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Use of colorimetry for the distinction and classification of 24 species of rosewood and palisander (*Dalbergia* spp.) from Madagascar

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Abstract

Madagascar is among the main source countries of rosewood and palisander, which include several precious timber species belonging to the *Dalbergia* genus. The designation of the names *rosewood* and *palisander* has always been based on wood color, which has historically been assessed subjectively. This research therefore investigates the application of colorimetry to distinguish 24 Malagasy *Dalbergia* species having valuable timbers that are targeted by illegal trade. The color parameters L^* , a^* , b^* , C^* , and h differ significantly across species and wood surfaces, except for *D. normandii*, which displays wood color homogeneity. A strong positive correlation between L^* and b^* indicates that lighter-colored woods tend toward yellow hues. The classification proposed by Camargos and Gonçalves classifies the species into five color categories: reddish-brown (1 species), dark-brown (11 species), purplish-brown (5 species), reddish-black (5 species), and unclassified (2 species). Additionally, a hierarchical clustering analysis divides species into three groups dominated by yellowish, brownish, or reddish tones. By comparing color deviations from *D. louvelii* (reference rosewood), four species, *D. bathiei*, *D. maritima*, *D. normandii*, and *D. occulta*, showed close resemblance, supporting their classification as *rosewoods*. While phenol content does not significantly affect color parameters, luminance L^* tends to decrease as extractive content increases. Overall, colorimetry emerges as a promising, low-cost, and objective tool for distinguishing rosewood and palisander species.

Keywords: Wood colorimetry, wood classification, CIELab, palisander, rosewood, Madagascar

1. Introduction

Dalbergia genus includes 284 accepted species of trees, shrubs, and lianas, mainly found in tropical and subtropical areas (POWO 2026). Among these, woody *Dalbergia* species are particularly prized for their aesthetic and structural attributes. Madagascar hosts a remarkable diversity with 84 *Dalbergia* species, including 58 that qualify as large trees, i.e. those exceeding 20 cm in diameter or 20 m in height and are source of precious wood (Wilding et al. 2023). These trees are frequently trafficked for use in furniture and musical instrument manufacturing, largely exported to markets in China and Singapore. In response, *Dalbergia* species were added to Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) in 2013 to promote their sustainable trade (Mason et al. 2016). A key challenge in implementing CITES is the accurate identification of species. Wood color has traditionally been used to differentiate *Dalbergia* specimens (Normand 1998; Bosser and Rabevohitra 1996), with commercial denominations such as *rosewood* and *palisander* denoting reddish-purple and brownish hues, respectively. Despite belonging to the same genus and sharing similar anatomical structures (Ramanantsialonina et al. 2023), these two categories are subject to different market realities. Rosewood commands significantly higher prices in international illegal traffic compared to palisander (Ratsimbazafy et al. 2016). A few studies have named specific rosewood species (Normand 1988; Bosser and Rabevohitra 2002; Ratsimbazy et al. 2016). However, this practice has been largely subjective and lacks a formal measurement system or database.

To reduce the subjectivity in color assessment, spectrophotometry, a branch of colorimetry, has been used in the literature. Numerous studies have validated its relevance in wood science, as color remains a major wood trait (Gonçalves et al. 2014). Camargos and Gonçalves (2001) developed a reference framework for wood color classification. Silva et al. (2015, 2017) used spectrophotometry in the CIELab color space to characterize native and tropical woods. This method also helps track changes in wood color due to heat treatment (Bourgois et al. 1991; Brischke et al. 2007; Salca et al. 2016; Herrera-Builes et al. 2022), drying techniques (Gonçalves et al. 2014; Konopka et al. 2020), or wood aging (Zanetti et al. 2003; Almeida et al. 2021). Color correlates with both physical (Amorim et al. 2013; Ramanantoandro et al. 2013; Sousa et al. 2019) and chemical characteristics of wood (Klumpers et al. 1993; Kokutse et al. 2006; Moya and Berrocal 2010; Liu et al. 2024) .

Because each species exhibits unique color traits, many researchers have used color coordinates to classify wood. Colorimetry with visible (VIS) spectrometry was largely used to identify, classify and discriminate Brazilian wood species in the literature (Sousa et al. 2019; Santos et al. 2022; Vieira et al. 2022; Reis et al. 2023). Hirata et al (2020) demonstrated that cutting orientation affects color, with cross-sections generally appearing darker and more reddish. They also easily distinguished the darker, reddish, and yellowish cross-section due to a distinct color contrast. Nisgoski et al (2017) successfully distinguished *Eucalyptus* from *Corymbia* using Principal Component Analysis and spectrophotometry. The technique also differentiates *Eucalyptus* from *Pinus* (Krisdianto 2007; Amorim et al. 2013) and helps distinguish three Fabaceae species including *Inga vera*, *Machaerium paraguariense*, and *Muelleria campestris* (Viera et al. 2022) and *Quercus* species (Defoirdt et al. 2012). Therefore, colorimetry holds promise as a low-cost and objective identification method (Sotelo-Montes et al. 2013). Despite its potential, to the best of our knowledge, the application of colorimetry to Malagasy timber species remains significantly limited. The study by Ramanantoandro et al. (2013) represents the only existing reference that has quantitatively explored the aesthetic attributes (color and texture) of Malagasy woods using the CIEL*a*b* color space. However, their research was primarily focused on identifying consumer preferences for furniture in Antananarivo and included a range of 12 different timber species, featuring only two species of the *Dalbergia* genus (*D. baronii* and *D. trichocarpa*). This study did not aim to provide a tool for taxonomical discrimination within the genus. Consequently, there is currently no objective database or comparative study dedicated to distinguishing the vast diversity of Malagasy *Dalbergia* species for conservation and regulatory purposes. Our study addresses this gap by evaluating the extent to which colorimetry can distinguish Malagasy *Dalbergia* species, shifting the focus from aesthetic preference to systematic identification and CITES enforcement.

2. Materials and methods

2.1. Wood blocks sampling

A total of 143 wood block samples (2 cm × 2 cm × 2 cm), representing 24 Malagasy *Dalbergia* species, were collected from 143 individual trees across Madagascar, with one sample collected per tree (Table 1, Fig. 1). Due to the endangered status of these species and their listing under CITES Appendix II, a non-destructive sampling method was used. This necessity for minimal impact explains the small dimensions of the samples, as they were obtained without felling the trees to ensure the continued survival of the individuals in their natural habitat. The selection of these 143 trees was based on the presence of mature individuals in the field with a diameter large enough to provide accessible heartwood. Locating and reaching these individuals represented a significant logistical challenge, requiring extensive fieldwork through difficult terrain in remote and often inaccessible forest areas across the island. Consequently, the sampling was opportunistic, and the frequency per species, ranging from 1 to 20 samples (Table 1), is a direct reflection of their natural occurrence and the geographical constraints encountered during the field missions. Species identification was carried out by taxonomists from Missouri Botanical Garden (MBG Madagascar) and National Museum of Natural History (MNHN France). Each block was prepared by sanding the three wood ligneous planes (transverse RT, tangential LT, and radial LR) using P100 and then P120 grit sandpaper. This step removed machining marks and oxidized surface layers (Vieira et al. 2019).

