

Victor Fassina Brocco*, Juarez Benigno Paes, Lais Gonçalves da Costa, Grant T. Kirker and Sérgio Brazolin

Wood color changes and termiticidal properties of teak heartwood extract used as a wood preservative

<https://doi.org/10.1515/hf-2019-0138>

Received May 10, 2019; accepted August 27, 2019; previously published online November 8, 2019

Abstract: The aim of this study was to evaluate the change in colorimetric patterns and the termite resistance of light-colored and low durability wood when impregnated with teak (*Tectona grandis*) heartwood extractives. Hot water and ethanol extracts were obtained from 20-year-old teak heartwood and used to evaluate the influence on color change and the natural resistance of 10-year-old teak sapwood and *Pinus* sp. For wood impregnation, a full-cell (Bethell) treatment was conducted. To verify the influence of the teak extracts, the colorimetric patterns of wood were determined using the Munsell and CIE-L*a*b* systems. Choice and no-choice feeding tests were performed under laboratory conditions to test the efficacy of the teak extract solutions against two termite species *Nasutitermes corniger* and *Cryptotermes brevis*. All of the extract solutions promoted a significant darkening of the wood, bringing the color of the impregnated wood closer to older teak heartwood than the untreated samples of the respective species. Ethanol extracts increased the resistance and mortality against *N. corniger* in both choice and no-choice tests. Resistance to *C. brevis* was not clearly affected.

Keywords: eco-friendly preservative, natural extracts, *Tectona grandis*, termite resistance, wood color modifier, wood protection

***Corresponding author: Victor Fassina Brocco**, Department of Forest and Wood Science, Federal University of Espírito Santo, Av. Governador Lindenberg, 316, 29550-000 Jerônimo Monteiro, Espírito Santo, Brazil, e-mail: vfbrocco@hotmail.com.
<https://orcid.org/0000-0003-2529-6656>

Juarez Benigno Paes and Lais Gonçalves da Costa: Department of Forest and Wood Science, Federal University of Espírito Santo, Av. Governador Lindenberg, 316, 29550-000 Jerônimo Monteiro, Espírito Santo, Brazil

Grant T. Kirker: USDA-FS Forest Products Laboratory, One Gifford Pinchot Drive, Madison, WI 53726-2398, USA

Sérgio Brazolin: Institute for Technological Research of São Paulo State – IPT, Center for Forest Resources Technology, Av. Prof. Almeida Prado, 532, 05508-901 São Paulo, SP, Brazil

Introduction

The presence of extractives not only influences the durability of wood, but also its color (Amusant et al. 2008; Pâques et al. 2012). According to Amusant et al. (2004), the relationship between natural resistance and the color of the wood is directly linked to the species, quantity and type of extractives present in the wood. Sapwood most often has a light color and low biological resistance when compared to heartwood, which usually has higher resistance to decay and is darker than sapwood (Thulasidas et al. 2006; Moya and Berrocal 2010). According to Hillis (1971) and Moya et al. (2014), this difference can be explained by the chemical and physiological changes that occur during the formation of the heartwood.

In relation to wood quality, color is a factor that has been studied and may affect its commercialization (Costa et al. 2011; Ribeiro et al. 2018). Overall, light-colored woods are related to lower natural durability and lower market acceptance, requiring techniques to increase the natural resistance and to darken the original color, thus adding value to these woods (Lopes et al. 2014b). Due to this fact, these woods are undervalued in the market, requiring techniques to improve their color characteristics and natural resistance (Kelley et al. 2002; Thulasidas et al. 2006; Moya and Berrocal 2010).

Among wood-destroying organisms, termites are a problem for wood in service and are of considerable economic importance. Species of *Nasutitermes* and *Cryptotermes brevis* Walker (Blattodea: Kalotermitidae) attack wood furniture and wood structures in both rural and urban environments. *Nasutitermes corniger* Motschulsky (Blattodea: Termitidae) is an arboreal termite widely distributed in the Neotropical region and is common in several Brazilian regions where it is becoming an increasingly common urban pest (Gazal et al. 2014; Paes et al. 2015a; de Faria Santos et al. 2017).

Preservative treatments are required to protect low durability wood from these insects. However, recently concerns have arisen regarding the potentially hazardous management of wood treated with conventional chemicals

(Lin et al. 2009; Bolin and Smith 2011; Kartal et al. 2015; Wang et al. 2016). Several studies have highlighted the use of substances extracted from wood and plant species as potential preservatives (Syofuna et al. 2012; Kirker et al. 2013; Tascioglu et al. 2013; Mohammed et al. 2016; Hassan et al. 2017). In addition, plant extracts are biodegradable and do not present the same environmental concerns related to conventional pesticides (Tascioglu et al. 2012).

Some techniques to control, modify the color and improve the natural resistance of the wood have been developed. According to Moya et al. (2014), these techniques include controlled drying, thermal modification and the use of chemicals, but no references of color change with the use of heartwood extractives have been mentioned.

In this context, extracts from durable heartwood and plant species may provide alternatives for color modification and wood protection. Teakwood (*Tectona grandis* L. f.) is known worldwide for its durability and attractiveness with a golden yellow or brown color (Bhat and Florence 2003; Bhat et al. 2005; Thulasidas et al. 2006). In terms of termite resistance, several researches have reported its efficacy (Rudman et al. 1958; Rudman and Gay 1961, 1963) and it is well established that this resistance is attributed to the compounds present in the heartwood, mainly quinones and their derivatives (Haupt et al. 2003; Kokutse et al. 2006; Dungani et al. 2012). However, research on the biocidal effects of these compounds on the termite genera *Nasutitermes* and *Cryptotermes* is scarce, especially when impregnated in non-durable woods.

Therefore, according to the role of extractives in the color and natural resistance of wood, the aim of this study was to evaluate the change in colorimetric patterns and the termite resistance of young teak sapwood and *Pinus* sp. when impregnated with 20-year-old teak heartwood extractives.

Materials and methods

Species, extractions and wood treatment: The extracts used in this research were obtained from the heartwood of four 20-year-old teak trees (*T. grandis*) from the Celulose Nipo-Brasileira – CENIBRA SA company, located in Belo Oriente in the region of Vale do Rio Doce, Minas Gerais state, Brazil (19°15'00" S, 42°22'30" W).

Teak heartwood shavings were collected during the wood processing, ground and classified through the 0.30-mm sieve and then subjected to hot water extraction (HW) and cold extraction in absolute ethanol (AE). A total of 2 kg of sawdust along with 10 l of solvent (water or AE) was introduced into the extraction vessel. After the extractions, HW and AE extracts were concentrated to 4% content (w:v) via a rotary evaporator, according to the results previously obtained in toxicity tests (Brocco et al. 2017).

Extracts in HW, AE and the mixture of them (HW+AE; 1:1, v:v) were used to impregnate the sapwood of 10-year-old teak and *Pinus* sp. via the full-cell process (Bethell process) in a pilot plant consisting of an autoclave with a total useful treatment time of 110 min, with an initial vacuum of 53 kPa (15 min), pressure of 882 kPa (90 min) and final vacuum of 40 kPa (5 min). The dimensions of the species were established by the termite tests, 2.54×2.54×0.64 cm (radial×longitudinal×tangential) and 2.0×10.16×0.64 cm for the no-choice and choice feeding tests against *N. corniger*, respectively, and 2.3×7.0×0.6 cm for the drywood termite (*C. brevis*) test.

After the preservative treatment, the samples were oven-dried at 60°C until a constant weight was achieved. This temperature was used to avoid degradation or loss of extractives by high temperatures (Syofuna et al. 2012). Retention behaviors were previously described by Brocco et al. (2017) and ranged from 10 to 15 kg m⁻³ and 21 to 23 kg m⁻³ for teak sapwood and pinewood, respectively.

The samples selected for color readings were stored in black plastic bags in a conditioning room (25±2°C and 65±5% relative humidity) to prevent color changes caused by oxidation or light. As described by Lopes et al. (2014a), the samples were sanded in a sequence of 80 and 120 grit size in order to remove irregularities and to obtain an oxidation-free surface.

