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Resistance to Termites and Colour Change in Gombong Bamboo (*Gigantochloa pseudoarundinacea*) Modified with Boron Compounds, Vegetable Oil, and Heating

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ABSTRACT

Bamboo is a potential material in the furniture, construction, and craft industries due to its rapid growth and good physical and mechanical properties. However, its vulnerability to attacks by wood–destroying organisms, particularly termites, necessitates preservation to extend its service life. This study evaluated the resistance of gombong bamboo to subterranean and drywood termites, as well as its color changes. The modification treatments involve boric acid equivalent (BAE) impregnation, heat treatment (60 °C, 150 °C, and 180 °C), and vegetable oils (linseed and neem oil). Statistical analysis using one-way ANOVA was performed to determine the significance of each treatment factor on weight loss and colour parameters, followed by Duncan's Multiple Range Test for mean comparison. In addition, color change and the chemical composition of the most effective oil treatment in terms of termite resistance were analysed using Gas Chromatography-Mass Spectrometry (GC-MS). The results showed that BAE, neem oil, and the combined treatments (BAE-vegetable oils) effectively improved bamboo resistance to both termite tests. The synergy between BAE impregnation, heat treatment (180 °C), and neem oil produced the highest level of termite resistance. Heat treatment at elevated temperatures also caused significant colour changes, particularly a reduction in brightness (L^*) and an increase in dark brown tones attributed to thermal degradation of hemicellulose and extractives. GC-MS analysis revealed that neem oil was dominated by fatty acids and other compounds known for their antimicrobial, antifeedant, and termite-repellent activities, which likely contributed to the enhanced biological performance of the treated bamboo.

1. Introduction

Bamboo is a renewable, environmentally friendly material with favorable mechanical properties, making it a promising resource for diverse industrial applications (Shen et al. 2019). Bamboo offers advantages due to its strength and flexibility, making it suitable for various structural applications, including construction, furniture, and engineering products (Adier et al. 2023). Gombong bamboo (*Gigantochloa pseudoarundinacea*) is one of the most widely utilized bamboo species in Indonesia. It is found naturally in Java, Sumatra, and Kalimantan and has long played an important role in local communities' economic activities and cultural practices.

Gombong bamboo can grow up to 26 m in height, with a diameter of 25–30 cm, thick walls of about 2 cm, and joints measuring 35–45 cm (Akinlabi et al. 2017). Physically, Gombong bamboo has a specific gravity of 0.5–0.8, while its mechanical properties include a modulus of elasticity of 19.84–29.18 kgf/cm^2, a modulus of rupture of 174–211 kgf/cm^2, and a tensile strength of 130–195 kgf/cm^2 (Sujarwanta and Zen 2020). Its large size, combined with its mechanical performance, makes this species widely used in traditional construction, structural frames, furniture, woven products, handicrafts, and various household and industrial applications.

Despite its extensive use and abundant availability, Gombong bamboo has a major limitation, its low natural durability. The species is classified as durability class IV against both subterranean and drywood termites (Damayanti et al. 2019), indicating that it is highly susceptible to biological degradation. As a lignocellulosic material, bamboo serves as a primary food source for termites (Wu et al. 2021). Termites can degrade bamboo cell wall components using their natural cellulolytic enzymes, assisted by symbiotic microorganisms in their digestive systems (Martin and Lopez 2023). This makes untreated bamboo especially vulnerable, resulting in a relatively short service life, particularly under humid or termite-prone conditions.

Improving the durability of Gombong bamboo, especially its resistance to termites, is important to increase its usability. Enhanced biological resistance can extend the service life and reliability of bamboo products and support the growth of value-added bamboo industries. Strengthening its durability also contributes to sustainable material development because bamboo grows quickly and can serve as an alternative to wood. Bamboo can be protected from termites through chemical preservation or bio-based materials such as vegetable oils (Fahim et al. 2022). Therefore, research on preservation treatments combined with thermal modification is important to overcome the inherent low durability of Gombong bamboo and to support its wider and more sustainable application.

Improvements in bamboo durability can be achieved by impregnation, thermal treatment, or a combination of both. Impregnation has been widely applied to enhance durability and extend service life. Boric acid equivalent (BAE) is a boron-based preservative (a mixture of borax and boric acid) that effectively increases bamboo's resistance to fungi, insects, and termites. (Erper et al. 2019). However, boron compounds are water-soluble, making them prone to leaching when used outdoors (Ghani 2021). Thermal treatment is commonly used as a quality enhancement method, as it can improve dimensional stability and reduce hygroscopicity (Zhang et al. 2021), thereby reducing boron leaching. The use of vegetable oil has been shown to reduce preservative leaching by creating a hydrophobic barrier and limiting water penetration into the wood substrate (Priadi et al. 2021).

Vegetable oils derived from plants have potential as natural preservatives with insecticidal, antifungal, and antibacterial properties (Kaur et al. 2016). Linseed oil is one of the drying oils used in the paint and varnish industry and the wood industry. This oil is the most widely used oil for wood applications in Europe (Arminger et al. 2020). The phenol and lignan content in linseed oil provides antioxidant and antimicrobial properties (Koçak 2024). The application of linseed oil to wood surfaces can slow weathering under outdoor exposure, especially when applied properly and allowed to dry (Sansonetti et al. 2020). Neem oil contains various bioactive compounds. Previous research has identified 112 compounds in neem oil, including phenolics, fatty acids, and benzimidazole and pyrimidine derivatives, which act as antibacterial, antifungal, and antioxidant agents and have repellent, antifeedant, and toxic effects on termites (Selvarajan et al. 2023).

