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SELECTION OF *Corymbia* AND *Eucalyptus* CLONES FOR FIREWOOD SUPPLY FOR THERMAL AND ELECTRICAL ENERGY GENERATION

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ABSTRACT

In Brazil, thermal and electric power generation from wood chips and agroforestry residues has expanded in regions favored by biomass availability and transportation logistics. Globally, wood stands out as a strategic renewable source, with potential for integration into cogeneration systems to enhance energy efficiency. The development and selection of new genotypes that meet the requirements for forest productivity and wood quality are important strategies for companies aiming to ensure a wood supply for bioenergy. The primary objective of this study was to investigate the differences in energy potential of new *Corymbia* and *Eucalyptus* clones intended for direct combustion in thermal and electrical energy cogeneration systems. We utilized the Scott-Knott hierarchical cluster analysis to classify the genetic materials based on the similarity of the evaluated properties. The study analyzed 16 genotypes of *Corymbia* spp., *Eucalyptus* spp., and their hybrids. In each treatment, corresponding to a genotype, three trees were harvested at 81 months of age with a medium diameter, spaced 6 m x 1,5 m totaling 48 sample units. We determined the basic and energy densities, elemental chemical composition, higher, lower, and useful heating values, and available energy. Among the *Eucalyptus*

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genus, clone 2 *Eucalyptus cloeziana* (gympie messmate) excelled in basic and energy densities, and useful heating value. Within the *Corymbia* hybrids and across all genetic materials evaluated, clone 4 exhibited the best performance in providing quality wood to meet the needs of bioenergy projects intended for thermal and electrical energy cogeneration systems. This superiority is attributed to its high basic and energy densities, available energy, and useful heating value, coupled with the best results in the combined analysis of average annual increase and wood dry weight increase.

Keywords: Biomass energy, Brazil, Cogeneration, *Corymbia spp*., *Eucalyptus spp.*, energy density, wood biomass, wood fuels.

INTRODUCTION

In the context of the energy transition, it is essential to implement power generation projects that prioritize the reduction of coal, natural gas, oil, and their derivatives, given their substantial contribution to the intensification of climate change. Firewood obtained from planted forests significantly contributes to the sustainable energy mix worldwide (Siarudin *et al.* 2023). Wood possesses unique physical and chemical characteristics, unmatched by other energy materials. Its versatility has spurred increased utilization in recent years (Qing *et al.* 2021). However, to ensure success in forestry projects focused on bioenergy with short-rotation species, it is essential to select new hybrids that are more efficient at converting nutrients and biomass (Barros *et al.* 2024).

As a renewable resource, wood captures carbon in forests and stores it as biomass, significantly contributing to the reduction of greenhouse gas emissions (Boiger *et al.* 2024). A study across seven emerging countries demonstrated that biomass usage in energy generation from 2000 to 2018 mitigated CO_2 emissions, confirming its vital role in achieving the sustainable development goals (SDGs) (Gyamfi *et al.* 2021).

In the forestry sector, several companies have replaced fossil fuel-powered boilers with biomass-fueled ones, indicating a shift toward new technological pathways for decarbonization (IBA 2023). resulting in a total of 48 sample units

In Brazilian thermoelectric plants, sugarcane bagasse is the primary biomass source, generating electricity at 27,3 % a figure lower than that from fossil fuels (9 % coal, 31,4 % natural gas, 23,7 % petroleum derivatives). The most prevalent forest-origin biomass in Brazil is black liquor at 6,2 % pointing to the potential for expanding this and other biofuels (ANEEL 2023). Projected sustainability methods estimate that the total potential contribution of bioenergy by 2050 could range between 110 and 245 EJ/year (Wu *et al.* 2019, Dias *et al*. 2021).

The potential cogeneration market encompasses industrial sectors that require substantial amounts of steam and electricity as part of their processes, including the pulp and paper, chemical and petrochemical, steel, sugar and alcohol, food, beverage, and textile industries (EPE 2022).

