C and average annual rainfall between 1600- and 1900 mm year⁻¹ (Alvares *et al.* 2013).

The species of camden white gum (*Eucalyptus benthamii* var. *benthamii* Maiden & Cambage), white gum (*Eucalyptus dunnii* Maiden), and blue gum (*Eucalyptus saligna* var. *saligna* Sm.) were planted in 2011 under a 3 m × 3 m spacing, totaling 1,111 trees ha⁻¹. Sample collection was undertaken in 2017 when the plantation was six years old. In the first stage of data collection, a census-type inventory was carried out measuring diameters at breast height (DBH) at 1.30 m above ground level for all standing trees in the stand. Stand survival was not assessed during the inventory.

Subsequently, six trees per species were randomly selected, based on the DBH average, and harvested as close as possible to the soil for better use of the above-ground biomass; the total and commercial (minimum diameter of 5 cm) height were obtained with the use of a measuring tape and then determined the individual volumes with bark using the Smalian method.

To obtain the total fresh biomass in the field, the trees were separated into four components (stem, bark, branches, and leaves) and these were weighed with the use of a digital scale with a maximum nominal load capacity of 50 kg and precision of 0,1 kg. For the determination of physical, chemical, and energetic properties, wood disk samples were taken from the stem at 0 %; 25 %; 50 %; 75 % and 100 % concerning the total height, and for the other components about 0,6 kg were collected, with the fresh mass of all samples measured in the field.

Wood basic density and heating value

The wooden discs were divided into four wedges passing through the pith, and the two smaller wedges were destined for determining the wood basic density according to the ASTM D2395-17 (2017); the remaining wedges and samples of bark, branches, and leaves were dried in an oven at 105 ± 5 °C until they reached a constant mass. The materials were processed and then classified, whereby the material that passed through the opening of 40 mesh (0,420 mm) and was retained in 60 mesh (0,250 mm) was reserved for laboratory analysis according to the TAPPI T257 sp-21 (2021). For the assessment of the energy quality of the components, the higher heating value (HHV) (dry mass basis) was determined by a digital calorimeter model C-5000 (IKA, Staufen, Germany) according to the ASTM E711-23e1 (2023); and lower heating value (LHV) (Equation 1) (dry mass basis) was calculated according to procedures described in the standard ISO 18125:2017 (2017).

$$\text{LHV} = \text{HHV} - (0,206H) \quad (1)$$

Where LHV is a lower heating value (MJ kg^{-1}); HHV is a higher heating value (MJ kg^{-1}), and H is the hydrogen amount.

Biomass and energy stock

Initially, the dry matter content of each component was determined (Equation 2). The dry biomass per component (Equation 3), total dry biomass per individual (Equation 4), and the contribution of each component in the total biomass of the tree (Equation 5) were calculated.

$$DM_{ij} = \left(\frac{dm_{ij}}{fm_{ij}} \right) \times 100 \quad (2)$$

$$B_{ij} = FB_{ij} DM_{ij} \quad (3)$$

$$BT_j = \sum B_{ij} \quad (4)$$

$$\%B_i = \frac{B_{ij}}{BT_j} \quad (5)$$

Where DM_{ij} is dry matter content of component i of tree j (%); dm_{ij} is a dry mass in the oven of component i of tree j (kg); fm_{ij} is fresh mass measured in the field of component i of tree j (kg); B_{ij} is dry biomass of component i of tree j (kg); FB_{ij} is fresh biomass of component i of tree j (kg); BT_j is total dry biomass of the tree j (kg) and $\%B_i$ is the contribution of component i in total tree biomass (%).

To extrapolate the biomass amount per tree to the biomass amount per hectare, total dry biomass of the tree (BT_j) was multiplied by the number of trees in a hectare (1,111). Stand survival was not assessed at the time of sampling; therefore, the extrapolations were based on the nominal planting density established at plantation establishment (1,111 trees ha^{-1}) and assumed full stand survival. Consequently, the biomass values reported on a hectare basis should be interpreted as potential stand-level estimates.

