Research Article
doi: 10.1590/01047760202632013745
vol(32), 2026

CERNE

Insights into growth performance and wood quality of Juvenile *Corymbia* spp. for metallurgical charcoal production

Sofia Maria Gonçalves Rocha[1], Caio Varonill de Almada Oliveira[2], Thayanne Caroline Castor Neto[3], Stéffany de Lima Araujo[3], Graziela Baptista Vidaurre[3].

[1]Eldorado Brazil Celulose S.A, Três Lagoas, Mato Grosso do Sul, Brazil.
[2] Suzano S.A., São Paulo, Brazil.
[3]Federal University of Espírito Santo, Department of Forest and Wood Sciences, Jerônimo Monteiro, Espírito Santo, Brazil

TECHNOLOGY OF FOREST PRODUCTS

ABSTRACT

Background: The steel industry demands raw materials capable of improving charcoal quality and production efficiency. The objective of the study was to identify and quantify the potential advantages of *Corymbia* wood for charcoal production compared with *Eucalyptus* and to evaluate the influence of dendrometric, wood and charcoal properties on the differentiation of these genetic materials.

Results: The *Corymbia* hybrids exhibited lower height growth than *Eucalyptus*, while presenting wood that was, on average, 20% denser and contained 44% less heartwood. The resulting charcoal showed, on average, 2% higher gravimetric yield, 15% higher density, and 8% greater mechanical resistance than *Eucalyptus* charcoal. Basic density was identified as the variable most strongly associated with the differentiation among the evaluated genera and hybrids of *C. torelliana* x *C. citriodora*.

Conclusions: Although *Corymbia* hybrids showed lower growth, they produced a charcoal mass per hectare similar to that of *E. urophylla* x *E. grandis*. These results indicate the potential of the evaluated *Corymbia* hybrids as an alternative source of raw material for steelmaking charcoal production.

Keywords: *Basic density; bioenergy; carbonization; mechanical resistance; steelmaking charcoal.*

HIGHLIGHTS

Evaluated *Corymbia* hybrids produced denser and more resistant charcoal.
Wood basic density was the main trait differentiating *Corymbia* from *Eucalyptus*.
Corymbia hybrids showed higher fixed carbon concentration per unit volume.
Juvenile *Corymbia* wood showed favorable traits for steelmaking charcoal.

ROCHA, S. M. G.; OLIVEIRA, C. V. A.; CASTOR NETO, T. C.; ARAUJO, S. L.; VIDAURRE, G. B. Insights into growth performance and wood quality of Juvenile *Corymbia* spp. for metallurgical charcoal production. CERNE, v. 32, e103745, 2026. DOI: 10.1590/01047760202632013745

✤Corresponding author: neto.thayanne@gmail.com
Scientific Editor: Paulo Ricardo Gherardi Hein

Received: May 18, 2025
Accepted: June 02, 2026

CERNE
ISSN 0104-7760
UNIVERSIDADE FEDERAL DE LAVRAS

INTRODUCTION

The wood used for charcoal production is one of the main factors that influence the properties of this carbonaceous and, consequently, on the adequacy of the product to the market and forest planning projections. The worldwide demand for charcoal in the steel industry is a growing fact, due to the productivity and economy involved in this conversion process and the renewability of the process (Empresa de Pesquisa Energética – EPE, 2025). But what is the challenge in selecting species and genetic materials compatible with charcoal production as a steelmaking bioreducer? The genus *Corymbia* has been reclassified from the genus *Eucalyptus* due to phylogenetic and cladistic differences and, mainly, due to the impossibility of hybridization with species of *Eucalyptus* (Hill and Johnson, 1995; Ladiges *et al*., 2010). Other characteristics that differentiate the genus include anatomical and structural differences in the wood, such as thicker fiber walls, greater permeability, and variations in vessel area and heartwood–sapwood proportions in *Corymbia* wood compared with *Eucalyptus* (Rocha *et al*., 2024). These characteristics are often associated with denser wood and may influence industrial performance, indicating the potential of *Corymbia* hybrids for applications where wood quality is a key requirement.

Despite all the information about the species of *Corymbia*, researches that highlight the main differences between the wood from hybrids of the genera *Corymbia* and *Eucalyptus* are scarce. The gains in terms of energy and/or economic efficiency that the new genus correct use provides to the production chain and the quality of charcoal are, so far, little known worldwide. The comparison between the two genus is not the only key to obtaining greater efficiency, but the correct stratification of genetic materials favors the choice of better clones for investment. Thus, the combination of growth and wood quality has shown significant results in the characteristics of the final product (Barros Junior *et al*., 2026; Melo *et al*., 2024; Brito *et al*., 2020).

The higher density of the wood is said to be responsible for the physical and mechanical properties of charcoal, such as its density. More dense charcoal, in general, contributes to higher fixed carbon concentration per volume, and provides lower specific consumption in the reduction of iron ore in the blast furnace, contributing to maximizing pig iron production (Biswas *et al*., 2011; Assis *et al*., 2015; Pereira *et al*., 2025). Studies have highlighted satisfactory gravimetric yield in charcoal and its high density when produced with *Corymbia* wood (Barros Junior *et al*., 2026; Peres *et al*., 2019; Costa *et al*., 2017). Previous studies have indicated that hybrids of *Corymbia* torelliana × *Corymbia* citriodora may represent a promising alternative for steelmaking charcoal production, particularly due to the association between wood density and charcoal density and mechanical strength (Loureiro *et al*., 2019).

Although several studies have reported favorable wood and charcoal characteristics for *Corymbia* hybrids, information integrating growth performance, wood quality, and charcoal properties of juvenile *Corymbia* hybrids remains limited. In particular, there is a lack of studies quantifying the potential gains of these materials relative to commercially established *Eucalyptus* clones and identifying the traits that most contribute to their differentiation for steelmaking charcoal production. Addressing this gap may improve the selection of genetic materials and support decision-making in breeding and industrial deployment programs. Based on the reported association between wood density and charcoal quality, we hypothesized that juvenile *Corymbia* hybrids would exhibit superior properties than juvenile *Eucalyptus* clones, despite their early stage of development. Therefore, the objective of this work was to compare growth performance, wood quality, and charcoal properties of *Corymbia* hybrids and *Eucalyptus* clones, quantify potential differences between these materials, and identify the dendrometric, wood, and charcoal traits that most contribute to their differentiation.

MATERIAL AND METHODS

Plant material and experimental design

Ten clones were evaluated: one clone of *E. urophylla* x *E. grandis*, used as a reference material, and nine hybrids of *C. torelliana* x *C. citriodora*. The trees were 3.2 years old and originated from an experimental plantation located in the rural area of Bom Despacho, Minas Gerais, Brazil (-19.691333° S, -45.216105° W; 768 m above sea level). The experiment was established on clayey dystrophic Oxisol. During the study period (2013–2019), the site presented a mean annual precipitation of 1,088 mm and a mean annual temperature of 20.1 °C.

The planting spacing was 4.5 × 2.5 m. The experimental area covered 2.5 ha, with approximately 0.5 ha allocated to each clone. All plots received the same silvicultural treatments and were established under identical site preparation, planting date, and spacing conditions to minimize environmental variation among genetic materials.

Dendrometric data and wood and charcoal characterization

For wood characterization and charcoal production, four trees per clone were sampled, totaling 40 experimental units, including 36 trees of *C. torelliana* × *C. citriodora* and four trees of *E. urophylla* × *E. grandis*. Dendrometric measurements were obtained for all trees in the experiment and included total height (TH), measured from the base of the stem to the top of the crown; commercial height (CH), measured from the stem base to the point where the stem diameter reached 5 cm; diameter at breast height with bark (DBHwb, cm), measured at 1.3 m above ground level; wood volume with bark (Volwb, $m^3\ ha^{-1}$); mean annual increment with bark (MAIwb, $m^3\ ha^{-1}\ yr^{-1}$); and wood biomass ($t\ ha^{-1}$), calculated as the product of wood volume without bark and basic wood density.

