Chemical, Energetic, and Thermal Characteristics of *Corymbia* Hybrid Progenies and Clones for Sustainable Charcoal Production

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Many countries are seeking to reduce their dependence on non-renewable energy sources, particularly fossil fuels. This study evaluated the chemical, energetic, and thermal characteristics of wood from non-commercial hybrid progenies and clones of *Corymbia torelliana* × *C. henryi*, *C. torelliana* × *C. maculata*, *C. torelliana* × *C. citriodora* × *C. maculata*, and *C. torelliana* × *C. citriodora*, at 3 and 4 years of age, to assess their potential for energy production. The genotypes exhibited variation in wood density, chemical composition, and energetic properties. Higher heating values ranged from 19.0 to 19.6 MJ kg^{-1}, although differences among genotypes were not statistically significant. Energy density ranged from 9.15 to 11.8 GJ m^{-3}, with clone CTC2 exhibiting the highest value (11.8 GJ m^{-3}) and the highest basic wood density (616 kg m^{-3}). Clone CTM2 stood out for its high extractive, lignin, and fixed carbon contents, supporting its potential for charcoal production. Thermogravimetric analysis showed that clone CTC6 had the highest residual mass (31.0%), indicating greater thermal stability under the tested conditions. Fourier-transform infrared spectroscopy identified functional groups associated with the main wood constituents, while X-ray diffraction revealed the highest crystallinity index in clone CTCM (38.4%). Overall, clones CTC2 and CTM2 showed promising wood properties for metallurgical charcoal production, highlighting the potential of non-commercial *Corymbia* genetic materials for energy applications.

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INTRODUCTION

Most countries are facing the urgent need to significantly reduce their dependence on non-renewable energy sources, particularly oil, and to decrease greenhouse gas (GHG) emissions to mitigate global climate change (Protásio *et al*. 2013). Non-renewable energy

sources, including coal, petroleum, and natural gas, remain essential to the global economy but contribute to GHG emissions. In contrast, renewable energy sources, such as solar, wind, hydropower, and biomass, offer opportunities to diversify energy supplies, improve energy security, and stimulate economic development through investments, employment generation, and technological innovation. In 2024, renewable energy sources accounted for almost three-quarters of the increase in global electricity generation, reflecting their growing importance in the transition toward lower-carbon energy systems (IEA 2025). In Brazil, renewable sources contribute substantially to the energy matrix, with biomass playing an important role in energy supply and charcoal serving as a viable alternative to fossil fuels in the steel industry (EPE 2022).

Wood charcoal is an important biomass-derived fuel worldwide, contributing to household energy supply and industrial activities, particularly iron and steel production. Global charcoal production reached approximately 59 million tonnes in 2024, with Africa accounting for the largest regional share. Brazil was the world's leading charcoal producer, with approximately 6.7 million tonnes, followed by Ethiopia and Nigeria, with about 5.0 and 4.9 million tonnes, respectively. Other important producing countries include the Democratic Republic of the Congo, India, and Ghana (FAO 2025; IBÁ 2025). The charcoal sector contributes to employment, income generation, and industrial production, particularly in developing economies. In Brazil, charcoal is especially relevant to the steel industry because it can serve both as an energy source and as a reducing agent in pig iron production. Nevertheless, its environmental benefits depend on sustainable forest management, the origin of the feedstock, and the efficiency of the production process.

For metallurgical applications, charcoal quality is associated with properties such as fixed-carbon content, ash content, density, calorific value, and mechanical strength. High fixed-carbon content and adequate density and mechanical strength, together with low ash content, are desirable for reducing-agent performance and resistance to fragmentation during handling and furnace operation. However, the required properties vary according to the metallurgical process and the intended application (Han and Tangstad 2024). Biomass plays a vital role in the transition toward renewable energy systems because it can be derived from renewable biological resources and used for heat, electricity, and industrial applications. When produced sustainably, biomass can contribute to reducing net GHG emissions compared with fossil fuels, although its overall environmental performance depends on production practices, carbon stocks, and the time required for biomass regrowth. The main source of forest biomass for energy in Brazil comes from species within the *Eucalyptus* genus, particularly *E. urophylla* and *E. grandis*, which make up more than 85% of the species cultivated for this use. The preference for these species and their hybrids is linked to their rapid growth, high adaptability to the country's edaphoclimatic conditions, and wood properties desirable for charcoal production in the steel industry (Massuque *et al*. 2023).

Expanding forest plantations into regions with different environmental conditions remains a challenge for the Brazilian forestry industry, despite the importance of *Eucalyptus* as a source of biomass for energy production (Silva *et al*. 2022a). Considering the complexities of climate change, particularly events like El Niño and La Niña (Melo *et al*. 2024), it is essential to explore and classify new genotypes with broad environmental adaptability to the diverse conditions of each region and their impact on wood quality. Currently, some plant breeding programs are exploring the potential of pure species and interspecific hybrids from the *Corymbia* genus as an alternative energy source to *Eucalyptus* (Silva *et al*. 2022b).

Species including *C. torelliana*, *C. citriodora*, *C. henryi*, and *C. maculata*, as well as their interspecific hybrids, demonstrate significant promise in substituting or enhancing the conventional charcoal production usually carried out by *Eucalyptus* species. This is due to their desirable wood properties, particularly the high wood density, which often exceeds 500 kg/m^3, directly impacting the production of high-quality metallurgical charcoal (Damacena *et al*. 2021). Additionally, genotypes of this genus can tolerate a range of biotic and abiotic stresses, including pests and diseases, wind damage, low temperatures, frost, and water deficits, and they exhibit ease of vegetative propagation. As a result, they play a crucial role in creating genetic variations that can thrive in various environments (Lee 2007). Nevertheless, wood properties alone cannot establish the quality of the resulting charcoal, which also depends on carbonization conditions and requires direct evaluation of the final product (Han and Tangstad 2024). This study evaluated the chemical, energy, and thermal properties of young wood from non-commercial progenies and hybrid clones of *C. torelliana* × *C. henryi*, *C. torelliana* × *C. maculata*, *C. torelliana* × *C. citriodora* × *C. maculata*, and *C. torelliana* × *C. citriodora*. The goal was to select and classify the highest-quality genotypes for the sustainable production of metallurgical charcoal.