Table 1 Number of wood blocks according to species

Botanical names	Number of wood blocks
<i>Dalbergia orientalis</i> Bosser & R. Rabev.	20
<i>Dalbergia monticola</i> Bosser & R. Rabev.	19
<i>Dalbergia chlorocarpa</i> R. Vig.	18
<i>Dalbergia greveana</i> Baill.	17
<i>Dalbergia trichocarpa</i> Baker	9
<i>Dalbergia purpurascens</i> Baill.	8
<i>Dalbergia bemarivensis</i> Phillipson & N. Wilding	8
<i>Dalbergia normandii</i> Bosser & R. Rabev.	7
<i>Dalbergia louvelii</i> R. Vig.	6
<i>Dalbergia delphinensis</i> Bosser & R. Rabev.	4
<i>Dalbergia occulta</i> Bosser & R. Rabev.	3
<i>Dalbergia madagascariensis</i> Vatke	3
<i>Dalbergia lemurica</i> Bosser & R. Rabev	3
<i>Dalbergia baronii</i> R. Vig.	3
<i>Dalbergia tsiandalana</i> R. Vig.	2
<i>Dalbergia humbertii</i> R. Vig.	2
<i>Dalbergia maritima</i> R. Vig.	2
<i>Dalbergia davidii</i> Bosser & R. Rabev	2
<i>Dalbergia chapelieri</i> Baill.	2
<i>Dalbergia suaresensis</i> Baill.	1
<i>Dalbergia pervillei</i> Vatke	1
<i>Dalbergia neoperrieri</i> Bosser & R. Rabev	1
<i>Dalbergia manongarivensis</i>	1
<i>Dalbergia bathiei</i> R. Vig.	1

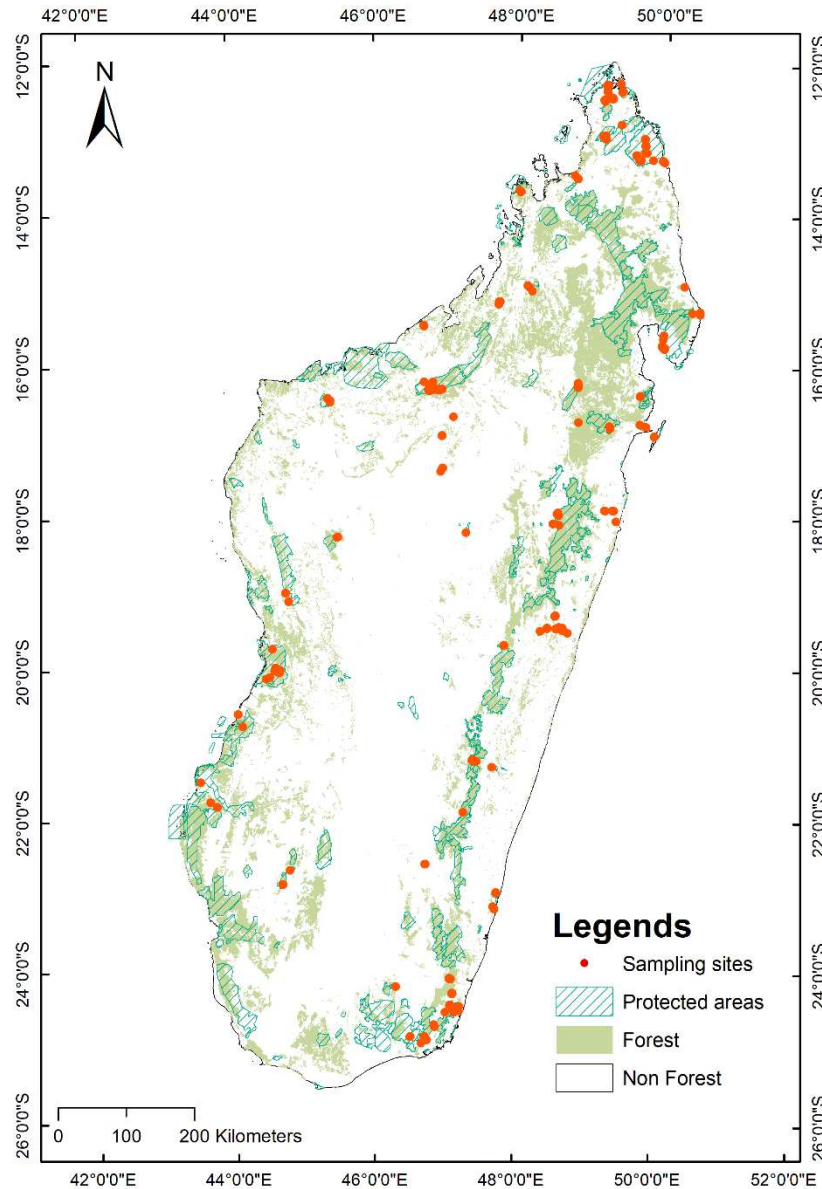


Fig. 1 Wood blocks sampling sites

Source: Geographical and Hydrological Institute of Madagascar (FTM) BD500; Google Earth, 2023

Geographic reference system: GCS International 1924

Realization: Andry Clarel Raobleina

2.2. Colorimetric data measurements

In the CIEL a^*b^* space defined by the International Commission on Illumination (ICE), color attributes such as lightness (L^*), red-green coordinate (a^*), yellow-blue coordinate (b^*), chroma (C^*), and hue angle (h) were measured on the three wood planes of the heartwood portion using a CM-5 spectrophotometer (Konica Minolta, Osaka, Japan). To mitigate the influence of surface texture, the spectrophotometer was configured to specular component included (SCI) and used the standard 10° observer angle, following International Commission on Illumination (ICE) guidelines (Camargos and González 2001). A 3 mm aperture was used for the measurement mask to define the area of the sample for color measurement. The D65 standard illuminant, simulating natural daylight at 6504 K, was used as the light source (Schanda 2015). Calibration of the instrument was performed before each session, using white and black reference tiles. Six measurements distributed across each ligneous plane (transversal, radial, tangential) were recorded, totaling 18 measurements per block. Their average was considered as the representative color value of each plane. Color groups were then assigned based on the reference scale developed by Camargos and González (2001, Fig. 2).

