Performance of Thermally Modified Tauari (*Couratari* sp.) Wood Against Fungal and Termite Biodeterioration

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Thermal modification is a process capable of improving properties affecting wood performance, such as biological durability. This study aimed to assess the potential of thermal modification in enhancing the resistance of *Couratari* sp. wood to deterioration by *Trametes versicolor*, *Nasutitermes corniger*, and *Cryptotermes brevis*. Five treatments were analyzed, represented by the untreated and thermally modified wood at 180, 190, 200, and 210 °C. The wood's chemical composition and resistance to biodeterioration in laboratory tests were evaluated. Thermal modification, especially at 210 °C, altered the chemical composition and increased the wood's durability class against the fungus. However, the process did not affect termite attack. There was a significant positive correlation between corrected mass loss and hemicellulose and total extractive contents, as well as mass loss caused by *T. versicolor* and lignin and hemicellulose contents. The use of thermal modification in 190 °C is recommended for *Couratari* sp. wood due to its enhanced biological durability, with 210 °C being particularly effective.

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INTRODUCTION

Species of the genus *Couratari* (Lecythidaceae), known as tauari, have a considerable distribution in the Amazon rainforest (Instituto de Pesquisas Tecnológicas 2024), and historically their wood has been applied in low commercial value products, such as packaging. Because of their color, these and other species are classified in the tropical wood market as "white wood" and are associated with low natural durability. Yet, this general classification can be erroneous and hinder the marketability of these species (Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis 1997; Andrade *et al.* 2023).

Tauari wood has been increasingly traded over the last years (2012-2022) due to its availability (Timberflow 2022) and the scarcity of traditional species. Hence, the last years have faced the valorization of tauari wood, with the production of flooring and furniture, for example.

Since it does not use biocidal or toxic chemicals, thermal modification can be an alternative to traditional preservation methods to improve wood durability, mainly against rot fungi (Hill 2006; Jones and Sandberg 2020). Rather, the use of high temperatures (140 – 230 °C) changes the wood anatomy, chemical composition, and hygroscopicity, resulting in a more durable material (Ringman *et al*. 2016; Thybring *et al*. 2018; Priadi *et al*. 2021; Bi *et al*. 2024).

Despite the commercial importance of the wood and the process, few studies have been carried out on thermally modified tauari wood, with approaches to its physical and mechanical properties, color, surface roughness, and performance in both natural and artificial weathering tests (Zhou *et al.* 2013; Laskowska *et al.* 2021; Paula, 2021; Silva, 2021; Andrade *et al.* 2023; Ferreira 2024). This is the first study on the biological durability of thermally modified tauari wood.

Indeed, thermally modified tropical wood has been less studied than wood species from temperate zones, as well as from fast-growing forests, such as teak and eucalypt. In the context of tropical regions and increasing global warming, studies on the durability against termites are important, because their damage is economically relevant.

Wood-feeding termites can be divided into two groups, according to their dependence on moisture. Drywood termites can attack wood with <13% moisture content (Zabel and Morrel 2020) and the "West Indian drywood termite" (*Cryptotermes brevis* Walker, Kalotermitidae) is among the most damaging and invasive species in this group (Maistrello 2018; McDonald *et al.* 2022). On the other hand, dampwood and subterranean termites require more moisture, usually from ground contact (Zabel and Morrel 2020). Another moisture-dependent group, the arboreal termites, commonly build their nests on trees and produce carton-covered tunnels to connect the nest to the ground. According to Boulogne *et al*. (2017), the genus *Nasutitermes* is among the most abundant wood-feeding Termitidae in the tropics, and many species are structural pests. For example, the "conehead termite" *Nasutitermes corniger* (Motschulsky) is considered the most economically detrimental pest in this genus in South America.

Because of the economic importance and wide geographic distribution of *Cryptotermes brevis* and *Nasutitermes corniger*, some studies have been carried out about their attack in thermally modified wood (Pessoa *et al.* 2006; Batista *et al.* 2016; Brito *et al.* 2018; Lima 2019; Melo *et al.* 2019; Medeiros *et al.* 2020; Brito *et al.* 2022). The effect of the process on increasing the wood resistance against rot fungi is well known. However, its effect on the resistance against termite attack is still unclear, justifying further studies.

For example, some studies reported that the thermal modification had no effect (Pessoa *et al.* 2006; Batista *et al.* 2016; Brito *et al.* 2018) and in some cases, thermally modified wood may even become more susceptible to termite attack (Melo *et al.* 2019; Medeiros *et al.* 2020; Esteves *et al.* 2021). However, in other studies, positive effects of the process have been reported (Mburu e*t al.* 2007; Lima 2019; Brito *et al.* 2022). In all cases, changes in wood chemistry seem to be the most plausible hypothesis for the effect of thermal modification on wood durability against termites. We suggest the effects are dependent on the combination of four main factors: the wood species, the termite species, the test conditions, and the type of process (*e.g.* time, temperature, atmosphere, closed *x* open system).

The objective of this study was to evaluate the effect of thermal modification on the resistance to biodeterioration of tauari wood (*Couratari* sp.).

EXPERIMENTAL

Materials and Treatments

The tauari wood (*Couratari* sp., Lecythidaceae, unknown age) was collected in a managed area in the Tapajós National Forest (3° 31' 01" S; 55° 04' 23" W) (Santarém – Pará – Brazil). Ten logs were sawmilled and the central planks were sampled; 150 defect-free samples of 50 x 50 x 150 mm^3 (tangential x radial x longitudinal) were produced from the heartwood portion between the pith and the bark. These samples were equally divided into five groups, according to the treatments studied, where the first corresponded to untreated wood and the others for thermal modification. The samples were previously conditioned in a climatic chamber (20 ± 2 °C; 65 ± 5% relative humidity) until reaching equilibrium with the environment (*ca.* 12% moisture content, to prevent molds and stain fungi.

Thermal Modification

The thermal modification was conducted in a laboratory electric oven (FANEM, model 315 SE, São Paulo, Brazil), under atmospheric pressure (open system), at four final temperatures (180, 190, 200, and 210 °C). The thermal modification schedule was carried out in four stages, based on Severo and Calonego (2011): 1) Drying at 100 °C for 24 h, followed by weighing on a digital semi-analytical balance (0.01 g); 2) Heating at 1.3 $°C.min^{-1}$ until reaching the final temperature (180, 190, 200, or 210 °C); 3) Maintenance of the final temperature for 150 min; 4) Cooling to 40 °C by turning off the equipment, followed by reweighing of the samples. The thermal modification resulted in a corrected mass loss (CML) of 2.69% (standard deviation - SD - ± 0.62%), 3.40% (SD ± 0.62%), 5.56% (SD ± 0.79%), and 8.33% (SD ±1.36%), respectively for 180 °C, 190 °C, 200 °C, and 210 °C. The CML was calculated according to the method described by Gomes *et al.* (2023) using the data of total extractives content (Table 2).

