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Non biocide treatments for the protection of short rotation teak wood against subterranean termites

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ABSTRACT

Short rotation teak wood is susceptible to biodeterioration, particularly to termite attack. The objective of this work was to investigate the effect of chemical and thermal treatment on resistance of sapwood, transition wood, and heartwood of short rotation teak against Asian and European subterranean termites. In a second time, the "non biocidal" aspect of different treatments was evaluated using "choice" and "non-choice" screening termite tests. Furfurylation (FA), thermal treatment (HT), and combination of chemical and thermal treatment using glycerol-maleic anhydride (GMA) were performed on sapwood, heartwood, and their transition fractions (50:50, sapwood:heartwood). On one side, the wood samples were exposed to Asian subterranean termite (*Macrotermes gilvus*) under field test, in Indonesia. On the other side, the wood samples were also tested against the attack of European subterranean termite (*Reticulitermes flavipes*) under non-choice and choice screening test, in laboratory. From field tests, the results show that heartwood exhibited a lower mass loss compared to sapwood due to its extractive content. FA and GMA at 220 °C treatments performed in better termite resistance after field test according to their mass losses. Results from the choice and no-choice tests show that chemical and thermal modifications improved termite resistance due to their low mass loss. No surviving termites were observed after the non-choice test on chemically and thermally modified wood. The high termite survival rate in the choice test confirmed the hypothesis that chemical and thermal modification treatments were non-biocidal to termites compared to borax control samples. The FA and GMA treatment could be considered as eco-friendly modification methods to protect the short rotation teak wood and wood in general against subterranean termites.

1. Introduction

Total log production in Indonesia is 64.65 million m^3 in 2022, the largest production being fast-growing species of about 60 % [3]. The majority of a fast-growing wood supply has been developed by wood plantation companies in Indonesia. Short-rotation teak is one of the fast-growing woods currently widely cultivated in Indonesia. Perhutani, a state forest enterprise in Indonesia, reported that potential production area of Plus Perhutani teak as short rotation teak wood in 2020–2024 reaches 250,871 ha [26]. Short rotation teak as a fast-growing tree can be considered as a renewable resource for the future green economy. Short rotation teak has several advantages such as short cutting cycle (7–15 years), lesser branches, straight and cylindrical trunk. However, short rotation teak wood has low quality especially in resistance to bio-deterioration and bio-degradation [28,29]. Lukmandaru and Takahashi [17] reported that sapwood and heartwood in 8-year-old teak trees are the most susceptible to termites compared to 30- and 51-year-old trees, mainly due to the content of quinone compounds level, which increases according to the age of the tree. Our previous study also found that sapwood of short rotation teak wood present low natural durability than those of heartwood, against subterranean termite (mainly *Macrotermes gilvus* species) attacks in field test conditions [21].

Termites are a serious problem, especially in tropical and Mediterranean climates due to favorable temperature and humidity conditions for their proliferation. Subterranean termites are the main insect pests of wood which can cause the most damage compared to other termite

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species. According to Rust and Su [31], subterranean termites cause an estimated US$ 32 billion in global economic losses for the control and damage repair costs in 2010. Subterranean termite attacks contribute about 70 % of construction damage and about 90 % of total economic losses. Kuswanto et al. [14] reported that subterranean termites are an economically important pest in Asian countries because they cause hundreds of millions or even billions of dollars in economic losses annually. Subterranean termites from the *Coptotermes* genus have the largest number of species followed by *Macrotermes* sp., *Reticulitermes* sp. and *Odototermes* sp. Rust, Su [31]. In order to reduce or prevent the damage due to subterranean termite attack, wood modification represents one of the most effective methods to increase wood durability.

Non-biocide methods based on chemical and thermal modifications are potential wood protecting ways to biological attacks. Thermal modification is a wood modification currently being developed on an industrial scale and leads to an improvement of wood properties, especially increasing dimensional stability and decay resistance [12,18,28]. However, thermal modification does not allow to improve the wood resistance against termite attack [33,34,35]. In some cases, thermally modified wood can be more appetent for termites and thus degraded, even if a higher mortality rate at the end of the test is observed than those of untreated wood [4,25].

Many previous studies reported that chemical modification, such as acetylation, DMDHEU (1.3-dimethylol-4.5-dihydroxyethyleneurea), and furfurylation, can improve wood durability against termite attack [8,11,22]. Furfurylation process has also been developed on industrial scale. Furfurylated wood has been reported to be resistant to termite attack [8,15,16,19]. However, the termite resistance can be achieved by furfurylation only if a large amount of chemicals impregnated into the wood leading to impact the high weight percent gain.

Combination of low concentration chemical and thermal modification can be a promising and an attractive alternative to increase termite resistance. Mubarok et al. [23] reported that beech wood modified by glycerol or polyglycerol maleate aqueous solution (10 % or 40 %, w/w) followed by thermal modification at 180, 200, or 220 °C present higher durability against the subterranean termite compared to untreated wood or to the only thermally modified wood. Martha et al. [20] also conducted wood modification using 10 % of glycerol-maleic anhydride (GMA) combined with thermal modification at 150 or 220 °C on sapwood of 15-year short rotation teak wood. The result showed that the use of GMA combined with thermal treatment can be valuable to protect the sapwood against termite. The present study aimed to

assess the effect of non-biocide treatments based on various combination of chemical and thermal modifications, on the conferred termite resistance to sapwood, heartwood, and transition wood from short rotation teak. The termite resistance of short rotation teak was evaluated under field test with Asian subterranean termites (*Macrotermes gilvus*) and laboratory screening test with European subterranean termites (*Reticulitermes flavipes*) with the objectives of demonstrating the improvement of durability conferred by the different treatments, but also to demonstrate their non-biocide characters. Besides introducing environmentally friendly wood modification methods, the results of this study are also expected to contribute to optimizing the utilization of short rotation teak wood by providing more uniform modified boards for market applications.

2. Material and methods

2.1. Sample preparation

Short rotation teak (*Tectona grandis* Linn.f.) woods were obtained from a managed plantation forest located at Bogor, West Java, Indonesia (6° 33’ 15” S, 106° 40’ 07” E). The climatic condition of the growing area is characterized by an average rainfall around 2000–3000 mm year^{-1}, and minimal and maximal average temperatures of 15 and 31 °C, respectively [36]. Three short rotation teak trees of 13 years old with 27 cm in average diameter at breast height were selected for the study. For each tree, a log sections in length of 1 m were taken at the bottom part of three stem. The wood blocks for chemical and thermal modifications were prepared to a size of 200 ×50 x 20 mm^3 (L x R x T). The samples were air dried up to the final moisture content of 12–15 % at 23 ± 2 °C and 50 ± 5 % relative humidity. Wood block samples were taken from preceding wood boards presenting sapwood (SW), transition wood (TW) – 50 % of sapwood and 50 % of heartwood, and heartwood (HW). Six different treatment modalities were investigated: untreated, furfurylation (FA), thermal treatment at 150 °C (HT150), thermal treatment at 220 °C (HT220), GMA-thermal treatment at 150 °C (GMA150), and GMA-thermal treatment at 220 °C (GMA220). After treatment, three wood block samples per each treatment were cut into smaller pieces for the different tests. Samples of 25 ×10 x 5 mm^3 (L, R, T) were prepared for laboratory tests and samples of 200 ×10 x 20 mm^3 (L, R, T) for field tests. For transition wood, wood blocks were divided into two parts: transition sapwood (TS) and transition heartwood (TH) (Fig. 1).

