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ARTÍCULO

X-ray densitometry and colorimetry for the characterization of ten native Brazilian timber species

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Abstract:
The research responds to the limited availability of technical data on native Brazilian woods, which constrains their industrial application and sustainable management. The commercial use of timber from native Brazilian species is hindered by a scarcity of data on fundamental properties related to wood quality, limiting its use in the wood industry. This study sought to characterize the timber of ten native Brazilian species using X-ray densitometry and colorimetric analysis. Timber samples of various ages and 2 mm thickness were evaluated. The X-ray images enabled the identification of anatomical characteristics such as wood porosity and parenchyma. Densitometric profiles showed woods with high densities (ranging between 550 kg/m³ and 1000 kg/m³). Variations were identified in each sample due to transitions between earlywood and latewood, with latewood presenting higher density, and parenchyma and pore areas showing lower density values. Standard deviation values ranging from 84,6 (Tabebuia) to 162,8 (Bowdichia) indicated differing homogeneity in wood density across the samples. Colorimetric characterization using the CIELAB system allowed the identification of desirable visual characteristics, with species ranging from lighter (L*46,7) to darker (L*25,7) tones and significantly different colors from yellow to purple. Thus, the techniques used in this study proved effective in characterizing native timber through novel analytical methods, contributing to their better utilization.

Keywords: Brazilian native species, CIELAB color system, tropical timber, wood colorimetry, wood density.

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Introduction

Brazil stands out for having the greatest biodiversity of forest species on the planet, with 46497 taxa, of which 33098 are angiosperms and 30 are gymnosperms (Flora do Brasil 2020). Despite the vast richness of species, the sustainable exploitation of these resources is currently limited due to the scarce information reported in the literature, mainly on aspects related to wood quality (Duarte *et al.* 2021).

The scarcity of information regarding the properties of these woods entails several relevant consequences and implications. From an industrial perspective, the lack of limits the utilization of these species, reduces the competitiveness of the timber and furniture sectors, and may lead to resource waste due to inappropriate use of the wood (Santos *et al.* 2021). From an environmental perspective, the lack of information hinders the sustainable exploitation of native forests, potentially contributing to the overharvesting of some species, the underutilization of others, and, consequently, the loss of biodiversity (Farias and Melo 2020).

Therefore, new information about wood from native Brazilian species is desirable, since the versatility of these materials can provide several applications, including use in civil construction, naval construction and the manufacture of luxury furniture (Blanco-Flórez *et al.* 2015).

Density is one of the main parameters for evaluating wood quality, since characteristics such as wood stiffness, strength and workability are directly influenced by this characteristic (Gao *et al.* 2017). Thus, knowing the wood density contributes to ensuring that these species are used appropriately, in accordance with the characteristics of interest for each application. Conventional methods for determining apparent density are mostly considered destructive, as they cause changes in the chemical, physical, mechanical, or anatomical characteristics of the samples (Surdi *et al.* 2014). In this context, non-destructive techniques emerge as viable alternatives, among which X-ray densitometry stands out. This methodology offers significant advantages, such as increased speed in data collection and analysis processing, thereby optimizing the determination of apparent density (Castro *et al.* 2017).

According to Veloso *et al.* (1991), native Brazilian woods present values that vary from medium to high density. In their study, Silveira *et al.* (2013) evaluated the density of nine species native to the Amazon and found values between 561,0 kg/m^3 and 720,0 kg/m^3 for three species, being classified as medium density wood, and for the other six species, values ranged from 835,0 kg/m^3 to 909,0 kg/m^3 and were classified as high density. Farias and Melo (2020) studied the physical properties of five species of wood native to the Caatinga and reported values of 790,0 kg/m^3 and 1005,0 kg/m^3 for the wood of aroeira (*Myracrodruon urundeuva* Allemão.) and angico-branco (*Anadenanthera colubrina* (Vell.) Brenan.), respectively, corroborating the density values of Brazilian native woods.

Color is a parameter used by furniture and lumber industries to characterize the quality of wood (Valverde and Moya 2014) and to predict its physical and mechanical properties, as well as chemical composition (Amorim *et al.* 2013). It is observed in the literature that the visual classification of color in the identification of woods, at the species level, is very subjective, since characteristics such as anatomical elements, chemical constitution, genetics, age, place of growth, oxidation and different positions in the trunk (radial and longitudinal) can change the natural color of the wood (Sousa *et al.* 2020, Wu *et al.* 2020).