Color changes of impregnated wood: The influence of the teak heartwood extracts on the colorimetric patterns of the impregnated wood was determined according to the Munsell color chart (Munsell 2000) and the CIE-L*a*b* color system (Commission Internationale de l'Éclairage – CIE 1976). After extract impregnation, the treated samples with dimensions of 2.3×7.0×0.6 cm were compared with control samples (without treatment) of 10-year-old teak and pine sapwood. In addition, comparisons were also performed with the 20-year-old teak heartwood, from which the extracts were obtained, and 10-year-old teak heartwood in order to evaluate the effect of the extracts on darkening and homogeneity when compared to heartwood color.

The color determination using the Munsell color chart (Munsell 2000) was performed by visual interpretation of three evaluators who chose the color of the timber according to the following attributes: hue, value and chroma. There are five principal hues (color attribute): red (R), yellow (Y), green (G), blue (B), purple (P); and five intermediate hues: yellow-red (YR), green-yellow (GY), blue-green (BG), purple-blue (PB), red-purple (RP). The Munsell value indicates the lightness of a color – 0 for pure black to 10 for pure white, and chroma represents the saturation or brilliance of a color.

The colorimetric parameters of the wood by the CIE-L*a*b* system were determined using a portable spectrophotometer (Konica Minolta CM-2600d, Tokyo, Japan) that performed five evaluations equally distributed in equidistant points along the radial-longitudinal face of each sample. The parameters of color determination were as follows: an opening diameter of 3 mm ("SAV – small area view"), standard illuminant D65, a 10° observation angle and specular light included (SCI, i.e. measurements include specular and diffuse reflected light).

The variations in the colorimetric patterns were evaluated in light of the changes caused by the tested impregnation solutions. The three color coordinates (L*, a* and b*) of the treated wood were compared with control samples and with the 10- and 20-year-old teak heartwood, so changes were calculated at each coordinate (ΔL^* , Δa^* and Δb^*). ΔL^* , Δa^* and Δb^* represent the change in brightness, redness(+)-greenness(–) and yellowness(–)-blueness(–),

Table 1: Classification of total color variation (ΔE^*) of wood after impregnation.

Total color variation (ΔE^*)	Classification
Negligible	0.0–0.5
Slightly perceivable	0.5–1.5
Noticeable	1.5–3.0
Appreciable	3.0–6.0
Very appreciable	6.0–12.0

Source: Adapted from Hikita et al. (2001). Classifications greater than 12.0 are considered “beyond” very appreciable.

respectively, due to the impregnation with the extracts. The total color change of the wood after impregnation was also determined using Equation 1 (Konica Minolta 2007):

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

After the calculations, the total color variations of the impregnated samples were classified using the table proposed by Hikita et al. (2001) based on visual perception levels (Table 1).

No-choice feeding test against *N. corniger*: A laboratory no-choice feeding test with *N. corniger* termite was performed according to ASTM D 3345 (ASTM:D3345 2017) with slight modifications (Paes et al. 2015a). The assay was prepared in 600 ml screw top bottles filled with 200 g of sterile and sifted sand along with 36 ml of distilled water. One gram of *N. corniger* was then added to each bottle, which corresponded to approximately 350 individuals, 80% workers and 20% soldiers. This was the natural ratio found by weighing five groups of 1 g and it is in accordance with the natural ratio of other colonies worked in our laboratory (Paes et al. 2007; Tiburtino et al. 2015).

After the test period (28 days), the samples were brushed free of debris, oven-dried and the treatment efficacy was evaluated based on visual damage (ratings), mortality (%), weight loss (%) and time (days) to death of termites. Control samples (without preservative treatment) were used in all cases and bottles without termites were also used to evaluate the operational wood weight loss. The wood resistance was also compared to the 20-year-old teak heartwood from which the extractives were obtained.

Choice feeding test against *N. corniger*: A choice test was performed according to the methodology described by Paes et al. (2015c). Samples with dimensions of $2.54 \times 10.16 \times 0.64$ cm (radial $\times$ longitudinal $\times$ tangential) were distributed according to a randomized block design in a 250-l capacity box and filled with a 10-cm layer of moistened sand ($18 \pm 2\%$). The moisture content of the sand was weekly inspected by withdrawing samples from four edges of the box and corrected by the addition of distilled water.

The samples were fixed in the sand up to one third of their height (3.4 cm) and evenly spaced in the center of the box (Figure 1a). The termite colony (*N. corniger*) used in the test was collected in a rural area of Jerônimo Monteiro, Espírito Santo, Brazil, and arranged in a grid supported by two ceramic blocks placed on the sand layer (Figure 1b).

The samples were exposed to termites for 45 days, after which the resistance of treated wood was evaluated via weight loss and visual damage rating caused by the termites.



Figure 1: The specimens were randomly distributed and remained under termite action for 45 days.

Distribution of specimens in the choice test for *N. corniger* termite (a) and termite colony placed on support grid inside the box (b).

Resistance to drywood termites: An assay was performed according to IPT/DIMAD D-2 (IPT 1980). Control and treated samples, measuring $2.3 \times 0.6 \times 7.0$ cm (radial $\times$ tangential $\times$ longitudinal), were exposed to the drywood termite *C. brevis*. The specimens were grouped two by two into five sets. A glass container with a diameter of 3.5 cm and a height of 4.0 cm was fixed with paraffin. Inside the container, 40 termites were introduced, consisting of 39 workers and one soldier. Each set of two specimens, either formed by the teak sapwood or pinewood samples, was introduced into a Petri dish to prevent termite escape.

After 45 days, the assay was stopped and any remaining termites were removed and counted to evaluate mortality and visual damage. The holes made by the termites were also evaluated, and only those that completely crossed the sample were counted. Specimens were oven-dried as described earlier and weighed to evaluate weight loss, which was also corrected for the operational loss from non-termite-exposed wood controls.

Statistical analysis: Colorimetric readings and termite tests were evaluated based on 10 replicates per extractive solution type and treatment. A completely randomized design evaluated the effects of

Table 2: Summary values of color attributes and classification of wood color by the Munsell scale according to the species and extracts tested as determined by observers ($n=3$).

Species	Impregnation	Munsell scale			Classification
		Hue	Value	Chroma	
Teak sapwood	Control	5 Y	8	3	Pale yellow
	HW	5 Y	7	2	Light grey
	AE	2.5 Y	7	4	Pale yellow
	HW + AE	2.5 Y	6	4	Light yellowish brown
10-year-old teak heartwood		7.5 YR	6	6	Reddish yellow
20-year-old teak heartwood		10 YR	5	4	Yellowish brown
<i>Pinus</i> sp.	Control	2.5 Y	8	3	Pale yellow
	HW	10 YR	6	3	Pale brown
	AE	10 YR	6	6	Brownish yellow
	HW + AE	10 YR	6	4	Light yellowish brown

HW, AE and HW + AE: impregnation with extracts in hot water, absolute ethanol and combination of extracts (1:1; v:v), respectively.

the treatment solutions on the test parameters. If significant differences were detected in an analysis of variance (F test with $P \leq 0.05$), the Tukey test ($P \leq 0.05$) was used for comparing the factor or interaction means (when appropriate for the model).

Data normality and the homogeneity of variances were verified using the Lilliefors and Cochran's C tests, respectively. When necessary, the colorimetric data (L^* , a^* , b^* and ΔE^*) were transformed by $\log_{10}$ (L^* , a^* or ΔE), the weight loss data (WL) in $\arcsin \sqrt{(WL_{(\%)}/100)}$ and damage (ratings) or mortality (days) in $\arcsin \sqrt{(x+0.5)}$.