Chemical Analyses

A 25-mm length portion was cut from every sample and hammer-milled (1-mm diameter mesh), resulting in a compound sample for each treatment. Subsequently, the material was ground in a Wiley-type knife mill and sieved (40 to 60 mesh), and the 60-mesh material was used in this study. Table 1 summarizes the chemical analyses that were carried out, as well as its methods.

Table 1. Summary of the Chemical Analyses

Standard	Evaluation	Source
T264 cm-97	Total extractives	Technical Association of The Pulp and Paper Industry (2007)
T222 cm-97	Total lignin	Technical Association of The Pulp and Paper Industry (2002)
T203 cm-99	Alpha-cellulose	Technical Association of The Pulp and Paper Industry (1999)
-	Holocellulose	Wise *et al.* (1946)
D1762-84	Ash content	American Society for Testing and Materials (2021)

Biodeterioration Tests

White-rot fungus

The resistance to biodeterioration was tested using pure cultures of *Trametes versicolor* (L.) Lloyd (white rot) (Mad-697), according to standard EN 113-2 (2020). The authors tested 30 specimens per treatment, measuring 20 x 20 x 50 mm^3 (radial x tangential x longitudinal), which were oven-dried at 103 ± 5 °C for 24 h and subsequently weighed (M1, 0.001 g). The specimens were conditioned before testing in a climatic chamber (20 ± 2 °C; 65 ± 5% relative humidity) until constant weight. Ten specimens of beech (*Fagus sylvatica* L.) were tested to verify the virulence.

The test was carried out for 16 weeks in an incubation chamber (22 ± 2 °C; 70 ± 5% relative humidity) (Fig. 1 B). After that, the specimens were smoothly cleaned with a brush, weighed (0.001 g), oven-dried, and weighed again (M2, 0.001 g), as previously described. The mass loss (ML) caused by the fungus was calculated: ML, % = $[(M_1 - M_2) / M_1] \times 100$.

Arboreal and drywood termites

The resistance to biodeterioration by the arboreal termite *Nasutitermes corniger* (Motschulsky, Termitidae) was tested according to standard AWPA E1-16 (2016). Five specimens were tested per treatment, measuring 25 mm x 25 mm x 6 mm (radial x tangential x longitudinal), in addition to *Pinus* sp. (reference). The specimens were oven-dried at 103 ± 5 °C for 24 h and then weighed (M_1, 0.001 g). The test was conducted in glass jars (600 mL) (Fig. 1 C) prepared with 150 g of sieved, washed, and sterilized sand, with one specimen per jar. Approximately 400 termites were placed in each jar, according to the ratio of soldiers and workers observed in the colony. The test was carried out for 28 days, in the dark, in a climatic chamber (27 ± 2 °C, and 65 ± 5% relative humidity).

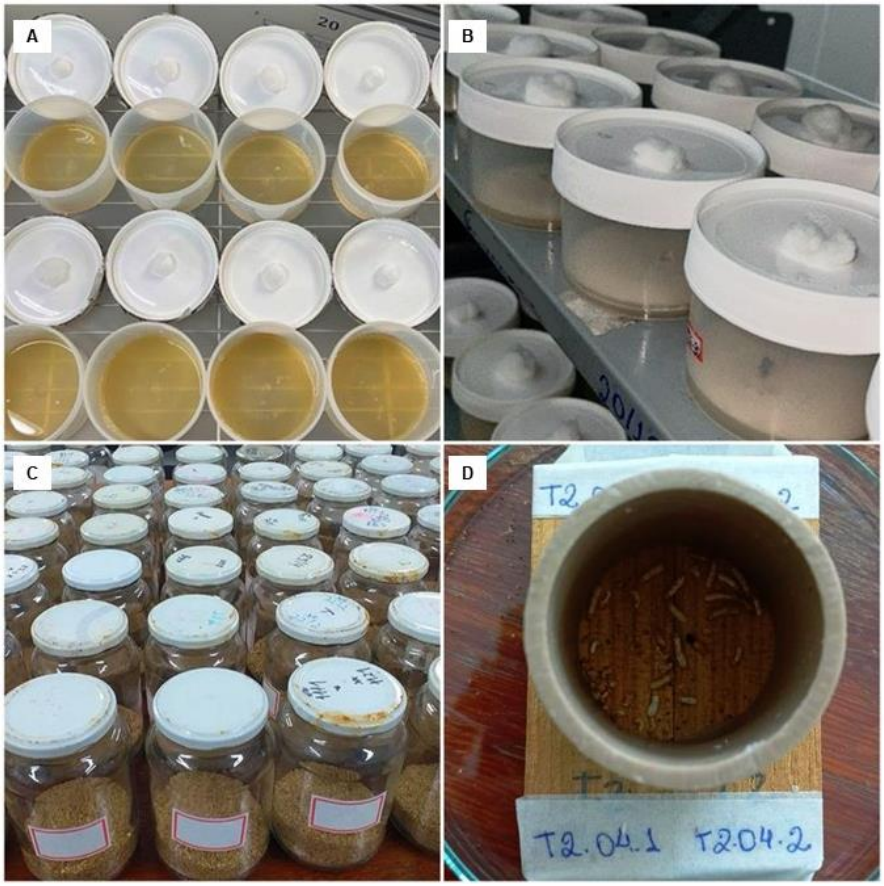

Fig. 1. Representation of the test specimens: A and B – white-rot fungus; C – arboreal termite, and D – drywood termite

After that, the specimens were cleaned with a brush, oven-dried, and weighed (M_2, 0.001 g) as previously described. The mass loss was calculated as described in the fungus test. Additionally, wood resistance was assessed by assigning wear scores to the specimens and by determining the termite mortality (%).

The resistance to biodeterioration by the drywood termite *Cryptotermes brevis* (Walker, Kalotermitidae) was tested according to the method of the Instituto de Pesquisas Tecnológicas (1980), which is similar to the described by Maistrello (2018). There were 10 specimens tested per treatment, measuring 23 x 6 x 70 mm^3 (radial x tangential x longitudinal), paired, and placed in Petri dishes. A polyvinyl chloride (PVC) container (Fig. 1 D), 35-mm diameter and 40-mm height was affixed with paraffin onto each pair. Forty termites were introduced into each PVC container, consisting of 39 workers and one soldier. The test was carried out for 45 days, in the dark, in a climatic chamber (27 ± 2 °C and 65 ± 5% relative humidity). The mass loss and the mortality were analyzed in the same manner as in the test with arboreal termites. A wear score was assigned to each specimen as 0 – “sound”, 1 – “slight”, 2 – “moderate”, 3 – “heavy”, and 4 – “failure”.

