

Article

Colour Stability and Indoor Ageing of Tropical Woods from a 50-Year Xylarium Collection

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Abstract

The diverse colour range of tropical woods is a highly valued commercial feature for specialized interior applications. This study evaluates the long-term indoor colour changes in 98 tropical wood species from Goa (India), Mozambique, and East Timor, stored in a xylarium for 45–50 years. Using the CIEL*a*b* system, surface colour changes ΔL^* , Δa^* , Δb^* and ΔE were quantified by comparing unexposed reference surfaces, obtained through sanding, with the long-term exposed surfaces. Results showed that darkening occurred in 96% of the species, though visual assessments identified colour differences in only 58% of the samples. *Pteleopsis myrtifolia* (Lawson) Engl. and Diels and *Bombax malabaricum* DC. (both light yellowish-brown) exhibited almost no change, while *Cedrela odorata* (light pinkish-brown) and *Pterocarpus antunesii* (moderate orange-brown) showed slight lightening. The initial wood colour was not a significant predictor of the magnitude of chromatic change. Total colour difference (ΔE) was primarily driven by reductions in lightness (ΔL^*), followed by hue change (Δh^*). The chromatic components contributing to ΔE differed according to the initial lightness class: in lighter woods ($L^* > 50$), redness change (Δa^*) showed the strongest chromatic contribution to ΔE , whereas in darker woods ($L^* \leq 50$), yellowness change (Δb^*) was the dominant chromatic contribution. With a mean total ΔE of only 5.76, the overall wood chromatic identity of most species was maintained over time. These findings indicate that indoor ageing of tropical woods is mainly characterized by progressive darkening rather than by drastic chromatic shifts, supporting their long-term aesthetic suitability for premium interior applications over several decades.

Keywords: tropical woods; indoor ageing; CIEL*a*b* system; wood colour change; xylarium; long-term storage

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1. Introduction

Colour is one of the main factors for wood appreciation, and when selecting a timber species for applications such as furniture, cabinet making, panelling or flooring, it is an important characteristic often associated with market value. This is especially true for tropical woods, which display an exceptionally broad range of colours, from almost white to nearly black, with diverse tonalities of yellow, brown, red, violet, or green, and distinctive colour patterns [1]. The colour palette of tropical woods is wide-ranging, although it is generally darker than the yellow-brown colours typical of temperate softwoods and hardwoods. Beyond qualitative descriptions based on visual perception and subjective

appreciation, quantitative and measurable colour values are fundamental for material characterization. This was formalized by the Commission Internationale de l'Éclairage (CIE), which adopted the CIELAB ($L^*a^*b^*$) system in 1976. The basis for CIELAB measurements is the opponent-colour theory, which proposes that the human brain perceives colour as opposing pairs: light vs. dark, red vs. green, and yellow vs. blue. This nonlinear system describes perceptual colour attributes using three coordinates: L^* , lightness (0 for black and 100 for white); a^* , the red-green axis (positive values for red and negative values for green); and b^* , the yellow-blue axis (positive values for yellow and negative values for blue). This system has been widely applied to different materials, and because it represents a perceptually uniform colour space in which the numerical distance between two points (ΔE) correlates with the colour difference perceived by the human eye, it has become the standard approach for analysing and characterising wood colour [2,3]. Its derived parameters (L^* , a^* , b^* , C^* , h , and ΔE) provide complementary information on lightness, chromaticity, and overall colour differences, enabling comprehensive quantitative assessment and comparison among wood colour studies. For example, in temperate species, wood lightness (L^*) has been reported to range from 57 (*Juglans regia* L. and *Populus alba* L.) to 89 (*Acer* sp.), and chroma (C^*) from 22.8 (*Carpinus betulus* L. and *Acer* sp.) to 39.5 (*Robinia pseudoacacia* L.), while the highest redness was reported for *Pyrus communis* L. ($a^* = 16.4$) and the highest yellowness for *Robinia pseudoacacia* ($b^* = 37.4$) [3]. In contrast, in tropical species, *Dalbergia melanoxylon* Guill. and Perr. is characterized by very dark wood ($L^* = 25.9$), *Aleurites moluccana* Willd. by very light wood ($L^* = 85.1$), *Pterocarpus indicus* Willd. by reddish wood ($a^* = 20.3$) and *Morus lactea* Mildbr. by yellowish wood ($b^* = 34.9$) [1]. Wood from species such as *Peltogyne* spp., *Pterocarpus* spp., and *Diospyros* spp. is particularly valued for its distinctive purple, orange and dark tones, respectively. However, most wood descriptions still refer to colour in qualitative terms, mainly in relation to lightness and tonality, and relatively few studies have reported quantitative colour data, particularly for tropical woods [1,4–6].

Colour is a critical economic attribute in high-end wood products, where consumers prioritize visual appeal over mechanical performance (e.g., modulus of elasticity or compressive strength). Darker tones are often perceived as more valuable, partly due to their association with tropical species with traditionally higher market value [7,8]. Therefore, colour modification of temperate woods has gained increasing attention as a strategy to emulate the appearance of darker tropical timbers, using surface coatings [9], photoirradiation [10], thermal treatments and heating processes [11,12].

Wood colour is highly dynamic, shifting significantly when exposed to external environmental factors. Weathering typically induces lightening and a characteristic silvery-grey patina, mostly driven by lignin photodegradation and the subsequent leaching of degradation products [13–15]. The magnitude and direction of wood colour change vary among species, reflecting the unique chemical composition and extractive content of each timber [16,17]. Several studies have examined weathering and ageing processes (e.g., [9,15,18–21]), showing that temperature, radiation (namely, UV from sunlight), contact with air, steam or other agents affect wood and induce surface colour changes mostly related to the reactivity of wood chemical compounds by photolysis, thermolysis, oxidation and hydrolysis, which mostly affect lignin and hemicelluloses. Colour stability has also been linked to other wood properties, such as wood durability [22], and correlations between colour parameters, density and anatomical features of tropical wood species revealed a significant positive correlation between L^* and b^* , a strong negative correlation between wood density and L^* , but no strong correlations with anatomical features [1].

In contrast to outdoor weathering, fewer studies have addressed colour changes under mild indoor conditions, where exposure is limited to natural or artificial light filtered through windows [16,23,24]. Although indoor ageing progresses slowly and is often con-

sidered negligible [25,26], long-term chromatic evolution remains insufficiently documented. Xylaria, as systematic collections of woods from diverse geographic origins, offer unique opportunities for studying long-term ageing and are used as archives for wood knowledge. Beyond their role in wood identification, particularly of CITES endangered tropical species and conservation of historical artefacts [27,28], xylaria provide stable references for wood quality studies and emerging authentication technologies [1,29,30]. While wood specimens are known to exhibit minimal physical degradation even under direct sunlight [31], their wood colour stability has received comparatively little attention.

Given the widespread use of tropical woods in interior applications, understanding their long-term behaviour is essential, as light-induced colour changes are often viewed as a significant aesthetic drawback affecting perceived quality and consumer expectations. Quantifying how the wood colour of different species evolves during prolonged indoor exposure provides critical data for predicting chromatic changes over time. Such knowledge enables more informed material selection for indoor applications, helps manage consumer expectations regarding colour stability, and facilitates a deeper interpretation of the aesthetic shifts that occur across the broad spectrum of tropical timbers.

However, several information gaps remain: despite the commercial relevance of colour stability, systematic data on chromatic changes after decades of indoor exposure are scarce; most existing studies focus on short-term ageing or limited species sets, and it is unclear whether initial colour parameters can predict long-term chromatic variation; the extent to which prolonged indoor exposure affects the aesthetic identity of tropical woods has not been comprehensively evaluated as an essential criterion for high-value interior applications.

To address these gaps, this study investigates the colour variation of a large set of 98 tropical woods stored for 45–50 years in a xylarium environment, comparing the long-term exposed surfaces with unexposed reference surfaces using the CIE-L*a*b* system. The aim is to provide broad characterization of long-term indoor colour change, identify the chromatic components driving these changes, and assess their implications for the aesthetic value of tropical woods in furniture, flooring, cabinetry and other interior applications.