With the aim of reliably characterizing the color of wood, quantitative colorimetry stands out for being a non-destructive, fast technique, offering low cost and good accuracy (Sedliačiková *et al.* 2021).

Few studies were found in the literature addressing X-ray densitometry and colorimetry in native Brazilian wood. Therefore, considering hypotheses such as the accuracy of X-ray densitometry and colorimetry techniques, this study aimed to characterize the wood of native Brazilian species using X-ray densitometry and colorimetric analysis.

Material and methods

Origin of material

Ten native Brazilian species of different ages, from the xylotheque of the Laboratory of Wood Properties at the Federal University of Viçosa (LPM - UFV), were used (Table 1). The selection of species was based on the use of the main native woods of commercial relevance in Brazil. The woods were collected from adult specimens, presenting mature wood, and were previously stored in the xylotheque for approximately 9 years. Species were selected for being knowingly used in construction or to produce items of furniture.

Table 1: Description of native species.

Scientific name	Scientific name Abbreviated	Family	Common name in Brazil
Bowdichia spp.	*Bowdichia* spp.	Fabaceae	Sucupira
Dalbergia brasiliensis Vogel.	*D. brasiliensis*	Fabaceae	Jacarandá
Hymenaea spp.	*Hymenaea* spp.	Fabaceae	Jatobá
Hymenolobium petraeum Ducke	*H. petraeum*	Fabaceae	Angelim-pedra
Melanoxylon brauna Schott	*M. braúna*	Fabaceae	Braúna
Mimosa hostilis Benth.	*M. hostilis*	Fabaceae	Jurema-preta
Myrocarpus spp.	*Myrocarpus* spp.	Fabaceae	Bálsamo
Peltogyne spp.	*Peltogyne* spp.	Fabaceae	Roxinho
Plathymenia foliolosa Benth.	*P. foliolosa*	Fabaceae	Vinhático
Tabebuia spp.	*Tabebuia* spp.	Bignoniaceae	Ipê

Preparation of wood samples

From samples measuring 10×2 cm, width x thickness in the pith-bark direction, with the aid of a vertical band saw, samples of 2 millimeters in thickness were taken, sectioned on a table saw. The samples were stored in a climate-controlled room at 20 °C and 65 % relative humidity for 24 hours (Lima *et al.* 2023). The experimental design of this study can be seen in Figure 1.

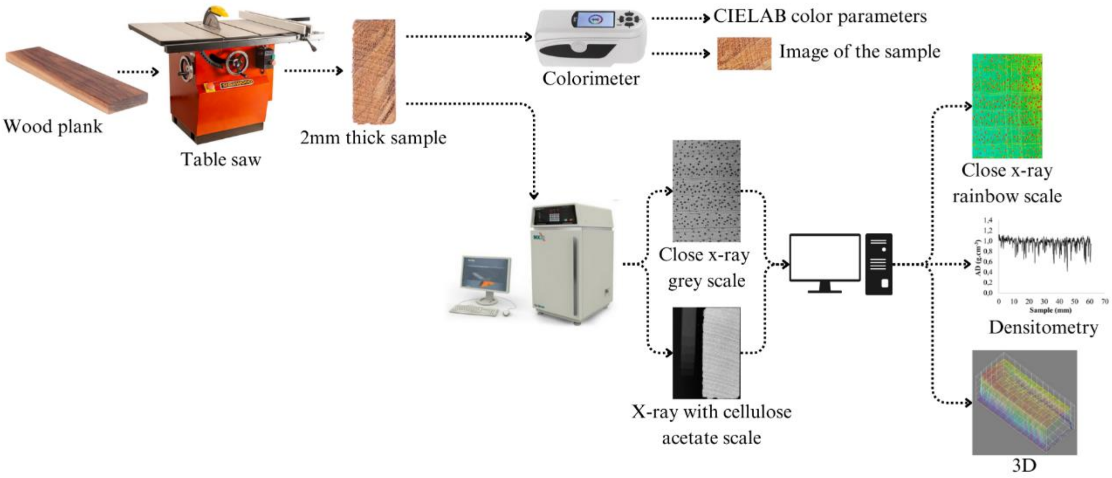


Figure 1: Experimental study design.