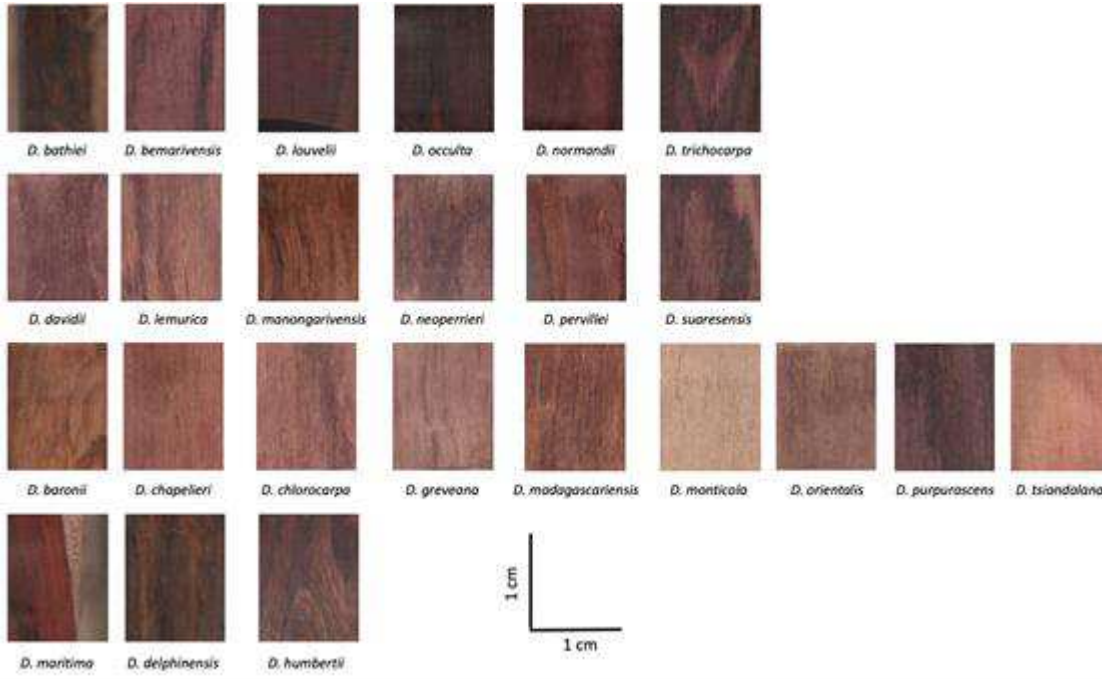


Fig. 2 Heartwood color of the 24 *Dalbergia* species

2.3. Data analysis

2.3.1. Effect of species and wood ligneous planes on color

Data normality was assessed using the Shapiro-Wilk test. A two-way Analysis of Variance (ANOVA) was used to evaluate the interaction effects between species and wood planes on color attributes. Pearson's correlation coefficients (r) or Spearman (ρ) in case of non-normal data, were calculated to determine relationships among color parameters. All tests were conducted using R software v.4.3.2 (R Core Team 2023), with statistical significance set at a 5%.

2.3.2. Species classification by color parameters

The classification process consisted of three stages. Species were first grouped using Camargos and Gonalez's table (2001) based on the average color measurements from all three planes. Color differences (ΔE^*ab) were then calculated using the formula defined by ICE (Robertson 1977), which quantifies perceptible differences in the CIEL*a*b space:

$$\Delta E^*_{ab} = \sqrt{(L^*_S - L^*_R)^2 + (a^*_S - a^*_R)^2 + (b^*_S - b^*_R)^2} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

Where:

L^*_S, a^*_S, b^*_S : value of the colorimetric coordinates of the tested sample S

L^*_R, a^*_R, b^*_R : value of the reference colorimetric coordinates R

ΔL^* : Difference in lightness between S and R

Δa^* : Difference in the value of a^* between S and R

Δb^* : Difference in the value of b^* between S and R

This metric indicates the shortest color distance between a tested sample (S) and the reference sample (R). References used were *D. louvelii* which is known to be classified among rosewood species (Du puy 2002; Normand 1988) and *D. chlorocarpa*, which is categorized among Madagascar palisander. ΔE^*ab values were interpreted using the scale as defined by Bieske (2007, Table 2). Species with $\Delta E < 4$ compared to these references were grouped accordingly.

Table 2 Color difference interpretation scale (Bieske 2007)

ΔE	Color difference
------------	------------------

0.0 - 0.5	No or almost no color difference
0.5 - 1.0	The difference can be noticeable to a trained eye
1.0 - 2.0	The color difference is barely noticeable
2.0 - 4.0	The color difference is certainly observed
4.0 - 5.0	The color difference is significant
>5.0	The difference is evaluated as another color

2.3.3. Hierarchical ascending clustering (HAC) based on color metrics

The Hierarchical Ascending Clustering analysis (HAC) was performed on R v.4.3.2 software (R Core Team 2023) with the *stats* (R Core Team 2023) and *factoextra* (Kassambra and Mundt, 2020) packages to group species with similar color ranges. For each species, measurements from different samples were averaged to obtain species-level values for each colorimetric parameter and for each wood plane. For each wood plane, a Euclidean distance matrix was first computed based on the averaged species-level colorimetric data. Hierarchical clustering was then conducted using Ward's method (Ward.D2) based on this dissimilarity matrix (R Core Team 2023). Observations with values too distant from their class centroid were removed to ensure cluster reliability.

2.3.4. Effect of extractives content on color

To investigate the relationship between heartwood chemistry and coloration, data regarding extractive and phenolic contents for 23 of the 24 species studied were sourced from the previous analyses conducted by Razafimahatratra et al. (2019). These chemical parameters were cross-referenced with the colorimetric data obtained in the present study. Correlation was evaluated using Pearson or Spearman correlation coefficient, based on data normality. A simple linear regression was applied to variables with statistically significant correlation. R software and the stats package v4.1.2 (R Core Team 2023) were used for these computations.