EXPERIMENTAL

Study Area and Sampling

The study was carried out with eleven non-commercial hybrids progenies and clones of *Corymbia* in the age of 3 and 4 years. The wood was collected from trial plantations located in Bom Despacho and Martinho Campos municipalities, Eastern Minas Gerais, Brazil, which belongs to ArcelorMittal S.A. company. The region's climate is classified as *Cwa*, with mean annual precipitation and temperature of 1.375 mm and 23.1 ° C, respectively, according to Köppen's classification. The soil is classified as Dystrophic Red Latosol (Alvares *et al*. 2013). The planting spacing was 7.5 m^2 and the forestry management practices were consistent among all genotypes (Table 1).

Table 1. Genotypes of *Corymbia* Characteristics from a Trial Plantation

Genotype	Provenance	Identification	DBH	Age	Latitude	Longitude
C. torelliana × *C. henryi*	Progeny	PTH	15.3	3	19º34'35"S	45°20'27''W
C. torelliana × *C. maculata*	Progeny	PTM	16.1	4	19°33'41''S	45°20'8''W
C. torelliana × *C. citriodora* × *C. maculata*	Tri clone	CTCM	13.5	3	19°25'43''S	45°20'27''W
C. torelliana × *C. maculata*	Clone	CTM1	12.6	3	19°25'43''S	45°20'27''W
C. torelliana × *C. maculata*	Clone	CTM2	12.9	3	19°25'43''S	45°20'27''W
C. torelliana × *C. citriodora*	Clone	CTC1	12.0	3	19°25'43''S	45°20'27''W
C. torelliana × *C. citriodora*	Clone	CTC2	12.1	3	19°25'43''S	45°20'27''W
C. torelliana × *C. citriodora*	Clone	CTC3	12.6	3	19°25'43''S	45°20'27''W
C. torelliana × *C. citriodora*	Clone	CTC4	16.1	4	19°25'43''S	45°8'44''W
C. torelliana × *C. citriodora*	Clone	CTC5	12.9	4	19°25'43''S	45°8'44''W
C. torelliana × *C. citriodora*	Clone	CTC6	15.6	4	19°25'43''S	45°8'44''W

*DBH (cm), age (years-old).

Three trees per genotype were sampled, totaling 33 trees. After felling, cross-sectional disks approximately 5 cm thick, including bark, were removed from each tree at various positions along the trunk: 0% (base of the tree), diameter at breast height (DBH), 25%, 50%, 75%, and 100% of the commercial height of the tree (considering a minimum diameter of 5 cm). All disks were then stored for subsequent wood quality analysis (Fig. 1).

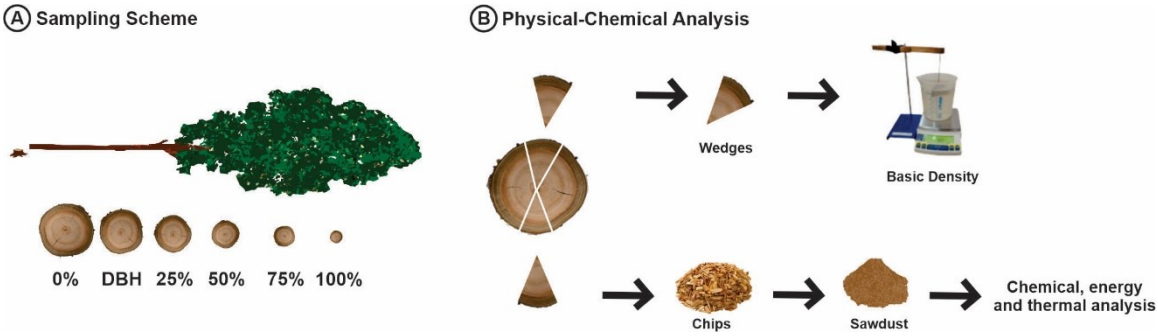


Fig. 1. Tree sampling scheme and wood analysis of *Corymbia* genotypes from non-commercial plantations

Physical-Chemical Analysis of Wood

To determine the basic wood density (BWD), a wedge was oriented to pass through the pith and cut from each disk, considering only the portion of the wood free of defects (knots, cracks, and reaction wood) (Fig. 1). The bark was removed from each wedge, and the wedges were submerged in water to saturate the fibers and then dried in an oven to obtain the dry mass, following the recommendations of standard NBR 11941 (ABNT 2003). The density of each wedge was then determined, and the BWD was calculated as the arithmetic mean of the six longitudinal positions of the trunk.

The chemical and energy properties were analyzed in composite samples from all longitudinal positions of the trunk. The wood was converted into chips and sawdust using a knife mill, and the sawdust fraction retained between 40 and 60 mesh sieves was used for the analyses. The ashes content and volatile materials were determined according to standard D1762-84 (ASTM 2021) at temperatures of 600 and 900 ºC, respectively. The fixed carbon content was calculated by using Eq. 1,

$$FC = 100 - (VM + Ashes) \quad (1)$$

where: FC is the fixed carbon content, VM is the volatile materials content, and $Ashes$ is the ashes content, based on the dry mass of the wood.

The total extractives content was determined according to 264 cm-97 (TAPPI 1997) using three extraction sequences: alcohol-toluene in a 1:2 proportion for 5 hours, alcohol for 4 hours, and hot water (100 °C) for 1 hour. The insoluble lignin content was determined based on the Klason method, modified according to the procedure described in Gomide and Demuner (1986), while the soluble lignin content was measured using a UV spectrophotometer, as proposed by Goldschimid (1971). The total lignin content was obtained by summing the insoluble and soluble lignin, and the holocelluloses were calculated by difference from the other chemical components of the wood, as described by Eq. 2.

$$Holocellulose = 100 - (Lignin + Extractives + Ashes) \quad (2)$$

The higher heating value (HHV) was determined using an adiabatic bomb calorimeter, model IKA C-200, according to standard E711-87 (ASTM 1996), while the lower heating value (LHV) was estimated by assuming the hydrogen content of the wood as 6%, in accordance with standard EN 14918 (DIN 2010) (Eq. 3). The energy density (ED) was calculated by using Eq. 4,

$$LHV = HHV - (206 * H) \quad (3)$$

where: *LHV* is the lower heating value (MJ kg^{-1}), *HHV* is the higher heating value (MJ kg^{-1}), and *H* is the hydrogen content of the wood (%).

$$ED = \frac{(BWD * HHV)}{1000} \quad (4)$$

In Eq. 4, ED is the energy density (GJ m^{-3}), BWD is the wood basic wood density (kg m^{-3}), and HHV is the higher heating value (MJ kg^{-1}).