The energy stock for each species was made based on the relation between dry biomass per component and lower heating value of the component so that it was calculated according to Equation 6 and Equation 7.

$$EP_{ij} = B_{ij} LHV_{ij} \quad (6)$$

$$EP_j = \sum EP_{ij} \quad (7)$$

Where EP_{ij} is potential energy stock of component i of tree j (MJ kg^{-1}); B_{ij} is dry biomass of component i of tree j (kg); LHV_{ij} is lower heating value of component i of tree j (MJ kg^{-1}); and EP_j is the potential energy stock of tree j (MJ kg^{-1}).

To extrapolate the energy value per tree to the energy value per hectare, potential energy stock of tree (EP_j) was multiplied by the number of trees in a hectare (1,111). Accordingly, the reported energy stock values per hectare represent potential estimates based on the nominal stand density.

Statistical procedures

The experiment was conducted in a completely randomized design in a 3 × 4 factorial arrangement (species × component), with six sampled trees per species. Each sampled tree was considered an experimental unit. For variables measured in the different tree components (bark, branches, leaves, and stem), observations were organized according to the factorial structure, using the six trees of each species as replicates. Data were analyzed using R software version 4.2.1 (R Core Team 2023). The effects of species and component were evaluated by analysis of variance (ANOVA), and when significant, means were compared using Tukey’s test at the 5 % significance level.

RESULTS AND DISCUSSION

Biomass yield

Brazil is a reference in *Eucalyptus* forestry technology reflecting the high averages in productivity compared to the rest of the world (Cunha *et al.* 2021). The plantations evaluated in this research showed low variation for the dendrometric variables (Table 1) and obtained average productivity of 40 m³ ha⁻¹ year⁻¹ - 45 m³ ha⁻¹ year⁻¹, and this performance is higher than the Brazilian average (32,7 m³ ha⁻¹ year⁻¹) (Indústria Brasileira de Árvores 2025), evidencing the high potential of the analyzed species in volume and biomass production.

Table 1: Average values of dendrometric variables.

Species	DBH (cm)	Ht (m)	Volume (m ³ ha ⁻¹)
<i>E. benthamii</i>	18,01 ± 1,10	21,85 ± 0,85	275 ± 1,33
<i>E. dunnii</i>	17,11 ± 0,53	21,82 ± 0,47	245 ± 0,51
<i>E. saligna</i>	17,04 ± 0,88	21,13 ± 0,64	257 ± 1,02

DBH: diameter at breast height, Ht: total height.

The stem is the morphological component with the greatest contribution to biomass production in eucalyptus trees (Simetti *et al.* 2018b). For blue gum (*Eucalyptus saligna* var. *saligna* Sm.) the stem contributed 81 %, for white gum (*Eucalyptus dunnii* Maiden) the contribution was 76 % while camden white gum (*Eucalyptus benthamii* var. *benthamii* Maiden & Cambage) it was 66 % (Figure 1), this implies that if this species is managed to use only the stem, camden white gum (*Eucalyptus benthamii* var. *benthamii* Maiden & Cambage) will produce the smallest number of by-products with potential for bioenergy application.

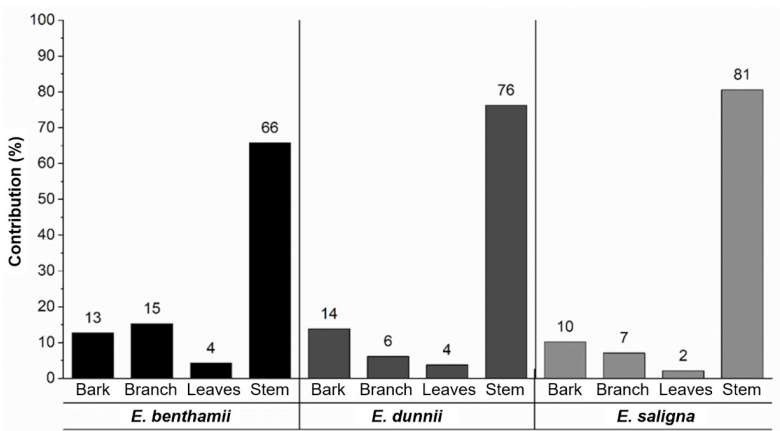


Figure 1: Contribution of each component in the total dry biomass of the tree.

