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ARTÍCULO

Biological resistance of thermally modified *Gmelina arborea* wood

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Abstract:

Thermal modification of wood is an environmentally friendly method to improve wood durability, mainly against microorganisms. By employing a process similar to the ThermoWood®, various *Gmelina arborea* (gamhar) wood specimens were thermally modified at 180 °C, 200 °C, and 220 °C for 3 hours. The effects of the thermal modification process on the resistance to decay by rot-fungi, and attack by subterranean, arboreal, and dry-wood termites were determined. Generally, the thermal modification improved the resistance of *Gmelina arborea* (gamhar) to decay by *Trametes versicolor* with increasing process temperature. However, the effect of the process was null on the resistance to biodeterioration by the brown-rot fungus *Coniophora puteana* and the dry-wood termites *Cryptotermes brevis*. Even so, the visual damage caused by *Cryptotermes brevis* was slight. Untreated and thermally modified woods recorded higher resistance to *Coniophora puteana* than *Trametes versicolor*. Mass loss caused by *Nasutitermes corniger* also decreased with increasing thermal modification temperature. According to the visual damage rating values, the attack by *Nasutitermes corniger* was slight. However, the thermal modification inversely impacted *Gmelina arborea* (gamhar) attack by *Macrotermes* sp., as its resistance in the field to the termites decreased with increasing modification temperature. Thus, the thermal modification process contributed to improving the decay resistance of the modified wood to white-rot fungus *Trametes versicolor* and attack by the arboreal termites *Nasutitermes corniger* exposed indoors. On the other hand, thermally modified *Gmelina arborea* (gamhar) wood was very susceptible to *Macrotermes* sp. in the field. This work would provide a reliable reference document to guide wood industry stakeholders in assessing the performance of untreated and thermally modified *Gmelina arborea* (gamhar) wood in situations exposed to fungi and termite species adopted.

Keywords: *Coniophora puteana*, *Cryptotermes brevis*, decay resistance, durability, fungi, *Macrotermes* spp., *Nasutitermes corniger*, thermal modification, termite, *Trametes versicolor*.

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Introduction

Intrinsic properties of wood such as environmental friendliness, ability to fix carbon, good aesthetics, and good relationship between mass and strength, make it one of the most preferred materials for civil construction, furniture, and internal and external flooring. However, one key consideration for the use of wood in exterior applications is how to enhance its service life and reduce the frequency of maintenance (Sandberg *et al.* 2017).

Biological durability remains one of the most important properties of wood (Calonego *et al.* 2010). Different organisms degrade wood by attacking the cell wall polymers and metabolizing them into digestible units by the action of specific enzymes (Paes *et al.* 2004).

Thus, Boonstra (2008) reported widespread governmental restrictive regulations regarding the use of toxic chemicals in wood treatment. Hence, the demand for environmentally-friendly durability enhancement or use of highly durable wood, especially, in Europe and North America, has necessitated the focus on thermal modification of wood (Sandberg and Kutnar 2015).

Thermal modification processes have been well-developed and widely commercialized in the last decades (Hill *et al.* 2021). Wood species that are considered to be of no commercial value could be of immense use after thermal modification (Korkut and Guller 2008). These processes make the wood darker, more dimensionally stable, and more durable, especially against decay fungi.

The enhanced resistance of thermally modified timber against white and brown rot decay is well established. Several studies have reported different thermal modification methods such as Retification (Kamdem *et al.* 2002), the Plato process (Tjeerdsma *et al.* 2000), the Oil Heat Treatment (OHT) (Sailer *et al.* 2000), and the Thermowood® process (Viitanen *et al.* 1994). Thermally modified malapapaya (*Polyscias nodosa* (Blume) Seem.) showed improved resistance to brown-rot fungi (*Lenzites striata*) more than white-rot fungi (*Formes lividus*) at 200 °C when heated for 60 or 120 min. Maximum decay resistance to both fungal species was observed in wood samples treated for a more extended period (120 min) compared to 60 min heated samples (Jimenez Jr. *et al.* 2011).

Calonego *et al.* (2010) showed that an increase in thermal modification intensity (temperature and time) increased the decay resistance of rose gum (*Eucalyptus grandis* W.Hill ex Maiden) wood against the decay fungus *Picnoporus sanguineus*. Wood-digesting insects such as termites use wood as a food source, with subterranean termites causing more severe destruction to wood compared to dry-wood termites (Wang *et al.* 2018).

Sivrikaya *et al.* (2015) indicated that thermally modified wood is generally less resistant to termites (*Reticulitermes grassei*) attacks than untreated wood, while Brischke and Meyer-Veltrup (2016) discouraged the use of thermally modified wood in ground contact applications where termites are prevalent.