Thermogravimetric Analysis

Thermogravimetric analysis (TG/DTG) was conducted using a DTG-60H thermal analyzer (Shimadzu, Kyoto, Japan) with 4 mg of sawdust retained between 200 and 270 mesh sieves. The analysis was performed in an inert atmosphere of high-purity nitrogen gas (N_2) (99.99%) with a flow rate of 60 mL min^{-1}. The temperature ranged from ambient (20 to 35 °C) to a final temperature of 800 °C, with a heating rate of 15.5 °C min^{-1}. The first derivative of the TG curve was used to identify the mass loss rate per minute with increasing temperature and the stages of combustion in terms of differential thermogravimetry (DTG).

Fourier Transform Infrared Spectroscopy (FTIR)

FTIR spectra for each wood sample were collected by using a Bruker type Tensor 27 spectrometer. The acquisition was carried out using an ATR accessory with 32 scans, with a resolution of 4 cm^{-1} in the region between 600 and 4000 cm^{-1}. The wood samples were ground in a Wiley-type knife mill to obtain a fine powder (fraction retained on a 270-mesh sieve). This analysis aims to identify functional groups in the wood samples.

X-Ray Diffraction (XRD)

Cellulose crystallinity was analyzed by using X-ray diffraction (XRD), which makes it possible to identify the crystalline structure of cellulose and the determination of its degree of crystallinity. Analyses were performed using a Rigaku MiniFlex 600 diffractometer (Tokyo, Japan) with copper Kα radiation (λ = 1.54 Å). The samples were scanned over a 2θ range from 3º to 90º, with a step size and scanning rate of 0.05º and one 2θ unit per minute, respectively. The main crystallinity peaks were identified, and the crystallinity index (CI) was calculated by using the empirical method proposed by (Segal *et al*. 1959), Eq. 5,

$$CI = \frac{I(002) - I(am)}{I(002)} \text{x}100 \quad (5)$$

where *CI* is the cellulose crystallinity index (%), $I_{(200)}$ is the maximum intensity of the main diffraction peak related to the crystalline plane at 2θ = 22º and 20º, and $I_{(am)}$ represents the amorphous halo at 2θ = 18º for cellulose I.

Statistical Analysis

The experimental design employed was a completely randomized design (CRD) with eleven treatments (genotypes) and three replicates (trees). The data were subjected to variance homogeneity tests (Bartlett's Test) and residual normality tests (Shapiro-Wilk Test), both at a 5% significance level. To analyze the chemical, energy, and thermal characteristics of wood, analysis of variance (ANOVA) was performed, considering the genotypes as the source of variation ($p < 0.05$). When significant effects were detected, the Scott-Knott test ($p < 0.05$) was used for multiple comparisons of means. Principal component analysis (PCA) was applied to cluster the genotypes and identify the variables contributing most to the principal components. All statistical analyses were conducted by using R statistical software, version 4.2.2 (R Core Team 2023).

RESULTS AND DISCUSSION

Basic Wood Density

A significant difference in BWD was observed (F-test, $p < 0.05$), leading to the formation of four distinct groups of *Corymbia* genotypes, represented by different shades of green (Scott-Knott test, $p < 0.05$) (Fig. 2). Group 1 consisted exclusively of the clone CTC2 (616 kg m^{-3}), while group 2 included one progeny and three clones, all with densities exceeding 580 kg m^{-3}. The progeny PTH and the clones CTC4, CTM2, and CTM1 were grouped in group 3 (554 to 571 kg m^{-3}). The group 4 was formed by two clones of low density (<500 kg m^{-3}).

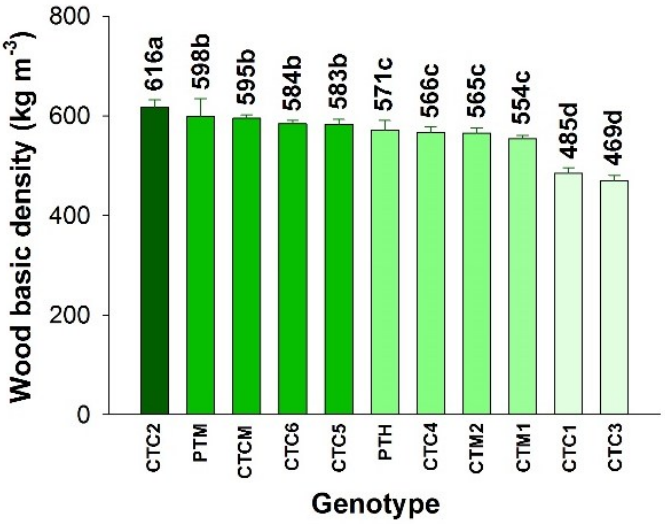


Fig. 2. Classification of genotypes of *Corymbia* according to basic wood density (A). Differences in color represent the groups of means by the Scott-Knott test ($p < 0.05$) and errors bars, the standard deviation

When the intended use is for energy applications, the wood should have a density of at least 500 kg m^{-3}, as this range is ideal for the steel industry. This density ensures lower specific wood consumption during carbonization, a final product with higher density and mechanical strength, as well as greater yield and volumetric productivity in masonry kilns (Massuque *et al*. 2022). One advantage of the genotypes studied is the higher wood density compared to the most widely planted *Eucalyptus* clones in Brazil, such as the *E. urophylla*

clone, whose density ranges from 536 to 662 kg m^{-3} (Almeida *et al*. 2022a), and the *E. grandis* × *E. camaldulensis* clone, which reaches a density of 520 kg m^{-3} (Câmara *et al*. 2020).

In Brazil, studies have demonstrated the potential of *Corymbia* species and their hybrids for metallurgical charcoal production. *Corymbia citriodora* exhibited a basic wood density of 0.583 g cm^{-3} and an apparent charcoal density of 0.459 g cm^{-3} (Marchesan *et al*. 2020). Recent studies conducted in Brazil have corroborated the potential of wood from *Corymbia* species based on the basic wood density (Araújo *et al*. 2023; Barros Junior *et al*. 2026; Melo *et al*. 2024; Rocha et al. 2024). Similarly, Brazilian hybrid *Corymbia* clones showed promising potential for industrial charcoal production, although considerable variation in charcoal yield and quality was observed among genetic materials (Loureiro *et al*. 2021). In Nigeria, wood species used for charcoal production have also been investigated for their physical and thermochemical properties, highlighting the importance of selecting suitable raw materials for energy applications (Yunusa *et al*. 2024). However, the available studies do not provide a sufficiently consistent basis for directly comparing Brazilian and Australian *Corymbia* genotypes in terms of charcoal quality. Therefore, further comparative research under standardized experimental conditions is needed to determine how Brazilian breeding and selection programs have influenced the suitability of these genotypes for metallurgical charcoal production.