Statistical Analysis

The statistical analysis was performed using a completely randomized design, and the significance level adopted was up to 5% probability for all tests. Statistical data was processed using Statgraphics 19 software (trial version). The effect of treatments on the data of chemical analyses, and mass loss of the biodeterioration tests was assessed by analysis of variance (ANOVA). Bartlett’s test checked the homogeneity of variances beforehand, and in cases where the null hypothesis was accepted ($p > 0.05$), ANOVA was performed. In cases of the alternative hypothesis, the H-test of Kruskal-Wallis was performed. Considering that the tested treatments are quantitative, in cases where there was a significant effect of ANOVA, regression analysis was carried out. The significance of the parameters (b_0, b_1, and b_2) of the equations was tested using the Student t-test (tc). These analyses aimed to assess the effect of thermal modification temperature (process), and therefore, the untreated wood was not considered.

Wear scores in termite tests (discrete data), as well as data that did not meet the assumptions for ANOVA, were analyzed using the H-test of Kruskal-Wallis. In cases where the null hypothesis was rejected, mean scores were differentiated by the Bonferroni test.

Pearson correlation analyses were carried out between the means of some variables, as discussed in the next section. The significance of correlation coefficients was tested using the Student t-test (tc). Finally, the qualitative classification of the correlation coefficient (r) was conducted following (Appolinário 2012): r = 0 – null; r = 0.01 to 0.10 – very weak; r = 0.11 to 0.30 – weak; r = 0.31 to 0.59 – moderate; r = 0.60 to 0.80 – strong; r = 0.81 to 0.99 – very strong; 1.00 – absolute.

RESULTS AND DISCUSSION

Chemical Analysis

The results of the chemical analyses are summarized in Table 2. According to the ANOVA (Fc, $p > 0.05$), there was no significant effect of thermal modification on the alpha-cellulose content. This null effect was also reported for other tropical hardwoods, such as *Gmelina arborea* (Minkah *et al.* 2021) and *Tectona grandis* (Gomes *et al.* 2023). Cellulose has good thermal resistance (Kalia *et al.* 2011), which differs from hemicelluloses (Boonstra and Tjeerdsma 2006), and this may explain why thermal modification did not significantly impact the alpha-cellulose content. This result is reinforced by the “very weak” and non-significant correlation (r = -0.10; tc = -0.18^{ns}) between the corrected mass loss and the alpha-cellulose.

Table 2. Summary of the Results of Chemical Analyses Per Treatment

Treatment	Alpha-Cellulose (%)	Total Lignin (%)	Hemicelluloses (%)	Total Extractives (%)	Ash (%)
Untreated	42.03 (0.78)	36.53 (1.95)	18.00 (2.33)	5.25 (2.41)	0.63 (6.17)
180 °C	42.92 (2.94)	36.60 (0.53)	16.65 (3.27)	5.29 (3.99)	0.86 (5.55)
190 °C	40.97 (1.31)	38.70 (0.45)	14.09 (5.46)	5.42 (8.47)	0.76 (0.69)
200 °C	40.71 (3.26)	38.59 (1.33)	10.84 (0.75)	5.63 (6.37)	0.70 (2.80)
210 °C	42.35 (0.70)	39.18 (0.92)	8.56 (8.29)	6.82 (3.73)	0.80 (3.12)
Barlett’s test	5.92^{ns}	4.35^{ns}	5.70^{ns}	2.86^{ns}	-
Fc	3.39^{ns}	24.36*	147.54*	13.82*	-
Coefficient of variation (%) in parentheses; "ns" and "*": respectively, not significant and significant at the 5% probability level					

For all chemical analyses, the means of the 180 °C treatment were similar to those of the untreated wood (Table 2). Thermal modification at 180 °C resulted in a low corrected mass loss (2.69%), indicating that the process under these conditions was not sufficient to significantly alter the chemical composition of the wood. However, it is worth noting that an increase of 0.71% in the corrected mass loss of the 190 °C treatment (3.40%) was sufficient to indicate more changes in lignin and hemicelluloses compared to the untreated wood, as also evidenced by the regression analyses (Figs. 2 A and B).

Because lignin is more thermally stable, the reduction in hemicelluloses and extractives causes an increase in the proportion of lignin in the cell wall (Boonstra and Tjeerdsma 2006; Esteves *et al.* 2008; Silva 2012). This was also observed in this study, as shown in Fig. 2A, and reinforced by the very strong (although not significant) correlation (r = 0.85; tc = 2.75^{ns}) between lignin and corrected mass loss. A positive trend in total lignin with increasing temperature was noted (Fig. 2A), reaching stability at 210 °C.

This increase in the lignin content of thermally modified wood at temperatures greater than or equal to 190 °C was also observed for other tropical hardwoods (Paula 2016; Severo *et al.* 2016; Minkah *et al.* 2021). Although lignin degrades at the beginning of the thermal modification process, an increase in its content may occur because the degradation is slower than that of the hemicelluloses (Windeisen *et al.* 2007). Additionally, lignin’s polycondensation reactions and cross-linking with other components occur at temperatures above 185 °C (Tjeerdsma and Militz 2005; Boonstra and Tjeerdsma 2006; Silva 2012).