2. Material and Methods

Wood samples of 98 tropical species from Goa (India), Mozambique and East Timor were used in this study: 17 from Goa, India (coded I), 48 from Mozambique (coded M from ULisboa and N from UEM) and 33 from East Timor (coded T), as described in detail in Bessa et al. [32]. The samples were selected from wood collections of the Forest Research Center, School of Agriculture (Portugal LISFLw xylarium), and the Tropical Botanical Garden (Portugal LISJCw xylarium) from the University of Lisbon (ULisboa) in Portugal, and from the University of Eduardo Mondlane (UEM) in Maputo, Mozambique.

The wood samples had overall dimensions of approximately 13 cm × 6 cm × 1 cm and were kept in closed cabinets with occasional indoor displays for observation, i.e., with minimum natural or artificial light exposure. With a few exceptions, the wood samples consisted only of heartwood and presented no wood defects.

Wood colour was measured directly on the longitudinal sections (13 cm × 6 cm, showing a more regular and uniform distribution of early and latewood) of each sample, in heartwood only, using a Minolta CM-3630 spectrophotometer (Minolta Co., Ltd., Osaka, Japan), with diffuse/0° geometry, D65 illuminant and a 10° standard observer. The diameter of the measurement window was 30 mm, and four measurements were taken on each surface, using a grid dividing the sample into four rectangles and measuring in a central position, thereby covering 36% of the surface area. Preliminary tests showed that this measurement intensity was adequate to obtain a representative global colour mean value.

The data showed low within-specimen variability, as indicated by the coefficient of variation obtained from the four colour measurements for each specimen. For unexposed surfaces, the CV ranged from 0.1% to 11.38% for L^* , from 0.13% to 10.12% for a^* and from 0.15%–10.56% for b^* . For the long-term indoor-exposed surfaces, the corresponding values were 0.05%–3.58% for L^* , 0.16%–12.22% for a^* and 0.11%–22.31% for b^* . The latter range does not include the exceptionally high CV of *Dalbergia melanoxylon* due to its very low b^* values. For simplicity, the mean values of the four measurements were reported and analysed by Papercontrol ver. 2.

The CIELAB colour parameters L^* , a^* , and b^* were obtained, and the following parameters were calculated:

- colour saturation or chroma as $C^* = (a^{*2} + b^{*2})^{1/2}$;
- hue angle or hue as $h = \tan^{-1} (b^*/a^*)$;

The colour measurements were made on the wood samples after 45–50 years of indoor storage, corresponding to preserved air exposure in room conditions in a temperate environment with standard ambient temperature and humidity (20 °C and 65%, respectively), and without exposure to direct sun radiation. The samples were kept in the dark in cabinet drawers and only occasionally taken out into the room environment, but without direct sunlight exposure, as is usual in xylaria. The open room exposure of the samples that were taken out of the drawers was estimated to correspond to short periods distributed along the overall storage time.

The initial or reference colour of the wood samples was obtained by sanding the wood surface using a belt sanding machine with P120 and P400 sand belt grits to obtain a freshly prepared and uniform surface. This procedure was necessary to standardize colour measurements and minimize the influence of surface alterations resulting from long-term storage conditions and is frequently used to restore the reference wood colour, i.e., the initial wood colour of wooden artefacts [5].

The difference in the colour parameters (L^* , a^* , b^* , C^* and h) between the final and the initial values measured (respectively on the long-term indoor exposed surface and the reference freshly sanded surface) represents the variation induced by the indoor exposure and was calculated as ΔL^* , Δa^* , Δb^* , ΔC^* and Δh . The total colour variation (or difference) between exposed and unexposed wood surface was calculated as $\Delta E = (\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})^{1/2}$.

The linear relationships among the initial wood colour variables and their variation after long-term indoor exposure were analysed by Pearson's correlation coefficient (r), after verification of the underlying assumptions (linearity, normality, homoscedasticity, and independence of observations). When these assumptions were not fully met, Spearman's rank correlation coefficient (ρ) was additionally applied. The consistency between Pearson and Spearman results confirmed the robustness of the observed relationships; therefore, only Pearson's coefficients are reported. Statistical significance was evaluated at $p < 0.05$, $p < 0.01$ and $p < 0.001$. Principal component analysis (PCA) was used to identify directions of maximal variance after exposure, and a clustering analysis (CA) was performed using the UPGMA method (unweighted pair-group average) to express the relationships existing between taxa based on their pairwise similarities. Statistical analyses were performed using R version 4.3.3 (2024-02-29 ucrt).

3. Results and Discussion

The present study analyses the wood colour of 98 samples from tropical species upon prolonged exposure in indoor conditions and seeks a pattern of the colour variations in relation to their initial wood colour. The diversity in natural colour of these 98 wood samples was high, spanning a large range of colour parameters, e.g., L^* 24.0–84.4, a^* 2.6–20.4,

and b^* 1.8–36.6, as previously reported, thereby confirming the broad colour spectrum of tropical woods [1].

3.1. Wood Colour Variation with Long-Term Indoor Exposure

Exposure to the indoor environment caused variations in all the wood colour parameters, as shown in Table 1. The within-specimen coefficients of variation calculated from the four measurement points were generally low (see Section 2), indicating good repeatability of the colour measurements despite the natural heterogeneity of wood surfaces. After 45–50 years of indoor exposure in the xylarium, the tropical wood specimens showed overall mean values of 51.93 ± 12.89 , 11.35 ± 3.65 and 21.88 ± 6.60 for wood lightness (L^*), redness (a^*) and yellowness (b^*), respectively. Although lightness (L^*) exhibited the highest absolute standard deviation, the coefficient of variation showed that redness (a^*) was proportionally the most variable colour parameter, followed by yellowness (b^*). Lightness therefore displayed the lowest relative variability among the three chromatic components.

Table 1. Wood colour parameters for samples with long-term air exposure in room environment and their variation (ΔL^* , Δa^* , Δb^* and ΔE) in relation to the initial wood colour for 98 tropical wood species.