On the other hand, Brito *et al*. (2022) reported improved durability of thermally modified rose gum (*Eucalyptus grandis* W.Hill ex Maiden) and teak (*Tectona grandis* L.f.) wood against arboreal termite (*Nasutitermes corniger*). Batista *et al*. (2016) reported a null effect of the process on the resistance of thermally modified rose gum (*Eucalyptus grandis* W.Hill ex Maiden) wood against dry-wood termites (*Cryptotermes* sp.). The same effect was reported by Shi *et al*. (2007) for thermally modified aspen (*Populus tremuloides* Michx.), jack pine (*Pinus banksiana* Lamb.), and tulip tree (*Liriodendron tulipifera* L.) tested with subterranean termite (*Reticulitermes flavipes*). On the other hand, the attack on thermally modified scots pine (*Pinus sylvestris* L.) was higher than its untreated wood.

Thus, the results of the resistance of thermally modified wood against termite attack remain inconclusive. The results are likely specific to the species of wood and termites, as well as the thermal modification process adopted. Therefore, confirmation of durability against termites of other thermally modified wood species should be encouraged.

Research on the thermal modification of some short-rotation species (eucalypts and teak) is reported in the literature, but other woods also require studies. Gamhar (*Gmelina arborea* Roxb.) is a plantation-grown species in Ghana introduced from Southeast Asia and promises to be a good alternative to the dwindling primary timber species. It is regarded as a medium-density lesser-used species (LUS) (Mitchual *et al.* 2018, Mitchual *et al.* 2019).

Minkah *et al.* (2021a) reported that thermal modification of gamhar (*Gmelina arborea* Roxb.) wood significantly reduced its hygroscopicity and improved dimensional stability, making it suitable for indoor and outdoor applications. Gamhar (*Gmelina arborea* Roxb.) sapwood is not distinct from the heartwood (Sulaiman and Lim 1989). Some literature report that the heartwood is mildly to extremely durable and it is highly resistant in wet soil conditions. Thus the heartwood would not require preservative treatment in many cases. Conversely, the sapwood is non-durable and has to be treated with preservatives to improve resistance to fungal decay and insect attacks, while resistance of gamhar (*Gmelina arborea* Roxb.) wood to termite attack is uncertain (ITTO

2021). Owoyemi *et al*. (2011) rated 11-year-old untreated gamhar (*Gmelina arborea* Roxb.) wood as naturally non-durable to subterranean termite attacks, stressing that it requires preservative treatment to enhance its service life.

Consequently, this study adopted the ThermoWood® process to thermally modify gamhar (*Gmelina arborea* Roxb.) wood to improve its durability against wood-rotting fungi, subterranean, arboreal, and dry wood termites.

Materials and methods

Source of material and preparation

Four gamhar (*Gmelina arborea* Roxb.) trees with a diameter at breast height (DBH) of 35 - 55 cm were obtained from the 40-year-old plantation of the Council for Scientific and Industrial Research - Forestry Research Institute of Ghana (CSIR - FORIG) research plot at Abofour, Offinso District in the Ashanti Region of Ghana (7°8"0' N; 1°45"0' W). Abofour is located within the moist semi-deciduous forest zone with an average annual rainfall of 1400 mm.

The trees were bucked into 2,5 m length bolts and sawn into 25 mm thick boards (Figure 1). The boards were air-dried for at least 12 months until wood moisture contents (MC) were below 20 %. Boards were randomly obtained from a 15 cm radius from the pith, ensuring the use of the heartwood. These boards were further processed into test slats of 20 mm × 50 mm × 650 mm (radial × tangential × longitudinal) for the thermal modification process.

The slats were sorted according to mass and those in the range of 300 - 400 g were used for the study. This pre-sorting was necessary for the homogenization of the lot and to minimize the effect of the initial density on the results.

Thermal modification process and mass loss test

An open thermal modification system similar to the ThermoWood® process (Mayes and Oksanen 2002) was employed, using a 65 L capacity laboratory-scale reactor (Figure 1). Firstly, the temperature in the vessel was raised to 100 °C at 12 °C/h and then to 130 °C at 4 °C/h to allow high-temperature drying of the slats to nearly 0 % MC. Secondly, the temperature was increased at 12 °C/h until reaching the target temperatures of 180 °C, 200 °C, and 220 °C. Each target temperature was held for 3 hours. Finally, the temperature was decreased at 20 °C/h until reaching 65 °C, at which the vessel was opened, and the wood slats were removed.

For the mass loss test, the procedure reported by Metsä-Kortelainen *et al.* (2006) was applied to determine the mass loss caused by the thermal modification (ML_{TM} %) process for each modified slat. The mass and the corresponding moisture content were recorded for each slat before and immediately after the process. The moisture contents obtained were used to reduce the masses of the slats respectively, to determine their oven-dry masses for the computation of the mass loss.

Mass loss % ($ML_{TM,}$ %) was thus calculated as in Equation 1. Oven-dry mass (m_{dry}, g) was calculated as follows Equation 2.

$$ML_{TM\,(\%)} = \frac{\left(m_1 - m_2\right)}{m_1}100 \qquad (1)$$

Where: m_1 is the oven-dry mass of the sample before thermal modification, (g), and m_2 is the oven-dry mass of the sample after thermal modification, (g).