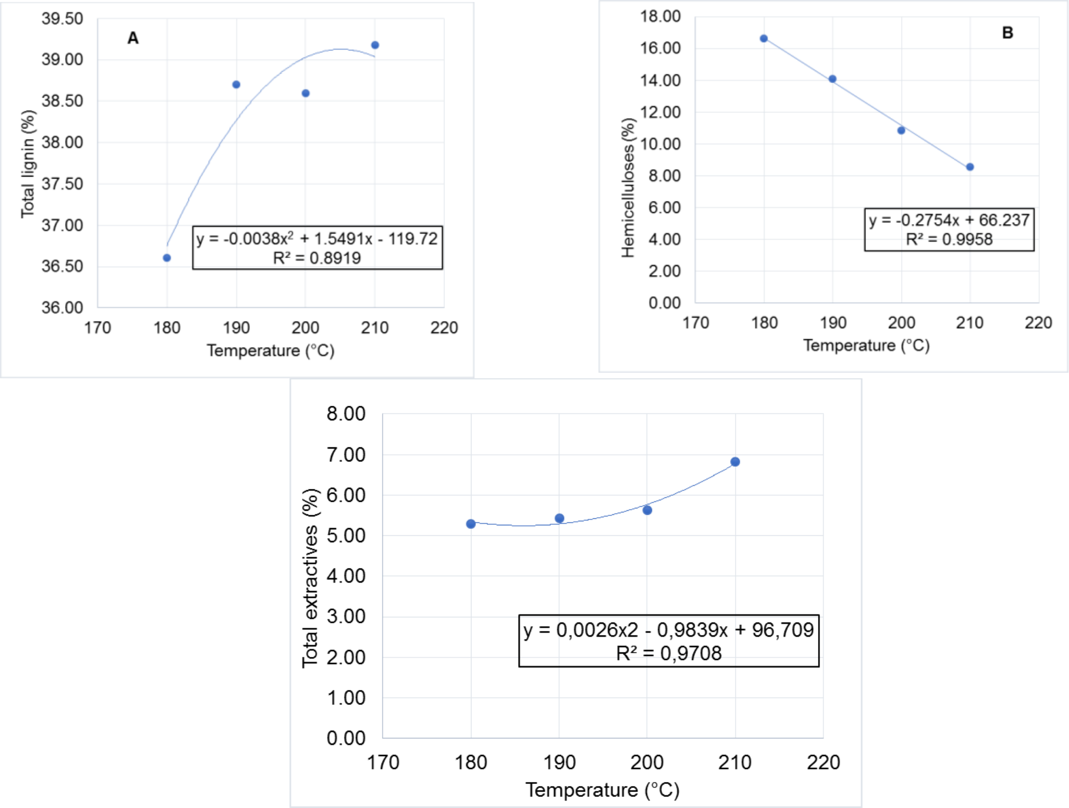

Fig. 2. Regression analyses of the chemical composition. The parameters of all models were statistically significant according to the Student t-test. tc in parentheses – total lignin (b0:-3.21*; b1: 4.04*; b2:-3.84*); hemicelluloses (b0: 22.21*; b1:-18.03*); total extractives (b0: 2.64*; b1: -2.61*; b2: 2.74*).

With increasing temperature, hemicelluloses are the first structural components of the cell wall to degrade or alter, at temperatures around 180 and 200 °C, along with extractives (Hill 2006; Esteves *et al.* 2008). This trend was also observed in this study, where there was a very strong and significant correlation (r = -0.97; tc = -7.41*) between corrected mass loss and hemicelluloses content. Gomes *et al.* (2023) also reported similar trends and correlations for thermally modified *Tectona grandis* wood.

A linear and negative trend in hemicelluloses content with increasing temperature was observed (Fig. 2B). The 18% content of untreated wood (highest mean) was reduced to 8.56% (lowest mean) at 210 °C. This reduction was also observed in the holocellulose for *Khaya ivorensis* (Lima 2019) and *Tectona grandis* (Lengowski *et al.* 2020), and in hemicelluloses for *Tectona grandis* (Menezes 2017; Gomes *et al.* 2023).

There was not much effect of thermal modification up to 200 °C on the extractives content (Fig. 2C), where untreated wood had the lowest mean (5.25%) and the highest mean (210 °C) was 1.57% higher. In other words, thermal modification influenced the extractives content more effectively at 210 °C. Similar results were found in studies of other thermally modified tropical hardwoods (Paula 2016; Severo *et al.* 2016; Lima 2019).

Typically, extractives are volatilized during the thermal modification process in open system; however, new compounds resulting from the degradation of polysaccharides can be accounted for in the extracted fraction, resulting in an increase in extractives content and possibly changing its composition (Esteves *et al.* 2008; Esteves and Pereira 2009; Silva 2012). It is noteworthy the very strong and significant correlation between corrected mass loss and extractives content (r = 0.89; tc = 3.33*), which is related to the same result between corrected mass loss and hemicelluloses. The means of extractives content at 190 °C and 200 °C may have revealed a compensatory balance between the volatilization of wood extractives and the production of new extractable compounds. In contrast, the amount of extractives generated at 210 °C was greater than the volatilized fraction.

Because some authors highlighted the influence of ash content on the natural durability of tauari wood (Okino *et al.* 2015; Lima 2019), the present authors decided to perform this analysis. However, according to the results presented in Table 2, the ash content was very low for all treatments (< 1%). Then, the possibility of the influence of ash content on the results of the biodeterioration tests was discarded.

Biodeterioration Tests

Wood resistance against white-rot

The results of the test with the white-rot fungus *Trametes versicolor* are shown in Table 3. The virulence of the colony was confirmed by 22.4% mass loss in *Fagus sylvatica* test specimens according to EN 113-2 (2020).

Table 3. Summary of the Results of the Fungal Test with *Trametes versicolor* per Treatment

Treatment	Median Mass Loss (%)	Mean Score	Durability Class**
Untreated	5.23	94.65 AB	2 – Durable
180 °C	7.83	107.87 A	2 – Durable
190 °C	2.59	72.63 BC	1 – Very durable
200 °C	1.90	59.73 C	1 – Very durable
210 °C	1.31	42.62 C	1 – Very durable
Bartlett’s test	-	49,90*	-
H-test	-	43.75*	-

*Significant at a 5% probability level. Mean scores followed by the same letter in a column do not differ significantly (Bonferroni’s test; p > 0.05). **Standard EN 113 (2020)

Untreated wood was assessed as Class 2 – “Durable,” which is in agreement with other studies that classified *Couratari* species as resistant or moderately resistant to white rot (Okino *et al.* 2015; Reis *et al.* 2019). In contrast, the genus *Couratari* is classified as susceptible by the Instituto de Pesquisas Tecnológicas (2024) and non-durable (Class 5) by the Centre de Cooperátion Internationale en Recherche Agronomique pour le Développement - CIRAD (2017). However, CIRAD (2017) highlighted that tauari comprises various species, indicating that natural durability can vary widely within the genus.

According to the results in Table 3, thermally modified wood at 200 and 210 °C had lower mass loss than untreated wood, resulting in a better durability class. In contrast, the improvement in the durability class was also verified at 190 °C, as this treatment also received the best classification (Class 1 – “very durable”).

The 180 °C treatment, with low corrected mass loss (2.69%), did not differ from untreated wood in terms of the mean score of mass loss and had a similar chemical composition (Table 2), where both had the same durability class (Class 2 – “Durable”). As mentioned, the positive effect of thermal modification on tauari wood resistance is related to the reduction in hemicelluloses and the concomitant proportional increase in total lignin in the cell wall. This is reinforced by the correlations made between the mass loss caused by the fungus and the results of chemical analyses, revealing a "very strong" and significant correlation with total lignin (r= -0.89*; tc = -3.32*) and hemicelluloses (r= 0.90*; tc = 3.48*). Specifically for the 210 °C treatment, which performed best, this result may also be related to the higher extractives content (Table 2).