Combining heating with boron compounds or plant oils, such as sesame oil at 200 °C, enhanced the resistance of poplar wood to termites (Fatima et al. 2021), while the combination of boron, candlenut oil, neem oil, and linseed oil at 140 °C enhances the resistance of manii wood to termites and fungi. Additionally, thermal treatment causes the wood to darken in color (Priadi et al. 2022). Thermal treatment with oil at 180 °C resulted in a uniform color change in Korean pine wood, with increases in brightness and redness, and an average total color change of 18.4 (Lee et al. 2015). Heat treatment can improve dimensional stability by reducing thickness swelling in engineered bamboo (bamboo-oriented strand board), due to chemical changes in hemicellulose and a decrease in hydroxyl groups caused by heating (Mangurai et al. 2022).

Previous studies have explored the combined use of boric acid-equivalent preservatives, vegetable oils, and heat treatment for wood, and their application to bamboo, which differs from wood in its anatomical structure or chemical composition. A more detailed understanding of how these integrated treatments perform specifically is therefore needed, especially regarding their potential to enhance bamboo's biological resistance. In addition, unlike previous studies using a boron-oil-heat sequence, the risk of oil volatilization at high temperatures makes applying oil impregnation as the final step more appropriate for bamboo preservation. This study aimed to investigate the effects of a combination of boric acid-equivalent preservatives, heating, and vegetable oils (linseed or neem oil) on improving the resistance of *G. pseudoarundinacea* to termite attack (*Coptotermes curvignathus* and *Cryptotermes cynocephalus*). This study will improve the use of bamboo and offer an environmentally friendly approach to preservation.

2. Materials and Methods

2.1. Materials and Impregnants

The primary material used in this study was gombong bamboo (*G. pseudoarundinacea*) measuring 5–6 m in length and 10–12 cm in diameter. The bamboo was sourced from a bamboo and wood business in the Pamijahan area of Bogor Regency. Other materials include subterranean termites (*Coptotermes curvignathus*) and drywood termites (*Cryptotermes cynocephalus*). The impregnation materials used consist of boric acid (H_3BO_3) and borax ($Na_2B_4O_7$), obtained from CV. Aneka Sarana Labotatorium Bogor with PA (pro-analysis) grade. The second impregnation material, namely two types of vegetable oil, linseed oil (*Linum usitatissimum*) and neem oil (*Azadirachta indica*), was purchased from Indoplant Yogyakarta and Kimia Jaya Abadi Semarang.

2.2. Bamboo Modification Method

The bamboo was dried with a fan at room temperature until its moisture content reached approximately 12%. Bamboo strips were prepared as test samples for termite resistance testing (modified SNI 7207:2014) and color testing. Each test was conducted with five replications. The dimensions of the test samples for dry wood termite resistance were 5 cm × 2.5 cm × 0.61 cm (length, width, thickness), for subterranean termites resistance were 2.5 cm × 2.5 cm × 0.57 cm (length, width, thickness), and for color testing were 8 cm × 3 cm × 0.91 cm (length, width, thickness). The weight and sample dimensions were measured using an analytical balance (Kern, Germany) and a digital caliper (Deli, China), with a precision of 2 decimal places.

The first impregnation using BAE involved test samples being immersed in these solutions until fully submerged, then placed in an impregnation tank (a pressure cylinder with a length of 5 m and a diameter of 45 cm) at 7 kg/cm^2 for 3 hours. Before this, the bamboo test samples were measured for volume and weighed. After impregnation, the test samples were drained and weighed to obtain the preservative retention value (Equation 1). The bamboo was then dried in an oven (Memmert, Germany) at 50°C again until the moisture content reached ± 12%. In the second stage, the heat treatment was carried out in a convection oven (Memmert, Germany) without air pressure control at 60 °C, 150 °C, and 180 °C. The heating was carried out for 2 hours each, referring to the research by Hao et al. (2021). The samples were placed in the oven after the oven reached the heat-treatment temperature.

The second impregnation with linseed or neem oil was carried out using the same process as impregnation 1. Before that, bamboo was weighed. Then, the impregnated samples were removed from the tank and left to drain. After the impregnation process was complete, the test samples were dried again at 50°C until the moisture content reached ±12 %, then weighed, and the weight percent gain was calculated using Equations 1–2. The combination of BAE, vegetable oil treatment, and bamboo heating is presented in **Table 1**. For example, in the BM180 treatment, the samples were first impregnated with BAE and then heated to 180 °C. After that, the samples were subjected to a second impregnation using neem oils before further testing.

$$Retention = \frac{B1 - B0}{V} \; x \; K \qquad (1)$$

$$WPG = \frac{Bb1 - Bb0}{Bb0} \; x \; 100 \qquad (2)$$

where *V* is the volume of bamboo, *B0* is the weight of bamboo before impregnation 1, *B1* is the weight of bamboo after impregnation 1, *WPG* is the weight percent gain, *Bb0* is the weight of bamboo before impregnation 2, and *Bb1* is the weight of bamboo after impregnation 2.

Table 1. The combinations of bamboo modification treatments

Code	First impregnation	Heating			Second impregnation	
	BAE	60 °C	150 °C	180 °C	Linseed oil	Neem oil
TB60 (control)	–	√	–	–	–	–
TB150	–	–	√	–	–	–
TB180	–	–	–	√	–	–
TBR60	–	√	–	–	√	–
TBR150	–	–	√	–	√	–
TBR180	–	–	–	√	√	–
TBM60	–	√	–	–	–	√
TBM150	–	–	√	–	–	√
TBM180	–	–	–	√	–	√
B60	√	√	–	–	–	–
B150	√	–	√	–	–	–
B180	√	–	–	√	–	–
BR60	√	√	–	–	√	–
BR150	√	–	√	–	√	–
BR180	√	–	–	√	√	–
BM60	√	√	–	–	–	√
BM150	√	–	√	–	–	√
BM180	√	–	–	√	–	√

Notes: T (without BAE, without oil); TBR (without BAE with linseed oil); TBM (without BAE with neem oil); B (with BAE, without oil); BR (BAE with linseed oil) BM (BAE with neem oil); 60 = heating at 60 °C; 150 = heating at 150 °C; 180 = heating at 180 °C.