Oven dry mass (g), m_{dry}, was calculated as follows (Equation 2).

$$m_{dry(g)} = \frac{100m_u}{MC + 100}100 \qquad (2)$$

Where: m_u is the mass of the sample at moisture content u, (g) and MC - moisture content of the sample, (%).

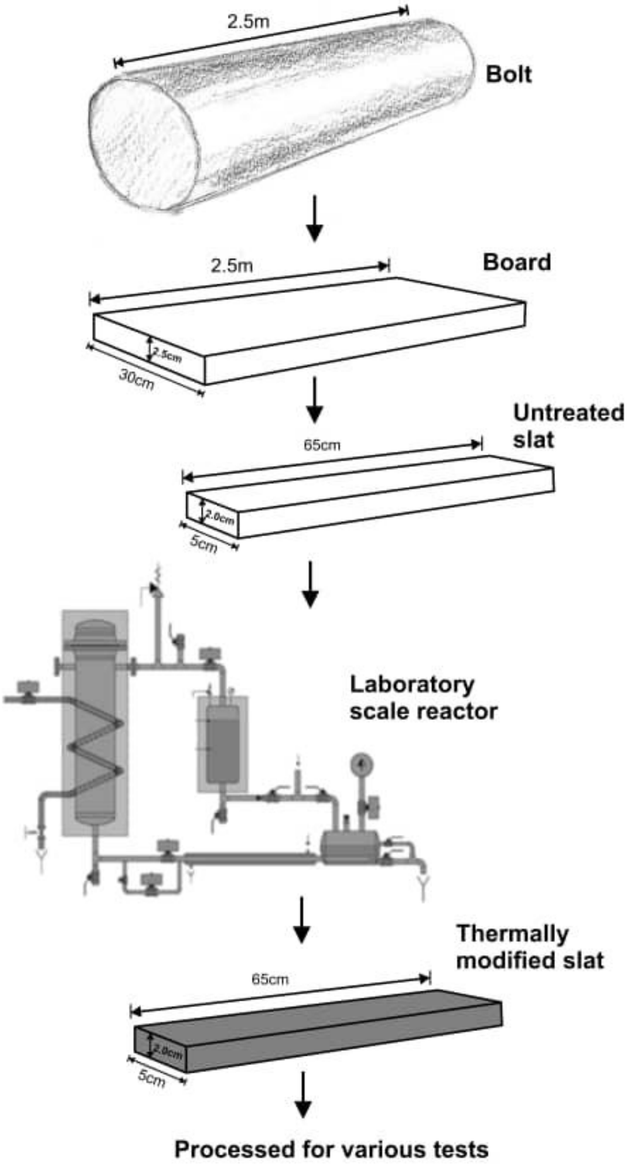

Figure 1: Material preparation process for biological resistance tests.

Fungal decay test

The fungal decay test of untreated and thermally modified test specimens of gamhar (*Gmelina arborea* Roxb.) wood was evaluated according to the European Standard - EN 113-2 (2021). Twenty - five replicate specimens with dimensions of 15 mm × 25 mm × 50 mm (radial × tangential × longitudinal), were oven-dried at 103 ± 2 °C until constant mass and weighed to the nearest 0,001 g to determine the oven-dry mass. After steam sterilization in an autoclave at 121 °C (103 kPa) for 20 min, sets of two specimens of the same treatment were placed on fungal mycelium in Kolle flasks (100 mL malt extract agar, 4 %).

The following fungal strains were used for the tests: the brown rot fungus *Coniophora puteana* (Schumach.) P. Karst. and the white-rot fungus *Trametes versicolor* (L.) Lloyd. F. Further 10 replicates made from scots pine (*Pinus sylvestris* L.) sapwood and beech (*Fagus sylvatica* L.) were used as virulence controls.

All specimens were incubated for 16 weeks at 22 ± 2 °C and 65 ± 5 % relative humidity. After incubation, specimens were cleaned from adhering fungal mycelium, weighed to the nearest 0,001 g, oven-dried at 103 ± 2 °C until constant mass, and weighed again to determine mass loss through wood-destroying basidiomycetes according to Equation 3.

$$ML_{F\,(\%)} = \frac{m_0 - m_{0,inc}}{m_0} 100 \qquad (3)$$

Where: ML_F is the mass loss by fungal decay (%), m_0 is the oven-dry mass before incubation, (g), and $m_{0,\,inc}$ is the oven-dry mass after incubation (g).