Code	Species Name	Colour After Long-Term Exposure			Variation in Relation to Initial Colour			
		L^*	a^*	b^*	ΔL^*	Δa^*	Δb^*	ΔE
I1	<i>Acacia catechu</i> Willd.	36.24	18.01	20.30	−10.32	1.40	−1.96	10.60
I2	<i>Aegle marmelos</i> Corrêa	68.92	6.55	24.98	−1.69	0.22	1.05	2.00
I3	<i>Albizia lebbeck</i> Benth.	33.22	10.73	12.57	−7.75	−1.37	−2.38	8.22
I4	<i>Artocarpus integrifolia</i> L.	55.71	16.12	35.39	−6.53	2.66	2.56	7.50
I5	<i>Bombax malabaricum</i> DC.	62.76	7.65	26.13	0.37	1.35	3.03	3.34
I6	<i>Careya arborea</i> Roxb.	50.07	14.65	23.50	−4.10	2.44	2.47	5.37
I7	<i>Dalbergia sissoo</i> Roxb.	31.00	9.19	7.25	−6.01	1.90	−1.09	6.40
I8	<i>Eugenia jambolana</i> Lam.	44.80	11.15	15.94	−8.68	0.79	−0.03	8.72
I9	<i>Ficus indica</i> Roxb.	63.29	4.10	15.81	−2.49	0.68	1.52	3.00
I10	<i>Lagerstroemia parviflora</i> Roxb.	52.25	11.69	19.25	−2.55	0.86	−0.76	2.80
I11	<i>Mangifera indica</i> L.	55.61	6.80	19.26	−4.91	0.33	−0.43	4.94
I12	<i>Polyalthia fragrans</i> Benth. and Hook	71.37	5.56	27.86	−1.58	−0.08	−0.22	1.60
I13	<i>Tectona grandis</i> L.	40.50	11.28	20.01	−6.12	2.52	0.00	6.62
I14	<i>Terminalia bellirica</i> Roxb.	63.71	8.42	27.00	−6.13	1.38	1.23	6.40
I15	<i>Terminalia paniculata</i> Roth	56.97	8.97	33.01	−4.67	1.35	4.25	6.46
I16	<i>Terminalia tomentosa</i> W. et Arn.	47.01	11.35	21.62	−7.84	−0.56	−1.92	8.09
I17	<i>Xylia dolabriformis</i> Benth.	39.57	13.36	17.54	−2.77	0.49	−0.98	2.98
M1	<i>Adina microcephala</i> (del.) Hiern	50.57	13.63	27.79	−10.23	3.42	5.34	12.04
M2	<i>Afrormosia angolensis</i> (Bak.) Harms	40.59	9.04	17.95	−3.76	1.10	−0.15	3.92
M3	<i>Azelia quanzensis</i> Welw.	49.75	18.71	27.38	−6.10	3.10	2.25	7.20
M4	<i>Albizia adianthifolia</i> W. F. Wight	66.93	9.41	36.78	−3.72	2.70	4.32	6.31
M5	<i>Albizia versicolor</i> Welw. ex Oliv.	38.50	11.66	17.15	−4.39	1.17	−0.44	4.56
M6	<i>Amblygonocarpus obtusangulus</i> Harms	36.27	15.46	14.21	−5.11	1.06	−1.00	5.31
M7	<i>Androstachys johnsonii</i> Prain.	54.98	12.04	23.39	−2.53	1.12	1.73	3.26
M8	<i>Bombax rhodognaphalon</i> K. Schum. Ex. Engl.	44.80	16.95	24.34	−6.25	2.02	1.52	6.74
M9	<i>Burkea africana</i> Hook.	34.47	14.59	15.35	−8.46	2.40	−0.22	8.80
M10	<i>Celtis durandii</i> Engl.	71.30	6.16	28.14	−4.33	2.23	5.48	7.33
M11	<i>Celtis kraussiana</i> Bernh.	69.67	7.11	26.14	−4.13	1.20	2.84	5.15
M12	<i>Chlorophora excelsa</i> (<i>Milicia excelsa</i>) (Welw.) Benth. Hook	42.44	13.00	22.26	−6.12	2.15	−0.13	6.49
M13	<i>Colophospermum mopane</i> Kirk.	31.26	13.92	12.47	−6.40	2.19	−0.45	6.78
M14	<i>Combretum imberbe</i> Wawra	55.73	12.12	25.10	−0.21	1.57	1.53	2.20
M15	<i>Cordyla africana</i> Lour.	61.12	11.63	28.35	−3.00	2.14	4.82	6.07
M16	<i>Dalbergia melanoxylon</i> Guill. and Perr.	22.10	3.24	2.54	−3.81	1.38	1.57	4.35
M17	<i>Dialium schlechteri</i> Harms	30.24	10.01	9.88	−4.05	0.03	−1.07	4.19
M18	<i>Diospyros mespiliformis</i> Hochst. ex A. DC.	61.44	10.63	19.03	−0.09	2.70	4.23	5.02
M19	<i>Erythrophleum africanum</i> (Benth.) Harms	36.36	16.21	15.92	−4.36	1.64	−0.23	4.66
M20	<i>Erythrophleum guineense</i> Don	37.56	12.46	15.47	−7.04	1.92	−0.48	7.31
M21	<i>Khaya</i> sp.	37.16	13.56	17.24	−16.09	1.70	−3.86	16.63
M22	<i>Khaya</i> sp.	37.16	13.56	17.24	−16.09	1.70	−3.86	16.63

M23	<i>Millettia stuhlmannii</i> Taub.	30.76	8.99	11.60	−8.95	1.25	−1.73	9.20
M24	<i>Morus lactea</i> Mildbr. (<i>Celtis lactea</i> Sim.)	62.25	10.20	38.31	−5.13	1.43	3.42	6.33
M25	<i>Ostryoderris stuhlmannii</i> Dunn ex Baker f.	64.67	9.58	28.57	−5.78	1.98	1.38	6.26
M26	<i>Piliostigma thonningii</i> (Schumach.) Milne-Red-head	43.35	8.83	15.21	−2.84	0.02	−0.20	2.85
M27	<i>Piptadenia buchananii</i> Bak. (<i>Newtonia buchani</i>)	56.86	14.94	28.73	−9.27	3.58	4.90	11.08
M28	<i>Pteleopsis myrtifolia</i> (Lawson) Engl. and Diels	64.60	7.37	28.01	0.01	0.19	2.99	3.00
M29	<i>Pterocarpus angolensis</i> DC.	47.04	14.50	24.37	−3.22	2.02	3.76	5.35
M30	<i>Ricinodendron rautanenii</i> (Schinz) Radcl-Sm	74.50	4.85	24.68	−0.52	1.36	2.55	2.94
M31	<i>Spirostachys africana</i> Sond.	44.16	10.74	18.33	−0.18	0.01	0.42	0.46
M32	<i>Sterculia quinqueloba</i> (Garcke) K. Schum.	61.39	12.30	30.00	−5.28	1.53	0.58	5.53
M33	<i>Swartzia madagascariensis</i> Desv.	37.60	19.98	17.89	−2.27	0.21	1.15	2.55
T1	<i>Albizia lebbeckioides</i> (DC) Benth.	49.32	12.45	22.69	−6.63	−0.04	−0.80	6.68
T2	<i>Aleurites moluccana</i> Willd.	83.63	3.26	23.42	−1.48	0.04	1.70	2.25
T3	<i>Alstonia scholaris</i> (L.) R. Br.	72.19	6.75	26.69	−0.68	1.22	3.59	3.85
T4	<i>Artocarpus integrifolia</i> L.	56.23	14.58	35.02	−4.65	3.39	1.13	5.86
T5	<i>Bischofia javanica</i> Blume	31.91	10.99	10.13	−6.25	−1.86	−3.71	7.50
T6	<i>Calophyllum inophyllum</i> L.	57.55	9.32	24.28	−5.32	3.41	10.25	12.04
T7	<i>Canarium commune</i> L.	66.42	8.71	21.47	−1.56	−0.26	0.12	1.59
T8	<i>Cassia fistula</i> L.	51.11	15.29	21.61	−6.84	2.86	1.79	7.63
T9	<i>Casuarina junghuhniana</i> Miq.	41.43	13.63	17.21	−1.27	3.60	2.91	4.80
T10	<i>Cedrela toona</i> var. <i>australis</i> Roxb. C. DC.	40.42	16.45	20.66	−3.19	0.86	−0.73	3.38
T11	<i>Decaspermum paniculatum</i> Kurz	54.66	8.64	18.08	−3.31	0.67	0.03	3.38
T12	<i>Elaeocarpus sphaericus</i> K. Schum.	75.17	6.03	22.51	−4.64	1.76	4.42	6.65
T13	<i>Ficus macrophylla</i> Roxb.	69.60	8.49	26.71	−4.02	1.64	0.56	4.38
T14	<i>Ganophyllum falcatum</i> Blume	72.98	9.17	28.25	−3.48	1.24	3.95	5.41
T15	<i>Hibiscus tiliaceus</i> L.	45.07	4.18	9.51	−6.58	−2.23	0.35	6.96
T16	<i>Homalium tomentosum</i> Benth.	58.66	12.30	26.94	−6.79	2.91	5.55	9.24
T17	<i>Intsia bijuga</i> O. K.	41.00	12.33	17.95	−1.79	2.00	1.04	2.88
T18	<i>Macaranga tanarius</i> Muell.	56.37	8.83	19.75	−4.23	0.25	0.60	4.28
T19	<i>Melaleuca leucadendron</i> L.	52.94	12.01	19.07	−6.73	0.76	0.84	6.82
T20	<i>Pometia pinnata</i> Forst.	46.01	15.70	22.18	−5.07	2.01	2.42	5.97
T21	<i>Pterocarpus indicus</i> Willd.	42.48	20.44	22.06	−7.11	0.15	−1.25	7.22
T22	<i>Pterospermum acerifolium</i> Will.	64.62	7.68	17.48	−2.78	0.34	0.81	2.91
T23	<i>Pygeum</i> sp.	65.22	6.86	18.28	−2.77	−0.05	0.87	2.90
T24	<i>Santalum album</i> L.	59.67	10.06	26.55	−0.84	−1.69	−1.77	2.59
T25	<i>Sarcocephalus cordatus</i> Miq.	45.36	17.26	29.71	−10.05	3.49	−2.52	10.93
T26	<i>Schleichera oleosa</i> Miq.	57.21	12.92	21.66	−2.69	1.27	0.67	3.05
T27	<i>Sterculia foetida</i> L.	56.33	11.80	26.11	−6.38	0.86	2.44	6.88
T28	<i>Tamarindus indica</i> L.	29.33	9.89	7.68	−5.88	0.44	−2.25	6.31
T29	<i>Tectona grandis</i> L.	51.17	10.71	25.74	−4.27	1.78	2.54	5.28
T30	<i>Terminalia cattapa</i> L.	49.87	13.79	21.50	−3.07	0.02	0.65	3.14
T31	<i>Thespesia populnea</i> Soland, ex Correa	46.44	11.89	19.61	−0.93	0.04	−0.42	1.02
T32	<i>Timonius rumphii</i> DC.	66.05	7.46	23.51	−6.15	1.48	1.91	6.61
T33	<i>Vitex pubescens</i> Vahl	65.39	7.85	24.22	−4.57	1.35	3.00	5.63
N1	<i>Acacia robusta</i> Burch	60.44	6.81	24.32	−3.87	2.51	4.36	6.35
N2	<i>Amblygonocarpus andongensis</i> (Oliv.) Excell and Torre	34.09	14.50	11.91	−7.15	0.24	−2.49	7.57
N3	<i>Berchemia discolor</i> (Klotzsch) Hemsley	42.65	16.96	21.37	−2.94	0.05	1.01	3.11
N4	<i>Cedrela odorata</i> L.	54.59	12.73	21.10	4.57	−2.36	−2.34	5.65
N5	<i>Cleistanthus schlechteri</i> (Pax) Hutch.	35.53	10.36	12.85	−4.66	−0.04	−1.64	4.94
N6	<i>Combretum zeyheri</i> Sond.	57.12	15.92	27.62	−3.74	1.82	3.19	5.24
N7	<i>Diplorhynchus condylocarpon</i> (Mull. Arg.) Pichon	60.72	11.63	27.95	−4.15	1.62	1.11	4.59
N8	<i>Melaleuca leucadendron</i> (L.) L.	56.01	14.37	25.93	−4.30	1.70	2.59	5.30
N9	<i>Morus mesozygia</i> Stapf	48.56	14.12	26.04	−5.36	0.75	−2.61	6.01
N10	<i>Pterocarpus antunesii</i> (Tab.) Harms	75.51	8.79	34.74	2.48	−1.07	0.30	2.72
N11	<i>Rhodognaphalon schumannianum</i> A. Robyns	56.77	13.69	24.88	−2.15	1.02	0.69	2.48
N12	<i>Schrebera trichoclada</i> Welw	55.29	13.30	24.28	−3.72	0.68	0.25	3.79
N13	<i>Syncarpia glomulifera</i> (Sm.) Wield	44.92	11.73	17.46	−13.20	3.09	0.53	13.57
N14	<i>Syringa vulgaris</i> L.	65.54	12.04	26.11	−1.84	1.06	1.70	2.72
N15	<i>Xylia torreana</i> Brenan	49.22	14.28	21.95	−12.58	0.57	−2.20	12.78