2.3. Testing the Resistance of Bamboo to Subterranean Termites

The resistance of bamboo to termites was tested according to SNI 7207:2014, with modifications to the test sample size and drying temperature. Test samples with calculated dry weights were placed in glass bottles along with 200 healthy and active worker caste termites (*C. curvignathus* Holmgren) and 20 soldier caste termites in glass bottles containing 200 g of moist sand with a moisture content of ± 6% below water holding capacity and stored for 4 weeks in a dark room with the room temperature (± 28°C) and humidity measured periodically (± 75%). The bamboo is weighed again after testing to determine weight loss using Equation 3, and it is classified according to **Table 2**.

$$WL\ (\%) = \frac{W1 - W0}{W1} \times 100 \qquad (2)$$

where *WL* is the bamboo weight loss, *W1* is the dry weight of the bamboo before testing, and *W2* is the dry weight of the bamboo after testing.

Table 2. Classification of wood resistance to subterranean termites (BSN 2014)

Class	Resistance	Weight loss
I	Very resistance	< 3.5
II	Resistance	3.5–7.4
III	Moderate	7.5–10.8
IV	Not resistance	10.9–18.9
V	Very vulnerable	> 18.9

2.4. Testing the Resistance of Bamboo to Drywood Termites

The resistance of bamboo to drywood termites was tested according to SNI 7207:2014, with modifications to the test sample size and drying temperature. Every two bamboo strips, whose dry weight (W1) had been calculated, were combined and tied together with rubber bands. One of the widest sides of the bamboo was attached to a pipe using hot glue. Fifty active worker termites (*Cryptotermes cynocephalus*) were placed in the pipe and covered with cotton. The test unit was placed in a dark room for 12 weeks, with the room temperature (± 28 °C) and humidity (± 75%) measured periodically. The dry weight of the bamboo after testing (W2) is weighed again to determine the bamboo weight loss (WL) using Equation 3, and the bamboo is then classified using **Table 3**.

Table 2. Classification of wood resistance to drywood termites (BSN 2014)

Class	Resistance	Weight loss
I	Very resistance	< 2.0
II	Resistance	2.0–4.3
III	Moderate	4.4–8.1
IV	Not resistance	8.2–28.1
V	Very vulnerable	> 28.1

2.5. Color Testing

Bamboo color change testing was conducted using the CIELAB method with a CHN Spec CS–10 colorimeter. Each test sample was measured at three predetermined points to obtain *L**, *a**, and *b** values. The CIELAB method is a quantitative color measurement system. The parameter *L** indicates brightness, the parameter *a** indicates red (+) or green (-) color, and the parameter *b** indicates yellow (+) or blue (-) color (Yin et al. 2022). This color change test was conducted only on the vegetable oil treatment that was most effective at increasing bamboo's resistance to termite attacks. Visual evaluation is important for detecting color changes in bamboo, especially when used for aesthetic or structural purposes. Color changes are calculated using Equation 4.

$$\Delta E = \sqrt{[(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2]} \quad (4)$$

where ΔL, Δa, and Δb represent changes in the brightness values of $L*$, $a*$, and $b*$ between the compared test samples, and then classified based on **Table 4**.

Table 4. Classification of discoloration (Hrčková et al. 2018)

Color change value	Effect
ΔE ≤ 0.2	Invisible changes
0.2 < ΔE ≤ 2	Small changes
2 < ΔE ≤ 3	Color changes are visible with a high-quality filter
3 < ΔE ≤ 6	Color changes are visible with a medium-quality filter
6 < ΔE ≤ 12	Distinct color changes
ΔE > 12	A different color

2.6. GC–MS Analysis

Gas chromatography-mass spectrometry analysis by Agilent GC–MS (California, USA). The test was conducted to identify the active compounds in the most effective vegetable oil treatment for enhancing bamboo resistance to termite attack. The test used a DB-5MS silica column (30 cm × 0.25 mm) with helium as the carrier gas. A total of 1 µL of sample was injected at 250 °C. Scanning was performed from 40 °C to 300 °C with a total analysis time of 47 minutes and a mass range of 50–600 Da. Compound identification was performed by matching mass spectral fragmentation patterns to the NIST Library.

2.7. Data Analysis

Statistical analysis of the combined effects of boron compounds, heating, and vegetable oil on bamboo weight loss and termite mortality was performed using a completely randomised factorial design with three factors (Meifiani et al. 2019). The first factor consisted of two levels: BAE and no BAE. The second factor consisted of 3 levels, namely heating temperatures of 60 °C, 150 °C , and 180 °C. The third factor had 3 levels: linseed oil, neem oil, and no vegetable oil. If the results obtained from the analysis of variance (ANOVA) had a significant effect at a 95% confidence interval, data processing was continued with Duncan's test.

3. Results and Discussion

3.1. Preservative Retention Value of BAE and Weight Percent Gain of Oils Treatment

The success of preservation can be measured by the amount of preservative that enters the bamboo. Retention is an important factor because it affects the effectiveness of protection and extends the use of preserved bamboo. The retention of BAE obtained in this research was 18.13 ± 1.32 kg/m^3. This value is in accordance with SNI 03-5010.1-1999 (BSN 1999), which requires preservative retention for indoor and outdoor use to be at least 8.2 kg/m^3 and 11.3 kg/m^3, respectively.