Durability classification

The durability classification of the tested materials was calculated as the quotient, x-value as European Standard - CEN/TS 15083-2 (2005), of the median ML_F of the tested timber and the median ML_F of the beech controls according to Equation 4.

$$x = \frac{ML_{F,med,tested\ timber}}{ML_{F,med,control}} \qquad (4)$$

Where $ML_{F,\ med,\ tested\ timber}$ is the median mass loss of the tested timber (%), and $ML_{F,med,\ control}$ - the median mass loss of the control timber (%) according to EN 113-2 (2021).

Durability classes (DC) were derived either from median ML_F, as (EN 113-2 (2021)) or the different x-values according to EN 350 (2016), and CEN/TS 15083-2 (2005) in the scheme shown in Table 1.

Table 1: Durability classes of wood to basidiomycetes attack.

Durability class	Description	Percentage mass loss $(ML_F)^1$	x-value
DC 1	Very durable	$ML_F \leq 5$ %	$x \leq 0,10$
DC 2	Durable	5 % $< ML_F \leq 10$ %	$0,10 < x \leq 0,20$
DC 3	Moderately durable	10 % $< ML_F \leq 15$ %	$0,20 < x \leq 0,45$
DC 4	Less durable	15 % $< ML_F \leq 30$ %	$0,45 < x \leq 0,80$
DC 5	Non durable	$ML_F > 30$ %	$x > 0,80$

$(ML_F)^1$ = highest of the median mass losses (%) determined for test specimens exposed to each of the used test fungi determined in decay tests according to EN 113-2 (2021).

Hardwoods: x-value = median value of mass loss for timber test specimens / median value of mass loss for beech reference test specimens according to EN 350 (2016), and CEN/TS 15083-2 (2005).

Field subterranean termite test

Seven clear wood specimens per treatment were used to determine the resistance to the subterranean termite (*Macrotermes* sp.). Specimens measured 20 mm × 20 mm × 300 mm (radial × tangential × longitudinal). Known for its low durability, kapok tree (*Ceiba pentandra* (L.) Gaertn.) specimens of equal dimensions and number were used as a control. A total of 35 specimens were used for the testing. Specimens were exposed to equilibrate with ambient conditions for 7 days. Two extra stakes from each treatment group of specimens were oven-dried at 103 ± 2 °C until a constant mass (nearest 0,001 g). The average moisture content (MC), was determined and used to correct the mass of the conditioned stakes (i.e., initial oven-dry mass) using Equation 5.

$$M_{to(g)} = \frac{100Mu}{100 + MC} \qquad (5)$$

Where: M_{to} is the theoretical oven-dry mass of the test specimen, (g), M_u - is the mass of the test specimen after conditioning, (g), and MC - average moisture content (%).

Wood specimens were exposed to subterranean termites (*Macrotermes* sp.) in the rainy season in a graveyard test, modified after EN 252 (2015) in a termite-prone area in the College of Agriculture and Natural Resources (CANR) farm in the Ashanti region of Ghana. Specimens were randomly inserted vertically in the soil to half their length in an even distribution and a spacing of 30 cm between the stakes. The stakes were inspected monthly. After 24 weeks of field exposure, the stakes were withdrawn and air-dried for 24 h to constant mass. The stakes were subsequently gently cleaned with a soft brush and their oven-dry mass was determined after drying at 103 ± 2 °C.

The percentage mass loss caused by termites (ML_T) i.e., the percentage of the difference between the calculated initial mass (corrected oven-dry mass) and the final oven-dry mass, as an indication of the level of deterioration of each stake, was determined according to Equation 6.

$$ML_{T\,(\%)} = \frac{\text{Corrected ovendry mass - Final ovendry mass}}{\text{Corrected ovendry mass}} 100 \qquad (6)$$

The ratings used for the mass loss according to Eaton and Hale (1993) were: 0-5 % very durable, 6-10 % durable, 11-40 % moderately durable, and 41-100 % non-durable. Damage rating codes used to categorize wear caused by termites on the wood specimens according to EN 252 (2015) adapted for smaller cross-sections were: 0 = No attack, 1 = Slight attack, 2 = Moderate attack, 3 = Severe attack, 4 = Failure.

Non-choice arboreal termite feeding test

A non-choice feeding test with arboreal termites *Nasutitermes corniger* Motsch. was performed according to the American Wood Protection Association - AWPA E1-16 (2016), and adapted to Paes *et al.* (2015). The colony was then installed to facilitate collection. Ten specimens were tested per treatment with dimensions of 6,4 mm × 25 mm × 25 mm (radial × tangential × longitudinal). Additionally, ten specimens of *Pinus* sp. sapwood were tested as a control. All specimens were previously oven-dried (103 ±2 °C) to determine the initial oven-dry mass - M_1 (nearest 0,001 g), followed by conditioning at room temperature for 14 days.

A colony of *Nasutitermes corniger* attached to a coffee bush (*Coffea* sp. L.) was collected in the municipality of Jerônimo Monteiro Espírito Santo state, Brazil, and brought to the laboratory to facilitate the collection of termites for the test. Glass bottles (600 mL) with metal screw lids were filled with 200 g of washed and sieved sand and sterilized in an oven at 110 ± 2 °C for 48 hours. To moisten the sand, 39 mL of distilled water was added to every bottle according to the previously calculated water-holding capacity of the sand.

