

## EFFECT OF THE THERMAL TREATMENT ON THE CHEMICAL COMPONENTS, SORPTION, AND SHRINKAGE PROPERTIES OF

### *Tectona grandis* JUVENILE WOOD

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#### ABSTRACT

The effect of thermal treatment on the chemical components, equilibrium moisture content (EMC), and shrinkage of teak juvenile wood was studied. Heartwood and sapwood samples were thermally-treated at 180 °C and 200 °C. Extractive, Klason lignin, holocellulose, and  $\alpha$ -cellulose contents, as well as pH on untreated and thermally-treated woods, were determined. The EMC was reached at five relative humidity (RH) levels using saturated salt solutions: 86 % (KCl), 76 % (NaCl), 58 % (NaBr), 33 % (MgCl<sub>2</sub>), and 0 % (P<sub>2</sub>O<sub>5</sub>). Linear and volumetric shrinkages were calculated for all EMCs. The ratio of sorption (S), coefficient of shrinkage ( $h$ ), and fiber saturation point (FSP) were also determined. Thermally-treated wood exhibited lower holocellulose and  $\alpha$ -cellulose contents than untreated wood and increased acidity due to degradation of the hemicelluloses. The thermal treatment reduced the EMC of heartwood and sapwood. However, sapwood was more sensitive to RH variations than heartwood regardless of the treatment. Thermally-treated woods had higher hygroscopic and dimensional stabilities, and lower FSP than untreated wood. The thermal treatment did not affect radial shrinkage of the heartwood between 33 % and 86 % RH. Heartwood was more sensitive to the effect of the thermal treatment on shrinkage and degradation of cell wall polymers compared to sapwood.

**Keywords:** Chemical modification, dimensional stability, equilibrium moisture content, shrinkage, teak, *Tectona grandis*.

## INTRODUCTION

39

40 Thermal modification is a technique that has been extensively studied in the last years because it  
41 enhances several wood properties such as lower hygroscopicity and higher dimensional stability  
42 (Giebeler 1983) and decay resistance (Weiland and Guyonnet 2003). The treatment provokes physical  
43 and chemical changes to wood, such as extractive volatilization, formation of new compounds (e.g.  
44 anhydrosugars and phenolic compounds), degradation of the hemicelluloses (Esteves *et al.* 2011),  
45 changes in the lignin structure (Kim *et al.* 2014), increase of crystalline cellulose (Li *et al.* 2015), and  
46 mass losses (Garcia *et al.* 2012), among other modifications. These chemical changes reduce the OH<sup>-</sup>  
47 groups available in cell walls, promoting lower hygroscopicity and higher dimensional stability to  
48 thermally-treated woods.

49 The teak (*Tectona grandis*) plantations in Brazil have shorter cutting cycles (15 to 25 years) compared  
50 to those in its native region and other regions around the world (Tsukamoto Filho *et al.* 2003, FAO  
51 2000) due to favorable edaphoclimatic conditions and management techniques. However, teak wood  
52 from fast-grown plantations exhibits high proportions of juvenile wood and sapwood, which have  
53 different anatomical, physical, chemical, and aesthetic properties than those of mature wood and  
54 heartwood (Bhat *et al.* 2001, Lopes 2012, Darmawan *et al.* 2015). Studies have shown that the  
55 proportion of juvenile wood measured at breast height (1.3 m) is 80-100 % for 20-year-old trees (Bhat  
56 *et al.* 2001) and 100 % for 10-year-old trees (Darmawan *et al.* 2015). Juvenile wood presents, for  
57 example, lower density, lower shrinkage, shorter fibers, higher microfibril angle, and lower bending  
58 strength than mature wood (Darmawan *et al.* 2015). Teak heartwood presents good dimensional  
59 stability and high biological durability due to some substances such as caoutchouc (Yamamoto *et al.*  
60 1998), tectoquinone ( $\beta$ -methyl anthraquinone), 2-(hydroxymethyl) anthraquinone, and lapachol  
61 (Niamké *et al.* 2011). On the other hand, teak sapwood presents a lighter color, lower dimensional  
62 stability and low resistance to the attack of xylophagous organisms than heartwood (Lopes 2012,  
63 Motta *et al.* 2013). Therefore, treatments to improve the properties of sapwood are required to

64 increase the yield of this raw material. Previous studies have shown that thermal treatments provide  
65 color uniformity to pieces of teak wood containing heartwood and sapwood (Lopes *et al.* 2014). In  
66 addition, thermally-treated teak wood can show higher color stability after exposure to ultraviolet  
67 radiation depending on the treatment conditions (Garcia *et al.* 2014).  
68 Studies about the dimensional stability of wood are essential for its use because it depends on the  
69 relationships between specific gravity and the relative humidity (RH) of the air (Tsoumis 1991).  
70 Particularly for teak species, studies have reported the volumetric swelling (Kartikawati *et al.* 2020)  
71 and anti-swelling efficiency of heat-treated and untreated 15-year-old teak wood from Indonesia  
72 (Priadi *et al.* 2019), the maximum shrinkage of teak wood from the West Africa region (tree age was  
73 not specified) (Govorčín *et al.* 2010) among others. However, there are no studies on the dimensional  
74 stability of thermally-treated teak juvenile wood under different RH conditions, in particular teak  
75 wood from fast-growing plantations in Brazil, which highlights the originality of our study. In  
76 general, teak wood is popular in outdoor applications (Weaver 1993), which require materials with  
77 attractive color, high dimensional stability under different climatic conditions, and high resistance to  
78 pathogens and weathering (Kokutse *et al.* 2006).  
79 With the ultimate goal of contributing to a better understanding of the properties of teak wood after  
80 heat treatment and to enhance the use of teak wood from young plantations in Brazil, this study aimed,  
81 in the first part, to assess the effect thermal treatments on the chemical composition of juvenile teak  
82 wood (heartwood and sapwood), while in the second part, we studied the EMC and the variation of  
83 shrinkage under different RH of thermally-treated wood.

## 84 MATERIAL AND METHODS

### 85 Material and thermal treatment

86 Twelve-year-old teak (*Tectona grandis* Linn. f.) trees were harvested from a plantation located in  
87 Caceres city, Mato Grosso State, Brazil (Latitude: 16° 04' 14" S, Longitude: 57° 40' 44" W). Based  
88 on previous studies (Bhat *et al.* 2001; Flórez *et al.* 2014; Darmawan *et al.* 2015), we have assumed

89 that the samples contained only juvenile wood as they were obtained from fast-growing young trees.  
90 In addition, samples were taken from the second log cut from the diameter at breast height, where the  
91 proportion of juvenile wood is greater. Samples of 150 mm (L) x 75 mm (T) x 20 mm (R) were  
92 prepared from heartwood or sapwood.

93 Wood samples were heat-treated in a muffle furnace of 600 mm x 600 mm x 700 mm equipped with  
94 a temperature and time controller. The treatment was performed at four steps: (1) heating up to 100  
95 °C for 2 h, (2) heat increasing from 100 °C to final temperature (180 °C or 200 °C) for 30 min, (3)  
96 thermal exposure at the final temperature for 2,5 h, and (4) cooling for approximately 24 h. Before  
97 and after thermal treatment, samples were conditioned at 20 °C and 65 % RH until mass equilibrium  
98 was reached.

#### 99 **Chemical analysis**

100 Chemical analyses were done according to ASTM-D1105-96 (ASTM 2001) and ASTM-D1106-96  
101 (ASTM 2001) to determine extractive, Klason lignin, holocellulose, and  $\alpha$ -cellulose contents. The  
102 extractive contents were obtained after extractions in a Soxhlet apparatus for 24 h using three organic  
103 solvents of increased polarity: cyclohexane, ethyl acetate, and methanol.

104 The Klason lignin was obtained after treatment of approximately 300 mg extractive-free dry ground  
105 wood with 72 % sulfuric acid ( $H_2SO_4$ ) in a water bath at 30 °C for 1 h, followed by dilution to 84 mL  
106 distilled water and refluxing for 4 h. The residue was washed with 500 mL hot distilled water and  
107 oven-dried at  $103 \text{ °C} \pm 2 \text{ °C}$  for 24 h. The Klason lignin content was estimated by dividing the oven-  
108 dry weight of the residue (insoluble lignin) by the weight of the extractive-free wood.

109 The holocellulose fraction was determined by the chlorination method using 2,5 g of extractive-free  
110 dry wood added of 80 mL hot distilled water, 0,5 mL acetic acid, and 1 g sodium chlorite ( $NaClO_2$ ).  
111 The mixture was heated in a water bath at 70 °C, and another dose of 0,5 mL acetic acid and 1 g  
112  $NaClO_2$  were added every 1 h until the fibers were completely separated. The mixture was left for 24  
113 h without reagent addition and was then filtered under vacuum and washed with distilled water until

114 the yellow color and chlorine odor completely disappeared. The residue was oven-dried at 103 °C ±  
115 2 °C for 24 h and weighed. The holocellulose content was then estimated by dividing the oven-dry  
116 weight of the residue (holocellulose) by the weight of the extractive-free wood.

117 The α-cellulose was obtained after treatment of 2 g dry holocellulose with 10 mL of 17,5 % sodium  
118 hydroxide (NaOH) in a water bath at 20 °C. Another 5 mL of 17,5 % NaOH was added to the mixture  
119 at 5 min intervals for a total treatment of 45 min. A 33 mL distilled water at 20 °C was added and left  
120 for 1 h. The mixture was filtered under vacuum and subsequently washed with 100 mL of 8,3 %  
121 NaOH and with distilled water. The cellulose residue was oven-dried at 103 °C ± 2 °C for 24 h. The  
122 cellulose content was estimated by dividing the oven-dry weight of the cellulose residue by the weight  
123 of the dry holocellulose residue.