Wood resistance against termite attack

Table 4 shows the results of the test with the arboreal termite *Nasutitermes corniger*. The mean mass loss of *Pinus* sp. (reference) was 17.8% (coefficient of variation - CV = 35.74%), with minimum and maximum values of 10.1% and 24.8%, respectively. The mean mortality was 97% (CV = 5.46%), with minimum and maximum values of 88% and 100%, respectively. The genus *Couratari* is generally considered susceptible to termite attack (Centre de Cooperátion Internationale en Recherche Agronomique pour le Développement 2017; Instituto de Pesquisa Tecnológicas 2023). Total mortality was also observed for tropical woods, equally with high wear grades (sound specimens or with superficial attacks) (Paes *et al.* 2003) and the same trend was also observed in this study. For *N. corniger*, high mortalities (> 67%) were observed in other studies with tropical species (Paes *et al.* 2003, 2010; Souza 2009; Lima 2019).

Table 4. Summary of the Results of the Test with the Arboreal Termite *Nasutitermes corniger* Per Treatment

Treatment	Mass Loss (%)	Mean Score of Mass Loss	Wear Grades			Mean Wear Scores	Mortality (%)
			Min.	Mean	Max.		
Untreated	2.67 (10.03)	8.0	9.0	9.0	9.0	14.0	100
180 °C	3.23 (43.79)	13.2	9.0	9.2	10.0	16.2	100
190 °C	4.56 (36.71)	17.4	9.0	9.0	9.0	14.0	100
200 °C	3.33 (27.21)	13.2	8.0	8.8	9.0	11.8	100
210 °C	4.05 (69.42)	13.2	7.0	8.2	9.0	9.0	100
Bartlett's test	14.72*	-	-	-	-	-	-
H-test	-	4.11^{ns}	-	-	-	6.73^{ns}	-

Coefficient of variation (%) in brackets; ns and *: not significant and significant at the 5% probability level, respectively

According to the results of mass loss and wear grades (Table 4), there was no significant difference between the treatments. This means that the effect of thermal modification in the different temperatures tested was null. The mean wear grades varied between 8 and 9, classifying the termite attack as "moderate attack" (3 to 10% of the area attacked) and "light attack" (3% of the area attacked), respectively, according to the classification of the American Wood Protection Association (2016). The null effect of thermal modification was also reported by Lima (2019) for *Khaya ivorensis* and Batista (2012) for *Eucalyptus grandis* (closed system).

The changes in the chemical composition of thermally modified tauari wood (Table 2) were not enough to improve the durability against the attack by *Nasutitermes corniger* as verified for *Tectona grandis* (Lima 2019; Brito *et al.* 2022). Thus, for arboreal termites, there is still no consensus in the literature on the effect of thermal modification on wood durability.

Table 5 shows the results of the test with the termite *Cryptotermes brevis*. The low mass loss of untreated wood (0.28%) was contrary to what was found in the literature, which reports that tauari wood is susceptible to termite attack, including the low amount of extractives as a reason (Laskowska *et al.* 2021). In the same way, as in the test with arboreal termites (Table 4), there was no significant difference in mass loss and wear grades among the treatments, implying that the effect of thermal modification was null.

Table 5. Summary of the Results of the Test with the Drywood Termite *Cryptotermes brevis* per Treatment

Treatment	Mass Loss (%)	Mean Score of Mass Loss	Wear Grades			Mean Score of Wear Grade	Mortality (%)
			Min.	Mean	Max.		
Untreated	0.28 (62.5)	24.0	1	1.5	2	19.5	52.0 (15.35)
180 °C	1.33 (220.3)	29.6	1	2.3	3	34.6	47.0 (33.51)
190 °C	2.42 (290.2)	21.5	1	1.8	2	26.1	49.5 (22.97)
200 °C	0.31 (43.5)	27,3	1	1.9	2	28.3	59.0 (10.63)
210 °C	0.43 (118.4)	25.2	1	1.5	3	19.0	56.5 (21.12)
Bartlett's Test	129.90*	-	-	-	-	-	-
H-test	-	1.79^{ns}	-	-	-	10.08^{ns}	-

Coefficient of variation (%) is in parentheses; ns and *: non-significant and significant at the 5% probability level, respectively

Considering the mass loss, the coefficients of variation were high, the same as verified in the arboreal termite test, indicating a high range between the results among the test specimens. In this condition of high variability, the treatments 180, 190, and 210 °C stood out. This null effect of thermal modification has also been observed in other studies with this same termite species for eucalyptus wood (Pessoa *et al.* 2006; Batista *et al.* 2016) and *Liriodendron tulipifera* (Brito *et al.* 2018).

In this work, low colony vigor could be suggested; however, the mortality rate was not 100% in any of the treatments (Table 5). It should be noted that the method (Instituto de Pesquisas Tecnológicas 1980; Maistrello 2018) requires that the number of holes in the specimens be recorded, which were not verified in any treatment. In contrast, some studies with thermally modified *Khaya ivorensis* (Lima 2019), *Eucalyptus grandis*, and *Tectona grandis* (Brito *et al.* 2022) reported improved durability against *C. brevis* attack.

Many Amazonian woods are naturally durable or have phage-inhibiting substances (such as extractives and high ash content) that prevent the attack by xylophagous termites, such as *C. brevis* (Pierrot *et al.* 2022). However, no studies were found that corroborate this for the genus *Couratari*. In some cases, thermal modification can cause changes in the chemical composition of the extractives and make the wood more resistant (Lima 2019;

Brito *et al.* 2022) or more susceptible (Esteves *et al.* 2021) and also result in a null effect, as discussed previously.

Therefore, according to the literature, the cause-and-effect relationship of thermal modification concerning biodeterioration caused by these termites is still ambiguous. It is suggested that tests be carried out with other fungi, such as staining and brown rot fungi, as well as boring beetles. Considering that the effect of thermal modification was null in the tests with termites, it is suggested that the tests be repeated with the food preference method. Finally, it is also recommended to identify the extractives to better verify the natural durability of tauari wood against fungi and termites.

CONCLUSIONS

1. Thermal modification was a viable process for tauari wood, in which the best result of resistance to biodeterioration was found at 210 °C. Thermal modification at 180 °C was not effective against *Trametes versicolor* and termites.
2. The corrected mass loss increased with increasing thermal modification temperature. There was a very strong and significant correlation between the corrected mass loss and the contents of hemicelluloses and total extractives. The contents of total lignin and total extractives tended to increase with increasing thermal modification temperature. The opposite trend was observed for the hemicelluloses, while there was no effect of the process on the alpha-cellulose.
3. Thermally modified wood at 190, 200, and 210 °C was classified as very durable (Class 1) against the white rot fungus *Trametes versicolor*. There was a very strong and significant correlation between the mass loss caused by *Trametes versicolor* and total lignin and hemicelluloses.
4. The effect of thermal modification was null concerning biodeterioration caused by the termites *Nasutitermes corniger* (arboreal) and *Cryptotermes brevis* (drywood).

