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Classification of young *Corymbia* genotypes for steelmaking charcoal production based on their wood properties

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Abstract

Background: The continuous assessment of new genotypes is essential to boost industries such as that for charcoal production. This is because wood properties can significantly change among different genotypes. The aim of the present study is to assess the wood quality of different *Corymbia* genotypes to identify those with desirable features and to improve the ability to classify and select the best genotypes for charcoal production.

Methods: Different *Corymbia* genotypes were assessed, including two progenies and nine clones. Trees in the age group 3 and 4 years were collected from two trial crops in Minas Gerais State, Brazil, in collaboration with a company from the steel sector. Genotype assessment demanded several wood analyses focused on physical, chemical, energy and anatomical parameters. The collected data were subjected to multivariate analysis to cluster the genotypes. This procedure allowed classifying the genotypes presenting the most desirable features for charcoal production.

Results: The study revealed significant variations in *Corymbia* genotypes' wood density, bark features, chemical composition, energy and anatomical features. Genotypes were categorised into different groups based on wood and bark density, bark thickness and content, and heartwood content. Notably, genotype influenced parameters such as ash, volatile matter and fixed carbon content. Total extractives, lignin and holocellulose content showed significant variability across genotypes. Genotypes did not significantly affect energy composition, except for energy density. Principal component analysis highlighted key wood properties that contribute to data variability in order to help genotype classification.

Conclusions: The study provides understandable insights into the wood quality of *Corymbia* genotypes, and points out that wood properties work as reliable indicators to classify and select superior *Corymbia* genotypes for charcoal production. These properties reasonably predict the impact of raw material features on charcoal quality in a quite accurate way. All assessed genotypes emerged as having promising initial potential for charcoal production or for other energy applications, and it also indicates that *Corymbia* wood properties were comparable to, or even better than, those of genus *Eucalyptus*.

Keywords: Bioenergy; breeding; clones; progenies; wood quality

Introduction

Brazil holds a prominent position as one of the world's leading charcoal producers and consumers. The country extensively employs charcoal as a thermoreducer in pig iron, steel and metal alloy manufacture. Brazil has an abundant wood source for charcoal production given its 10.5 million hectares of planted forest, besides playing a crucial role in global steel production (Bichel & Telles 2021; IBA 2025). Wood from different *Eucalyptus* species, including hybrid clones, is the primary raw material source for energy purposes (Loureiro et al. 2019). This genus stands out in the country for its adaptability to different climate and soil gradients, high yield and for producing high quality wood aimed at conversion into charcoal, which is the very target of the steel industry. However, forests planted with this genus are not enough to meet the growing demand for charcoal. Current concerns with wood supply for charcoal production are timely due to climate change uncertainties resulting from global warming. These uncertainties have been threatening planted forest yield and, consequently, wood production (Protásio et al. 2021).

Insufficient *Eucalyptus* spp. wood supply underscores the relevance of breeding new genotypes of other species. This effort is pivotal to boost charcoal production, establish non-commercial genotypes for energy applications and to standardise technologies for charcoal-production wood. Consequently, it helps in improving financial returns and diversifying the wood-based energy matrix. The primary challenge faced by breeding programs aimed at increasing charcoal production lies on shortening the harvesting cycle while simultaneously enhancing wood quality and charcoal yield parameters in order to develop new superior genotypes (Pereira et al. 2021). Given the several consequences of global climate change, the urgent development of new superior genotypes is necessary to address yield in areas facing plantation yield and wood quality decrease issues. It is essential to prevent raw material supply shortage for charcoal production (Silva et al. 2022a).

Corymbia species, which were previously classified as belonging to genus *Eucalyptus* (until 1995), are emerging as promising candidates for charcoal production and for potentially completing or replacing traditional *Eucalyptus* species (Damacena et al. 2021). These species stand out for their desirable wood quality, which is featured by high wood density —more than 500 kg m^{-3}, on average. —(Araujo et al. 2023), high extractives content (Loureiro et al. 2019) and low moisture content (Rocha et al. 2024). In addition, they show high charcoal yield and tolerance to several pests, diseases and environmental stress such as wind, cold, frost and drought, as well as excellent vegetative propagation capacity (Lee 2007). Another advantage of genus *Corymbia* lies in its ability to propagate and hybridise genotypes with superior reproductive and developmental potential in comparison to pure species. This process leads to increased biomass production, growth and rooting rates (Reis et al. 2014). Some well-known species, such as *C. citriodora* subsp. *citriodora*, *C. citriodora* subsp. *variegata*, *C. henryi*, and *C. torelliana,* and their interspecific hybrids, have already been assessed (Moutinho et al. 2017; Melo et al. 2024; Loureiro et al. 2021; Rocha et al. 2024); however, the continuous assessment of new genotypes, even from known cross-breeding, is essential to improve industries such as charcoal production, mainly because wood features can significantly change among them. Researchers and industries, can identify genotypes with desirable properties by improving the capacity, classification and selection of the best genotypes for charcoal production by assessing new genotypes.

Numerous studies point out the promising potential of genus *Corymbia* for charcoal production, but a critical gap remains in using wood quality features as criteria to classify and select superior genotypes. Oftentimes, the selection of *Eucalyptus* and *Corymbia* genotypes deeply depends on genetic parameters; therefore overlooking wood quality parameters as crucial for charcoal production efficiency. The process to select genotypes for charcoal production can be more understandable by integrating wood quality parameters, such as wood density, bark features, heartwood content, chemical and energy composition and anatomical features. Furthermore, wood parameters inclusion can make the identification of superior genotype easier and promote a more logical approach to charcoal production. Therefore, the aim of the present study was to assess the wood quality of different *Corymbia* genotypes by addressing two questions: i) Are wood properties good parameters for breeding programs to classify and select superior *Corymbia* genotypes? and ii) Is the wood quality of *Corymbia* genotypes comparable to, or even better than, that of *Eucalyptus* species targeting high-quality charcoal production?

Methods

Study site, genotypes and wood sampling

The study was carried out in trial crops set between January 2018 and February 2019 in Bom Despacho and Martinho Campos municipalities, Minas Gerais State, Brazil, in collaboration to ArcelorMittal S.A. The stands were planted at density of 1.333 tree per hectare in Red Dystrophic Oxisoil soil type based on the following management: subsoiling (0.3% boron + 0.2% zinc + 0.2% copper), dolomitic limestone application (relative neutralising power > 90%), first fertiliser application (NPK 18-00-18 + 4% sulphur + 1% boron) and second fertiliser application (NPK 08-00-32 + 3% sulfer + 0.7% boron). Climate in the region is classified as *Cwa*, which is a subtropical type featured by dry winter and mild temperature (yearly mean temperature of 22.5 °C), and hot and rainy summer (yearly mean rainfall = 1275 mm), according to the Köppen's classification (Alvares et al. 2013) (Table 1).

The growth and site features of the two progenies and of nine *Corymbia* hybrid clones that were assessed in this study are described in Table 1. All progenies and clones were created through controlled pollination and they are young genotypes currently assessed in field trials.

TABLE 1: Growth and site features of young *Corymbia* genotypes.