For wood characterization, 12 discs were collected per tree at six positions along the stem corresponding to the sections used in Smalian's method: 0%, DBHwb (1.3 m), 25%, 50%, 75%, and 100% of the commercial height (Figure 1). Discs were collected from sections free of visible defects. Basic density (BD, t m^{-3}), bark content (BK, %), sapwood proportion (SW, %), heartwood proportion (HW, %), and the heartwood-to-sapwood ratio (H/S) were determined as the average of the six sampling positions.

Basic wood density was determined according to NBR 11941 (ABNT, 2003). The volume of bark-free saturated discs was measured, and the samples were subsequently dried in a forced-air oven at 103 ± 2 °C until constant mass. Bark, sapwood, and heartwood proportions were determined by visually identifying their boundaries on previously sanded discs after water application. When the heartwood boundary was not clearly visible, a solution containing 1 g of dimethyl yellow dissolved in 500 mL of ethanol was applied to enhance the distinction between heartwood and sapwood.

Wood carbonization was carried out in an industrial rectangular AM32 kiln measuring 32 m in length, 5 m in width, and 4 m in wall height, with a dome rise of 1.27 m and a total capacity of 320 m^3 of wood with bark.

To enable the identification and recovery of charcoal produced from each clone, the wood samples were placed inside cylindrical metal containers (60 cm in diameter, 85 cm in height, and 200 L capacity) before being loaded into the kiln. Each container held logs obtained from a single tree, cut into 75-cm-long sections, as illustrated in Figure 2. The containers allowed the experimental charcoal to be separated from the remaining charcoal produced during the industrial carbonization process.

The metal containers were distributed among eight wood stacks already loaded in the kiln, with five containers placed on each stack. The central stacks were intentionally excluded because this region is known to exhibit greater temperature variability during carbonization. During kiln loading, the containers were randomly assigned to the selected stacks and positioned parallel to the wood piles, ensuring that the perforations in the containers remained unobstructed throughout the process.

Carbonization temperature was continuously monitored using a supervisory control system connected to twelve thermocouples installed along the kiln side walls and roof at intervals of 3.5 m. Carbonization was initiated simultaneously by eight ignition points located near the kiln floor. The ignition points were progressively sealed according to the average roof temperature as follows: (a) 50% at 150 °C; (b) 75% at 200 °C; (c) 90% at 250 °C; and (d) 100% at 280 °C.

The average maximum temperatures recorded at the kiln roof, chimney wall, and opposite wall during carbonization were 325 °C, 165 °C, and 150 °C, respectively. The final carbonization temperature was 300 °C, and the kiln was opened when the internal temperature reached 38 °C. The entire charcoal production cycle lasted 368 h, comprising 87 h of carbonization and 281 h of natural cooling.

The charcoal was characterized for gravimetric charcoal yield (GCY, %), charcoal production per hectare

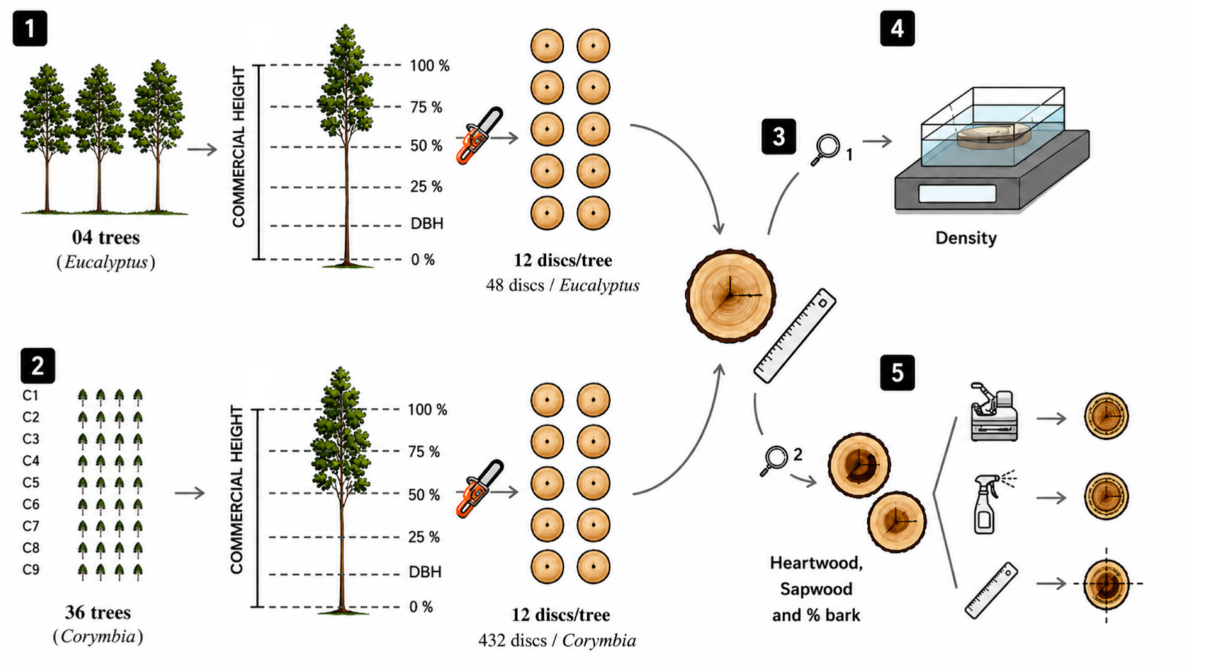


Figure 1: Experimental design and wood sampling procedure used for the evaluation of wood properties in *Eucalyptus* clone and *Corymbia* hybrids. (1) *Eucalyptus* sampling; (2) *Corymbia* sampling; (3) Preparation of wood discs; (4) Determination of basic wood density; (5) Evaluation of heartwood, sapwood, and bark proportions.

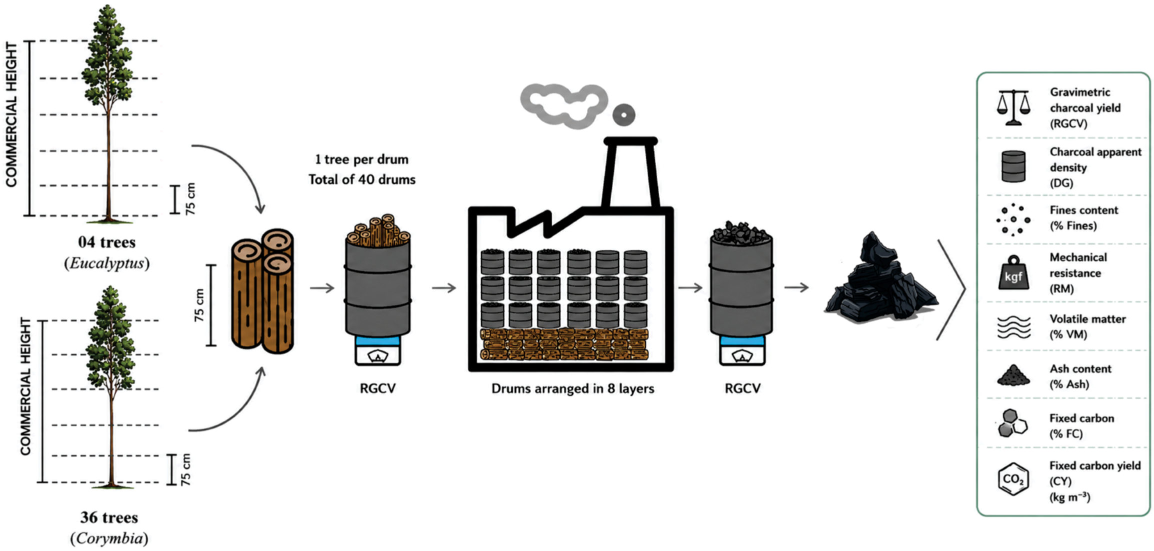


Figure 2: Experimental design and charcoal production used for the evaluation of charcoal properties from *Eucalyptus* and *Corymbia* wood.

