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Relationships between colorimetry and technological properties of wood from species grown in an agroforestry system

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Abstract The technological characterization of wood is essential for its proper market insertion and appropriate end-use applications. In Brazil, wood produced in agroforestry systems remains underexplored, highlighting the need for studies that support its valorization and rational use. Therefore, this study aimed to characterize and compare the colorimetric properties of wood from *Eucalyptus grandis*×*Eucalyptus urophylla*, *Schizolobium parahyba* (Vell.) Blake, *Peltophorum dubium* (Spreng.) Taub., and *Parapiptadenia rigida* (Benth.) Brenan grown in an agroforestry system, as well as to evaluate their relationships with chemical, energy, and physical properties. A wood disc was collected from each tree at 1.30 m above ground level for color determination on the transverse, radial, and tangential planes, in addition to chemical composition analyses (lignin, extractives, holocellulose, and ash content), energy properties (higher heating value, fixed carbon, and volatile matter), and a physical property (basic density). Significant differences were observed among species for the colorimetric parameters, with *Schizolobium parahyba* showing the highest lightness values ($L^*=81.55$), while *Parapiptadenia rigida* presented the highest reddish ($a^*=15.20$) and yellowish ($b^*=32.25$) pigmentation intensities. In

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addition, *Parapiptadenia rigida* exhibited the highest basic density (0.652 g cm^{-3}), whereas *Eucalyptus grandis*×*Eucalyptus urophylla* showed the highest higher heating value (4753 kcal kg^{-1}). The colorimetric parameters L^* and a^* effectively distinguished the studied species and showed significant correlations with physical, chemical, and energy-related properties of the wood, indicating their potential use as non-destructive indicators of wood quality and technological and energy performance. These findings demonstrate that wood from agroforestry systems exhibits technological performance comparable to that of conventional plantations.

Keywords Wood properties · Colorimetry · Chemical composition · Energy properties · Wood density · Wood technology

Introduction

Agroforestry systems represent a sustainable land-use strategy based on integrated management, combining tree species with agricultural crops. These systems provide multiple environmental and socioeconomic benefits, including biodiversity conservation, improved soil resilience, climate change mitigation, and increased economic returns for rural properties (Brown et al. 2018; Satish et al. 2024). Although numerous studies have focused on evaluating the agronomic advantages of crops in agroforestry systems, research specifically addressing the forest component remains limited, particularly regarding the technological characterization of wood produced in these integrated systems (Santos et al. 2019; Bhandari et al. 2025).

In general, current knowledge regarding wood quality is largely derived from homogeneous commercial plantations, in which growing conditions and silvicultural practices differ substantially from those observed in integrated production systems (Mascarenhas et al. 2021; Minini et al. 2024). This lack of information hinders the assessment of the actual economic potential of wood produced in agroforestry systems, limiting the valorization of the forest component and, consequently, restricting the broader adoption of these systems. Furthermore, studies integrating colorimetric, chemical, energetic, and physical properties of wood produced in agroforestry systems remain scarce, especially for native Brazilian species cultivated under contrasting growth conditions.

Wood is a widely used renewable resource; however, it is a heterogeneous and highly variable material whose technological quality, industrial applicability, and commercial value result from the interaction between intrinsic properties and the biotic and abiotic factors of the growing site. Among these properties, colorimetry stands out as an important organoleptic attribute, since wood color strongly influences aesthetic preference and market acceptance, in addition to playing a fundamental role in the identification, classification, and standardization of wood quality (Kwak and Choi 2025). Moreover, colorimetric analysis is rapid and non-destructive, making it a practical tool for wood quality assessment (Bonfatti Júnior and Lengowski 2018).

Previous studies have demonstrated the potential of wood colorimetry for species characterization and the estimation of technological properties. Amorim et al. (2013), for example, evaluated the relationships between colorimetric parameters and wood properties in *Pinus caribaea* and *Eucalyptus grandis*, while Vieira et al. (2022) used colorimetry to differentiate Fabaceae species cultivated in southern Brazil. In tropical plantation species, Moya et al. (2012) reported associations between wood color and the contents of extractives and phenolic compounds in *Acacia mangium* and *Vochysia guatemalensis*. More recently, Campos et al. (2025) related colorimetric variation to the chemical composition, density, and biological resistance of teak wood. However, these studies were conducted predominantly using wood from conventional plantations or native forests, with few investigations integrating colorimetric, chemical, energetic, and physical properties of wood produced in agroforestry systems.

In addition to color, properties such as chemical composition, calorific value, and basic density are determinant factors for the technological quality of wood and its suitability for different end uses. Basic density is a key indicator of mechanical strength and structural performance, whereas chemical composition is closely related to the natural durability, resistance to biodeterioration, and thermal behavior of wood (Schubert et al. 2022). Together, these properties also influence the energetic behavior of wood, particularly in applications requiring high thermal efficiency, such as bioenergy production and

the metallurgical sector. Studies have shown that the physical and chemical attributes of biomass, including density and chemical composition, are directly associated with the energy quality and calorific value of lignocellulosic biofuels (Kamperidou 2022).

An integrated analysis of these properties is essential to advance the understanding of wood technological performance, since color, chemical composition, basic density, and energetic properties do not act independently (Araújo et al. 2022; Eloy et al. 2024), but rather exhibit interrelationships that can be explored through correlation analyses (Vale et al. 2010). Colorimetric parameters may reflect variations in the chemical composition and density of wood, which, in turn, directly affect the energetic performance and technological quality of the material. The identification of significant correlations among these variables makes it possible to explore the potential of visual and physicochemical attributes as auxiliary tools for evaluating the technological and energetic quality of wood.

In this context, statistical approaches constitute relevant tools for investigating the existence and strength of these relationships, contributing to the development of more efficient methods for wood evaluation, classification, and end-use allocation, especially in production systems characterized by greater heterogeneity, such as Agroforestry systems. The generation of this knowledge may expand the industrial utilization potential of associated tree species, support more efficient management strategies, and strengthen sustainable and diversified production chains.

