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The analysis of tropical wood discoloration caused by simulated sunlight

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Abstract This study investigated the wood surface discoloration due to simulated sunlight of tropical woods native to South America. Wood of jatoba (*Hymenaea courbaril* L.), massaranduba (*Manilkara bidentata* A. Chev.), tigerwood (*Astronium graveolens* Jacq.), angelim amargoso (*Vatairea* spp.), angelim pedra (*Hymenolobium* spp.) and angelim vermellho (*Dinizia excelsa* Ducke) was exposed to a treatment by xenon-arc lamp light simulating outdoor sunlight, for 144 hours. Colour measurement of exposed and non-exposed areas of samples was performed by means of a spectrophotometer measuring in *CIEL*a*b** colour system. The resulting wood discoloration was evaluated according to the value of the overall colour change ΔE^*. Changes of particular parameters (L^*, a^* and b^*) were also observed during exposure. The wood surface darkened rapidly during the first hours of exposure to simulated sunlight. Later, samples showed only a slight increase in lightness. Within one wood species the colour changes were more significant (higher ΔE^*) for lighter samples.

Untersuchung der Verfärbung tropischer Hölzer aufgrund simulierter Sonneneinstrahlung

Zusammenfassung In dieser Studie wurde die Verfärbung von Holzoberflächen aufgrund von simulierter Sonneneinstrahlung an den in Südamerika beheimateten tropischen Holzarten Jatoba (*Hymenaea courbaril* L.), Massaranduba (*Manilkara bidentata* A. Chev.), Tigerwood (*Astronium graveolens* Jacq.), Angelim amargoso (*Vatairea* spp.), Angelim pedra (*Hymenolobium* spp.) und Angelim vermellho (*Dinizia excelsa* Ducke) untersucht. Dabei wurden diese über eine Dauer von 144 Stunden mit einer Xenonlampe bestrahlt. Mit einem Spektralphotometer wurden Farbmessungen an bestrahlten und nicht bestrahlten Probenflächen unter Verwendung des *CIEL*a*b** Farbsystems durchgeführt. Die Gesamtverfärbung wurde entsprechend des Wertes ΔE^* beurteilt. Bei der Bestrahlung wurde die Änderung der Parameter L^*, a^* und b^* ebenfalls bestimmt. In den ersten Stunden der Bestrahlung dunkelte die Holzoberfläche schnell, später nahm die Helligkeit leicht zu. Innerhalb einer Holzart waren die Farbveränderungen bei den helleren Proben stärker ausgeprägt (größeres ΔE^*).

1 Introduction

The anatomic structure and the chemical composition of wood affect not only its mechanical and physical properties, but also its aesthetic properties. Wood colour and its fastness are one of the most important aesthetic aspects of wooden products used in the exterior, but mainly in the interior. Wood colour is important for routine actions like wood identification, aesthetic considerations, and it may sometimes determine its market value (Gonçalez 1993).

The colour of wood depends on chemical components interacting with light, i.e., the presence or absence of extractives (Hon and Minemura 2001). This is highly variable, not only between various wood species, but also within one species and often even for one piece of wood (Panshin and de Zeeuw 1980). The organic components in wood are primarily polysaccharides and polyphenolics: cellulose, hemicelluloses, and lignin. There is also a relatively small amount of additional components of usually dark hue in

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wood—these are extractives, and their concentration determines colour, odour, and other non-mechanical properties of wood species (Feist and Hon 1984).

Wood colour can change dramatically due to various factors (sunlight, moisture, temperature, microorganisms, contact with metals, etc.). From the perspective of wood atmospheric degradation the most important influence on colour change is the ultra violet (UV) part of sunlight (wavelength <380 nm), which induces photochemical reactions in wood (Hon 2001; Tolvaj et al. 2001; Müller et al. 2003; Evans et al. 2005). Extractives play an essential role in the photodegradation of wood, and the rate of wood degradation is reduced by the presence of extractives (Chang et al. 2010). Nzokou and Kamdem (2006) also state that extractives work as antioxidants and they protect the wood against photodegradation. After extraction of water-extractable compounds, the exposed surface darkened much more in comparison to unextracted samples.