The bark is the second most abundant component in biomass of the analyzed individuals for white gum (*Eucalyptus dunnii* Maiden) and blue gum (*Eucalyptus saligna* var. *saligna* Sm.), while the branches varied among the species, whereby in camden white gum (*Eucalyptus benthamii* var. *benthamii* Maiden & Cambage) it represented 15 % of the total biomass of the trees, twice as much as that observed in the other materials, justifying the low proportion of the stem to total dry biomass. The leaves showed low contribution, especially in blue gum (*Eucalyptus saligna* var. *saligna* Sm.), with only 2 %. Generally, the presence of bark in species of the genus *Eucalyptus* can vary between 10 % and 20 %, the content of branches can reach 10 %, and leaves between 4 % and 8 % (Dick *et al.* 2016, Simetti *et al.* 2018a, Silva *et al.* 2015).

The components showed biomass yield in different amounts, where the leaves and stem were the most statistically discrepant compared to bark and branches (Table 2).

Table 2: Average values for dry biomass of the different components of *Eucalyptus* trees.

Component	<i>E. benthamii</i>	<i>E. dunnii</i>	<i>E. saligna</i>
Bark (kg tree ⁻¹)	23,26 ± 1,33 aB	16,78 ± 0,92 bB	14,10 ± 1,03 bB
Branches (kg tree ⁻¹)	27,98 ± 0,67 aB	7,47 ± 0,75 bC	9,78 ± 0,37 bB
Leaves (kg tree ⁻¹)	7,76 ± 0,35 aC	4,55 ± 0,23 bD	2,85 ± 0,25 cC
Stem ^{ns} (kg tree ⁻¹)	123,97 ± 2,79A	92,47 ± 1,40A	111,04 ± 3,16A
Total	182,97 ± 2,64	121,27 ± 1,65	137,77 ± 3,28

^{ns}: non-significant for the species factor within the component factor at 95 % probability; equal lowercase letters in the line do not differ among species and equal uppercase letters in the column do not differ among components at 5 % significance level by Tukey’s test.

The stem did not present the statistical difference among the species, however, camden white gum (*Eucalyptus benthamii* var. *benthamii* Maiden & Cambage) showed the highest results in dry biomass for by-products (bark, branches, and leaves), justifying the high production of total dry biomass per tree. The same species obtained the highest results per hectare totaling 171 Mg ha⁻¹, while 55 Mg ha⁻¹ corresponds to forest by-products showing that it has room to improve the use of its biomass as a raw material in bioenergetic systems (Figure 2).

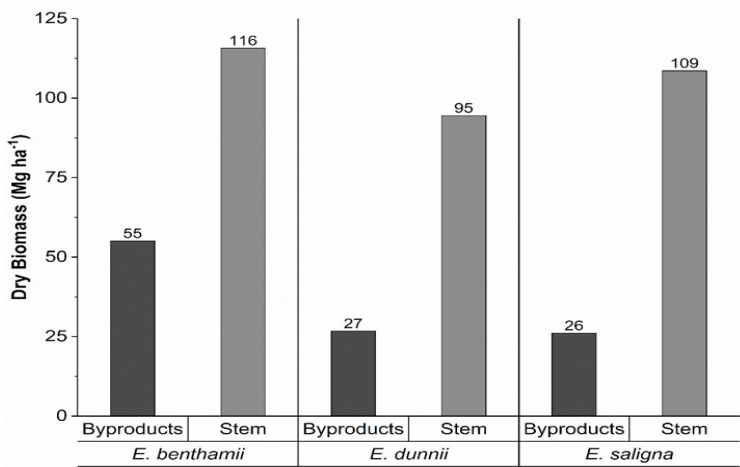


Figure 2: Dry biomass yield per hectare of the stem and by-products.