The species evaluated in this study were selected because they represent contrasting ecological and technological characteristics, with potential application in diversified agroforestry systems. The hybrid *Eucalyptus grandis*×*Eucalyptus urophylla* was included due to its widespread commercial use and recognized importance for timber, pulp, and energy production. The native species *Schizolobium parahyba*, *Peltophorum dubium*, and *Parapiptadenia rigida* were selected because they exhibit distinct growth patterns, wood densities, and technological characteristics, allowing the evaluation of different wood quality profiles under agroforestry conditions. Furthermore, these species have recognized silvicultural potential and may contribute to the diversification and valorization of forest components in integrated production systems.

Considering the differences in growth and interspecific interactions in agroforestry systems, the hypothesis of the present study is that the evaluated species exhibit distinct colorimetric patterns associated with variations in wood density, chemical composition, and energetic performance. In addition, significant correlations are expected between the colorimetric parameters and the other technological properties of wood, enabling the use of colorimetry as an auxiliary tool for inferring the technological quality of wood produced in agroforestry systems.

Therefore, this study aimed to characterize and compare the colorimetric, chemical, energetic, and physical properties of the wood of *Eucalyptus grandis*×*Eucalyptus urophylla*, *Schizolobium parahyba* (Vell.) Blake, *Peltophorum dubium* (Spreng.) Taub., and *Parapiptadenia rigida* (Benth.) Brenan cultivated in an agroforestry system, as well as to evaluate the relationships among these properties and the potential of colorimetric parameters as indirect indicators of the technological quality of wood produced in agroforestry systems.

Materials and methods

Experimental site description and sampling

The material used in this study was obtained from an agroforestry system characterized by a planting spacing of 12.0 × 1.5 m (12.0 m between rows and 1.5 m between plants within the row), located in the municipality of Frederico Westphalen, Rio Grande do Sul state, southern Brazil (27°22′ S; 53°25′ W; 480 m above sea level).

According to the Köppen climate classification, the region presents a Cfa climate, classified as humid subtropical (Alvares et al. 2013). Climatic data reported by Caron et al. (2024) indicate that. between 2008 and 2017. the mean annual air temperature in Frederico Westphalen was 19.4 °C, with recorded extremes ranging from − 2.3 to 36.3 °C, while annual precipitation varied between 1.578.6 and 2.103.2 mm.

The agroforestry system comprised the following 9-year-old forest species: a eucalyptus hybrid (*Eucalyptus grandis*×*Eucalyptus urophylla*). *Schizolobium parahyba* (Vell.) Blake (guapuruvu). *Peltophorum dubium* (Spreng.) Taub. (canafístula),

and *Parapiptadenia rigida* (Benth.) Brenan, corresponding to one exotic and three native species, respectively.

For wood analyses, five trees per species. representative of the stand, were felled. From each tree, a wood disc was collected at 1.30 m above ground level, corresponding to breast height diameter (DBH), as illustrated in Fig. 1.

Colorimetry

For color characterization of the studied species, two specimens per species were prepared with dimensions of 5.0 × 5.0 × 1.5 cm (length × width × thickness. respectively), obtained from the intermediate position of the wood disc and randomly selected. The samples did not receive any surface treatment and were conditioned in a light-free environment under controlled temperature and relative humidity conditions.

Colorimetric characterization of the samples from the four species was performed using a Konica Minolta CR-300 colorimeter operating under the CIELab color system. Measurements were taken in triplicate on each anatomical plane (X: transverse; C: cross; T: tangential). The colorimetric parameters obtained were lightness (L^*), chromatic coordinate on the green–red axis (a^*), and chromatic coordinate on the blue–yellow axis (b^*), which were used to calculate chroma (C^*) and hue angle (H°), according to Eqs. (1) and (2).

$$C^* = \frac{(a^* + b^*)}{2} \tag{1}$$

$$H^\circ = arctg\left(\frac{b^*}{a^*}\right) \tag{2}$$

where C^* is chroma (saturation); a^* is the chromatic coordinate on the green–red axis; b^* is the chromatic coordinate on the blue–yellow axis; h° is the hue angle; *arctan* denotes the inverse tangent function.

Chemical. energy. and physical characterization

The wood discs collected during sampling were marked into opposite wedges, of which two were

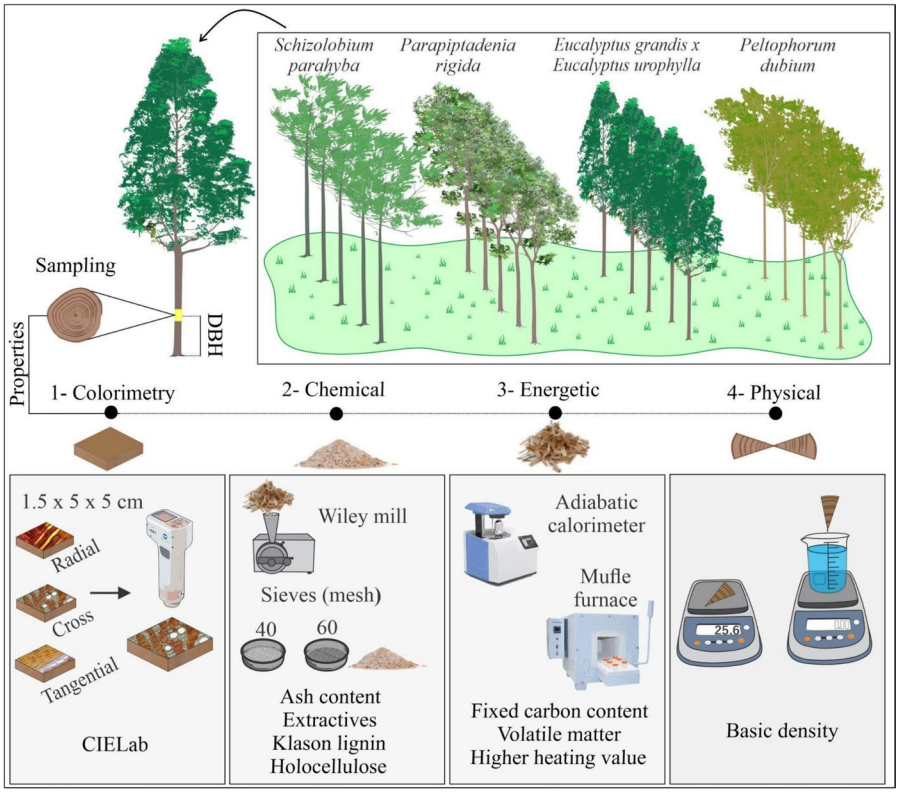


Fig. 1 Workflow of wood sampling and colorimetric chemical energetic and physical analyses

allocated for chemical and energy analyses and two for the determination of basic density. The wedges designated for chemical and energy analyses were reduced to small sticks and ground using a Wiley-type knife mill. Subsequently. the material was classified using 40/60 mesh sieves. The material obtained from the five discs of each species was homogenized to form a composite sample.