Results and discussion

Color changes of impregnated wood

Munsell system

In the color classification assigned by the Munsell scale, the control samples of teak sapwood were classified as pale yellow (Table 2). The teak sapwood impregnated with HW extracts received a light gray classification. It was noted that this classification was assigned due to the reduction of the “value” and “chroma”, reaching the lowest value when compared to other impregnations.

The impregnations with AE and HW + AE extracts reached similar results in the teak sapwood, although HW + AE obtained the lowest brightness and was classified as light yellowish brown. The 10- and 20-year-old teak heartwood employed as the standard for comparison were classified as reddish yellow and yellowish brown, respectively, with values indicating their lowest brightness.

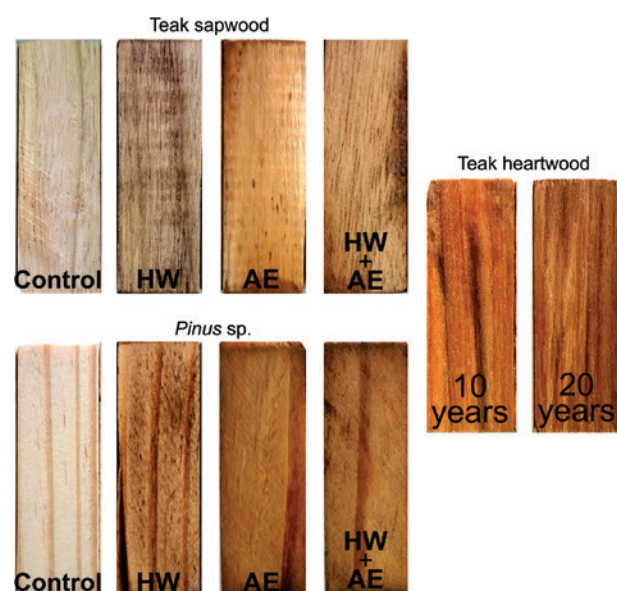


Figure 2: Visual aspects of teak sapwood and *Pinus* sp. impregnated with teak heartwood extracts and the 10- and 20-year-old teak heartwood used for comparison. HW, Hot water; AE, absolute ethanol; HW + AE, mixture of extracts.

Using the Munsell system, Thulasidas et al. (2006) studied 35-year-old teak heartwood from three locations in India and classified the wood color with 9 YR, 5 and 4 for “hue”, “value” and “chroma”, respectively. These values are close to the ratings received by 20-year-old heartwood used in this study.

The impregnation with HW + AE extracts provided the greatest color change in teak sapwood, reaching the classification “light yellowish brown”, which was the closest classification to the teak heartwood color. Figure 2 shows a visual representation of the colorimetric changes in the

impregnated woods compared with the teak heartwood controls. In addition to teak sapwood, the control samples of *Pinus* sp. were classified as pale yellow but with 2.5 Y for hue.

Pinewood treated with HW extracts received a pale brown classification. For AE and HW + AE treatments, it was classified as brownish yellow and light yellowish brown, respectively, in which there were increases in the parameter “chroma”. Visually these two treatments were the ones that provided a gain in the brownish tone for the pinewood.

The evaluation of the color according to the Munsell scale visually enabled the remarkable perception of color changes depending on the extracts tested. However, it is an interpretation based on visual perception and can be influenced by personal judgment of color, requiring methods with greater accuracy to integrate and perform more sensitive classifications of color (Camargos and González 2001).

CIE-L*a*b* system

The CIE-L*a*b* is a quantitative method for color determination that is accurate and objective in which sensitive differences can be detected, enabling comparison levels within and between species at the local level (Thulasidas et al. 2006). Figure 3 gives the average L*, a* and b* values for each treatment group, while Table 3 gives color differences as compared to the respective sapwood controls and Table 4 gives color differences of the treatment groups with respect to the teak heartwood specimens of the two age groups (10 years and 20 years).

It was noted in Figure 3 where for both species, there was a significant reduction in the L* coordinate compared to the impregnated samples and their untreated controls. Also, for both cases, there was no difference in this coordinate between tested extracts and 10-year-old teak heartwood, while there were differences with respect to the 20-year-old teak heartwood.

The impregnation with HW, AE and the combined extracts (HW + AE) caused a darkening in relation to the teak sapwood control sample, reducing the L* coordinate (75) to 60, 63 and 60 (ΔL^* : ≈ -15 , -12 and -14), respectively, making it not statistically different from the brightness of the 10-year-old heartwood teak (ΔL^* : ≈ -16).

Regarding teak sapwood, Lopes et al. (2014a) found a mean reduction in lightness (L* coordinate) of 74 to 63 when the timber was heat-modified at 180°C. This reduction caused by the thermal modification made by Lopes et al. (2014a) is similar to the effects obtained for the

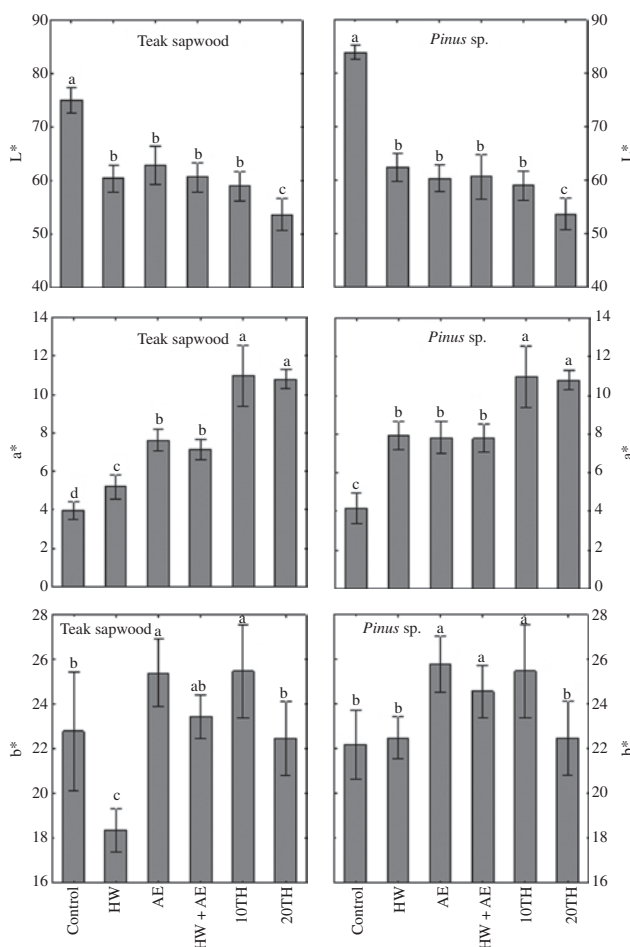


Figure 3: Mean coordinates L*, a* and b* from samples of teak sapwood and pine according to the extracts tested ($n=10$). Intervals represent ± 1 standard deviation (SD). Means followed by the same letter, for each coordinate and species, do not differ statistically (Tukey $P > 0.05$). HW, Hot water; AE, absolute ethanol; HW + AE, mixture of extracts; 10TH and 20TH, 10- and 20-year-old teak heartwood, respectively.

impregnation performed with extracts of teak heartwood used in this work.

By comparing the difference in the L* variable between the heartwood and sapwood of 12-year-old teak wood without treatment, Lopes et al. (2014b) found similar variation (ΔL^* : ≈ 15) to the variation found between untreated teak sapwood and 10-year-old teak heartwood in this study (≈ 16) (Table 3).

For the pinewood, the brightness variation (ΔL^*) that impregnations caused in relation to the control samples was higher when compared to the changes in impregnated teak sapwood. This was because the impregnations reduced the brightness to values similar to those obtained in teak sapwood and due to the higher lightness of pine-wood (L^* : ≈ 84).

Table 3: Values of color changes for each coordinate and the total color difference caused by the impregnation solutions compared to control samples of each species.