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REFERENCES CITED

American Society for Testing and Materials (2021). "D1762-84: Standard test method for chemical analysis of wood charcoal," ASTM International, West Conshohocken, PA, USA.

American Wood Protection Association (AWPA) (2016). "E1-16: Laboratory methods for evaluating the termite resistance of wood-based materials: Choice and no-choice tests," in: *AWPA Book of Standards*, AWPA Standards, Birmingham, AL, USA, pp. 379–384.

Andrade, F. W. C., Moutinho, V. H. P., Severo, E. T. D., Ferreira, J. S. S., and Ballarin, A. W. (2023). "Impact of thermal modification on swelling and mechanical behavior of *Couratari* spp.," *BioResources* 18(3), 5242-5252. DOI: 10.15376/biores.18.3.5242-5252

Appolinário, F. (2012). *Metodologia da Ciência - Filosofia e Prática da Pesquisa [Methodology of Science - Philosophy and Practice of Research]*, Cengage Learning, São Paulo, Brazil.

Batista, D. C. (2012). *Modificação Térmica da Madeira de Eucalyptus grandis em Escala Industrial pelo Processo Brasileiro VAP Holzsysteme® [Thermal Modification of Eucalyptus grandis Wood on an Industrial Scale by the Brazilian Process VAP Holzsysteme®]*, Ph.D. Thesis, Federal University of Paraná, Curitiba, Paraná, Brazil.

Batista, D. C., Nisgoski, S., Silva Oliveira, J. T., Muñiz, G. I. B. de, and Paes, J. B. (2016). "Resistance of thermally modified *Eucalyptus grandis* W. Hill ex Maiden wood to deterioration by dry-wood termites (*Cryptotermes* sp.)," *Ciência Florestal* 26(2), 671-678. DOI: 10.5902/1980509822766

Bi, Z., Zhou, X., Chen, J., Lei, Y., and Yan, L. (2024). "Effects of extracts on color, dimensional stability, and decay resistance of thermally modified wood," *European Journal of Wood and Wood Products* 82, 387-401. DOI: 10.1007/s00107-023-02024-4

Boonstra, M. J., and Tjeerdsma, B. (2006). "Chemical analysis of heat treated softwoods," *Holz als Roh- und Werkstoff* 64(3), 204–211. DOI: 10.1007/s00107-005-0078-4

Boulogne, I., Constantino, R., Amusant, N., Falkowski, M., Rodrigues, A. M. S., and Houël, E. (2017). "Ecology of termites from the genus *Nasutitermes* (Termitidae: Nasutitermitinae) and potential for science-based development of sustainable pest management programs," *Journal of Pest Science* 90, 19-37. DOI: 10.1007/s10340-016-0796-x

Brito, A. F., Calonego, F. W., Bond, B. H., and Severo, E. T. D. (2018). "Color changes, EMC and biological resistance of thermally modified yellow poplar," *Wood and Fiber Science* 50(4), 439-446. DOI: 10.22382/wfs-2018-055

Brito, T. M., Ferreira, G., Silva, J. G.M. da, Mendonça, A. R. de, Fantuzzi Neto, H., Paes, J. B., and Batista, D. C. (2022). "Resistance to biodeterioration of thermally modified *Eucalyptus grandis* and *Tectona grandis* short-rotation wood," *Wood Material Science & Engineering* 18(1), 3-10. DOI: 10.1080/17480272.2022.2150985

Centre de Cooperátion Internationale en Recherche Agronomique pour le Développement. (2017). "Tauari," Tropix, (https://tropix.cirad.fr/FichiersComplementaires/EN/America/TAUARY%202024.pdf), Accessed 21 Aug 2024.

EN 113 (2020). "Durability of wood and wood-based products. Test method against wood destroying basidiomycetes – Part 2: Assessment of inherent or enhanced durability," European Committee for Standardization, Brussels, Belgium.

Esteves, B., Ferreira, H., Viana, H., Ferreira, J., Domingos, I., Cruz-Lopes, L., Jones, D., and Nunes, L. (2021). "Termite resistance, chemical and mechanical characterization of *Paulownia tomentosa* wood before and after heat treatment," *Forests* 12(8), article 1114. DOI: 10.3390/F12081114

Esteves, B., Graça, J., and Pereira, H. (2008). "Extractive composition and summative chemical analysis of thermally treated eucalypt wood," *Holzforschung* 62(3), 344–351. DOI: 10.1515/HF.2008.057

Esteves, B. M., and Pereira, H. M. (2009). "Wood modification by heat treatment: A review," *BioResources* 4(1), 370-404. DOI: 10.15376/biores.4.1.370-404

Ferreira, J. S. S. (2024). *Estabilidade da cor da Madeira de Tauari (Couratari spp.) Modificada Termicamente Submetida ao Intemperismo Natural [Color stability of Thermally Modified Tauari Wood (Couratari spp.) Subjected to Natural Weathering]*, Master's Thesis, Federal University of Espírito Santo, Jerônimo Monteiro, Espírito Santo, Brazil.

Gomes, F. S., Reis, M. S., Rupf, A. C. O., Silvares, P. H. S., Ferreira, J. S. S., Dias, L.C., Madi, J. P. S., Cademartori, P. H. G., Fantuzzi Neto, H., Paes, J. B., and Djeison Cesar Batista (2023). "Chemical composition and color of short-rotation teak wood thermally modified in closed and open systems," *Applied Sciences* 13(24), article ID 13050. DOI: 10.3390/app132413050

Hill, C. A. S. (2006). *Wood Modification: Chemical, Thermal and Other Processes*, John Wiley & Sons, West Sussex, UK.

Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (1997). *Madeiras da Amazônia: Características e Utilização [Amazon Woods: Characteristics and Uses],* M. H. B. Marques (ed.), IBAMA, Distrito Federal, Brazil.

Instituto de Pesquisas Tecnológicas (2024). "Informações sobre madeiras: Tauari [Information about wood: Tauari]," Governo do Estado de São Paulo, (https://madeiras.ipt.br/tauari/), Accessed 21 Aug 2024.