If wood is exposed to natural or artificial sunlight even for a short time, there are easily visible changes in wood colour and brightness. Due to the light, the colour of most wood species changes to yellow up to brown because of lignin and extractive photooxidation. In the exterior, the surface then gradually turns grey as brown degradation products of lignin are leached from the wood surface (Feist and Hon 1984; Kučerová 2005). The degradation of the least stable lignin only occurs in the surface layers of wood. Neither the UV light nor visible light are able to penetrate deeper than 75 μm and 200 μm, respectively. The observed darkening of wood up to the depth of 2–3 mm is caused by the following chain reactions of developed free radicals (Hon 2001; Kučerová 2005).

This study deals with the wood surface discoloration caused by simulated sunlight. Each wood species changes its colour under the influence of light, but the extent, the speed and the process of the change varies in dependence of the species. Six species of tropical woods from South America were used in this study: jatoba (*Hymenaea courbaril* L.), massaranduba (*Manilkara bidentata* A. Chev.), tigerwood (*Astronium graveolens* Jacq.), angelim amargoso (*Vatairea* spp.), angelim pedra (*Hymenolobium* spp.) and angelim vermellho (*Dinizia excelsa* Ducke).

2 Material and methods

2.1 Specimens

Specimens of dimensions $140 \times 45 \times 15$ mm^3 ($L \times T \times R$) were conditioned at ambient temperature of 20 ± 2°C and relative humidity 65 ± 5%. The surface to be exposed to the simulated sunlight was sanded prior to the experiment. After this, the specimens were stored in a dark room. For each selected wood species 14 specimens were used.

2.2 Impact of artificial sunlight

The specimens were exposed to artificial sunlight in the xenon test chamber Q-SUN Xe-1, Q-Lab Corporation, U.S.A. (1800W xenon arc lamp—full-spectrum, irradiance 0.55 W/m^2—340 nm, black panel temperature 60°C) for various times, ranging from 0 up to 144 hours. Half of each specimen was covered with an aluminium foil prior to exposure so that the contrast between the exposed and the original surface was clearly visible. The position of the specimens in the chamber was changed regularly to prevent a more intensive irradiation of some specimens due to possibly uneven distribution of radiation. During the exposure, the specimens were taken out regularly for the purpose of discoloration measuring.

2.3 Colour measuring

The discoloration of wood surface was measured during exposure by means of the mobile spectrophotometer Spectroguide 45/0 (45/0 measuring geometry, 10°standard observer, D65 standard illuminant, aperture 11 mm, *CIEL*a*b** colour system) from the BYK company. The L^*, a^*, b^*, and ΔE^* parameters were measured for each specimen at five places; subsequently, the average value was calculated.

To describe the colour space the *CIEL*a*b** rectangular colour system defined by three axes—the achromatic lightness axis (L^*), the chromatic green-red axis (a^*) and the chromatic blue-yellow axis (b^*)—was used. The lightness ranged from 0 (black) to 100 (white). The colour of the area is described by two parameters—a^* and b^*—which gain no value limits ($+a^*$—red, $-a^*$—green, $+b^*$—yellow, $-b^*$—blue). L^*, a^*, b^* coordinates clearly define the colour in its shade, saturation and brightness.

The overall discoloration of the surface is established by the colour deviation ΔE^* calculated using the following formula:

$$\Delta E^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2},$$

where ΔL^*, Δa^*, Δb^* represent the differences between the original and the final coordinates (before and after surface exposure). A low value of ΔE^* means a low change in colour.

The colour of the surface of specimens was measured in the following intervals—0, 2, 4, 6, 12, 24, 48, 98, and 144 hours.

3 Results and discussion

3.1 Overall colour change ΔE^* during exposure

The colour of wood exposed to external conditions can rapidly change in quite a short time. Generally, all wood

Fig. 1 Visual comparison of contrast among the exposed and non-exposed surface (from *left*: jatoba, massaranduba, tigerwood, amargoso, pedra, vermellho; *upper half*—unexposed, *lower half*—exposed for 144 hours)
Abb. 1 Visueller Vergleich des Unterschieds zwischen bestrahlter und nicht bestrahlter Fläche (von *links*: Jatoba, Massaranduba, Tigerwood, Amargoso, Pedra, Vermellho; *obere Hälfte*: nicht bestrahlt, *untere Hälfte*: über eine Dauer von 144 Stunden bestrahlt)

Table 1 Overall colour change (ΔE^*) during exposure
Tab. 1 Gesamtfarbänderung (ΔE*) bei der Bestrahlung