Chemical analyses were performed according to standard technical procedures to determine fixed carbon, volatile matter, and ash content (TAPPI T211 om-93), extractives content (TAPPI T264 cm-97), Klason lignin (TAPPI T222 om-98), and holocellulose (cellulose and hemicelluloses), which was calculated by difference, as described in Eq. (3).

$$HOLO = 100 - (AC + EXT + LIG) \quad (3)$$

where HOLO is the holocellulose content (%); AC is the ash content (%); EXT is the total extractives content (%); and LIG is the lignin content (%).

For energy analysis, the higher heating value (HHV) was determined using a digital adiabatic bomb calorimeter (model C5000 Cooling System, IKA Werke), according to ASTM D5865 (2013b). Proximate analysis was performed following ASTM D1762-84 (2013a), from which volatile matter, fixed carbon, and ash contents were obtained. For the physical analysis of basic density, two symmetrically opposite wedges containing both heartwood and sapwood were used. All procedures were carried out according to ASTM D2395 (2014).

Experimental design and data analysis

The experiment was evaluated using a completely randomized design, with five replicates per species. Statistical analyses were performed using the Statistical Analysis System software (SAS 2003). The assumptions of analysis of variance (ANOVA) were tested using the F-test, Shapiro–Wilk test for normality, and Bartlett's test for homogeneity of variances, all at a significance level of $p < 0.05$. When significant differences were detected by ANOVA, mean comparisons were performed using Tukey's test ($p < 0.05$).

Functional relationships among colorimetric, chemical, energy, and physical properties were evaluated using Pearson's correlation analysis, considering all values of the analyzed variables, Statistical significance was defined at $p < 0.05$.

To reduce data dimensionality and explore multivariate relationships, principal component analysis (PCA) was applied, allowing the interpretation of associations among variables and species. The variables included in the PCA were surface lightness (L^*), green–red axis (a^*), blue–yellow axis (b^*), chroma (C^*), hue angle (h°), lignin content (LIG), extractives content (EXT), holocellulose content (HOLO), higher heating value (HHV), volatile matter (VM), fixed carbon content (FCC), ash content (AS), and basic density (BD), considering the four forest species grown in an agroforestry system: *Eucalyptus grandis* × *Eucalyptus urophylla*, *Peltophorum dubium*, *Parapiptadenia rigida* (Benth.) Brenan and *Schizolobium parahyba* (Vell.) Blake. Two principal components were selected, and two-dimensional biplots were generated with axes designated as principal component 1 (PC1) and principal component 2 (PC2). PCA was performed using the R software environment.

Results and discussion

Colorimetry

The mean values of the colorimetric parameters (L^*, a^*, and b^*) for each anatomical plane (X: transverse; C: cross; T: tangential) of the wood from *E. grandis* × *E. urophylla*. *S. parahyba, P. dubium* and *P. rigida* are presented in Table 1.

The colorimetric parameters L^*, a^*, and b^* differed significantly among the evaluated species, indicating clear variations in wood coloration. Overall, the wood of all species and anatomical planes was classified as having high lightness (> 56), with mean L^* values ranging from 57.11 to 84.39. An exception was observed for the tangential plane of *P. rigida*, which presented a mean L^* value of 54.98, indicating a relatively darker coloration. Among species. *S. parahyba* exhibited the lightest wood (84.39), whereas *P. dubium* (61.27) and *P. rigida* (57.11) showed the lowest lightness values, characterizing visually darker woods.

Regarding anatomical planes. the L^* parameter showed higher variation in the transverse plane, particularly for *E. grandis* × *E. urophylla* (68.42) and *P. rigida* (60.15), whereas *S. parahyba* (83.97) and *P.*

Table 1 Mean values of the colorimetric parameters *L**, *a**, and *b** for the transverse, cross, and tangential anatomical planes of *E. grandis*×*E. urophylla*, *S. parahyba*, *P. dubium*, and *P. rigida* wood from an agroforestry system

Specie	Planes	Colorimetric parameters		
		*L**	*a**	*b**
		Mean	Mean	Mean
E. grandis×*E. urophylla*	X	$63.05^{\pm 4.13}$ b	$12.53^{\pm 2.08}$ a	$30.86^{\pm 5.20}$ a
	C	$68.41^{\pm 6.70}$ a	$12.53^{\pm 0.95}$ a	$28.11^{\pm 2.25}$ a
	T	$70.08^{\pm 3.93}$ a	$13.13^{\pm 1.24}$ a	$31.69^{\pm 5.95}$ a
	Mean	67.18 B	12.7 B	30.22 AB
S. parahyba	X	$81.28^{\pm 2.92}$ a	$3.88^{\pm 0.74}$ a	$27.34^{\pm 0.70}$ b
	C	$84.89^{\pm 4.56}$ a	$5.41^{\pm 2.28}$ a	$30.20^{\pm 2.39}$ ab
	T	$78.49^{\pm 9.63}$ a	$7.25^{\pm 3.69}$ a	$32.01^{\pm 2.09}$ a
	Mean	81.55 A	5.51 C	29.85 AB
P. dubium	X	$64.82^{\pm 5.55}$ a	$10.55^{\pm 5.51}$ a	$24.73^{\pm 7.62}$ a
	C	$57.44^{\pm 2.89}$ a	$14.40^{\pm 0.70}$ a	$28.65^{\pm 1.28}$ a
	T	$61.85^{\pm 7.28}$ a	$10.81^{\pm 5.44}$ a	$25.28^{\pm 6.64}$ a
	Mean	61.37 C	11.9 B	26.22 B
P. rigida	X	$57.11^{\pm 3.12}$ ab	$13.94^{\pm 4.58}$ a	$28.60^{\pm 9.62}$ a
	C	$62.14^{\pm 4.14}$ a	$14.96^{\pm 3.07}$ a	$32.62^{\pm 3.39}$ a
	T	$54.98^{\pm 2.55}$ b	$16.65^{\pm 0.70}$ a	$35.84^{\pm 2.53}$ a
	Mean	58.08 C	15.20 A	32.25 A