Weight percent gain (WPG) was used to quantify the penetration of oils (linseed and neem) in bamboo following the impregnation process. The results showed that the highest WPG value was obtained with linseed oil impregnation without BAE at 60 °C (**Fig. 1**). Variation in impregnant type and heating temperature influenced the WPG values. Both the individual factors (oil impregnation, BAE impregnation, and heat treatment) and their combinations had a significant effect on the WPG values ($p < 0.05$). The Duncan test showed that the WPG of neem and linseed oils in bamboo that had not been previously treated with BAE was significantly higher than that of bamboo previously treated with BAE. These findings align with the fact that BAE treatment reduces the available void space within the bamboo structure. The deposition of BAE within the cell lumens and microvoids limits the space accessible for oil penetration. Consequently, the WPG values of oil-impregnated bamboo are lower when BAE treatment is applied beforehand compared to samples without prior BAE treatment.

In addition, the WPG of linseed oil was significantly higher than that of neem oil. The difference in WPG values was affected by the viscosity. Oils with higher viscosity will limit deeper penetration into the wood (Zlahtiča et al. 2017). Linseed oil has a lower viscosity than neem oil. In this study, the viscosity of linseed oil was approximately 32.43 cP, whereas other studies reported a value of around 27.4 cP (Patel et al. 2016). Conversely, the viscosity of neem oil in this study was 55.58 cP**,** whereas other reports indicated values of about 46.7 cP (Rimtip and Tanko 2022). This variation in viscosity values is related to the differences in the chemical composition of the two oils, particularly the types of organic compounds and fatty acid profiles.

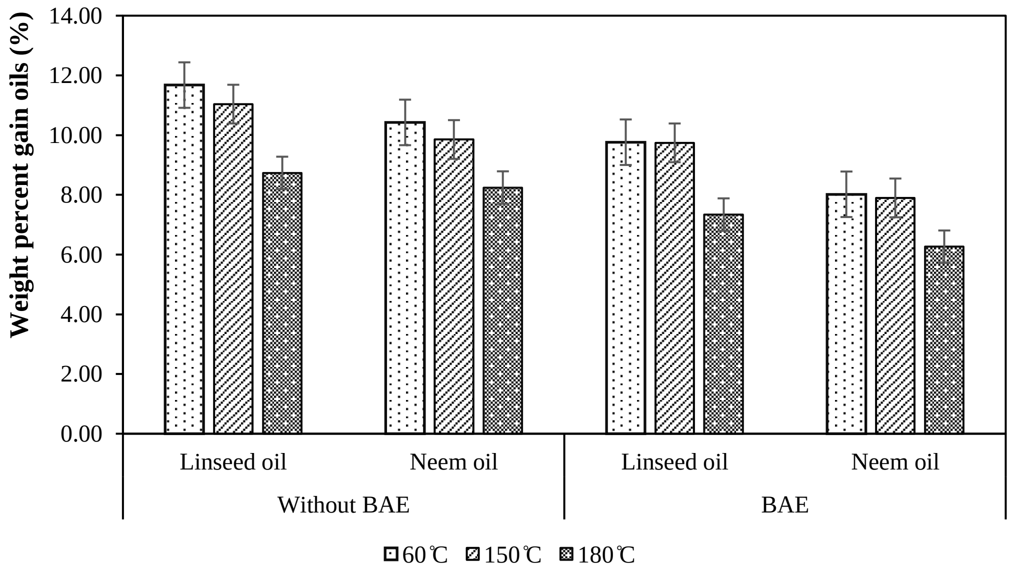

Fig. 1. Weight percent gain of bamboo after oil impregnation and subsequent heat treatment.

Heating at 180°C resulted in a lower WPG than at 60 °C. This is due to reduced water content and densification of the bamboo structure caused by chemical changes at higher temperatures. Heating at high temperatures (150–240 °C) reduces the amount of hydroxyl groups and the equilibrium moisture content of bamboo (Hill et al. 2021). Heating can cause cross-linking reactions between components, forming a denser structure, making the wood hydrophobic and more dimensionally stable (Ali et al. 2021). This dense structure can hinder the penetration of oils.

The evaluation of preservative penetration levels shows variations in durability among bamboo types, influenced by differences in anatomical factors and permeability (Yusof et al.

2023). The characteristics of the preservation agent also impact penetration. The high retention of boric acid in bamboo is related to its physicochemical properties. Boric acid has a relative molecular weight of approximately 61.83 g/mol and a density of 1.435 (Kursuncu and Yaras 2017), making it easy to penetrate the structure and tissues of bamboo, thereby increasing preservation effectiveness.

3.2. Bamboo Resistance to Subterranean Termites Attack

The combined application of neem oil, BAE, and high-temperature heat treatment enhanced subterranean termite resistance, attributable to thermally induced chemical modifications and bioactive components from the preservatives (**Fig. 2**). Heat treatment only also showed a trend of increasing termite resistance, with higher temperatures resulting in better resistance. In addition, neem oil demonstrated a more pronounced effect on enhancing termite resistance than linseed oil, as indicated by lower weight loss values. According to the SNI 7207:2014 standard (BSN 2014), bamboo impregnated with BAE or a combination of BAE and vegetable oil showed an increase in resistance to termites, from class IV to class II–III.

The impregnated materials and the applied heating temperature influenced the weight loss of bamboo caused by subterranean termites. BAE and heating treatment significantly reduced weight loss due to termites ($p < 0.05$). Bamboo treated with BAE at 60 °C showed a reduction in weight loss of up to 0.75 times that of the control (TB60). This is consistent with the known protective role of boric acid in BAE, where it acts as an effective insecticide. Priadi et al. (2022) reported that boric acid significantly reduced wood mass loss caused by subterranean termites, placing treated samples in resistance class I. This compound is widely known as a chemical insecticide.