The overall change in wood colour parameters was as follows: lightness (ΔL^*) -4.67 ± 3.33 , redness (Δa^*) 1.18 ± 1.25 , yellowness (Δb^*) 0.96 ± 2.37 , chroma (ΔC^*) 1.46 ± 2.40 , hue (Δh) -1.82 ± 3.10 and total colour variation (ΔE) 5.76 ± 3.05 . Although wood lightness (ΔL^*)

showed moderate relative variability (71%), the chromatic components (Δa^* , Δb^* , ΔC^* and Δh) exhibited substantially higher coefficients of variation (105%, 246%, 164%, and 170%, respectively), indicating that proportional chromatic shifts were more unstable than lightness changes. In contrast, total colour variation (ΔE) displayed the lowest relative variability (53%) among all parameter changes.

This dispersion reflects the natural heterogeneity among tropical wood species. Even if the sampling design prioritized taxonomic coverage over intra-specific replication, therefore not allowing information on within-species wood colour variations, the overall patterns of long-term indoor colour change remain clearly identifiable.

The colour range of the tropical woods after long-term indoor environmental exposure is broad, with the lightest, blackest, reddest, and yellowest woods being from the light yellowish-brown wood of *Aleurites moluccana* (T2), the black wood of *Dalbergia melanoxylon* (M16), the moderate reddish-brown wood of *Pterocarpus indicus* (T21) and the light to pale brown wood of *Morus lactea* (M24), respectively. The minimum chroma (C^*) value was found for *Dalbergia melanoxylon* (M16) wood, and the maximum for *Morus lactea* (M24) wood. The general positioning of the different species regarding their reference wood colour parameters, hue and chromaticity, as described in Bessa et al. [1], was maintained after the indoor exposure.

Visual images of wood grain and colour changes before and after exposure of the wood specimens are given for representative examples in Figure 1. The major colour differences after long-term indoor exposure were found in wood lightness (L^*), which decreased by 8% on average. Almost all of the tropical woods (96% of the total) became darker (L^* decreased) except for the typically light yellowish-brown woods of *Pteleopsis myrtifolia* (M28) and *Bombax malabaricum* (I5), which showed almost no change, and the light pinkish-brown wood of *Cedrela odorata* (N4) and the moderately orange-brown wood of *Pterocarpus antunesii* (N10), which became slightly lighter (L^* increased). On average, wood redness increased by 12%, while wood yellowness increased by 5%, with a red shift (positive Δa^*) observed in 88% of the tropical species and yellowing (positive Δb^*) in 65% of the species. Greater reddening was detected for *Casuarina junghuhniana* (T9), *Piptadenia buchananii* (*Newtonia buchanii*) (M27), and *Sarcocephalus cordatus* (T25) than *Cedrela odorata* (N4) and *Hibiscus tiliaceus* (T15), typically described as light-brown, light yellowish-brown and light pinkish-brown woods. Yellowing was greatest in *Calophyllum inophyllum* (T6), typically described as yellowish-brown wood, in the light brown woods of *Homalium tomentosum* (T16) and *Celtis durandii* (M10), and in the light yellowish-brown wood of *Adina microcephala* (M1) ($\Delta b^* > 5.0$), whereas the lowest values were observed for *Khaya* sp. (M21, M22), typically light pinkish-brown wood, and *Bischofia javanica* (T5), typically reddish-brown wood. After indoor exposure, chroma (C^*) increased by 6% on average, whereas hue decreased by 3%.

The visual assessment of a different colour is possible when $\Delta E > 5$, with only perceptible changes when $1 < \Delta E < 5$, according to the Bieske scale mentioned in [33]. The total colour difference (ΔE) was visually assessed in 58% of the tropical species, and slightly perceptible colour changes ($1 < \Delta E < 3$) were found in 18 species, such as *Polyalthia fragrans* (I12), and in one species the change was not perceptible to the human eye (Figure 1). While the overall colour change mean was considered perceptible ($\Delta E = 5.76$), very high changes ($\Delta E \geq 12$) were only observed in 7 species. The greatest perceptible colour change ($\Delta E = 16.63$) was detected in *Khaya* spp. (M21 and M22), while the lowest colour change ($\Delta E = 0.46$), which was not perceptible, was detected in *Spirostachys africana* (M31). Although a decrease in wood lightness (negative ΔL^*) was observed due to wood indoor ageing, several wood species maintained their chromatic identity after 45–50 years without showing extreme chromatic changes.