3. Results and discussion

3.1. Effect of species and wood planes on color and relationship between colorimetric attributes

3.1.1. Species and planes effects on wood color

For the 24 *Dalbergia* species, luminance (L^*) ranges from 28.08 to 58.43, whereas a^* and b^* range respectively from 3.82 to 19.93 and 4.78 to 21.35. Saturation (C^*) ranges from 7.79 to 27.87, and hue angle (h) ranges between 24.56 and 60.60 (Table 5). Among these parameters, h shows the least variation across species with, a coefficient of variation (CV) of 17.66–19.91%, while b^* exhibits the most (CV = 28.32–35.96%). Across all species, heartwood is generally dark ($L^* < 56$), with the exception of *D. tsiandalana*, which shows $L^* > 56$ on both radial and tangential planes. Transverse planes tend to have lower luminance L^* . The coordinates a^* and b^* are consistently positive across all planes. For most species, a^* is usually higher on the radial face, with an average value of 12.93 ± 3.19 , except for *D. maritima*, *D. suaresensis*, and *D. tsiandalana*, where the highest value is observed on the tangential plane. For b^* , the highest or lowest values vary by species. C^* is typically higher on the radial plane for most species (18.51 ± 4.80), compared to the tangential (17.18 ± 4.86) and transverse planes (13.66 ± 3.87), except for *D. bathiei*, *D. chapelieri*, *D. maritima*, *D. suaresensis* and *D. tsiandalana*. Our results are consistent with those of Sousa et al (2019) and Burguer (1991), who found that the radial plane is much brighter than the other two surfaces due to the effect of horizontal ray bands. Other authors have also found that chemical compounds in the wood are concentrated in the ray parenchyma cells, which explains the greater brightness and slight yellowish hue observed on the radial surface (Mottonen and Karki 2008; Luostarinen and Möttönen 2009). According to Silva et al (2015), the radial surface is lighter due to a larger exposed surface area of the parenchyma, the presence of larger rays, the presence of reserve substances in the parenchyma, and the closer proximity between the radial cells.

ANOVA results (Table 3) reveal that the SPECIES $\times$ PLANE interaction has no significant influence on the colorimetric coordinates. Species have however a significant effect ($p < 0.05$) on all colorimetric variables. For the colorimetric coordinates, significant differences were also observed for almost all species across the wood

ligneous plane for the a^* coordinate (except *D. maritima* and *D. normandii*) the b^* coordinate (except *D. baronii*, *D. delphinensis*, and *D. normandii*) and the saturation C^* (except *D. baronii*, *D. maritima*, and *D. normandii*). *D. normandii* is the only species showing no significant colorimetric variation across all the ligneous planes (Table 3). Significant differences of wood color were also observed between wood ligneous planes, for L^* , a^* , b^* , and C^* , whereas no significant difference was found for h . Pairwise comparisons show significant L^* differences between at least two wood ligneous planes for nearly all species, except for *D. baronii*, *D. bathiei*, *D. normandii*, and *D. trichocarpa*.

Table 3 ANOVA results for species and ligneous plane effects on colorimetric coordinates

Factors	Statistical parameters	$L^*(\log 10)$	$a^*(\log 10)$	b^*	C^*	h
Species	F-statistic	32.01	13.69	13.43	13.68	10.57
	p-value	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Ligneous planes	F-statistic	11.35	27.99	11.54	26.21	0.52
	p-value	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.58

3.1.2. Relationship between colorimetric parameters

Strong positive correlations, especially between L^* and b^* are observed ($r \approx 0.8$, Table 4), indicating that lighter woods are more yellow. L^* is also correlated with h , suggesting that increased luminance shifts chromatic position toward the yellow axis. *D. monticola*, which has the highest L^* on the transverse plane (49.41), also has a high hue angle ($h = 54.76$), close to the yellow axis. The b^* coordinate shows a strong relationship with both C^* ($r = 0.9$) and h ($r = 0.8$, Table 4), implying that yellowish surfaces tend to be more saturated and vibrant ($h > 45$). Species with low b^* , such as *D. normandii* and *D. louvelii*, show lower saturation and hue angles, giving their wood a redder and duller tone. A positive correlation between the luminance L^* and the coordinate C^* is particularly observed on the tangential plane ($r = 0.76$, Table 4), indicating that species with light luminance tend to be more vivid due to high saturation. A low luminance of the wood face is however associated with a low saturation, as observed in *D. normandii* ($L^* = 29.23$, $C^* = 11.06$) and *D. tsiandalana* ($L^* = 57.77$, $C^* = 27.87$). A comparison with the colorimetric data from Ramananantoandro et al. (2013) shows differences for *D. trichocarpa*. Ramananantoandro et al. (2013) reported a relatively light, reddish, and yellowish wood ($L^* = 51.92$; $a^* = 11.91$, $b^* = 16.91$) while samples used in this study were significantly darker and less red, and duller ($L^* = 35.17$, $a^* = 7.99$, $b^* = 5.92$). The results for *D. baronii* are however more nuanced. The chromaticity coordinates are relatively similar between the two studies, with our values ($a^* = 10.56$; $b^* = 16.05$) being very close to those reported in Ramananantoandro (2013) ($a^* = 10.21$; $b^* = 17.38$). However, there is a remaining difference in luminance, as our samples are darker ($L^* = 41.73$ vs. $L^* = 50.42$). These variations likely come from differences in the age of the wood blocks, natural intra-specific variability, or the geographic origin of the trees across Madagascar. These variations highlight the importance of developing a database that includes multiple samples from different geographic regions to consider the exhaustive range of color variation within these species.

Table 4 Correlation matrix between colorimetric parameters. * indicates statistical significance at the 0.05 level ($p < 0.05$).

Colorimetric parameters	L^*	a^*	b^*	c^*	h
Tangential plane (LT)					
L^*	1				
a^*	0.219*	1			
b^*	0.837*	0.305*	1		
c^*	0.765*	0.660*	0.912*	1	
h	0.709*	-0.243*	0.817*	0.533*	1
Transversal plane (RT)					
L^*	1				
a^*	0.184*	1			

b*	0.793*	0.364*	1		
c*	0.696*	0.694*	0.919*	1	
h	0.720*	-0.142*	0.835*	0.574*	1
Radial plane (RT)					
L*	1				
a*	0.146*	1			
b*	0.807*	0.285*	1		
c*	0.689*	0.676*	0.895*	1	
h	0.738*	-0.260*	0.822*	0.505*	1

3.2. Classification of the 24 *Dalbergia* species

3.2.1. Classification based on the color table of Camargos and Gonçalves (2001)

Based on the average values of the color parameters of the three wood planes, the 24 *Dalbergia* species can be classified into four groups according to the color table of Camargos and Gonçalves (2001) (Table 5). The first group, characterized by a reddish-brown colored wood, includes only *D. tsiandalana*. The high values of L^* , a^* and b^* coordinates contribute to the formation of this color, with a lighter effect of the a^* parameter. In the first quadrant of chromaticity, this group is positioned right on the line that divides the first quadrant into two equal parts. The second group, with a dark brown colored wood, includes *D. baronii*, *D. chapelieri*, *D. chlorocarpa*, *D. greveana*, *D. lemurica*, *D. madagascariensis*, *D. manongarivensis*, *D. monticola*, *D. orientalis*, *D. pervillei*, and *D. purpurascens*. This group shows a prevalence of the yellow pigment b^* over the red pigment a^* . The wood of this group is more yellowish than that of the previous group, with a slight reddish hue. In the chromaticity plane (a^* ; b^*), these species are located closer to the yellow axis. The third group, with a purplish-brown wood color, includes *D. bemarivensis*, *D. delphinensis*, *D. humbertii*, *D. maritima*, and *D. suaresensis*. This group is characterized by a much more pronounced influence of the a^* parameter than b^* , resulting in a redder wood color. The luminance L^* for this group is considerably lower than that of the previous two groups. These parameters give the wood a fairly dark and purplish color. The last group includes species with lower values of the chromatic coordinates a^* and b^* , resulting in low saturation C^* , which, combined with the minimum value of L^* for all species, produces a reddish-black color. This group includes *D. bathiei*, *D. louvelii*, *D. normandii*, *D. occultat*, and *D. trichocarpa*. It can be observed that the wood of species in the first two groups exhibits a light yellowish color (dominant contribution of b^* and high L^*), while the wood of species in the last two groups has a dark reddish color (dominant contribution of a^* and low L^*).