124 The pH of wood was determined as described by Lelis (1995). A 5 g of ground wood oven-dried at  
125 103 °C ± 2 °C for 24 h was mixed with distilled water at room temperature and left for 24 h. The  
126 mixture was filtered and the pH was measured with an electronic pHmeter.

127 Three replicates per treatment were used for each chemical component and pH analysis.

### 128 **Sorption tests**

129 Samples of 20 mm (L) x 15 mm (T) x 13 mm (R) were prepared with the untreated and heat-treated  
130 wood pieces of each wood type: heartwood and sapwood. Firstly, the samples were full saturated  
131 following a mild procedure in three steps: (1) adsorption in desiccators containing potassium chloride  
132 - KCl (86 % RH) at 21 °C with mass measurements until equilibrium was reached; (2) adsorption in  
133 desiccators over deionized water until mass equilibrium was reached; and (3) immersion in deionized  
134 water for seven days until full saturation was reached. Afterward, samples were separated into five  
135 matched groups. One group was immediately put in a desiccator over phosphorus pentoxide - P<sub>2</sub>O<sub>5</sub>  
136 (0 % RH). The other four groups were placed for desorption in desiccators at four levels of RH: 86  
137 %, 76 %, 58 %, and 33 %, by using saturated salt solutions of potassium chloride (KCl), sodium  
138 chloride (NaCl), sodium bromide (NaBr), and magnesium chloride (MgCl<sub>2</sub>), respectively. A total of

139 42 samples, 7 replicates for each treatment [wood type (sapwood and heartwood) and temperature  
140 (control or untreated, and treated at 180 °C, and 200 °C)] were used for each sorption condition.  
141 Samples were placed into two desiccators per RH condition.  
142 Desorption tests were conducted simultaneously on all samples using sorption vats as described by  
143 Hernández and Pontin (2006). The temperature of the vats was established at 21 °C. These vats  
144 provided temperature control of  $\pm 0,01$  °C for long periods and thus allowing control of RH in the  
145 various desiccators serving as small sorption chambers. The samples were placed in plastic supports  
146 with a perforated base to promote the exchange of moisture. The weight of samples was measured  
147 periodically without removing them from the desiccators until a constant mass was reached.  
148 All mass of samples was taken to the nearest 0,001 g and their dimensions were measured in the three  
149 principal directions with a micrometer to the nearest 0,001 mm after full saturation. Dimensions and  
150 mass of the four groups of conditioned samples were also measured once their corresponding sorption  
151 equilibrium condition was reached and then they were immediately oven-dried at 103 °C for 24 h.  
152 Samples dimensions at the oven-dried state were measured after a 20 min period of cooling over P<sub>2</sub>O<sub>5</sub>.

### 153 **Equilibrium moisture content and ratio of sorption**

154 The EMC of untreated and thermally-treated woods was calculated with the mass of the samples at  
155 equilibrium and the oven-dried mass, expressed as a percentage of oven-dry mass.

156 The sorption ratio (S) is a parameter of hygroscopicity proposed by Noack *et al.* (1973) to characterize  
157 the sensitivity of the EMC variation ( $\Delta EMC$ ) related to the variation in RH ( $\Delta RH$ ) (Equation 1). This  
158 parameter assumes that there is a linear relationship between EMC and RH. Therefore, the S-ratio  
159 was calculated for desorption between 33 % and 76 % RH.

$$160 \quad S = \Delta EMC / \Delta RH \quad (1)$$

### 161 **Shrinkage and coefficient of shrinkage**

162 The linear shrinkages in the tangential ( $\beta_T$ ), radial ( $\beta_R$ ), and longitudinal ( $\beta_L$ ) directions were  
163 calculated in percentage. Volumetric shrinkage was estimated as the sum of these three directional

164 measurements [ $\beta_V$  involves the product  $\beta_T \times \beta_R$  in order to achieve sufficient accuracy within the  
165 range of  $\beta_T$  and  $\beta_R$  values normally found for wood, as described by Skaar (2012)] (Equation 2).  
166 Shrinkages of untreated and thermally-treated woods were obtained for all EMCs.

$$167 \quad \beta_V(\%) = \beta_T + \beta_R + \beta_L - (\beta_T \times \beta_R) \quad (2)$$

168 The coefficient of shrinkage ( $h$ ) is a general index of dimensional stability proposed by Noack *et al.*  
169 (1973) to determine the swelling/shrinkage of the wood for every 1 % RH. The  $h$ -coefficient was  
170 calculated with the volumetric shrinkage ( $\Delta\beta_V$ ) for desorption between 33 % and 76 % RH (Equation  
171 3).

$$172 \quad h = \Delta\beta_V / \Delta RH \quad (3)$$

### 173 **Statistical analysis**

174 Statistical analyses were done with a STATISTIC 10.0 software. Analysis of variance (ANOVA) and  
175 Tukey's tests (at 0,01 of the probability level) were used to verify the effects of the wood type  
176 (heartwood and sapwood) and temperature (control or untreated and treated at 180 °C, and 200 °C)  
177 on the extractives, Klason lignin, hemicellulose, and  $\alpha$ -cellulose contents, pH, EMC, and shrinkage  
178 components ( $\beta_T$ ,  $\beta_R$ ,  $\beta_L$ , and  $\beta_V$ ). The normality and homogeneity of variance were verified by the  
179 Shapiro-Wilk and Levene's tests.

## 180 **RESULTS AND DISCUSSION**

### 181 **Chemical changes**

182 A significant interaction was found between wood type (heartwood, sapwood) and temperature for  
183 all chemical components (extractive, Klason lignin, holocellulose, and  $\alpha$ -cellulose) and pH (Tables 1  
184 and 2). The untreated heartwood had a higher extractive content than the untreated sapwood. The  
185 extractive content gradually increased as the temperature of treatment increased for both wood types  
186 (Table 3). The total extractive content of treated heartwood and sapwood respectively increased by  
187 53 % and 64 % at 180 °C and by 122 % and 100 % at 200 °C compared to untreated woods. Similar  
188 behavior for the extractive content was observed by other authors after thermal treatments (Gašparík

189 *et al.* 2019, Bellon 2013, Lengowski 2011). Gašparík *et al.* (2019) found an increase of 56 % on teak  
 190 extractive after the ThermoWood® treatment at 210 °C. Also, the extractive content increased by 135  
 191 % (Bellon 2013) and 158 % (Lengowski 2011) in the 160 °C-treated teak wood from VAP  
 192 HolzSysteme® industrial process compared to untreated wood. However, these studies did not  
 193 separate heartwood from sapwood material. The increase of the extractive content is not related to  
 194 the natural extractives of wood, which are in large part volatilized during the thermal treatment, but  
 195 to by-products formed mainly from the degradation of the hemicelluloses. According to International  
 196 ThermoWood Association (2003), temperatures ranging from 120 °C to 180 °C increase the  
 197 extractive content of wood while the temperature up to 230 °C causes a decrease in extractives.

198 **Table 1:** F-values obtained from the ANOVA of the effects of the wood type (heartwood, sapwood)  
 199 and temperature treatment on the extractive content of teak wood.

Source of variation	Extractive content			Total extractive content
	Cyclohexane	Ethyl acetate	Methanol	
Wood type	37,4**	1367,2**	722,5**	34,9**
Temperature	865,1**	443,4**	375,0**	1218,6**
Wood type*Temperature	111,8**	15,4**	23,3**	24,7**

\*\*Significant at the 1 % probability level.

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201 **Table 2:** F-values obtained from the ANOVA of the effects of the wood type (heartwood, sapwood)  
 202 and temperature treatment on the chemical components and pH of teak wood.

Source of variation	Klason lignin	Holocellulose	$\alpha$ -cellulose	pH
Wood type	6,1*	784,0**	1312,7**	2212,1**
Temperature	6,6*	707,2**	33,3**	512,1**
Wood type*temperature	2,0 <sup>ns</sup>	109,1**	2,6 <sup>ns</sup>	21,6**

\*, \*\* Significant at the 5 % and 1 % probability level respectively; <sup>ns</sup> not significant.

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**Table 3:** Means of the extractive contents of untreated and thermally-treated teak heartwood and sapwood.

Wood type	Temperature (°C)	Extractive content (%)			Total extractive content (%)
		Cyclohexane	Ethyl acetate	Methanol	
Heartwood	Control	1,60 (0,12) d	2,63 (0,05) e	2,63 (0,05) c	6,86 (0,21) c
	180	2,15 (0,08) b	4,58 (0,05) b	3,73 (0,08) b	10,46 (0,25) b
	200	4,52 (0,05) a	5,13 (0,08) a	5,56 (0,10) a	15,21 (0,40) a
Sapwood	Control	0,51 (0,06) e	2,70 (0,05) e	0,61 (0,08) f	3,82 (0,16) d
	180	1,93 (0,03) c	3,23 (0,08) d	1,12 (0,08) e	6,28 (0,01) c
	200	2,41 (0,05) b	3,71 (0,08) c	1,50 (0,05) d	7,62 (0,03) c

The number in parentheses are standard errors. Means within a column followed by the same letters are not significantly different at the 1 % probability level.