2.2. Chemical modification by furfurylation

Furfuryl alcohol solution containing weight percentages of 45 % furfuryl alcohol, 5 % tartartic acid as catalyst, and 50 % distilled water was prepared at room temperature. All the reagents were acquired from Sigma-Aldrich Chimie SARL, France. The impregnation solution was mixed under vigorous mechanical stirring during 15 min. Sapwood, transition, and heartwood block samples were previously dried at the temperature 103 ± 2 °C °C for 48 h. Then, the FA treatment was carried out in an autoclave. The FA process consisted of wood samples treatment carried out in a vacuum condition of 8–10 kPa for 15 min followed by immersion in furfuryl alcohol solution under vacuum conditions of 4–5 kPa for 15 min, and followed by a last treatment step performed under a pressure of 1200 kPa for 30 min. The FA impregnated samples were then air-dried at room temperature (around 20 ± 5 °C) for 48 h and were then wrapped in aluminum foil. In order to polymerize furfuryl alcohol in wood, impregnated samples were cured at 120 °C for 16 h under nitrogen condition. Subsequently, aluminum foil was removed, and samples were further oven-dried at 103 ± 2 °C for 48 h to reach their final oven-dried mass.

2.3. Thermal modification

Sapwood, transition, and heartwood block samples were previously oven-dried at 103 ± 2 °C for 48 h. Thermal modification was then performed under nitrogen condition at the initial temperature of 20 ± 5 °C and then the temperature was increased to the target temperature of 150 or 220 °C, with a heating rate of 20 °C min^{-1}. To reach the target temperature, it took 4 hours for 150°C and 6 hours for 220°C. The duration of the treatment was 20 h at the target temperature. After the thermal modification, the heat-treated samples were allowed to cool down to room temperature under an inert atmosphere. Finally, samples were oven-dried at 103 ± 2 °C for 48 h to reach their final oven-dried mass.

2.4. Combination of chemical and thermal modification

Combination of chemical and thermal modification was carried out by impregnation of glycerol-maleic anhydride (GMA) solution followed by thermal modification. Glycerol and maleic anhydride were purchased from Sigma-Aldrich Chimie SARL, France. According to Mubarok et al. [23], GMA solution was made by reacting 1 mol of glycerol (92.09 g mol^{-1}) and 2 mol of maleic anhydride (98.06 g mol^{-1}) and heating at 80 °C for 3 h [30]. GMA solution and distilled water were stirred with the final concentration of 10 % w/w. Sapwood, transition, and heartwood samples before GMA impregnation were oven dried at 103 ± 2 °C for 48 h. Wood blocks were placed in an autoclave and a vacuum of 8–10 kPa was applied for 15 min. Wood blocks were covered

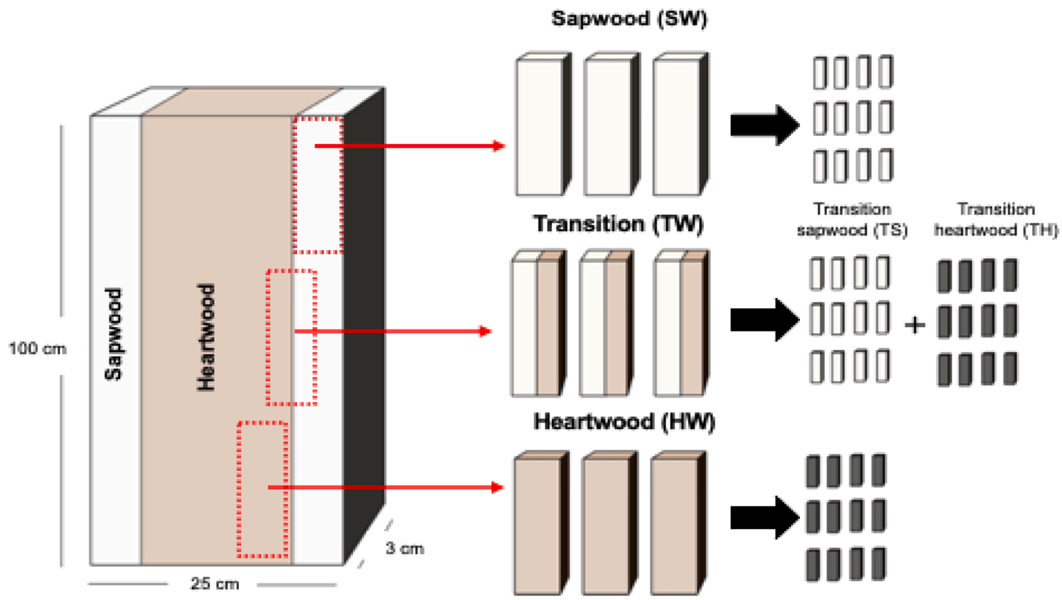


Fig. 1. Cutting sample schematic for sample preparation.

by GMA solution under vacuum conditions 4–5 kPa for 15 min and a pressure of 1200 kPa for 60 min was then applied. All of impregnated samples were air conditioned for 48 h. The wood blocks were wrapped in aluminum foil and placed in a reactor under nitrogen. The curing stage was performed at 150 or 220 °C for 20 h under nitrogen, according to the same process used for the thermal modification treatment. After curing stage, GMA treated samples were oven-dried at 103 ± 2 °C for 48 h to reach their final oven-dried mass.

2.5. Retention and mass change

For each modification modality, retention (except for thermal modification only) and mass change were calculated for all wood blocks using the following equations (Eqs. 1 and 2):

$$\text{Retention (kg.m}^{-3}\text{)} = 0.1 \text{ x } (m_1 - m_0)/V_0 \quad (1)$$

$$\text{Mass change (\%)} = ((m_2 - m_0) / m_0) \text{ x } 100 \quad (2)$$

where m_0 is the initial mass of wood at 103 ± 2 °C before treatment, m_1 is the mass of wood after impregnation, m_2 is the final mass of wood at 103 ± 2 °C after treatment and V_0 is the initial volume of wood at 103 ± 2 °C before treatment.