Table 5 Classification of the 24 *Dalbergia* species following Camargos and Gonçalves (2001) color table on the tangential plane

Group	Species	Colorimetric values					Wood color
		L^*	a^*	b^*	c^*	h	
1	<i>D. tsiandalana</i>	54.7	17.95	18.55	25.93	45.71	Reddish-brown
	<i>D. baronii</i>	41.73	10.56	16.05	19.29	55.53	
	<i>D. chapelieri</i>	47.45	14.71	18.74	23.91	51.88	
	<i>D. chlorocarpa</i>	46.53	11.73	13.28	18.01	46.96	
	<i>D. greveana</i>	49.71	11.42	12.06	17.12	45.05	
	<i>D. lemurica</i>	46.58	12.93	11.57	17.46	40.87	
2	<i>D. madagascariensis</i>	43.34	11.72	16.27	20.16	52.82	Dark brown
	<i>D. manongarivensis</i>	36.19	11.64	14.14	18.32	50.13	
	<i>D. monticola</i>	52.21	9.93	14.96	18.22	55.1	
	<i>D. orientalis</i>	46.74	9.34	13.23	16.35	53.01	
	<i>D. pervillei</i>	41.1	17.46	14.66	22.8	40.02	
	<i>D. purpurascens</i>	50.36	9.61	13.14	16.43	52.94	

3	<i>D. bemarivensis</i>	40.56	8.66	8.03	12.28	40.37	Purplish-brown
	<i>D. delphinensis</i>	35.65	9.64	11.84	15.4	48.25	
	<i>D. humbertii</i>	37.9	12.77	11.09	16.96	40.69	
	<i>D. maritima</i>	32.53	12.31	8.63	15.05	34.84	
	<i>D. suaresensis</i>	42.89	11.92	9.92	15.59	38.65	
4	<i>D. bathiei</i>	28.8	5.51	7.32	9.24	52.89	Reddish-black
	<i>D. louvelii</i>	29.85	9.8	7.07	12.13	36.62	
	<i>D. normandii</i>	28.89	10	5.8	11.61	31.93	
	<i>D. occulta</i>	30.52	8.45	6.36	10.62	37.67	
	<i>D. trichocarpa</i>	35.17	7.99	5.92	10.02	35.71	
Unidentified	<i>D. davidii</i>	45.67	14.72	7.66	16.68	27.21	NA
	<i>D. neoperrieri</i>	47.95	11.65	9.83	15.26	40.03	

NA: The corresponding color according to the Camargos and González table is unavailable

3.2.2. Classification according to the relative difference in wood color from that of reference species

The L^* - C^* diagrams (Fig. 3) reveal significant color variation across the three wood planes, with two distinct groups. One group has lower L^* and C^* values (duller wood color), while the other features higher L^* and C^* (brighter and lighter color). The two reference species *D. louvelii* (rosewood) and *D. chlorocarpa* (palisander) are always classified respectively in the first and second group on any woody plane on any diagram. The first group (rosewood), includes four species (*D. bathiei*, *D. maritima*, *D. normandii*, *D. occulta*) with wood color close to that of *D. louvelii*, especially on transversal and tangential planes (ΔE_{RT} average of 3.07 ± 1.08 and ΔE_{LT} average of 3.07 ± 3.28 , Table 6). The wood color of *D. normandii* and *D. occulta* are the most similar to that of *D. louvelii* based on the radial surface, with a $\Delta E_{RT} \leq 1.40$. The second group includes seven species (*D. greveana*, *D. lemurica*, *D. madagascariensis*, *D. neoperrieri*, *D. orientalis*, *D. purpurascens*, and *D. suaresensis*) with wood color close to that of *D. chlorocarpa*, especially on the tangential plane (ΔE_{LT} average of 3.89 ± 2.01 , Table 6). The wood color difference between *D. suaresensis* and *D. chlorocarpa* is the lowest on this surface, with a $\Delta E_{LT} \leq 1.64$. The eleven remaining species showed no close match to either reference, suggesting distinct coloration.

Even if it was possible to group some species into distinct groups using ΔE_{ab} and the chromacity diagrams, it appears that many species remain unclassified. This suggests that a suitable classification of the *Dalbergia* species requires strictly more than two groups, as suggested by the classification based on the table of Camargos and González (2001), which grouped these species into four groups. The wood color of species in the fourth group is, however, indeterminate according to the table by Camargos and González (2001).

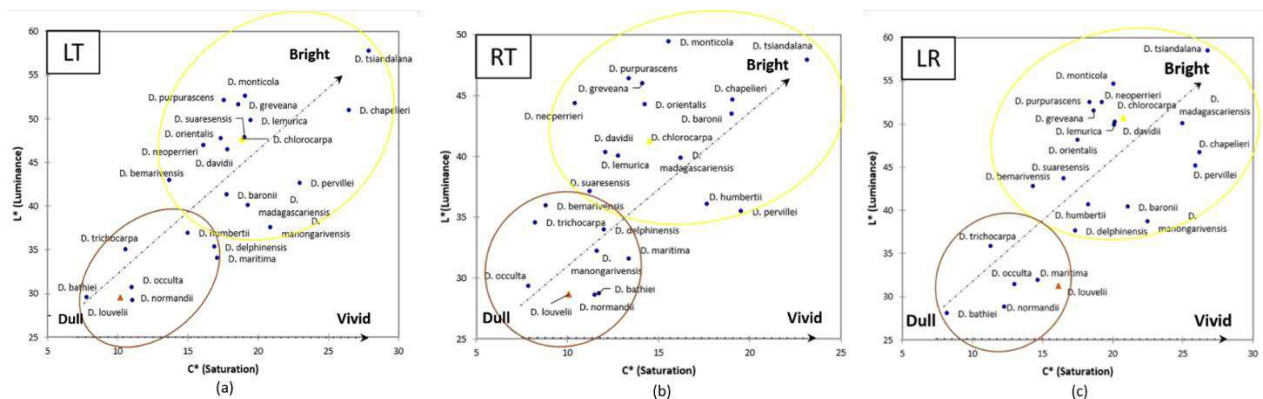


Fig. 3 Chromaticity diagram of species along the tangential (a), transversal (b) and radial (c) plane.