Instituto de Pesquisas Tecnológicas (1980). *IPT/DIMAD D – 2: Ensaio Acelerado de Laboratório da Resistência Natural ou Madeira Preservada ao Ataque de Térmitas do Gênero Cryptotermes [IPT/DIMAD D – 2: Accelerated Laboratory Test of Natural Resistance or Preserved Wood to the Attack of Termites of the Genus Cryptotermes]*, IPT/DIMAD, São Paulo, Brazil.

Jones, D., and Sandberg, D. (2020). "A review of wood modification globally – Updated findings from COST FP1407," *Interdisciplinary Perspectives on the Built Environment* 1(1), 1-31. DOI: 10.37947/ipbe.2020.vol1.1

Kalia, S., Dufresne, A., Cherian, B. M., Kaith, B. S., Avérous, L., Njuguna, J., and Nassiopoulos, E. (2011). "Cellulose-based bio- and nanocomposites: A review," *International Journal of Polymer Science* 2011, article ID 837875. DOI: 10.1155/2011/837875

Laskowska, A., Marchwicka, M., Trzaska, A., and Boruszewski, P. (2021). "Surface and physical features of thermo-mechanically modified Iroko and Tauari wood for flooring application," *Coatings* 11(12), article 1528. DOI: 10.3390/coatings11121528

Lengowski, E. C., Bonfatti, E. A., Nisgoski, S., Muñiz, G. I. B, and Klock, U. (2020). "Properties of thermally modified teakwood," *Maderas. Ciencia y Tecnología* 23(10), 1-16. DOI: 10.4067/S0718-221X2021000100410

Lima, A. C. B. (2019). *Efeito da Modificação Térmica nas Propriedades da Madeira de Mogno africano (Khaya ivorensis A. Chev.) [Effect of Thermal Modification on the Properties of African Mahogany Wood (Khaya ivorensis A. Chev.)]*, Master's Thesis, Federal University of Espirito Santo, Jerônimo Monteiro, Espírito Santo, Brazil.

Maistrello, L. (2018). "Termites and standard norms in wood protection: a proposal targeting drywood termites," in: *Termites and sustainable management, V2 – Economic losses and management*, M. A. Khan, and W. Ahmad (ed.), Springer, Cham, Switzerland, pp. 261-287.

Mburu, F., Dumarçay, S., Huber, F., Petrissans, M., Gérardin, P. (2007). "Evaluation of thermally modified *Grevillea robusta* heartwood as an alternative to shortage of wood resource in Kenya: Characterisation of physicochemical properties and improvement of bio-resistance," *Bioresource Technology* 98, 3478-3846. DOI: 10.1016/j.biortech.2006.11.006

McDonald, J., Fitzgerald, C., Hassan, B., and Morrell, J. J. (2022). "Thermal tolerance of an invasive drywood termite, *Cryptotermes brevis* (Blattodea: Kalotermitidae)," *Journal of Thermal Biology* 104, article 103199. DOI: 10.1016/j.jtherbio.2022.103199

Medeiros, N. L., Brito, D. Y. O., Santana, D. S. S., Brito, E. G. S., Melo, L. E. L., and Motta, J. P. (2020). "Análise tecnológica da madeira termorretificada de *Schizolobium parahyba* var. *amazonicum* (Huber ex Ducke) Barneby [*Technological analysis of thermally modified Schizolobium parahyba var. amazonicum (Huber ex Ducke) Barneby wood*]," in: *Agronomia: Jornadas Científicas [Agronomy: Scientific Conferences]*, Editora Científica Digital, Guaruja, Brazil, pp. 130-135. DOI: 10.37885/200400089

Melo, R. R., Silva, A. G. M. F., Sabino, M., Stangerlin, D. M., Batista, F. G., and Souza, M. J. C. (2019). "Efeito do tratamento térmico sobre a resistência da madeira de cambará a cupins subterrâneos [Effect of heat treatment on the resistance of cambara wood to subterranean termites]," *Revista de Ciências Agrárias* 42(3), 786-791. DOI: 10.19084/rca.17079

Menezes, W. M. (2017). *Efeito da Modificação Térmica em Escala Industrial na Qualidade da Madeira de Tectona grandis Linn. F*. [*Effect of Industrial-Scale Thermal Modification on Tectona grandis Linn. F Wood Quality of.]*, Ph.D. Thesis, Federal University of Santa Maria, Santa Maria, Rio Grande do Sul, Brazil.

Minkah, M. A., Afrifah, K. A., Batista, D. C., and Militz, H. (2021). "Chemical and mechanical characterization of thermally modified *Gmelina arborea* wood," *Les/Wood* 70(1), 31-44. DOI: 10.26614/les-wood.2021.v70n01a02

Okino, E. Y. A., Pastore, T. C. M., Camargos, J. A. A., Coradin, V. T. R., Teixeira, D. E., Santana, M. A. E., and Fagg, C. W. (2015). "Ensaio acelerado de laboratório de três espécies de madeiras da amazônia chamadas de tauari, expostas aos fungos de podridão-branca e parda e resposta colorimétrica de acordo com o sistema CIE L* A* B* [Accelerated laboratory test of three Amazonian species called tauari, exposed to white and brown rot fungi and colorimetric response according to the

CIE system L* A* B*],” *Ciência Florestal* 25(3), 581-593. DOI: 10.5902/1980509819609

Paes, J. B., Morais, V. M, Farias Sobrinho, D. W. de, and Bakke, O. A. (2003). “Resistência natural de nove madeiras do semi-árido brasileiro a cupins subterrâneos, em ensaio de laboratório [Natural resistance of nine woods from the Brazilian semi-arid region to subterranean termites, in a laboratory test],” *Cerne* 9(1), 36-47, (https://cerne.ufla.br/site/index.php/CERNE/article/view/601/511), Accessed 21 Aug 2024.

Paes, J. B., Souza, A. D., Lima, C. R., and Mederiso Neto, P. N. de (2010). “Eficiência dos óleos de nim (*Azaridachta indica)* e de mamona (*Ricinus communis)* na proteção da madeira de sumaúma (*Ceiba pentandra)* contra cupins xilófagos em ensaio de preferência alimentar [Efficiency of neem and castor oils on the protection of sumaúma wood against termites in choice test,” *Cerne* 16(1), 105-113. DOI: 10.1590/S0100-67622011000400020

Paula, M. H. (2016). *Efeito do Tratamento Térmico em Propriedades Tecnológicas das Madeiras de Angelim vermelho (Dinizia excelsa Ducke) e Sapucaia (Lecythis pisonis Cambess) [Effect of Heat Treatment on Technological Properties of Red Angelim (Dinizia excelsa Ducke) and Sapucaia (Lecythis pisonis Cambess) Woods]*, Master’s Thesis, University of Brasília, Brasília, Distrito Federal, Brazil.