2.6. Field test with Asian subterranean termite

Field test was performed to determine the resistance of natural and modified short-rotation teak woods against Asian subterranean termites, in uncontrol outdoor conditions. The termite field test was carried out on the research site of the Faculty of Forestry, located at the Institut Pertanian Bogor (IPB University), Bogor, Indonesia (6° 33' 27.0" S, 106° 43' 46.2" E). The dominant subterranean termite species present and identified in this area was *Macrotermes gilvus* Hagen. Three replicates of SW, TS, TH, and HW stakes for each treatment modality were used with dimensions of 200 ×10 x 20 mm^3 (L, R, T). All stakes were previously oven-dried at 103 ± 2 °C until reach a constant mass (m_3). The wood stakes were then distributed randomly for all replicates of each treatment on the field test. All stakes were buried vertically in the ground up to 3/4 of their length (150 mm) with a distance of 300 mm between each sample (Fig. 2) and were exposed for 12 weeks. After exposure, all stakes were removed carefully from the soil, washed with water and cleaned with a brush. Then, all tested samples were dried at room temperature (23 ± 2 °C and 50 ± 5 of relative humidity, for 3 days) and followed by oven drying of 103 ± 2 °C until constant weight (m_4). The oven-dried mass loss (ML_f) of each exposed wood samples, due to termite attack, were determined according to the following equation (Eq. 3):

$$ML_f = ((m_3 - m_4) / m_3) \text{ x } 100 \quad (3)$$

where ML_f (%) is the percentage of oven-dried mass loss, and m_3 and m_4 are oven-dried masses of the samples before and after termite field test exposure, respectively.

The raw and modified wooden stakes were evaluated according to the AWPA E7–07 standard (Table 1). Rating of tested samples were determined by visual damage and wood thickness attack by termites (the average depth of cross-sectional area affected due to termite attack). Wood thickness attack by termites was calculated by the average value of the volume divided by the area of wood affected.

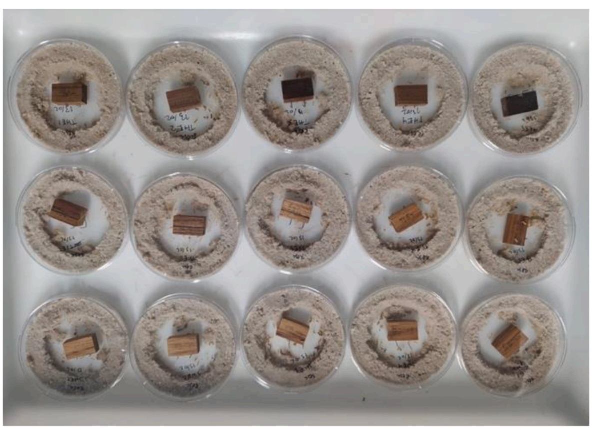
2.7. Non-choice and choice test with European subterranean termite

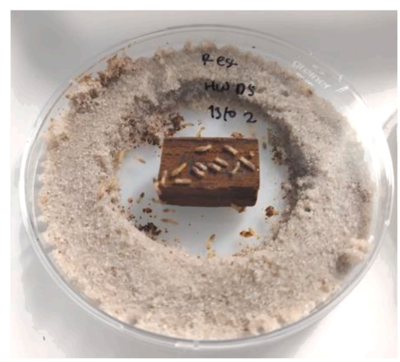
Termite resistances of all teak wood samples, in laboratory conditions, were carried out by screening non-choice and choice tests according to the specifications of the EN 117 [6] standard, with some adjustments concerning the sample size, termite number and exposure duration. Wood samples for each treatment were used with the sample size of 25 ×15 x 10 mm^3 (L, R, T). Sodium tetraborate decahydrate (borax) were used as biocide controls (G). In this sense, three replications of Scots pine sapwood sample were impregnated by 4 % Boric Acid Equivalent (BAE) solution and then used for comparison with chemical and thermal treatment, in the termite screening laboratory tests. Scots pine sapwood samples were immersed by borax solution under vacuum conditions 85 mbar for 30 minutes. Borax treated samples were air conditioned for 48 h and then were oven dried at 103 ± 2 °C for 48 h. Native Scots pine sapwood samples were also used as virulence controls (V) for each test modality. Before performing non-choice and choice test, all the samples were oven dried at 103 ± 2 °C until constant weight, their weight was measured and recorded (m_5). *Reticulitermes flavipes, ex. santonensis* were used to determine termite resistance against European subterranean termite. For this purpose, a colony was collected from Oleron Island, France (Lat. 45°49'5.9''N; Long.−1°13'47.8''W). The colony were reared in several box containers and kept in a climatic chamber at 27 ± 2 °C and relative humidity higher than 75 %.

- 3 replicates of SW, TS, TH, and HW stakes for each treatment.

NON-CHOICE TEST

- 5 replicates of SW, TS, TH, and HW samples for each treatment
- 3 replicates of borax-impregnated Scots pine wood
- 10 samples of Scots pine as virulence control





CHOICE TEST

- 3 replicates of SW and HW samples for each treatment
- 3 replicates of borax-impregnated Scots pine wood
- 45 samples of Scots pine as virulence control

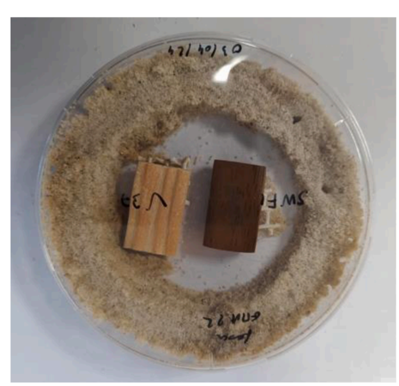


Fig. 2. Sample conditions for field test, non-choice and choice screening test.

Table 1
Rating of termite attacks according to AWPA E7-07 standard.

Rating	Description
10	Sound
9.5	Trace, surface nibbles permitted.
9	Slight attack, up to 3 % of cross-sectional area affected.
8	Moderate attack, 3–10 % of cross-sectional area affected.
7	Moderate/severe attack and penetration, 10–30 % of cross-sectional area affected.
6	Severe attack, 30–50 % of cross-sectional area affected.
4	Very severe attack, 50–75 % of cross-sectional area affected.
0	Failure

Five replications of SW, TS, TH, and HW for each treatment modality and three replications of borax-treated samples were used for non-choice screening test. Five virulence control sample for each box containers were also tested separately. Each specimen was placed on a small stainless-steel brace in the center of a 9 cm diameter petri dish. Meanwhile, three replications of SW and HW for each treatment and three replications of borax-treated samples were used for choice test. Then, each sample were placed on petri dish with one Scots pine sapwood virulence sample (Fig. 2). In addition, three devices containing two virulence control samples were also performed. The Petri dish contained 35 g of Fontainebleau wet sand (4 volumes of sand:1 vol of deionized water). Fifty termite workers, one nymph, and one soldier were put into each Petri dish. All the test devices were then placed for 4 weeks in a dark climatic chamber conditioned at 27 ± 2 °C and relative humidity higher than 75 %. All samples were observed once a week in order to add some water in the petri dish keeping the sand humidity and check the termite behavior. After 4 weeks of exposure, the wood samples were removed and carefully cleaned. Then, the wood samples were oven dried at 103 ± 2 °C until constant weight, their final oven-dried mass was measured and recorded (m_6). A visual rating corresponding to the damage caused by termite was attributed to all samples according to the specifications of the EN 350 [7] standard, with some adjustments relating to the sample size (Table 2). In addition, the termite survival rate (Sv) and mass loss (ML_s) of the sample due to termite degradation were determined by the following equations (Eq. 4 and 5):

$$Sv(\%) = n/50 \times 100 \quad (4)$$

where n is the number of live termite workers remaining after 4 weeks of testing.

$$ML_s = ((m_5 - m_6) / m_5) \text{ x } 100 \quad (5)$$

Where ML_s (%) is the percentage of mass loss, and m_5 and m_6 are oven-dried weight of the samples before and after the termite test, respectively.