According to Bilgili *et al.* (2015) and Toklu (2017), energy cogeneration in biomass combustion systems is essential, achieving conversion efficiencies of 80 % to 90 % into electrical energy, compared to just 17 % to 33 % in conventional steam turbine systems.

The selection of genetic materials for producing firewood with higher energy conversion efficiency necessitates comprehensive studies on aspects such as chemical composition, heating value, and the basic and energy densities of the wood. This data is crucial for selecting clones in breeding programs designed to expand planted areas for bioenergy production (Silva *et al*. 2022, Vieira *et al*. 2023).

Furthermore, selecting new genetic materials that can adapt to the intense temperature and precipitation variations brought about by climate change is vital for the efficiency of the bioenergy sector (Massuque *et al*. 2024).

Given the substantial volume of wood required for bioenergy production, whether as firewood, chips, or charcoal, *Corymbia* and *Eucalyptus* have emerged as leading materials (Massuque *et al*. 2023).

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To fulfill the requirements of bioenergy projects through energy forests, it is essential to identify genotypes that excel in converting raw materials into energy. The main objective of this study was to classify new *Corymbia* and *Eucalyptus* clones as to their suitability in direct combustion within thermal and electrical energy cogeneration systems.

MATERIAL AND METHODS

The study involved collecting three medium-diameter trees from each of 16 genotypes, all 81 months old and spaced at 6 m x 1,5 m, yielding a total of 48 sample units. The experimental plantations are owned by a charcoal production company located in Itamarandiba, Minas Gerais (17º44'45" S, 42º45'11" W, at an altitude of 1000 m). Detailed descriptions of the genotypes used and their dendrometric data are provided in Table 1.

Table 1: Description of *Corymbia* and *Eucalyptus* genotypes.

Clone	Genotypes	% bark (2)	AAI (3) w/o bark ($m^3 \cdot ha^{-1} \cdot yr^{-1}$)	AAI (4) w/ bark ($m^3 \cdot ha^{-1} \cdot yr^{-1}$)
1	*C. citriodora x C. torelliana*	13,9	26,2	30,5
2	*E. cloeziana*	23,4	37,9	49,6
3	*C. citriodora x C. torelliana*	16,5	43,2	51,7
4	*C. citriodora x C. torelliana*	12,9	51,2	58,8
5	*C. citriodora x C. torelliana*	14,4	26,5	30,9
6	*E. urophylla x Eucalyptus spp.*(1)	10,5	41,2	46,1
7	*E. urophylla x Eucalyptus spp.*(1)	9,7	48,7	54
8	*E. urophylla x Eucalyptus spp.*(1)	10,6	55,6	62,2
9	*E. grandis x E. urophylla*	9,9	30,6	34
10	*E. urophylla x (E. camaldulensis x E. grandis)*	10,8	41	45,9
11	*(E. camaldulensis x E.grandis) x E. urophylla*	9,3	46,9	51,8
12	*(E. camaldulensis x E. grandis) x E. urophylla*	8	48,4	52,6
13	*(E. camaldulensis x E. grandis) x E. urophylla*	9,9	55,5	59,5
14	*(E. camaldulensis x E. grandis) x E. urophylla*	7,7	46,9	50,8
15	*(E. camaldulensis x E. grandis) x E. urophylla*	9,9	41,8	46,4
16	*E. urophylla x E. pellita*	11,1	56,7	63,8

(1) Spontaneous hybrid of *Eucalyptus* spp.; (2) Average value weighted by tree volume; (3) AAI - Average annual increase without bark; (4) AAI - Average annual increase with bark. Average annual increase with and without bark, calculated by the Smalian method.

For wood analysis, discs (approximately 7 cm thick) were sectioned from specific distances from the base of the tree: the base (0 % position), diameter at breast height (DBH), and 25, 50, 75 and 100 % of the commercial height. Each disc was subdivided into four parts, using the medullary region as a reference point. Two opposite quarters were ground into sawdust using a Wiley mill, following the TAPPI 257 CM-85 standard (2001). The samples were then combined to form a composite sample. This composite sample from each tree was analyzed for chemical properties and higher heating value. The remaining two opposite quarters were used to determine the basic density of the wood. Figure 1 illustrates the sequence of these steps.