After 72 hours, the termites were collected from the carton of paper to set up the experiment. One specimen was added per bottle, partially buried in the sand and arboreal termites (an average of 400 termites - 12 % soldiers and 88 % workers) were added per bottle. The bottles were stored in a conditioned room (28 ± 2 °C and 65 ± 5% relative humidity) for 28 days. After that, the specimens were removed from the bottles and gently cleaned with a soft brush.

A score corresponding to the wear caused by the termites was attributed to each specimen according to a rating system: 10 – sound, surface nibbles permitted; 9 – light attack; 7 – moderate attack penetration; 4 – heavy; 0 – failure. The guidelines of AWPA E1-16 (2016) were followed for the mortality assessment during the test and it was classified as 0-33 % - slight; 34-66 % - moderate; 67-99 % - heavy; 100 % - complete. The final oven-dried mass – M_2 and the mass loss caused by the termite have been calculated the same way as in the fungal decay test.

Non-choice dry wood termite feeding test

A non-choice feeding test with dry-wood termites, *Cryptotermes brevis* Walker, was performed according to the method of Instituto de Pesquisas Tecnológicas de São Paulo IPT/DIMAD-D2 (1980), which is similar to that described by Maistrello (2018). Ten specimens of gamhar (*Gmelina arborea* Roxb.) wood were tested per treatment with dimensions of 23 mm × 6 mm × 70 mm (radial × tangential × longitudinal).

Additionally, ten specimens of *Pinus* sp. wood were tested as a control. All specimens were previously oven-dried (103 ± 2 °C) for the determination of initial oven-dried mass – M_1 (nearest 0,001 g) followed by moisture stabilization under laboratory conditions for 14 days.

For each treatment, the specimens were grouped in pairs, forming five sets per treatment. A polyvinyl chloride (PVC) tube (35 mm diameter × 40 mm high) was attached to each pair with paraffin and 40 termites were introduced representing 39 workers and one soldier. Once assembled, each pair was placed in a Petri dish and the tubes were covered with a piece of fabric net to prevent termites from being preyed upon by spiders, ants, and wall lizards. The sets were stored in a conditioned room (28 ± 2 °C and 65 ± 5 % relative humidity) for 45 days. At the end of the test, the remaining termites were removed and counted to assess the mortality.

The damage and the number of holes in the specimens were also evaluated. Only those holes that ran through the surfaces of the specimens were considered. The damage scores (visual ratings) were classified as 0 – sound, 1 – slight, 2 – moderate, 3 – heavy, and 4 – failure. The final oven-dried mass – M_2 and the mass loss caused by the termite action were calculated the same way as in the rot-fungi test.

Statistical analysis

The significance level was 5 % for all biological tests and the experiment was carried out in a completely randomized design. The homogeneity of variances was verified by Bartlett's test. Once the null hypothesis was confirmed (p > 0,05), the effect of treatments (untreated, 180 °C, 200 °C, 220 °C, and control) was verified by analysis of variance (ANOVA), using Tukey's test to differentiate means.

In cases where the variances were not homogeneous (Bartlett’s test, p < 0,05), the effect of the treatments was verified by the H-test of Kruskal-Wallis, using Bonferroni’s test to differentiate the means of the scores. The damage ratings, which are discrete data, also were analyzed with the H-test of Kruskal-Wallis.

Results and discussion

Mass loss by thermal modification process and resistance against decay fungi

For the same gamhar (*Gmelina arborea* Roxb.) wood slats used in this research, Minkah *et al.* (2021b) obtained mass losses of 5,44 %, 10,08 %, and 15,13 % at 180 °C, 200 °C and 220 °C respectively. High mass loss implies more pronounced changes in wood properties, for example, density, strength properties, and proportions of cellulose, hemicellulose, and extractives (Esteves and Pereira 2009).

Mass loss due to decay caused by *C. puteana* (brown rot) and *T. versicolor* (white rot) on untreated and thermally modified gamhar (*Gmelina arborea* Roxb.) wood are presented in Table 2. *C. puteana* caused mass loss of 0,74 % in untreated wood which generally decreased with increased modification temperature to a minimum at 220 °C (0,08 %). The score mass loss values for wood thermally modified at 200 ºC (36,69) and 220 ºC (23,27) were significantly lower than for untreated wood (61,48). However, both untreated and thermally modified woods were classed as very durable (x-value < 0,10) against *C. puteana*. *T. versicolor* caused a mass loss of 25,71 % in untreated wood while the lowest mass loss was recorded in the wood modified at 220 °C (0,27 %), thus, the mass loss significantly decreased with increasing modification temperature.

Table 2: Mass loss caused by *Coniophora puteana*, and *Trametes versicolor* fungi in thermally modified wood.