Apparent density and X-ray densitometry

To capture the digital images, the samples were placed with the cellulose acetate calibration scale in the Faxitron LX-60 equipment (Faxitron, Lincolnshire, England), previously calibrated for automatic reading, at 26 Kv for 19 seconds, and saved in DICOM format (Faxitron 2009).

The images were analyzed in the software ImageJ, where the values for apparent density were obtained with measurements in every pixel along the sample. The mean of the measurements is the apparent density of the sample. The standard deviation was also calculated.

The densitometric profiles were plotted with the values of apparent density for each pixel along the wood sample, and the values allowed the determination of the standard deviation in the apparent density. The variation of density in each sample can also be visualized in the 3D surface plot of the samples used in the X-ray.

Apparent density was analyzed using grayscale images with the calibration ImageJ software. The grayscale digital images were transformed into a rainbow scale with Photoshop software, to help better visualize the density differences, and the analysis of the density variation on the 3D surface was performed with ImageJ software. In grayscale images, the tones closest to white and black colors were characterized at highest and lowest density, respectively (Castro *et al.* 2022). On the rainbow scale, shades of blue, green, yellow and red were associated, in descending order, from lowest to highest density, respectively (Boddy *et al.* 2010).

Colorimetric test

The colorimetric test was performed with a 3nh colorimeter (High-quality colorimeter NR200, Shenzhen, China), based on the CIE L*a*b* system, where L* is the luminosity, a* is the red/green coordinate (+ a indicates red and –a indicates green), b* is the yellow/blue coordinate (+b indicates yellow and –b indicates blue). Three measurements on each specimen in cross section were performed. After tabulating the data, the mean values of the parameters L*, a*, b*, C (chroma) and h (hue) for each of the specimens, as well as the standard deviation were calculated. The colorimetric data were submitted to analysis of variance and when the difference between treatments was significant, the data were compared by Tukey's test at a significance level of 5 % using the ExpDes.pt package of the R software (version 4.1.3).

Results and discussion

X-ray and densitometric profiles

The X-ray densitometry data for the 10 timber species can be seen in Table 2.

Table 2a: Grayscale and Rainbow X-ray of native species, X-ray densitometry and 3D image of X-ray.