Structural Chemical Composition

The levels of total extractives, total lignin, and holocellulose were significantly influenced by the genotypes (Fig. 3). The values ranged from 6.56% to 10.9% for total extractives, from 23.6% to 28.8% for total lignin, and from 60.4% to 68.6% (CTC5) for holocellulose content. Overall, the *Corymbia* genotypes evaluated in this study showed higher extractive contents compared to *Eucalyptus*, even at younger ages, as in the case of *E. urophylla* at 6 years old (3.69% to 5.42%) (Almeida *et al*. 2022a). The greater production and accumulation of extractives in *Corymbia* wood can be attributed to its adaptive characteristic of increased resistance to abiotic stresses, particularly water deficit (Lee 2007).

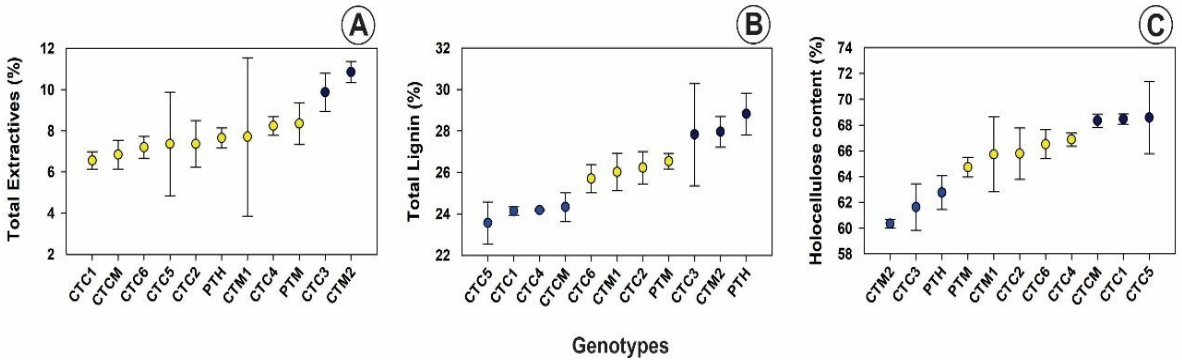


Fig. 3. Total extractives (A), total lignin (B), and holocellulose content (C) of the *Corymbia* genotypes. Differences in color represent the groups of means by the Scott-Knott test ($p < 0.05$) and errors bars, the standard deviation.

Extractives play a vital role in plant metabolism by serving as an energy source and protecting against disruptions and water scarcity. As they accumulate in plant tissues, they function as antioxidants, protecting plant cells from reactive oxygen species (ROS) generated by oxidative stress (Almeida *et al*. 2022b). Therefore, *Corymbia* genotypes are preferable for charcoal production, as high levels of extractives, especially those from phenolic type, increase the charcoal yield (Poletto 2016).

Compared with *Eucalyptus*, *Corymbia* genotypes may exhibit lower total lignin contents, even at young ages. For instance, the lignin content of two-year-old *Eucalyptus grandis* × *E. urophylla* clones ranges from 29.6% to 31.9% (Zanuncio *et al*. 2019). Although a lignin content of at least 28% has been associated with charcoal yields above 30% (Ramos *et al*. 2023), this value should not be interpreted as a universal threshold for genotype selection, as charcoal yield also depends on other wood characteristics and carbonization conditions. Lignin is an important parameter because of its relatively high thermal resistance and its contribution to charcoal formation during carbonization (Yang *et al*. 2007). Therefore, although eight of the evaluated genotypes presented lignin contents below 28%, their potential should be assessed based on the combined performance of multiple wood-quality traits, rather than lignin content alone. Nevertheless, because charcoal yield and quality were not directly determined in the present study, these genotypes should be considered candidates for further evaluation rather than definitively recommended for industrial charcoal production.

Regarding holocelluloses, the wood of *Corymbia* clones at 3.75 years of age has a holocellulose content of 64.2% (Loureiro *et al*. 2019), which is lower than that of five hybrid clones of *E. grandis* × *E. urophylla* at a younger age (2.25 years), with a range of 68.4% to 72.8% (Hsing *et al*. 2016). Lower holocellulose content is desirable in the steel industry, as cellulose and hemicelluloses have low thermal resistance, leading to a reduced charcoal yield (Trugilho *et al*. 2015).

Proximate Composition and Energy Productivity

A significant effect of genotype was observed on the ashes content, volatile materials, and fixed carbon, which ranged from 0.39% to 0.85%, 83.9% to 86.0%, and 13.3% to 15.2%, respectively (Table 2).

Overall, the genotypes evaluated in this study exhibited low ashes content (<1%), which is desirable for the charcoal-based steel industry. For metallurgical applications, low ashes content is desirable because mineral impurities can increase slag formation and affect the quality of the resulting metal. In the Brazilian charcoal-based steel industry, ashes content below 1% have been reported as a desirable characteristic, alongside high fixed-carbon content, high apparent density, and adequate mechanical strength (Pereira *et al*. 2012; Pereira *et al*. 2013; Andrade *et al*. 2018). However, acceptable ash levels may vary depending on the metallurgical process and its operational requirements.