Where *L** lightness, *a** chromatic coordinate on the green–red axis, *b** chromatic coordinate on the blue–yellow axis

SD standard deviation, X transverse, C cross, T tangential

Means followed by the same letter within columns do not differ statistically according to Tukey's test at a 5% significance level

Lowercase letters indicate comparisons among anatomical planes. whereas uppercase letters with shading indicate comparisons among species. Superscript values indicate the standard deviation

dubium (62.04) did not present significant differences among planes. This behavior indicates that the orientation of the cutting plane can influence the optical response of wood. especially in the transverse direction, due to differences in the anatomical organization of cellular elements, as reported in previous studies (Nishino et al. 2000; Atayde et al. 2011; Reis et al. 2022).

Positive *a** values were observed for all species, ranging from 2.41 to 9.36, indicating a predominance of reddish tones, *P. rigida* showed the highest red color intensity (9.36), whereas *S. parahyba* exhibited the lowest value (2.41). Intermediate values were observed for *E. grandis*×*E. urophylla* (6.18) and *P. dubium* (5.72). No significant differences in *a** were detected among anatomical planes, a pattern similar to that reported by Vieira et al. (2022), who emphasized that the absence of variation among planes is not a universal behavior across species. In contrast, Minini (2024), studying heartwood and sapwood of *Khaya grandifoliola* from different sites, reported that the transverse plane generally differed from the radial and tangential planes for all colorimetric parameters (*L**. *a**. and *b**), which did not differ from each other.

The *b** parameter, associated with the blue–yellow axis, showed positive values for all species, with mean values ranging from 10.12 to 24.87, indicating a predominance of yellowish tones, *P. rigida* exhibited the highest yellow pigmentation intensity (24.87), followed by *E. grandis*×*E. urophylla* (21.43), while *P. dubium* presented intermediate values (16.58) and *S. parahyba* showed the lowest intensity (10.12), reflecting a more neutral coloration. In general, *b** showed less variation among anatomical planes compared with *L**, suggesting that yellow coloration is less sensitive to cutting plane orientation and more strongly associated with intrinsic wood characteristics, such as chemical composition and extractive distribution (Gonçalez et al. 2001; Barros et al. 2014).

The relatively low colorimetric variation among anatomical planes observed for most species may be associated with the age of the evaluated trees and the predominance of juvenile wood, which is characterized by lower structural differentiation and, consequently, reduced optical contrast among cutting planes (Ruano and Hermoso 2021). From a technological and commercial perspective, this color homogeneity among anatomical planes represents a favorable attribute, as it indicates higher visual uniformity of sawn wood products regardless of cutting orientation, a feature highly valued in the timber market (Paula et al. 2016). These differences among species and the relatively consistent behavior among anatomical planes support the hypothesis that wood produced in agroforestry systems exhibits distinct colorimetric profiles associated with technological characteristics intrinsic to each species.

Therefores to improve the visualization and interpretation of the colorimetric parameters, the wood coloration of the four species was classified according to the methodology proposed by Camargos and Gonçalez (2001), as presented in Table 2. As no significant differences were generally observed among

Table 2 Mean values of the colorimetric parameters of the transverse. radial. and tangential anatomical planes of wood from *E. grandis*×*E. urophylla*, *S. parahyba*, *P. dubium*, and *P. rigida* grown in an agroforestry system (AFS), compared with values reported in the literature

Species	*L**	*a**	*b**	*C**	H°	Color description	Reference
E. grandis × *E. urophylla*	67.18	12.73	30.22	32.80	67.03	Olive-brown	
E. grandis × *E. urophylla* (clones. 8 years)	74.41 - 77.62	5.94 - 10.41	17.21 - 22.99	18.22 - 24.94	63.90 - 71.11	Values close to: grayish-white or olive-brown	Martins et al. (2015)
S. parahyba	81.55	5.51	29.85	30.44	79.85	Grayish-white	
(15 years)	80.41	5.68	19.06	19.90	73.46	Grayish-white	Colanego. (2017)
(native)	Straw-white or pale yellow						Souza et al. (2003)
(15 years)	Straw-white with yellowish or pinkish nuances						Nisgoski et al. (2012)
P. dubium	61.37	11.92	26.22	28.87	66.49	Olive-brown	
P. dubium (native)	Pinkish-brown						IPT (1983)
P. rigida	58.08	15.18	32.35	35.76	64.85	Yellow-orange	
P. rigida (native)	Light brown to pinkish-brown						IPT (1983)
(32-39 years)	67.55	11.92	24.79	27.52	64.27	Reddish-orange	Machado (2016)

Where *L** lightness, *a** green–red axis, *b** blue–yellow axis, *C** chroma (saturation), H° hue angle

*The red lines indicate the values obtained from the wood of the species evaluated in this study

anatomical planes, mean values of *L**, *a**, and *b** were used, and chroma (*C**) and hue angle (h°) were calculated considering the combined X, R, and T planes. The wood of *E. grandis*×*E. urophylla* and *P. dubium* was classified as olive-brown, *S. parahyba* as grayish-white, and *P. rigida* as yellow-orange.

The study of wood colorimetry in species grown in agroforestry systems is essential to verify whether the wood produced under integrated management conditions is consistent with the color characteristics reported for these species in the literature. It can be observed that the coloration and colorimetric parameters of the evaluated species and hybrid corroborate the values reported for different forest plantation systems (Table 2). These results suggest that wood produced in agroforestry systems can meet established color quality standards similarly to wood obtained from conventional monoculture plantations.