Figure 1. Representative examples of wood colour changes between the initial (reference) and long-term indoor exposure surfaces (arrow direction, left to right), illustrating different magnitudes and patterns of chromatic variation among tropical species: (a) the lowest colour change in *Spirostachys africana* (M31) ($\Delta E = 0.46$, $\Delta L^* = -0.18$); (b) the slightly perceptible colour changes in *Polyalthia fragrans* (I12) ($\Delta E = 1.60$, $\Delta L^* = -1.58$); (c) the slightly perceptible colour changes in *Swartzia madagascariensis* (M33) ($\Delta E = 2.55$, $\Delta L^* = -2.27$); (d) minimal colour change in the light yellowish-brown wood of *Bombax malabaricum* (I5) ($\Delta L^* = 0.37$, $\Delta E = 3.34$); (e) darkening of the light brown wood of *Albizia lebbek* (I3) ($\Delta L^* = -7.75$, $\Delta E = 8.22$); (f) yellowing of the light brown wood of *Homalium tomentosum* (T16) ($\Delta b^* = 5.55$, $\Delta E = 9.24$); (g) reddening of the light brown wood of *Piptadenia burchaninii* (*Newtonia burchaninii*) (M27) ($\Delta a^* = 3.58$, $\Delta E = 11.08$); (h) minimal colour and the lowest yellowness in *Bischofia javanica* (T5) ($\Delta E = 6.96$, $\Delta b^* = 0.35$); (i) pronounced colour change in *Hibiscus tiliaceus* (T15) ($\Delta E = 6.96$, $\Delta L^* = -6.58$); (j) naturally reddish wood of *Pterocarpus indicus* (T21) ($\Delta E = 7.22$, $\Delta L^* = -7.11$); (k) colour change in the wood of *Morus lactea* (M24), which exhibited the highest initial yellowness ($\Delta E = 6.33$, $\Delta L^* = -5.13$); (l) the natural within-specimen colour heterogeneity in *Millettia stuhlmannii* (M23) ($\Delta E = 9.20$, $\Delta L^* = -8.95$); (m) marked yellowness in *Adina microcephala* (M1) ($\Delta E = 12.04$, $\Delta b^* = 5.34$); and (n) colour change in *Khaya* spp. (M21) ($\Delta E = 16.63$, $\Delta L^* = -16.09$).

These results confirm the darkening tendency (L^* decrease) for most of the species studied here from Goa (India), Mozambique and East Timor, which is corroborated by other studies in the literature made with woods exposed to light (natural and artificial), air, heat/steam or over time. This effect has been reported especially for temperate species, such as *Picea abies* ($\Delta L^* = -11.3$), *Robinia pseudoacacia* ($\Delta L^* = -10.9$), *Quercus mongolica*, and *Betula dahurica*, due to indoor sunlight/natural irradiation [16,34], and for *Betula* spp., *Quercus robur*, *Picea abies*, and *Pinus sylvestris*, due to artificial light irradiation [23]. For tropical species, similar results were reported due to the indoor light environment [5]. However, these authors refer to the opposite trend, i.e., wood lightening with solar-type light exposure (accelerated photoaging), namely for *Intsia* spp. ($\Delta L^* = 1.1$), *Handroanthus* spp. ($\Delta L^* = 6.3$) and dark woods such as *Pterocarpus soyauxii* ($L^* = 43.82$), *Millettia laurentii* ($L^* = 30.45$) and *Lophira alata* ($L^* = 36.95$) [4,22]. In the present study, only the wood of *Cedrela odorata* (N4) and *Pterocarpus antunesii* (N10) exhibited slight lightening.

Yellowing has already been reported for indoor light environment exposure in 25 tropical species from Brazil [5] as well as for temperate woods under natural irradiation conditions [34] or in *Alnus glutinosa* under simulated indoor sunlight exposure [16]. In contrast, wood reddening tendencies were reported in temperate species, for example in *Robinia pseudoacacia*, while redness decrease was observed in *Prunus avium* and *Pyrus communis* due to indoor sunlight simulation [16].

Wood ageing in an indoor environment is mainly related to room conditions (temperature, humidity, irradiation, and atmosphere) and time, and the main impacts on wood are photooxidation, lignin destruction and photo-yellowing [26,35]. The discolouration process is mostly explained by lignin photodegradation and by the content and composition of extractives, since a low colour change is expected for woods with a high content of polyphenolic extractives [4,24]. Wood darkening is well known for thermally treated woods and is often a desired target [12]. However, the temperatures applied (160–260 °C) are much higher than those prevailing in indoor conditions.

Wood colour variation is also known to be species- and light source-specific (e.g., [9,16,22,23,34]). Other factors, such as wood surface texture, also affect wood discolouration; for example, the colour stability in high-quality tropical woods was greater in woods with smooth, straight textures (e.g., *Millettia laurentii*) and lower in woods with distinct increment zones (e.g., *Pericopsis elata*) [33].

3.2. Relationships Between Wood Colour Parameters and Chromatic Variation

The initial and exposed colour parameters were strongly positively correlated among all the 98 species and within two different lightness classes: darker woods ($L^* \leq 50$, $n = 31$) and lighter woods ($L^* > 50$, $n = 67$) (Figure 2). Despite measurable chromatic changes during long-term indoor exposure, the overall chromatic identity of each wood species was largely maintained: light woods remained light, dark woods remained dark, and woods initially more yellowish or reddish preserved their relative chromaticity after exposure.

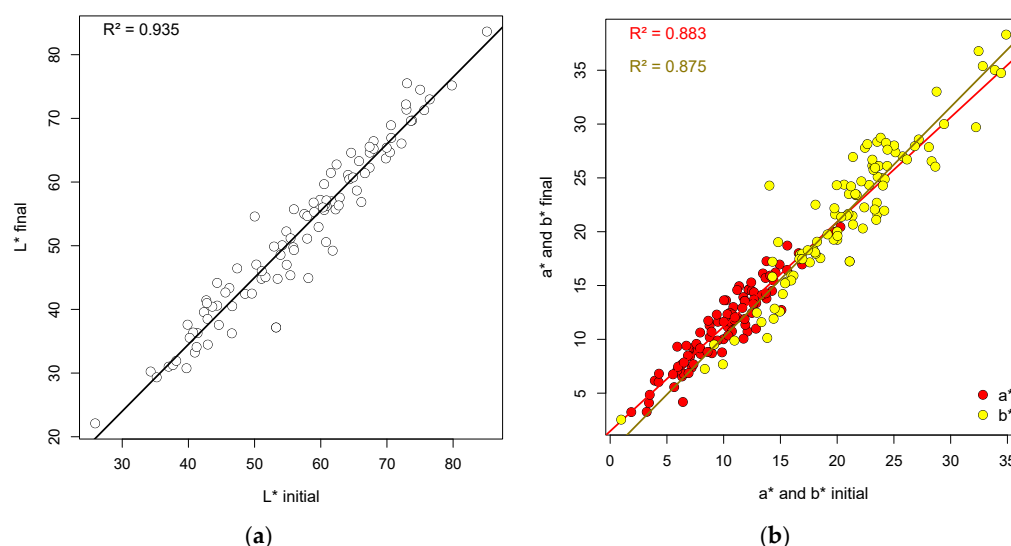


Figure 2. Relationships between initial and exposed (a) wood lightness (L^*) and (b) redness (a^*) and yellowness (b^*) for the 98 tropical species listed in Table 1. Fitted linear regressions and R^2 , respectively: $L^*_{\text{final}} = 1.0495 \times L^*_{\text{initial}} - 7.4743$, $a^*_{\text{final}} = 0.972 \times a^*_{\text{initial}} + 1.468$ and $b^*_{\text{final}} = 1.0682 \times b^*_{\text{initial}} - 0.4633$.

The relationships between the exposed wood colour parameters (final values) and their respective chromatic changes ranged from weak to moderate, indicating that the final colour partly reflects the direction and extent of chromatic variation (Table 2). These relationships were generally clearer in initially light woods ($L^* > 50$), whereas, in initially dark woods ($L^* < 50$), they were weaker or non-significant ($p > 0.05$), except for the wood lightness (L^*) (Table 2).

Table 2. Pearson's correlation coefficients and statistical correlation significance between the exposed CIE $L^*a^*b^*$ colour variables (L^* , a^* , b^*), chroma (C^*), hue (h) and the colour changes (ΔL^* , Δa^* , Δb^* , ΔC^* , Δh and ΔE) for the 98 tropical species listed in Table 1. The woods are grouped into two classes of wood lightness (L^*): above the diagonal woods with $L^* > 50$ ($n = 67$) and below the diagonal woods with $L^* \leq 50$ ($n = 31$). *** Correlation is significant at the 0.001 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed).