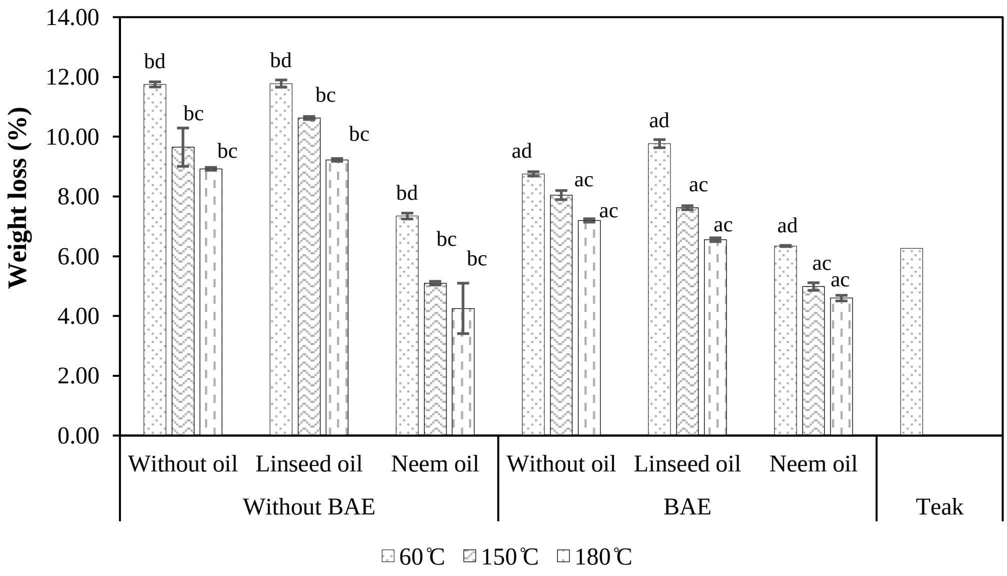

Fig. 2. Weight loss of treated and non-treated bamboo in subterranean termite testing.

Bamboo heated at 150 °C and 180 °C, and impregnated with heated water, showed increased resistance to termites, with weight losses 0.82 and 0.76 times lower, respectively, than those of bamboo heated only at 60 °C. Heating at high temperatures degrades hemicellulose, polysaccharides, and starch, and alters the chemical structure of bamboo (Huang et al. 2019; Yu and Wang 2023). Research by Adebawo et al. (2022) also supports the idea that heating African white wood to 140 ℃ can reduce weight loss due to termite attack compared to untreated wood.

In addition to these effects, the interaction between BAE and vegetable oils showed distinct patterns depending on the oil type. Linseed oil exhibited an additive effect when combined with BAE, as reflected in the lower weight loss of BAE and linseed oil compared to samples treated with linseed oil alone. This pattern indicates that linseed oil provides moderate protection, but its performance is substantially enhanced when supported by BAE. The relatively limited independent effect of linseed oil may be attributed to its primary mechanism, forming a hydrophobic barrier, rather than delivering strong biocidal activity.

In contrast, neem oil–treated samples showed no substantial difference in weight loss between those with and without BAE. This suggests that neem oil alone already provides strong termite resistance, likely masking the contribution of BAE. The bioactive compounds in neem oil possess potent insecticidal, antifeedant, and growth-regulating properties, making it an effective standalone preservative. This observation is consistent with the findings of Adfa et al. (2023), who reported that neem oil (*A. excelsa*) extracted predominantly for fatty acids, such as hexadecanoic acid, significantly increased the mortality of subterranean termites at increasing extract concentration.

3.3. Bamboo Resistance to Drywood Termites Attack

According to Zalsabila et al. (2024), the lower the weight loss of a material after termiticide testing, the more effective the preservative. Test results showed that treatments involving BAE, heating, and oil were able to enhance the resistance of gombong bamboo to drywood termite attacks, as shown in **Fig. 3**. The best treatment was obtained from the combination of BAE, heating at 180 ℃ with neem oil, with a weight loss value 0.43 times lower than the control (heating at 60 ℃). This treatment increased the resistance class from IV (untreated) to III. In addition to the bamboo samples, teakwood was also tested under the same subterranean termite exposure conditions. The weight loss of teakwood was measured experimentally and used as a reference material for comparative evaluation. Based on the resistance classification, the treated bamboo exhibited resistance comparable to that of teakwood under the same testing conditions.

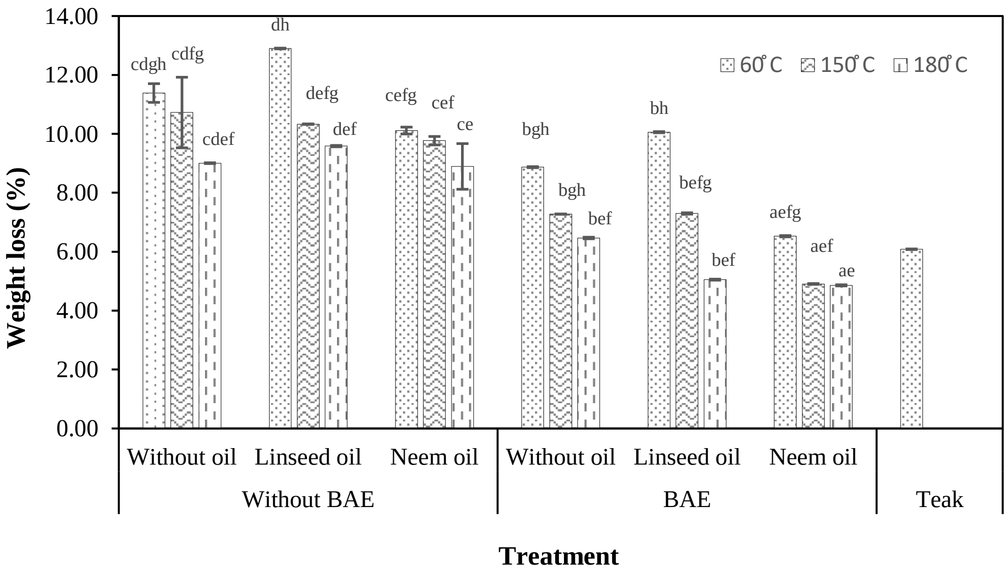

Fig. 3. Weight loss of treated and non-treated bamboo in drywood termite testing.