205 **Table 4:** Means of the chemical component contents and pH of untreated and thermally-treated teak  
 206 heartwood and sapwood.

Wood type	Temperature (°C)	Klason Lignin (%)	Holocellulose (%)	$\alpha$ -cellulose (%)	pH
Heartwood	Control	29,3 (1,5) b	63,6 (0,4) b	45,4 (1,1) c	5,55 (0,03) d
	180	31,3 (1,5) ab	57,0 (0,2) d	42,6 (1,4) c	4,86 (0,02) e
	200	35,7 (3,1) a	47,3 (0,8) e	39,6 (1,4) d	4,72 (0,09) f
Sapwood	Control	29,7 (3,2) ab	66,5 (0,6) a	60,8 (1,6) a	6,53 (0,01) a
	180	27,7 (1,5) b	63,6 (0,7) b	58,6 (0,8) ab	5,72 (0,03) c
	200	31,3 (1,5) ab	59,4 (0,1) c	57,5 (0,5) b	5,92 (0,02) b

The number in parentheses are standard errors. Means within a column followed by the same letters are not significantly different at the 1 % probability level.

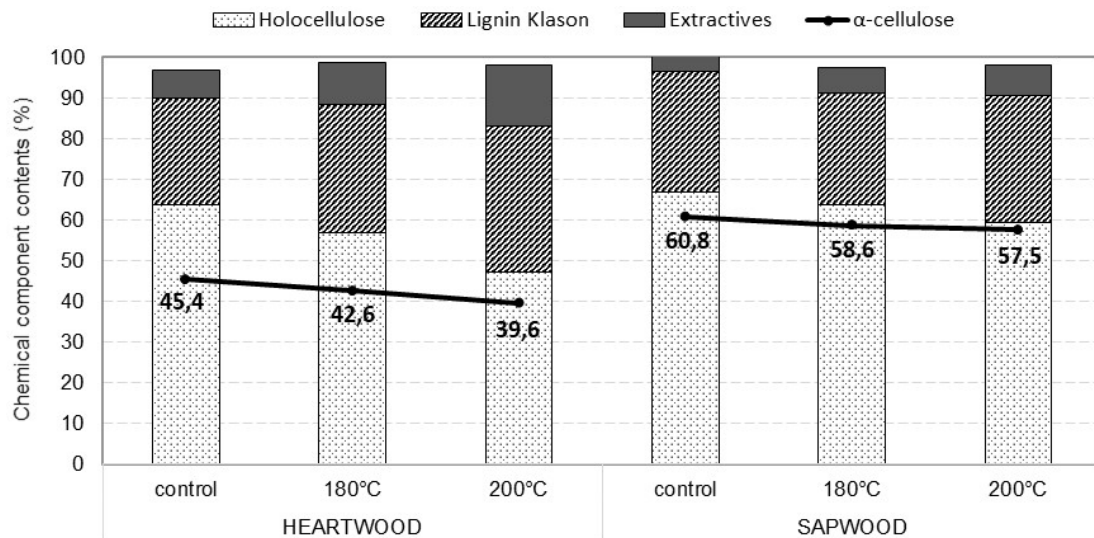
207 The treatment at 200 °C increased the Klason lignin content in heartwood but not in sapwood (Table  
 208 4). The increase in lignin content was also found in thermally-treated teak (Bellon 2013; Lengowski  
 209 2011), Caribbean pine (Poubel *et al.* 2013), and eucalypt (de Moura *et al.* 2012) woods. Several works  
 210 have reported chemical changes in lignin structure due to thermal treatments. Chemical analysis of  
 211 thermally-treated teak wood assessed by Fourier-transform infrared (FTIR) spectroscopy showed an  
 212 increase in band intensity at 1328 cm<sup>-1</sup> assigned to C-H vibration in cellulose and C<sub>1</sub>-O vibration in  
 213 syringyl derivative-condensed structures in lignin, which suggest the formation of condensed  
 214 structures (Li *et al.* 2015). Kim *et al.* (2014) also reported depolymerization (cleavage of  $\beta$ -O-4  
 215 linkage) and condensation between lignin fragments during thermal treatment. Although the thermal  
 216 treatment affects lignin due to depolymerization, hemicelluloses reach a more advanced stage of  
 217 degradation starting at 180 °C compared to lignin, which results in an apparent lignin increase in  
 218 relation to the other components of the cell wall (Sundqvist 2004).

219 The untreated sapwood exhibited the highest holocellulose and  $\alpha$ -cellulose contents (Table 4).  
 220 According to Stamm (1964), hemicellulose and cellulose (amorphous portion and crystallite surfaces)  
 221 are the main responsible for the hygroscopicity of wood while lignin plays a secondary role.

222 Holocellulose content decreased gradually with the temperature increase for both wood types (Table  
 223 4). The holocellulose content of treated heartwood and sapwood decreased by 10 % and 4 % at 180  
 224 °C, and by 26 % and 11 % at 200 °C, respectively. The holocellulose decrease in treated woods was

225 probably due to the degradation of hemicelluloses. The results regarding the heartwood and sapwood  
226 behavior confirm those of previous works. Lopes *et al.* (2018) used infrared spectroscopy to assess  
227 the chemical modification of the surface of thermally-modified teak wood. A more pronounced  
228 decrease in OH<sup>-</sup> groups in heartwood than in sapwood after heat treatment was observed. The authors  
229 provide a good discussion about the different chemical changes in teak heartwood and sapwood after  
230 heat treatment and the greater sensitivity of the heartwood to thermal degradation compared to  
231 sapwood, but it is not yet clear why this occurs. No significant differences were found between  $\alpha$ -  
232 cellulose contents of untreated and 180 °C-treated woods. On the other hand, the  $\alpha$ -cellulose content  
233 decreased in the 200 °C-treated heartwood and sapwood. Among the chemical constituents of the cell  
234 wall, hemicelluloses are primarily consumed because they are easily degraded at low temperatures  
235 (140 °C) while cellulose is more resistant to thermal degradation (Sundqvist 2004). Other authors  
236 reported a holocellulose decrease of 24-25 % in teak (Bellon 2013, Lengowski 2011), 18,6 % in  
237 *Eucalyptus grandis*, and 4,6 % in *Pinus taeda* woods after thermal treatment at 160 °C by the VAP  
238 HolzSysteme<sup>®</sup> process (Lengowski 2011).

239 In summary, the chemical changes caused by the thermal treatment were more important in heartwood  
240 than in sapwood (Figure 1). The apparent total extractive content (or by-products formed mainly from  
241 the degradation of hemicelluloses) increased more in the thermally-treated heartwood than in the  
242 thermally-treated sapwood due to greater susceptibility to thermal degradation of the former. The  
243 relative lignin content increased by 20 % in 200 °C-treated heartwood while no significant change  
244 was found in the sapwood. The holocellulose content decreased more in heartwood than in sapwood  
245 at both thermal treatment degrees. The  $\alpha$ -cellulose content decreased by 12,8 % in heartwood and 5,4  
246 % in sapwood after the treatment at 200 °C. Studies realized by Lopes *et al.* (2018) using FTIR  
247 spectroscopy also reported a more important thermal degradation in heartwood than in sapwood.



**Figure 1:** Chemical component contents of untreated and thermally-treated teak wood.

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250 The untreated heartwood was more acid (pH = 5,55) than the untreated sapwood (pH = 6,53) (Table  
 251 4). The high acidity of heartwood compared to sapwood has often been reported in the literature for  
 252 several hardwood species (Kakavas *et al.* 2018; Passialis *et al.* 2008). Untreated woods usually have  
 253 a pH near to 5,0-5,5 (Boonstra *et al.* 2007), however, pH values depend on the extraction conditions  
 254 (Geffert *et al.* 2019). Lower pH values are found with hot water extraction compared to cold water,  
 255 due to the greater release of acetic acid (Geffert *et al.* 2019). Therefore, the extraction method used  
 256 in our study can explain the high pH values found in untreated teak woods, principally sapwood. The  
 257 thermal treatment significantly decreased the pH values of both types of wood, principally of the  
 258 heartwood. The most expressive chemical degradation in the heartwood after thermal treatment can  
 259 be also confirmed by its higher acidity. The increased acidity in thermally-treated woods can be  
 260 explained by the hemicellulose degradation and formation of acetic acid. This acid also acts as  
 261 catalysts in the depolymerization process of the cellulose microfibrils breaking them into smaller  
 262 chains (Boonstra *et al.* 2007), in addition to the condensation and degradation reactions in lignin  
 263 structure (Li *et al.* 2015) that result in the formation of phenolic groups (Kim *et al.* 2014).

264 **Equilibrium moisture content**

265 The ANOVAs showed respectively a significant effect of the heat treatment and wood type on the  
 266 EMC for all moisture sorption conditions, except in the anhydrous state (Table 5). As expected, the

267 analysis of untreated samples showed that the EMC was lower in heartwood than sapwood (Table 6).  
268 This can be attributed to the higher proportion of extractives present in heartwood (Table 3). Previous  
269 work about the chemical composition of teak juvenile wood assessed by FTIR spectroscopy also  
270 showed a higher extractive content (quinones, oils, and waxes) in heartwood than sapwood (Lopes *et*  
271 *al.* 2018). In fact, several works have shown that teak wood and other tropical woods have a  
272 hydrophobic behavior due to the presence of extractives in their tissues (Hernández 2007a, Jankowska  
273 *et al.* 2017). Furthermore, EMC decreased due to the heat treatments (control to 180 °C to 200 °C)  
274 for all moisture sorption conditions and wood types (Table 6). For instance, the EMC of heartwood  
275 and sapwood treated at 180 °C significantly decreased 3,9 % and 1,1 % MC compared to the  
276 corresponding untreated samples in desorption at 86 % RH, respectively. EMC decreased even more  
277 for samples treated at 200 °C, namely 4,9 % for heartwood and 4,7 % MC for heartwood and sapwood  
278 at the same RH. For all cases, the decrease in EMC due to the heat treatment was higher for heartwood  
279 than for sapwood.