Table 2. Mean Proximate Composition and Energy Productivity of Genotypes of *Corymbia*

Genotype	Proximate Composition (%)			Energy Productivity		
	Ashes	Volatile materials	Fixed carbon	HHV (MJ kg^{-1})	LHV (MJ kg^{-1})	ED (GJ m^{-3})
PTH	0.77 ± 0.12b	84.14 ± 0.38b	15.08 ± 0.33a	19.15 ± 0.41a	17.92 ± 0.41a	10.93 ± 0.39b
PTM	0.39 ± 0.16c	85.00 ± 1.29b	14.61 ± 1.34a	18.96 ± 0.27a	17.72 ± 0.27a	11.33 ± 0.81a
CTCM	0.51 ± 0.03c	85.78 ± 0.65a	13.70 ± 0.62b	18.97 ± 0.36a	17.73 ± 0.36a	11.29 ± 0.33a
CTM1	0.54 ± 0.08c	86.00 ± 0.96a	13.45 ± 0.91b	19.57 ± 0.48a	18.33 ± 0.48a	10.85 ± 0.33b
CTM2	0.85 ± 0.15a	83.92 ± 0.08b	15.23 ± 0.12a	19.32 ± 0.33a	18.08 ± 0.33a	10.91 ± 0.04b
CTC1	0.85 ± 0.18a	84.66 ± 0.41b	14.49 ± 0.25a	19.19 ± 0.42a	17.95 ± 0.42a	9.31 ± 0.13c
CTC2	0.63 ± 0.08c	86.04 ± 0.43a	13.33 ± 0.35b	19.13 ± 0.53a	17.89 ± 0.53a	11.77 ± 0.05a
CTC3	0.68 ± 0.05b	84.67 ± 1.08b	14.65 ± 1.09a	19.51 ± 0.48a	18.28 ± 0.48a	9.15 ± 0.25c
CTC4	0.70 ± 0.05b	85.36 ± 0.76a	13.94 ± 0.73b	19.33 ± 0.36a	18.09 ± 0.36a	10.95 ± 0.02b
CTC5	0.50 ± 0.07c	85.57 ± 1.31a	13.93 ± 1.33b	19.26 ± 0.46a	18.02 ± 0.46a	11.23 ± 0.34a
CTC6	0.60 ± 0.05c	85.25 ± 0.60a	14.15 ± 0.56b	19.44 ± 0.52a	18.20 ± 0.52a	11.36 ± 0.43a
Cve (%)	17.27	0.94	5.55	2.19	2.34	3.58

Mean ± standard deviation. Cve: the experimental coefficient of variation. HHV: higher heating value; LHV: lower heating value; ED: energy density. The same lowercase letters in the column do not differ statistically according to the Scott-Knott test at 5% of significance level.

Volatile matter plays an important role in the combustion behavior of biomass, although its effects depend on the intended application and operating conditions. During direct biomass combustion, lower volatile matter contents may be associated with reduced smoke and tar formation under certain conditions, whereas higher volatile matter contents can facilitate ignition and flame development. However, the release of volatile compounds does not necessarily ensure cleaner combustion, as emissions also depend on combustion efficiency and the oxidation of released gases. During wood carbonization, volatile compounds are released as gases and condensable products, and their effects on charcoal yield and quality depend on feedstock characteristics and process conditions (Lubwama *et al*. 2021).

The *Corymbia* genotypes evaluated in this study presented volatile matter contents comparable to or higher than those reported for *Eucalyptus urophylla* (81.9%) and *E. urophylla* × *E. camaldulensis* (84%) by Protásio *et al*. (2019), suggesting their potential for further investigation as feedstocks for charcoal production. From a sustainability perspective, the use of these genotypes could contribute to more resource-efficient charcoal production and the replacement of fossil carbon in metallurgical applications, proving that biomass is sourced from sustainably managed plantations and carbonization processes are efficient. Nevertheless, these environmental benefits cannot be confirmed from volatile matter content alone and require further assessment of biomass productivity, charcoal yield, process emissions, and resource use.

Fixed carbon content is a critical parameter for energy potential. High concentrations are strongly associated with the calorific value of wood and slower combustion, resulting in greater thermal resistance and higher carbon retention during carbonization (Carneiro *et al*. 2016). The fixed carbon values found for the *Corymbia*

genotypes in this study were lower compared to *E. urophylla* × *E. camaldulensis* (17.1%) and *E. urophylla* (17.9%) (Protásio *et al*. 2019).

Significant effects were observed for energy density and non-significant effect for higher heating value, and lower heating value. The range was from 9.15 to 11.77 GJ m^{-3}, 18.96 to 19.57 MJ kg^{-1}, and 17.72 to 18.33 MJ kg^{-1}, respectively (Table 2). Energy density represents the amount of energy contained in each volume of wood. High values are desirable as it results in greater mass of charcoal produced per unit volume (Jesus *et al*. 2017). The values found in this study are consistent with those reported for *E. urophylla* (10.7 to 11.3 GJ m^{-3}) (Lima *et al*. 2020) and *Eucalyptus* spp. (8.22 to 9.01 GJ m^{-3}) (Neves *et al*. 2013).

The calorific value is defined as the amount of heat released during the complete carbonization of a unit mass or volume of fuel, with higher values indicating better energy performance of the biomass during carbonization (Protásio *et al*. 2011). The average range from *Corymbia* genotypes in this study is comparable to those reported for five *Eucalyptus* genotypes at three years old (19.7 to 19.9 MJ kg^{-1}) (Carneiro *et al*. 2017), as well as for one clone of *E. urophylla* (18.6 to 18.8 MJ kg^{-1}), a spontaneous hybrid of *C. citriodora* x *C. torelliana* (18.6 to 19.0 MJ kg^{-1}), and a spontaneous hybrid of *C. torelliana* x *C. citriodora* (18.1 to 18.5 MJ kg^{-1}) (Lopes *et al*. 2022).

Based on the evaluated wood properties, CTM1 exhibited the highest higher and lower heating values (19.6 and 18.3 MJ kg^{-1}, respectively), whereas CTC2 presented the highest energy density (11.8 GJ m^{-3}). PTM showed the lowest ashes content (0.39%), which may be advantageous for energy applications. These characteristics indicate that CTM1, CTC2, and PTM are promising candidates for further evaluation in energy production. However, their suitability for the European charcoal market cannot be confirmed solely from the properties of uncarbonized wood. According to EN ISO 17225-1:2021, charcoal quality assessment includes parameters such as ash content, fixed carbon, moisture, bulk density, and net calorific value. Therefore, charcoal production and subsequent characterization are necessary to determine whether these genotypes meet the relevant quality specifications for commercial applications.

Thermogravimetric Decomposition

Figure 4A illustrates the combustion behavior of wood through thermogravimetric analysis across different *Corymbia* genotypes studied. Based on the curves, the order of genotypes in terms of thermal stability during combustion, as indicated by residual mass, is as follows: CTC6 (31.0%), CTC1 (29.7%), and CTC4 (25.6%). Conversely, the genotypes with the lowest thermal stability are CTC2 (17.0%), PTH (18.4%), and CTC5 (19.6%).