Genotype	**Type**	**Code**	**DBH**	**Lat.**	**Long.**	**Alt.**	**Age**
C. torelliana x *C. henryi*	Progeny	PTH	15.3	19°34’35’’S	45°20’27’’W	754	3
C. torelliana x *C. maculata*	Progeny	PTM	16.1	19°33’42’’S	45°20’8’’W	763	4
C. torelliana x *C. citriodora* x *C. maculata*	Tri-clone	CTCM	13.5	19°33’42’’S	45°20’8’’W	763	4
C. torelliana x *C. maculata*	Clone	CTM1	12.6	19°25’43’’S	45°20’27’’W	754	4
C. torelliana x *C. maculata*	Clone	CTM2	12.9	19°25’43’’S	45°20’27’’W	754	4
C. torelliana x *C. citriodora*	Clone	CTC1	12.0	19°25’43’’S	45°20’27’’W	754	3
C. torelliana x *C. citriodora*	Clone	CTC2	12.1	19°25’43’’S	45°8’44’’W	740	3
C. torelliana x *C. citriodora*	Clone	CTC3	12.6	19°25’43’’S	45°8’44’’W	740	3
C. torelliana x *C. citriodora*	Clone	CTC4	16.1	19°25’43’’S	45°8’44’’W	740	3
C. torelliana x *C. citriodora*	Clone	CTC5	12.9	19°25’43’’S	45°20’27’’W	754	4
C. torelliana x *C. citriodora*	Clone	CTC6	15.5	19°25’43’’S	45°20’27’’W	754	4

Where: DBH = diameter at breast height over bark as the mean of 3 trees (cm); Lat. = latitude (m); Long = longitude (m); Alt = altitude (m) and Age (years-old).

These genotypes are part of ArcelorMittal’s breeding programme, which aims at classifying and selecting superior *Corymbia* genotypes. The ultimate goal is to grow these superior genotypes at commercial scale for steelmaking charcoal production purpose.

An important observation is that *C. torelliana* x *C. maculata* clones (CTM1 and CTM2) do not derive from the *C. torelliana* x *C. maculata* cross-breeding progeny. These clones represent a different development line within the breeding program that have undergone a separate cultivation process to refine their unique features. Although the herein assessed *Corymbia* genotypes arise from the cross-breeding of top-quality charcoal, it is essential to emphasise that progenies and clones currently under assessment have been selected to show improved traits in compliance with the company´s objectives. Therefore, they represent innovative genotypes presenting features yet to be comprehensively assessed.

Criteria outlined by the company’s clonal testing selection programme were followed to assess wood physical, chemical, energy and anatomical properties. Three trees from each progeny and clone presenting average diameter were selected totalling 33 sampled trees. Trees located on the borderlines or showing signs of any disease were excluded from the study. One 5-cm-thick disc (including bark) was meticulously removed from specific longitudinal stem points after tree felling: at 0% (base of the three), at DBH, as well as at 25%, 50%, 75% and 100% commercial height by taking into consideration the minimum diameter of 5 cm (Figure 1).

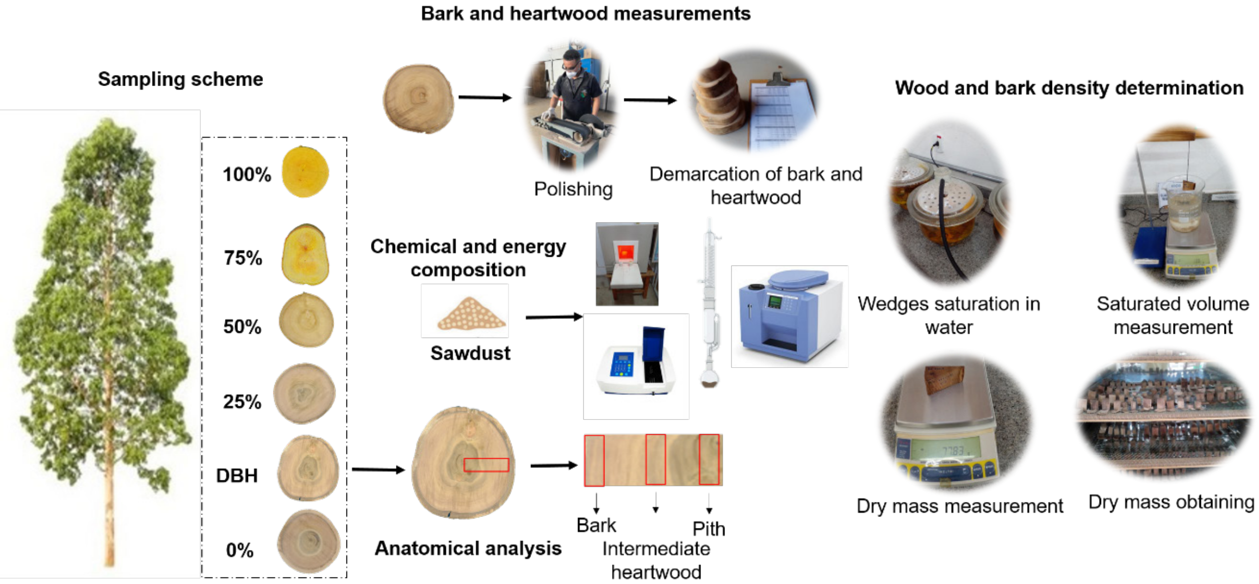

FIGURE 1: Sampling scheme of the assessment applied to the wood features of young *Corymbia* genotypes.

Analysis of wood physical properties

A systematic approach was used to accurately determine wood basic density (WBD) (kg m^{-3}) and bark basic density (BBD) (kg m^{-3}). A 45° wedge passing through the pith was cut from each disc. This wedge was carefully selected to avoid defect spots (knot, cracks and wood reaction) in the disc. Both wood and bark samples underwent water saturation and dry mass determination in compliance with recommendations by the Brazilian standard NBR 11941 (ABNT 2003) after barks were removed from the wedges (Figure 1). Mean wood and bark densities were calculated by taking into consideration the arithmetic mean across the longitudinal stem points to find the basic density of each wedge.

Bark thickness (BT) (cm), bark content (BC) (%) and heartwood content (HC) (%) measurements were taken on discs that were first polished with belt sander using 50-grain sandpaper then manually sanded with 80-grain sandpaper to enhance surface visual analysis (Figure 1). Diameter difference with and without bark was measured to calculate BT with the aid of a 10-mm precision ruler. This difference was divided by 2 to find the mean bark thickness. Bark content (BC) was determined by calculating the ratio of difference between disc total area with and without bark, and total disc area. This ratio was multiplied by 100 to find the BC rate.

The heartwood delimitation process encompassed visual inspection for colour contrast, which was easily accomplished by sprinkling water onto the disc surfaces. This method improved the difference between heartwood and sapwood, besides enabling accurate delineation. Measurements were taken with 10-mm precision ruler to ensure accurate boundary determination. An alternative method was employed to discs at the 75% and 100% longitudinal stem points where it was challenging to visualise the heartwood region. These discs were transversely cut into two parts; one part was treated with Dimethyl Yellow (indicator grade) diluted to 0.2% concentration in ethanol (standard solution provided by Sigma-Aldrich, St. Louis, USA). Measurements were taken after treatment application (Figure 1). Heartwood content (HC) was calculated by setting the association between the heartwood area, which was determined through the cylinder equation, and the total area of each disc. This ratio was multiplied by 100 to find the HC rate (Brito et al. 2019).

Determining wood chemical and energy composition

The chemical composition analysis was based on creating composite samples collected from all longitudinal stem points. The final sample was a composite sample from 6 wedges representing the longitudinal stem points, i.e. an average sample of the 6 wedge from each tree. Wood samples were processed into chips and sawdust in knife mill. The sawdust fraction retained by 40 and 60-mesh sieves were selected for analysis. Ash content (AC) (%) and volatile matter content (VMC) (%) determination followed the standard method D1762-84 (ASTM 2021). AC was measured in furnace oven heated to 600ºC, whereas VMC was determined at 900ºC. Fixed carbon content (FCC) (%) was calculated through Equation 1:

$$FCC = 100 - (AC + VMC)$$

Wherein *FCC* is fixed carbon content (%), *AC* is ash content (%), *VMC* is volatile matter (%) based on wood dry mass (%).