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**Table 5:** F-values obtained from the ANOVAs of the effects of the wood type (heartwood, sapwood) and temperature treatment on the EMC and each shrinkage component.

0% RH					
Source of variation	EMC	$\beta_T$	$\beta_R$	$\beta_L$	$\beta_V$
Wood type	4,5 <sup>ns</sup>	29,3 <sup>**</sup>	35,1 <sup>**</sup>	0,01 <sup>ns</sup>	40,7 <sup>**</sup>
Temperature	1,3 <sup>ns</sup>	16,4 <sup>**</sup>	26,6 <sup>**</sup>	4,8 <sup>ns</sup>	29,5 <sup>**</sup>
Wood type*temperature	1,9 <sup>ns</sup>	4,4 <sup>*</sup>	3,1 <sup>ns</sup>	0,01 <sup>ns</sup>	5,2 <sup>*</sup>
33% RH					
Source of variation	EMC	$\beta_T$	$\beta_R$	$\beta_L$	$\beta_V$
Wood type	14,3 <sup>**</sup>	21,9 <sup>**</sup>	12,0 <sup>**</sup>	3,3 <sup>ns</sup>	19,3 <sup>**</sup>
Temperature	67,6 <sup>**</sup>	11,7 <sup>**</sup>	2,4 <sup>ns</sup>	0,8 <sup>ns</sup>	5,8 <sup>**</sup>
Wood type*temperature	4,7 <sup>*</sup>	3,4 <sup>*</sup>	1,6 <sup>ns</sup>	0,4 <sup>ns</sup>	4,8 <sup>*</sup>
58% RH					
Source of variation	EMC	$\beta_T$	$\beta_R$	$\beta_L$	$\beta_V$
Wood type	40,1 <sup>**</sup>	80,5 <sup>**</sup>	25,05 <sup>**</sup>	0,6 <sup>ns</sup>	34,3 <sup>**</sup>
Temperature	84,9 <sup>**</sup>	12,8 <sup>**</sup>	2,3 <sup>ns</sup>	1,75 <sup>ns</sup>	9,8 <sup>**</sup>
Wood type*temperature	3,4 <sup>*</sup>	2,2 <sup>ns</sup>	2,6 <sup>ns</sup>	0,33 <sup>ns</sup>	3,7 <sup>*</sup>
76% RH					
Source of variation	EMC	$\beta_T$	$\beta_R$	$\beta_L$	$\beta_V$
Wood type	49,1 <sup>**</sup>	112,1 <sup>**</sup>	15,2 <sup>**</sup>	0,01 <sup>ns</sup>	83,7 <sup>**</sup>
Temperature	107,5 <sup>**</sup>	20,8 <sup>**</sup>	2,8 <sup>ns</sup>	1,7 <sup>ns</sup>	14,3 <sup>**</sup>
Wood type*temperature	2,6 <sup>ns</sup>	3,7 <sup>*</sup>	2,2 <sup>ns</sup>	2,2 <sup>ns</sup>	5,9 <sup>**</sup>
86% RH					
Source of variation	EMC	$\beta_T$	$\beta_R$	$\beta_L$	$\beta_V$
Wood type	126,9 <sup>**</sup>	34,6 <sup>**</sup>	2,8 <sup>ns</sup>	2,2 <sup>ns</sup>	13,2 <sup>**</sup>
Temperature	101,1 <sup>**</sup>	6,1 <sup>**</sup>	1,9 <sup>ns</sup>	2,7 <sup>ns</sup>	2,2 <sup>ns</sup>
Wood type*temperature	12,6 <sup>**</sup>	2,3 <sup>ns</sup>	0,1 <sup>ns</sup>	0,1 <sup>ns</sup>	1,6 <sup>ns</sup>

\*,\*\* Significant at the 5 and 1 % probability level respectively; <sup>ns</sup> not significant.

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**Table 6:** Means of the equilibrium moisture content (EMC) of untreated and thermally-treated teak heartwood and sapwood for different sorption conditions at 21 °C.

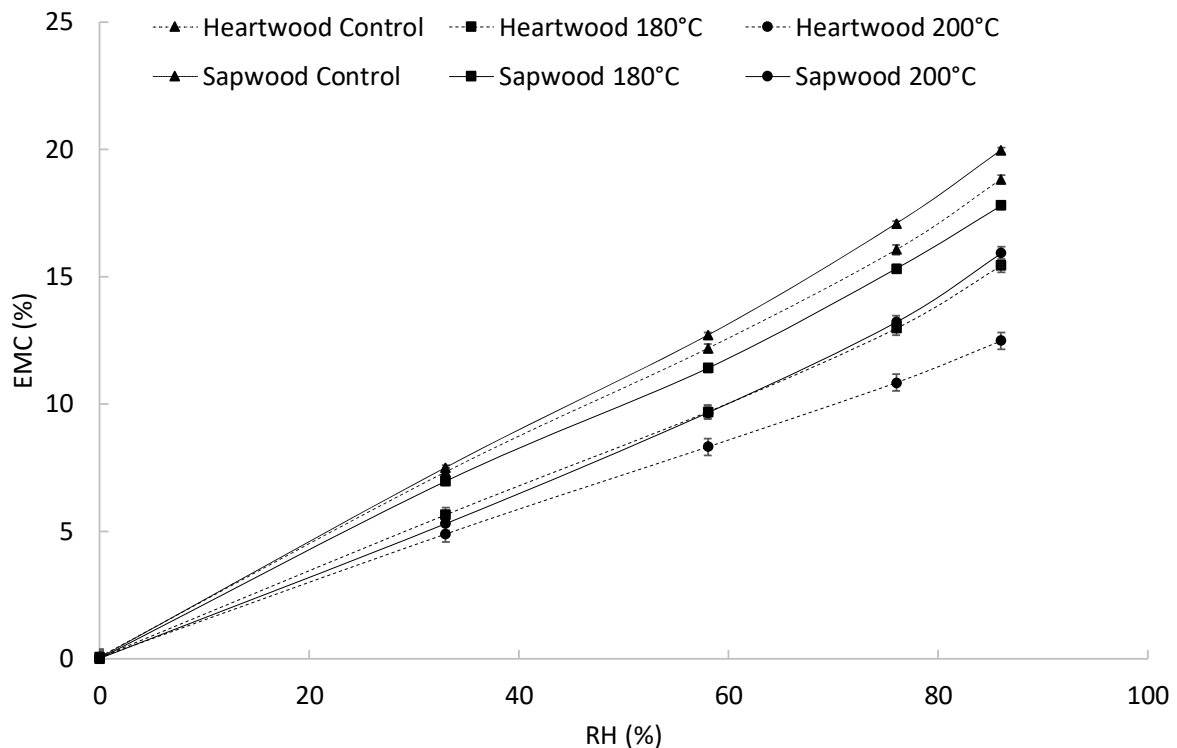
Temperature (°C)	EMC in desorption (%)									
	0 % RH		33 % RH		58 % RH		76 % RH		86 % RH	
	Heart-wood	Sap-wood	Heart-wood	Sap-wood	Heart-wood	Sap-wood	Heart-wood	Sap-wood	Heart-wood	Sap-wood
Control	0,09 Aa (0,08) <sup>1</sup>	0,04 Aa (0,04)	7,3 Aa (0,1)	7,5 Aa (0,1)	12,2 Aa (0,2)	12,7 Aa (0,1)	16,1 Ba (0,2)	17,1 Aa (0,1)	19,9 Ba (0,3)	21,9 Aa (0,02)
180	0,07 Aa (0,06)	0,01 Aa (0,04)	5,7 Bb (0,2)	7,0 Aa (0,6)	9,7 Bb (0,3)	11,4 Ab (0,1)	13,0 Bb (0,3)	15,3 Ab (0,1)	16,0 Bb (0,4)	20,8 Ab (0,3)
200	0,05 Aa (0,03)	0,01 Aa (0,04)	4,9 Ac (0,2)	5,3 Ab (0,4)	8,3 Bc (0,3)	10,0 Ac (0,4)	10,5 Bc (0,5)	12,8 Ac (0,4)	15,0 Bb (0,7)	17,2 Ac (0,3)

<sup>1</sup> The standard error is given in parentheses. Means followed by the same letters are not significantly different at the 5 % probability level. Uppercase letters: mean comparisons between wood types, for each temperature and RH separately. Lowercase letters: mean comparisons among thermal treatments within a column.