The yield of stem biomass in camden white gum (*Eucalyptus benthamii* var. *benthamii* Maiden & Cambage) was like that presented by Resquin *et al.* (2019) who observed an average of 104 Mg ha⁻¹, while for by-products it was higher than 34 Mg ha⁻¹ found by Simetti *et al.* (2018a) on 7-year-old trees.

Wood basic density and heating value

There was no statistical difference between the basic densities of the woods studied (p -value = 0,2712), the values found were 0,493, 0,499, and 0,476 g cm⁻³ for camden white gum (*Eucalyptus benthamii* var. *benthamii* Maiden & Cambage), white gum (*Eucalyptus dunnii* Maiden), and blue gum (*Eucalyptus saligna* var. *saligna* Sm.) respectively. Wood basic density is an important tool for the choice of potential species, because it may indicate, indirectly, the dry biomass yield and the potential energy stock contained in the material; the higher the basic density, the more suitable the wood is for bioenergy production, starting from a minimum value of 0,460 g cm⁻³ (Lengowski *et al.* 2020). For comparison purposes, blue gum (*Eucalyptus saligna* var. *saligna* Sm.) wood, widely planted in southern Brazil, has a basic density varying between 0,381 and 0,436 g cm⁻³ (Cremonez *et al.* 2019), that is, the three species studied have greater potential for stem biomass production as they are denser.

To evaluate the energy quality of the materials was determined the HHV and LHV, dry basis (Table 3); according to the result of the analysis of variance, it was found that there is a significant difference between the analyzed factors, equals for HHV and LHV.

Table 3: Higher and lower heating value of tree components.

Variable	Component	Species		
		<i>E. benthamii</i>	<i>E. dunnii</i>	<i>E. saligna</i>
HHV (MJ kg ⁻¹)	Bark	16,79 ± 0,03 aC	16,11 ± 0,11 bC	15,97 ± 0,14 bC
	Leaves	20,66 ± 0,11 aA	20,76 ± 0,03 aA	20,12 ± 0,08 bA
	Stem	18,32 ± 0,09 aB	17,79 ± 0,06 bB	17,95 ± 0,04 abB
	Branches ^{ns}	18,17 ± 0,04 B	17,99 ± 0,33 B	18,11 ± 0,07 B
LHV (MJ kg ⁻¹)	Bark	15,43 ± 0,03 aC	14,75 ± 0,12 bC	14,62 ± 0,14 bC
	Leaves	19,31 ± 0,12 aA	19,41 ± 0,03 aA	18,76 ± 0,09 bA
	Stem	16,16 ± 0,09 aB	16,44 ± 0,07 bB	16,60 ± 0,04 abB
	Branches ^{ns}	16,81 ± 0,04 B	16,64 ± 0,08 B	16,76 ± 0,08 B

HHV: higher heating value; LHV: lower heating value; ^{ns}: non-significant for the species factor within the component factor at 95 % probability for the Fisher's test; equal lowercase letters in the line do not differ among species; equal uppercase letters in the column do not differ among components at 95 % probability by Tukey's test.