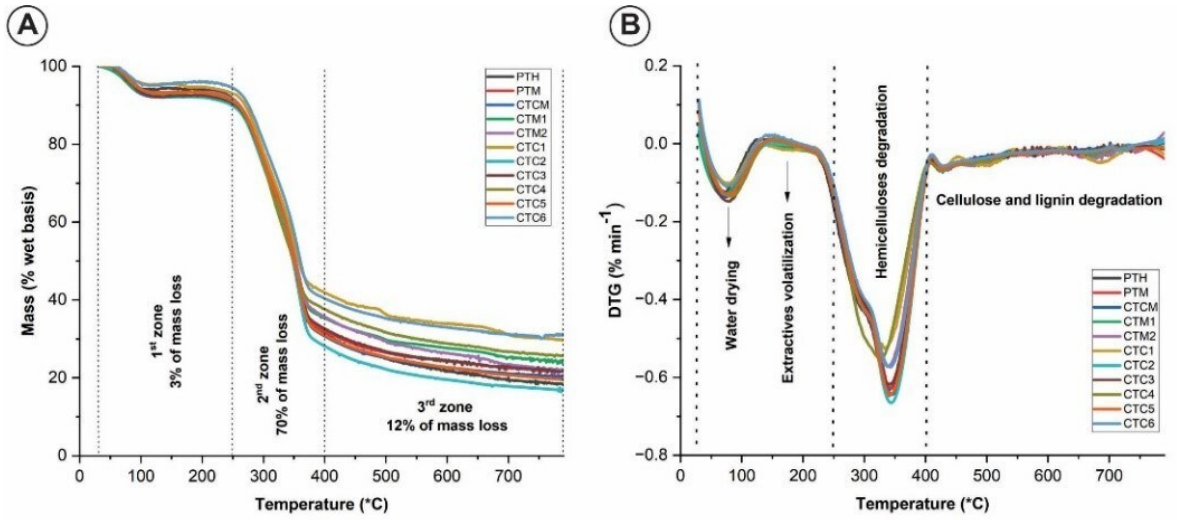


Fig. 4. Thermogravimetric curves (A) and Thermogravimetric derivate (B) of the *Corymbia* genotypes

Figure 4B shows the DTG curve (first derivative of the TG curve), which displays the different stages of wood combustion. The first zone, up to 250 °C, is known as the thermal stability zone of the wood and is characterized by a low mass loss (approximately 3%). This zone is associated with the evaporation of water, indicated by a peak around 80 °C, and the release of volatile substances occurring from 80 °C to approximately 250 °C. The second zone, located between 250 °C and 400 °C, corresponds to the thermal degradation of hemicelluloses and part of the cellulose, and is the stage with the highest mass loss (approximately 70%). The third and final zone, occurring between 400 °C and 790 °C, is associated with the degradation of cellulose and lignin, with a mass loss of approximately 12%.

FTIR Spectra and Cellulose Crystallinity

The FTIR spectra presented in Fig. 5A reveals that the chemical functional groups levels of the wood from the *Corymbia* genotypes are highly similar, as there are no significant differences in the spectra. This similarity is attributed to all genotypes belonging to the same genus. The first broad band is located at 3340 cm^{-1}, associated with the absorbance associated with the stretching of the O-H bond, probably from cellulose (Kwon *et al*. 2013). The second band, situated at 2920 cm^{-1}, corresponds to the asymmetric stretching of the C-H bond, also probably from cellulose. The band at 1733 cm^{-1} represents stretching of the C=O bond in ketone, carbonyl, and non-conjugated aliphatic groups found in hemicelluloses and lignin (Huang *et al*. 2008).

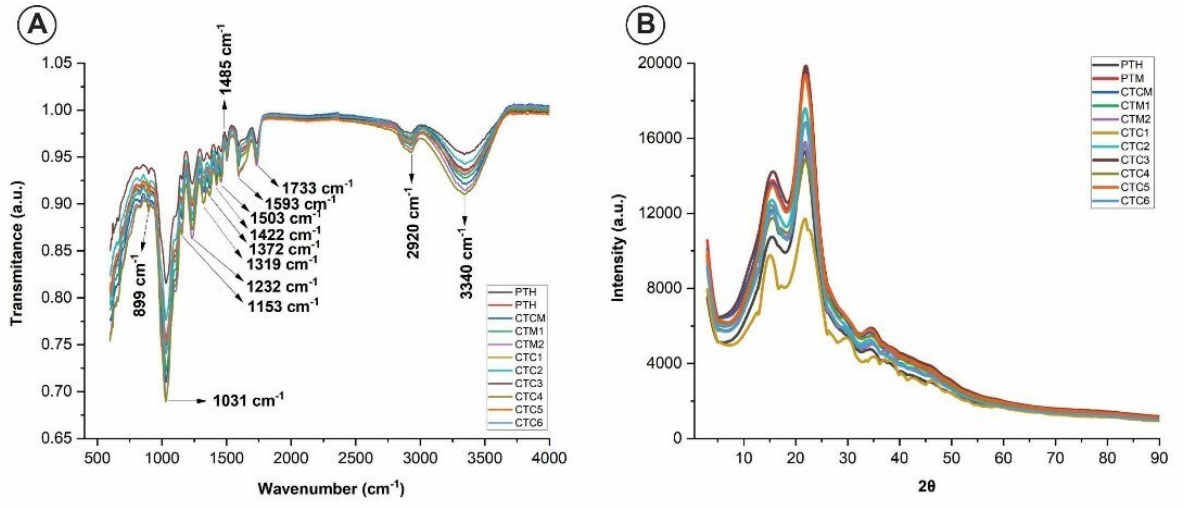


Fig. 5. Main FTIR spectra (A) and XRD curves (B) obtained for the *Corymbia* genotypes wood

Additionally, well-defined peaks were identified between the regions of 1593 cm^{-1} and 899 cm^{-1}. Peaks at 1593 and 1503 cm^{-1} correspond to non-conjugated aromatic skeletal groups in lignin. Peaks at 1485 and 1422 cm^{-1} are attributed to in-plane, asymmetric and symmetric angular deformation of the C-H bond in lignin and carbohydrates (Kwon *et al*. 2013). Peaks at 1372 and 1319 cm^{-1} represent the symmetric in-plane angular deformation of the C-H bond and the in-plane angular deformation of the O-H bond in cellulose, hemicellulose, and lignin (Huang *et al*. 2008). Bands at 1232, 1153, 1031, and 899 cm^{-1} correspond to the syringyl ring and C-O stretching in lignin and xylan, C-O-C vibration in cellulose and hemicelluloses, C-O stretching in cellulose and hemicelluloses, and a stretching of the C-O-C in cellulose, respectively (Schwanninger *et al*. 2004).