2.8. Data analysis

Analysis of variance (ANOVA) of the completely randomized design with 2 factors (treatment and wood part) was carried out in order to identify the significant differences between the group samples. The mean differences between the group samples were determined using Duncan's multiple range test at 5 % significant level.

Table 2
Class of durability of wood species against termite attack based on [7].

Durability class	Description
Class D (Durable)	≥ 90 % of the tested specimens are rated 0 or 1 and maximum of 10 % of quotation 2 (0 % are rated 3 or 4)
Class M (Moderately Durable)	< 50 % of the tested specimens are rated 3 of 4
Class S (Sensible)	≥ 50 % of the tested specimens are rated 3 or 4

3. Results and discussions

3.1. Retention and mass change

Retention and mass change values on sapwood, transition, and heartwood board of short rotation teak woods, according to the applied treatment way, are presented in Table 3. The difference in retention values between FA and GMA treatments was attributed to the different concentrations of additives that were impregnated into the short rotation teak wood samples. As previous scientific research, the retention value of the impregnated woods with chemical additives increases as the additive concentrations increase [23]. Sapwood presented the highest retention value with FA treatment, followed by transition and heartwood. The retention value for GMA treatment between sapwood, transition and heartwood did not differ significantly according to Duncan's multiple range test. The same phenomenon is also occurred in the mass change value. Mass change values in sapwood for FA treatment were higher compared to those from transition and heartwood. Damayanti et al. [5] reported that the permeability of sapwood and heartwood in young teak can be increased by applying pressure during the treatment process. These authors also reported that heartwood has low permeability and the area of transition wood appeared to be refractory toward impregnation. The result presented in Table 3 indicates that the FA and GMA impregnation treatments could be applied to short rotation teak wood, as well as in sapwood, transition, and heartwood board. The presence of extractive compounds might also contribute to the low retention and mass change values in transition and heartwood boards. The mass change value of thermal and GMA treatment increased as the temperature increased. The effect of the combination of GMA impregnation followed by HT220 treatment generated a slightly lower mass loss compared to the mass loss obtained under HT220. These results indicate that GMA impregnation tended to reduce the effect of thermo-degradation reactions undergone by thermal modification.

3.2. Termite resistance against Asian subterranean termite

Fig. 3 shows the mass losses due termite attacks during the field test exposure for untreated and treated sapwood, transition sapwood, transition heartwood and heartwood samples from short rotation teak wood. For untreated modalities, sapwood had the highest mass loss (85.82 %), while heartwood had the lowest mass loss (2.73 %). A similar phenomenon was observed for untreated transition wood, the mass loss of

Table 3
Retention and mass change values on sapwood, transition, and heartwood of untreated and the different treated short rotation teakwood samples.

Treatments	Part	Retention (kg.m^{-3})	Mass change (%)
Untreated	SW	0.00 ± 0.00 (a)	0.00 ± 0.00 (cde)
	TW	0.00 ± 0.00 (a)	0.00 ± 0.00 (cde)
	HW	0.00 ± 0.00 (a)	0.00 ± 0.00 (cde)
FA	SW	313.05 ± 18.25 (e)	50.91 ± 6.25 (i)
	TW	231.47 ± 35.06 (d)	33.19 ± 6.24 (g)
	HW	251.10 ± 43.54 (d)	39.40 ± 6.18 (h)
HT150	SW	0.00 ± 0.00 (a)	−0.81 ± 0.07 (bcd)
	TW	0.00 ± 0.00 (a)	−1.49 ± 0.46 (bcd)
	HW	0.00 ± 0.00 (a)	−1.91 ± 0.85 (bcd)
HT1220	SW	0.00 ± 0.00 (a)	−8.00 ± 0.56 (a)
	TW	0.00 ± 0.00 (a)	−7.32 ± 0.48 (a)
	HW	0.00 ± 0.00 (a)	−7.55 ± 0.42 (a)
GMA150	SW	65.68 ± 0.78 (c)	6.59 ± 0.18 (f)
	TW	43.96 ± 9.29 (bc)	4.04 ± 1.00 (ef)
	HW	36.47 ± 8.48 (b)	2.84 ± 0.74 (def)
GMA220	SW	62.31 ± 5.46 (bc)	−1.44 ± 0.14 (bcd)
	TW	52.11 ± 2.25 (bc)	−2.16 ± 0.36 (bc)
	HW	35.89 ± 8.88 (b)	−5.51 ± 0.73 (ab)

Note: Value was the average of 3 replicates. Values followed by the same letter in parentheses do not differ significantly (α = 0.05) based on one-way ANOVA test using Duncan test.

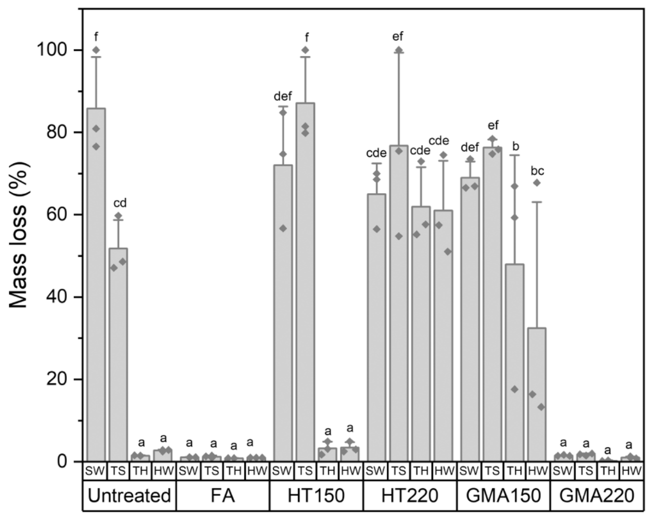


Fig. 3. Mass losses due to termite attacks during field test exposure of untreated and the different treated sapwood (SW), transition sapwood (TS), transition heartwood (TH) and heartwood (H) samples from short rotation teak wood. Note: Value was the average of 3 replicates. Values associated by the same letter (upper the histogram value) do not differ significantly (α = 0.05) based on one-way ANOVA test using Duncan test.

transition sapwood (51.82 %) was significantly higher compared to transition heartwood (1.47 %). The heartwood of short rotation teak wood contains higher extractive content than sapwood. Among these extractives, tectoquinone is the main chemical compound which plays an important role in the natural durability of wood against termite attacks [21]. HT150 treated wood exhibited a similar trend as untreated wood. Mass loss caused by HT150 treatment were 72.06 %; 87.10 %; 3.25 %; and 3.46 % for sapwood, transition sapwood, transition heartwood and heartwood, respectively. On the contrary, all parts of the short rotation teak wood by HT220 treatment were severely degraded after field test exposure (mass loss up to 65.02 %; 76.76 %; 61.93; and 61.00 % for sapwood, transition sapwood, transition heartwood and heartwood, respectively). Salman et al. [33] reported that mass loss of beech and pine wood against termite attack increase with the intensity of thermal modification. Wood thermally modified at higher temperatures is more susceptible to termite attack compared to wood thermally modified at lower one. Other studies also reported that thermal modification does not improve the termite resistance (Srivikaya et al., 2015; [20,24,33]). The present study confirms this tendency for short rotation teak wood, showing a more important effect of thermal treatment temperature on heartwood and transition heartwood samples compared to those from sapwood and transition sapwood.