(CPH, t ha^{-1}), bulk density (BKD, t m^{-3}), fines content (FN, %), mechanical resistance (MR, %), coarse charcoal content (CC, %), fine charcoal content (FC, %), volatile matter content (VMC, %), fixed carbon stock per unit volume (FCV, t m^{-3}), ash content (ASH, %), and fixed carbon content (FC, %).

Mechanical resistance was determined as the percentage of charcoal retained after compression under a load of 1 ton without generating fines. Coarse charcoal corresponded to particles larger than 25 mm, whereas fine charcoal corresponded to particles smaller than 25 mm.

Gravimetric charcoal yield was calculated according to Equation 1:

$$\mathrm{GYC}\left(\%\right) = \frac{\mathrm{MC}}{\mathrm{MDW}} * 100 \quad (1)$$

where MC is the charcoal mass (kg) and MDW is the oven-dry wood mass (kg).

Volatile matter, fixed carbon, and ash contents (proximate analysis) were determined according to NBR 8112 (ABNT, 1986). Charcoal granulometry was evaluated according to NBR 7402 (ABNT, 1982), considering coarse charcoal as the fraction retained on the 63- and 25-mm sieves and fine charcoal as the fraction retained on the 19- to 9.5-mm sieves.

Charcoal mechanical resistance was determined using a manual hydraulic press operating at a compression load of one ton per minute for each particle-size class, according to the methodology proposed by Soares *et al.* (2021). The final value for each genetic material corresponded to the mean of the evaluated particle-size classes.

Data analysis

Dendrometric, wood, and charcoal data were subjected to the Shapiro–Wilk and Bartlett tests to verify the assumptions of normality and homogeneity of variances, respectively. Subsequently, the data were analyzed using analysis of variance (ANOVA), and means were grouped by the Scott–Knott test at the 5% significance level when appropriate.

To investigate the pattern of dissimilarity between *Corymbia* hybrids and the reference *Eucalyptus* clone, canonical variable analysis was performed using the traits that showed significance for at least one source of variation in the ANOVA. Genotype clustering based on canonical variable scores was carried out using the k-means algorithm. Separate canonical variable and cluster analyses were also performed for the dendrometric, wood, and charcoal traits that showed significance for the *Corymbia* versus *Eucalyptus* source of variation in the initial ANOVA.

The relative contribution of each trait to genotype differentiation was estimated according to Singh's criterion (1981), using the generalized Mahalanobis distance matrix and considering the 12 traits that were significant for at least one source of variation in the ANOVA.

Correlation network analysis was used to graphically represent the relationships among phenotypic correlations between groups of traits. In the network, the proximity between nodes was proportional to the absolute correlation coefficient. Edge thickness was scaled according to the magnitude of the correlation, and only correlations with $|r| \geq 0.50$ were highlighted. Positive correlations were represented by green edges, whereas negative correlations were represented by red edges. All statistical analyses were performed using R software (R Core Team, 2022).

RESULTS

Among the 22 traits evaluated, 12 showed significant differences ($p < 0.05$), either among the 10 clones, between *Corymbia* and *Eucalyptus*, or among the nine clones of *C. torelliana* × *C. citriodora* (Figure 3). The partitioning of the sources of variation into treatments (10 clones), *Corymbia* versus *Eucalyptus* (mean of the nine *Corymbia* hybrids versus the *Eucalyptus* clone), and among *Corymbia* hybrids revealed significant differences for two of the six dendrometric traits (TH and CH), three of the five wood traits (HW, H/S, and BD), and seven of the eleven charcoal traits (GCY, BKD, MR, CC, FC, FCV, and ASH). Significant differences among *C. torelliana* × *C. citriodora* clones were also detected for BD, GCY, and MR (Figure 3)

For the dendrometric traits TH and CH, the *Corymbia* hybrids were, on average, 12% and 24% smaller than the *Eucalyptus* clone, respectively (Figure 3). The *Corymbia* hybrids also exhibited, on average, 44% lower heartwood content and a heartwood-to-sapwood ratio 47% lower than that observed for *E. urophylla* × *E. grandis*. Regarding wood basic density, all *Corymbia* hybrids presented higher BD values than the *Eucalyptus* clone, with differences of 25%, 21%, and 15% among the groups identified by the Scott–Knott test (Figure 3).

Three distinct groups were identified for gravimetric charcoal yield (GCY), corresponding to high, intermediate, and low yield classes, with mean values of 38.5%, 36.6%, and 34.4%, respectively. The *Eucalyptus* clone was grouped with the *Corymbia* hybrids that exhibited intermediate GCY values (Figure 3). All *Corymbia* hybrids produced charcoal with higher bulk density than the *Eucalyptus* clone, with differences of 18% and 11% for groups a and b, respectively (Figure 3).

The charcoal produced from five *C. torelliana* × *C. citriodora* clones showed mechanical resistance values