Chemical, energy and physical characterization of the species

ANOVA indicated that the chemical, energy and physical properties of the wood differed significantly among the evaluated species. For lignin content (LIG). *E. grandis*×*E. urophylla* (21.5%) and *P. dubium* (20.1%) exhibited the highest mean values and did not differ statistically from each other (Table 3). Mean lignin contents close to 21–22% have been reported for *Eucalyptus* hybrids evaluated under agricultural and energy-oriented conditions (Jambers et al. 2025). However, Venega et al. (2023) reported higher values, close to 23.6%.

The higher lignin content contributes not only to the energetic potential of the wood, due to its higher calorific value and thermal stability, but also to increased rigidity and mechanical resistance, which are important attributes for technological performance (Eloy et al. 2024).

In contrast, opposite trends were observed for extractives content (EXT), with the highest value recorded for *P. rigida* (19.8%), whereas the lowest mean values were obtained for *E. grandis*×*E.s urophylla* (9.9%) and *S. parahyba* (11.6%). This characteristic contributes to enhanced wood durability, since extractives play a key role in protecting wood against biotic and abiotic agents. It is also important to highlight that extractives content is strongly influenced by species genetics, material origin, tree age, and longitudinal position within the stem (Silvério et al. 2008; Heim et al. 2022).

Table 3 Mean comparison test for the chemical, energy and physical properties of the four forest species

Species	Chemical. energy. and physical properties							
	LIG (%)	EXT (%)	HOLO (%)	FCC (%)	VM (%)	AS (%)	HHV (kcal kg^{-1})	BD (g cm^{-3})
E. grandis×*E. urophylla*	$21.5^{\pm3.1}$ a	$9.9^{\pm0.4}$ c	$68.0^{\pm2.1}$ ab	$17.8^{\pm0.7}$ a	$81.5^{\pm0.7}$c	$0.6^{\pm0.02}$ d	$4753^{\pm15.5}$ a	$0.509^{\pm0.03}$ b
S. parahyba	$18.7^{\pm0.1}$ ab	$11.6^{\pm0.7}$ c	$68.7^{\pm0.6}$ a	$12.6^{\pm0.3}$ c	$86.5^{\pm0.3}$ a	$1.0^{\pm0.02}$ c	$4685^{\pm6.9}$ b	$0.277^{\pm0.02}$ d
P. dubium	$20.1^{\pm0.4}$ a	$14.8^{\pm0.6}$ b	$63.5^{\pm0.9}$ b	$14.1^{\pm0.3}$ b	$84.2^{\pm0.3}$ b	$1.6^{\pm0.02}$ a	$4721^{\pm16.9}$ ab	$0.488^{\pm0.02}$ c
P. rigida	$15.0^{\pm0.03}$ b	$19.8^{\pm1.0}$ a	$63.9^{\pm1.1}$ b	$17.2^{\pm0.5}$ a	$81.5^{\pm0.6}$ c	$1.3^{\pm0.1}$ b	$4717^{\pm17.2}$ b	$0.652^{\pm0.03}$ a

Where LIG lignin content, EXT extractives content, HOLO holocellulose content, FCC fixed carbon content, VM volatile matter, AS ash content, HHV higher heating value, BD basic density.

Means followed by the same lowercase letters within a column do not differ significantly among species according to Tukey's test at a 5% probability level. Superscript values indicate the standard deviation

For holocellulose content (HOLO), *S. parahyba* (68.7%) exhibited the highest value and did not differ statistically from *E. grandis*×*E. urophylla* (68.0%), which in turn did not differ from the other species. Holocellulose represents the total polysaccharide fraction of wood, and higher contents are associated with increased cellulose and pulp yields, making these species more suitable for pulp and paper applications (Ruiz-Aquino et al. 2019).

Regarding fixed carbon content (FCC), *E. grandis*×*E. urophylla* (17.8%) and *P. rigida* (17.02%) showed the highest values, followed by *P. dubium* (14.1%) and *S. parahyba* (12.6%). According to Silva and Vale (2018), FCC values in wood from different forest species typically range from 14 to 23%, depending on species and sampling conditions. Higher FCC values can be interpreted as an indicator of higher capacity to retain carbon in the solid phase after combustion, suggesting slower and more stable burning behavior, which increases the residence time of the material during combustion (Bianchini et al. 2025).

Conversely, *S. parahyba*, which presented the lowest FCC, also exhibited the lowest basic density. This behavior is generally associated with wood density, as higher basic density contributes to higher stability and improved performance of the charcoal produced (Ramos et al. 2024). However, this species showed the highest volatile matter content (VM; 86.5%). differing significantly from the other evaluated species. As a result, *S. parahyba* tends to present faster combustion, leading to lower energy yield from the material (Protásio et al. 2019).

For ash content (AS), *P. dubium* (1.6%) and *E. grandis*×*E. urophylla* (0.6%) exhibited the highest and lowest values, respectively, both within an acceptable range for the studied species. Ash content is highly variable among forest species, reflecting intrinsic differences in wood mineral composition, which are influenced by multiple factors. In general, woods with ash contents below 1% are considered suitable for energy applications. However, certain species or materials with higher mineral accumulation may exceed 4%, surpassing recommended limits and impairing performance in thermal and combustion processes (Bianchini et al. 2025; Maj et al. 2025). Elevated ash contents are associated with an increased risk of slagging, fouling, and inorganic residue deposition in boilers, reducing operational efficiency and potentially increasing maintenance costs (Ghazidin et al. 2023).