Paula, M. H. de (2021). *Propriedades Tecnológicas de Madeiras Submetidas a Tratamentos Térmicos Para Estabilização Dimensional [Technological Properties of Wood Submitted to Thermal Treatments for Dimensional Stabilization]*, PhD Thesis, Federal University of Brasília, Brasília, Federal District, Brazil.

Pessoa, A.M. das C., Berti Filho, E., and Brito, J.O. (2006). *“Avaliação da madeira termorretificada de Eucalyptus grandis submetida ao ataque de cupim de madeira seca, Cryptotermes brevis [Evaluation of the thermally modified Eucalyptus grandis wood to the attack of the drywood termite Cryptotermes brevis],” Scientia Forestalis* 72, 11-16, (https://www.ipef.br/publicacoes/scientia/nr72/cap01.pdf), Accessed 21 Aug 2024.

Pierrot, L. M., Morais, J. W., Godoy, B. S., Nascimento, C. S. do, Mendonça, D. R. M. de, and Barbosa, A. P. (2022). “Effect of extracts of two Amazonian Fabaceae on *Cryptotermes brevis* (Walker) (Isoptera: Kalotermitidae),” *BioAssay* 15, article ba15001. DOI: 10.37486/1809-8460.ba15001

Priadi, T., Suhailiyah, W., and Karlinasari, L. (2021). “The resistance of heat-modified fast growing woods against decay fungi,” *IOP Conference Series: Earth and Environmental Science* 891(1), 1-9.

Reis, A. R. S., Loch, A. G., Moreira, S. M. C. O., Gondim, M. D. C., Silva, M. R., and Santos, P. S. B. (2019). “Natural resistance of wood from three forest species exposed to *Pycnoporus sanguineus* xylophagous fungus,” *Advances in Forestry Science* 6(4), 839-842. DOI: 10.34062/afs.v6i4.9492

Ringman, R., Pilgard, A., Kölle, M., Brischke, C., and Richter, K. (2016). “Effects of thermal modification on *Postia placenta* wood degradation dynamics: Measurements of mass loss, structural integrity and gene expression,” *Wood Science and Technology* 50, 385-397. DOI: 10.1007/s00226-015-0791-z

Severo, E. T. D., and Calonego, F. W. (2011). “Processo de modificação térmica, por irradiação de calor, para a melhora da estabilidade dimensional e da durabilidade biológica de madeira sólida [Thermal modification process, by heat radiation, to improve the dimensional stability and biological durability of solid wood],” in:

Instituto Nacional de Propriedade Industrial (INPI), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), Brazil. DOI: 10.17616/R31NJN39

Severo, E. T. D., Calonego, F. W., Sansígolo, C. A., and Bond, B. (2016). "Changes in the chemical composition and decay resistance of thermally-modified *Hevea brasiliensis* wood," *PLOS ONE* 11(3), 1-10. DOI: 10.1371/journal.pone.0151353

Silva, M. R. (2012). *Efeito do Tratamento Térmico nas Propriedades Químicas, Físicas e Mecânicas em Elementos Estruturais de Eucalipto citriodora e Pinus taeda [Effect of Heat Treatment on Chemical, Physical and Mechanical Properties of Structural Elements of Eucalyptus and Pinus taeda]*, Ph.D. Dissertation, University of São Paulo, São Carlos, São Paulo, Brazil. DOI: 10.11606/T.88.2012.tde-18012013-093404

Silva, M.F.C. (2021). *Comportamento da Madeira de Tauari (Coouratari oblongifolia Ducke) Tratada Termicamente e Comparada a Madeira Tratada com um Produto de Acabamento Submetidas à Fotodegradação Artificial [Performance of Thermally Modified Tauari Wood Compared to Surface-Finished Wood in Artificial Weathering Tests]*, Bachelor Thesis, Federal University of Brasília, Brasília, Federal District, Brazil.

Souza, A. D. (2009). *Rendimento, Caracterização Física e Eficiência do óleo de Nim (Azadirachta indica A. Juss) e de mamona (Ricinus communis L.) na Melhoria da Resistência da Madeira de Sumaúma (Ceiba pentandra (L.) GAERT.) ao Cupim Xilófago Nasutitermes corniger (Motsch.) [Yield, Physical Characterization and Efficiency of Neem (Azadirachta indica A. Juss) and Castor Oil (Ricinus communis L.) in Improving the Resistance of Kapok Wood (Ceiba pentandra (L.) GAERT.) to the Xylophagous Termite Nasutitermes corniger (Motsch.)]*, Graduation Thesis, Federal University of Campina Grande, Patos, Paraíba, Brazil.

TAPPI T203 cm-99 (1999). "Alpha-, beta- and gamma-cellulose in pulp," TAPPI Press, Atlanta, GA, USA.

TAPPI T222 cm-97 (2002). "Acid-insoluble lignin in wood and pulp," TAPPI Press, Atlanta, GA, USA.

TAPPI T264 cm-97 (2007). "Preparation of wood for chemical analysis," TAPPI Press, Atlanta, GA, USA.

Thybring, E.E., Kymäläinen, M., and Rautkari, L. (2018). "Moisture in modified wood and its relevance for fungal decay," *iForest – Biogeosciences and Forestry* 11(3), 418-422. DOI: 10.3832/ifor2406-011

Timberflow (2022). "Fluxo Madereiro [Timber Flow]," Timberflow; IMAFLORA, (https://timberflow.org.br/fluxo-madeireiro), Accessed 21 Aug 2024.

Tjeerdsma, B. F., and Militz, H. (2005). "Chemical changes in hydrothermal treated wood: FTIR analysis of combined hydrothermal and dry heat-treated wood," *Holz als Roh- und Werkstoff* 63(2), 102-111. DOI: 10.1007/s00107-004-0532-8

Windeisen, E., Strobel, C., and Wegener, G. (2007). "Chemical changes during the production of thermo-treated beech wood," *Wood Science and Technology* 41(6), 523-536. DOI: 10.1007/s00226-007-0146-5

Wise, L. E., Murphy, M., and D'addieco, A. A. (1946). "Chlorite holocellulose, its fractionation and bearing on summative wood analysis and studies on the hemicelluloses," *Paper Trade Journal* 122(35), pp. 35-43.

Zabel, R. A., and Morrel, J. J. (2020). *Wood Microbiology: Decay and Its Prevention,* Academic Press, London, UK.

Zhou, Q., Tu, D., Liao, L., and Guo, Q. (2013). "Variation of equilibrium moisture content of heat-treated *Couratari oblongifolia*, *Fraxinus excelsior*, and *Quercus rubra* wood," *BioResources* 8(1), 182-188.

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