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297 The difference in EMC between untreated samples and both treated woods (180 °C or 200 °C),  
 298 increased as RH increased from 33 % to 86 %, for both heartwood and sapwood (Figure 2). The most

299 important decrease in EMC occurred at 200 °C. The 200 °C-treated wood had lower holocellulose  
300 and  $\alpha$ -cellulose contents (Table 4) and higher total extractive content (by-products formed during  
301 thermal degradation) (Table 3) than other treatments. These chemical modifications may explain the  
302 lowest EMC of 200 °C-treated heartwood and sapwood compared to the other treatments. Other  
303 studies have reported reductions in EMC of teak wood thermally-treated at 160 °C (Lengowski 2011,  
304 Bellon 2013).  
305 Generally, the sapwood had higher EMC than the heartwood after the heat treatments (Table 6, Figure  
306 2). This is due to the higher holocellulose and  $\alpha$ -cellulose contents in sapwood (Table 4) which are  
307 the most hygroscopic polymers of cell walls. The higher extractive content of treated heartwood could  
308 also affect the EMC because they decrease the wood hygroscopicity.



309 **Figure 2:** Equilibrium moisture content (EMC) in desorption of untreated and thermally-treated  
310 teak wood as a function of relative humidity (RH) at 21 °C.  
311

### 312 Shrinkage

313 The results of untreated samples confirmed that teak wood presents low values of partial and total  
314 shrinkages compared to other tropical hardwoods (FPL 2010). As expected, untreated heartwood had

315 lower total and partial linear and volumetric shrinkages than untreated sapwood at all moisture  
316 sorption conditions. The total  $\beta_T$ ,  $\beta_R$ ,  $\beta_L$ , and  $\beta_V$  of heartwood were of 4,6 %, 2,6 %, 0,5 %, and 7,7  
317 % while those of untreated sapwood were of 5,2 %, 3,3 %, 0,5 %, and 8,8 %, respectively (Table 7).  
318 However, given the very low values, no significant difference was found between heartwood and  
319 sapwood for  $\beta_L$ . These results are similar to those reported by Miranda *et al.* (2011) to 50-70 years-  
320 old teak wood, which were 5,2 %, 3,5 %, and 7,6 % (mean from pith to bark) for  $\beta_T$ ,  $\beta_R$ , and  $\beta_V$ ,  
321 respectively. The lower shrinkage in heartwood is attributed to the high extractive content observed  
322 in this wood type (Hernández 2007b, Jankowska *et al.* 2017).

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340 **Table 7:** Means of the shrinkage of untreated and thermally-treated teak heartwood and sapwood  
 341 for different sorption conditions at 21 °C.

Tangential shrinkage – $\beta_T$ (%)										
Temperature (°C)	0 % RH		33 % RH		58 % RH		76 % RH		86 % RH	
	Heart-wood	Sap-wood	Heart-wood	Sap-wood	Heart-wood	Sap-wood	Heart-wood	Sap-wood	Heart-wood	Sap-wood
Control	4,6 Ab (0,3)	5,2 Aa (0,4)	3,1 Ba (0,3)	3,8 Aa (0,2)	1,7 Ba (0,1)	2,5 Aa (0,1)	0,9 Ba (0,08)	1,5 Ab (0,07)	0,4 Ba (0,1)	0,9 Aa (0,1)
180	2,9 Ba (0,2)	5,2 Aa (0,1)	2,2 Bb (0,2)	3,8 Aa (0,1)	1,3 Bb (0,1)	2,5 Aa (0,06)	0,8 Ba (0,08)	1,8 Aa (0,05)	0,3 Ba (0,04)	0,8Aa (0,06)
200	2,7 Ba (0,3)	3,7 Ab (0,3)	2,1 Ab (0,3)	2,6 Ab (0,3)	1,2 Bb (0,07)	1,9 Ab (0,2)	0,5 Bb (0,1)	1,1 Ac (0,08)	0,3 Ba (0,04)	0,5 Ab (0,04)
Radial shrinkage – $\beta_R$ (%)										
Temperature (°C)	0 % RH		33 % RH		58 % RH		76 % RH		86 % RH	
	Heart-wood	Sap-wood	Heart-wood	Sap-wood	Heart-wood	Sap-wood	Heart-wood	Sap-wood	Heart-wood	Sap-wood
Control	2,6 Ba (0,2)	3,3 Aa (0,1)	1,5 Aa (0,1)	1,9 Aa (0,2)	0,8 Ba (0,07)	1,0 Aa (0,1)	0,5 Aa (0,06)	0,6 Aa (0,04)	0,4 Aa (0,03)	0,9 Aa (0,1)
180	1,5 Bb (0,1)	2,7 Ab (0,1)	1,2 Ba (0,1)	2,0 Aa (0,2)	0,7 Ba (0,04)	1,2 Aa (0,04)	0,5 Ba (0,02)	0,8 Aa (0,06)	0,3 Aa (0,05)	0,4 Aa (0,1)
200	1,7 Ab (0,2)	2,1 Ac (0,2)	1,2 Aa (0,2)	1,5 Aa (0,1)	0,7 Aa (0,1)	0,9 A (0,02)	0,4 Aa (0,06)	0,5 Aa (0,07)	0,1 Aa (0,03)	0,3 Aa (0,1)
Longitudinal shrinkage – $\beta_L$ (%)										
Temperature (°C)	0 % RH		33 % RH		58 % RH		76 % RH		86 % RH	
	Heart-wood	Sap-wood	Heart-wood	Sap-wood	Heart-wood	Sap-wood	Heart-wood	Sap-wood	Heart-wood	Sap-wood
Control	0,51 Aa (0,01)	0,50 Aa (0,04)	0,33 Aa (0,06)	0,23 Aa (0,02)	0,14 Aa (0,07)	0,15 Aa (0,07)	0,11 Aa (0,03)	0,12 Aa (0,02)	0,15 Aa (0,05)	0,10 Aa (0,04)
180	0,42 Aa (0,02)	0,43 Aa (0,06)	0,27 Aa (0,03)	0,24 Aa (0,04)	0,16 Aa (0,05)	0,08 Aa (0,04)	0,04 Aa (0,02)	0,09 Aa (0,04)	0,20 Aa (0,04)	0,16 Aa (0,03)
200	0,34 Aa (0,04)	0,34 Aa (0,04)	0,25 Aa (0,04)	0,19 Aa (0,04)	0,07 Aa (0,02)	0,04 Aa (0,05)	0,13 Aa (0,04)	0,07 Aa (0,02)	0,27 Aa (0,04)	0,19 Aa (0,06)
Volumetric shrinkage – $\beta_V$ (%)										
Temperature (°C)	0 % RH		33 % RH		58 % RH		76 % RH		86 % RH	
	Heart-wood	Sap-wood	Heart-wood	Sap-wood	Heart-wood	Sap-wood	Heart-wood	Sap-wood	Heart-wood	Sap-wood
Control	7,7 Ba (0,4)	8,8 Aa (0,4)	4,7 Ba (0,3)	5,8 Aa (0,3)	2,7 Ba (0,2)	3,7 Aa (0,2)	1,5 Ba (0,1)	2,2 Ab (0,08)	0,9 Aa (0,1)	1,4 Aa (0,2)
180	4,9 Bb (0,3)	8,3 Aa (0,2)	3,6 Bb (0,3)	6,1 Aa (0,4)	2,2 Bab (0,1)	3,7 Aa (0,1)	1,3 Bab (0,08)	2,6 Aa (0,08)	0,6 Ba (0,2)	1,4 Aa (0,1)
200	4,7 Bb (0,5)	6,1 Ab (0,4)	3,9 Aab (0,5)	4,2 Ab (0,3)	2,0 Ab (0,2)	2,5 Ab (0,3)	1,1 Bb (0,2)	1,7 Ac (0,1)	0,7 Aa (0,07)	0,9 Aa (0,1)

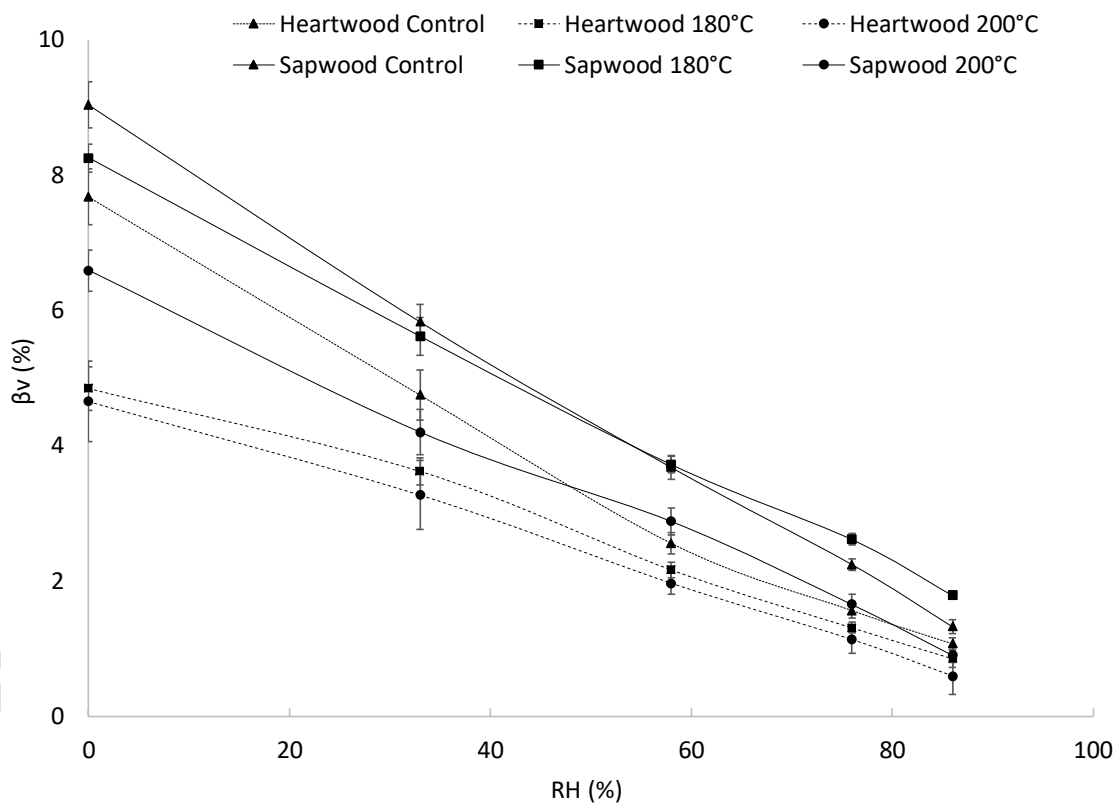
The standard error is given in parentheses. Means followed by the same letters are not significantly different at the 5 % probability level. Uppercase letters: mean comparisons between wood types within a row, for each RH separately. Lowercase letters: mean comparisons among temperatures within a column, for each shrinkage type separately.