Species	ΔE^*	
	2 hours	144 hours
Jatoba	6.50	11.34
Massaranduba	4.97	8.65
Tigerwood	10.62	18.68
Amargoso	7.46	14.36
Pedra	5.11	5.63
Vermellho	7.36	12.72

species turn yellowish or brown. The cause of these phenomena is mainly degradation (photooxidation) of lignin and extractives. Wood rich in extractives can fade before browning shows distinctly (Feist 1983). In the photodegradation of the least stable lignin, degradation products of brown shade are created and they settle in the surface layers of wood. During the first two hours of simulated sunlight radiation the surface colour of all specimens changed visibly. The deviation ΔE^* of all the wood species exceeded the value of 3 (see Table 1), which is considered the limit for the visibility to the naked eye (Hon and Minemura 2001). The longer the time of exposure, the higher was the difference between the compared halves. Figure 1 shows the clear contrast between the exposed and the original surface. A distinct change in colour into darker shades of brown can be seen.

Oltean et al. (2008) examined softwood of the temperate zone and they observed a rapid change in ΔE^* during the first 12 hours of exposure to UV radiation. Most of the measured wood species reached stable values of ΔE^* after 120 hours of exposure and the subsequent irradiation only caused a slight, to the naked eye invisible, increase or decrease in the value of the total colour deviation. Similar conclusions can be drawn on the basis of measuring the discoloration of tropical wood species conducted by Pastore et al. (2004). In this research here, the change in colour (ΔE^*) was more significant during the first 12 hours of exposure, then the values changed only slightly and were hardly discernible (see Fig. 2). The rapid change in the first hours of exposure is caused by the reaction of extractives contained in the wood to UV radiation. Pandey (2005) compared the behaviour of unextracted and extractive free wood of *Acacia auriculaeformis*. Unextracted wood surface showed a rapid colour change at the initial period of exposure which decreased upon prolonged exposure. Extractive free specimens exhibited a monotonous increase in colour change with increasing irradiation time. The largest colour change ($\Delta E^* = 18.7$) after 144 hours was observed in tigerwood; the least distinct darkening of the surface was observed in the wood of pedra ($\Delta E^* = 5.6$). Therefore, except for pedra, one can speak of intensive and very intensive discoloration according to the scale proposed by Jirouš-Rajković and Ljuljka (1999) for all wood species examined.