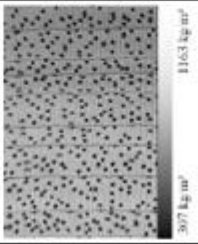
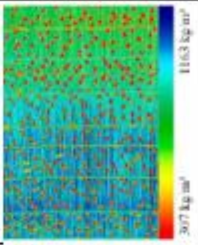
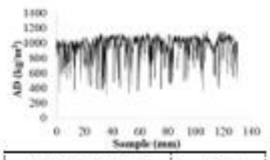
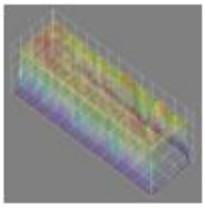
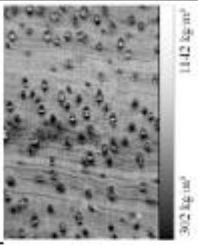
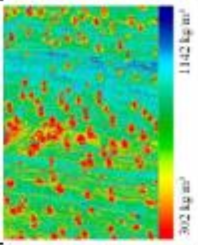
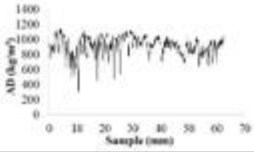
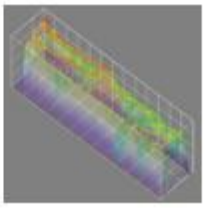
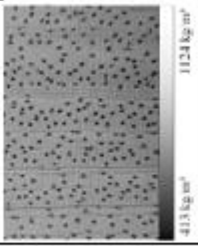
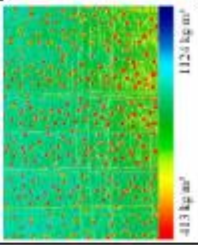
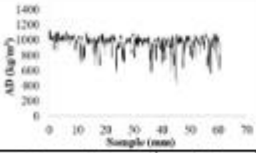
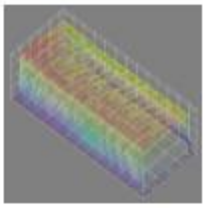
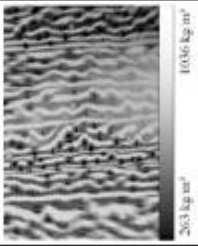
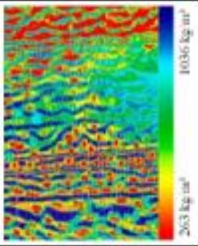
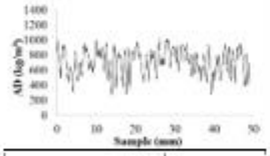
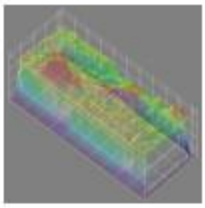
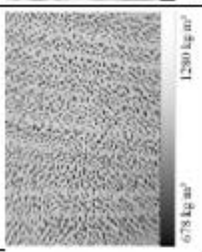
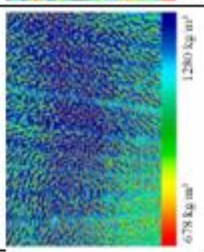
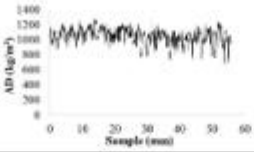
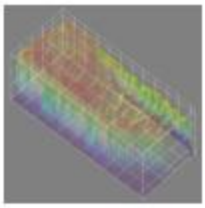
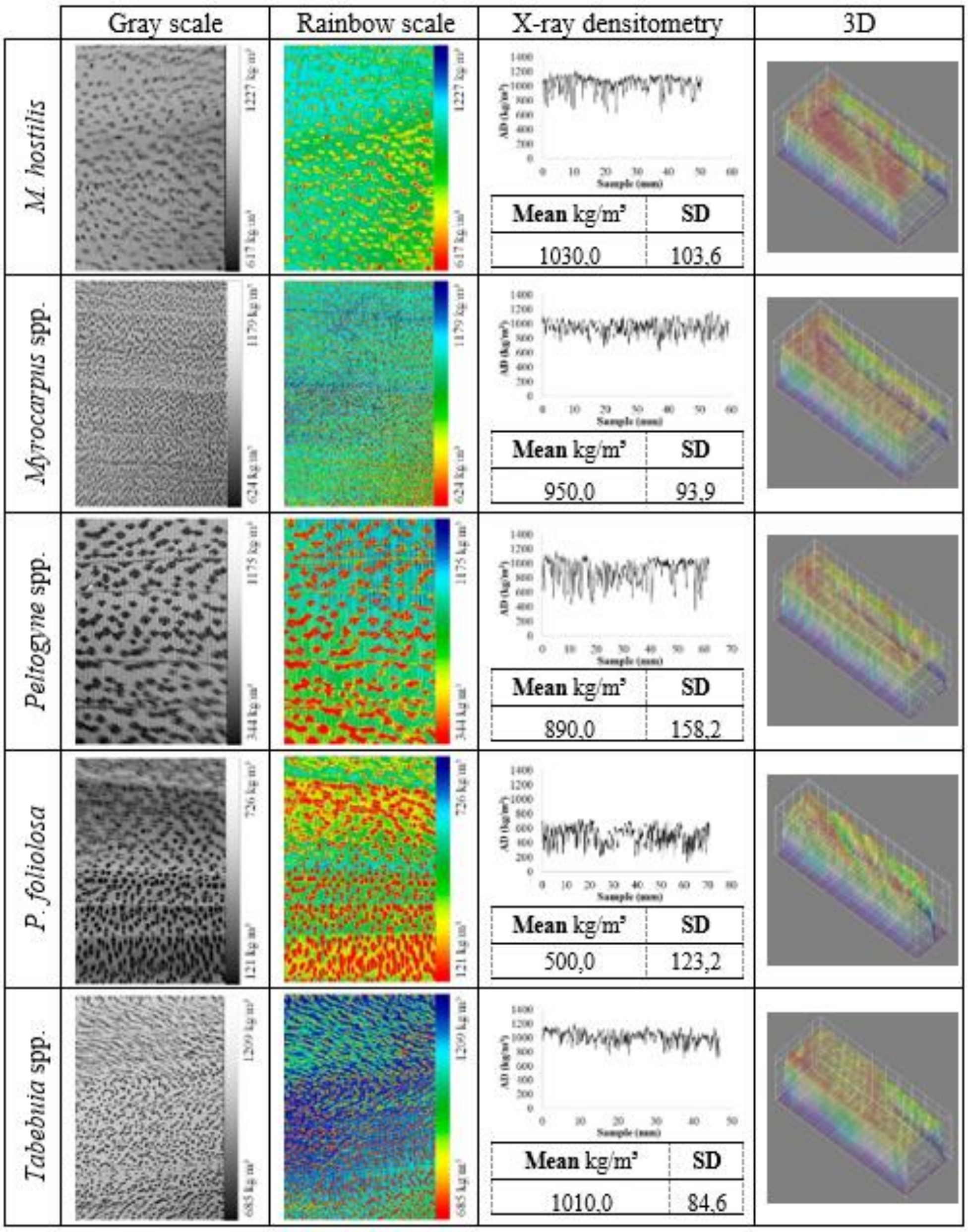
	Gray scale	Rainbow scale	X-ray densitometry	3D
Bowdichia spp.			 Mean kg/m³: 940,0 ; SD: 162,8	
D. brasiliensis			 Mean kg/m³: 910,0 ; SD: 122,1	
Hymenaea spp.			 Mean kg/m³: 960,0 ; SD: 98,7	
H. petraeum			 Mean kg/m³: 710,0 ; SD: 161,2	
M. brauna			 Mean kg/m³: 1050,0 ; SD: 98,7	