For the higher heating value (HHV), the results showed that *E. grandis*×*E. urophylla* (4758 kcal kg^{-1}) presented the highest value. In contrast. *S. parahyba* and *P. rigida* exhibited the lowest HHV values, whereas *P. dubium* showed an intermediate result, with no significant differences among the evaluated species. These values are comparable to those reported for other forest species within a broad HHV range, highlighting that the energy released during wood combustion can vary substantially among species (Eloy et al. 2014). In this context, the differences observed among species indicate variations in biomass energy potential, a parameter that is fundamental for selecting wood intended for thermal energy generation, charcoal production, and other thermochemical conversion processes (Protásio

Table 4 Mean values of the chemical. energy. and physical properties of wood from *E. grandis*×*E. urophylla*, *S. parahyba*, *P. dubium*, and *P. rigida* grown in an agroforestry system (AFS), compared with values reported in the literature

Species	LIG (%)	EXT (%)	HOLO (%)	FCC (%)	VM (%)	AS (%)	HHV (kcal.kg^{-1})	BD (g.cm^{-3})	References
E. grandis × *E. urophylla*	21.5	9.9	68.0	17.8	81.5	0.60	4753	0.509	
	30.7	-	-	-	-	0.99	4363	-	Alves et al. (2025)
7 years	21.4		74.2			1.0	4330	0.472	Barreiros et al. (2021)
7 years							4840	0.470	Soares (2014)
4.5 years	26.3	4.8	68.6	20.1	79.5	0.31	4845	0.525	Oliveira (2019)
10 years	28.3	5.6	66.1	11.6	88.2	0.15	4549	0.565	Silva (2024)
S. parahyba	18.7	11.6	68.7	12.6	86.5	1.0	4685	0.277	
15 years	-	-	-	-	-	-	-	0.240	Calonego et al. (2020)
18 years	21.0	8.6	69.4	-	-	0.80	-	0.390	Trianosky (2010)
S.amazonicum (14 years)	28.6	6.6	64.7	-	-	0.600	-	-	Modes et al. (2018)
9 and 11 years	29.5	4.4	-	-	-	-	4436 - 4454	0.275 – 0.303	Vidaurre et al. (2012)
-	-	-		19.1	80.4	0.6	4389	-	Ferreira et al. (2019)
-	-	-	-	-	-	-	4544	-	Jara (1989)
P. dubium	20.1	14.8	63.5	14.1	84.2	1.60	4721	0.488	
3 years	-	-	-	-	78.6	0.80	4190	-	Baricatti et al. (2015)
20 to 25 years old	26.8	24.4	47.2	-	-	1.30	4473	-	Longui et al. (2025)
	-	-	-	-	-	-	4755	-	Jara (1989)
10 years	-	-	-	-	-	-	-	0.500	Vivian et al. (2010)
P. rigida	15.0	19.8	63.9	17.2	81.5	1.30	4717	0.652	
-	-	-	-	-	-	-	5324	-	Jara (1989)
-	24.8	-	68.2	-	-	2.10	4499	0.780	Paes et al. (2013)

Where LIG lignin content, EXT extractives content, HOLO holocellulose content, FCC fixed carbon content, VM volatile matter, AS ash content, HHV higher heating value. BD basic density

The red lines indicate the values obtained from the wood of the species evaluated in this study

et al. 2019). Thus, the assessment of HHV provides important support for decision-making regarding the energetic allocation of wood in productive systems.

Analysis of basic density revealed significant differences among species. The highest value was observed for *P. rigida* (0.652 g cm^{-3}), followed by *E. grandis*×*E. urophylla* (0.509 g cm^{-3}), *P. dubium* (0.488 g cm^{-3}), and *S. parahyba* (0.277 g cm^{-3}). Based on basic density, the species can be classified to better guide their technological and industrial applications. According to the classification proposed by Romero et al. (2024), *S. parahyba* can be considered a low-density species, *E. grandis*×*E. urophylla* and *P. dubium* as medium-density species, and *P. rigida* as a high-density species.

When comparing the wood property values of species grown in agroforestry systems with those reported in the literature for conventional plantations (Table 4), a close agreement among results is observed. This similarity reinforces the suitability of the arboreal component in integrated systems for producing wood with technological quality comparable to that obtained from conventional forest plantations.

Overall, the values obtained in this study are consistent with those reported in the literature for the same species or for comparable materials, confirming the reliability of the results. The differences observed among studies are mainly associated with variations in tree age, interspecific differences, growth conditions, silvicultural management, and analytical methods employed. While species such as *E. grandis*×*E. urophylla* and *S. parahyba* are well documented in the literature, there is a clear lack of studies that

Table 5 Pearson's correlation coefficients between colorimetric parameters and the chemical, energy, and physical properties of wood

	*a**	*b**	C	H°	LIG	EXT	HOLO	HHV	VM	FCC	AC	BD
*L**	-0.91*	-0.09^{ns}	-0.37^{ns}	0.93*	0.15^{ns}	-0.64*	0.81*	-0.51*	0.70*	-0.59*	-0.45^{ns}	-0.89*
*a**		0.37^{ns}	0.63*	-0.95*	-0.21^{ns}	0.52*	-0.53*	0.60*	-0.84*	0.78*	0.19^{ns}	0.92*
*b**			0.95*	-0.09^{ns}	-0.35^{ns}	0.17^{ns}	0.17^{ns}	-0.02^{ns}	-0.27^{ns}	0.32^{ns}	-0.38^{ns}	0.24^{ns}
C				-0.38^{ns}	-0.38^{ns}	0.33^{ns}	-0.04^{ns}	0.16^{ns}	-0.49^{ns}	0.51^{ns}	-0.24^{ns}	0.49^{ns}
Hº					0.08^{ns}	-0.46^{ns}	0.59*	-0.68*	0.83*	-0.75*	-0.28^{ns}	-0.90*
TL						-0.76*	0.11^{ns}	0.65*	-0.74*	0.76*	-0.31^{ns}	-0.36^{ns}
TE							-0.72*	-0.22^{ns}	-0.32^{ns}	0.19^{ns}	0.66*	0.67*
HC								-0.10^{ns}	0.24^{ns}	-0.10^{ns}	-0.74*	-0.61*
PCS									-0.74*	0.76*	-0.31^{ns}	0.49^{ns}
TMV										-0.98*	0.17^{ns}	-0.88*
TCF											-0.33^{ns}	0.80*
TCZ												0.24^{ns}

Where *L** lightness, *a** green–red axis, *b** blue–yellow axis, *C** chroma (saturation), H° hue angle, LIG lignin content, EXT extractives content, HOLO holocellulose content, HHV higher heating value, VM volatile matter content, FCC fixed carbon content, AC ash content, BD basic density

*significant Pearson correlation at 5% probability level, ns = non-significant Pearson correlation

comprehensively evaluate the chemical, energy, and physical properties of native species such as *P. rigida* and *P. dubium*. This knowledge gap highlights the relevance of the results presented in this study.