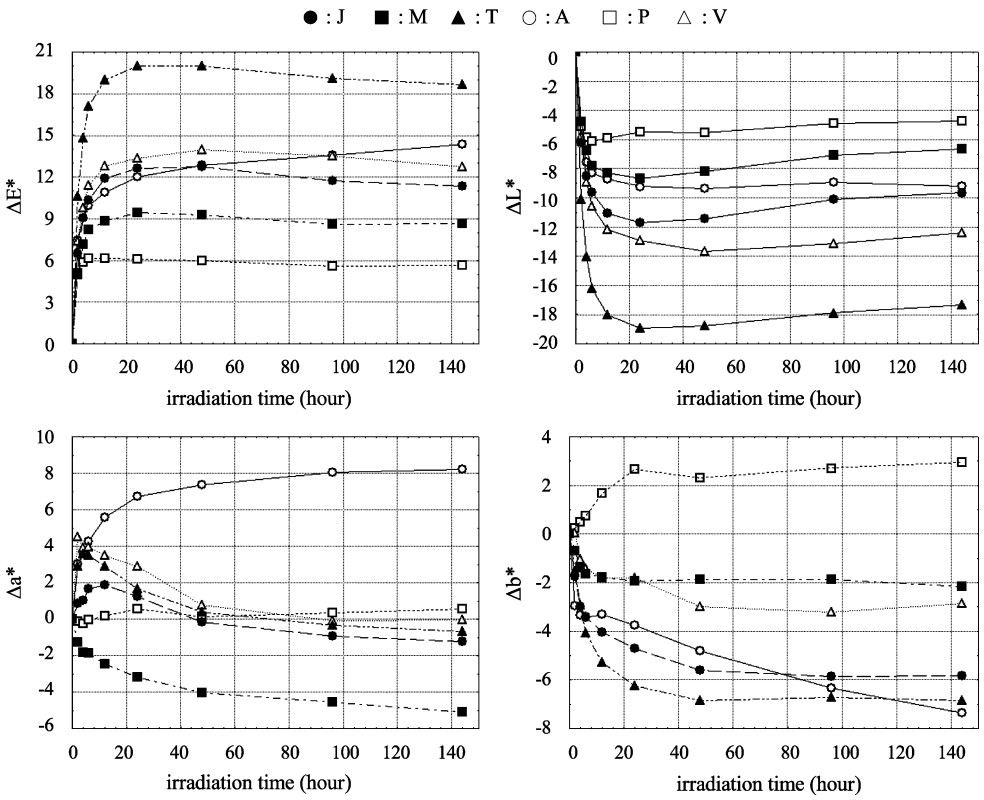

Fig. 2 Progress of deviation of parameters L^*, a^*, b^* and overall colour change ΔE^* during light irradiation (J—jatoba, M—massaranduba, T—tigerwood, A—amargoso, P—pedra, V—vermellho)
Abb. 2 Veränderung der Parameter L^*, a^*, b^* und der Gesamtfarbänderung ΔE^* in Abhängigkeit der Bestrahlungsdauer (J—Jatoba, M—Massaranduba, T—Tigerwood, A—Amargoso, P—Pedra, V—Vermellho)

3.2 Parameters L^*, a^*, b^* during exposure

Hon and Minemura (2001) classify wood into five groups according to their different behaviour during changes in lightness: darkening only, darkening and subsequent lightening, darkening-lightening-darkening, only lightening, and lightening and subsequent darkening. In many tropical wood species, the stages of darkening and lightening alternate during their exposure. The graph of ΔL^* dependence on the time of exposure (see Fig. 2) shows two different kinds of curves. During the first 12 hours the lightness of the measured surface was reduced considerably. Then, for 24–48 hours of exposure, the trend reverted—the wood surface started lightening slightly. Similar behaviour was observed for all tested wood species—first, a considerable darkening and a subsequent slight lightening. All specimens exposed to the simulated sunlight for 144 hours had negative values of ΔL^*, i.e., the exposed surface was darker.

By the course of parameter a^*, the examined wood species can be divided into three groups (see Fig. 2). In the first group (jatoba, tigerwood, pedra, vermellho), the values of parameter a^* increased in the first hours of irradiation. Then there was a decrease and stabilization to approximately the original value. However, the wood of pedra did not manifest considerable changes in parameter a^* like the other woods. In another group, with the wood of amargoso, the values of parameter a^* only grew during the exposure (the wood reddened). For the wood of massaranduba, the process was quite the opposite, the value of parameter a^* only decreased.

The progress of changes in parameter b^* in most of the wood species were similar to the change in lightness—a more significant decrease in the initial stage and the subsequent stabilization of values. A different behaviour was observed for the wood of pedra, where the values of parameter b^* increased. For the wood of amargoso, which when measuring the original surface appeared to be the 'yellowest' one, the value of parameter b^* did not stabilize during exposure as it continued dropping quite sharply. The different behaviour of individual wood species regarding chromatic parameters is probably caused by the presence of specific types of extractives in the wood. When exploring the impact of extractives on discoloration, Nzokou and Kamdem (2006) found that this relation is to a great extent dependent on the nature and chemical composition, and the total amounts of extractives is not so important.

3.3 Influence of non-exposed wood colour on discoloration

Davis (1962) states that light-coloured woods may not necessarily manifest a greater change in colour than dark woods. However, within one wood species, there is a more considerable change in colour in lighter or sapwood samples than in darker or heartwood samples. Extractives affect the wood colour significantly. Using the wood of *Larix* spp., Gierlinger et al. (2004) confirmed the hypothesis that wood

Table 2 Coordinates of *CIEL*a*b** colour system for individual woods (CV the variation coefficient—%)
Tab. 2 Koordinaten des *CIEL*a*b** Farbsystems der einzelnen Holzarten (CV—Variationskoeffizient in %)