Table 2b: Grayscale and Rainbow X-ray of native species, X-ray densitometry and 3D image of X-ray.



Wood from *Bowdichia* spp. (sucupira) (Fabaceae), vessels showed diffuse porosity, predominantly solitary. The regions of porosity showed shades of red in the rainbow scale X-ray image, indicating lower density, and an alternation of shades of blue and green was observed, indicating the transition between earlywood and latewood. In the densitometric profile of sucupira (*Bowdichia* spp.) wood, the latewood regions (higher density) are characterized by density peaks, while the early wood areas where the density is lower are represented in the graph by the lowest valleys. In the 3D surface plot, variation of peaks and valleys within the same line was observed, indicating greater density heterogeneity in that region. In addition to the variation of lines in the graph, it was possible to observe the variation of colors throughout the sample rainbow scale X-ray image. These fluctuations in density can be explained by anatomical characteristics especially defined by the marginal parenchyma (Soares *et al.* 2014).

In the wood of *Dalbergia brasiliensis* Vogel. (jacarandá) (Fabaceae), the vessels showed diffuse porosity, solitary, multiples of 2 to 3, with occurrence of obstruction by tyloses, that can be seen in the gray scale X-ray. In the rainbow scale X-ray the regions of porosity have red tones, and the parenchyma regions showed shades of yellow, demonstrating lower density in these regions. The wood densitometric profile showed regions of lower density represented by lower valleys in the initial portion of the sample. The same trend was observed on the 3D surface plot, where in the tangential direction it was possible to verify density fluctuations with alternating peaks and valleys. In addition, there was a greater variation in colors in the rainbow scale X-ray, indicating greater heterogeneity in wood density.

The wood of *Hymenaea* spp. (jatobá) (Fabaceae) presented growth layers individualized by parenchyma. The vessels showed diffuse porosity, solitary and multiple. This can be seen in the rainbow scale X-ray, where the regions of porosity showed red tones, and the axial parenchyma and the growth layers separated by parenchyma showed shades of yellow, demonstrating lower density in these regions. For jatobá (*Hymenaea* spp.) wood, the densitometric profile followed the same pattern as hardwoods with high density, with well-defined growth rings and a marginal parenchyma strip delimiting the region of greater wood density (Albuquerque *et al.* 2016, Santos *et al.* 2022). When plotting the surface in 3D, it was possible to observe a homogeneous distribution of peaks and valleys, as well as less variation in color in the rainbow scale X-ray throughout the sample.