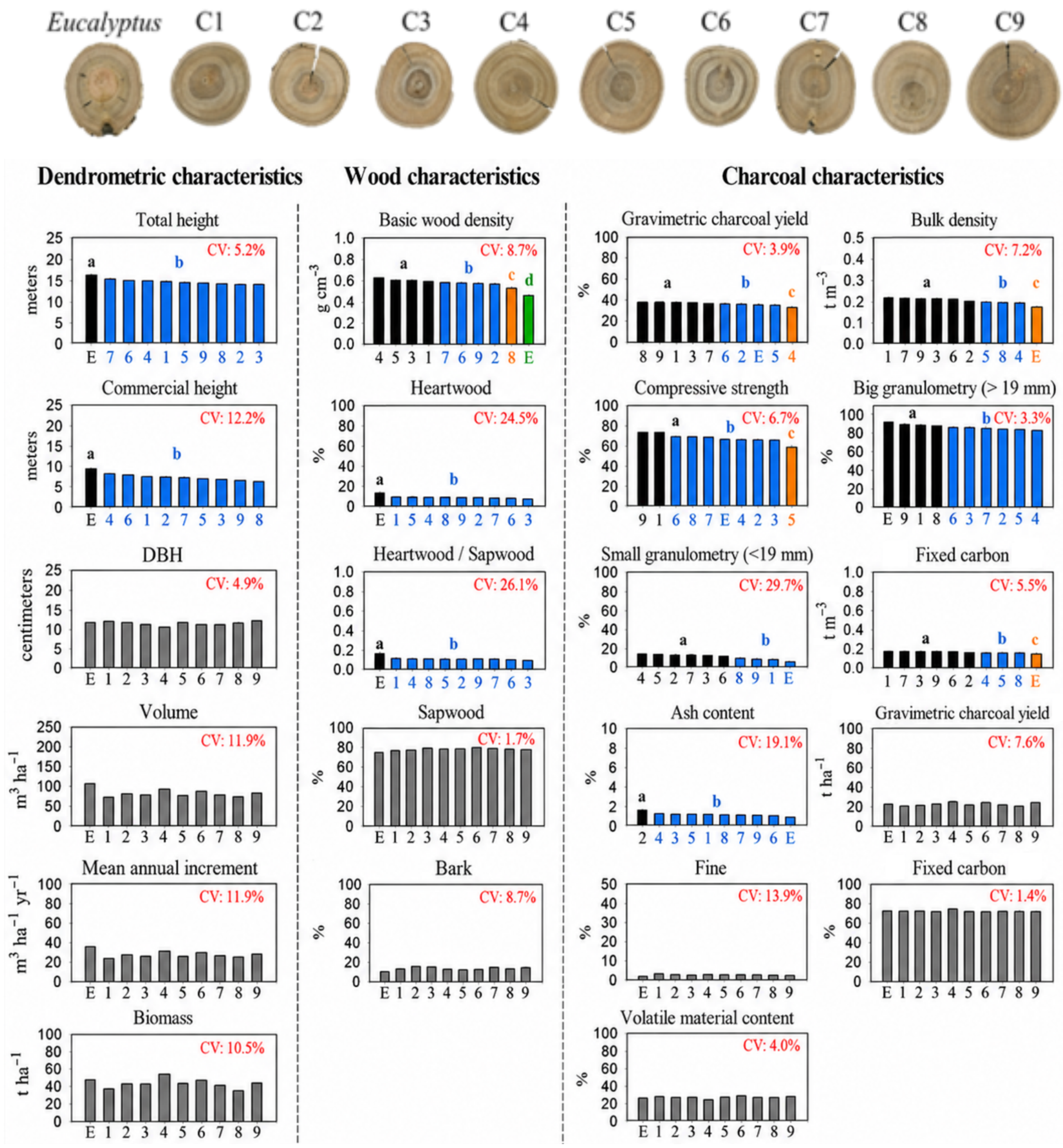


Figure 3: Mean values of dendrometric, wood, and charcoal traits for nine clones of *C. torelliana* × *C. citriodora* (1–9) and one clone of *E. urophylla* × *E. grandis* (E). Different letters indicate significant differences among genetic materials according to the Scott–Knott test ($p < 0.05$). Traits without letters did not show significant differences among genetic materials. CV: coefficient of variation.

4–11% higher than those observed for the *Eucalyptus* clone and the remaining *Corymbia* hybrids (group c). In contrast, clone C8 exhibited mechanical resistance approximately 10% lower than that of group c (Figure 3). Clones C2, C3, and C4, which showed the highest mechanical resistance values, were grouped together with the *Eucalyptus* clone for coarse charcoal content, presenting approximately 5% more coarse charcoal (63–25 mm) and, consequently, 40% less fine charcoal (25–9 mm) than the remaining clones (Figure 3).

The charcoal produced from clones C3, C4, and C9 presented fixed carbon per unit volume values approximately 12% higher than those observed for the remaining *Corymbia* hybrids and *E. urophylla* × *E. grandis* (Figure 3). Ash content was similar among most *Corymbia* hybrids and the *Eucalyptus* clone; however, clone C5 exhibited ash contents approximately 36% higher than those of the other genetic materials (Figure 3).

Overall, the *C. torelliana* × *C. citriodora* clones were characterized by lower total and commercial heights, lower heartwood proportion, higher wood basic density, and higher charcoal bulk density than the *E. urophylla* × *E. grandis* clone (Figure 3).

The first two canonical variables explained 80.27% of the total variation in the dataset. Based on the canonical variable scores and k-means clustering, all *Corymbia* hybrids were grouped together, whereas *E. urophylla* × *E. grandis* remained isolated (Figure 4A). The analysis of trait contributions for the *Corymbia* versus *Eucalyptus* source of variation indicated that BD and H/S were the main contributors to genotype differentiation, whereas TH, CC, and HW contributed least to the observed divergence among genetic materials (Figure 4B).

Canonical variable analysis and k-means clustering performed separately for the significant dendrometric (TH and CH), wood (HW, H/S, and BD), and charcoal traits (GCY, BKD, MR, CC, FC, FCV, and ASH) also resulted in a clear separation between the *C. torelliana* × *C. citriodora* clones and the *E. grandis* × *E. urophylla* clone, consistent with the pattern observed when all 12 significant traits were analyzed simultaneously (Figure 5).

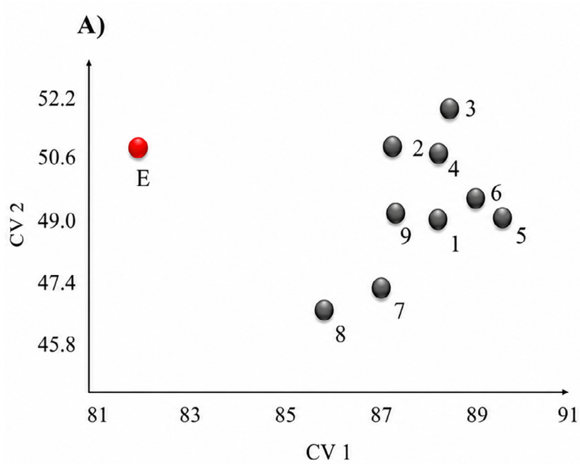
Greater similarity among *Corymbia* hybrids was observed for wood characteristics than for dendrometric and charcoal characteristics (Figure 5). Among the evaluated clones, the pairs C1–C6 and C3–C4 showed the greatest similarity for dendrometric and charcoal characteristics. In contrast, clones C7 and C8 were the most distinct from the remaining clones for these traits, although they exhibited values similar to those of the other genetic materials for most wood characteristics (Figure 5).

For the *C. torelliana* × *C. citriodora* hybrids, the correlation network revealed weak associations among traits belonging to different groups. In general, traits within the same group, particularly the dendrometric traits, showed stronger correlations with each other than with wood or charcoal traits (Figure 6). In contrast, the *E. urophylla* × *E. grandis* clone showed stronger correlations among traits from different groups, particularly between wood biomass, gravimetric charcoal yield, and bark content (Figure 6)

DISCUSSION

The significant difference in tree height between *Corymbia* and *Eucalyptus* explains the higher volumetric wood production observed for *Eucalyptus*, given that stem diameters were similar between the genera. However, the comparable biomass production (t ha^{-1}) observed for both groups suggests that the main differences are related to tree architecture rather than to total wood biomass production. These results suggest differences in biomass allocation patterns between *Corymbia* and *Eucalyptus*.

In general, *Corymbia* hybrids exhibit volumetric wood production (m^{3} ha^{-1} yr^{-1}) that is 20–30% lower than



B)

Variable	S.j	Value in %
BD	1109.30	48.56
H/S	656.18	28.72
MTV	258.38	11.31
BKD	130.29	5.70
CH	93.81	4.11
FC	36.41	1.59
HT	0.00	0.00
GCY	0.00	0.00
HT	0.00	0.00

Note: BD = basic density (kg m□^{3}), H/S = heartwood/sapwood ratio, MTV = volatile matter (%), BKD = bark density (%), CH = commercial height (m), FC = fixed carbon (%), HT = total height (m), and GCY = gravimetric charcoal yield (%).

Figure 4: (A) Dispersion of nine C. torelliana × *C. citriodora* clones and one *E. urophylla* × *E. grandis* clone based on the first two canonical variables. (B) Relative contribution of significant traits to genetic divergence among the evaluated materials.