Species	Before exposure						After exposure					
	L^*		a^*		b^*		L^*		a^*		b^*	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Jatoba	50.34	8.84	14.49	10.16	22.32	6.92	40.70	9.41	13.28	7.90	16.49	12.80
Massaranduba	45.37	7.13	13.51	5.94	15.54	11.82	38.74	7.02	8.40	8.22	13.39	12.47
Tigerwood	56.20	10.00	15.37	8.87	25.24	8.86	38.84	14.19	14.70	8.69	18.38	22.96
Amargoso	54.84	2.88	10.03	8.31	34.07	5.99	45.64	3.92	18.25	4.37	26.73	4.14
Pedra	65.38	2.33	10.22	5.62	26.50	3.97	60.63	2.16	10.77	5.35	29.47	2.86
Vermellho	53.93	4.75	11.17	11.59	18.64	7.24	41.54	5.89	11.14	7.80	15.78	9.18

Table 3 Linear regression equations of overall colour change (ΔE^*) and lightness of original surface (L^*) and coefficient of correlation (r) and determination (r^2)
Tab. 3 Lineare Regressionsgleichungen der Gesamtfarbänderung (ΔE^*) in Abhängigkeit der Probe vor der Bestrahlung (L^*) sowie Korrelationskoeffizient (r) und Bestimmtheitsmaß (r^2)

Species	Fitted linear function	r	r^2
Jatoba	$\Delta E^* = 0.631L^* - 19.811$	0.564	0.318
Massaranduba	$\Delta E^* = 0.343L^* - 6.718$	0.499	0.249
Tigerwood	$\Delta E^* = 0.323L^* + 1.237$	0.238	0.057
Amargoso	$\Delta E^* = 0.580L^* - 17.288$	0.589	0.347
Pedra	$\Delta E^* = 0.440L^* - 23.077$	0.540	0.291
Vermellho	$\Delta E^* = 0.492L^* - 13.795$	0.483	0.233
All	$\Delta E^* = -0.007L^* + 12.581$	−0.009	0.000

colour is related to the content of extractives. The a^* coordinate turned out to be strongly correlated with phenolics. Thus, it can be assumed that a higher proportion of extractives within one wood species can cause a darker colour of the wood. Pandey (2005) found that extractive free samples manifest higher resulting values of colour deviation ΔE^* when compared to unextracted wood. Similarly, there was a higher colour change in sapwood (without extractives) of two hybrid poplars than in their heartwood (Oltean et al. 2010). Therefore, it can be concluded that lighter samples manifest a larger colour change due to sunlight. The regression analysis was used for investigating if the lightness of the original wood surface influences the overall colour deviation (ΔE^*). Table 3 presents regression equations, correlation (r) and determination (r^2) coefficients describing this relationship for all tested wood species. The performed regression analysis showed medium positive correlation in most of the examined species. The same dependence was explored in the entire set of examined species but in this case the correlation was negligible (−0.009). When pedra samples were removed, the correlation of the remaining species was high (0.65—see Fig. 3). The wood of pedra differs from the other species by its lightness (see Table 2).

Figure 3 shows the regression analysis of the dependence of the overall colour change ΔE^* on the lightness of the

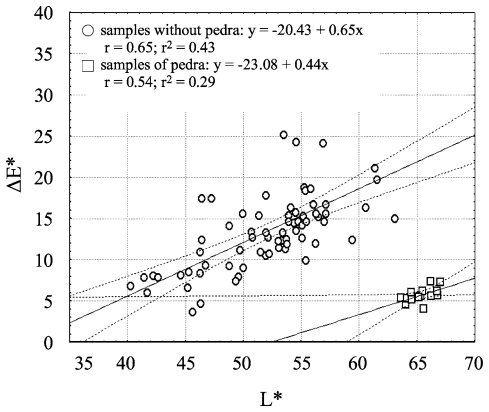

Fig. 3 Regression analysis of the dependence of overall colour change ΔE^* on lightness of the original surface L^*
Abb. 3 Regressionsanalyse des Zusammenhangs zwischen der Gesamtfarbänderung ΔE^* und der Helligkeit L^* der Probe vor der Bestrahlung

original surface for all species excluding pedra. It was confirmed that the lighter the surface prior to exposure (higher L^*), the more considerable was the discoloration. The darkest massaranduba showed the lowest colour deviation ΔE^* (see Table 1).