The combination of impregnation and heating influenced the weight loss caused by drywood termites. There was a significant effect of the interaction between oil treatment and heat treatment, as well as between BAE oil treatment, on the weight loss value of bamboo after testing against dry wood termites ($p < 0.05$). The combination of BAE and neem oil at 60 °C showed a significantly lower weight loss (6.53%) compared to the single BAE treatment at 60 °C (8.87%) and the single neem treatment at 60 °C (10.11%). The single treatments of BAE and neem oil also showed lower weight loss than the control (heating at 60 °C), with decreases of 22% and 11%, respectively. Heat treatment significantly reduced weight loss from termite attack. Heating treatment partially degraded cellulose and extractive compounds (polysaccharides), reduced hygroscopicity and moisture content, and altered the cell wall structure (Priadi et al. 2025). All of which enhance bamboo's overall resistance and reduce weight loss.

BAE contains boron compounds with fungicidal and insecticidal properties (Percin et al. 2015). Chen et al. (2024) showed that boron impregnation of *Cunninghamia konishii* resulted in lower weight loss than untreated wood and increased termite mortality by more than 99%. The main components in neem oil are nimbin, nimbidin, nimbolide, mahmoodin, meliacin, meliacinol, and gedunin, which have antibacterial, anti-inflammatory, and insecticidal properties (Risuleo 2020). The complex tetranortriterpenoid limonoids found in the seeds exhibit insecticidal activity (Islas et al. 2020). The high tannin and alkaloid content in neem seed is thought to contribute to its anti-termite activity, leading to lower weight loss than with other treatments (Adebawo et al. 2015). Research by Ahmed et al. (2020) also proved that the application of neem oil on *Acacia nilotica*, *Dalbergia sissoo*, and *Pinus wallichiana* can increase resistance to termites, as indicated by a decrease in weight loss and an increase in termite mortality. Overall, this study shows that the use of BAE, neem oil, and a combination of BAE with vegetable oils (linseed and neem) improves the resistance of gombong bamboo to dry-wood termite attacks, from class IV to class II to class III.

3.4. Visual Evaluation of Color Change

The combined treatment of boron impregnation, heating, and neem oil application caused color changes in the bamboo (**Fig. 4**). In general, the L value (brightness) decreased after treatment, especially in the high temperature combinations (heating at 150 °C and 180 °C). This indicates that bamboo tends to become darker after heat treatment, especially when combined with boron and neem oil. The a value (redness) shows an increasing trend after treatment (a#), indicating a color shift towards red. Meanwhile, the b value (yellowish) shows a less significant variation between before and after treatment.

The analysis of variance showed that the BAE treatment and temperature had significant effects on L, a, b, and color change ($p < 0.05$). Based on the classification of color change (**Table 3**), the combination of treatments at 60 °C fell into the category of very small ($0.2 < \Delta E \leq 2$) to medium ($3 < \Delta E \leq 6$), while at 150 °C fell into the category of large ($6.0 < \Delta E \leq 12$) to different colors ($\Delta E > 12$). The 180 °C treatment produced the most visually distinct color change (**Fig. 5**).

The presence of BAE within the bamboo structure enhances the extent of color change during heat treatment. BAE may interact directly with the bamboo structure during heating, thereby intensifying color change. This is consistent with a previous study that found that BAE preservatives darken *Cunninghamia konishii* (Chen et al. 2024). The color changes observed in heat-treated bamboo are primarily driven by hemicellulose degradation and chemical reactions involving extractives, including reducing sugars and amino acids, as well as the caramelisation of holocellulose components (Zhang et al. 2021). Previous studies by Lee et al. (2018 and 2021) stated that increasing the treatment temperature decreased the color value of *Phyllostachys edulis* and *Phyllostachys bambusoides* bamboo species. Higher temperatures (150–200 °C) intensify the thermal degradation of hemicellulose and lignin oxidation (Mastouri et al. 2021), accompanied by reactions involving extractives, quinones, amino acids, and bamboo sugars during heat treatment (Lee et al. 2020). These processes lead to a marked decrease in *L** values and an increase in *a** values, consistent with the findings of Cui and Matsumura (2019) and Torniainen et al. (2021).