	L^*	a^*	b^*	C	h	ΔL	Δa	Δb	ΔC	Δh	ΔE
L^*	--	−0.677 ***	0.361 **	0.15	0.866 ***	0.677 ***	−0.165	0.406 ***	0.303 *	0.300 *	−0.587 ***
a^*	0.377 *	--	0.189	0.438 ***	−0.809 ***	−0.429 ***	0.469 ***	−0.172	−0.033	−0.402 ***	0.393 **
b^*	0.867 ***	0.635 ***	--	0.965 ***	0.398 ***	0.224	0.349 **	0.353 **	0.374 **	−0.11	−0.098
C	0.759 ***	0.841 ***	0.952 ***	--	0.147	0.083	0.446 ***	0.271 *	0.330 **	−0.221	0.023
h	0.768 ***	−0.074	0.702 ***	0.460 **	--	0.566 ***	−0.213	0.390 **	0.273 *	0.334 **	−0.467 ***
ΔL	0.618 ***	−0.074	0.288	0.174	0.400 *	--	−0.344 **	0.295 *	0.166	0.543 ***	−0.924 ***
Δa	−0.148	0.046	0.076	0.071	0.021	−0.285	--	0.484 ***	0.648 ***	−0.583 ***	0.485 ***
Δb	0.259	0.064	0.326	0.254	0.288	0.35	0.600 ***	--	0.979 ***	0.293 *	−0.046
ΔC	0.084	0.076	0.219	0.184	0.144	0.105	0.844 ***	0.930 ***	--	0.117	0.088
Δh	0.196	−0.1	0.109	0.033	0.162	0.535 **	−0.285	0.431 *	0.146	--	−0.515 ***
ΔE	−0.379 *	0.094	−0.191	−0.098	−0.329	−0.776 ***	0.125	−0.451 *	−0.239	−0.498 **	--

The relationships between the initial wood colour parameters and the changes observed after indoor exposure were weak and mainly non-significant. The dispersion graphs presented in Figure 3 clearly show a lack of correlation. These results suggest that the initial wood colour was not a significant predictor of the magnitude of the chromatic changes. Nevertheless, when tropical woods are separated into two lightness classes, darker woods ($L^* \leq 50$, $n = 31$) and lighter woods ($L^* > 50$, $n = 67$), stronger correlations involving the initial colour-change parameters are generally observed for lighter woods (Table 3).

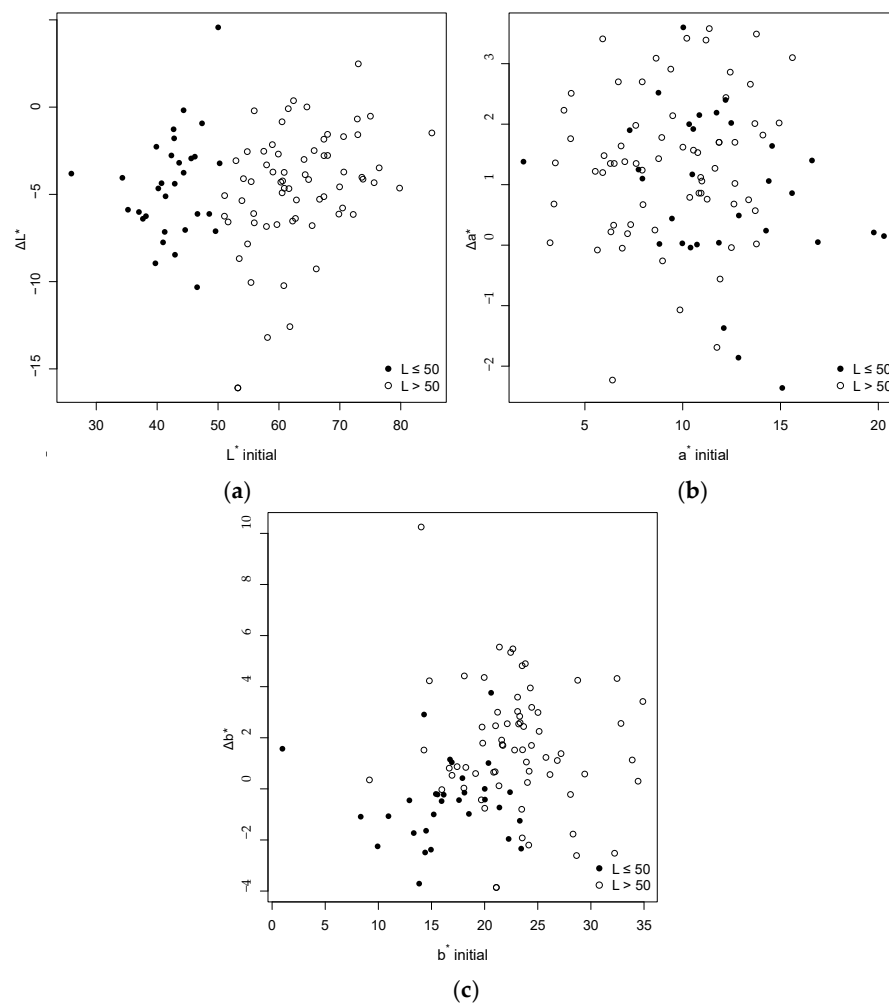


Figure 3. Variation of wood colour parameters: (a) ΔL^* , (b) Δa^* and (c) Δb^* upon long-term air exposure in a room environment for the 98 tropical wood species in relation to their respective initial colour parameters (L^* , a^* and b^*). Empty circles refer to woods with $L^* > 50$ and filled circles to $L^* \leq 50$.

Table 3. Pearson's correlation coefficients and statistical correlation significance between the initial CIE $L^*a^*b^*$ colour variables (L^* , a^* , b^*), chroma (C^*), hue (h) and the colour change (ΔL^* , Δa^* , Δb^* , ΔC^* , Δh and ΔE) upon long-term air exposure in a room environment for the 98 tropical species listed in Table 1. The woods are grouped into two classes of wood lightness (L^*): above the diagonal woods with $L^* > 50$ ($n = 67$) and below the diagonal woods with $L^* < 50$ ($n = 31$). ** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed).

	L^*	a^*	b^*	C^*	h	ΔL^*	Δa^*	Δb^*	ΔC^*	Δh	ΔE
L^*	--	−0.711 **	0.191	0.012	0.828 **	0.386 **	−0.048	0.373 **	0.303 *	0.126	−0.308 *
a^*	0.497 **	--	0.265 *	0.473 **	−0.792 **	−0.349 **	0.141	−0.379 **	−0.287 *	−0.227	0.254 *
b^*	0.929 **	0.661 **	--	0.974 **	0.344 **	0.096	0.137	−0.107	−0.074	−0.258 *	−0.082

C	0.838 **	0.854 **	0.954 **	--	0.132	0.008	0.158	−0.184	−0.133	−0.288 *	−0.017
h	0.728 **	−0.076	0.633 **	0.407 *	--	0.400 **	−0.01	0.306 *	0.246 *	−0.015	−0.306 *
ΔL^*	0.192	0.028	0.189	0.143	0.127	--	−0.344 **	0.295 *	0.166	0.543 **	−0.924 **
Δa^*	−0.02	−0.303	−0.117	−0.199	0.156	−0.285	--	0.485 **	0.648 **	−0.583 **	0.485 **
Δb^*	0.12	−0.147	0.016	−0.042	0.07	0.35	0.600 **	--	0.979 **	0.293 *	−0.046
ΔC^*	0.044	−0.22	−0.075	−0.136	0.068	0.104	0.844 **	0.930 **	--	0.117	0.088
Δh	−0.065	0.003	−0.027	−0.013	−0.324	0.535 **	−0.285	0.431 *	0.146	--	−0.515 **
ΔE	−0.023	0.046	−0.053	−0.023	−0.077	−0.776 **	0.125	−0.451 *	−0.239	−0.498 **	--

The major contributor to the total colour change (ΔE) was the lightness change (ΔL^*), which showed a significant negative correlation ($p < 0.001$), followed by the hue change (Δh), which also showed a significant negative correlation. For the darker woods ($L^* \leq 50$), the yellowness change (Δb^*) showed a stronger negative correlation with ΔE , whereas for the lighter woods ($L^* > 50$), the redness change (Δa^*) showed a stronger positive correlation with ΔE . Thus, changes in yellowness contributed more to the total colour change in the darker woods, while changes in redness contributed more to the total colour change in the lighter woods.