The X-ray diffraction (XRD) profiles are shown in Fig. 5B, where only cellulose type I is identified, as evidenced by the two diffraction peaks characteristic of cellulose. A lower intensity halo is observed at 2θ = 15.7º, corresponding to the (110) crystallographic plane. The second peak of higher intensity occurs at 2θ = 21.9º, corresponding to the (002) crystallographic plane, indicating a higher amount of crystalline material at this position. A third, less intense and imperceptible peak can be seen at 2θ = 34.7º, corresponding to the (040) crystallographic plane (Melo *et al*. 2022).

Table 3 presents the crystallinity index for each analyzed *Corymbia* genotype, showing that the PTM progeny exhibits the highest value. The IC is crucial for selecting and classifying genotypes for charcoal production, as wood with a higher IC is more resistant to thermal degradation (Pereira *et al*. 2013).

Clone CTC4 exhibited more intense peaks at the bands of 3340, 2920, 1372, 1319, 1153, and 1031 cm^{-1}, whereas clone CTM2 showed more pronounced peaks at 1733, 1593, 1485, 1503, 1422, 1232, and 899 cm^{-1}. This behavior suggests that these clones may exhibit higher relative contributions from the organic functional groups associated with the respective bands compared with the other genotypes.

Clone CTC3 exhibited lower peak intensities across nearly all the highlighted bands, suggesting a lower relative contribution of the organic functional groups identified by FTIR analysis in this genotype.

Table 3. Crystalline Index (CI) of the Genotypes of *Corymbia*

Genotypes	Crystalline Index, CI (%)
PTH	35.10
PTM	38.17
CTCM	38.41
CTM1	32.12
CTM2	31.89
CTC1	31.26
CTC2	35.90
CTC3	36.66
CTC4	26.40
CTC5	37.75
CTC6	37.13

Multivariate Clustering of Genotypes

The first two principal components (PC1 and PC2) explained 71.6% of the total data variability, indicating that they captured a substantial proportion of the variation in the evaluated wood properties. PC1 was primarily associated with volatile matter, holocellulose, fixed carbon, total extractives, total lignin, ash content, basic density, and energy density, whereas PC2 was mainly influenced by higher and lower heating values, basic and energy density, fixed-carbon content, and total lignin content (Table 4).

These results indicate that the differentiation among genotypes was associated with a combination of chemical composition, wood density, and energy-related characteristics. Similar multivariate approaches have been used to discriminate forest genetic materials based on wood and charcoal properties and to identify promising clones for energy and metallurgical applications (Loureiro *et al*. 2021; Fialho *et al*. 2022; Massuque *et al*. 2023).

Basic density and energy density contributed to the differentiation of the genotypes, highlighting their relevance for energy applications. Basic density is associated with the amount of biomass contained in a given wood volume, while energy density integrates this characteristic with the calorific value and therefore reflects the amount of energy stored per unit volume. Previous research has identified wood density as an important criterion for selecting *Eucalyptus* clones for charcoal production, particularly because higher-density wood can result in denser charcoal and improve the efficiency of industrial operations (Protásio *et al*. 2021).

In addition, lignin and fixed-carbon contents are relevant to energy performance because lignin contributes to the carbonaceous structure of wood and can influence charcoal yield and quality. Nevertheless, these relationships should be interpreted in the context of the raw material and carbonization conditions, as wood properties alone do not determine the final characteristics of charcoal (Loureiro *et al*. 2021).

Table 4. Eigenvectors Associated with the First Two Principal Components

Property	PC1	PC2
Basic wood density	**0.6515274**	**0.564598**
Total extractives	**-0.7574018**	0.1893273
Total lignin	**-0.7079882**	**0.427082**
Holocellulose content	**0.8301312**	-0.3502286
Ashes content	**-0.6773586**	-0.0849959
Volatile matter content	**0.8416281**	-0.375324
Fixed carbon content	**-0.7989948**	**0.446339**
Higher heating value	-0.446458	**-0.74969**
Lower heating value	-0.4569959	**-0.74555**
Energy density	**0.6310648**	**0.488326**

The PCA scores separated the evaluated genotypes into four groups (Fig. 6), indicating differences in their combinations of chemical, physical, and energy-related properties. Group 1 comprised progeny PTM and clones CTCM and CTC2. This group was characterized by relatively high basic and energy densities, consistent with the positive association between these variables in the PCA biplot. The relationship between wood density and energy density has also been reported in studies of *Eucalyptus* clones, supporting the use of these traits as complementary criteria for selecting materials for bioenergy applications (Silva *et al*. 2018). Accordingly, the genotypes in Group 1 may be promising candidates when high energy content per unit volume is a priority, although their suitability for metallurgical charcoal production requires direct evaluation of carbonization yield and charcoal quality.

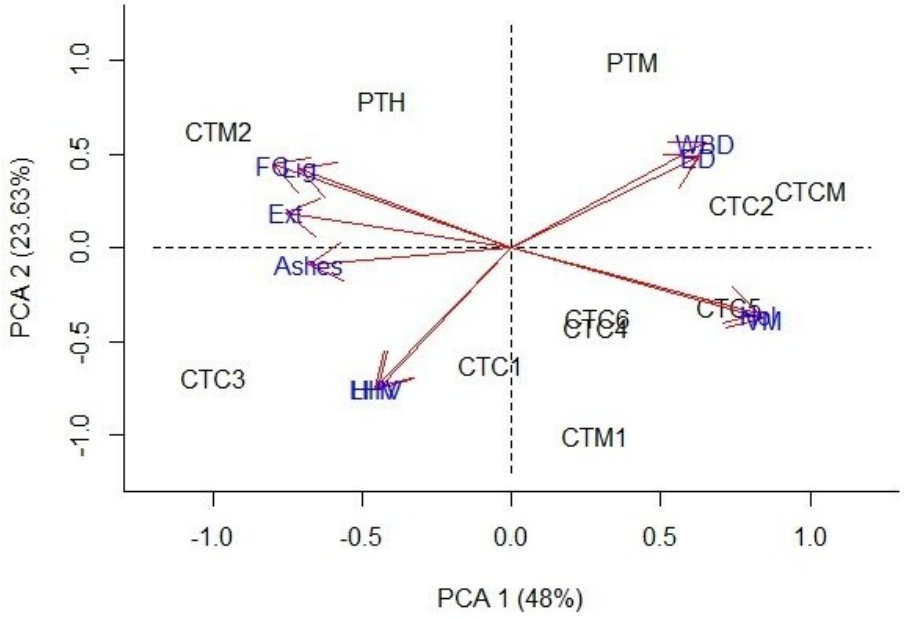


Fig. 6. Graph of the scores of the principal component analysis of the wood properties from the genotypes of *Corymbia*