Impregnation of FA and GMA polymers resulted in significantly better performance for protecting short rotation teak wood against Asian subterranean termites in field test conditions. However, GMA150 treated wood presented a higher mass loss than those of GMA220, after 12 weeks of field test exposure. Concerning the GMA150 treatment modality, the mass losses of sapwood, transition sapwood, transition heartwood and heartwood were 68.99 %; 76.35 %; 47.93 %; and 32.48 %, respectively. Similar result obtained from the field test exposure of heartwood and sapwood from short-rotation teak wood was also reported by Martha et al. [20]. Short rotation teak wood treated with GMA150 treatment is less resistant against termite compared to GMA220 treated samples. FA and GMA220 treatments provided the better termite resistance on short rotation teak wood. Mass loss due to field test for wood treated by FA and GMA220 were 1.09 % and 1.49 % in sapwood, 1.22 % and 1.73 % in transition sapwood, 0.85 % and 0.21 % in transition heartwood, 0.97 % and 1.01 % in heartwood, respectively. FA treatment is recently well known to greatly increase the resistance of wood against subterranean termite attacks [2,8,9,10]. Hadi et al. [10] reported that furfurylated wood has a higher density and becomes more resistant to water due to the hydrophobic poly-FA bulking in the wood cell wall as well as in the void. Therefore, termites have more difficulty feeding on harder and drier wood. Our previous study also showed that the reaction between the GMA polymer and lignin constituent occurs after GMA220 treatment [20]. The results also evidenced that the polymerization of GMA with wood components produces a new material that is non-digestible by termites. The modified lignin resulting from polymerization also acts as a physical barrier that can protect the cellulose component from termite attack. According to Duncan's multiple range test, no significant difference in mass loss values between transition sapwood and transition heartwood indicated that the short rotation teak wood became more homogeneous after FA and GMA220 treatment. The visual rating and termite resistance classification of short rotation teak woods are presented in Table 4.

According to AWPA E7–07 [1], the termite resistance of FA and GMA220 samples for all part of short rotation teak wood were classified in the durability class from 9 to 10. This indicates that FA and GMA220 treatments could be an effective method to enhance the resistance of short rotation teak wood against subterranean termites. The visual appearance of short rotation teak wood stakes after 12 weeks of field test exposure against subterranean termite is shown in Fig. 4.

3.3. Non-choice screening test against European subterranean termite

The different treatments carried out on the four parts of short-rotation teak wood led to various mass losses caused by the exposure of European subterranean termites in laboratory conditions, as presented in Table 5. Sapwood generally showed a higher mass loss due to termite degradation compared to heartwood. Similar trend was also observed for transition wood where the mass loss of transition sapwood was higher than those of transition heartwood. These results indicated that the heartwood parts of short-rotation teak wood presented better resistance against termites than sapwood. Heartwood contains quinone compounds, particularly tectoquinone, which has been reported to be active towards termites (Thaulasidas and Bhat 2007; [17,21]). There

Table 4
Visual rating and termite resistance classification according to [1] on different part for untreated and the different treated short rotation teak wood samples, after 12 weeks of termite exposure in field test conditions.

Treatments	Part	Wood thickness attack by termites (%)	Visual rating
Untreated	SW	100.00 ± 0.00 (c)	0
	TS	94.76 ± 4.70 (c)	0
	TH	0.00 ± 0.00 (a)	10
	HW	0.00 ± 0.00 (a)	10
FA	SW	0.00 ± 0.00 (a)	10
	TS	0.32 ± 0.43 (a)	9.5
	TH	0.00 ± 0.00 (a)	10
	HW	0.00 ± 0.00 (a)	10
HT150	SW	98.64 ± 1.54 (c)	0
	TS	89.30 ± 11.59 (c)	0
	TH	0.00 ± 0.00 (a)	10
	HW	0.00 ± 0.00 (a)	10
HT220	SW	100.00 ± 0.00 (c)	0
	TS	97.55 ± 4.24 (c)	0
	TH	96.62 ± 5.86 (c)	0
	HW	100.00 ± 0.00 (c)	0
GMA150	SW	91.22 ± 9.86 (c)	0
	TS	100.00 ± 0.00 (c)	0
	TH	78.28 ± 37.62 (c)	4
	HW	41.68 ± 50.62 (b)	6
GMA220	SW	1.10 ± 1.45 (a)	9
	TS	2.95 ± 1.15 (a)	9
	TH	0.00 ± 0.00 (a)	10
	HW	0.28 ± 0.49 (a)	9.5

Note: Value was the average of 3 replicates. Values followed by the same letter in parentheses do not differ significantly (α = 0.05) based on one-way ANOVA test using Duncan test.