Total extractive content (TEC) (%) determination followed TAPPI standard 264 cm-7 (TAPPI 1997). It demanded three extraction sequences: alcohol-toluene at 1:2 ratio for 5 hours followed by alcohol for 4 hours and, finally, by hot water (100 ºC) for 1 hour. Insoluble lignin content was determined through the modified Klason method based on the procedure by Gomide & Demuner (1986). Soluble lignin content was measured in UV spectrophotometer, as proposed by Goldschimid (1971). Total lignin content (TLC) (%) was calculated as the sum of insoluble and soluble lignin. Holocellulose content (Hol) (%) was found by calculating the difference between the other wood chemical components, as described in Equation 2.

$$Hol = 100 - (TCL + TEC + AC)$$

Where *Hol* is holocellulose content (%), *TLC* is total lignin content (%), *TEC* is total extractive content (%), *AC* is ash content (%) based on wood dry mass (%).

The highest heating value (HHV) (MJ kg^{-1}) was determined by using an adiabatic calorimetric bomb, model IKA C-200, in compliance with standard E711-87 (ASTM 1996). The lowest heating value (LHV) (MJ kg^{-1}) was estimated by taking into consideration 6% wood hydrogen content, as specified in standard DIN EN 14918 (DIN 2010) - Equation 3.

$$LHV = HHV - (206*H)$$

Where *LHV* is the lowest heating value (MJ kg^{-1}), *HHV* is the highest heating value (MJ kg^{-1}), *H* is wood hydrogen content (%).

Energy density (ED) (GJ m^{-3}) was calculated through Equation 4:

$$\text{ED} = (\text{WBD} * \text{HHV}) / 1000$$

Where *ED* is energy density (GJ m^{-3}), *WBD* is wood basic density (kg m^{-3}), *HHV* is the highest heating value (MJ kg^{-1}).

Measurement of anatomical parameters

Specimens measuring 1.0 x 1.5 x 2.0 cm (width x length x thickness) collected from three positions by the DBH-discs radius were sampled to measure the wood vessel and fibre dimensions:

(1) in the sapwood under the bark

(2) in the intermediate heartwood, and

(3) in the pith (Figure 1).

Twenty-five vessel and fibre dimension measurements were taken from each radius position based on guidelines outlined by COPANT (1974) at 1.5-mm sampling intervals. Vessel frequency (VF) (number per mm^2) and diameter (VD) (μm) were measured in 20-μm-thick cross-sectional histological sections. Subsequently, samples were converted into chips to prepare the macerate (Ramalho 1987). Anatomical slides were assembled with the macerated material and photomicrographed by digital camera coupled to the microscope. Fibre length (FL) (μm) and width (FW) (μm), and lumen diameter (LD) (μm) were measured right on the photomicrographs in Axivision® software, version 4.5. Fibre-wall thickness (FWT) (μm) was indirectly calculated by subtracting LD from FW and by dividing it by two. Fibre-wall fraction (FWF) (%) was determined by setting the association between FWT and FW, multiplied by 100.

Data analysis

Data underwent tests to check variance homogeneity (Bartlett) and residuals' normality (Shapiro-Wilk). It was done by taking into consideration a completely randomised design (CRD). Analysis of variance (ANOVA) was conducted at 5% significance level to assess genotype effect (progenies and clones) on wood properties. Scott-Knott test (p<0.05) was employed for post-hoc analysis whenever there was significant difference. Principal component analysis (PCA) was applied to group genotypes and identify the wood properties mostly contributing to components formation (PC's). Statistical analyses were conducted in R software, version 4.2.2, (R Core Team 2023) in packages such as *ExpDes* (Ferreira et al. 2014) and *MultivariateAnalysis* (Ferreira 2018). All figures were plotted in SigmaPlot software, version 14.0.

Results

Genotype effects on wood physical properties

Significant differences in WBD were observed among genotypes and it led to their separation into four density groups. According to Figure 2A, these genotypes are represented by varying shades of blue. Group 1 only comprised clone CTC2 and showed WBD values higher than 600 kg m^{-3}. Group 2 included progeny PTM and CTCM, CTC6, and CTC5 clones; all of them recorded WBD higher than 580 kg m^{-3}. Group 3 encompassed progeny PTH and CTC4, CTM2 and CTM1 clones; its WBD ranged from 554 to 571 kg m^{-3}. Genotypes CTC1 and CTC3 formed group 4, which was featured by WBD values lower than 500 kg m^{-3}.

Bark basic density (BBD) was also significantly influenced by genotype and categorised into two density groups (Figure 2B). Group 1 was separated from the second group by including three genotypes presenting higher bark density: CTC1, CTM2 and CTCM; all of them exceeded 400 kg m^{-3}. Group 2 comprised genotypes CTM1, PTM, CTC2, CTC5, PTH, CTC6, CTC3 and CTC4; its BBD ranged from 373 to 397 kg m^{-3}.

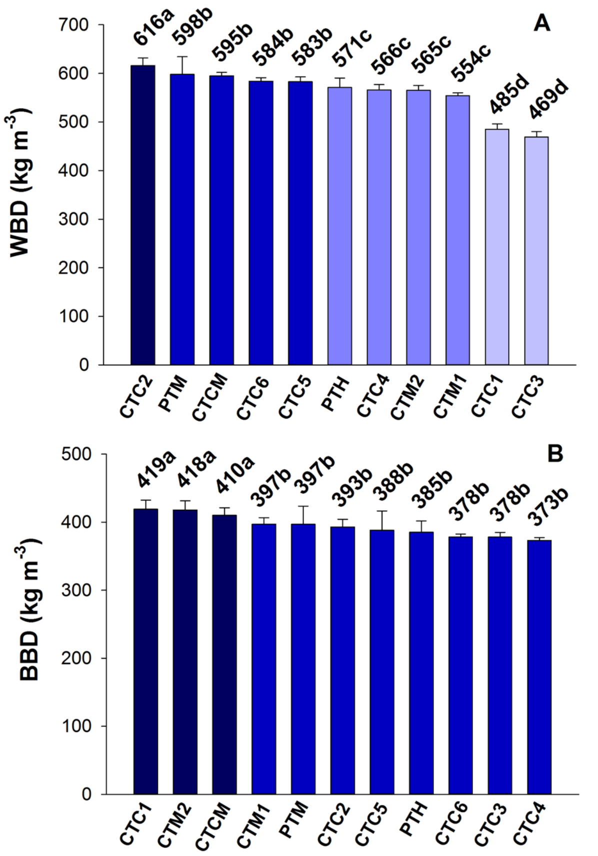

FIGURE 2: Young *Corymbia* genotypes classification based on wood basic density (A) and bark basic density (B). Different shades of blue represent the means recorded for group means recorded in the Scott-Knott ($p<0.05$) and error bars correspond to the standard deviation.

Mean BT, BC and HC were influenced by the genotypes (Figure 3). Genotypes were divided into three groups to find BT. The lowest mean value was observed in the CTC1 clone (0.31 cm), whereas the highest value was found in the CTC4 clone (0.59 cm) (Figure 3A). Bark content (BC) was categorised into two groups and its values ranged from 11.44% (CTC3 clone) to 16.43% (CTCM clone) (Figure 3B). Similarly, HC was also divided into three groups. The lowest mean value was recorded for the CTC1 clone (2.94%), whereas the highest was observed in the CTC5 clone (18.38%) (Figure 3C).

Differences in chemical and energy composition

Genotype had significant effect on wood immediate (AC, VMC, and FCC) and structural chemical (TEC, TLC, and Hol) composition. AC values ranged from 0.39% (PTM progeny) to 0.85% (CTM2 and CTC1 clones). VMC values ranged from 83.92% (CTM2 clone) to 86.04% (CTC2 clone), whereas FCC ranged from 13.33% (CTC2 clone) to 15.23% (CTM2 clone) (Figure 4).