Correlation between colorimetric parameters and the chemical, energy, and physical properties of wood

To better understand the relationships between colorimetric parameters and the chemical, energy, and physical properties of wood. Pearson's correlation analysis was performed (Table 5). Overall, most variables showed significant correlations with different magnitudes, either positive or negative, indicating complex interrelationships among wood properties. This behavior is consistent with previous studies, which have demonstrated that wood color is directly associated with its chemical composition (Moya et al. 2012; Traoré and Martínez Cortizas 2023; Yang et al. 2024).

However, no significant correlations were observed between lignin content (LIG) and any of the colorimetric parameters. Similarly, the *b** coordinate and chroma (*C**) did not show significant correlations with the evaluated chemical, energy, or physical properties. These results suggest that, for the species and conditions evaluated in this study, variations in wood color related to the yellow–blue axis and color saturation are less sensitive to changes in chemical composition and energetic or physical performance.

The *L** parameter showed negative correlations with extractives content (EXT; −0.64*), higher heating value (HHV; −0.51*), and basic density (BD; −0.89*), suggesting that lighter-colored woods tend to exhibit lower values for these variables. This behavior has also been reported for *Pinus caribaea* and *Eucalyptus grandis* (Amorim et al. 2013). These results are consistent with previous studies that associate darker wood coloration with higher contents of phenolic extractives and lignin, compounds that contribute to increased density, higher carbon content. and consequently higher calorific value (Garcia and Marinonio 2016; Amorim et al. 2013; Maia et al. 2020).

Conversely, *L** was positively correlated with hue angle (h°; 0.93*), holocellulose content (HOLO; 0.81*), and volatile matter (VM; 0.70*), indicating that lighter woods are characterized by higher polysaccharide content, higher volatility, and lower thermal stability. According to Costa et al. (2014), these factors contribute to reduced energetic potential of the wood.

The *a** parameter was negatively correlated with h° (−0.95*), HOLO (−0.53*), and VM (−0.84*), and positively correlated with extractives content (EXT; 0.52*), HHV (0.60*), fixed carbon content (FCC; 0.78*), and BD (0.92*). These results

indicate that woods with more intense reddish coloration are generally denser, thermally more stable, and exhibit superior energetic performance. This behavior agrees with findings reported by Amorim et al. (2013) for *Pinus* and *Eucalyptus*, and by Garcia and Marinonio (2016) for *Tectona grandis*, who demonstrated that increased red pigmentation and lower lightness are associated with woods of higher density and improved energy efficiency.

The b^* parameter showed a strong positive correlation with chroma (C^*; 0.95*), indicating that more yellowish tones are associated with higher color saturation. However, no significant correlations were observed between b^* and the evaluated chemical or energy-related variables, suggesting that this color coordinate is more strongly related to aesthetic attributes than to functional properties of the wood (Bonfatti Júnior and Lengowski 2018). Studies such as Maia et al. 2020 have reported that yellowish wood coloration is mainly associated with lipophilic substances. with limited influence on density or calorific potential.

Hue angle (h°) exhibited negative correlations with HHV (−0.68*), FCC (−0.75*), and BD (−0.90*), and positive correlations with HOLO (0.59*) and VM (0.83*), indicating lighter and less dense woods with higher holocellulose content and lower energetic performance. This trend suggests that, for energy-oriented applications, darker woods with lower hue angles (closer to reddish–purplish tones) are more desirable due to their higher contents of lignin, extractives, and fixed carbon (Castro et al. 2013; Dias et al. 2021).

Overall, the results indicate that wood color, particularly the L^* and a^* parameters, can be used as non-destructive indicators of energetic quality, corroborating previous studies that associate wood color with chemical composition and density (Mesquita et al. 2017; Campos et al. 2025). In general, L^* and a^* are more closely related to extractives and phenolic compounds, whereas b^* is commonly associated with lignin and polysaccharides (Gierlinger et al. 2004; Moya et al. 2012). The relationships observed between colorimetric parameters and the chemical, physical, and energetic properties of the wood reinforce the hypothesis that variations in wood color are associated with differences in technological characteristics among the evaluated species.

When analyzing lignin content (LIG), positive correlations were observed with HHV (0.65*) and FCC (0.76*), and a negative correlation with EXT (−0.72*). Lignin plays a fundamental role in increasing the calorific value of wood, since higher lignin contents are associated with higher fixed carbon content and, consequently, higher HHV (Castro et al. 2013; Oliveira 2003). In addition, higher lignin concentrations may be associated with lower ash contents, which are residues generated after combustion (Silva et al. 2017). Specifically, lignin is also important for briquetting processes, as it promotes the phenomenon known as *creep*, acting as a natural binder that enhances particle cohesion, compaction efficiency, and mechanical strength of densified biofuels (Dias et al. 2021).

To facilitate the visualization of the relationships between colorimetric parameters and wood properties for each species, principal component analysis (PCA) was performed (Fig. 2). The first two principal components (PC1 and PC2) jointly explained 80.9% of the total variance, with individual contributions of 69.5% and 24.9%, respectively. The variables that contributed most to the variance along PC1 were basic density (BD; 13.7%), a^* (13.4%), L^* (11.9%), hue angle (h°; 11.8%), volatile matter (VM; 11.4%), fixed carbon content (FCC; 9.5%), and chroma (C^*; 6.9%). In contrast, PC2 was mainly influenced by ash content (AS; 27.7%), holocellulose content (HOLO; 15.1%), extractives content (EXT; 13.6%), higher heating value (HHV; 12.5%), lignin content (LIG; 7.7%), and b^* (4.3%). As shown in the PCA ordination, the four tree species were distributed across three quadrants, with *P. dubium* positioned between two quadrants, indicating an intermediate behavior in relation to the evaluated colorimetric, chemical, energy, and physical properties.