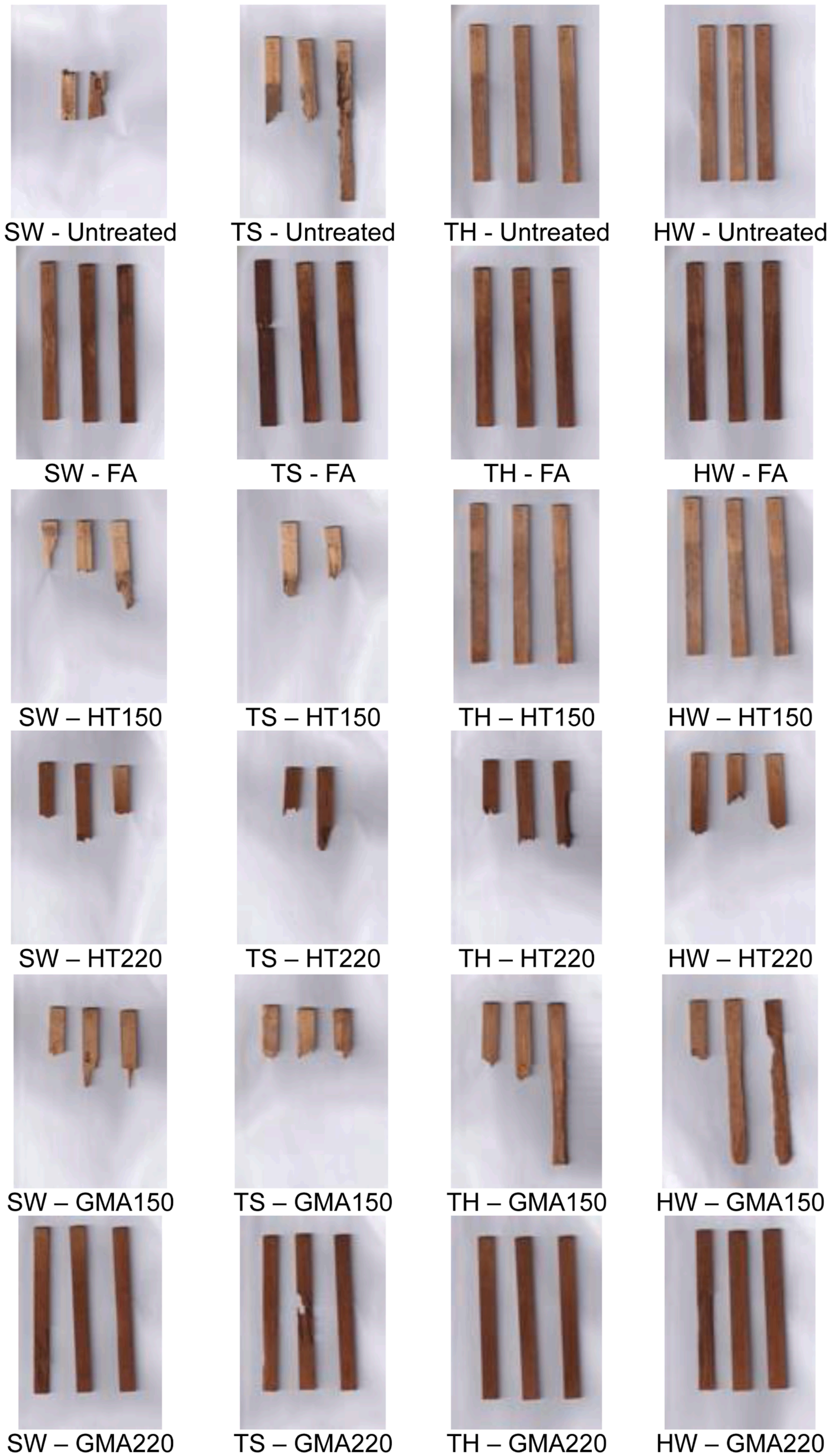


Fig. 4. Visual appearance of the wood specimens from different treatment carried out on sapwood, transition sapwood, transition heartwood, and heartwood of short rotation teak wood, as well their respective untreated samples, after 12 weeks of field test exposure.

Table 5
Termite resistance against European subterranean termite by laboratory non-choice test on different part for untreated and the different treated short rotation teak wood samples.

Treatments	Part	Mass loss (%)	Survival rate (%)	Visual rating	Durability class
Untreated	SW	1.66 ± 0.23 (f)	7.60 ± 4.98 (ab)	**3** [1]; **2** [4]	M
	TS	2.82 ± 0.44 (g)	11.60 ± 14.70 (b)	**3** [5]	S
	TH	0.82 ± 0.18 (ab)	10.40 ± 10.81 (b)	**1** [5]	D
	HW	1.08 ± 0.26 (abc)	10.40 ± 9.53 (b)	**2** [3]; **1** [2]	M
FA	SW	0.78 ± 0.16 (ab)	11.60 ± 6.07 (b)	**2** [1]; **1** [4]	M
	TS	1.04 ± 0.17 (abcd)	0.80 ± 1.79 (a)	**1** [5]	D
	TH	0.98 ± 0.22(abc)	10.80 ± 10.35 (b)	**1** [5]	D
	HW	0.70 ± 0.14 (ab)	6.00 ± 3.74 (ab)	**2** [1]; **1** [4]	M
HT150	SW	1.37 ± 0.19 (def)	7.60 ± 10.43 (ab)	**2** [1]; **1** [4]	M
	TS	1.48 ± 0.23 (ef)	4.40 ± 2.97 (ab)	**2** [3]; **1** [2]	M
	TH	0.88 ± 0.14 (ab)	0.80 ± 1.79 (a)	**3** [2]; **2** [3]	M
	HW	0.68 ± 0.03 (a)	4.00 ± 4.00 (ab)	**2** [1]; **1** [4]	M
HT220	SW	0.85 ± 0.16 (ab)	0.00 ± 0.00 (a)	**2** [5]	M
	TS	1.63 ± 0.19 (ef)	1.60 ± 2.19 (a)	**4** [4]; **3** [1]	S
	TH	0.75 ± 0.12 (ab)	0.00 ± 0.00 (a)	**4** [1]; **3** [4]	S
	HW	0.82 ± 0.30 (ab)	0.00 ± 0.00 (a)	**4** [1]; **3** [3]; **2** [1]	S
GMA150	SW	2.79 ± 0.20 (g)	0.00 ± 0.00 (a)	**2** [3]; **1** [2]	M
	TS	3.26 ± 0.36 (h)	0.00 ± 0.00 (a)	**4** [1]; **3** [1]; **2** [3]	M
	TH	1.68 ± 0.16 (f)	0.00 ± 0.00 (a)	**2** [1]; **1** [4]	M
	HW	1.28 ± 0.11 (cde)	0.00 ± 0.00 (a)	**2** [2]; **1** [3]	M
GMA220	SW	1.08 ± 0.19 (bcd)	0.00 ± 0.00 (a)	**2** [2]; **1** [3]	M
	TS	1.05 ± 0.22 (abcd)	0.00 ± 0.00 (a)	**3** [3]; **2** [1]; **1**[1]	S
	TH	0.98 ± 0.22 (abc)	0.00 ± 0.00 (a)	**4** [1]; **3** [1]; **2** [3]	M
	HW	1.28 ± 0.68 (cde)	0.80 ± 1.79 (a)	**4** [1]; **3** [2]; **2** [2]	S
Borax	G	1.01 ± 0.08	0.00 ± 0.00	**0** [1]; **1** [2]	D
Control	-	10.57 ± 3.40	69.00 ± 10.59	**4** [10]	S

Note: Value was the average of 5 replicates (except for borax treated sample, where 3 replicates were tested). Values followed by the same letter in parentheses do not differ significantly (α = 0.05) based on one-way ANOVA test using Duncan test.

was no significant difference in mass loss values among wood part after FA and GMA220 treatments based on Duncan's multiple range test.

Thermal and GMA treatments involved low termite survival rate (< 5.00 %) after 4 weeks in laboratory screening tests. In fact, no surviving termites were observed in the case of HT220, GMA150 and GMA220 after 4 weeks of non-choice tests. The weekly visual observation allowed to place the mortality of all the termites around 21 days for all these three treatment modalities.