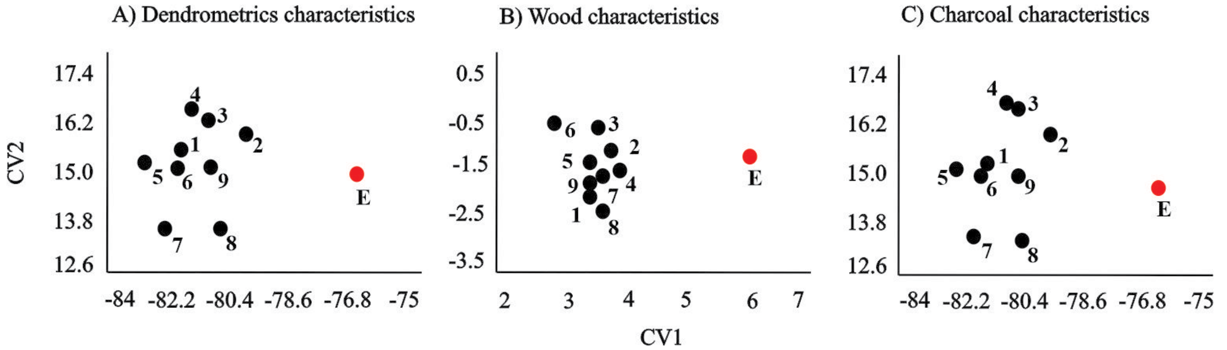
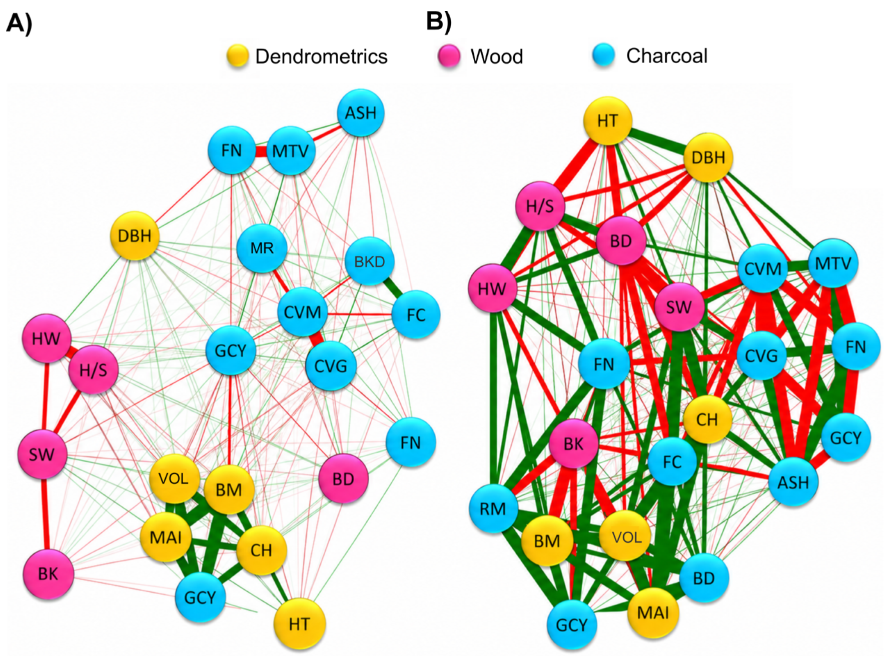


Figure 5: K-means clustering of C. torelliana × *C. citriodora* and *E. urophylla* × *E. grandis* based on significant (A) dendrometric, (B) wood, and (C) charcoal characteristics.

that reported for *Eucalyptus* species (Moura, 2001; Florez *et al*., 2019). Carbon assimilation and its allocation among tree components influence growth allometry and responses to environmental conditions (Paul *et al*., 2007). Previous studies have reported differences in biomass partitioning between *Eucalyptus* and *Corymbia* species, with average biomass allocation of 22% to branches, 10% to leaves, 10% to bark, and 56% to the stem in *Eucalyptus*, compared with 26%, 15%, 7%, and 50%, respectively, in *Corymbia* (Paul *et al*., 2008; Cernusak *et al*., 2011). The higher proportion of biomass allocated to branches and leaves reported for *Corymbia* hybrids may contribute to the growth patterns observed in the present study.

For *Eucalyptus* lower heartwood content has been associated with reduced stem diameter growth (Almeida *et al*., 2020). However, this pattern was not observed in the present study, as *Corymbia* and *Eucalyptus* clones exhibited similar stem diameters, whereas the *C. torelliana* × *C. citriodora* hybrids showed significantly lower heartwood contents. This result suggests differences in the relative proportions of heartwood and sapwood between the evaluated genetic materials. From a technological perspective, the combination of higher wood density and lower heartwood content may be favorable for charcoal production.

Sapwood proportion has been widely used as an indicator of leaf area because it represents the fraction of active conductive tissue responsible for water transport within the stem (Waring *et al*., 1982; Ribchoud and Mathven, 1992). Therefore, the higher sapwood proportions observed



Note: DBH = diameter at breast height (m), HT = total height (m), VOL = volume (m^3 ha^{-1}), CH = commercial height (m), MAI = mean annual increment (m^3 ha^{-1} $year^{-1}$), BD = basic density (kg m^{-3}), BM = wood biomass (t ha^{-1}), HW = heartwood (%), SW = sapwood (%), BK = bark content (%), H/S = heartwood/ sapwood ratio, GCY = gravimetric charcoal yield (%), MTV = volatile matter (%), FC = fixed carbon (%), ASH = ash content (%), FN = fines content (%), MR = mechanical strength (MPa).

Figure 6: Pearson correlation network among dendrometric, wood, and charcoal traits for (A) C. torelliana x *C. citriodora* hybrids and (B) *E. urophylla* x *E. grandis*.

in the *Corymbia* hybrids are consistent with reports indicating that some *Corymbia* species may develop larger crowns than *Eucalyptus* species (Vilas Bôas *et al*., 2009).

Age and growth rate are among the main factors influencing heartwood formation (Brito *et al*., 2020). Young plantations generally exhibit lower heartwood contents because of the greater proportion of active vascular tissue required to sustain growth (Gominho and Pereira, 2005; Tarelkina *et al*., 2023). Although early assessments of heartwood formation may provide useful information regarding future heartwood development, long-term evaluations are required to confirm these trends.

For both genera, the heartwood-to-sapwood ratio was lower than one, indicating that sapwood occupied a larger proportion of the stem than heartwood at approximately three years of age. This pattern was more pronounced in the *Corymbia* hybrids evaluated in the present study.

As observed for heartwood formation, basic wood density is strongly influenced by tree age and may vary considerably from approximately three years onward (Brito *et al*., 2020; Santos *et al*., 2024). Nevertheless, the hybrids evaluated in the present study exhibited marked differences in density even at a juvenile age, particularly between the two genera. Wood density is recognized as a trait with relatively high heritability (Tan *et al*., 2018), which may contribute to the consistent differences observed between the evaluated *Corymbia* hybrids and the *Eucalyptus* clone.

The basic density of *Eucalyptus* wood typically ranges from 0.350 to 0.650 g cm^{-3} (Barbosa *et al*., 2019; Almeida *et al*., 2020; Costa *et al*., 2020). In contrast, *Corymbia* species generally exhibit wood densities approximately 20% higher than those of *Eucalyptus*, ranging from 0.500 to 0.800 g cm^{-3} up to 15 years of age (Garcia *et al*., 2014; Glencross *et al*., 2014; Hung *et al*., 2016; Medeiros *et al*., 2016; Florez *et al*., 2019).

In the present study, the *C. torelliana* × *C. citriodora* hybrids were classified into three density groups: low (0.55 t m^{-3}), intermediate (0.61 t m^{-3}), and high (0.64 t m^{-3}). However, all hybrids exhibited higher wood density than the *E. grandis* × *E. urophylla* clone, reinforcing the distinct density pattern commonly reported for *Corymbia* materials.