For instance (Table 1), the highest perceptible colour change ($\Delta E = 16.63$) was found for *Khaya* spp. (M21 and M22), a wood with $L^* 53.25$. This was mainly associated with a pronounced decrease in wood lightness ($\Delta L^* = -16.09$), accompanied by a decrease in yellowness ($\Delta b^* = -3.86$) and a slight increase in red ($\Delta a^* = 1.70$). The lowest colour change, not perceptible to the human eye ($\Delta E = 0.46$), was found for *Spirostachys africana* (M31), a dark wood ($L^* = 44.34$), with minimal changes in lightness ($\Delta L^* = -0.18$), redness ($\Delta a^* = 0.01$) and a slight increase in yellowness ($\Delta b^* = 0.42$). The significant correlations between wood lightness change (ΔL^*) and colour parameters showed that a shift towards red (positive Δa^*) is moderately associated with reduced lightness, whereas a shift towards yellow (positive Δb^*) shows a weak positive correlation with lightness variation (ΔL^*). This was statistically significant for all 98 tropical species together, whereas within the two lightness classes, the correlations were only significant for the lighter woods ($L^* > 50$) (Table 3).

Despite these differences, the correlations between the initial colour parameters (L^* , a^* , b^*) and ΔE remain weak, suggesting that the magnitude of the colour change for these tropical species is not strongly dependent on the initial wood colour. This behaviour may partially reflect differences in wood density, since Bessa et al. [1] showed that wood colour variation was mainly explained by the negative correlation of L^* and b^* with wood density, whereas a^* only showed a weak positive correlation. However, only a very weak positive and non-significant trend was observed between wood density and ΔE , meaning that high wood species tended to show slightly greater colour changes, although with substantial interspecific variability. Regarding wood anatomical features, the same study [1] reported only a negative correlation between wood lightness (L^*) and fibre wall thickness. Since fibre wall thickness is strongly associated with wood density, woods with thicker fibres generally tend to exhibit lower L^* values and therefore a darker appearance. Thus, in these tropical species, the proportion of the other tissues, such as axial parenchyma and tracheids, that were not previously considered, and wood ring porosity may be crucial to explain wood colour variability, which is also related to wood grain variability and, likewise, to visual wood colour perception.

Wood colour changes result from many external factors and intrinsic wood characteristics, such as the presence and composition of extractives [36–38]. For instance, steamed *Prunus avium* wood becomes darker with more pronounced red and brown hues, and sapwood and heartwood become visually indistinguishable due to the reduction of cellular deposits in parenchyma cells during steaming [39]. The oxidation of extractives has also been reported following light exposure [34] and heat treatments [12]. In contrast, cellulose is less susceptible to ultraviolet radiation [40]. During thermal treatments, deg-

radiation products are formed, and extractives participate in the colour development of heat-treated wood [12].

Woods containing fewer extractives and with lower phenolic contents appear to be less resistant to light-induced degradation (solar type irradiation) [22]. Phenolic extractives, including tannins, stilbenes and flavonoids, play a significant protective role against UV-induced degradation by acting as free radical scavengers, UV absorbers, and inhibitors of carbonyl group and quinonoid structure formation [41–43]. These wood secondary metabolites may also reflect ecological and evolutionary adaptations due to their contribution to tree defence against biotic agents, growth responses to environmental conditions, species adaptation and wood natural durability [4,44–47]. Therefore, the interspecific differences observed here in wood colour may also be linked to these underlying ecological processes.

Chromatic changes observed in such a long-term data set are rare and have not been as extensively studied as they were here. However, some limitations are associated with interspecific, within-species and surface section variability, with limited sample availability, and the retrospective nature of the study. As the specimens originated from a historical xylarium collection, information regarding the initial environmental conditions and long-term exposure history was not available. Consequently, the observed colour changes reflect the cumulative effects of approximately 50 years of indoor ageing and cannot be directly attributed to specific environmental factors. In addition, the present study focused on mean values derived from four measurement points taken in a small-sized specimen. Future studies should also consider within-specimen colour variability to further characterize colour heterogeneity, namely by taking into account different wood sections, as well as different samples. Therefore, caution is required when discussing colour variability and extrapolating these findings to other storage conditions or outdoor exposure environments.

3.3. Multivariate Grouping of the Tropical Species by Wood Colour

Principal component analysis (PCA) revealed that the first three components explained approximately 79% of the colour variation, while the cumulative variance explained by PC1 and PC2 was 58.5% (Table 4). The first component (PC1) explained 35.0% of the variance and was strongly associated with yellowness change (Δb^*), hue (h) and wood lightness (L^*) in opposition to wood redness (a^*) (Figure 4). The second component (PC2) accounting for 23.5% of the total variance, was mainly driven by hue change (Δh) and lightness change (ΔL^*), in opposition to the total colour change (ΔE). The third component (PC3) explained 20.1% of the total variance and was strongly associated with the initial yellowness and chroma (b^* and C^*), in contrast with their corresponding changes (Δb^* , ΔC^* and Δa^*) (Figure 4).

Table 4. Total variance explained and calculated eigenvalues for the principal components for the 11 wood colour variables of the 98 tropical species.

Parameter	PC1	PC2	PC3	PC4
Eigenvalue	3.85	2.58	2.21	1.2
Variance (%)	35.03	23.47	20.10	10.91
Cumulative variance (%)	35.03	58.50	78.60	89.51

Therefore, species with positive PC1 scores tend to exhibit a higher initial hue angle (h), initial lightness (L^*) and yellowness change (Δb^*), whereas species with negative PC1 scores are characterized by comparatively higher redness values (a^*). Species with positive PC2 scores tend to show greater changes in lightness (ΔL^*) and hue (Δh), whereas species with negative PC2 scores are associated with larger total colour changes (ΔE) and

redness changes (Δa^*). Overall, PC1 described variation in initial wood colour, particularly lightness (L^*), hue (h) and redness (a^*). PC2 mainly reflected differences in colour changes after long-term indoor exposure, especially changes in lightness (ΔL^*) and hue (Δh), and PC3 contrasted initial chromatic shifts (chroma and yellowness) with their subsequent changes. Despite these associations, the PCA did not reveal well-defined groups, as most of the specimens occupied a continuous multivariate space with substantial overlap. This suggests that colour variation among these species in the xylarium is gradual rather than species-specific.