At the same time, all termites were died after 10 days due to the exposure to borax-treated sample. However, the only results from the non-choice test were not able to prove if the mortality of the termites was due to the toxicity of treatment or to the lack of accessible nutrient source. Therefore, choice tests were then conducted to assess the causes of termite mortality in relation to chemical and thermal modification treatments carried out on short-rotation teak woods. From these screening choice tests, there was no clear trend in the visual rating between untreated and treated sample after termite exposure. The short rotation teak wood did not increase in durability class after chemical and thermal modification, according to the screening non-choice test specifications.

3.4. Choice test against European subterranean termite

Mass loss and survival termite rate of sapwood and heartwood with different treatments after choice test are shown in Table 6. The virulence samples of sapwood and heartwood presented a very low termite resistance according to mass loss value (>10 %). The virulence samples also had a strong termite attack represented by a visual rating of 4 (sensible). The high termite attack of virulence samples confirms the validity of termite resistance test according to the specifications of the European standard [6]. The same phenomenon as the non-choice test, the mass loss due to *R. flavipes* attack on sapwood tended to be higher compared to heartwood. In the other hand, the mass losses of short rotation teak wood after chemical or thermal modifications were significantly lower (close to 0 %). These results indicate that termites might have preferred to attack pine wood as a control compared to short rotation teak wood, especially in chemically and thermally modified wood.

The virulence samples exhibited a high termite survival rate of 88.67 %. Similar results were also observed for short rotation teak wood. Termite survival rates observed for untreated and treated short rotation teak wood ranged from 58.00 % to 87.33 %. This value was significantly different from the results of the termite survival rate obtained by the non-choice test. Meanwhile, a maximum mortality of 100 % was observed for borax-treated sample after 14 days termite exposure. According to the visual rating, wood treated by HT150 and HT220 were classified as moderately durable. Previous studies reported that thermal modification provides low resistance against termite attack (Srivikaya et al., [4,33,18]). On the other hand, FA and GMA treatment increased the durability class to be durable. This result indicated that FA and GMA treatment could be valuable methods to protect short rotation teak wood against termite attack.

3.5. Choice test vs non-choice test

The distribution of mass consumption by termite according to the part of wood, the type of treatment and test modalities was illustrated in Fig. 5. According to Fig. 5, the mass loss between choice test and non-choice test showed a similar trend. Mass loss due to termite attack on short rotation teak wood for untreated and treated was relatively low (less than 5.00 %). Sapwood had a higher weight loss compared to heartwood due to the effect of extractives as termite repellent. According to the mass loss, chemically and thermally modified wood provided better protection against termites than respective untreated wood. However, in comparison, FA and GMA220 gave the best results with observed values of wood mass loss less than 1.00 %, after 4 weeks of termite exposure. Short rotation teak woods treated with FA or GMA220 were found to have no significant difference in mass loss between sapwood and heartwood, the same phenomenon was observed in the field test.

For borax-treated wood (G), the protection was effective against termites with a mass loss value of 1.00 % and 100 % termite mortality in less than 4 weeks. Previous studies reported that boron compounds provide a pretty good protection against termites, but are notably toxic to termites [13,32,37]. Thermal and GMA treatment also presented a termite mortality rate of 100 % for the non-choice test. Interestingly,

Table 6
Termite resistance against European subterranean termite by laboratory screening choice test on different part for untreated and the different treated short rotation teak wood samples.

Treatments	Sample	Mass loss (%)	Survival rate (%)	Visual rating	Durability class
Untreated	SW	2.82 ± 0.15 (f)	87.33 ± 4.16	**1** [2]; **2** [1]	M
	SW-V	15.15 ± 0.90	(f)	**4** [3]	S
	HW	0.78 ± 0.08 (cd)	82.67 ± 2.31	**1** [3]	D
	HW-V	15.67 ± 0.56	(cdef)	**4** [3]	S
FA	SW	0.42 ± 0.30 (ab)	85.33 ± 4.16	**1** [3]	D
	SW-V	11.97 ± 1.06	(ef)	**4** [3]	S
	HW	0.49 ± 0.09 (abc)	83.33 ± 1.15 (cdef)	**1** [3]	D
	HW-V	14.78 ± 0.65		**4** [3]	S
HT150	SW	1.59 ± 0.30 (e)	84.67 ± 7.57	**1** [2]; **2** [1]	M
	SW-V	14.74 ± 3.02	(def)	**4** [3]	S
	HW	0.72 ± 0.10 (bcd)	75.33 ± 5.03 (bcd)	**1** [3]	D
	HW-V	13.04 ± 0.68		**4** [3]	S
HT220	SW	0.74 ± 0.21 (bcd)	71.33 ± 11.02 (b)	**1** [2]; **2** [1]	M
	SW-V	12.89 ± 3.48		**4** [3]	S
	HW	0.63 ± 0.10(bcd)	77.33 ± 2.31	**1** [1]; **2** [2]	M
	HW-V	11.64 ± 1.41	(bcde)	**4** [3]	S
GMA150	SW	0.91 ± 0.24 (d)	78.00 ± 5.29	**1** [3]	D
	SW-V	12.80 ± 0.98	(bcdef)	**4** [3]	S
	HW	1.35 ± 0.08 (e)	58.00 ± 2.83	**1** [2]	D
	HW-V	10.72 ± 0.47	(a)	**4** [2]	S
GMA220	SW	0.41 ± 0.05 (ab)	81.33 ± 3.06	**1** [3]	D
	SW-V	14.62 ± 0.14	(cdef)	**4** [3]	S
	HW	0.28 ± 0.13 (a)	74.67 ± 1.15	**1** [3]	D
	HW-V	13.57 ± 0.36	(bc)	**4** [3]	S
Borax	G	1.06 ± 0.09	0.00 ± 0.00	**1** [3]	D
	G-V	2.13 ± 0.96		**1** [2]; **2** [3]	M
Control	V	8.47 ± 4.35	88.67 ± 1.15	**4** [5]; **3** [1]	S

Note: Value was the average of 3 replicates. Values followed by the same letter in parentheses do not differ significantly ($\alpha = 0.05$) based on one-way ANOVA test using Duncan test. SW= sapwood sample; SW-V= Scots pine as virulence in sapwood sample; HW= heartwood sample; HW-V= Scots pine as virulence in heartwood sample; G=borax-treated sample; G-V = Scots pine as virulence in borax-treated sample; V= Scots pine as virulence sample.

different results were found in the choice-test because more than 58.00 % of the termites were still alive after 4 weeks of termite exposure (Fig. 6). Termite mortality in the non-choice test might not be due to the chemical toxicity to termites in chemically and thermally modified wood. Instead, termites were reluctant to eat the chemically and thermally modified short rotation teak wood, therefore the termites lacked a food source which led to high termite mortality. This was confirmed in the choice test, the pine wood sample as the control showed high termite attack damage. These results proved that the chemical and thermal modification treatments used in this study were non-biocidal against termites. Moreover, furfurylated wood and thermally modified wood shows low toxicity of leachates to the crustacean *Daphnia magna* (De [27, 38]). Lande et al. [15] also reported that furfurylation is an environmentally friendly method for wood modification since it does not contaminate the material with any chemicals to any biocidal effects. According to the result of mass loss and termite survival rate, FA and GMA220 treatment performed better in protecting short rotation teak wood against subterranean termites. This result indicated that FA and GMA treatment could be a great non-biocide alternative method to improve termite resistance of short rotation teak wood.