The PCA results indicated clear differences among the studied species with respect to chemical, energy, and physical properties, as well as colorimetric characteristics. This variability among species is primarily attributed to differences in chemical composition (Longui et al. 2025). Among the evaluated variables, *E. grandis*×*E. urophylla* showed a stronger association with HHV, which is consistent with the correlation analysis results (Table 5). In contrast, *P. rigida* exhibited a strong relationship with basic density (BD) and extractives content (EXT), indicating denser wood with a higher concentration of

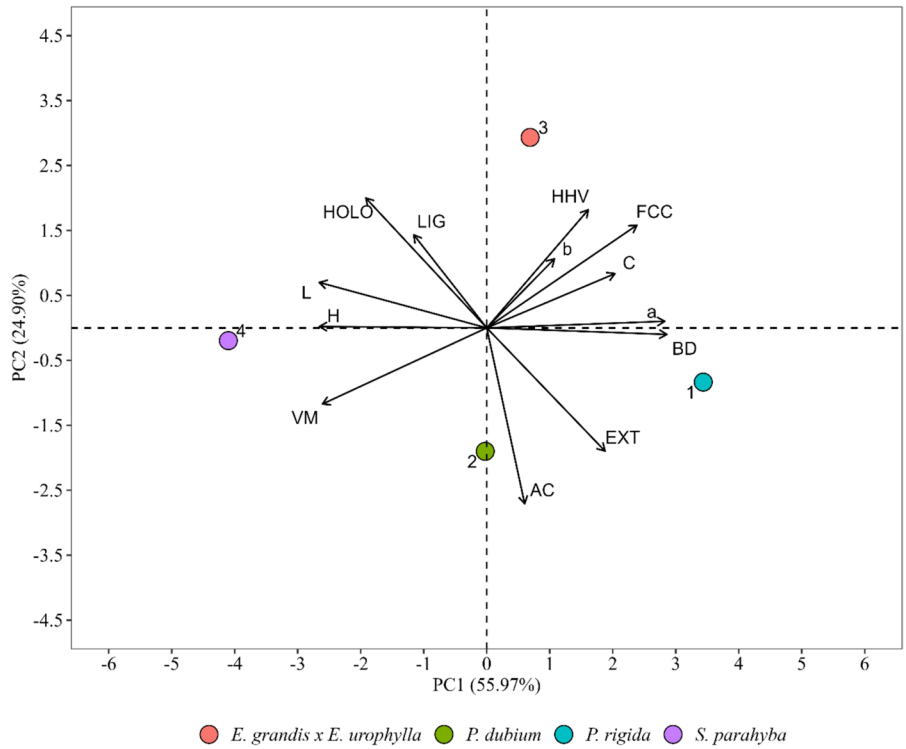


Fig. 2 Biplot of colorimetric parameters and energy-related properties of four forest species (*E. grandis*×*E. urophylla*, *P. dubium, P. rigida* (Benth.) Brenan, and *S. parahyba* (Vell.) Blake) grown in an agroforestry system, nine years after planting

secondary chemical compounds. Woods with these characteristics tend to present higher carbon concentration per unit volume (Nakagawa et al. 2016) and, therefore, higher overall energy potential, in addition to enhanced mechanical resistance and durability (Scott et al. 2025).

Conversely, *S. parahyba* showed an inverse association with BD and a strong relationship with holocellulose content (HOLO). This species is widely recognized for producing low-density wood with a high proportion of structural polysaccharides, such as cellulose and hemicelluloses, which are typical features of lightweight woods. The high contribution of HOLO explains the distinct position of *S. parahyba* in the PCA, reflecting its lower association with the other evaluated species. Elevated HOLO content is generally associated with lower heating value and reduced fixed carbon concentration (Ferreira et al. 2024), which is directly reflected in the separation observed along PC2.

In turn, *P. dubium* showed a strong association with ash content (AS), indicating a higher accumulation of inorganic mineral components. Elevated ash contents are recognized as a limiting factor for energy applications, as they reduce thermal efficiency and may cause operational problems during combustion and thermal conversion processes (Yunusa et al. 2024).

Consistent with the trends observed in the correlation analysis (Table 5), the PCA indicated that wood colorimetric properties can play a complementary role in species evaluation and end-use allocation, extending beyond purely aesthetic considerations and assuming technological and functional relevance. These results suggest that colorimetry may serve as an auxiliary tool to simplify and guide wood utilization, including for energy and structural applications, within the context of agroforestry systems.

Limitations of the study and perspectives for future research

The results obtained in this study demonstrated that colorimetric parameters show consistent relationships with the chemical, energetic, and physical properties of wood produced in an agroforestry system, highlighting the potential of colorimetry as an auxiliary tool for wood technological evaluation. However, future studies should expand this approach by

including different tree ages, comparisons between agroforestry systems and monocultures, and assessments of the longitudinal variability of wood properties along the stem.

In addition, future research may further explore the effects of interspecific interactions, growth conditions, and management practices in integrated systems on wood quality. The incorporation of non-destructive methods and modeling approaches may contribute to the development of more precise and comprehensive tools for evaluating the technological and energetic quality of wood produced in agroforestry systems. Long-term monitoring studies are also important to better understand how growth in integrated systems influences the variability of wood properties over time and under different environmental conditions. Future studies integrating colorimetry with spectroscopic and imaging techniques may further enhance the potential of non-destructive methods for wood quality assessment in agroforestry systems.

Conclusions

Statistical approaches proved to be effective tools for improving the understanding of relationships between wood colorimetry and the chemical. energy. and physical properties evaluated in this study, reinforcing the proposed hypothesis. Based on the results. the following conclusions can be drawn:

Wood colorimetric parameters differed among the evaluated species. *Eucalyptus grandis* × *Eucalyptus urophylla* and *Peltophorum dubium* were classified as olive-brown, *Schizolobium parahyba* as grayish-white, and *Parapiptadenia rigida* as yellow-orange.

Among the colorimetric parameters, L^* and a^* showed the strongest relationships with chemical, energy, and physical properties, supporting their use as non-destructive indicators of the energetic and technological potential of wood.

Darker and more reddish woods. characterized by lower lightness and lower hue angle, tend to present higher basic density, higher lignin and fixed carbon contents, and consequently superior energetic performance.

Colorimetric analysis acts not only as a descriptive attribute but also as an efficient tool to simplify wood quality assessment, reducing the need for destructive testing and supporting management decisions and functional allocation of wood resources.

Wood produced in agroforestry systems exhibited properties comparable to those reported for conventional plantations, indicating similar technological and energetic potential.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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