Species	Impregnation	ΔL^*	Δa^*	Δb^*	ΔE^*
Teak sapwood	Control	—	—	—	—
	HW	-14.59	1.22	-4.42	15.68 b (3.85)
	AE	-12.18	3.63	2.58	13.50 b (3.98)
	HW + AE	-14.32	3.16	0.65	14.87 b (4.51)
10-year-old teak heartwood		-15.97	7.00	2.68	17.98 ab (3.42)
20-year-old teak heartwood		-21.29	6.81	0.32	22.49 a (2.98)
<i>Pinus</i> sp.	Control	—	—	—	—
	HW	-21.41	3.78	0.30	21.84 c (2.58)
	AE	-23.46	3.66	3.58	24.16 bc (2.16)
	HW + AE	-23.21	3.62	2.38	23.75 bc (3.71)
10-year-old teak heartwood		-24.80	6.82	3.28	26.08 b (3.12)
20-year-old teak heartwood		-30.12	6.62	0.29	30.88 a (3.34)

Means followed by the same letter within each species group are not significantly different (Tukey $P > 0.05$). HW, AE and HW + AE: impregnation with extracts in hot water, absolute ethanol and combination of extracts (1:1; v:v), respectively. See Figure 3 for L^* , a^* and b^* for each treatment group. Values in parentheses are standard deviations.

As the L^* coordinate did not differ between impregnations, it can be said that they caused an average reduction of 22.70. Similar effects were obtained by Silva (2012) when analyzing in the radial direction the color of thermally treated *Pinus taeda* L., where there was a darkening of the color with an average reduction (ΔL^*) for the variable L^* of 6, 19 and 27 for the temperatures 160, 180 and 200°C, respectively.

For a^* (red tone), similar to L^* , impregnated samples differ when compared to the control sapwood samples and heartwood. For the teak sapwood, the most significant increase in the a^* values was those with AE extracts (Δa^* : ≈ 4) and the combination of extracts (HW + AE) (Δa^* : 3). However, the values of this coordinate were higher in the 10- and 20-year-old heartwood samples, with variations (Δa^*) around 7.

Lopes et al. (2014a) found an average increase (Δa^*) of approximately 4 to teak sapwood modified in 180°C. It was noted that the impregnations with AE and HW + AE caused a similar effect to that observed

by Lopes et al. (2014a) in increasing the Δa^* with thermal modification of wood. For the thermal treatment at 200°C, the average increase found by Lopes et al. (2014a) for a^* (Δa^*) was 5. When they compared the mean difference of the red tone (Δa^*) between the heartwood and sapwood with no heat treatment, Lopes et al. (2014b) found a difference of 5, close to the obtained variation in our study between the control samples and the 20-year-old heartwood (Table 3).

The impregnations significantly increased the values of the coordinate a^* of pinewood (a^* : 4.16), and this increase did not differ between the tested impregnations. Analogously to impregnations with HW and HW + AE for the teak sapwood, the extracts of HW, AE and HW + AE produced increases of 3.78, 3.66 and 3.62, respectively, for *Pinus* sp. These increments are intermediate values to those found by Silva (2012), when compared to the color change of *P. taeda* caused by thermal modification at temperatures of 160–180°C, wherein the mean increases in red pigment (Δa^*) were 2.62 and 4.82, respectively.

With regard to the yellow hue (b^*) (Figure 3, Table 3), a reduction of 19% was observed for the teak sapwood when impregnated with HW extracts (Δb^* : -4). The impregnation with the combination of the extracts reached an intermediate value between the two heartwood ages, and they did not differ from each other.

In the pinewood, values for b^* were similar to those in untreated teak sapwood and did not differ from the 20-year-old teak heartwood. The impregnation with HW extract alone did not change the values for this coordinate. The extracts obtained in AE and HW + AE achieved the yellow pigment value (b^*) of the 10-year-old heartwood.

In relation to the total variation of treatments and heartwood samples compared to control samples (Table 3), in the case of teak sapwood, the variations (ΔE^*) were similar between treatments, differing only in the color variation of the 20-year-old teak heartwood (ΔE^* : 22).

Common to both the teak and pinewood cases, the total color variation of the 10-year-old teak heartwood was statistically intermediate between the impregnations tested and the 20-year-old samples. The 20-year-old heartwood had the highest total color differences compared to the pinewood and was significantly different from the others.

It was noted that the impregnated specimens with AE and HW + AE extracts had similar values for the three colorimetric coordinates in both the teak sapwood and pinewood (Figure 3). As the pinewood was lighter colored than the teak sapwood, the total color differences of impregnations were higher for pinewood, which indicates a more significant color change. Using the comparison performed by Hikita et al. (2001) in Table 1, all extracts provided a

Table 4: Color variation caused by the tested extracts in comparison to the 10- and 20-year-old teak heartwood.

Species	Extracts	Δ – 10-year-old teak heartwood				Δ – 20-year-old teak heartwood			
		ΔL^*_{C10}	Δa^*_{C10}	Δb^*_{C10}	ΔE^*_{C10}	ΔL^*_{C20}	Δa^*_{C20}	Δb^*_{C20}	ΔE^*_{C20}
Teak sapwood	HW	1.38	–5.78	–7.10	10.12a (2.32)	6.70	–5.59	–4.11	10.37a (2.51)
	AE	3.78	–3.37	–0.10	6.28b (2.72)	9.10	–3.17	2.90	10.47a (5.31)
	HW + AE	1.64	–3.84	–2.03	6.00b (2.18)	6.96	–3.64	0.96	8.44a (2.80)
<i>Pinus</i> sp.	HW	3.39	–3.04	–2.99	6.94a (1.66)	8.71	–2.84	0.01	9.67a (4.36)
	AE	1.34	–3.15	0.30	5.30a (2.26)	6.66	–2.96	3.30	8.69a (3.24)
	HW + AE	1.58	–3.19	–0.90	7.12a (3.51)	6.90	–3.00	2.09	8.34a (4.89)

Means followed by the same letter within each species group are not significantly different (Tukey $P > 0.05$, or if no differences $F > 0.05$).

HW, AE and HW + AE: impregnation with extracts in hot water, absolute ethanol and combination of extracts (1:1; v:v), respectively. Values in parentheses are standard deviations.

classification of the total variation above the category “very appreciable”, which indicates a significant change of color, and it was even higher for the pinewood, as previously discussed.

The differences for the three colorimetric coordinates and total color variation were also assessed using untreated teak heartwood at 10 and 20 years of age as comparisons (Table 4) in order to check which extract yielded the lowest total change in color when compared to the heartwood. The analysis of variance indicated significant differences in the total color variation among the extracts tested only for the comparison of impregnated teak sapwood relative to the 10-year-old teak heartwood.

According to Table 4, it is possible to observe that, for both species, the total color variation (ΔE^*) of the treatment groups compared to the 10-year-old heartwood was lower than those compared to the 20-year-old heartwood. To the 10-year-old heartwood, the changes caused by the HW extract in teak sapwood (ΔE^* : 10) differ from the ethanol-containing extracts, with the AE and HW + AE extracts (ΔE^* : 6) providing minor variations, in which the total change of color in the latter was classified as appreciable to very appreciable according to Table 1. When compared to the 20-year-old heartwood, there was no significant difference between the variations caused by the extracts tested in teak sapwood, and the total change of color was 10, 10 and 8 for the HW, AE and HW + AE extracts, respectively.

For the pinewood, the lowest value was observed when comparing the 10-year-old samples with the pinewood impregnated with AE extracts (ΔE^* : 5), wherein the

total color variation was classified as appreciable according to Table 1.

In general, impregnated wood of both the sapwood of teak and pinewood achieved lower total color variations compared to those of the 10-year-old teak heartwood, wherein the HW + AE extracts to teak and AE to pine variation was classified as appreciable. For other extracts and in comparison with the 20-year-old heartwood, the total color variations were higher and classified as beyond very appreciable.

It is possible to state, depending on the variations in color parameters caused by impregnation with extracts, that the impregnated woods approached closer to the color of teak heartwood than the control samples of the respective species, in which the variations of the extracts were tested in comparison with the control samples. They were larger and far more expressive, out of the limit classification arranged in Table 1.