Trueman *et al*. (2012), evaluating *C. torelliana* × *C. citriodora* hybrids at three sites in Queensland, Australia, reported higher wood basic density and lower heartwood proportion in trees growing under conditions of lower rainfall and reduced growth. The authors also observed radial variation in wood density, with mean values of 574, 523, and 562 kg m^{-3} for sapwood, heartwood, and pith, respectively, resulting in an overall mean density of 553 kg m^{-3}. Combined with heartwood and sapwood proportions of 11.2% and 41.2%, respectively, these characteristics contributed to wood densities approximately 17% higher than those reported for E. cloeziana clones at 13.5 years of age.

Hybrid traits are often intermediate between those of their parental species (Rosenthal *et al*., 2002). Trueman *et al*. (2012) reported heartwood and sapwood proportions of 18.2% and 43.2%, respectively, as well as a wood basic density of 547 kg m^{-3} for *C. torelliana*. In the present study, the *C. torelliana* × *C. citriodora* hybrids exhibited higher heartwood and sapwood proportions, as well as higher wood density, than those reported for *C. torelliana* by Trueman *et al*. (2012). These differences may be associated with the contribution of *C. citriodora* to the hybrid phenotype.

Several studies have highlighted wood basic density as an important trait for charcoal quality, particularly for steelmaking applications (Pereira *et al*., 2013; Couto *et al*., 2015; Healey *et al*., 2016; Santos *et al*., 2016). In the present study, the *C. torelliana* × *C. citriodora* hybrids exhibited higher wood basic density and lower heartwood content than the *Eucalyptus* clone, indicating characteristics commonly associated with favorable charcoal properties.

The densest wood was not always associated with the densest charcoal, as observed for clones C7 and C8, suggesting that the relationship between wood density and charcoal properties is influenced by additional factors. Nevertheless, the *Corymbia* hybrids generally produced charcoal with higher bulk density and greater fixed carbon per unit volume than the *Eucalyptus* clone. Charcoal with higher density is often preferred for steelmaking applications because it can increase the amount of fixed carbon supplied per unit volume and may improve blast furnace occupancy (Pereira *et al*., 2025).

Several studies conducted in Brazil have investigated the potential use of *Corymbia* wood as an alternative to *Eucalyptus* for steelmaking charcoal production (Costa *et al*., 2017; Loureiro *et al*., 2019; Peres *et al*., 2019). The intrinsic characteristics of wood, particularly its density, are widely recognized as important factors influencing charcoal density (Moutinho *et al*., 2017; Dufourny *et al*., 2018). Relationships between wood basic density and fixed carbon content have been reported in previous studies (Loureiro *et al*., 2019; Ramos *et al*., 2019). However, the fixed carbon content of charcoal is influenced not only by wood characteristics but also by carbonization conditions, particularly residence time, heating rate, and final carbonization temperature (Couto *et al*., 2015; Pereira *et al*., 2025). Previous studies have shown that dense woods producing charcoal with high gravimetric yield and elevated volatile matter content may indicate incomplete carbonization (Trugilho and Silva, 2001). This occurs because charcoal quality is strongly affected by the thermal degradation process and the extent of biomass conversion during carbonization. Fixed carbon content and gravimetric charcoal yield are often characterized by a trade-off relationship, since the loss of volatile compounds and other solid fractions during carbonization tends to increase the relative concentration of fixed carbon in the remaining charcoal (Elyounssi *et al*., 2010).

The higher fixed carbon stock per unit volume observed for the *C. torelliana* × *C. citriodora* hybrids suggests that, although the fixed carbon content (%) was similar to that of the *Eucalyptus* clone, the greater charcoal density contributed to a higher amount of fixed carbon per unit volume. This characteristic may be relevant for steelmaking applications, where charcoal density is often associated with operational performance. Previous studies have reported that higher charcoal bulk density is associated with lower specific charcoal consumption during pig iron production, possibly due to reduced reactivity and improved blast furnace occupancy (Lima *et al*., 2022a; Lima *et al*., 2022b).

The fact that clones C3 and C4 produced denser charcoal with greater mechanical resistance was accompanied by a higher proportion of coarse charcoal particles, indicating an association among charcoal density, mechanical resistance, and granulometry in the evaluated *C. torelliana* × *C. citriodora* hybrids. Higher mechanical resistance is generally considered advantageous because it reduces charcoal fragmentation during handling and industrial use, contributing to the maintenance of particle size distribution under operational conditions (Assis *et al*., 2020).

Among the evaluated trait groups, wood properties showed lower variability among the *Corymbia* hybrids than dendrometric and charcoal traits. This pattern suggests that wood properties were more homogeneous among the evaluated genetic materials, whereas growth and charcoal characteristics exhibited greater variability. Such variability may reflect differences among genotypes as well as responses to management and carbonization conditions.

The clear separation between *C. torelliana* × *C. citriodora* hybrids and the *E. grandis* × *E. urophylla* clone, both when trait groups were analyzed separately and when all significant traits were considered together, highlights the ability of the evaluated variables to discriminate among genetic materials. These results reinforce the importance of jointly evaluating dendrometric, wood, and charcoal traits, since charcoal quality cannot be fully characterized by a single property.

The weak correlations observed among trait groups for the *C. torelliana* × *C. citriodora* hybrids (Figure 6) suggest that indirect selection based on a limited number of traits may be less effective for these materials. Consequently, more comprehensive evaluations incorporating multiple wood and charcoal properties may be required to support decision-making in breeding and selection programs.

Understanding the relationships among growth, wood, and charcoal traits can contribute to the selection of genetic materials with characteristics desirable for charcoal production. Previous studies have demonstrated that information on wood productivity and quality can assist in predicting charcoal performance and support the selection of materials for steelmaking applications (Protásio *et al*., 2014; Silva *et al*., 2018; Costa *et al*., 2020). In addition, such information may support forest planning and contribute to the evaluation of potential industrial applications of different genetic materials.

The results should be interpreted considering some limitations of experimental design. The comparison involved nine *Corymbia* hybrids and a single commercially established *Eucalyptus* clone used as a reference material. In addition, four trees were sampled per clone, which is consistent with operational wood-quality studies but may limit broader inferences regarding the variability within each genetic material. Furthermore, although carbonization was conducted under industrial conditions with temperature monitoring and randomized sample allocation, some thermal heterogeneity is inherent to large-scale kilns. Therefore, the conclusions should be restricted to the evaluated genetic materials and carbonization conditions.

CONCLUSIONS

The evaluated hybrids of *C. torelliana* × *C. citriodora* exhibited higher wood basic density, charcoal density, mechanical resistance, and fixed carbon per unit volume than the *E. grandis* × *E. urophylla* clone used as a reference material. These characteristics indicate the potential of the evaluated *Corymbia* hybrids for steelmaking charcoal production.

Although the *Corymbia* hybrids showed lower growth than *E. grandis* × *E. urophylla*, the differences in wood and charcoal properties suggest that these materials may represent promising alternatives for charcoal production under the conditions evaluated in this study.

Clear differences were observed between the *C. torelliana* × *C. citriodora* hybrids and the *E. grandis* × *E. urophylla* clone regarding dendrometric, wood, and charcoal characteristics. Among the *Corymbia* hybrids, the greatest similarity was observed for wood properties, whereas greater variability was found for growth and charcoal traits.

Indirect selection based on a limited set of traits may not be effective for *C. torelliana* × *C. citriodora* hybrids, given the low correlations observed among different groups of variables.

DATA AVAILABILITY

The datasets supporting the conclusions are included in the article.

AUTHORSHIP CONTRIBUTION:

Project Idea: SMGR, CVAO, GBV.
Funding: GBV.
Database: SMGR.
Processing: SMGR.
Analysis: SMVN; CVAO.
Writing: SMGR.
Review: SMGR, CVAO, TCCN, SLA,GBV.