Temperature (°C)	*Coniophora puteana*			*Trametes versicolor*		
	Mass loss (%)			Mass loss (%)		
	Mean	Mean Score	x-value	Mean	Mean Score	x-value
Untreated	0,75	61,48 A	0,02	25,71	88,42 A	0,99
180	0,71	72,56 A	0,02	12,13	67,58 B	0,36
200	0,19	36,69 B	0,00	3,60	39,73 C	0,10
220	0,08	23,27 B	0,00	0,27	14,27 D	0,00
Batlett's test	4,34*			4,11*		
H-test	47,21^{ns}			89,79		

Means followed by the same letter in the columns do not differ (Bonferroni's test; p > 0,05). *Significant (Batlett's test; p < 0,05); ^{ns} Non significant (H-test; p > 0,05).

The mean score mass loss of thermally modified wood decreased significantly to the lowest at 220 ºC (14,27) when compared with untreated wood (88,42). The durability rating increased to very durable class (x = 0,00) at 220 ºC. Literature indicated that reduction in mass loss from fungal is due to thermal modification products generated in the wood that act as fungicides, coupled with the modified wood structural components. These restrain fungi from recognizing the wood components for food to cause severe degradation (Weiland and Guyonnet 2003). Moreover, reduced fungal decay resistance of thermally modified gamhar (*Gmelina arborea* Roxb.) wood could be due to reduced affinity for water/moisture as modification temperature increased (Hakkou *et al*. 2006).

Generally, the gamhar (*Gmelina arborea* Roxb.) wood was more susceptible to decay by *T. versicolor* than *C. puteana* (Jimenez Jr *et al.* 2011). According to Calonego *et al*. (2010) and Severo *et al*. (2012), improvement in decay resistance in thermally modified wood to rot - fungi, results from changes in the chemical composition of the wood, mainly the unavailability of food (hemicelluloses) to the fungi, the production of new molecules that act as fungicides, lowered affinity of thermally modified wood to water, and the cross-linking between lignin and the polymer from the thermally degraded cellulose. The mean mass loss of 41,48 % and 28,92 % were caused by the action of *C. puteana* and *T. versicolor* on scot's pine sapwood (*Pinus sylvestris*) and beech (*Fagus sylvatica*) respectively, used as negative control, confirm the virulence of the fungi strains employed in this study.

Field test with subterranean termites

In Table 3, untreated wood was very durable against deterioration by *Macrotermes* sp. (mean mass loss = 4,63 %) while susceptibility to attack increased significantly with increased thermal modification temperature to a maximum mass loss of 55,83 % (non-durable) at 220 °C. The highest mass loss of 55,83 % at 220 °C was lower than in the case of kapok tree (*Ceiba pentandra* (L.) Gaertn.) control (83,70 %). The score mass loss values indicated significant decreases in the durability of thermally modified wood compared to untreated wood. A similar trend was recorded in the visual damage ratings, which was minimum in untreated wood (0,86) to a significant highest of 2,86 at 220 °C. According to Antwi-Boasiako *et al.* (2011), wood becomes susceptible to termite attack upon removal of extractives.

Table 3: Mass loss and visual damage rating caused by *Macrotermes* sp. in thermally modified wood.

Temperature (°C)	Mass loss (%)		Visual damage rating	
	Mean	Mean score	Mean	Mean score
Untreated	4,63	10,14 C	0,86	7,00 C
180	30,39	15,71 B	2,14	16,29 B
200	38,10	17,43 B	2,71	19,58 B
220	55,83	19,71 B	2,86	20,71 B
C. pentandra (control)	83,47	27,00 A	3,71	26,43 B
Bartlett's test	3,93*		-	
H-test	10,11*		15,73*	

Means followed by the same letter in the columns do not differ (Bonferroni's test; p > 0,05). *Significant (Bartlett's and H-tests p<0,05).

Significant loss of extractives content in thermally modified by Minkah *et al.* (2021b) for the same gamhar (*Gmelina arborea* Roxb.) wooden slats, could have accounted for this outcome. Also, intermittent exposure to rains while the termites managed to bring moisture into the wood tended to reduce the water-repellence effectiveness of the thermally modified wood than the untreated wood (Minkah *et al.* 2021a), making thermally modified gamhar (*Gmelina arborea* Roxb.) wood more susceptible to attack by *Macrotermes* sp. (Ali 2011). Contrary to Owoyemi (2011), untreated gamhar (*Gmelina arborea* Roxb.) wood was durable against subterranean termite attacks in this study. Consequently, the thermal modification process was ineffective in improving wood resistance to termites (*Macrotermes* sp.), making thermally modified wood less resistant to termite attack than untreated wood in the field (Sivrikaya *et al.* 2015).

Resistance against arboreal termites

According to the results in Table 4, the variances were not homogeneous making the ANOVA impossible. The H-test was used, which was significant ($p < 0,05$). A variance homogeneity test was not performed for damage rating because they are naturally discrete data.