No-choice feeding test against *N. corniger*

Analysis of variance showed a significant difference between extract and species tested. In the comparison of the means for weight loss, visual damage ratings and time to death of termites (Table 5), a significant increase in resistance was observed for both species treated. Termite mortality reached 100% in all cases and the data related to the time to death of the termites are described in Table 5.

Teak sapwood samples treated with HW extract showed a slight reduction in weight loss, but not enough

Table 5: Weight loss, visual damage ratings and time to death of the termites according to species and tested treatments in the no-choice test.

Wood species	Treatment	Weight loss (%)	Visual damage (ratings)	Time to death (days)
Teak sapwood	Control	7.51 a (1.42)	8.80 b (0.38)	15.50 a (3.75)
	HW	6.50 a (1.56)	8.80 b (0.61)	13.00 ab (2.40)
	AE	4.32 b (1.07)	9.18 b (0.44)	11.30 b (2.91)
	HW + AE	4.73 b (0.67)	9.70 a (0.14)	7.30 c (1.49)
20-year-old teak heartwood		1.16 c (0.72)	9.72 a (0.17)	15.20 a (2.04)
<i>Pinus</i> sp.	Control	9.76 a (1.35)	6.02 c (1.17)	22.40 a (2.07)
	HW	6.90 b (0.92)	7.62 b (0.72)	19.10 b (3.25)
	AE	3.35 c (1.28)	9.52 a (0.32)	8.50 d (1.78)
	HW + AE	4.01 c (1.15)	9.50 a (0.30)	9.40 d (1.07)
20-year-old teak heartwood		1.16 c (0.72)	9.72 a (0.17)	15.20 a (2.04)

Means followed by the same letter, within each treated species, do not differ (Tukey $P > 0.05$).

HW, AE and HW + AE: treatment with hot water, absolute ethanol and combination of extracts, respectively. Values in parentheses are standard deviations.

to differ from control samples. Treated samples with AE and HW + AE extracts significantly differed from the previous treatments, but did not differ from each other, showing increased resistance of 42 and 37%, respectively, when compared to the control samples.

Regarding visual damage ratings, teak sapwood samples followed the same pattern observed in weight loss. Control, HW extract- and AE extract-treated samples allowed an attack close to slight. The mixture of extracts reached a visual rating close to sound, similar to the 20-year-old teak heartwood and differing from other treatments mentioned earlier.

The teak sapwood control samples allowed the longest termite survival and did not differ from the heartwood samples. However, except for the treatment with HW, AE and AE + HW extracts significantly reduced the survival time of the termites at 27 and 53%, respectively.

Interestingly, wood treated with ethanol and mixed extracts caused faster mortality than the heartwood samples. In the original heartwood samples, the extracts acted differently as there was only a slight weight loss and termite avoidance was observed. As these compounds were impregnated in woods of lower resistance, they allowed some weight loss, probably due to a lower avoidance; however, this allowed the extracts to act in a more toxic way, reducing the time to death of termites.

Weight losses for treated *Pinus* sp. reached similar values to those produced for the treated teak sapwood, but the resistance gains for pinewood were higher due to the lower resistance of the control samples. All treatments differed from the control pine providing a resistance gain of 29, 66 and 59% for HW, AE and combination (AE + HW), respectively. Similar to the teak sapwood, treated pine did not reach the resistance exhibited by the teak heartwood.

Durability ratings of treated pine significantly differed from those of the control samples, which were classified between severe and moderate attack. Pine samples containing AE and the combination of the extracts (HW + AE) were classified between slight and sound attack and did not differ from teak heartwood.

Regarding the time to death of termites, AE and HW + AE treatments promoted a reduction of 62 and 58%, respectively, when compared to *Pinus* sp. without treatment (control). Again, the strong action of the extracts in reducing the time to death of the termites when impregnated in non-durable wood was observed, reaching values similar to those obtained in the treated teak sapwood.

The effectiveness of some teak heartwood extracts, ranging in age from 30 to 79 years and in concentrations from 2 to 10% (w:w), was tested by Dungani et al. (2012) in filter paper bioassays against the subterranean termite *Coptotermes curvignathus*. Acetone:water extracts showed a mean mortality of 95, 99 and 100% for 6, 8 and 10% concentration, respectively, while ethanol:water (8:2) showed 61, 83 and 99%, respectively. For the same situations, means of antifeedancy levels were 57, 72 and 78% for acetone:water and 30, 33 and 35% for ethanol:water.

Although Dungani et al. (2012) did not use these extracts for the treatment of wood, it was evident that acetone extracts exhibited stronger activity than ethanol and the results obtained corroborate those found in this study, highlighting the possibility that other solvents and concentrations not used in this work can guarantee better termite resistance.

Hassan et al. (2018) also corroborates with our results that termite mortality is dependent on extractive concentration. These authors tested ethanol:toluene teak extracts against subterranean termite *Heterotermes*

indicola Wasmann (Blattodea: Rhinotermitidae) both in filter paper bioassay and wood impregnation. The highest concentration (1% w:v) showed 95% of mortality and 80% of repellency.

According to Hassan et al. (2018), this concentration resulted in 100% of mortality and 3% of weight loss when impregnated in both southern pine and cottonwood. Interestingly, the weight loss was practically the same in both species, while in control samples these values were

around 26 and 42% for southern pine and cottonwood, respectively.

Choice feeding test against *N. corniger*

It was observed that when the set of samples with all species and treatments were offered to termites, the preference of attack was for pine samples. In the comparison between the weight loss (Figure 4) and visual durability ratings (Figure 5), there was no significant difference among teak sapwood treatments, where weight losses ranged from 4 to 5%.

Conversely, pine control samples showed the highest weight loss (22%), followed by pine treated with HW extracts without a significant difference. Compared to teak sapwood, the weight loss was almost 5 times higher than in pine control. However, pine treated with AE and HW + AE showed significant differences at 2 and 3%, respectively, which represented an increase in resistance of approximately 88%. In addition, pine with the AE treatment did not differ from both teak sapwood and heartwood samples used as controls in this experiment.

Regarding visual damage ratings (Figure 5), it was possible to observe that only pinewood control samples and those treated with HW extracts differed from the other samples tested, with ratings ranging between 0 and 4, representing an intermediate classification between “failure” and “heavy attack”. Visual damage ratings did not significantly differ in the other samples, ranging from 8 for the teak sapwood with HW extracts to 9 for the 20-year-old teak heartwood samples.

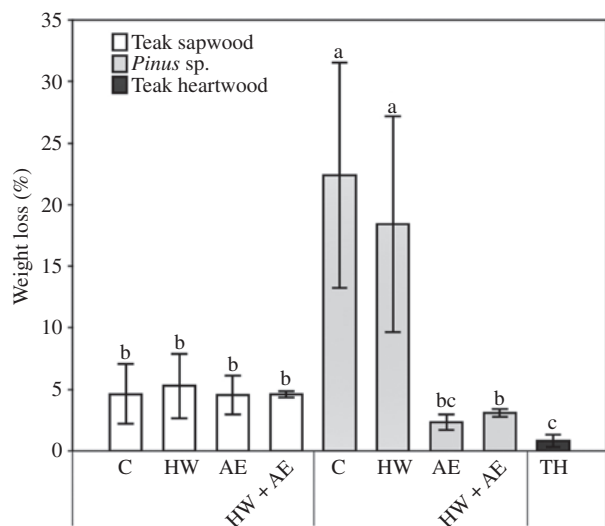


Figure 4: Teak sapwood and pinewood weight loss according to the treatments tested in the no-choice test against *N. corniger*. Means followed by the same letter, within each treated species, do not differ (Tukey $P > 0.05$). *C, Control. HW, Hot water; AE, absolute ethanol; HW + AE, combination of extracts; TH, 20-year-old teak heartwood.