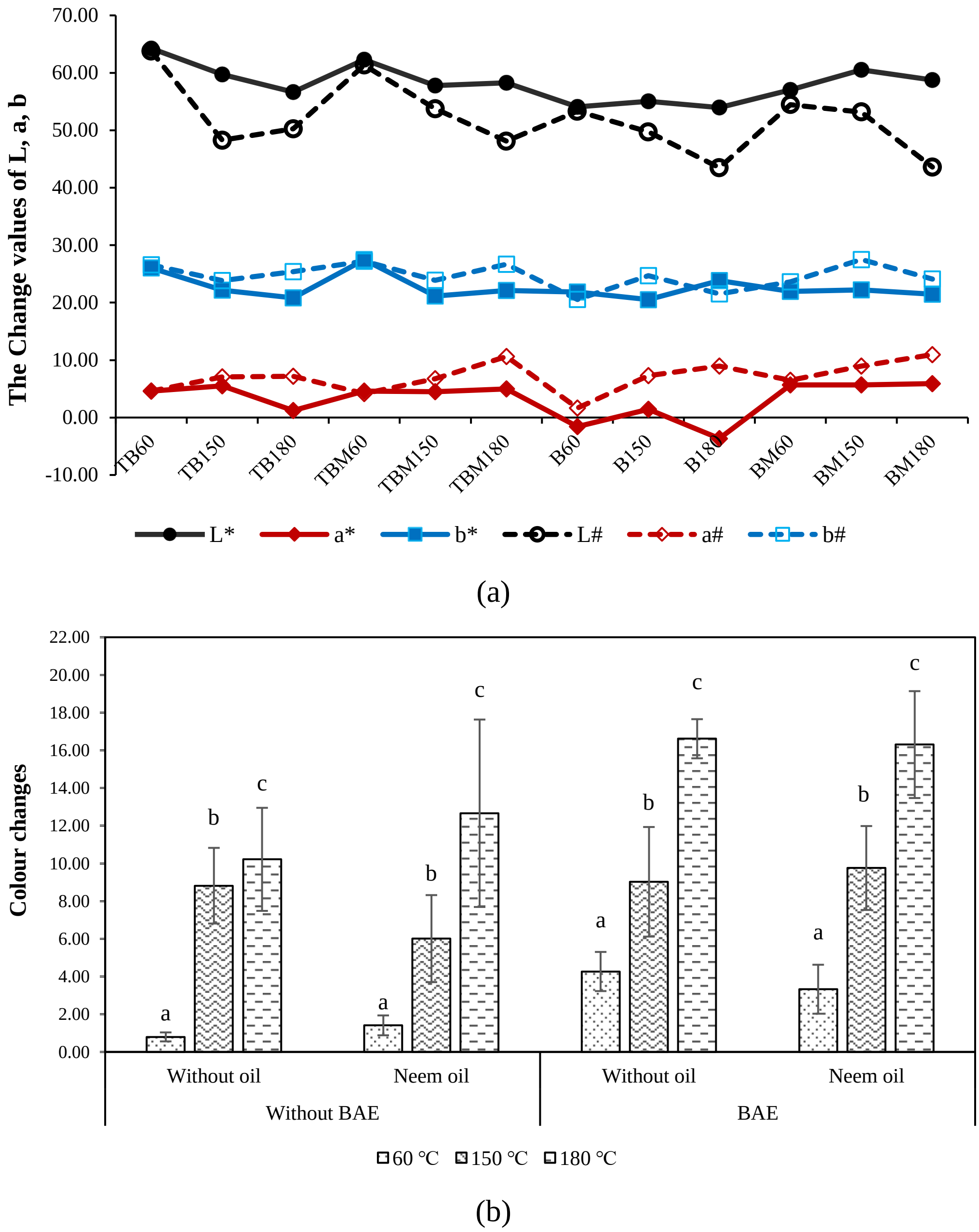

Fig. 4. The L, a, b values treatment without BAE (TB); without BAE-with neem oil (TBM); with BAE-without neem oil (B); with BAE-neem oil (BM) of gombong bamboo before (*) and after (#) treatment (a) and total color change (b).

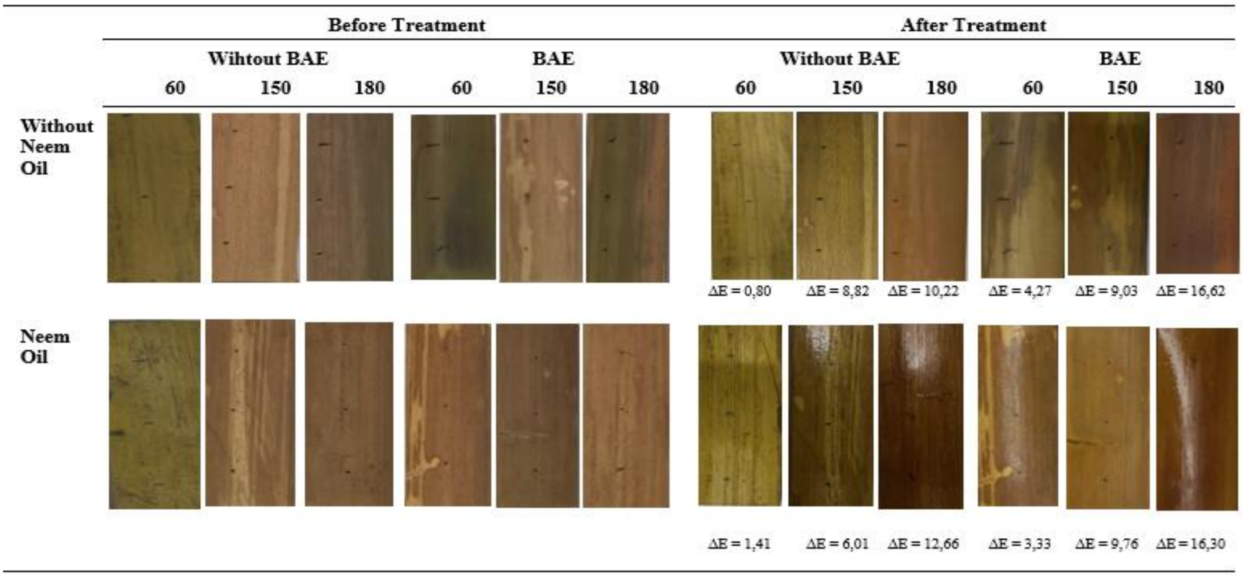

Fig. 5. The appearance of gombong bamboo before and after treatment with impregnation and heating.

The lack of significant effects can be attributed to the fact that the neem oil in this study was applied without heating, so no chemical or thermal reactions occurred that could modify the bamboo structure. As a result, the observed visual change was limited to a glossy appearance or enhanced surface shine, rather than an actual alteration in the bamboo's intrinsic color parameters.