REFERENCES

ALMEIDA, M. N. F.; VIDAURRE, G. B.; PEZZOPANE, J. E. M.; et al. Heartwood variation of Eucalyptus urophylla is influenced by climatic conditions. Forest Ecology and Management, v. 458, p. 1-10, 2020. https://doi.org/10.1016/j.foreco.2019.117743

ASSIS, M. R.; BRANCHERIAU, L.; GUIBAL, D.; et al. Towards a better understanding of the mechanical behavior of a fixed bed of eucalyptus charcoal in a blast furnace using a specific compression test. BioResources, v. 15, n. 4, p. 7660-7670, 2020. https://doi.org/10.15376/biores.15.4.7660-7670

ASSIS, M. R.; TRUGILHO, P. F.; ROSADO, S. C. S.; et al. Modeling of biomass and carbon stock in young Eucalyptus. Scientia Forestalis, v. 43, n. 105, p. 225-233, 2015.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (ABNT). NBR 7402: carvão vegetal – determinação granulométrica. Rio de Janeiro, 1982. 3 p.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (ABNT). NBR 8112: carvão vegetal – análise imediata. Rio de Janeiro, 1986. 13 p.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (ABNT). NBR 11941: madeira – determinação da densidade básica. Rio de Janeiro, 2003. 6 p.

BARBOSA, T. L.; OLIVEIRA, J. T. S.; ROCHA, S. M. G.; et al. Influence of site in the wood quality of Eucalyptus in plantations in Brazil. Southern Forests: a Journal of Forest Science, v.81, n.3, p. 247-253, 2019. https://doi.org/10.2989/20702620.2019.1570453

BARROS JUNIOR, U. O.; MARCELINO, P. R. C; SILVA, J. G. M. et al. Classification of young Corymbia genotypes for steelmaking charcoal production based on their wood Properties. New Zealand Journal of Forestry Science, v. 56, 2026. https://doi.org/10.33494/nzjfs562026x398x

BISWAS, A. K.; UMEKI, K.; YANG, W.; et al. Change of pyrolysis characteristics and structure of woody biomass due to steam explosion pretreatment. Fuel Processing Technology, n.92, n.10, p.1849–1854, 2011. https://doi.org/10.1016/j.fuproc.2011.04.038

BRITO, A. S.; SILVA, J. G. M.; VIDAURRE, G. B.; et al. Influência da idade nas propriedades da madeira de eucalipto. In.: VIDAURRE, G.B et al. Qualidade da madeira de eucalipto proveniente de plantações no Brasil. Vitória: EDUFES, 2020, p. 103 – 131.

CERNUSAK, L. A.; HUTLEY, L. B.; BERINGER, J.; et al. Photosynthetic physiology of eucalypts along a sub-continental rainfall gradient in northern Australia. Agricultural and Forest Meteorology, v. 151, n. 11, p. 1462-1470, 2011. https://doi.org/10.1016/j.agrformet.2011.01.006

COSTA, L. J.; TRUGILHO, P. F.; LIMA, J. T.; et al. Mechanic characterization of charcoal of Corymbia clones. Scientia Forestalis, v. 45, n. 116, p. 629-639, 2017. https://doi.org/10.18671/scifor.v45n116.04

COSTA, S. E. L.; SANTOS, R. C.; VIDAURRE, G. B.; et al. The effects of contrasting environments on the basic density and mean annual increment of wood from Eucalyptus clones. Forest Ecology and Management, v. 458, n. 15, p. 461- 470, 2020. https://doi.org/10.1016/j.foreco.2019.117807

COUTO, A. M.; TRUGILHO, P. F.; NAPOLI, A.; et al. Quality of charcoal from Corymbia and Eucalyptus produced at different final carbonization temperatures. Scientia Forestalis, v. 43, n. 108, p. 817-831, 2015. https://doi.org/10.18671/scifor.v43n108.7

DUFOURNY, A.; VAN DE STEENE, L.; HUMBERT, G.; et al. Influence of pyrolysis conditions and the nature of the wood on the quality of charcoal as a reducing agent. Journal of Analytical and Applied Pyrolysis, v. 137, p. 1-13, 2018. https://doi.org/10.1016/j.jaap.2018.10.013

ELYOUNSSI, K.; BLIN, J.; HALIM, M. High-yield charcoal production by two-step pyrolysis. Journal of Analytical and Applied Pyrolysis, v. 87, n. 1, p. 138-143, 2010. https://doi.org/10.1016/j.jaap.2009.11.002

EMPRESA DE PESQUISA ENERGÉTICA - EPE. Balanço Energético Nacional 2025: Ano base 2024. 62 p. Available at: <https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-885/topico-771/Relat%C3%B3rio%20Final_BEN%202025.pdf>. Accessed at: February 20th 2026.

FLOREZ, L. G.; VANCLAY, J. K.; GLENCROSS, K.; et al. Developing biomass estimation models for above-ground compartments in Eucalyptus dunnii and Corymbia citriodora plantations. Biomass and Bioenergy, v. 130, p. 1-15, 2019. https://doi.org/10.1016/j.biombioe.2019.105353

GARCIA, R. A.; OLIVEIRA, N. S.; NASCIMENTO, A. M.; et al. Colorimetry of woods from Eucalyptus and Corymbia genus and its correlation with density. Cerne, v. 20, n. 4, p. 509-517, 2014. https://doi.org/10.1590/01047760201420041316.

GLENCROSS, K.; PALMER, G.; PELLETIER, M. C.; et al. Basal area increment is unaffected by thinning intensity in young Eucalyptus dunnii and Corymbia variegata plantations across different quality sites. Forest Ecology and Management, v. 318, p. 326-333, 2014. https://doi.org/10.1016/j.foreco.2014.01.041.

GOMINHO, J.; PEREIRA, H. The influence of tree spacing in heartwood content in Eucalyptus globulus labill. Wood and Fiber Science, v. 37, n. 4, p. 582-590, 2005.

HEALEY, A. L.; LUPOI, J. S.; LEE, D. J.; et al. Effect of aging on lignin content, composition and enzymatic saccharification in Corymbia hybrids and parental taxa between years 9 and 12. Biomass and Bioenergy, v. 93, p. 50-59, 2016. https://doi.org/10.1016/j.biombioe.2016.06.016

HILL, K. D.; JOHNSON, L. A. S. Systematic studies in the eucalypts. A revision of the bloodwoods, genus Corymbia (Myrtaceae). Telopea, v. 6, p. 185-504, 1995. https://doi.org/10.7751/telopea19953017

HUNG, T. D.; BRAWNER, J. T.; LEE, D. J.; et al. Genetic variation in growth and wood-quality traits of Corymbia citriodora subsp. variegata across three sites in south-east Queensland, Australia. Southern Forests, v. 78, n. 3, p. 225-239, 2016. https://doi.org/10.2989/20702620.2016.1183095

LADIGES, P. Y.; BAYLY, M. J.; NELSON, G. J. East-west continental vicariance in Eucalyptus subgenus Eucalyptus. In: Williams, D.M., Knapp, S. (Eds.), Beyond Cladistics: The Branching of a Paradigm. University of California, p. 267–302, 2010.