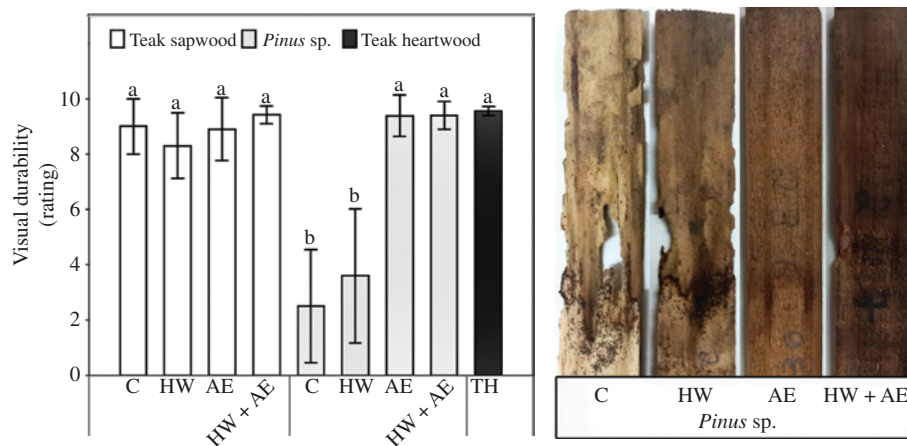


Figure 5: Visual damage ratings for teak sapwood and pinewood according to the treatments tested in the choice feeding test. Means followed by the same letter, within each treated species, do not differ (Tukey $P > 0.05$). *C, control. HW, hot water; AE, absolute ethanol; HW + AE, combination of extracts. TH, 20-year-old teak heartwood. Rating system: 10 – sound; 9 – light; 7 – moderate; 4 – heavy; 0 – failure.

The effect of teak AE extracts on pinewood against the termites tested is evident when visually compared to control samples (Figure 5). This test makes it possible to offer samples of different species and treatments to termites and allow to study combined effects. The resistance results obtained in the choice test correspond to conditions closer to field tests when compared to the no-choice test, and give more consistent data regarding the natural resistance of wood (Paes et al. 2011, 2015c; Syofuna et al. 2012).

Paes et al. (2007) and Motta et al. (2013) exposed teak sapwood samples to *Nasutitermes* sp. attack in the same choice test and obtained an average weight loss of 22 and 24%, respectively, with the visual durability rating ranging from 1 (failure) to 5 (heavy). In both studies, pinewood was not used for comparison.

In our present study, we expected teak sapwood to show larger weight losses in controls than in treated blocks, but the main choice occurred for pinewood. In addition to the preference for *Pinus* sp., some level of resistance to teak sapwood may have contributed to this response.

Lukmandaru and Takahashi (2008) tested resistance to teak among different ages and radial positions and found that even the lowest resistant sapwood position (8-year-old outer sapwood) showed higher antifeedant activity compared to control pinewood samples. Another finding from these authors was that unlike the outer sapwood, the resistance level between inner sapwood and heartwood had no significant difference for 30-year-old teakwood.

These results agree with those of other studies, which found that the main extractives in teak heartwood are also present in sapwood at lower levels and vary among sapwood to the transition zone, influencing the resistance

of wood in this position (Premrasmi and Dietrichs 1967; Lukmandaru and Takahashi 2008, 2009; Moya and Berrocal 2010; Niamké et al. 2011).

Resistance to drywood termites

In the comparison of the weight loss, visual damage rating and mortality, as well as the average number of holes caused by termites (Table 6), it was observed that there was a significant difference between the treatments, for both teak sapwood and *Pinus* sp. However, the variation in weight loss was smaller when compared to the choice and no-choice tests performed against *N. corniger*, with values lower than 2%.

The 20-year-old teak heartwood reached the lowest weight loss, differing from the other treatments tested. The measurement of weight loss in this test was intended to provide additional data, as the Brazilian IPT standard DIMAD D – 2 (IPT 1980) does not require the measurement of weight loss for the drywood termite test. However, due to the low values achieved, weight loss did not appear as an adequate parameter to evaluate the effectiveness of the extractive solutions tested, which may include systematic errors.

Regarding visual damage ratings, there was no significant difference between control and treated samples for the teak sapwood and pinewood, being classified as moderate attack. The wear caused by the termites in the heartwood samples was not very expressive, with ratings close to zero, indicating almost no wear.

Control samples of the teak sapwood reached moderate mortality to drywood termites. It was noted that the

Table 6: Weight loss, visual damage ratings, mortality and number of holes caused by drywood termites depending on the species and treatments tested.

Wood species	Treatment	Weight loss (%)	Visual damage (ratings)	Mortality (%)	Number of holes
Teak sapwood	Control	1.15 a (0.19)	2.08 a (0.33)	46.50 b (12.82)	0
	HW	0.62 b (0.18)	2.20 a (0.24)	49.50 ab (9.91)	0
	AE	0.72 b (0.17)	1.96 a (0.30)	66.10 ab (25.90)	1
	HW + AE	1.44 a (0.28)	1.80 a (0.35)	71.00 a (7.83)	0
20-year-old teak heartwood		0.08 c (0.08)	0.32 b (0.36)	72.00 a (11.10)	0
<i>Pinus</i> sp.	Control	1.76 a (0.55)	2.28 a (0.27)	44.50 b (10.06)	2
	HW	0.77 b (0.45)	2.08 a (0.30)	45.50 b (17.62)	1
	AE	0.27 bc (0.26)	1.80 a (0.00)	38.50 b (8.77)	1
	HW + AE	0.72 b (0.26)	1.80 a (0.00)	39.00 b (9.12)	1
20-year-old teak heartwood		0.08 c (0.08)	0.32 b (0.36)	72.00 a (11.10)	0

Means followed by the same letter, within each treated species, do not differ (Tukey $P > 0.05$).

HW, AE and HW + AE: treatment with hot water, absolute ethanol and combination of extracts, respectively. Values in parentheses are standard deviations. Rating system: 0 – No damage, 1 – surface, 2 – moderate, 3 – accentuated and 4 – deep damage.

treatment with the extracts combination differed from the control samples and showed values close to teak heartwood, where mortality was classified as high, while HW and AE treatments showed intermediate mortality, not differing between them. In general, there was an increase in mortality according to the treatments tested in the teak sapwood. However, the same trend could not be observed for *Pinus* sp., where no significant difference was observed among the treatments tested.

There was no appreciable difference between the average number of holes produced by termites in the teak sapwood compared to heartwood. All samples of *Pinus* sp. were perforated by drywood termites, ranging from 1 to 2 holes per sample. The control samples presented the highest mean number of holes, almost 2 per sample. For the treatments, this mean was reduced, ranging from 1 to 1.2.

Berrocal Jiménez and Rojas Acuña (2007) studied the resistance of teak wood from Costa Rica to the drywood termite *C. brevis* and found variations similar to those in our present study. According to the authors, there was no significant difference for the weight loss between heartwood and sapwood (1%). Mortality was classified as high in both positions, and wear (visual rating) was classified as moderate to sapwood and superficial to heartwood.

Paes et al. (2015b) evaluated the resistance of young teak wood to drywood termites and found significant differences, although not expressive values, for the weight loss between heartwood (0%) and sapwood (1%); however, the results did not reflect a significant difference in the mortality of termites. Still, according to Paes et al. (2015b), samples of both positions were not completely perforated by the termites.

Among teak extractives that play a key role in the natural resistance of wood, quinone derivatives have been reported to influence termite resistance in different ways (Dungani et al. 2012). For drywood termites, anthraquinones may act as repellents, while in subterranean termites their effects have been reported ranging from non-toxic, deterrents to toxic (Wolcott 1947; Rudman et al. 1967; Ismayati et al. 2016).

Our results do not suggest clear effects of the extracts tested on drywood termites, as the significant increase on termite mortality for the treated teak sapwood was not observed for the pinewood samples. Gonçalves et al. (2013) and Paes et al. (2013) evaluated different wood species for their drywood termite resistance and found that, besides the influence of extractives, a set of factors such as density and ash content affected the resistance of the wood. In addition, Paes et al. (2013) only found a significant correlation of drywood termite attack for the ash content of wood.