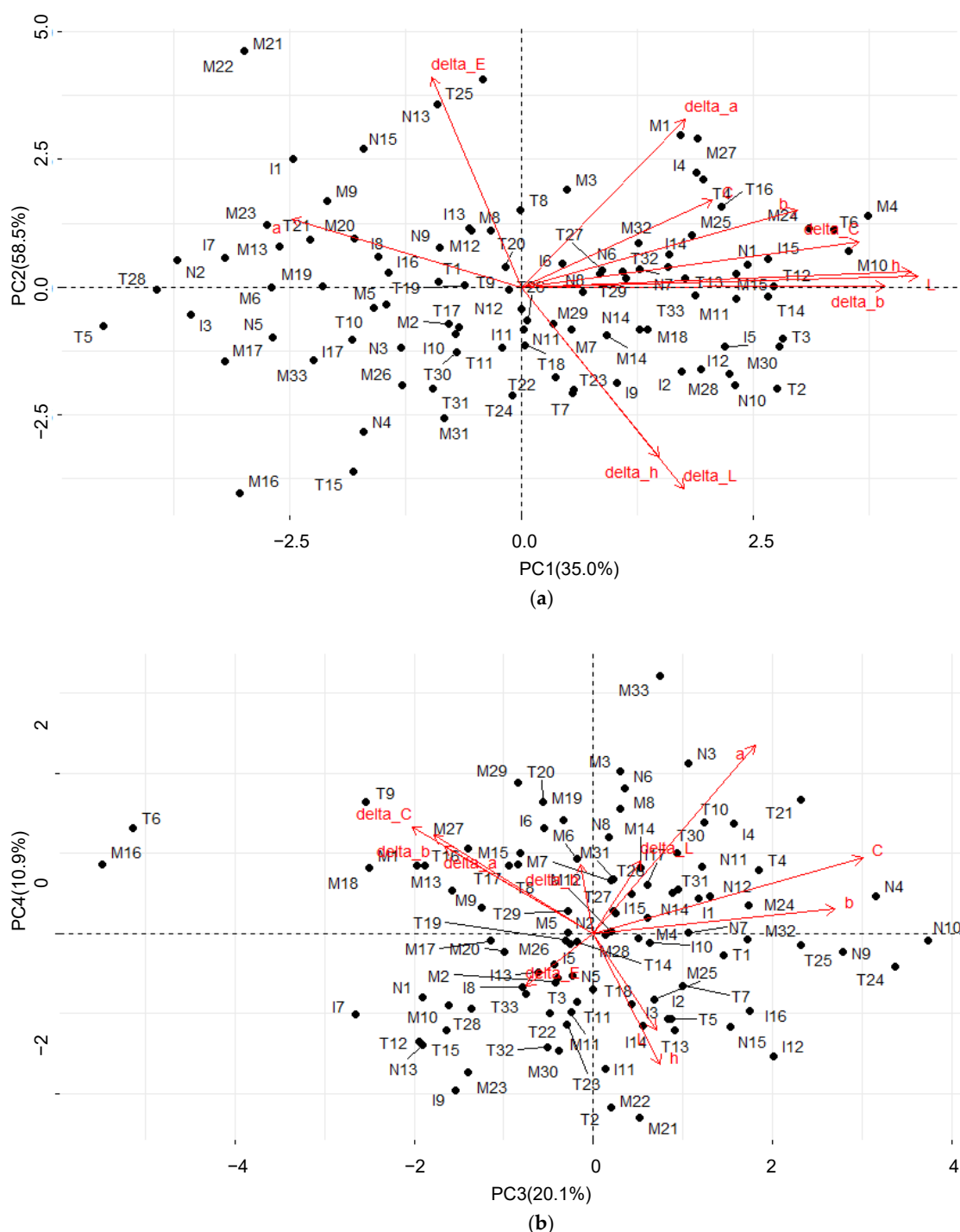


Figure 4. PCA biplots showing (a) PC1 vs. PC2 and (b) PC3 vs. PC4 for the 98 tropical wood species (codes are in Table 2) based on 11 colour variables. Notes: L, initial wood lightness (L^*); a, initial wood redness (a^*); b, initial wood yellowness (b^*); C, initial chromaticity (C^*); h, initial hue (h);

delta_L, L* change (ΔL^*); delta_a, a* change (Δa^*); delta_b, b* change (Δb^*); delta_C, C* change; delta_h, h change; and delta_E, total colour difference (ΔE).

These results corroborate the correlations discussed previously. The PCs based on wood colour parameters and wood colour changes did not reveal well-defined species clusters, indicating substantial wood colour overlap among species. Nevertheless, a few specimens were located at the periphery due to higher total colour change (ΔE). These included the black wood of *Dalbergia melanoxylon* (M16), the light brown wood of *Hibiscus tiliaceus* (T15), *Khaya* spp. (M21, M22), the yellowish-brown wood of *Calophyllum inophyllum* (T6), the dark brown wood of *Syncarpia glomulifera* (N13), and the light yellowish-brown wood of *Sarcocephalus cordatus* (T25).

This pattern is consistent with the hierarchical clustering analysis, which also revealed diffuse group boundaries and substantial overlap among species, with only a few specimens showing some degree of separation (Figure 5). The absence of distinct clusters suggests that colour variation among the studied tropical species is continuous, driven by gradual variations in colour parameters rather than being species-specific. As a result, samples from different species may exhibit overlapping colour characteristics.

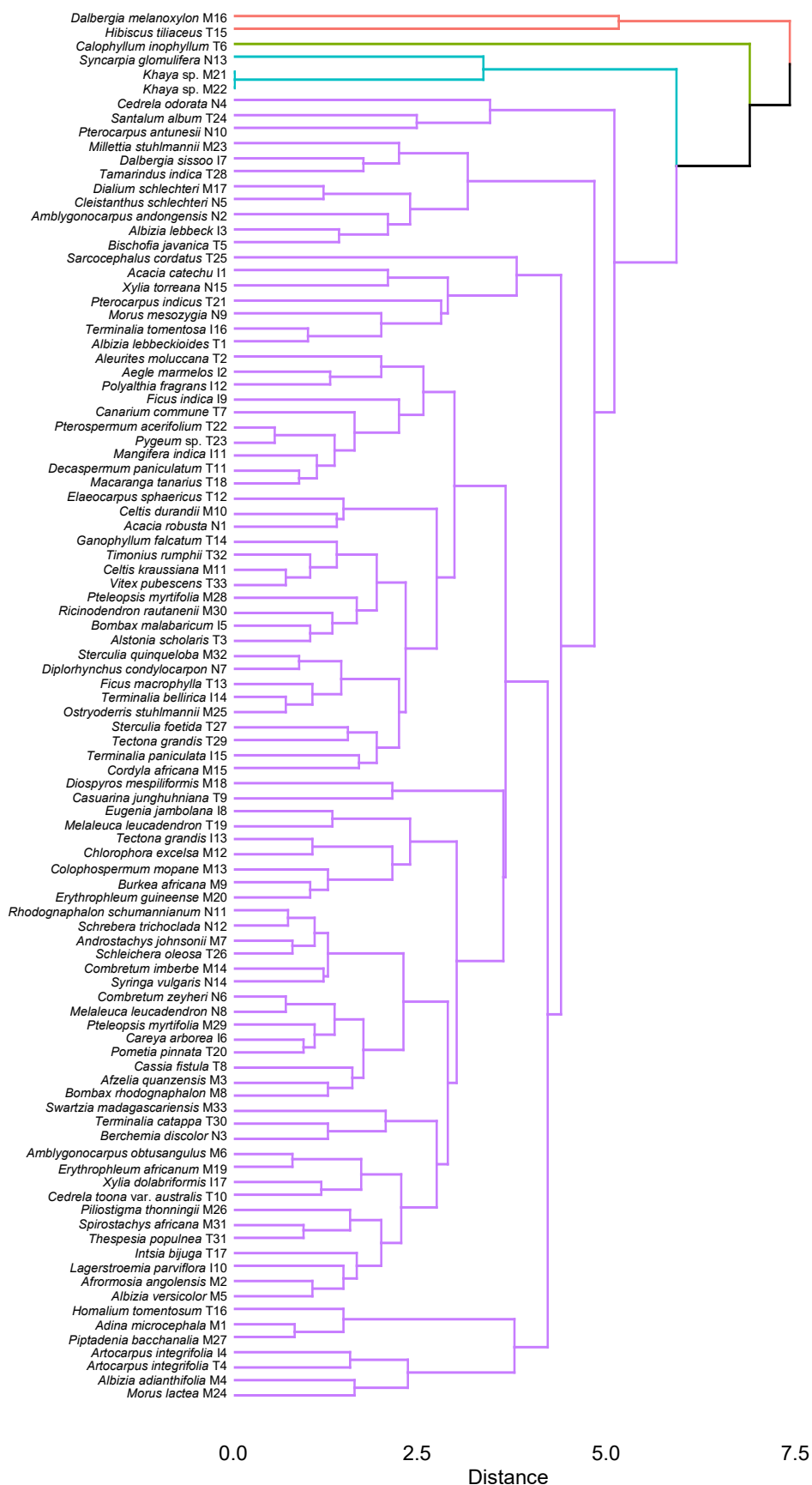


Figure 5. Hierarchical classification of 98 tropical wood species (codes listed in Table 1) based on 11 colour variables, obtained using the UPGMA clustering method (cophenetic correlation, $c = 0.767$).

Branch colours highlight the major clustering structure, with most specimens grouped in a single large cluster (purple) and only few peripheral branches (other colours).

4. Conclusions

An insight was obtained into the wood colour variation patterns of 98 tropical species in an indoor environment, covering a large spectrum of wood colours:

1. After long-term air exposure in an indoor xylarium environment, the tropical woods showed a darkening effect, as well as a shift towards redness, with only a few exceptions showing no colour change or a change to lighter colours correlated with a yellow shift;
2. The colour variability found between the different woods after exposure was high, reflecting natural interspecific heterogeneity, but the pattern of colour stability was relatively maintained;
3. A substantial overlap of wood colour was observed, and only a few tropical species with high colour change were located on the periphery, as revealed by multivariate analysis, suggesting gradual colour variation among species;
4. The observed wood colour changes were weakly correlated with the reference wood colour parameters, suggesting that other intrinsic wood characteristics are more important than the initial reference colour parameters;
5. The indoor photodegradation of tropical woods was primarily characterized by a decrease in lightness, with changes in chromatic coordinates playing a secondary role, suggesting that perceived discolouration is driven by darkening rather than shifts in hue;
6. The discolouration observed after prolonged indoor exposure did not diminish the aesthetic value of these tropical woods, which retain their potential for high-value interior applications.

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