LIMA, M. D. R.; TRUGILHO, P. F.; BUFALINO, L.; et al. Efficiency of near-infrared spectroscopy in classifying Amazonian wood wastes for bioenergy generation. Biomass and Bioenergy, v. 166, 2022a. https://doi.org/10.1016/j.biombioe.2022.106617

LIMA, M. D. R.; MASSUQUE, J.; BUFALINO, L.; et al. Clarifying the carbonization temperature effects on the production and apparent density of charcoal derived from Amazonia wood wastes. Journal of Analytical and Applied Pyrolysis, v. 166, 2022b. https://doi.org/10.1016/j.jaap.2022.105636

LOUREIRO, B. A.; VIEIRA, T. A. S.; COSTA, L. J.; et al. Selection of superior clones of Corymbia hybrids based on wood and charcoal properties. Maderas. Ciencia y tecnología, v. 21, n. 4, p. 619-630, 2019. http://dx.doi.org/10.4067/S0718-221X2019005000417

MEDEIROS, B. L. M. A.; GUIMARÃES JUNIOR, J. B.; RIBEIRO, M. X.; et al. Evaluation of physical and chemical properties Corymbia citriodora and Eucalyptus urophylla x Eucalyptus grandis wood, cultured in Piauí, Brazil. Nativa, v. 4, n. 6, p. 403-407, 2016. https://doi.org/10.14583/2318-7670.v04n06a10

MELO, A. B.; SILVA, P. H. M.; ARAUJO, S. L.; et al. Productivity and wood quality traits of Corymbia and Eucalyptus species in two soil water deficit sites. Industrial Crops and Products, v. 219, 2024. https://doi.org/10.1016/j.indcrop.2024.119141

MOURA, V. P. G. Potencial e uso de espécies de Eucalyptus e Corymbia de acordo com locais e usos. Brasília: Embrapa Recursos Genéticos e Biotecnologia. 2001. 32 p.

MOUTINHO, V. H. P.; TOMAZELLO FILHO, M.; BRITO, J. O.; et al. Characterization and statistical correlation between charcoal's physical and mechanical properties of Eucalyptus and Corymbia clones. Ciência Florestal, v. 27, n. 3, p. 1095-1103, 2017. https://doi.org/10.5902/1980509828684

PAUL, K. I. ; BOOTH, T. H.; JOVANOVIC, T.; et al. Calibration of the forest growth model 3-PG to eucalypt plantations growing in low rainfall regions of Australia. Forest Ecology and Management, v. 243, n. 2-3, p. 237-247, 2007. https://doi.org/10.1016/j.foreco.2007.03.029

PAUL, K. I.; JACOBSEN, K.; KOUL, V.; et al. Predicting growth and sequestration of carbon by plantations growing in regions of low-rainfall in southern Australia. Forest Ecology and Management, v. 254, n. 2, p. 205-2016, 2008. https://doi.org/10.1016/j.foreco.2007.08.003

PEREIRA, A. K. S.; LONGUE JUNIOR, D.; SILVA, A.; et al. How pyrolysis conditions shape the structural and functional properties of charcoal? A study of tropical dry forest biomass. Renewable Energy, v. 243, 2025. https://doi.org/10.1016/j.renene.2025.122575

PEREIRA, B. L. C.; CARNEIRO, A. C. O.; CARVALHO, A. M. L.; et al. Study of thermal degradation of Eucalyptus wood by thermogravimetry and calorimetry. Revista Árvore, v. 37, n. 3, p. 567-576, 2013. https://doi.org/10.1590/S0100-67622013000300020.

PERES, L. C.; CARNEIRO, A. C. O.; FIGUEIRÓ, C. G.; et al. Clonal selection of Corymbia for energy and charcoal production. Advances in Forestry Science, v.6, n.3, p.749-753, 2019. DOI: http://dx.doi.org/10.34062/afs.v6i3.8293

PROTÁSIO, T. P.; GOULART, S. L.; NEVES, T. A.; et al. Commercial clones of Eucalyptus at different ages for bioenergetic use of wood. Scientia Forestalis, v. 42, n. 101, p. 113-127, 2014.

R CORE TEAM, a language and environment for statistical computing, & Computing, R. C. T. 2022. R Foundation for Statistical Computing.

RAMOS, D. C.; CARNEIRO, A. C. O.; TANGSTAD, M.; et al. Quality of wood and charcoal from Eucalyptus clones for metallurgical use. Floresta e Ambiente, v. 26, n. 2, 2019. https://doi.org/10.1590/2179-8087.043518

RIBCHOAUD, E.; MATHVEN, I. The applicability of the pipe model theory for the predicitions of foliage biomass in threes for natural, untreated black spruce stands. Canadian Journal of Forest Research, v. 22, n. 8, p. 1118-1123, 1992. https://doi.org/10.1139/x92-148

ROCHA, S. M. G.; BARROS JUNIOR, U. O.; OLIVEIRA, L. J.; et al. Association between the anatomical features and the natural drying of young wood from hybrid Corymbia torelliana and Corymbia citriodora clones. European Journal of Wood and Wood Products, 82, 1901–1912 (2024). https://doi.org/10.1007/s00107-024-02134-7

ROSENTHAL, D. M.; SCHWARZBACH, A. E.; DONOVAN, L. A.; et al. Phenotypic differentiation between three ancient hybrid taxa and their parental species. International Journal of Plant Sciences, v. 163, n. 3, p. 387-398, 2002. https://doi.org/10.1086/339237

SANTOS, R. C.; CARNEIRO, A. C. O.; VITAL, B. R.; et al. Effect of properties chemical and siringil/guaiacil relation wood clones of eucalyptus in the production of charcoal. Ciência Florestal, v. 26, n. 2, p. 657-669, 2016.

SANTOS, V. B.; CONCEIÇÃO, G. J.; RODRIGUES, P. D.; et al. Impact of age and genotype on the quality of eucalyptus wood for dissolving pulp. Industrial Crops and Products, v. 218, 2024. https://doi.org/10.1016/j.indcrop.2024.118930

SILVA, M. F.; FORTES, M. M.; SETTE JUNIOR, C. R. Characteristics of wood and charcoal from Eucalyptus clones. Floresta e Ambiente, v. 25, n. 3, p. 1-10, 2018. https://doi.org/10.1590/2179-8087.035016

SOARES, J. D.; DE PAULA, M. O.; CARNEIRO, A. D. C. O.; et al. Parameters to determine mechanical strength of charcoal in a hydraulic press. Revista Brasileira de Ciências Agrárias, v.16, n.4, p. 1-6, 2021. https://doi.org/10.5039/agraria.v16i4a9096

TAN, B.; GRATTAPAGLIA, D.; WU, H. X.; et al. Genomic relationships reveal significant dominance effects for growth in hybrid Eucalyptus. Plant Science, v. 267, p. 84-93, 2018. https://doi.org/10.1016/j.plantsci.2017.11.011

TARELKINA, T. V.; GALIBINA, N. A.; ERSHOVA, M. A.; et al. Age of heartwood initiation in trunks of young Pinus sylvestris L. trees in the taiga zone. IAWA Journal, v. 45, p. 375 – 390, 2023. https://doi.org/10.1163/22941932-bja10144

TRUEMAN, S. J.; DICKINSON, G. R.; HUTH, J. R.; et al. Characterizing wood properties for deployment of elite subtropical and tropical hardwoods. Project Report. CSIRO Plant Industry, 2012.

TRUGILHO, P. F.; SILVA, D. A. Influência da temperatura final de carbonização nas características físicas e químicas do carvão vegetal de jatobá (Hymenea courbaril L.). Scientia Agraria, v.2, n.1-2, p.1-9, 2001. http://dx.doi.org/10.5380/rsa.v2i1.976

VILAS BÔAS, O., MAX, J.C.M., MELO, A.C.G. Crescimento comparativo de espécies de Eucalyptus e Corymbia no município de Marília, sp. Revista Instituto Florestal, São Paulo, v. 21, n. 1, p. 63-72, 2009. https://doi.org/10.24278/2178-5031.2009211200

WARING, R. H.; SCHROEDER, P. E.; OREN, R. Application of the pipe model theory to predict canopy leaf area. Canadian Journal of Forest Research, v. 12, n. 3, p. 556-560, 1982. https://doi.org/10.1139/x82-086