Conclusions

Teak heartwood extracts tested provided a remarkable action in the color change and resistance gain for both pine and teak sapwood tested. Ethanol and mixture of extracts showed darker appearances in the impregnated wood compared to the control samples. This darkening effect allowed a smaller gap between the tested wood color and 20-year-old teak heartwood, making it possible to reduce the undesirable characteristics associated with lighter color woods on the market.

The extracts contributed to the reduction of the time to death of the termite *N. corniger*, and the most expressive resistance gains observed in the choice feeding test. The resistance of wood to the attack by the drywood termite *C. brevis* was not clearly changed, although termite mortality increased for termites exposed to treated teak sapwood.

The use of teak extract shows potential for use as a natural color modifier and wood preservative against termites. However, further studies are required for a more realistic approach using viable sources such as sawmill waste, as well as testing other classes of extracts and improving methods for extraction on a larger scale. In addition, weathering and leaching tests would provide data to better understand the performance of these extracts in the treated non-durable wood.

Author contributions: All the authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.

Research funding: This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

Employment or leadership: None declared.

Honorarium: None declared.

Conflict of interest: The authors wish to confirm that there are no known conflicts of interest associated with this publication.

References

- Amusant, N., Beauchene, J., Fournier, M., Janin, G., Thevenon, M. (2004) Decay resistance in *Dicorynia guianensis* Amsh: analysis of inter-tree and intra-tree variability and relations with wood colour. *Ann. For. Sci.* 61:373–380.
- Amusant, N., Fournier, M., Beauchene, J. (2008) Colour and decay resistance and its relationships in *Eperua grandiflora*. *Ann. For. Sci.* 65:806–812.
- American Society for Testing and Materials (ASTM) (2017) D3345-17. Standard Test Method for Laboratory Evaluation of Wood and Other Cellulosic Materials for Resistance to Termites. ASTM

- International, West Conshohocken, PA, 2017. doi:10.1520/D3345-17.
- Berrocal-Jiménez, A., Rojas-Acuña, L.V. (2007) Teak (*Tectona grandis* L.f.) wood resistance, from forest plantation, to the attack of dry wood termites *Cryptotermes brevis* (Walker). *Rev. For. Mesoam.* Kurú 4:1–15.
- Bhat, K.M., Florence, E.J.M. (2003) Natural decay resistance of juvenile teak wood grown in high input plantations. *Holz-forschung* 57:453–455.
- Bhat, K.M., Thulasidas, P.K., Maria Florence, E.J., Jayaraman, K. (2005) Wood durability of home-garden teak against brown-rot and white-rot fungi. *Trees Struct. Funct.* 19:654–660.
- Bolin, C.A., Smith, S. (2011) Life cycle assessment of ACQ-treated lumber with comparison to wood plastic composite decking. *J. Clean. Prod.* 19:620–629.
- Brocco, V.F., Paes, J.B., da Costa, L.G., Brazolin, S., Arantes, M.D.C. (2017) Potential of teak heartwood extracts as a natural wood preservative. *J. Clean. Prod.* 142:2093–2099.
- Camargos, J.A.A., Gonçalves, J.C. (2001) Applied colorimetry as instrument in the elaboration of a timber color chart. *Bras. Florest.* 71:30–41.
- Commission Internationale de l'Éclairage – CIE. Colorimetry. Part 4: CIE 1976 (L*a*b*) System. 2nd ed. Vienna, 1986. CIE no. 15.2.
- Costa, M.A., Costa, A.F., Pastore, T.C.M., Braga, J.W.B., Gonçalves, J.C. (2011) Characterization of wood decay by rot fungi using colorimetry and infrared spectroscopy. *Cienc. Florest.* 21:567–577.
- de Faria Santos, A., Fernandes Carrijo, T., Marques Cancellato, E., Coletto Morales-Corrêa E Castro, A. (2017) Phylogeography of *Nasutitermes corniger* (Isoptera: Termitidae) in the Neotropical Region. *BMC Evol. Biol.* 17:230.
- Dungani, R., Bhat, I.U.H., Khalil, H.P.S.A., Naif, A., Hermawan, D. (2012) Evaluation of antitermitic activity of different extracts obtained from Indonesian teakwood (*Tectona grandis* L.f.). *BioResources* 7:1452–1461.
- Gazal, V., Bailez, O., Viana-Bailez, A.M., Aguiar-Menezes, E.L., Menezes, E.B. (2014) Behavioral responses of the arboreal termite *Nasutitermes corniger* (Isoptera: Termitidae) to wood extracts. *Wood Sci. Technol.* 48:581–590.
- Gonçalves, F.G., Pinheiro, D.T.C., Paes, J.B., de Carvalho, A.G., de Oliveira, G.L. (2013) Natural durability of wood forest species to dry-wood termite attack. *Floresta e Ambient.* 20:110–116.
- Hassan, B., Mankowski, M.E., Kirker, G., Ahmed, S. (2017) Effects of heartwood extractives on symbiotic protozoan communities and mortality in two termite species. *Int. Biodeterior. Biodegradation* 123:27–36.
- Hassan, B., Ahmed, S., Mankowski, M., Kirker, G., Ibach, R.E., Misbah ul Haq, M. (2018) Effects of teak, *Tectona grandis* Linn, heartwood extractives against *Heterotermes indicola* (Isoptera: Rhinotermitidae). *Proceedings of the International Research Group on Wood Protection, Johannesburg, South Africa. Document No. IRG/WP 18-10910.*
- Haupt, M., Leithoff, H., Meier, D., Puls, J., Richter, H.G., Faix, O. (2003) Heartwood extractives and natural durability of plantation-grown teakwood (*Tectona grandis* L.) – a case study. *Holz als Roh- und Werkst.* 61:473–474.
- Hikita, Y., Toyoda, T., Azuma, M. (2001) Weathering testing of timber-discoloration. In: *High-Performance Utilization of Wood for Outdoor Uses*. Ed. Imamura, Y. Press-Net, Kyoto, Japan. pp. 27–32.
- Hillis, W.E. (1971) Distribution, properties and formation of some wood extractives. *Wood Sci. Technol.* 4:272–289.
- Instituto de Pesquisas Tecnológicas – IPT/DIMAD. D-2. Ensaio acelerado de laboratório da resistência natural ou Madeira preservada ao ataque de térmitas do gênero *Cryptotermes*. São Paulo: IPT/DIMAD, 1980. 1p. (Publicação IPT 1157). In Portuguese.
- Ismayati, M., Nakagawa-Izumi, A., Kamaluddin, N., Ohi, H. (2016) Toxicity and feeding deterrent effect of 2-methylantraquinone from the wood extractives of *Tectona grandis* on the subterranean termites *Coptotermes formosanus* and *Reticulitermes speratus*. *Insects* 7:63.
- Kartal, S.N., Terzi, E., Yilmaz, H., Goodell, B. (2015) Bioremediation and decay of wood treated with ACQ, micronized ACQ, nano-CuO and CCA wood preservatives. *Int. Biodeterior. Biodegradation* 99:95–101.
- Kelley, S.S., Jellison, J., Goodell, B. (2002) Use of NIR and pyrolysis-MBMS coupled with multivariate analysis for detecting the chemical changes associated with brown-rot biodegradation of spruce wood. *FEMS Microbiol. Lett.* 209:107–111.
- Kirker, G.T., Blodgett, A.B., Arango, R.A., Lebow, P.K., Clausen, C.A. (2013) The role of extractives in naturally durable wood species. *Int. Biodeterior. Biodegradation* 82:53–58.
- Kokutse, A.D., Stokes, A., Bailleres, H., Kokou, K., Baudasse, C. (2006) Decay resistance of Togolese teak (*Tectona grandis* L.) heartwood and relationship with colour. *Trees* 20:219–223.
- Konica Minolta. Precise Color Communication: Color Control from Perception to Instrumentation, Konica Minolta Sensing Inc., Japan, 2007.
- Lin, L.-D., Chen, Y.-F., Wang, S.-Y., Tsai, M.-J. (2009) Leachability, metal corrosion, and termite resistance of wood treated with copper-based preservative. *Int. Biodeterior. Biodegradation* 63:533–538.
- Lopes, J.O., Garcia, R.A., Latorraca, J.V.F., Nascimento, A.M. (2014a) Color change of teak wood by heat treatment. *Floresta e Ambient.* 21:521–534.
- Lopes, J.O., Garcia, R.A., Nascimento, A.M., Latorraca, J.V.F. (2014b) Color uniformization of the young teak wood by heat treatment. *Rev. Árvore* 38:561–568.
- Lukmandaru, G., Takahashi, K. (2008) Variation in the natural termite resistance of teak (*Tectona grandis* Linn. fil.) wood as a function of tree age. *Ann. For. Sci.* 65:708–716.
- Lukmandaru, G., Takahashi, K. (2009) Radial distribution of quinones in plantation teak (*Tectona grandis* L.f.). *Ann. For. Sci.* 66:605–605.
- Mohammed, S.A., Madhan, B., Demissie, B.A., Velappan, B., Tamil Selvi, A. (2016) *Rumex abyssinicus* (mekmeko) Ethiopian plant material for preservation of goat skins: approach for cleaner leather manufacture. *J. Clean. Prod.* 133:1043–1052.
- Motta, J.P., Oliveira, J.T.S., Paes, J.B., Alves, R.C., Dambroz, G.B.V. (2013) Natural resistance of *Tectona grandis* wood in laboratory assay. *Ciência Rural* 43:1393–1398.
- Moya, R., Berrocal, A. (2010) Wood colour variation in sapwood and heartwood of young trees of *Tectona grandis* and its relationship with plantation characteristics, site, and decay resistance. *Ann. For. Sci.* 67:109.
- Moya, R., Bond, B., Quesada, H. (2014) A review of heartwood properties of *Tectona grandis* trees from fast-growth plantations. *Wood Sci. Technol.* 48:411–433.
- Munsell Color. Munsell Soil Color Charts. Kollmorgen Instruments Corp., Baltimore, MD, 2000.