In the wood of *Hymenolobium petraeum* Ducke (angelim-pedra) (Fabaceae), the vessels showed diffuse porosity, solitary and multiple, which showed shades of red in the rainbow scale. The area where the inorganic materials, that are characteristic of the species, occur is shown with lighter tones in the gray scale X-ray image and blue/green in the rainbow scale X-ray image. The areas of parenchyma are shown as red in the upper part of the color X-ray image and in green in the middle area, which evidentiates the increase of density in the areas with inorganic materials. The densitometric profile showed high variability of density values. On the 3D surface plot, the variation of peaks and valleys was observed throughout the sample, as well as in the colors. Regions in red indicate greater density, which can be explained by the presence of crystals (Ferreira *et al.* 2004). The wood of *Melanoxylon brauna* Schott (braúna) (Fabaceae) showed distinct growth layers. The rainbow scale X-ray image showed alternating shades of blue and green, indicating the transition between earlywood and latewood and the regions of porosity showed red tones. X-ray densitometry showed homogeneity of peaks throughout the sample, with less variation between areas of low and high apparent density, which was confirmed by the coefficient of variation. In the 3D surface plot, it was possible to observe small fluctuations in the lines, indicating greater homogeneity of density and predominance of the red color along the tangential profile of the sample, characteristic of regions with high density.

The wood of jurema-preta (*Mimosa hostilis* Benth) (Fabaceae) is popularly known as Jurema-preta. In the rainbow scale X-ray image, the regions of porosity presented red tones, and the parenchyma showed shades of yellow. The densitometric profile of jurema-preta (*Mimosa hostilis* Benth) wood showed a higher peak in high density areas and the presence of low-density valleys, which can be explained by the presence of parenchyma bands delimiting the growth layers (Silva *et al.* 2011). On the 3D surface plot, variations in shades were observed along the tangential axis, with areas in red of greater density and zones in yellow, indicating the presence of growth layers.

The wood of *Myrocarpus* spp. (bálsamo) has regions with higher density separating growth layers, evident in the top part of the X-ray image, which is not present in the other species. In the rainbow scale X-ray image, the regions of porosity showed red tones, and the axial parenchyma showed shades of yellow. In addition, regions with interlocking grains were observed. The X-ray densitometry showed a similar pattern to other high-density hardwoods, with greater homogeneity in the peaks that is confirmed by the low coefficient of variation in the densitometric profile. When plotting the surface in 3D, a small variation of peaks and valleys within the same line was observed, indicating greater density homogeneity. In addition, regions in red were noted less frequently in the rainbow scale image, indicating greater density.

The wood of *Peltogyne* spp. (roxinho) (Fabaceae) shows predominantly unilateral axial parenchyma, that was also observed by Duarte *et al.* (2021). The growth rings were defined by parenchyma lines. The regions of porosity presented red tones in the rainbow scale image. X-ray densitometry indicated greater variability of densities along the sample. The abrupt transition in density is related to the marginal parenchyma, which delimits the growth layers (Duarte *et al.* 2021). On the 3D surface plot, it was possible to observe density fluctuations throughout the sample, which corroborates with the higher standard deviation for the densitometric profile.

In the wood of *Plathymenia foliolosa* Benth (vinhático) (Fabaceae), the rainbow scale image showed alternating shades of blue and green, indicating the transition between earlywood and latewood. The regions of porosity showed red tones, being very evident in the image for this species, along with areas colored in yellow that probably are paratracheal axial parenchyma. The densitometric profile showed variability with a tendency to lower density values. The highest density peaks may refer to the fibrous zones that demarcate the growth layers. The 3D surface plot showed density fluctuations along the tangential profile of the sample, with the presence of higher density peaks in red and valleys in blue and green tones, which indicates the presence of growth rings.

In the wood of *Tabebuia* spp. (ipê) (Bignoniaceae), the vessels are diffusely porous, small and numerous. The rainbow scale image showed alternating shades of blue and green, indicating the transition between earlywood and latewood. The top part of the rainbow x-ray has areas of lighter blue and green that probably indicate paratracheal parenchyma, with the regions of porosity shown in red and yellow tones. Regions with interlocked grain were observed. In the wood of ipê (*Tabebuia* spp.), the densitometric profile showed high average density, with greater homogeneity of values throughout the sample and with low coefficient of variation. In the 3D surface plot, smaller density fluctuations were observed, with high density peaks in red, which may be associated with the fibrous zones and marginal parenchyma that delimits the growth layers.