Table 6 ΔE values comparing each species to reference *D. louvelii* (rosewood) and *D. chlorocarpa* (palisander)

ΔE of the 24 species compared to <i>D. louvelii</i>				ΔE of the 24 species compared to <i>D. chlorocarpa</i>			
Species	ΔE_{LT}	ΔE_{RT}	ΔE_{LR}	Species	ΔE_{LT}	ΔE_{RT}	ΔE_{LR}

<i>D. baronii</i>	14.78	17.97	12.19	<i>D. baronii</i>	6.89	6.27	10.43
<i>D. bathiei</i>	4.49	3.39	8.78	<i>D. bathiei</i>	21.19	12.86	25.71
<i>D. bemarivensis</i>	13.77	7.44	11.92	<i>D. bemarivensis</i>	7.31	7.88	10.46
<i>D. chapelieri</i>	27.34	18.68	19.11	<i>D. chapelieri</i>	8.75	6.18	6.97
<i>D. chlorocarpa</i>	20.15	13.38	20.43	<i>D. chlorocarpa</i>	0.00	0.00	0.00
<i>D. davidii</i>	18.62	12.12	19.39	<i>D. davidii</i>	7.27	5.66	6.67
<i>D. delphinensis</i>	9.41	6.11	7.99	<i>D. delphinensis</i>	12.44	7.72	13.45
<i>D. greveana</i>	23.53	17.74	20.66	<i>D. greveana</i>	4.00	4.78	2.63
<i>D. humbertii</i>	8.78	10.7	9.74	<i>D. humbertii</i>	11.65	6.21	10.84
<i>D. lemurica</i>	22.29	11.68	19.21	<i>D. lemurica</i>	2.67	3.14	2.62
<i>D. louvelii</i>	0.00	0.00	0.00	<i>D. louvelii</i>	20.15	13.38	20.43
<i>D. madagascariensis</i>	14.45	13.12	22.12	<i>D. madagascariensis</i>	7.67	2.81	5.32
<i>D. manongarivensis</i>	13.85	4.32	11.45	<i>D. manongarivensis</i>	10.33	9.4	12.18
<i>D. maritima</i>	8.23	4.46	1.72	<i>D. maritima</i>	14.21	9.97	20.34
<i>D. monticola</i>	25.01	21.73	24.66	<i>D. monticola</i>	5.43	8.57	4.8
<i>D. neoperrieri</i>	18.34	15.67	21.58	<i>D. neoperrieri</i>	3.85	5.07	3.8
<i>D. normandii</i>	1.25	2.09	4.74	<i>D. normandii</i>	20.4	13.43	23.99
<i>D. occulta</i>	1.4	2.34	3.25	<i>D. occulta</i>	18.87	13.62	20.84
<i>D. orientalis</i>	20.00	16.47	17.85	<i>D. orientalis</i>	2.4	3.65	4.23
<i>D. pervillei</i>	18.32	11.68	17.12	<i>D. pervillei</i>	7.42	8.06	8.68
<i>D. purpurascens</i>	24.11	18.31	21.99	<i>D. purpurascens</i>	5.00	5.55	3.05
<i>D. suaresensis</i>	20.38	8.59	12.49	<i>D. suaresensis</i>	1.64	5.94	8.66
<i>D. trichocarpa</i>	5.47	6.19	6.71	<i>D. trichocarpa</i>	15.35	9.21	17.69
<i>D. tsiandalana</i>	33.3	23.26	29.54	<i>D. tsiandalana</i>	13.66	11.06	10.08
Mean	3.84	3.07	4.62	Mean	3.89	4.42	4.33
Sd	3.28	1.08	3.03	Sd	2.01	1.22	2.14
CV (%)	85.47	35.32	65.63	CV (%)	51.74	27.65	49.92
	Species having wood color close to that of <i>D. louvelii</i> at least on one of the three wood ligneous planes				Species having wood color close to that of <i>D. chlorocarpa</i> at least on one of the three wood ligneous planes		

3.2.3. Hierarchical ascending clustering based on colorimetric attributes

The results of the HCA (Fig. 4) show that the 24 *Dalbergia* species can be classified into three groups. However, some species belong to different groups depending on the wood plane, demonstrating color variability across wood planes. Among the 24 studied species, 21 consistently belong to the same group on at least two of the three wood planes. (Figure 6). Based on these 21 species, the first class includes therefore eight species (*D. baronii*, *D. chapelieri*, *D. chlorocarpa*, *D. madagascariensis*, *D. monticola*, *D. orientalis*, *D. purpurascens*, *D. greveana* and *D. tsiandalana*) and is characterized by high luminance L^* ($48 < L^* < 53.2$), stronger saturation C^* , and a hue angle h greater than 45° . The combination of the values of these parameter results to a predominance of yellow coloration (b^*) allowing to classify the species in this class as having yellowish colored wood.

The next class includes four species (*D. davidii*, *D. lemurica*, *D. suaresensis*, and *D. neoperrieri*) whose wood exhibits medium luminance ($40 < L^* < 40.50$), and saturation C^* that is very close to the yellowish class. However, the hue angle for this class is much lower ($35^\circ < h < 38.52^\circ$), resulting a predominance of the red pigment (a^*). The values of the colorimetric parameters of species belonging to this class classify them as having brownish colored wood.

The third class includes nine species (*D. bathiei*, *D. bemarivensis*, *D. louvelii*, *D. maritima*, *D. normandii*, *D. occulta*, *D. trichocarpa*, *D. humbertii* and *D. delphinensis*). This class is different from the two previous ones in terms of luminance which is lower ($31 < L^* < 33.2$) and varies very little between the three wood surfaces. This class has a hue angle close to that of the second class ($35^\circ < h < 36.8^\circ$) and thus exhibits the same pigmentation

characteristic. However, its saturation is much less pronounced ($8.90 < C^* < 11.80$). This class therefore includes species with reddish colored wood, which are much darker than the two previous class, with more saturated color, and higher red pigment

D. louvelii and *D. chlorocarpa* always belong to the reddish and yellowish classes respectively, which correspond to the two groups distinguished in the previous classification based on color difference and the LC chromaticity diagram. Based on the HAC, we meet the previous results, but with third class including brownish colored wood, which can be observed on every wood surface. The species are thus well distributed between groups strictly greater than two. Even though several species remain uncertain between two classes using HAC, its results provide a better clustering of the species compared to the use of color difference and the Camargos and Gonçalves (2001) table, because all samples were classified into three classes.