Camden white gum (*Eucalyptus benthamii* var. *benthamii* Maiden & Cambage) was the species that presented the highest averages for the stem, leaves, and bark components. Analyzing the components, the leaves presented the largest amount of calorific energy released due to the structure of its chemical constituents rich in hydrocarbons (Kouki *et al.* 2023), similar values for leaf higher heating value were also reported in another study on *Eucalyptus* species, which found approximately 20,50 MJ kg⁻¹ (Habitzreiter *et al.* 2009). On the other hand, the bark obtained the lowest averages because of the high percentage of ash present in the composition of its biomass (James *et al.* 2012). The bark is the component that provides mechanical protection to the stem and presents a high accumulation of nutrients, these factors are the main justifications for the low result in calorific energy; the average HHV in *Eucalyptus* bark can vary from 15,06 to 17,15 MJ kg⁻¹ (Rocha *et al.* 2016, Simetti *et al.* 2018a, Bonfatti Júnior *et al.* 2025), where the ash content is the property that correlates negatively with the energy released decreasing the energy efficiency of biomass (Bonfatti-Júnior *et al.* 2023).

The averages obtained for HHV of the stem and branches did not differ statistically due to the similarity in the structural constitution. For the woody biomass of trees, HHV values close to 18,8 MJ kg⁻¹ are expected (Telmo and Lousada 2011).

Energy stock

In energy stock, camden white gum (*Eucalyptus benthamii* var. *benthamii* Maiden & Cambage) was the one that presented the highest averages among species; the stem was the component with the highest amount of stored energy due to its greater contribution to biomass yield than the other by-products (Table 4).

Table 4: Potential energy stock for *Eucalyptus* tree components.

Variable	Component	Species		
		<i>E. benthamii</i>	<i>E. dunnii</i>	<i>E. saligna</i>
Energy stock (GJ tree ⁻¹)	Bark	0,36 ± 0,10 aB	0,25 ± 0,05 bB	0,21 ± 0,12 bB
	Leaves	0,15 ± 0,02 aC	0,09 ± 0,01 bC	0,05 ± 0,01 cC
	Stem ^{ns}	2,11 ± 0,51 A	1,53 ± 0,23 A	1,85 ± 0,55 A
	Branches	0,47 ± 0,06 aB	0,12 ± 0,03 bC	0,16 ± 0,02 bB

^{ns}: non-significant for the species factor within the component factor at 95 % probability for the Fisher's test; equal lowercase letters in the line do not differ among species; equal uppercase letters in the column do not differ among components at 95 % probability by Tukey's test.

When extrapolating these results by area unit it is possible to have a better projection of the potential of these materials for bioenergetic use; white gum (*Eucalyptus dunnii* Maiden) and blue gum (*Eucalyptus saligna* var. *saligna* Sm.) presented a total energy stock in the order of 360 GJ ha⁻¹ and 698 GJ ha⁻¹, respectively. While studying the energy stock for white gum (*Eucalyptus dunnii* Maiden) in short-rotation plantations in Uruguay, Bentancor *et al.* (2019) there values were found below those observed in this study (345 GJ ha⁻¹).

Camden white gum (*Eucalyptus benthamii* var. *benthamii* Maiden & Cambage) was the species that stood out with a higher result for the total energy stock with about 766 GJ ha⁻¹, explained by the high biomass yield and, among components, the largest energy stock is in the stem (563 GJ ha⁻¹); a similar result was observed for this same material by Silva *et al.* (2015) when quantifying 560 GJ ha⁻¹ in the stem.

The potential energy stored in forest by-products should be highlighted due to the high quantity verified, camden white gum (*Eucalyptus benthamii* var. *benthamii* Maiden & Cambage) obtained the highest average with 203 GJ ha⁻¹, followed by white gum (*Eucalyptus dunnii* Maiden) (109 GJ ha⁻¹) and *E. saligna* (89 GJ ha⁻¹), considering the bark, branches, and leaves components. However, leaves should not be considered for the dimensioning of the demanding industry by three factors: (i) In Brazil, forest by-products remain on average up to 60 days in the site until they are collected, enough time for part of the leaves to dry out and fall to the ground; (ii) the leaves should remain on the forest site to provide nutrient cycling to the soil; (iii) as the material is not very dense, thermal machines like boilers and ovens are not adapted to use leaves as biofuel.