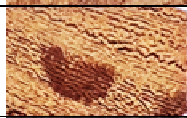
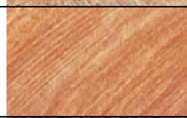
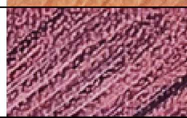
In general, the wood of the species used in this study is distinguished by its high apparent density, which could provide remarkable physical and mechanical properties, such as high resistance to compression, bending, impact, and wear, as well as potential natural durability against biological agents, making it highly valued in the industrial wood sector. These characteristics make these woods candidates for use in structural applications, including high-traffic flooring, bridges, long-lasting furniture, and elements exposed to weathering. However, the same density that ensures its technological advantages also imposes limitations on the industry, increasing energy consumption during cutting and drilling, prolonging drying time, and restricting its suitability for products requiring greater workability.

As exceptions, the woods of *Plathymenia foliolosa* (vinhático) and *Hymenolobium petraeum* (angelim-pedra) stand out due to their intermediate density, which provides a balance between mechanical strength and workability. Timber with this density usually exhibits physical and mechanical properties suitable for compression, bending, and impact resistance, as well as moderate natural durability against fungi and woodboring insects. This combination of properties may make their use suitable for medium-performance structural applications, including light civil construction, flooring, furniture, and components subjected to moderate stress. However, despite being more manageable compared to high-density species, limitations still exist, particularly regarding relative mechanical strength, requiring careful structural design and appropriate determination of industrial applications.

Colorimetric characterization of native woods

The color parameters using the CIELAB space are presented in Table 3, as well as an image of the analysed sample. It is possible to observe the variations in color between the studied woods.

Table 3: Colorimetric test of Brazilian native woods.

Species	L*	a*	b*	C*	H	Image of the sample
Bowdichia spp.	$35,9 \pm 1,0^{b}$	$7,7 \pm 0,2^{cd}$	$8,6 \pm 0,2^{c}$	$11,6 \pm 0,2^{c}$	$48,2 \pm 1,1^{de}$	
D. brasiliensis	$27,5 \pm 1,4^{cd}$	$2,3 \pm 0,6^{e}$	$1,8 \pm 0,6^{e}$	$2,9 \pm 0,9^{e}$	$37,6 \pm 2,2^{fg}$	
Hymenaea spp.	$36,9 \pm 0,9^{b}$	$9,7 \pm 0,4^{f}$	$11,1 \pm 0,7^{abc}$	$14,7 \pm 0,8^{ab}$	$48,8 \pm 1,4^{cde}$	
H. petraeum	$46,7 \pm 1,5^{a}$	$9,4 \pm 0,8^{b}$	$13,6 \pm 2,1^{a}$	$16,5 \pm 2,2^{a}$	$55,2 \pm 2,2^{bc}$	
M. brauna	$25,7 \pm 0,4^{d}$	$1,4 \pm 0,2^{bc}$	$1,1 \pm 0,2^{e}$	$1,8 \pm 0,3^{e}$	$36,2 \pm 1,8^{g}$	
M. hostilis	$44,9 \pm 1,4^{a}$	$7,8 \pm 1,0^{f}$	$10,3 \pm 1,4^{bc}$	$12,9 \pm 1,7^{bc}$	$52,6 \pm 0,4^{cd}$	
Myrocarpus spp.	$37,5 \pm 2,7^{b}$	$12,3 \pm 0,3^{cd}$	$11,5 \pm 0,8^{ab}$	$16,8 \pm 0,5^{a}$	$43,1 \pm 2,2^{ef}$	
Peltogyne spp.	$34,1 \pm 1,5^{b}$	$6,4 \pm 0,6^{a}$	$-0,2 \pm 0,1^{e}$	$6,4 \pm 0,6^{d}$	$358,2 \pm 1,3^{a}$	
P. foliolosa	$37,4 \pm 0,8^{b}$	$7,4 \pm 0,2^{d}$	$13,4 \pm 0,3^{a}$	$15,3 \pm 0,4^{ab}$	$61,3 \pm 0,3^{b}$	
Tabebuia spp.	$29,8 \pm 0,8^{c}$	$3,3 \pm 0,9^{e}$	$5,7 \pm 0,5^{d}$	$6,6 \pm 0,9^{d}$	$60,2 \pm 5,5^{b}$	

L* = lightness; a* = red/green coordinate (+a indicates red and –a indicates green); b* = yellow/blue coordinate (+b indicates yellow and –b indicates blue); C* = chroma; H = hue.
Means followed by different letters in the same column are significantly different ($p < 0,05$) by the Tukey Test.