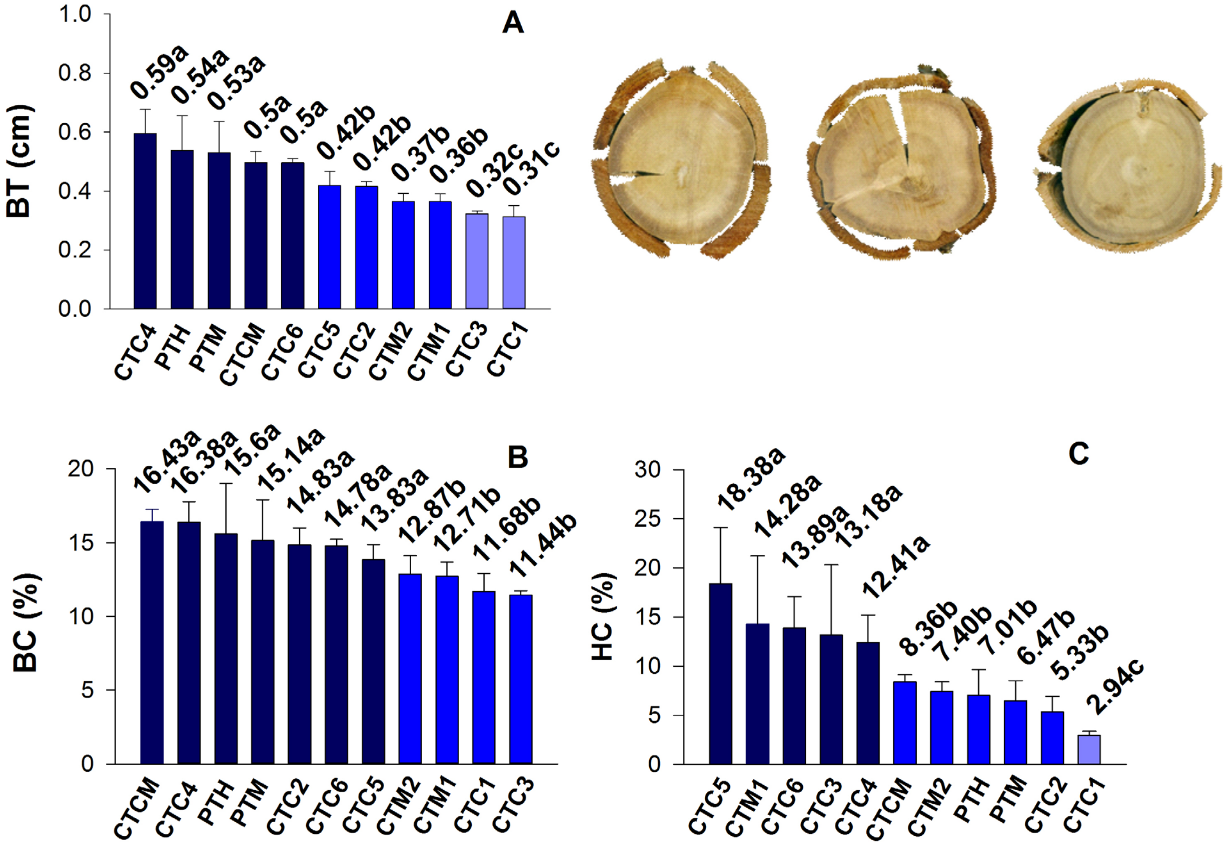

FIGURE 3: Young *Corymbia* genotypes classification based on bark thickness (A), bark content (B) and heartwood content (C). Different shades of blue represent the groups of means recorded through Scott-Knott ($p<0.05$) and error bars correspond to the standard deviation.

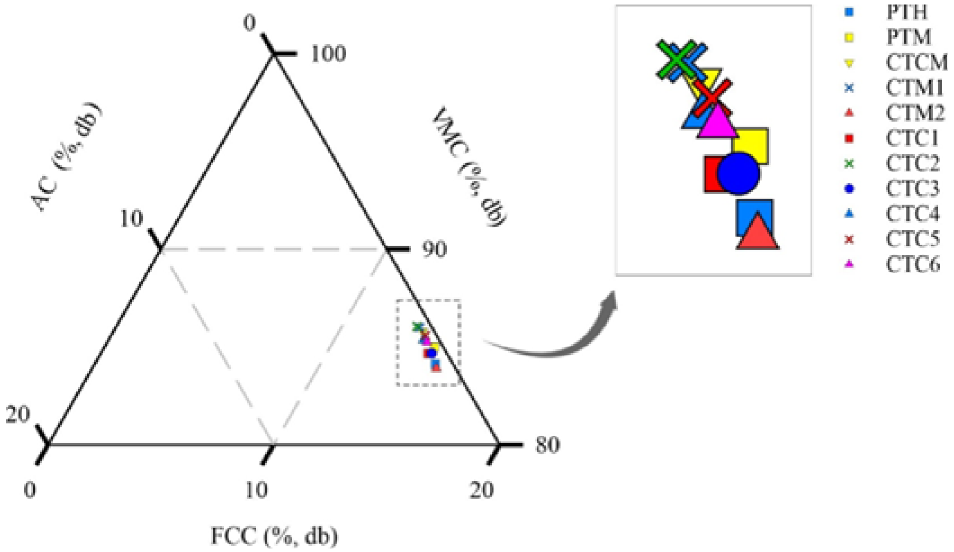

FIGURE 4: Ternary diagram of young *Corymbia* genotypes' wood proximate composition.