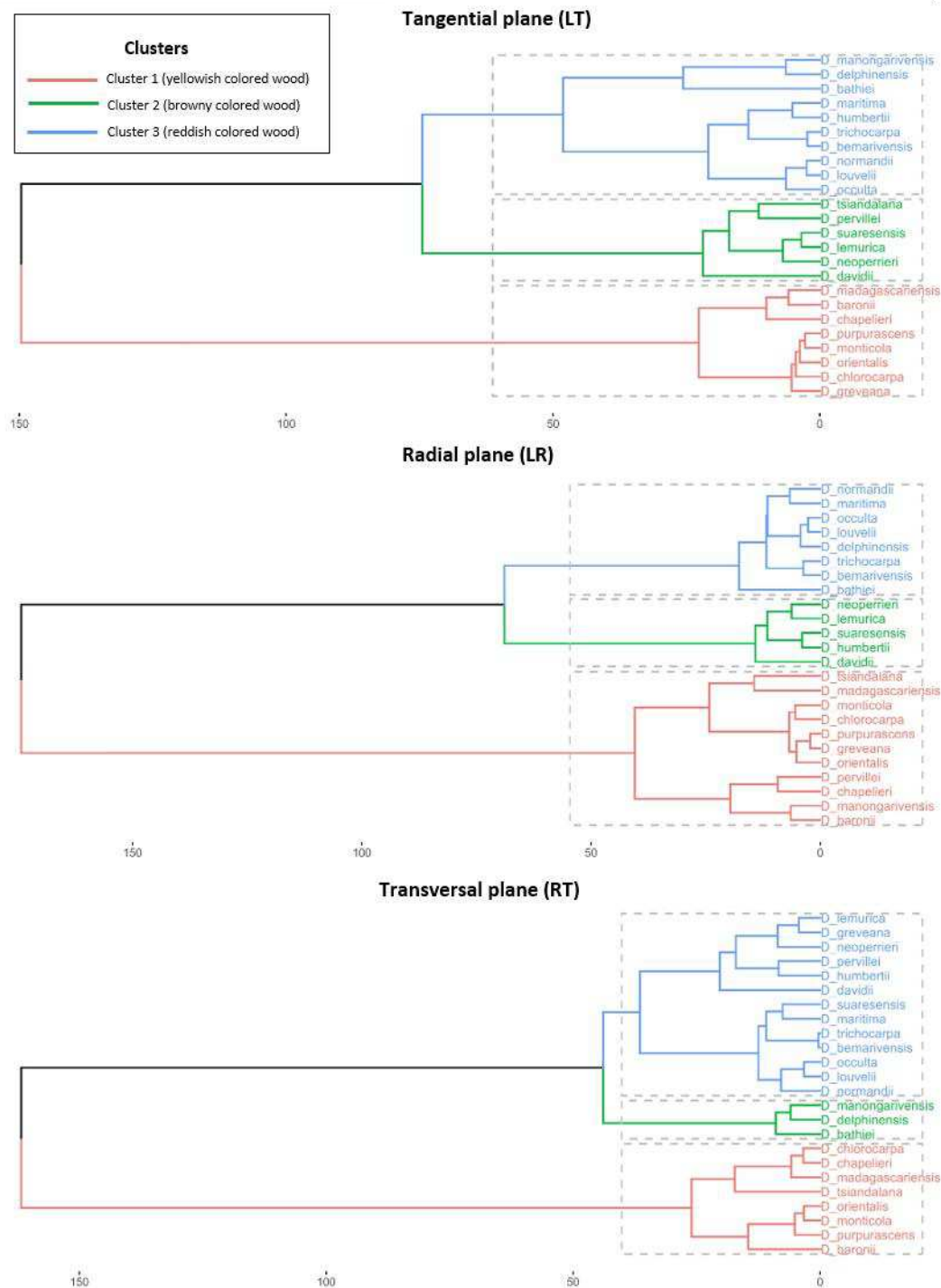


Fig. 4 Hierarchical Ascendant Clustering of the 24 *Dalbergia* species based on wood colorimetric data across

the three wood planes

3.3. Effect of extractives content on wood color

Color variations in malagasy *Dalbergia* likely relate to differences in phytochemical composition, particularly within the heartwood. According to Razafimahatratra et al. (2019), the total extractives content in Malagasy *Dalbergia* wood ranges from 3.13% to 14.24%, with a coefficient of variation of 41.73%. The phenol content varies from 9.82 to 21.48 mg gallic acid equivalent/g of dry weight, with a coefficient of variation of 17.97%. The correlation analysis using colorimetric data and chemical data on common 23 *Dalbergia* species from this study and the study of Razafimahatratra et al (2019) shows that the phenol content does not influence the colorimetric parameters (Table 8). However, the total extractive content shows a negative linear correlation with the luminance L^* of the wood on the tangential ($r = -0.43$, $p < 0.045$) and transverse surface ($r = -0.48$, $p < 0.05$). The luminance L^* thus decreases with increasing extractive content, and the darker the wood, the higher the amount of extractives present in the wood. Approximately 43% of the variation in L^* can be explained by extractives content, supporting the idea that colored extractives are the primary contributors to wood color (Yazaki 2015), and the abundance of these extractives results in a darker wood color (FPL 2010). These findings are consistent with those of Ma et al (2022), Masendra et al (2023) and Ren et al (2025), who found respectively that the heartwood color of *Dalbergia latifolia* and *Dalbergia odorifera* is related to the higher presence of flavonoids. Moya et al. (2014), who observed a similar trend in *Vochysia guatemalensis* Donn Sm. While extractives influence lightness, phenol content alone was not significantly correlated with any of the colorimetric parameters. This suggests that phenols are not solely responsible for heartwood coloration. Different phenolic compound types and concentrations may vary among species. These conclusions are in line with Moya et al (2014), who also reported no correlation between phenol content and color in *Acacia mangium*. However, other authors (Dellus et al. 1997; Burtin et al. 1998; Dunisch and Richter 2010) have linked dark coloration to phenol abundance. A more precise chemical breakdown, potentially using techniques like gas chromatography-mass spectrometry (GC-MS), is needed for a clearer understanding. Indeed, as noted by Yazaki (2015), heartwood color results from extractive compounds containing pigments, which are generally more concentrated in the heartwood than in the sapwood. For the *Dalbergia* genus, these compounds can differ substantially by species (Vasudeva et al. 2009; Saha et al. 2013). Though no phytochemical analyses have yet been performed specifically on Malagasy *Dalbergia* species, other studies attribute yellow hues to pigments like bavin, vicianin I, isoliquiritigenin C-glucoside, and 3,5,7,2',4'-pentahydroxyflavone (Imamura 1980; Robinson and Venkataraman 1929). Light brown or reddish-brown wood may derive its color from catechin and epicatechin (Yazaki, 2015), while red wood may be linked to compounds like Santalin A, B, and AC (Kinjo et al. 1995). Further molecular and chemical studies are essential to pinpoint the extractives responsible for coloration in Malagasy *Dalbergia* heartwood.