The lightness parameter (L) is expressed by smaller values close to black (0) and higher values close to white (100). The wood of *M. brauna* is the darkest, but the woods of *D. brasiliensis* and *Tabebuia* spp. also stand out. The values found in the literature for *Tabebuia serratifolia* were (L* 49,37; a* 9,14; b* 23,26; C* 24,90) (Romagnoli *et al.* 2013). The woods of *H. petraeum* and *M. hostilis* were lighter, with values for *H. petraeum* similar to those found by Santos *et al.* (2021) (L*44,12; a*11,82; b*16,34; C* 20,2; h 53,89). The wood *Myrocarpus* spp. presented the greatest deviation, being characteristic of the species due to the alternation of lighter and darker colors in the wood, as observed in Table 3.

For a* (red/green coordinate) positive values were observed in all woods, belonging to the red axis. For b* (yellow/blue coordinate), the values of most species were positive and are located on the yellow axis, except for *Peltogyne* spp. wood, since this wood has a purple color. Other color studies of the species *Peltogyne lecointei*, however, found positive values on this axis (L* 55,67; a* 12,10; b* 5,89) (Almeida *et al.* 2021).

The chroma values (C*) represent the distance from the central axis and the colors with the highest saturation, with the highest values observed in *Myrocarpus* spp., *H. petraeum*, *P. foliolosa* and *Hymenaea* spp. The lowest C* value was observed in *M. brauna* and *D. brasiliensis* woods, with a characteristic dark color. Among the values found in the literature for these woods, Silva *et al.* (2015) studied *Myrocarpus* spp. (L* 48,44; a* 8,78; b* 16,22) and two species of the genus *Hymenaea* were studied by Costa *et al.* (2011) (L* 50,12; a* 13,63; b* 19,02; C* 23,41; h 54,38) and Santos *et al.* 2021 (L* 42,31; a* 9,93; b* 14,72; C* 17,89; h 54,79).

The angle between the axes represents the hue (h). Most values are between 0 and 90, which characterizes the quadrant between the red and yellow axes. The exception is wood from *Peltogyne* spp. with hue value in the quadrant between blue and red.

Conclusions

The results found for apparent density using the X-ray densitometry technique showed high density for these species, with means varying from 550 kg/m^3 and 1000 kg/m^3, corroborating the apparent density values of native woods reported in the literature. In addition, grayscale and rainbow scale X-ray images made it possible to study the variation in density, identifying regions of higher and lower density in the wood. The colorimetric characterization determined the color of the timber based on the parameters of the CIELAB color system. As previously described, colorimetry is not a technique used to identify species due to the different parameters that influence the natural color of the wood. However, this analysis can be useful to define better quality and consumer preference woods by the furniture and lumber industries. The detailed characterization of density and color of native timber contributes to overcoming limitations in their industrial use, allowing the selection of species and batches with properties suitable for specific applications, thereby increasing efficiency and sustainability in the forest production chain. For the timber and furniture industries, this information enables more precise decisions regarding processing, classification, and allocation of the final product, enhancing the economic value of the species. However, this study presents limitations, including the analysis being restricted to individual samples, which prevents robust statistical analysis, and the influence of environmental factors on color and density, which were not fully controlled. Future research should expand the number of samples and include intraspecific variability and environmental conditions.

Authors contributions

C.C.N.M.: Conceptualization, methodology, investigation, original draft preparation, writing. L.C.P.: Methodology, investigation, original draft preparation, writing, editing. N.F.L.: Writing, editing, review. R.S.G.C.: Methodology, investigation. L.A.L.: Methodology, investigation. V.R.C.: Methodology, investigation, conceptualization, supervision, review. A.C.O.C.: Supervision, review. A.M.M.L.C.: Supervision, review.

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