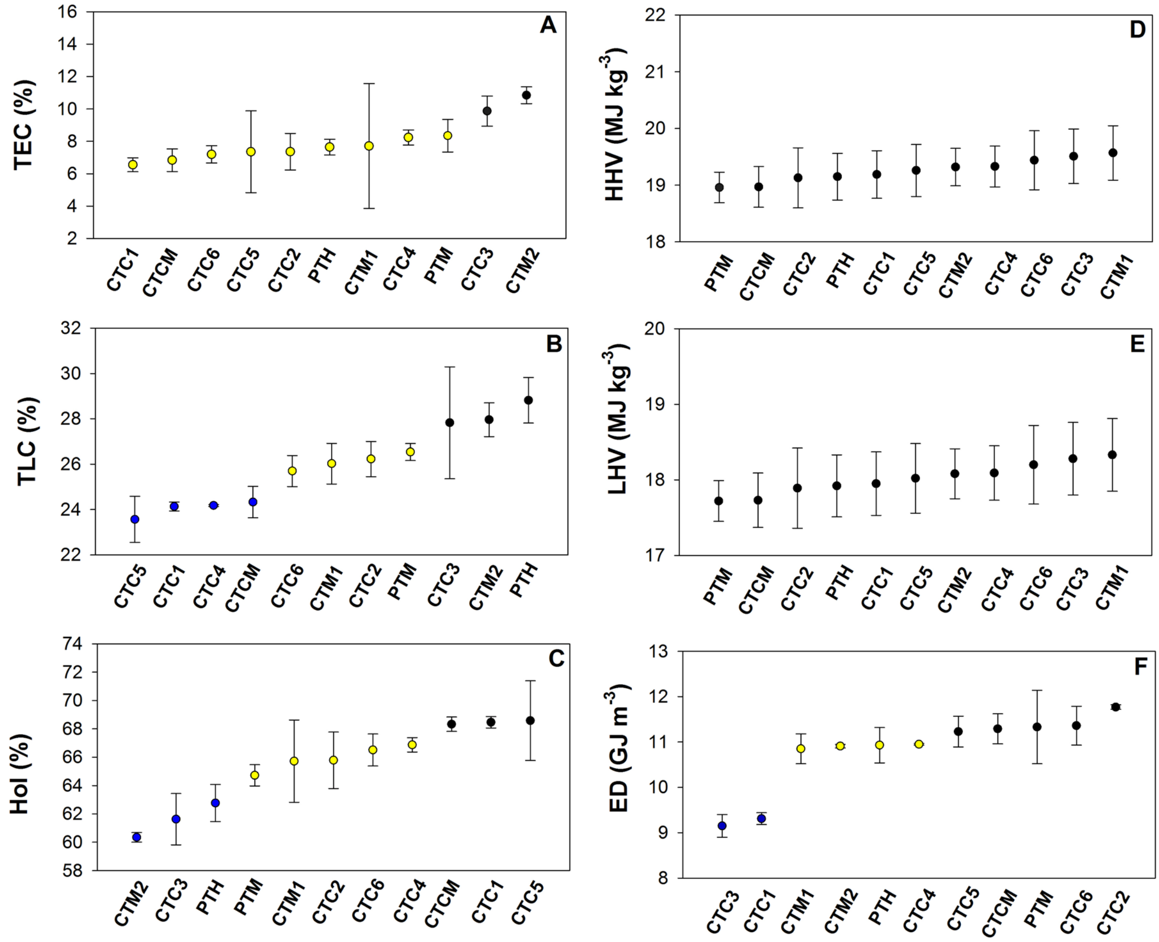

FIGURE 5: Total extractives (A), total lignin (B), holocellulose content (C), highest heating value (D), lowest heating value (E) and energy density (F) of young *Corymbia* genotypes. Different circle colours represent the groups of means recorded through Scott-Knott (*p<0.05*) and error bars represent the standard deviation. The black, yellow and blue colour circles are the first, second and third groups, respectively.

Clones CTC1 (6.56%) and CTM2 (10.85%) recorded the lowest and highest TEC values, respectively. TLC and Hol range spanned from 23.56% (CTC5 clone) to 28.82% (PTH progeny), and from 60.35% (CTM2 clone) to 68.58% (CTC5 clone), respectively (Figure 5A, B and C). Genotypes did not significantly affect energy properties. HHV ranged from 18.96 MJ kg^{-3} (PTM progeny) to 19.57 MJ kg^{-3} (CTM1 clone), LHV ranged from 17.72 MJ kg^{-3} (PTM) to 18.33 MJ kg^{-3} (CTM1 clone) and ED ranged from 9.15 GJ m^{-3} (CTC3 clone) to 11.77 GJ m^{-3} (CTC2 clone) (Figures 5D, E, and F).

Vessel and fibre dimensions

Vessel frequency (VF) was influenced by the genotypes, and its mean values ranged from 8.33 per mm^2 (CTM1 clone) to 14.11 per mm^2 (CTCM clone). Vessel diameter (VD) ranged from 87.77 µm (CTM2 clone) to 103.84 µm (CTC5 clone), and showed no significant genotype effect (Table 2). With respect to fibre parameters, only fibre length (FL) was significantly affected by the genotypes and ranged from 751.58 µm (CTC3 clone) to 907.52 µm (CTM1 clone). The other fibre parameters showed varying ranges: fibre width (FW), from 13.44 µm (CTC6 clone) to 15.77 µm (CTC1 clone); lumen diameter (LD), from 5.25 µm (CTCM clone) to 6.35 µm (CTM1 clone); fibre-wall thickness (FWT), from 3.85 µm (CTC6 clone) to 4.86 µm (CTC1 clone) and fibre-wall fraction (FWF), from 27.97% (CTC2 clone) to 30.76% (CTC1 clone) (Table 2).

Multivariate genotype clustering

According to PCA, the first three components explained 68.63% total data variability (Table 3). Wood properties mostly contributing to main components formation were:

PCA 1: Wood basic density, bark thickness and content, ashes, volatile matter, fixed carbon, total extractives, lignin and holocellulose contents, energy density and fibre length.

PCA 2: Bark thickness and content, heartwood content, volatile matter and fixed carbon content, highest and lowest heating values, vessel frequency and diameter, fibre length, lumen diameter and fibre-wall fraction.

TABLE 2: Vessel and fibre dimensions of young *Corymbia* genotypes.

Genotype	VF	VD	FL	FW	LD	FWT	FWF
PTH	11.95±0.77b	93.88±5.63a	813.93±33.21c	15.39±0.85a	6.12±0.75a	4.63±0.22a	30.15±0.47a
PTM	10.58±0.98c	97.13±9.24a	841.67±34.80b	15.38±1.54a	6.01±0.67a	4.68±0.45a	30.47±0.49a
CTCM	14.11±0.84a	89.26±9.12a	800.05±27.76c	13.45±0.51a	5.25±0.27a	4.10±0.14a	30.47±0.44a
CTM1	8.33±0.33d	101.00±11.73a	907.52±16.34a	14.99±0.58a	6.35±0.14a	4.32±0.30a	28.81±0.94a
CTM2	11.56±0.84b	87.77±3.54a	779.15±23.44d	13.99±1.44a	5.39±0.38a	4.30±0.57a	30.68±1.07a
CTC1	11.33±0.88b	98.06±8.37a	819.00±29.77c	15.77±1.78a	6.05±0.75a	4.86±0.70a	30.76±1.88a
CTC2	12.33±1.20b	90.06±5.43a	834.43±10.08b	14.22±1.05a	6.26±0.48a	3.98±0.34a	27.97±0.91a
CTC3	11.33±1.45b	97.20±6.38a	751.58±13.16d	14.07±0.82a	5.74±0.41a	4.16±0.33a	29.59±1.15a
CTC4	12.11±0.69b	95.87±3.97a	778.40±26.62d	14.75±0.57a	5.87±0.39a	4.44±0.09a	30.13±0.54a
CTC5	11.22±0.38b	103.87±4.81a	848.16±40.18b	14.73±0.52a	5.78±0.36a	4.48±0.44a	30.35±1.90a
CTC6	10.44±0.77c	92.46±5.09a	801.35±32.91c	13.44±1.24a	5.74±0.35a	3.85±0.47a	28.60±0.98a

Where VF is vessel frequency (number per mm^2), VD is vessel diameter (µm), FL is fibre length (µm), FW is fibre width (µm), LD is lumen diameter (µm), FWT is fibre-wall thickness (µm) and FWF is fibre-wall fraction (%).

PCA 3: Bark wood density, heartwood content, total extractives, lignin and holocellulose contents, highest and lowest heating values, vessel diameter, fibre length and width, lumen diameter, fibre-wall thickness and fraction.

Corymbia genotypes wood was grouped based on their physical, chemical, energy and anatomical properties. PCA enabled categorising *Corymbia* genotypes into four groups. The dispersion of the assessed *Corymbia* genotypes followed the scores resulting from principal components analysis (Figure 6).

TABLE 3: Correlation between wood properties and the first three principal components.