Figure 1: Preparation of samples for determining the physical and chemical properties of wood. (a) Partial view of the experimental plot; (b) Cut discs from the trunk; (c) Distance of the discs measured from the base of the tree; (d) Wood discs; (e) Samples for determining basic density; (f) Sawdust for determining chemical properties.

The basic density of wood was calculated using the average values estimated by the arithmetic mean of the densities from opposite quarters, weighted by the volume of the sections along the trunk, as depicted in Equation 1 (Vital 1984):

$$BD = \frac{\sum_{i,j=1}^{n} \left(\frac{BDi + BDj}{2} \right) vi}{\sum_{i=1}^{n} Vi} \quad (1)$$

Where BD: basic density of wood (kg/m^3); BDi: basic density of disk i; BDj: basic density of disk j; vi: volume of section i using Smalian's formula (m^3); and Vi: total volume (m^3).

The increase in wood dry weight (in t ha^{-1}.yr^{-1}) was determined from the values of average annual increase (AAI) and basic density of wood (BD), using Equation 2.

$$DWI = AAI \ x \ BD \quad (2)$$

Where DWI: wood dry weight increase (t.ha^{-1}.year^{-1}); AAI: average annual increase (m^3.ha^{-1}.yr^{-1}); and BD: basic density of wood (kg/m^3).

The elemental chemical composition of wood was analyzed in duplicate, in a CHNS-O elemental analyzer (Vario MICRO cube) (Paula *et al*. 2011). To enhance accuracy, the ash content was subtracted.

The immediate chemical composition of wood was calculated according to ABNT NBR 8112 (1986).

To determine the upper heating value of wood, an IKA300 adiabatic bomb calorimeter (EN 14918 (2010)) was employed.

The lower heating value was calculated by Equation 3:

$$LHV = HHV - \left(600\left(\frac{9H}{100}\right)\right) \quad (3)$$

Where LHV = lower heating value of wood (in $MJ.kg^{-1}$); HHV = higher heating value of wood ($MJ.kg^{-1}$); and H = hydrogen content (%).

The useful heating value (UHV) was calculated using Equation 4.

$$UHV = LHV(1-m) - (600m) \quad (4)$$

Where UHV = useful heating value of wood ($MJ.kg^{-1}$); LHV = lower heating value of wood ($MJ.kg^{-1}$); and m = wood moisture content (%).

Thermal energy generation was estimated based on the energy density of wood (EDW), calculated as the product of the higher heating value (HHV) and the basic density of wood, according to Equation 5:

$$EDW = BD\ x\ HHV \quad (5)$$

Where EDW = energy density of wood ($GJ.m^{-3}$); BD = basic density (kg/m^3); and HHV = higher heating value ($MJ.kg^{-1}$).

The energy potential or available energy of wood ($kWh.ha^{-1}.yr^{-1}$) was determined using Equation 6:

$$AE = WDW\ x\ HHV \quad (6)$$

Where AE = available energy ($kWh.ha^{-1}.yr^{-1}$); WDW = wood dry weight ($t.ha^{-1}.yr^{-1}$); and HHV = higher heating value of wood ($MJ.kg^{-1}$).

The wood property data obtained from the analyses were evaluated using descriptive analyses to ascertain measures of dispersion and position. Subsequently, an analysis of variance was conducted, followed by the application of the Scott-Knott cluster test at a 95 % probability level, using R statistical software (R Core Team 2021).

RESULTS AND DISCUSSION

The genetic materials evaluated exhibited significant differences in terms of volumetric growth and dry weight production of wood, crucial indicators for genetic selection as they directly influence the planning of forestry implementation activities. Table 2 presents the mean values and respective measures of dispersion for each property.

The coefficient of variation for the basic density of the wood was approximately 12 %. This physical property is strongly correlated with other significant wood properties (Gonçalves *et al*. 2009, Cruz *et al*. 2019).

Accordingly, distinct groups were formed based on other properties of interest for selecting genetic materials intended for the generation of thermal and electrical energy.