Fourteen days after the start of the experiment, termite mortality was complete for all treatments, except for the control slash pine (*Pinus elliottii* Engelm.), which reached this mark at 21 days. It is emphasized that, according to AWPA E1-16 (2016), the test should last 28 days. This indicates that the wood of gamhar (*Gmelina arborea* Roxb.) may have some natural chemical compound with toxic properties to these termites. Since, in the control bottles, without the presence of wood, the termites built galleries, which denote the activity and vigor of the colony used. Terpenes and terpenoids are present in pine wood and have an action against *Nasutitermes* sp. (de la Cruz *et al.*

2014, Lepage *et al.* 2017). Thus, the mortality of termites, before the 28 days foreseen in the aforementioned standard.

Table 4: Mass loss and visual damage rating caused by *Nasutitermes corniger* in thermally modified wood.

Temperature (°C)	Mass loss (%)		Visual damage rating	
	Mean	Mean score	Mean	Mean score
Untreated	3,98	33,8 AB	9,5	36,8 A
180	2,60	21,4 BC	8,6	22,2 AB
200	1,79	12,2 C	8,6	21,6 AB
220	2,07	14,6 C	8,4	18,3 B
Pinus elliottii (control)	9,58	43,5 A	8,2	15,4 B
Bartlett's test	11,89 *		-	
H-test	30,94 *		16,27 *	

Means followed by the same letter in the columns do not differ (Bonferroni's test; p > 0,05). *Significant (Bartlett's and H-tests p < 0,05).

For durability of clones of rose gum (*Eucalyptus grandis* W.Hill ex Maiden) × popo (*Eucalyptus urophylla* S.T.Blake) wood and used termites from the same colony, Medeiros (2021) observed higher mass loss (22,9 %) and a lower mortality (52,38 %) at the end of the test. Thus, the results can be considered a response to the effect of the gamhar (*Gmelina arborea* Roxb.) wood natural chemical compound and the adopted thermal modification temperatures.

A complete mortality of *N. corniger* for untreated and thermally modified teak (*Tectona grandis* L.f.) wood, as well as for slash pine (*Pinus elliottii* Engelm.) (control), also was reported by Brito *et al.* (2022). Thus, the discrepant results of termite mortality in eucalypt (Medeiros 2021) and gamhar (*Gmelina arborea* Roxb.) wood are likely to be related to the natural chemical compound present in this wood. However, it is suggested a study about this for further clarification.

Resistance increased when wood was thermally modified at 200 °C and 220 °C, compared to untreated wood and the control. There was no difference between untreated and thermally modified wood at 180 °C. Brito *et al.* (2022) also reported increased resistance of thermally modified rose gum (*Eucalyptus grandis* W.Hill ex Maiden) and teak (*Tectona grandis* L.f.) wood against the attack of *N. corniger*. On the other hand, Batista (2012) reported a null effect of thermal modification on the resistance of rose gum (*Eucalyptus grandis* W.Hill ex Maiden) wood to the same termite.

The increase in resistance to attack by *N. corniger* as modification temperature increased could be ascribed principally to the chemical alteration of main wood polymers, reduced hygroscopicity of thermally modified wood (Minkah *et al.* 2021a), the effect of which overrode the effect of the extractives content (Minkah *et al.* 2021b), since most of them are evaporated or percolated to the surface of the wood, being eliminated from the wood during the machining process of the test samples.

For the visual damage rating, the highest absolute value was attributed to the untreated wood, which means less damage according to the visual classification of AWPA E1-16 (2016). However, the damage rating of untreated wood did not differ from the temperatures at 180 °C and 200 °C. In general, after visual damage analyses, the attack caused by *N. corniger* on the specimens could be classified as "light" to "moderate", as AWPA E1-16 (2016) classification.

Resistance against dry-wood termites

According to the results in Table 5, the variances were not homogeneous making the ANOVA impossible. The H-test was used, which was significant ($p < 0,05$). A variance homogeneity test was not performed for damage rating because they are naturally discrete data. As for mortality, homogeneity of variances between temperatures was observed, allowing the application of ANOVA.

The statistical decision was the same for both mass loss and visual damage rating, where there was no difference between untreated and thermally modified gamhar (*Gmelina arborea* Roxb.) wood. This same trend was reported in studies with thermally modified eucalypt wood (Batista *et al*. 2016, Medeiros 2021), teak (*Tectona grandis* L.f.) wood (Brito *et al.* 2022), and *Schizolobium parahyba* wood (Calonego 2017).

Table 5: Mass loss, visual damage rating, and mortality caused by *Cryptotermes brevis* in thermally modified wood.