Property	PC1	PC2	PC3
Wood basic density	**0.3198**	-0.1487	-0.0935
Bark basic density	-0.0808	-0.1584	**0.2255**
Bark thickness	**0.23**	**-0.1984**	-0.0533
Bark content	**0.2956**	**-0.2338**	-0.0663
Heartwood content	0.0732	**0.279**	**-0.2062**
Ashes content	**-0.2871**	-0.0903	0.0036
Volatile matter content	**0.3378**	**0.197**	-0.0341
Fixed carbon content	**-0.3173**	**-0.2027**	0.0376
Total extractives content	**-0.2746**	-0.063	**-0.2335**
Total lignin content	**-0.2284**	-0.0853	**-0.1763**
Holocellulose content	**0.2855**	0.0868	**0.2181**
Highest heating value	-0.1641	**0.3457**	**-0.2282**
Lowest heating value	-0.1678	**0.3441**	**-0.229**
Energy density	**0.3168**	-0.1083	-0.1287
Vessel frequency	0.0758	**-0.362**	-0.0467
Vessel diameter	0.0026	**0.3329**	**0.254**
Fibre length	**0.1855**	**0.238**	**0.2254**
Fibre width	-0.0799	0.0792	**0.4444**
Lumen diameter	0.0428	**0.2563**	**0.1988**
Fibre wall thickness	-0.1236	-0.0384	**0.4575**
Fibre wall fraction	-0.142	**-0.2293**	**0.2647**

Discussion

Genotype effects on wood physical properties

The steelmaking charcoal industry mostly uses wood presenting density higher than 500 kg m^{-3}. This density range is highly desirable for the steel industry, as it ensures the production of higher-density charcoal (Ramos et al. 2023). Based on this density range criteria, most genotypes assessed in this study stand out for their strong charcoal-production potential. However, CTC1 and CTC3 clones do not meet the required density criteria and are not recommended for charcoal production if one only takes into account wood density as classification parameter. Wood density equals to, or higher than, 500 kg m^{-3} is quite advantageous for charcoal production because it leads to reduced wood consumption in masonry ovens and optimises operational efficiency. Furthermore, it enhances volumetric yield and leads to denser charcoal with higher mechanical strength. Altogether, these factors contribute to the production of higher-quality charcoal. Moreover, higher wood density accounts for lower operational costs in charcoal production facilities, and it turn this wood type into an economically advantageous choice (Protásio et al. 2015).

Results have shown 147 kg m^{-3} difference between genotypes with the highest and lowest WBD, both in *C. torelliana* x *C. citriodora* hybrids. This finding points out substantial genetic variability, and it is noteworthy, because all the produced wood in the age group 3 and 4 years present juvenile features. These outcomes are crucial for the breeding program since they suggest genotype-selection potential to enhance biomass yield for both charcoal production and other energy applications. Wood density is an ideal trait for genetic manipulation due to its significant variation between trees, high heritability and low genotype x environment

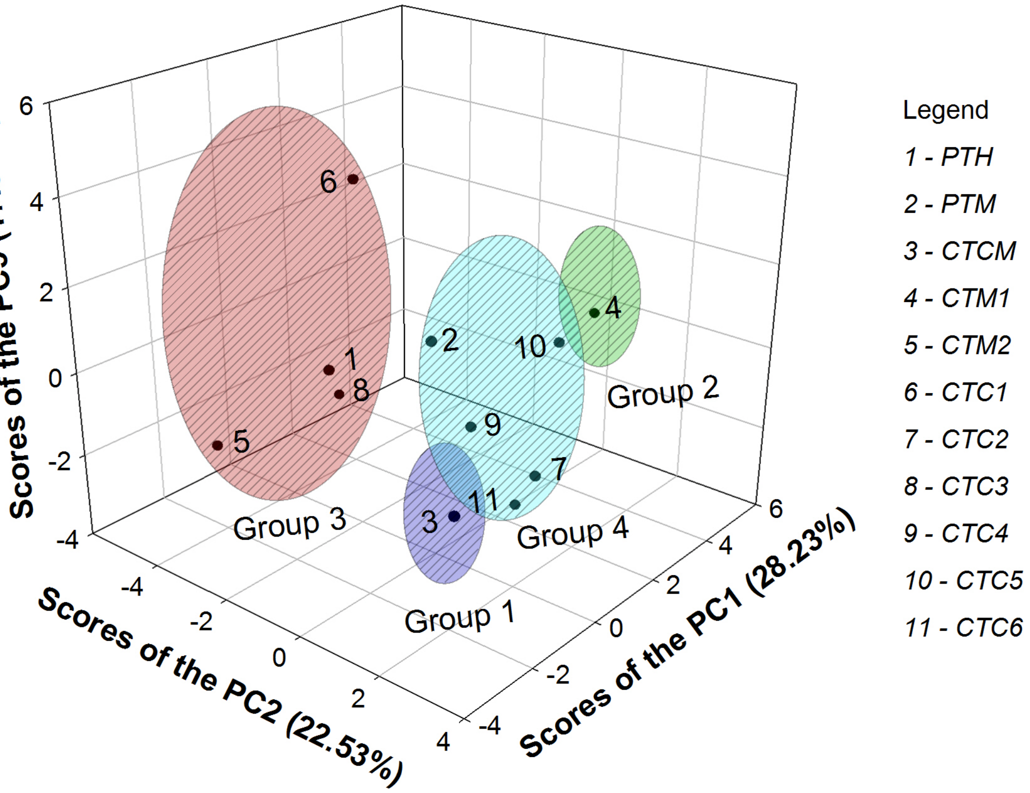

FIGURE 6: 3-D scatter graphic of young *Corymbia* genotypes multivariate clustering.

interaction (Brawner et al. 2012). Notably, progeny PTM (group 2) recorded density even higher than that observed for CTM clones, and this finding highlights that the resulting PTM progeny was assumingly formed from cross-breeding between parents presenting density higher than that accounting for CTM clones' formation. Consequently, with respect to *C. torelliana* x *C. maculata* progenies, it is essential focusing wood density in clone trees, since they will result in higher wood density for charcoal production.

Comparisons between the current wood density results and other already established *Corymbia* genotypes showed that findings in the present research show higher densities than those reported by Loureiro et al. (2019) for *C. citriodora* x *C. torelliana* and *C. torelliana* x *C. citriodora* clones at the age of 3.8 years (density ranging from 506 to 641 kg m^{-3}). In addition, the current results are in compliance with findings by Massuque et al. (2023) for the wood presented by pure species *C. citriodora*, *C. henryi* and *C. variegata* at the age of 6 years, when wood density reached 662 kg m^{-3}. It is crucial to compare *Corymbia* to *Eucalyptus*, given *Eucalyptus*' prominence as primary feedstock for charcoal production. Remarkably, *Corymbia* genotypes in the current study recorded density range comparable to that of the most planted and significant *Eucalyptus* clones, such as *Eucalyptus urophylla* (670 kg m^{-3}) and *Eucalyptus grandis* x *E. camaldulensis* (520 kg m^{-3}), both at the age of 6 years (Câmara et al. 2020).

The higher wood density shown by *Corymbia* genotypes, even at younger ages or at ages comparable to that of other *Corymbia* and *Eucalyptus* varieties, highlights the core feature of the genus, namely: its early wood-density development. This trait is particularly advantageous for high-quality charcoal production and for shortening harvesting cycles. These results are pivotal for the cultivation of *Corymbia* genotypes in commercial crops. They suggest that theses genotypes can provide feedstock in a shorter time frame without compromising wood quality. Furthermore, using high-density *Corymbia* wood from crops accounting for acceptable growth rates requires less land area and produces less wood volume yield with the same charcoal volume. This aspect of genus *Corymbia* is economically and environmentally beneficial, as it reduces costs and conserves natural resources.

Bark features assessment, i.e., bark density, thickness and content, is crucial, because bark residue significantly influences both charcoal industrial production processes and ultimate quality (Foelkel 2010). Bark presence can enhance gravimetric and fixed carbon yield, as well as increase ash content in charcoal, mainly when it is intended for iron alloys or calcium carbide production. The phosphorus found in wood bark can be incorporated into charcoal and cause cracks and fissures to metal alloys, which reduces their mechanical strength and makes them unsuitable for use in certain materials (Vital et al. 1989). In addition, bark represents a cumulative waste product that causes several technical issues such as high moisture and ash accumulation in peelers and boilers (Miranda et al. 2012).