342



343 The ANOVAs showed a significant effect of the wood type and the thermal treatment on the linear  
344 (except for  $\beta_L$ ) and volumetric shrinkages for almost all moisture sorption conditions. The wood type  
345 showed a more important effect on partial and total shrinkages compared to the temperature treatment  
346 (Table 5). The thermal treatment decreased partial shrinkage in both heartwood and sapwood,  
347 however, this effect would be more important in sapwood (Table 7, Figure 3). Total linear and  
348 volumetric shrinkages also decreased with the thermal treatments for both wood types but this effect  
349 would be more important in heartwood (Table 7). At 200 °C, the  $\beta_T$  of the heartwood and sapwood  
350 decreased respectively by 41 % and 29 %,  $\beta_R$  decreased by 35 % and 36 % and  $\beta_V$  decreased by 39  
351 % and 31 %, compared to untreated woods.

352



353 **Figure 3:** Volumetric shrinkage ( $\beta_V$ ) of teak wood as a function of relative humidity (RH) at 21 °C.  
354  
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356 The effects of the thermal treatment were more important in  $\beta_T$  than in  $\beta_R$ . However,  $\beta_L$  was not  
357 affected neither by the wood type nor the thermal treatment (Table 5). The greater dimensional  
358 variations of the wood occur in the tangential direction from 2,4 % to 11 % followed by radial

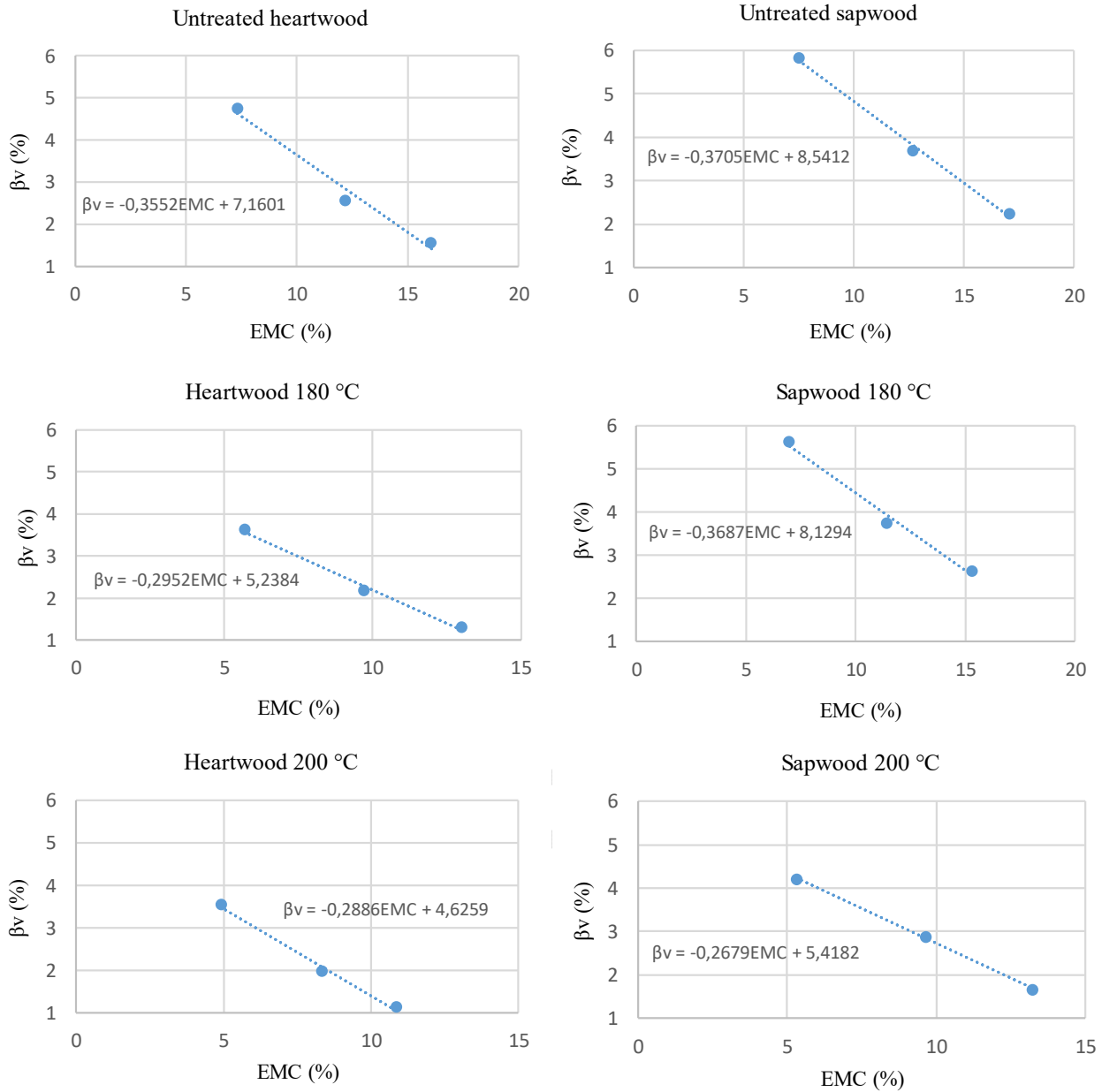
359 direction from 3,5 % to 5 % while those in the longitudinal direction are almost negligible from 0,1  
 360 % to 0,6 % (Kollmann and Côté Jr. 1968). Several factors can explain the anisotropy of wood such  
 361 as anatomical and chemical structure, mainly due to restriction of rays in the radial direction and the  
 362 helical arrangement of the cellulose microfibrils in the cell wall (Kollmann and Côté Jr. 1968).  
 363 Nevertheless, the relationships between anatomical structure, chemical composition, extractive  
 364 content, and density cause variations in shrinkage and swelling among wood species.  
 365 The hygroscopic and dimensional stability of teak wood were improved after thermal treatment. The  
 366 increase in the temperature treatment resulted in a decrease of the EMC. The S-ratio was calculated  
 367 from the EMC-RH curve in the highest sorption linear range from 76 % to 33 % RH (Figure 2). The  
 368 S-ratio was higher in sapwood than in heartwood in all thermal treatments (Table 8). It clearly shows  
 369 that sapwood is more sensitive to RH changes than heartwood. These results can be explained by the  
 370 higher holocellulose and  $\alpha$ -cellulose contents in sapwood compared to heartwood (Table 4) and also  
 371 by the lower natural extractive content in the untreated sapwood (Table 2). The caoutchouc found in  
 372 the cell walls and lumens is responsible for the greater hydrophobicity of teak heartwood (Yamamoto  
 373 *et al.* 1998) which has higher concentrations than that of the sapwood (Lopes *et al.* 2018). The highest  
 374 decrease in the S-ratio was found with the 200 °C treatment in both wood types (heartwood and  
 375 sapwood), which could be explained by the greater chemical changes.

376 **Table 8:** Ratio of sorption (S), coefficient of shrinkage (h), and estimated fiber saturation point  
 377 (FSP) of untreated and thermally-treated teak woods.

Temperature (°C)	S-ratio		h-coefficient		FSP	
	Desorption 76 % - 33 % (% EMC / % RH)		Desorption 76 % - 33 % (% $\beta_v$ / % RH)			
	Heartwood	Sapwood	Heartwood	Sapwood	Heartwood	Sapwood
Control	0,203	0,223	0,074	0,083	20,2	23,1
180	0,170	0,194	0,054	0,070	17,7	22,1
200	0,138	0,184	0,056	0,059	16,0	20,2

378  
 379 Heartwood was more dimensional stable compared to sapwood in untreated and thermally-treated  
 380 conditions. Thermally-treated woods showed lower h-coefficient values compared to untreated  
 381 woods (Table 8), which means that the temperature treatments improve the dimensional stability for

382 both wood types. For sapwood, the treatment at 200 °C was more efficient compared to 180 °C since  
383 it provided greater dimensional stability (h-lower coefficient). For heartwood, both temperature  
384 treatments resulted in a similar h-coefficient. The curve of the  $\beta_v$  as a function of EMC from 33 % to  
385 76 % RH was used to estimate the FSP by the intersection to zero shrinkage method for all samples  
386 (Figure 4). Sapwood exhibited a higher FSP than heartwood for all treatments. Heartwood FSP was  
387 similar to that found by Kokutse *et al.* (2010). The higher h-coefficient and higher FSP of the sapwood  
388 (Table 8) again show that it is less stable than heartwood and more prone to defects caused by the  
389 shrinkage of wood during drying. The greater dimensional stability of thermally-treated woods is due  
390 to lower hygroscopicity caused by chemical changes in the cell wall polymers which decrease the  
391 water absorption sites (mainly OH groups), and consequently the FSP, and shrinkage (Priadi and  
392 Hiziroglu 2013). Overall, the improvement of the dimensional stability of teak wood with temperature  
393 treatments, as a result of the diminution of its hygroscopicity (EMC, S, and FSP) and changes in its  
394 dimensions (h-values) will optimize the utilization of the wood in several end-uses, such as outdoor  
395 furniture, decks, and indoor flooring.