In this context, considering only the bark and branches components, the energy stock decreases an average of 20 %, with camden white gum (*Eucalyptus benthamii* var. *benthamii* Maiden & Cambage) containing 181 GJ ha⁻¹, followed by white gum (*Eucalyptus dunnii* Maiden) (98 GJ ha⁻¹) and *E. saligna* (81 GJ ha⁻¹). This shows that the biomass from forest by-products should be a rich and potential source of raw material to supply power generation systems from the transformation of this biomass via direct combustion because they are materials with lower costs, good energy performance and from renewable sources, favoring a reduction in the consumption of fossil fuels (Clauser *et al.* 2021).

The stem energy stock did not present statistical difference among the species, however, camden white gum (*Eucalyptus benthamii* var. *benthamii* Maiden & Cambage) showed the highest results in dry biomass for by-products (bark, branches, and leaves), justifying the high production of total dry biomass per tree. The same species obtained the highest results per hectare totaling 171 Mg ha⁻¹, while 55 Mg ha⁻¹ corresponds to forest by-products showing that it has room to improve the use of its biomass as a raw material in bioenergetic systems (Figure 2).

Although the sampling intensity adopted in this study is consistent with destructive biomass and bioenergy assessments commonly reported for *Eucalyptus* plantations, the results should be interpreted within the context

of the evaluated conditions. The analyses were based on six sample trees per species collected from a single plantation site at six years of age under specific environmental and management conditions. Therefore, biomass allocation patterns, biomass yield, and energy stock estimates may vary according to stand age, site productivity, climate, soil characteristics, genetic material, and silvicultural practices. Consequently, caution should be exercised when extrapolating the observed results to other production systems or growing conditions. Future studies involving multiple sites, age classes, and management regimes would contribute to a broader understanding of biomass distribution and bioenergy potential in *Eucalyptus* plantations.

CONCLUSIONS

The stem is the morphological component that most contributes to the total biomass yield of *Eucalyptus* trees, and the three species studied have a dendrometric performance greater than the Brazilian average. However, the forest by-products show a significant amount of biomass per hectare and a high energy stock, standing out as a potential raw material for bioenergy applications.

The wood basic densities of the species studied in this work can be considered high when compared to those of other *Eucalyptus* species exploited in Brazil.

It is worth mentioning that among the forest by-products, the leaves obtained a good energy performance due to its higher heating value; but it is recommended that this component remains on the plantation site to ensure the cycling of nutrients and incorporation into the soil.

The stem and branches presented similar heating values in all species.

All species presented great potential for bioenergy use, however, camden white gum (*Eucalyptus benthamii* var. *benthamii* Maiden & Cambage) stood out for its higher biomass yield, better energy performance, and higher energy stock for the stem and forest by-products.

This study contributes to reducing current uncertainties regarding biomass allocation and energy stock distribution among stem and forest byproducts in *Eucalyptus* plantations. The results demonstrate that, although the stem represents the largest biomass and energy reservoir, bark and branches also contribute substantially to the total energy stock and should be considered in biomass utilization strategies for bioenergy production. However, these findings were obtained under specific site, age, and management conditions and should therefore be interpreted within the scope of the evaluated plantation. Additional studies involving different ages, environmental conditions, and management regimes are recommended to confirm the broader applicability of the observed patterns.

Authorship contributions

E. A. B-J.: Resources, data curation, investigation, methodology, validation. R. S-O.: Resources, data curation, investigation, methodology, validation. B. M-C.: Conceptualization, supervision, funding acquisition, writing – original draft. E. C. L.: Visualization, methodology, project administration, software, writing – review & editing. D. A. D-S.: Data curation, investigation. Alan S. D-A.: Resources, methodology. U. K.: Methodology, visualization, writing – review & editing.

Conflict interest

The authors declare no conflicts of interest.

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