Bark density investigation is very important for the steel industry due to its straight impact on costs and charcoal quality changes. Higher BBD results in larger bark-attached wood mass to be transported from the field to the furnace. This is because many steelmaking charcoal companies do not remove bark from trunks. Consequently, transportation costs, including fuel consumption, increases and leads to higher final charcoal costs. Moreover, higher bark rates will be introduced in masonry ovens at charcoal production facilities, and it potentially compromises charcoal quality, as previously discussed. Bark density values recorded for the assessed *Corymbia* genotypes is compliant with those reported for *Eucalyptus*, which often range from 374 to 454 kg m^{-3} (Quilhó & Pereira 2001). However, some studies have reported values lower than 374 kg m^{-3}. Rocha et al. (2016) found mean BBD equals 300 kg m^{-3} in wood of commercial *Eucalyptus* hybrids at the age of 7 years. It is worth noticing a limited number of studies focused on assessing BBD in genus *Corymbia*. According to research available, BBD values have ranged from 301 kg m^{-3} in the *C. citriodora* x *C. torelliana* hybrid at the age of 1 year (Lopes et al. 2017) to 415 kg m^{-3} in the *C. torelliana* x *C. citriodora* hybrid at the age of 7 years (Rocha et al. 2024). Given the significant challenges posed by bark to industrial charcoal production, it is recommended to further feature *Corymbia* bark to find alternative applications to unlock its potential value.

Bark thickness and content are equally crucial factors because thicker bark translates to higher bark volume on trunks. Consequently, this process reduces the wood volume available inside masonry ovens. This undesirable feature has been documented in other studies carried out with genus *Corymbia*, including *C. citriodora* subsp. *variegata*, *C. maculata* and *C. henryi* at the age of 3 years when bark content ranged from 14% to 16.5% (Silva et al. 2022b). Similarly, Melo et al. (2024) reported bark thickness up to 0.69 cm in another study conducted with *C. subsp. citriodora*, *C. subsp. variegata*, *C. henryi*, and *C. torelliana,* at the age of 6 years. The same author reported 23.2% bark content and it confirmed the negative influence of bark thickness on final wood volume. Reducing the final bark volume poses significant challenge to *Corymbia* breeding programs. However, this target may be achievable through genetic selection due to substantial bark thickness variability in species belonging to this genus. It is worth noticing that with *Corymbia* genotypes bark detaches more easily from trunks (see Figure 3) than *Eucalyptus* bark. Not all bark volume is incorporated to masonry ovens because part of loss during wood harvesting and transporting.

Heartwood content is a very important parameter to assess wood quality in the steelmaking charcoal industry. Yet, it is often disregarded in the selection of superior genotypes for growth and volume production purpose. Lower HC is better for production, manly when juvenile wood is used, due to reduction in the time required for wood drying (water vapour and gas volatilisation) at the initial carbonization phase attributed to higher sapwood content (El-Juhany 2011). Heartwood, on the other hand, presents smaller diameter vessels full of extractives that delay the carbonisation process by limiting water release (Santos et al. 2013). Furthermore, higher HC significantly contributes to fines (charcoal as very fine grain) generation because water release impairments over initial carbonisation stages lead to cracks and fissures, smaller-grained and less mechanically resistant charcoal. The current study shows that *Corymbia* wood often shows lower HC than *Eucalyptus*, such as *E. grandis* x *E. urophylla* wood at the age of 4.5 years (ranging from 5.9% to 28.5%) (Santos et al. 2021). Lower *Corymbia* HC wood can lead to reduced fines generation and, consequently, to higher charcoal gravimetric yield and mechanical resistance. Moreover, *Corymbia* wood tends to dry faster and requires less storage time in charcoal production facilities due to its lower HC. Ultimately, it results in higher wood volume for carbonisation in shorter periods-of-time (Rocha et al. 2024).

Differences in chemical and energy composition

Table 4 compares the proximate and structural composition of *Corymbia* and *Eucalyptus* wood available in the literature. Notably, genotypes assessed in this study recorded ash below <1%, which is a desirable value for wood thermochemical processes. Higher ash content can have adverse impact on wood calorific value and lead to issues such as scale formation, corrosion and equipment clogging during combustion. It ultimately compromises final charcoal quality (Vieira et al. 2013). *Corymbia* wood shows higher mean volatile content values than *Eucalyptus* wood. High volatile content is mainly important for combustion applications due to reduced ignition time caused by the presence of these compounds in wood (Lubwama et al. 2021).

However, *Corymbia* fixed carbon content fell below that of *Eucalyptus* wood in the present study, and it is a less favourable outcome. Wood fixed carbon works as critical parameter for wood energy potential, since carbon is closely related to both high calorific values and slower burning. This process results in higher wood thermal resistance and in enhanced fixed carbon at carbonisation (Carneiro et al. 2016). The low values recorded in the present study are explained by the higher VMC value, because FCC is calculated based on the difference between AC and VMC.

The assessed *Corymbia* genotypes recorded higher total extractives content than *Eucalyptus* wood, even at younger ages. With respect to charcoal production, higher extractive rates, mainly those of phenolic–nature have the potential to enhance calorific values and fixed carbon, thereby increasing charcoal yield (Poletto et al. 2016). It is imperative to understand extractives' qualitative nature to understand the contribution from each of their categories to charcoal production. This *Corymbia* wood feature is linked to an adaptive advantage, namely: its higher resistance to abiotic stress, mainly drought, which results in higher production and accumulation of such substances in wood (Lee 2007).

Wood extractives play a dual role in plant physiology; they act as reserve energy sources for plant metabolism and provide defence mechanisms against environmental stresses. These compounds accumulate in plant tissues and work as antioxidants by safeguarding cells from oxidative stress induced by reactive oxygen species (ROS) (Almeida et al. 2022). The resilience of *Corymbia* species

TABLE 4: Proximate and structural chemical composition of *Corymbia* wood and of other *Eucalyptus* genotypes reported in the literature used for energy purposes.

Genotype	**Age**	**AC**	**VMC**	**FCC**	**TEC**	**TLC**	**Hol**	**HHV**	**LHV**	**ED**	**Reference**
E. grandis and *E. urophylla*	2.8	0.63			3.10	29.62	66.65				Santana et al. (2012)
	4	0.42			3.27	28.20	68.13				
E. urophylla	3				2.37	32.23	65.41	19.00			Castro et al. (2016)
	4				4.08	31.46	64.46	19.47			
E. urophylla x *E. grandis*	3				4.02	32.04	63.93	19.19			
	4				3.50	31.63	64.87	19.33			
Eucalyptus spp.	3.8	0.53				27.0	69.35			8.4	Protásio et al. (2014)
	4.8	0.23				31.0	62.5			9.83	
Eucalyptus spp. (clones)	6.8	0.13 - 0.27	81.6 - 84.0	15.8 - 18.2	0.7 - 2.6	27.1 - 32.6		19.05 - 19.68	17.66 - 18.27		Protásio et al. (2019)
E. camaldulensis	7.5	0.16			4.30	30.29	65.25				Pereira et al. (2012)
E. grandis (hybrid)		0.12			4.15	29.82	65.90				
***Corymbia**	3-4	0.64	85.13	14.23	8.00	23.94	65.43	19.26	18.02	10.83	This Study

Where Age (year-old); AC, VMC, FCC, TEC, TLC, and Hol (%, db); HHV and LHV (MJ kg^{-1}); and ED (GJ m^{3}). *Mean value of all *Corymbia* genotypes.

to water shortage gives them a significant environmental advantage. This trait allows *Corymbia* crops to growth in regions with limited water availability, such as North Eastern Brazil, and many other areas that face water restrictions worldwide. *Corymbia* crops contribute to the sustainability of forestry practices in these areas by thriving under such conditions, which leads to economic and ecological benefits.