Temperature (°C)	Mass loss (%)		Visual damage rating		Mortality (%)
	Mean	Mean score	Mean	Mean score	Mean
Untreated	0,51	27,4 AB	1,1	24,0 AB	60,5 AB
180	0,37	29,3 AB	1,1	23,2 AB	57,5 AB
200	0,20	21,8 B	0,8	20,9 B	71,0 A
220	0,07	13,7 B	0,9	19,1 B	68,0 A
Pinus elliottii (control)	1,80	35,4 A	2,5	40,5 A	43,0 B
Bartlett's test	90,91 *		-		8,29 ^{ns}
H-test	12,73 *		15,46 *		-
Fc	-		-		3,54 *

Means followed by the same letter in the columns do not differ (Bonferroni's or Tukey's tests; p > 0,05)
*Significant (Bartlett's and H-tests p < 0,05); ns: non-significant (p > 0,05) and *significant (p < 0,05) by Bartlett's, H, and F tests.

On the other hand, considering the absolute values, mass loss is reduced with increasing temperature of thermal modification. This was also verified for thermally modified *Schizolobium parahyba* wood, where better results were found for treatment at 220 °C than for untreated wood (Calonego 2017).

Compared to the control (*Pinus elliottii*), higher resistance was verified for thermally modified *G. arborea* wood at 200 °C and 220 °C. In general, the visual damage rating of gamhar (*Gmelina arborea* Roxb.) wood was classified as "slight" and for the control it was from "moderate to heavy", as IPT/DIMAD-D2 (1980).

The termite mortality had the same statistical decision as the previous analyses, indicating a good relationship between the results of termite mortality *vs* mass loss, as well as termite mortality *vs* visual damage rating. It was classified as moderate (control, untreated, and subjected to 180 °C) and high (200 °C and 220 °C), according to AWPA E1-16 (2016). Other studies with thermally modified wood reported a wide range of termite mortality, sometimes lower - 53 -60% (Medeiros 2021), similar - 52-76 % (Brito *et al.* 2022), or higher - 77-83 % (Batista 2012) than the results in Table 5 for gamhar (*Gmelina arborea* Roxb.).

Termite mortality values are related to the presence of some toxic substance in concentrations sufficient to cause the death of these insects, after consuming the wood (Gonçalves *et al*. 2013, Batista *et al*. 2016), especially those with antioxidant characteristics such as flavonols, tannic acid, morin, and catechin (Little *et al*. 2010), tectoquinone (β-methyl anthraquinone) (Brocco *et al*. 2020), which are effective against dry-wood termites. Another issue to be analyzed is the ash content (calcined minerals), which causes damage to the jaws of these insects, as observed by Kvedaras *et al*. (2009) for the sugarcane stem borer (*Eldana saccharina*), which makes wood scarification and insect feeding difficult.

Mortality of dry-wood termites (*Cryptotermes brevis*) may be related to densities, extractive and wood ash contents. Thus, there is no single characteristic that relates to the attack caused by termites, but rather a set of factors, such as age, position on the trunk, genetic and environmental attributes (Gonçalves *et al.* 2013). Another factor to be analyzed is the stress to which termites are subjected during the test, proposed by IPT/DIMAD D 2 (1980) and Maistrello (2018), in which they are exposed to the environment, while, in their attack on furniture, are protected by their galleries. To alleviate this stress and create a better environment during the test, Medeiros (2021) proposed that the test be mounted on trays and the samples placed one on top of the other. This provided lower termite mortality and a more effective attack on the test samples.

Associating the results of both tests with *N. corniger* and *C. brevis*, it is likely that gamhar (*Gmelina arborea* Roxb.) wood has good durability against the attack of these species of termites. It is suggested that further studies be carried out on natural chemical compounds present in this wood to identify the cause of its durability, as well as with other species of termites.

Conclusions

The effect of thermal modification was positive in increasing the resistance of *G. arborea* wood to biodeterioration by white-rot-fungus *Trametes versicolor,* and arboreal termite (*Nasutitermes corniger*), mainly for the highest temperatures tested.

On the other hand, the effect of the process was negative, for the field trial with subterranean termites, and null on resistance to biodeterioration by the brown-rot-fungi *Coniophora puteana* and *Cryptotermes brevis* (dry-wood termite). Due to the low performance of thermally modified *Gmelina arborea* wood in the field test with subterranean termites, we do not suggest its use in ground contact, mainly in places with high incidence of *Macrotermes* sp. termites.

Authorship contributions

M. A. M.: Conceptualization, writing - original draft, methodology, project administration, visualization. K. A. A.: Conceptualization, writing - review and editing, methodology, supervision. C. A-B.: Conceptualization, writing - review and editing, supervision. D. C. B.: Conceptualization, writing - review and editing, resources, supervision, visualization. A. P. S. S.: Investigation, resources. J. R. M.: Investigation, resources. J. B. P.: Writing - review and editing, investigation, resources. C. B.: Conceptualization, methodology, writing - review and editing, resources, supervision. H. M.: Conceptualization, methodology, resources, supervision.

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