4. Conclusions

Field test results indicate varying mass loss for the different wood segments, with heartwood showing better termite resistance due to its extractive content than the other wood parts. FA and GMA220 treatments effectively enhance the wood durability of short rotation teak wood against Asian subterranean termite. According to AWPA E7–07, the durability class of short rotation teak wood increase from class 0 to be class 10 after FA and GMA220 treatments. Chemically and thermally modified wood demonstrates enhanced resistance against European subterranean termites compared to untreated wood in both choice and non-choice tests. The mass loss due to field test and non-choice test between transition sapwood and transition heartwood is homogenized after FA and GMA treatments. Termite survival rates of untreated and treated wood ranges up to 80 % under choice test. The choice test proves that chemical and thermal modification are non-biocidal for termites. Indeed, termites are still alive at the end of the choice tests in the presence of chemically or thermally modified teak wood samples, while important mortality was observed in the choice test in the presence of borax treated samples. The mechanism by which FA and GMA treatments improve termite resistance in teak wood is still not completely understand, but it can be assumed that chemical modification of of wood components as well as density increase could be at the origin of the improvement of durability.

FA and GMA treatments appeared to be eco-friendly modification methods for enhancing termite resistance in wood materials and providing valuable insights for sustainable wood protection practices. Considering that furfurylation and thermal modification have been already developed on industrial scale in Europe, it seems reasonable to think that such treatments could be developed on short rotation teak wood allowing better valorization of this resource. Even if the cost of such treatments remains higher than that of conventional biocidal wood protection treatment, their performances and their lower environmental impact due to the limitation of the use of biocides, constitutes advantages for their development in the future. Moreover, GMA treatment at 200°C, which combines chemical and thermal treatments, could present the advantage to be less expensive due to the lower quantities of chemical used.

CRediT authorship contribution statement

Kevin Candelier: Writing – review & editing, Supervision, Methodology, Investigation. **Resa Martha:** Writing – original draft, Methodology, Investigation. **Philippe Gerardin:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Wayan Darmawan:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Istie Rahayu:** Writing – review & editing, Supervision, Investigation. **Béatrice George:** Writing – review & editing, Supervision, Investigation. **Marie-France Thevenon:** Writing – review & editing, Methodology, Investigation.

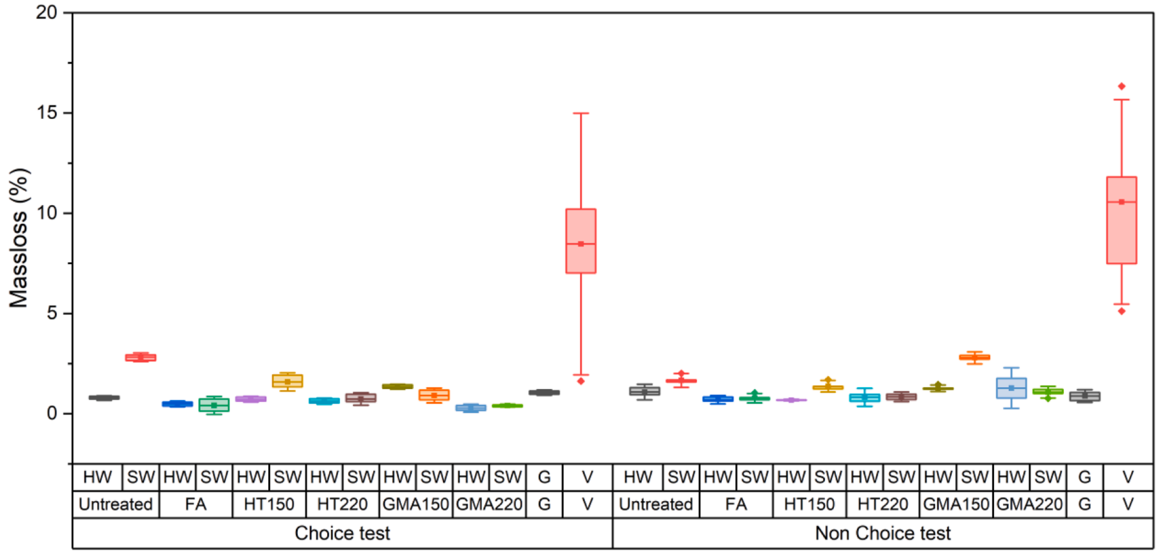


Fig. 5. Mass losses on heartwood and sapwood of different treatments for laboratory choice and non-choice test comparison.

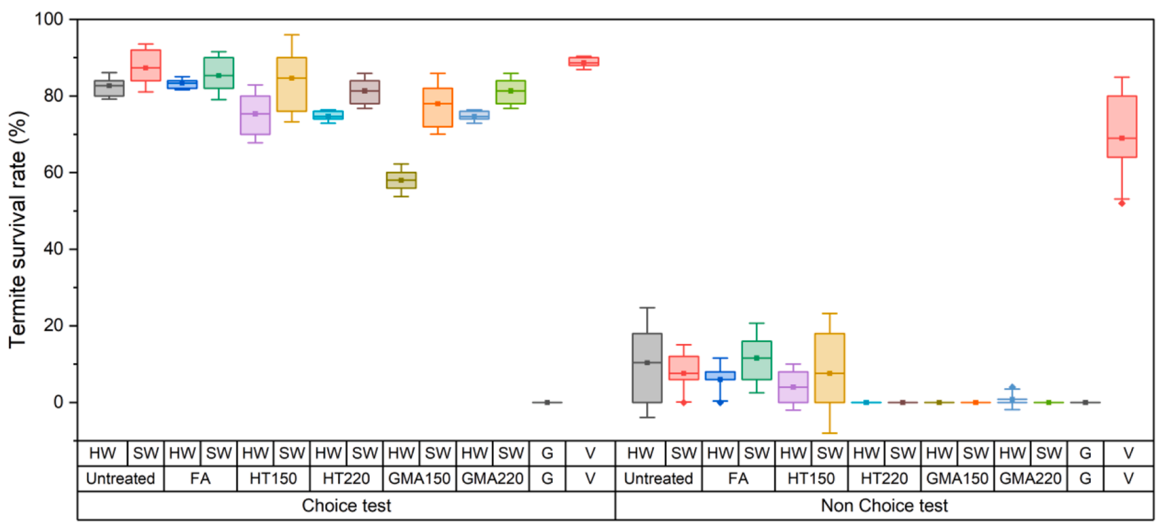


Fig. 6. Termite survival rates on heartwood and sapwood of different treatments for laboratory choice and non-choice test comparison.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. Resa MARTHA reports financial support was provided by Université de Lorraine. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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