Group 2 included clones CTM1, CTC1, CTC4, CTC5, and CTC6 and was associated with the positive relationship between volatile matter and holocellulose content. Holocellulose comprises cellulose and hemicelluloses, which undergo thermal decomposition during carbonization and contribute to the release of volatile products. These properties are relevant to the thermal behavior of wood, but their effects on ignition, charcoal yield, and final product quality depend on carbonization conditions and should not be inferred from the PCA alone.

Group 3 was associated with the positive correlation between higher and lower heating values. This association is expected because both variables represent related measures of the energy released during combustion, although they differ in their treatment of the latent heat of water vapor. Genotypes with favorable heating values may be attractive for energy applications; however, their overall suitability for charcoal production should also consider wood density, chemical composition, carbonization yield, and the properties of the resulting charcoal.

Group 4, comprising progeny PTH and clone CTM2, showed a positive association between fixed-carbon and total lignin contents, together with a weaker association between total extractives and fixed-carbon content. These relationships suggest that differences in lignocellulosic composition may contribute to the separation of these genotypes. Previous work on hybrid *Corymbia* clones has demonstrated that selecting materials based on multiple charcoal-quality parameters, including fixed-carbon content, density, calorific value, and gravimetric yield, can help identify promising materials for metallurgical applications (Loureiro *et al*. 2021). However, the correlations observed in the present study do not independently demonstrate higher charcoal yield, and this characteristic should be verified through carbonization experiments.

Overall, the PCA provided a useful framework for identifying similarities and differences among the evaluated progenies and hybrid clones. The results suggest that genotype selection should consider a combination of chemical composition, density, and heating value rather than relying on a single property.

The relevance of the evaluated wood properties to the steel industry is supported by studies that have directly investigated charcoal quality and industrial performance. Andrade *et al*. (2018) reported that desirable characteristics of metallurgical charcoal include high apparent density and mechanical strength, low moisture and ash contents, and high fixed-carbon content and calorific value. Similarly, Protásio *et al*. (2021) demonstrated that wood density, tree growth, and charcoal gravimetric yield are important criteria for selecting *Eucalyptus* clones for steel production, with high-density wood contributing to denser charcoal and lower specific wood consumption. More recently, a study of non-commercial *Corymbia* and *Eucalyptus* species identified promising materials based on charcoal energy density, apparent density, and reactivity (Massuque *et al*. 2023). These findings support the relevance of evaluating density, chemical composition, and heating value in the present study. However, because charcoal was not directly produced and characterized here, the evaluated genotypes should be considered promising candidates rather than materials whose compliance with industrial quality requirements has been confirmed.

From an environmental and practical perspective, the variation in wood properties among the evaluated *Corymbia* progenies and hybrid clones has implications for resource efficiency and their potential application in the steel industry. Genotypes with higher energy density may provide more energy per unit volume of wood, potentially reducing biomass handling, storage, and transportation requirements. Furthermore, charcoal

produced from sustainably managed forest plantations may contribute to steel-sector decarbonization by partially replacing fossil carbon, provided that biomass production, land use, and carbonization processes result in lower life-cycle greenhouse gas emissions (Bailis *et al*. 2013; Silva *et al*. 2024). From an industrial perspective, the favorable energy properties observed in selected genotypes, particularly the high heating value of CTM1 and the high energy density of CTC2, support their potential for further evaluation in charcoal-based steelmaking. However, the economic and environmental viability of large-scale deployment also depends on growth and biomass productivity, charcoal yield and quality, plantation establishment and harvesting costs, transport distances, and carbonization efficiency. As these factors were not directly assessed in the present study, life cycle assessment and techno-economic analyses, combined with field trials and charcoal characterization, are required to determine whether these genotypes can provide environmental and economic advantages over existing feedstocks.

Further studies should evaluate these genotypes under different growing conditions, harvest ages, planting spacings, and forest management practices. Carbonization trials and direct characterization of the resulting charcoal are also required to determine whether the favorable wood characteristics identified in this study translate into improved charcoal yield and quality for industrial applications.

CONCLUSIONS

1. The results of this study indicate that the evaluated *Corymbia* genotypes have potential for producing charcoal with properties relevant to the steel industry.
2. CTC2 (*C. torelliana* × *C. citriodora*) and CTM2 (*C. torelliana* × *C. maculata*) showed favorable results for selected properties associated with charcoal production. However, these findings do not establish their overall superiority over the genotypes evaluated, and genotype selection should consider the magnitude and practical relevance of difference among materials.
3. CTC2 showed high basic density and energetic density, together with elevated volatile matter content and a high crystallinity index. These characteristics highlight species aspects of its material properties but should be considered alongside other relevant parameters when assessing its sustainability for charcoal production.
4. CTM2 showed high extractives, lignin, and fixed-carbon contents, as well as a high calorific value and low holocellulose content. These characteristics identify potentially relevant attributes for energy applications, although their practical importance depends on the overall performance of the material and the requirements of the intended industrial process.
5. CTC1 (*C. torelliana* × *C. citriodora*) showed comparatively lower wood quality, extractives and lignin contents, and energetic density, together with higher holocellulose and ash contents. Although this profile differs from that of genotypes with more favorable values for some of the evaluated properties, it does not, by itself, establish that CTC1 is unsuitable for charcoal production or than it would be more appropriate for other energy applications.

6. Among the progenies, PTH showed favorable fixed-carbon content and heating value, whereas PTM had the lowest ash content. Although the progenies showed promising characteristics, they did not consistently outperform the clones across all evaluated parameters. Therefore, selecting superior genetic materials requires a multi-trait approach, followed by further assessment of growth performance, biomass productivity, and charcoal quality to confirm their suitability for industrial energy applications.

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