In contrast to total extractives content, *Corymbia* wood often shows lower lignin content than *Eucalyptus* wood. Despite the initial differences, *Corymbia* wood has the potential to meet or exceed the critical lignin content (28%) required to ensure charcoal yield higher than 30% (Ramos et al. 2023). Reaching the specified range is crucial due to lignin content significance as key parameter to select genotypes intending for charcoal production. Lignin works as primary wood structural component given its exceptional thermal resistance. Consequently, higher lignin content wood tends to achieve higher charcoal yield, which turns this parameter into critical factor for charcoal production process optimisation (Yang et al. 2007). The presence of holocellulose in *Corymbia* wood tends to be lower than in *Eucalyptus* wood, and it is a beneficial factor for charcoal production. Holocellulose is a substantial wood fraction that encompasses structural components such as cellulose and hemicelluloses. However, these compounds present relatively unstable and less resilient profile, which render them susceptible to higher degradation over the carbonisation process. Thus, high holocellulose content is undesirable for charcoal production due to its contribution to thermal instability, which potentially compromise both charcoal quality and yield (Trugilho et al. 2015).

Corymbia genotypes heating values (HHV and LHV) and energy density (ED) recorded in the current study compliant values reported in the literature for *Eucalyptus* wood. This finding points out similar energy performance potentials. These parameters are crucial to assess the amount of energy available per wood volume for heat, and it reflects its overall energy potential (Jesus et al. 2017). Factors such as wood chemical composition, mainly total extractives content (TEC) and total lignin content (TLC), as well as wood density, influence heating and energy values. Higher HHV, LHV, and ED values are desirable to produce high-quality charcoal in the steelmaking industry, and this outcome highlights wood properties relevance in determining final charcoal quality (Peres et al. 2019).

Vessel and fibre dimensions

Wood anatomical configuration deeply influences charcoal production. High wood density formation and, consequently, high charcoal density and gravimetric yield depend on using wood with thicker fibres, on higher wall fraction rate and on vessels with smaller diameters, and on high frequency (Oliveira et al. 2023). Vessels should have smaller diameters and higher frequency when wood use is destined for charcoal production, because, then, most of the wood will be filled by mass rather than by empty spaces, a fact that increases charcoal gravimetric yield (Pereira et al. 2016). According to Paula (2005), fibre-rich wood and high-wall-fraction are desirable qualities for multiple energy applications such as ethanol, metallurgic coke, firewood and charcoal, because it represents a higher mass to maintain wood thermal decomposition, which favours charcoal yield and final quality.

Overall, the anatomical *Corymbia* wood elements show different dimensions than those of *Eucalyptus* wood at the harvesting-cycle (≥ 7-year-old), and it is expressed for smaller diameter vessels at higher frequency; smaller length, width and lumen diameter fibre; and higher wall thickness (Pereira et al. 2016; Monteiro et al. 2017; Teixeira et al. 2024). These differences in *Corymbia* wood anatomy, mainly in fibre dimensions, can be the reason why *Corymbia* genotypes wood assessed in the present study showed higher density than *Eucalyptus*, and why these genotypes will assumingly produce higher-density charcoal and, consequently, better quality charcoal for the steel industry. The same anatomical differences were reported by Rocha et al. (2024) for the wood of four *C. citriodora* x *C. torelliana* and *C. torelliana* x *C. citriodora* clones in comparison to an *E. urophylla* clone, and it confirmed differences in wood anatomy between these genera.

Multivariate genotype clustering

The most important wood features in the first principal component were wood density, proximate composition and energy density. This finding made it clear that these features influence the selection of genotypes presenting higher capacity to convert CO_2 into biomass and higher energy amount stored per wood volume for biomass conversion into energy throughout the carbonisation process (Massuque et al. 2023). The highest and lowest heating values mostly affected principal component two, and it pointed out that the amount of energy released as heat during wood conversion into charcoal in steel blast furnace is essential for selecting the best genotypes for charcoal production (Teixeira et al. 2024). The anatomical elements of principal component three, mainly fibre width and wall thickness, were highly influential, and it has proven that wider width and high wall thickness fibre are very important for higher density wood formation and, consequently, to produce denser and higher yielding charcoal (Pereira et al. 2016).

Groups 1 and 2 only comprised the CTCM tri clone and the CTM1 clone, respectively. They showed wood properties that compromised their use in direct charcoal combustion, cogeneration and production for domestic use. This is because of their wood high density, low holocellulose content and, most of all, high volatile matter content, which are favourable features for wood use in direct combustion (Protásio et al. 2019). Assumingly, at the age of 7 years, these genotypes will present satisfactory wood properties for charcoal production in steel industry, mainly higher wood density, due to their age. Group 3 comprised PTH progeny; and CTM2, CTC1 and CTC3 clones; therefore, it had potential for charcoal production due to its high fixed carbon, heating values, energy density and low volatile matter, which result in high charcoal volumetric yield and high energy generation. In addition, the high lignin content observed in this group ensured higher charcoal gravimetric yield (Massuque et al. 2023). Finally, group 4 (PTM, CTC2, CTC4, CTC5 and CTC6) provided lower wood consumption in masonary ovens and higher density and mechanical strength charcoal due to its higher wood density. Using genotypes with higher wood density leads to positive effect on forest stand yield and in economic management.

Conclusions

According to the current study, wood properties work as reliable indicators to classify and select superior *Corymbia* genotypes for charcoal production. These features help accurately predicting raw material impact on charcoal quality. Findings have shown that all the assessed genotypes accounted for promising initial potential for charcoal production or for other energy applications, since they indicated wood properties with comparable or even better features than those recorded for the genus *Eucalyptus*. Special attention must be drawn to genotypes CTC2, PTM, CTCM, CTC5 and CTC6 due to their high wood density. Progeny PTH and clone CTM2, in their turn, stood out for their high fixed carbon, heating and energy density values.

Despite the relevance of the present findings in enhancing *Corymbia* genotypes breeding, young wood samples can reasonably represent the wood quality for charcoal production, although not 100%. As trees age, wood properties such as wood density, heartwood content, chemical composition and anatomical features undergo significant changes. As trees mature, wood density, heartwood and extractives content increase, whereas lignin content decreases, and it has impact on conclusions based on wood at the ages of 3 and 4 years. Any conclusion about the association between tree age and wood quality cannot be guaranteed. Therefore, further investigations remain necessary to address wood quality at harvesting time (≥ 7 years old), mainly when it concerns wood and charcoal yield and featuring. These additional studies can contribute to deepening understanding of how wood quality features of *Corymbia* genotypes influence top-quality charcoal production, mainly for its application in the steel industry.

List of abbreviations

AC – Ash content
BBD – Bark basic density
BC – Bark content
BT – Bark thickness
CTC – *C. torelliana* x *C. citriodora* clones
CTCM – *C. torelliana* x *C. citriodora* x *C. maculate* tri clone
CTM –*C. torelliana* x *C. maculata* clones
DBH - Diameter at breast height
ED- Energy density
FCC – Fixed carbon content
FL – Fibre length
FW – Fibre width

FWF – Fibre-wall fraction
FWT – Fibre-wall thickness
HC – Heartwood content
HHV – Higher heating value
Hol – Holocellulose content
LD – Lumen diameter
LHV – Lower heating value
NPK – Nitrogen, Phosphorus, Potassium
PTH –*C. torelliana* x *C. henryi* progeny
PTM –*C. torelliana x C. maculata* progeny
TEC – Total extractives content
TLC – Total lignin content
VD – Vessel diameter
VF – Vessel frequency
VMC – Volatile matter content
WBD – Wood basic density

Competing interests

The authors declare they have no competing interests.

Authors' contributions

UOBJ primary author: conducted the experiment, analyses, reviews and discussions. PRCM and SLA helped with laboratory analyses. GBV, JGMS, TPP and SMGR provided project supervision and contributed to its review and discussion. AVL, AFCFO and CVAO provided company partnership. All authors revised the manuscript and approved its final version.

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