**Figure 4:** Volumetric shrinkage ( $\beta_v$ ) of teak wood as a function of equilibrium moisture content (EMC) between 33 % and 76 % RH.

## CONCLUSIONS

The effects of thermal modification of teak heartwood and sapwood on the chemical components, EMC, and shrinkage at various RHs were investigated. The following conclusions can be drawn:

1. The untreated heartwood had higher extractive and Klason lignin contents than those of untreated sapwood, which exhibited higher holocellulose and  $\alpha$ -cellulose contents.

405 2. The thermal modification decreased the holocellulose and  $\alpha$ -cellulose contents in heartwood  
406 and sapwood and increased the acidity of wood. The degradation of hemicelluloses started at 180 °C  
407 while that of  $\alpha$ -cellulose started at 200 °C.

408 3. Chemical changes were more important in the heartwood than in the sapwood.

409 4. The thermal modification reduced the EMC of heartwood and sapwood at sorption conditions  
410 from 33 % to 86 % RH. The sapwood was more sensitive to RH variations than heartwood, regardless  
411 of the temperature.

412 5. The thermal modification provided higher dimensional and hygroscopic stabilities to wood.  
413 Generally, the thermal treatment decreased the shrinkage of heartwood and sapwood, however,  
414 shrinkage in heartwood was more sensible to the temperature treatment compared to sapwood.  
415 Thermally-treated woods also exhibited lower S and FSP compared to untreated ones.

416 6. Overall, the results of this research lead to a better understanding of dimensional stability of  
417 teak wood from young fast-growing plantations after thermal treatment, which may help define, from  
418 a practical point of view, the optimal use of juvenile teak wood in different relative humidity  
419 conditions.

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#### 425 **REFERENCES**

426 **American Society for Testing and Materials. 2001.** ASTM D-1106-96: Standard test method for  
427 acid-insoluble lignin in wood. ASTM. West Conshohocken, PA, USA.  
428 <https://www.astm.org/DATABASE.CART/HISTORICAL/D1106-96R01.htm>

- 429 **American Society for Testing and Materials. 2001.** ASTM D-1105-96: Standard test method for  
430 preparation of extractive-free wood. ASTM. West Conshohocken, PA, USA.  
431 <https://www.astm.org/DATABASE.CART/HISTORICAL/D1105-96R01.htm>
- 432 **Bhat, K.M.; Priya, P.B.; Rugmini, P. 2001.** Characterisation of juvenile wood in teak. *Wood Sci*  
433 *Technol* 34: 517-532. <https://doi.org/10.1007/s002260000067>
- 434 **Bellon, K.R.R. 2013.** Modificação térmica da madeira de três espécies de florestas plantadas pelo  
435 processo VAP HolzSysteme®. M.Sc. Dissertation, Federal University of Paraná, Curitiba, Brazil (in  
436 portuguese)
- 437 **Boonstra, M.J.; Van Acker, J.; Kegel, E.; Stevens, M. 2007.** Optimisation of a two-stage heat  
438 treatment process: durability aspects. *Wood Sci Technol* 41(1): 31-57.  
439 <https://doi.org/10.1007/s00226-006-0087-4>
- 440 **Darmawan, W.; Nandika, D.; Sari, R.K.; Sitompul, A.; Rahayu, I.; Gardner, D. 2015.** Juvenile  
441 and mature wood characteristics of short and long rotation teak in Java. *IAWA* 36(4): 428-442.  
442 <https://doi.org/10.1163/22941932-20150112>
- 443 **Esteves, B.; Videira, R.; Pereira, H. 2011.** Chemistry and ecotoxicity of heat-treated pine wood  
444 extractives. *Wood Sci Technol* 45(4): 661-676. <https://doi.org/10.1007/s00226-010-0356-0>
- 445 **Flórez, J.B.; Trugilho, P.F., Lima, J.T.; Hein, P.R.G.; Silva, J.R.M. 2014.** Characterization of  
446 young wood *Tectona grandis* L. F. planted in Brazil. *Madera y Bosques* 20(1): 11-20.  
447 [http://www.scielo.org.mx/scielo.php?script=sci\\_arttext&pid=S1405-04712014000100002](http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S1405-04712014000100002)
- 448 **Food and Agriculture Organization (FAO). 2000.** *Reforestación y plantaciones forestales.*  
449 [http://www.fao.org/montes/foda/wforcong/PUBLI/PDF/V3S\\_T12.PDF](http://www.fao.org/montes/foda/wforcong/PUBLI/PDF/V3S_T12.PDF)
- 450 **Forest Products Laboratory (FPL). 2010.** *Wood handbook—Wood as an engineering material.*  
451 Department of Agriculture, Forest Service, Forest Products Laboratory. Madison, WI: U.S.  
452 [https://www.fpl.fs.fed.us/documnts/fplgtr/fpl\\_gtr190.pdf](https://www.fpl.fs.fed.us/documnts/fplgtr/fpl_gtr190.pdf)

- 453 **Garcia, R.A.; Lopes, J.O.; Nascimento, A.M.; Latorraca, J.V.F. 2014.** Color stability of  
454 weathered heat-treated teak wood. *Maderas-Cienc Tecnol* 16(4): 453-462.  
455 <https://doi.org/10.4067/S0718-221X2014005000037>
- 456 **Garcia, R.A.; Carvalho, A.M.; Latorraca, J.V.F.; Matos, J.L.M.; Santos, W.A.; Silva, R.F.M.**  
457 **2012.** Nondestructive evaluation of heat-treated *Eucalyptus grandis* Hill ex Maiden wood using stress  
458 wave method. *Wood Sci Technol* 46(1): 41-52. <https://doi.org/10.1007/s00226-010-0387-6>
- 459 **Gašparík, M.; Gaff, M.; Kačík, F.; Sikora, A. 2019.** Color and chemical changes in teak (*Tectona*  
460 *grandis* L. f.) and meranti (*Shorea* spp.) wood after thermal treatment. *BioResources* 14(2): 2667-  
461 2683. <https://doi.org/10.15376/biores.14.2.2667-2683>
- 462 **Geffert, A.; Geffertova, J.; Dudiak, M. 2019.** Direct method of measuring the pH value of wood.  
463 *Forests* 10(10): 852. <https://doi.org/10.3390/f10100852>
- 464 **Giebeler, E. 1983.** Dimensional stabilization of wood by moisture-heat-pressure treatment. *Holz Roh*  
465 *Werkst* 41(3): 87-94. <https://doi.org/10.1007/BF02608498>
- 466 **Hernández, R.E; Pontin, M. 2006.** Shrinkage of three tropical hardwoods below and above the fiber  
467 saturation point. *Wood Fiber Sci* 38(3): 474-483. <https://wfs.swst.org/index.php/wfs/article/view/1233>
- 468 **Hernández, R.E. 2007a.** Moisture sorption properties of hardwoods as affected by their extraneous  
469 substances, wood density, and interlocked grain. *Wood Fiber Sci* 39(1):132-145.  
470 <https://wfs.swst.org/index.php/wfs/article/view/1008>
- 471 **Hernández, R.E. 2007b.** Swelling properties of hardwoods as affected by their extraneous  
472 substances, wood density, and interlocked grain. *Wood Fiber Sci* 39(1):146-158.  
473 <https://wfs.swst.org/index.php/wfs/article/view/203>
- 474 **International ThermoWood Association. 2003.** *ThermoWood® Handbook*. Helsinki, Finland.  
475 <https://cfpwoods.com/wp-content/uploads/2020/02/CFP-Woods-Thermowood-Handbook-2020.pdf>