Moreover, the dependence of deviation of individual parameters (L^*, a^*, b^*) on the values of unexposed surfaces was explored. For this purpose, the values measured on the unexposed surfaces and the resulting deviations (ΔL^*, Δa^*, Δb^*) after 144 hours of exposure were used. The most significant influence on the resulting deviation was found for parameter a^*. The change in parameter a^* had different character in different species. In the wood of amargoso considerable reddening occurred (increase in a^*). With increasing value of parameter a^* of the unexposed surface, the resulting value of the deviation decreased ($r = -0.8$). The wood of massaranduba only changed its colour towards blue. With increasing value of b^* of the original surface, the negative deviation increased ($r = -0.6$). The remaining woods reddened rapidly at the beginning of exposure and subsequently returned to the original value of a^* (see Fig. 2). In some samples the deviation after 144 hours was

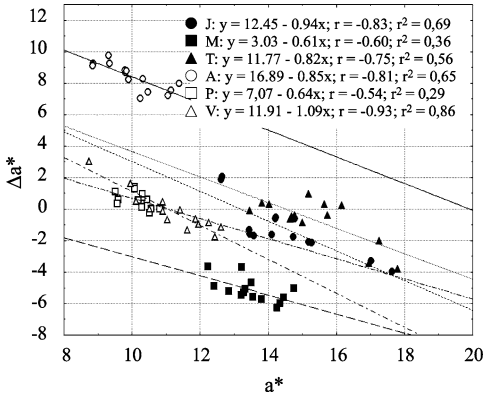

Fig. 4 Regression analysis of the dependence of colour change Δa^* on chromatic parameter a^* of unexposed surface (J—jatoba, M—massaranduba, T—tigerwood, A—amargoso, P—pedra, V—vermellho)
Abb. 4 Regressionsanalyse des Zusammengangs zwischen der Farbänderung Δa^* und dem Farbparameter a^* der nicht bestrahlten Probe (J—Jatoba, M—Massaranduba, T—Tigerwood, A—Amargoso, P—-Pedra, V—Vermellho)

positive, in some negative. For the interdependence between the colour of the original surface (a^*) and the resulting deviation, not only absolute values but also the direction of the change were taken into account. Regression equations and correlation and determination coefficients of individual wood species are presented in Fig. 4. The correlation in the general model for all species was high—0.63.

After exposure to artificial sunlight had finished, the surface of all specimens darkened (L^* parameter value decreased). Even now, the lighter specimens manifested a higher deviation in comparison to the darker ones. This applies both to the samples of one species and the samples of different species. The correlation coefficients within one species ranged between 0.35 and 0.69. The lowest correlation coefficient was in tigerwood, which can be probably attributed to its distinctive striping, i.e., a high variability in data. In this case, when all the six species were considered together, the correlation for this dependence was high ($r = 0.67$).

According to the changes in parameter b^*, the examined species can be divided into two groups: a change towards blue only (negative deviations), and a change towards yellow (positive deviations). The dependence within each of the groups was different. The trend found for the species which change parameter b^* towards blue during exposure (see Fig. 2) was that with the higher value of the original surface also the resulting deviation was higher. The influence of parameter b^* was mainly significant in the wood of amargoso ($r = 0.94$). This is a strongly yellow wood, which also corresponds to the highest value of parameter b^* (see Table 2). The correlation coefficients of the remaining species ranged within 0.44–0.52. The wood of pedra, which was the only one with increased value of parameter b^* during exposure, showed a contrasting dependence. With the higher value of b^* of unexposed surface, the resulting deviation Δb^* was lower ($r = 0.66$). When all examined species were used, the correlation between Δb^* and b^* was high—0.65.

4 Conclusion

Exposure to sunlight, both natural and artificial, causes changes in wood surface colour within a relatively short time. The exposed surface showed changes visible to the naked eye already after 2 hours. During the first hours of exposure to artificial sunlight the surface of the examined species darkened considerably. On the other hand, after a longer time of exposure, the surface of all species lightened slightly. The range and the course of the change depend on the species. After 144 hours of irradiation the largest total deviation (ΔE^*) was found for tigerwood ($\Delta E^* = 18.2$) and the smallest for pedra ($\Delta E^* = 5.6$). Lighter wood can be more susceptible to changes in colour and lightness of the surface, which was proved in the study both within one species and among various species. Moreover, a dependence between the values of parameters describing the colour of unexposed surface (L^*, a^*, b^*) and the resulting deviation ($\Delta L^*, \Delta a^*, \Delta b^*$) caused by the exposure to artificial sunlight was found. When measuring discoloration, especially as regards tropical wood species, it is recommendable to explore the proportion of extractives and their nature and chemical composition.

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