- Niamké, F.B., Amusant, N., Charpentier, J.P., Chaix, G., Baissac, Y., Boutahar, N., Adima, A.A., Kati-Coulibaly, S., Jay-Allemand, C. (2011) Relationships between biochemical attributes (non-structural carbohydrates and phenolics) and natural durability against fungi in dry teak wood (*Tectona grandis* L. f.). *Ann. For. Sci.* 68:201–211.
- Paes, J.B., Melo, R.R., Lima, C.R., Oliveira, E. (2007) Natural resistance of seven woods to *Nasutitermes corniger* (Motsch.) termite under alimentary preference assay. *Rev. Bras. Ciências Agrárias* 2:57–62.
- Paes, J.B., Souza, A.D.d., Lima, C.R.d., Medeiros Neto, P.N.d. (2011) Efficiency of neem (*Azadirachta indica*) and castor (*Ricinus communis*) oils on protection of *Ceiba pentandra* wood against xylophagous termites under feed preference assay. *Rev. Árvore* 35:751–758.
- Paes, J.B., Medeiros Neto, P.N.d., Lima, C.R.d., Freitas, M.d.F.d., Diniz, C.E.F. (2013) Effects of extractives and ash on natural resistance of four woods to xylophagous termites. *Cerne* 19:399–405.
- Paes, J.B., Brocco, V.F., Moulin, J.C., Motta, J.P., Alves, R.C. (2015a) Effects of extractives and density on natural resistance of woods to termite *Nasutitermes corniger*. *Cerne* 21:569–578.
- Paes, J.B., Santos, L.L., Silva, L.F., Motta, J.P., Braz, R.L., Lombardi, L.R. (2015b) Technological characterization of juvenile wood teak (*Tectona grandis*) to production of furnitures. *Brazilian J. Agric. Sci.* 10:437–442.
- Paes, J.B., Segundinho, P.G.d.A., Euflosino, A.E.R., Silva, M.R.d., Calil Junior, C., Oliveira, J.G.L.d. (2015c) Resistance of thermally treated woods to *Nasutitermes corniger* in a food preference test. *Madera y Bosques* 21:157–164.
- Pâques, L.E., García-Casas, M.D.C., Charpentier, J.-P. (2012) Distribution of heartwood extractives in hybrid larches and in their related European and Japanese larch parents: relationship with wood colour parameters. *Eur. J. For. Res.* 131:1269–1278.
- Premrasmi, T., Dietrichs, H.H. (1967) Nature and distribution of extractives in teak (*Tectona grandis* linn.) from Thailand. *Nat. Hist. Bull. Siam Soc.* 22:1–14.
- Ribeiro, E.S., González, J.C., Lima, C.M., Rodrigues, C.E.C., Paula, M.H., Mesquita, R.R.S., Queiroz, F.L.C., Lesses, O.M.G. (2018) Colorimetry and anatomical characterization of commercial wood species from the Brazilian Amazon. *Aust. J. Basic Appl. Sci.* 12:15–23.
- Rudman, P., Gay, F.J. (1961) The causes of natural durability in timber. Pt. VI. Measurement of anti-termite properties of anthraquinones from *Tectona grandis* L. f. by a rapid semi-micromethod. *Holzforschung* 15:117–120.
- Rudman, P., Gay, F.J. (1963) The causes of natural durability in timber Pt. X. The deterrent properties of some three-ringed carbocyclic and heterocyclic substances to the subterranean termite *Nasutitermes exitiosus* (Hill). *Holzforschung* 17:21–25.
- Rudman, P., Da Costa, E.W.B., Gay, F.J., Wetherly, A.H. (1958) Relationship of tectoquinone to durability in *Tectona grandis*. *Nature* 181:721–722.
- Rudman, P., Da Costa, E.W.B., Gay, H.J. (1967) Wood quality in plus trees of teak (*Tectona grandis* L.f.): an assessment of decay and termite resistance. *Sylvae Genet.* 16:102–105.
- Silva, M.R. Thermal rectification effect on the mechanical, chemical and physical properties in structural elements of *Eucalyptus citriodora* and *Pinus taeda*. PhD thesis. Universidade de São Paulo, São Carlos, Brazil, 2012. doi:10.11606/T.88.2012.tde-18012013-093404. In Portuguese.
- Syofuna, A., Banana, A.Y., Nakabonge, G. (2012) Efficiency of natural wood extractives as wood preservatives against termite attack. *Maderas. Cienc. Tecnol.* 14:155–163.
- Tascioglu, C., Yalcin, M., de Troya, T., Sivrikaya, H. (2012) Termiticidal properties of some wood and bark extracts used as wood preservatives. *BioResources* 7:2960–2969.
- Tascioglu, C., Yalcin, M., Sen, S., Akcay, C. (2013) Antifungal properties of some plant extracts used as wood preservatives. *Int. Biodeterior. Biodegradation* 85:23–28.
- Thulasidas, P.K., Bhat, K.M., Okuma, T. (2006) Heartwood colour variation in home garden teak (*Tectona grandis*) from wet and dry localities of Kerala, India. *J. Trop. For. Sci.* 18:51–54.
- Tiburtino, R.F., Paes, J.B., Vidaurre, G.B., Brocco, V.F., Arantes, M.D.C. (2015) Resistance of two bamboo species treated with CCB against termites and xilophagous beetles. *Cienc. Florest.* 25:425–435.
- Wang, L., Chen, S.S., Tsang, D.C.W., Poon, C.-S., Shih, K. (2016) Recycling contaminated wood into eco-friendly particleboard using green cement and carbon dioxide curing. *J. Clean. Prod.* 137:861–870.
- Wolcott, G.N. (1947) The permanence of termite repellents. *J. Econ. Entomol.* 40:124–129.