- 476 **Jankowska, A.; Drożdżek, M.; Sarnowski, P.; Horodeński, J. 2017.** Effect of extractives on the  
477 equilibrium moisture content and shrinkage of selected tropical woods. *BioResources* 12(1):597-607.  
478 <https://doi.org/10.15376/biores.12.1.597-607>
- 479 **Kakavas, K.V.; Chavenetidou, M.; Birbilis, D. 2018.** Chemical properties of Greek stump chestnut  
480 (*Castanea sativa* Mill.). *Nat Prod Chem Res* 6(4):1-4. [https://www.longdom.org/open-](https://www.longdom.org/open-access/chemical-properties-of-greek-stump-chestnut-castanea-sativa-mill-2329-6836-1000331.pdf)  
481 [access/chemical-properties-of-greek-stump-chestnut-castanea-sativa-mill-2329-6836-1000331.pdf](https://www.longdom.org/open-access/chemical-properties-of-greek-stump-chestnut-castanea-sativa-mill-2329-6836-1000331.pdf)
- 482 **Kartikawati, A.; Wahyudi, I.; Pari, G.; Karlinasari, L. 2020.** Color and dimensional stability of  
483 fast growing teakwood by mild pyrolysis and combination process. *IOP Conf. Series: Materials*  
484 *Science and Engineering* 935: 012014. <https://doi.org/10.1088/1757-899X/935/1/012014>
- 485 **Kim, J.-Y.; Hwang, H.; Oh, S.; Kim, Y.-S.; Kim, U.-J.; Choi, J.W. 2014.** Investigation of  
486 structural modification and thermal characteristics of lignin after heat treatment. *Int J Biol Macromol*  
487 66: 57-65. <https://doi.org/10.1016/j.ijbiomac.2014.02.013>
- 488 **Kokutse, A.D.; Brancheriau, L.; Chaix, G. 2010.** Rapid prediction of shrinkage and fibre saturation  
489 point on teak (*Tectona grandis*) wood based on near-infrared spectroscopy. *Ann For Sci* 67: 403.  
490 <https://doi.org/10.1051/forest/2009123>
- 491 **Kokutse, A.D.; Stokes, A.; Baillères, H.; Kokou, K.; Baudasse, C. 2006.** Decay resistance of  
492 Togolese teak (*Tectona grandis* L. f.) heartwood and relationship with colour. *Trees* 20(2): 219-223.  
493 <https://doi.org/10.1007/s00468-005-0028-0>
- 494 **Kollmann, F.F.P.; Côté, W.A. Jr. 1968.** *Principles of wood science and technology. I Solid wood.*  
495 Springer-Verlag, Berlin, Heidelberg, Germany. <https://www.springer.com/gp/book/9783642879302>
- 496 **Lelis, R. 1995.** Zur Bedeutung der Kerninhaltsstoffe obligatorisch verkernter Nadelbaumarten bei  
497 der Herstellung von feuchtebeständigen und biologisch resistenten Holzspanplatten, am Beispiel der  
498 Douglasie [*Pseudotsuga menziesii* (Mirb.) Franco]. Dissertation, Universität Göttingen, Germany. (in  
499 German)
- 500 **Lengowski, E.C. 2011.** Efeito da termorreificação nas propriedades anatômicas, físico mecânicas e



- 501 químicas das madeiras de *Pinus taeda*, *Eucalyptus grandis* e *Tectona grandis*. Monography, Federal  
502 University of Paraná, Curitiba, Brazil. (in Portuguese)
- 503 **Li, M.-Y.; Cheng, S.-C.; Li, D.; Wang, S.-N.; Huang, A.-M.; Sun, S.-Q. 2015.** Structural  
504 characterization of steam-heat treated *Tectona grandis* wood analyzed by FT-IR and 2D-IR  
505 correlation spectroscopy. *Chinese Chem Lett* 26: 221-225.  
506 <https://doi.org/10.1016/j.ccllet.2014.11.024>
- 507 **Lopes, J.O. 2012.** Uniformity and stability of color of the heat-treated *Tectona grandis* L. f. wood.  
508 Dissertation, Universidade Federal Rural do Rio de Janeiro, Brazil (in Portuguese).
- 509 **Lopes, J.O.; Garcia, R.A.; Nascimento, A.M.; Latorraca, J.V.F. 2014.** Color uniformization of  
510 the young teak wood by heat treatment. *Rev Árvore* 38(3): 561-568.  
511 <http://www.scielo.br/pdf/rarv/v38n3/v38n3a19.pdf>
- 512 **Lopes, J.O.; Garcia, R.A.; Souza, N.D. 2018.** Infrared spectroscopy of the surface of thermally-  
513 modified teak juvenile wood. *Maderas-Cienc Tecnol* 20(4): 737-746. [https://doi.org/10.4067/S0718-](https://doi.org/10.4067/S0718-221X2018005041901)  
514 [221X2018005041901](https://doi.org/10.4067/S0718-221X2018005041901)
- 515 **Miranda, I.; Sousa, V.; Pereira, H. 2011.** Wood properties of teak (*Tectona grandis*) from a mature  
516 unmanaged stand in East Timor. *J Wood Sci* 57(3): 171-178. [https://doi.org/10.1007/s10086-010-](https://doi.org/10.1007/s10086-010-1164-8)  
517 [1164-8](https://doi.org/10.1007/s10086-010-1164-8)
- 518 **Motta, J. P.; Oliveira, J. T. S.; Paes, J. B.; Alves, R. C.; Vidaurre Dambroz, G. B. 2013.** Natural  
519 resistance of *Tectona grandis* wood in laboratory assay. *Ciência Rural* 43(8): 1393-1398.  
520 <http://dx.doi.org/10.1590/S0103-84782013000800009>
- 521 **de Moura, L.F.; Brito, J.O.; Silva Júnior, F.G. 2012.** Effect of thermal treatment on the chemical  
522 characteristics of wood from *Eucalyptus grandis* W. Hill ex Maiden under different atmospheric  
523 conditions. *Cerne* 18(3): 449-455. <https://doi.org/10.1590/S0104-77602012000300012>  
524

- 525 **Niamké, F.B.; Amusant, N.; Charpentier, J.-P.; Chaix, G.; Baissac, Y.; Boutahar, N.; Adima,**  
526 **A.A.; Kati-Coulibaly, S.; Jay-Allemand, C. 2011.** Relationships between biochemical attributes  
527 (non-structural carbohydrates and phenolics) and natural durability against fungi in dry teak wood  
528 (*Tectona grandis* L. f.). *Ann Forest Sci* 68(1): 201-211. <https://doi.org/10.1007/s13595-011-0021-2>
- 529 **Noack, D.; Schwab, E., Bartz, A. 1973.** Characteristics for a judgment of the sorption and swelling  
530 behavior of wood. *Wood Sci Technol* 7(3): 218-236.  
531 <https://link.springer.com/article/10.1007/BF00355552>
- 532 **Passialis, C.; Voulgaridis, E.; Adamopoulos, S.; Matsouka, M. 2008.** Extractives, acidity,  
533 buffering capacity, ash and inorganic elements of black locust wood and bark of different clones and  
534 origin. *Holz Roh Werkst* 66(6):395-400. <https://doi.org/10.1007/s00107-008-0254-4>
- 535 **Priadi, T.; Hiziroglu, S. 2013.** Characterization of heat treated wood species. *Mater Design* 49: 575-  
536 582. <https://doi.org/10.1016/j.matdes.2012.12.067>
- 537 **Priadi, T.; Suharjo, A.A.C.; Karlinasari, L. 2019.** Dimensional stability and colour change of heat-  
538 treated Young teak Wood. *Int Wood Prod J* 10(3) : 119-125  
539 <https://doi.org/10.1080/20426445.2019.1679430>
- 540 **Poubel, D.S.; Garcia, R.A.; Santos, W.A.; Oliveira, G.L.; Abreu, H.S. 2013.** Effect of the heat  
541 treatment on physical and chemical properties of *Pinus caribaea* wood. *Cerne* 19(3): 391-398.  
542 <http://www.scielo.br/pdf/cerne/v19n3/05.pdf>
- 543 **Skaar, C. 2012.** *Wood-water relations*. Springer Science & Business Media. U.S.A.
- 544 **Stamm, A. J. 1964.** *Wood and cellulose science*. Ronald Press. New York. U.S.A
- 545 **Statistic. 2010.** Statistic software version 10.0. Statsoft. <https://www.statistica.com/en/>
- 546 **Sundqvist, B. 2004.** Colour changes and acid formation in wood during heating. Doctoral Thesis,  
547 Luleå University of Technology, Skellefteå, Sweden. [https://www.diva-](https://www.diva-portal.org/smash/get/diva2:999349/FULLTEXT01.pdf)  
548 [portal.org/smash/get/diva2:999349/FULLTEXT01.pdf](https://www.diva-portal.org/smash/get/diva2:999349/FULLTEXT01.pdf)

- 549 **Tsukamoto Filho, A.A.; Silva, M.L.; Couto, L.; Müller, M. D. 2003.** Economic analysis of a teak  
550 plantation submitted to thinning. *Rev Árvore* 27(4): 487-494. [https://doi.org/10.1590-](https://doi.org/10.1590/S0100-67622003000400009)  
551 [67622003000400009](https://doi.org/10.1590/S0100-67622003000400009)
- 552 **Tsoumis, G.T. 1991.** *Science and technology of wood: structure, properties, utilization.* Verlag  
553 Kessel. Remagen-Oberwinter, Germany.
- 554 **Yamamoto, K.; Simatupang, M.H.; Hashim, R. 1998** Caoutchouc in teak wood (*Tectona grandis*  
555 L. f.): formation, location, influence on sunlight irradiation, hydrophobicity and decay resistance.  
556 *Holz Roh Werkst* 56(3): 201-209. <https://doi.org/10.1007/s001070050299>
- 557 **Weaver, P.L. 1993.** *Tectona grandis* L. f. Teak. Verbenaceae. Verbena family. USDA Forest Service,  
558 International Institute of Tropical Forestry.  
559 [https://www.fs.fed.us/global/iitf/pubs/sm\\_iitf064%20%20\(18\).pdf](https://www.fs.fed.us/global/iitf/pubs/sm_iitf064%20%20(18).pdf)
- 560 **Weiland, J.J.; Guyonnet, R. 2003.** Study of chemical modifications and fungi degradation of  
561 thermally modified wood using DRIFT spectroscopy. *Holz Roh Werkst* 61(3): 216-220.  
562 <https://doi.org/10.1007/s00107-003-0364-y>