Table 2: Mean values and descriptive analysis of the properties of the wood of the different clones.

Property	Mean value
Basic density (kg/m^3)	533 (62,2)* (11,67)**
Average annual increase (m^3·ha^{-1}·yr^{-1})	49,3 (10,2) (20,77)
Increase in wood dry weight (t·ha^{-1})	181,8 (36,6) (20,14)
Carbon (%)	49,1 (0,43) (0,87)
Hydrogen (%)	5,9 (0,16) (2,66)
Oxygen (%)	44,6 (0,44) (0,98)
Nitrogen (%)	0,07 (0,02) (28,6)
Ash (%)	0,34 (0,11) (32,6)
Upper heating value (MJ·kg^{-1})	19,6 (0,32) (1,64)
Lower heating value (MJ·kg^{-1})	18,2 (0,32) (1,74)
Useful heating value (MJ·kg^{-1})	12 (0,22) (1,84)
Energy density (GJ·m^{-3})	10,4 (1,35) (12,9)
Available energy (kWh·ha^{-1}·yr^{-1})	121463 (24695) (20,3)

*Standard deviation; ** Coefficient of variation (%)

In the statistical clustering by the Scott-Knott test, the useful heating value was considered, reflecting the energy required to evaporate water during the endothermic phase of combustion.

Cluster analysis of the clones revealed the formation of up to six groups for certain properties critical to bioenergy projects (Table 3). This classification demonstrated that the new genetic materials evaluated possess very distinct characteristics, which directly affect the quality of the raw material intended for energy generation. The clones were ranked in descending order, from those with the best performance (group I), showing statistically superior results for a given property, to those with the worst performance (group VI), with statistically inferior results compared to the others.

Table 3: Grouping of clones for the properties of wood intended for thermal and electrical energy generation by the Scott-Knott test.

Wood property	Group					
	I	II	III	IV	V	VI
Basic density (kg/m³)	2;4	1;5	6;9;15;10	3;8	16;13;12;7	11;14
Average annual increase ($m^3 \cdot ha^{-1} \cdot yr^{-1}$)	16;8;13;4	7;12;11;3;14;2;15;6;10	9;5;1			
Increase in wood dry weight ($t \cdot ha^{-1}$)	4	8;2;16;13	3;7;12;6; 10;11;14	9;1;5	-	-
Useful heating value ($MJ \cdot kg^{-1}$)	1;2;10;15;4;5;6	13;12	11;8;3;7	14;9;16	-	-
Energy density ($GJ \cdot m^{-3}$)	2;4;1	5	6;15;10;9	3;8	13;12;7;16	11;14
Available energy ($kWh \cdot ha^{-1} \cdot yr^{-1}$)	4	2;8;16;13	3;7;6;15; 12;10	11;14;1;5;9	-	-

In the analysis of the basic density of the wood, four clones stood out in the first two groups, three of which belonged to the genus *Corymbia*. Specifically, the basic densities of the hybrids of lemon-scented gum (*Corymbia citriodora* (Hook.) K.D.Hill & L.A.S.Johnson) x cadaghi (*Corymbia torelliana* (F.Muell.) K.D.Hill & L.A.S.Johnson) (clones 4, 1, and 5) were 626, 613, and 597 kg/m³, respectively. Meanwhile, clone 2, representing the genus *Eucalyptus* in these groups, had a basic density of 637 kg/m³.

The average density for the *Corymbia* hybrids was similar to that reported by Loureiro *et al*. (2019) at 597 kg/m³. Mean values for gympie messmate (*Eucalyptus cloeziana* F.Muell) were similar to those reported by Pereira *et al*. (2000) and were lower than those observed by Cabral *et al*. (2006) and Paes *et al*. (2015). Although exhibiting good volumetric growth, the tri-cross hybrids evaluated in this study (clones 10 to 15) had low wood dry weight production and did not excel in the key properties targeted for bioenergy generation.