Table 8 Correlation coefficients of extractives and phenolic content vs. color parameters. *: significant at $p < 0.05$

	Radial plane				
	L^*	a^*	b^*	C^*	h
Extractives content	-0.43*	-0.16	-0.41	-0.37	-0.24
Phenol content	-0.02	0.33	0.22	0.31	0.09

3.4. Potential of colorimetry for the identification of malagasy *Dalbergia* woods in the precious timber supply chain

This study confirms that colorimetry can effectively group *Dalbergia* species based on heartwood coloration and corresponding L^* , a^* , b^* , C^* , and h values. This makes colorimetry a practical preliminary step in species identification. The use of visible spectra which is also related to wood color, with multivariate statistical methods can be interesting for in-depth species-level discrimination, as shown by Vieira et al (2022), who differentiated three trafficked Brazilian species using colorimetry and VIS spectra. However, the benchtop spectrophotometer used in this study, while precise, may not be ideal for routine or field use. Portable spectrophotometers offer a more viable alternative and should be tested on the same samples analyzed in this study. Studies by Sousa et al (2019) have shown the potential of portable spectrophotometer in accurately assessing color in ten different forest species. Compared to other identification methods, colorimetry can serve as among the rapid and accessible method for initial classification, particularly on sanded surfaces, without

complex sample preparation. Future studies should consider external factors like moisture and aging, which may influence in situ results.

3.5. Valorization of wood color database to support the categorization of malagasy wood species

Historically in Madagascar, trade terms such as *rosewood* and *palisander* have been assigned based on heartwood color of *Dalbergia* (Normand, 1988). However, these color assessments have always been appreciated visually and subjectively, as they can be affected by the observer's perception. Moreover, there are no yet objective databases on the wood color of Malagasy *Dalbergia* species. Rosewood was known as *purplish-red heartwood when freshly cut, turning black rapidly with exposure, with a slightly oily texture, a faint rose-like scent (hence the name) that intensifies when the wood is shaved, and a distinctly bitter and acrid taste* (Normand 1988). Palisander, deriving from *Palissandre* in French-speaking countries refer, to dark or brown tones in the *Dalbergia* genus, less red than *bois de rose*.

According to the literature, species source of rosewood include *Dalbergia louvelii* (Normand 1988; Bosser and Rabevohitra 2002; TRAFFIC 2013, Ratsimbazafy et al. 2016), *D. maritima* (Normand 1988; Bosser and Rabevohitra 2002; Ratsimbazafy et al. 2016), *Dalbergia baronii* (Bosser and Rabevohitra 2002, TRAFFIC 2013), *D. normandii* (Dupuy 2002; Bosser and Rabevohitra 2002, TRAFFIC 2013), *D. purpurascens*, *D. vigueri*, *D. tsiandalana*, *Dalbergia monticola* and *Dalbergia bathiei* (TRAFFIC 2013). These findings are consistent with the results of HAC grouping from the CIEL*a*b* for *D. louvelii*, *D. maritima*, *D. bathiei* and *D. normandii*. These three species fall within the reddish group, which is close to the color of rosewood. However, *D. baronii*, *D. monticola*, *D. purpurascens*, and *D. tsiandalana* although considered rosewood in the referenced literature, exhibited higher L* values and more yellowish hues. These species were grouped into the first HAC cluster (yellowish colored wood), suggesting that it may be more appropriately classified as light palisander. The first and second classes resulting from the hierarchical clustering analysis (Table 7), with wood of yellowish and brownish colors, respectively, are categorized as palisanders, while the third class, with reddish wood includes rosewoods. Six additional species (*D. bathiei*, *D. bemarivensis*, *D. occulta*, *D. trichocarpa*, *D. humbertii* and *D. delphinensis*) were therefore found to be similar to *D. louvelii* in this study, and are therefore likely to be classified as rosewoods as well. The other species identified as rosewood in TRAFFIC document (2013), *D. vigueri*, was not included in this study, as it was not among the analyzed species. It should be included in future research to broaden the dataset, as well as the other species of large trees that are sources of valuable wood and are affected by overlogging and illegal trade.

4. Conclusion

The color of *Dalbergia* heartwood varies significantly depending on both species and wood ligneous planes. Across the 24 species studied, luminance (L^*) ranged from 28.08 to 58.43, with a^* and b^* coordinates ranging respectively from 3.82 to 19.93 and 4.78 to 21.35. Saturation (C^*) values ranged between 7.79 and 27.87, and the hue angle (h) varied from 24.56 to 60.60. Most species exhibited dark-colored wood ($L^* < 56$), with a clear trend showing that lighter woods display more yellowish tones and higher brightness, regardless of the wood planes examined.

The use of colorimetric variables proved effective in classifying the 24 *Dalbergia* species into three distinct color-based classes: the first class features yellow-toned wood with high luminance (L^*), strong saturation (C^*), and dominant b^* values, accompanied by a hue angle exceeding 45° . The second class includes species with brownish heartwood, characterized by moderate luminance, high a^* values, similar saturation to the first group, and a hue angle between 35° and 38.52° . The third class groups species with red-colored wood, marked by low L^* ($31 < L^* < 33.2$), less saturation (C^* between 8.90 and 11.80), and a hue angle in the range of 35° to 36.8° . This work contributes to building a robust database on the wood color of Malagasy *Dalbergia* species, providing a scientific alternative to traditionally subjective assessments. The availability of these knowledge is also important for better valorizing wood properties, as color is one of the aesthetic parameters. These findings can support species identification, especially for enforcement of CITES regulations, by enabling initial classification into color-based groups before using more refined identification methods. Color, as quantified through spectrophotometry, may serve as an initial screening variable to cluster species with similar visual characteristics. This approach lays the groundwork for integrating more complex identification methods, such as those based on visible or near-infrared spectra, within each defined group.

However, this study presents some limitations. Firstly, the number of samples was limited for some species (1 to 3 samples), whereas color is influenced by several factors such as soil, climate, and altitude. Since wood color is closely linked to extractive content, site-dependent variations in tree metabolism could potentially shift colorimetric coordinates within the same species. Furthermore, the intra-plane color variation within the same

plane was not evaluated given the small size of the wood samples. Analyzing larger surface areas and a wider range of provenance could improve insights on spatial and environmental variation in wood color. However, this is logistically challenging, as it would require tree felling, an impractical and often impermissible approach given conservation concerns. To classify wood as rosewood or palisander, chemical analyses of extractive compounds may also be useful.

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