In a combined analysis of indicators for increase in volume and dry weight of wood, the best performance was observed for the hybrid of lemon-scented gum (*Corymbia citriodora* (Hook.) K.D.Hill & L.A.S.Johnson) x cadaghi (*Corymbia torelliana* (F.Muell.) K.D.Hill & L.A.S.Johnson) (clone 4). This result places this genetic material in a significant position for energy efficiency studies, potentially reflecting important differences in the required planting areas.

Sabatti *et al*. (2014), when evaluating six different poplar (*Populus*) genotypes for biomass production, planted under high-density spacing with multiple short-rotation cycles in northeastern Italy, reported an average biomass yield ranging from 16 to 20 t ha^{-1} $year^{-1}$ and a higher heating value ranging from 18.96 to 19.61 $MJ \cdot kg^{-1}$. Using the same short-rotation coppice technique in plantations in Poland, Berbec and Matyka (2020) obtained for *Populus L*. a potential dry wood yield of 15.8 t ha^{-1} $year^{-1}$ and a higher heating value of 17.9 $MJ \cdot kg^{-1}$.

In an assessment of the potential of eucalyptus wood for industrial thermal energy generation, Miranda *et al*. (2017) reported basic density and useful heating values of 500 and 11,3 $MJ.kg^{-1}$ (with a moisture content of 35 %), respectively. In contrast, this study found the basic density and useful heating values to be 513 kg/m³ and 12 $MJ.kg^{-1}$ for *Eucalyptus*, and 591 kg/m³ and 12,1 $MJ.kg^{-1}$ (moisture content: 30 %) for *Corymbia* hybrids, respectively.

For *Eucalyptus*, Ribeiro *et al*. (2021) obtained energy density values ranging from 8,9 to 10,7 $GJ.m^{-3}$, which align with the mean value of 10 $GJ.m^{-3}$ found for the eucalyptus hybrids evaluated in this study. In comparison, Jesus *et al*. (2017) found an average energy density between 5,9 and 7,5 $GJ.m^{-3}$ in six-year-old trees of five eucalyptus species, which is lower than the value found in this study. The genetic materials belonging to group I exhibited an average energy density value that was 25 % higher than that of the other genetic materials distributed across the other groups. For raw materials potentially intended for combustion in boilers, the genetic materials in group I could offer numerous advantages in energy conversion, leading to savings by reducing total planting areas, transportation, storage, and the supply of firewood to the boiler, among other factors.

For the *Eucalyptus* hybrids, the available energy varied between 85455 and 150615 $kWh.ha^{-1}.yr^{-1}$. Among the *Corymbia* hybrids, the performance of clone 4 was notable, with an average value of 174507 $kWh.ha^{-1}.yr^{-1}$. This value is 48 % higher than the average value obtained for the other genetic materials evaluated, suggesting both direct and indirect benefits from biomass conversion into electrical energy.

CONCLUSIONS

Among the clones tested, the hybrids of lemon-scented gum (*Corymbia citriodora* (Hook.) K.D.Hill & L.A.S.Johnson) x cadaghi (*Corymbia torelliana* (F.Muell.) K.D.Hill & L.A.S.Johnson) (clones 1, 4, and 5) and *E. cloeziana* (clone 2) were recommended due to their operational advantages for bioenergy projects; particularly, their superior energy production per unit volume of wood.

This efficiency results in reduced demand for forest plantation areas and offering numerous operational advantages that enhance the conversion efficiency of energy cogeneration systems.

The best-performing genetic materials identified in this study should be further investigated with regard to other properties relevant to forest biomass, as well as to confirm the expected yield performance in large-scale plantations.

The results suggest that the best-performing genetic materials constitute a promising renewable alternative for cogeneration systems, demonstrating competitive technical and environmental advantages aligned with the principles of a low-carbon economy.

Authorship contributions

W. P. S-J.: Investigation, formal analysis, writing – review & editing. A. C. O-C.: Project administration, conceptualization, funding acquisition. A. M. M. L-C.: Supervision. I. F-D.: Validation. L. A. C-R.: Resources, methodology. L. P-O.: Investigation. F. J-J.: Data curation. J. D-M.: Data curation.

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