3.5. Protection Mechanisms of Impregnation Agents and Chemical Characteristics

This study used three main impregnation agents: boric acid equivalent (BAE), linseed oil, and neem oil. BAE functions as a toxic agent against wood-deteriorating organisms and is known to inhibit enzymatic activity in insects. The use of oils serves as a hydrophobic agent, reducing moisture uptake and enhancing biological degradation. Although linseed oil is relatively non-toxic to termites, its combination with BAE improved overall performance and reduced weight loss. In this study, GC–MS analysis was performed only for neem oil because preliminary results indicated that it showed the greatest improvement compared with other oil treatments.

Neem oil produced from seeds is generally light brown or yellowish to dark brown in color, with a bitter flavour and characteristic pungent odour, resembling a mixture of garlic and peanuts (Tesfaye and Tefera 2017). Neem seed oil has been identified as a potential pest control option in agriculture (Adigwe et al. 2022). The GC–MS analysis of neem oil in this study (**Table 5**) showed that the main components were fatty acids, namely palmitic acid, oleic acid, and stearic acid. The results are in accordance with reports from previous studies that neem seeds contain about 45% oil, which is composed of oleic acid (50–60%), palmitic acid (13–15%), stearic acid (14–19%), linoleic acid (8–16%), and arachidic acid (1–3%) (Neto et al. 2023). Differences in fatty acid content and composition can be caused by growth location, plant species, and environmental conditions (Prayogo et al. 2023).

Several studies have shown that fatty acids have potential as biological agents to improve the resistance of natural materials to insect attacks and other pathogens. Fatty acids possess amphipathic properties, of a hydrocarbon carbon chain (hydrophobic) and a carboxylate group (hydrophilic), that disrupt microbial cell membranes, leading to metabolic dysfunction and cell death (Sama et al. 2021). In addition, fatty acids can act as antifeedants (Cruz-Estrada et al. 2019) and exhibit insecticidal activity by affecting the nervous system, reproduction, appetite, development, and moulting of insects (Campos et al. 2019; Oksari et al. 2025). Adfa et al. (2023) reported that neem oil, which is dominated by fatty acids such as hexadecanoic acid, 12-octadecadienoic acid (Z,Z)- and 9-octadecenal, significantly increases termite mortality of *Coptotermes curvignathus* (> 90% at high concentrations). Neem oil has also been widely recognized as a natural insecticide and repellent against various insect species, such as *Anopheles stephensi* and *A. culicifacies* mosquitoes, *Cnaphalocrocis medinalis*, *Diaphorina citri*, *Helicoverpa armigera*, *Mamestra brassicae*, *Nilaparvata lugens*, *Pieris brassicae*, and *Spodoptera frugiperda* (Ahmad et al. 2015; Chandramohan et al. 2016). Furthermore, Sazalee et al. (2022) reported that fatty acid-derived N-acyl glycine from palm oil exhibited high repellency and toxicity against *Microtermes diversus*, causing up to 100% mortality within 3 days.

Table 5. Chemical compound in neem oil

Compound name	RT (min)	Abundances (%)	MW (DB)	Compound group
n-Hexadecanoic acid	37.156	23.34	256.2	Fatty acid
Pentachloro-ethane	11.351	15.82	199.9	Alkyl halides/ chloroethane
Hexachloro-ethane	14.699	13.15	233.8	Alkyl halides/ chloroethane
cis–Vaccenic acid	42.122	8.03	282.3	Fatty acid
Tetrachloroethylene	5.369	7.84	163.9	Chloroethane
Allyl stearate	39.037	7.49	324.3	Fatty acid
Oleic Acid	40.203	4.52	282.3	Fatty acid
1-chloro-2-propanol	5.67	2.13	94	Secondary alcohol
Palmitoyl chloride	36.115	1.44	274.2	Fatty acid
1–Tetradecene	24.065	1.23	196.2	Alkenes
Isopropyl linoleate	41.996	1.10	322.3	Fatty acid
Tetradecanoic acid	32.742	1.01	228.2	Fatty acid
1–Dodecene	18.498	0.95	168.2	Dodecene
1-Octene	4.818	0.87	112.1	Octene
1,1,2,2-tetrachloroethane	9.043	0.85	165.9	Chloroethane
1-Undecene	15.376	0.79	154.2	Alkenes
1-Decene	11.978	0.75	140.2	Alkenes
1-Tridecene	21.382	0.70	182.2	Acyclic olefin
1-Nonene	8.316	0.69	126.1	Alkenes
Decanoyl chloride	21.934	0.55	190.1	Carboxylic acid halides
cis-9-Hexadecenal	30.912	0.49	238.2	Monounsaturated Fat
17-Octadecynoic acid	28.542	0.47	280.2	Fatty acid
Cycloundecene (E)	16.454	0.46	152.2	Cycloalkene
Bicyclo[5.1.0]octane	8.529	0.44	110.1	Cycloalkene
Cyclododecene	19.489	0.44	166.2	Alkenes
14-methyl-(Z)-14-methyl-8-Hexadecenal	35.501	0.43	252.2	Unsaturated aliphatic aldehyde
1-Pentadecene	26.598	0.43	210.2	Alkenes
Pentadecanal-	31.739	0.41	226.2	Saturated aliphatic aldehyde
Dodecanoic acid	28.316	0.40	200.2	Fatty acid
1,1-dichloro-2-Propanone	3.438	0.33	126	Ketone
8-Cyclohexadecen-1-one	31.037	0.28	236.2	Ketone
Acetic acid, chloro-, hexadecyl ester	28.981	0.27	318.2	Fatty acid
(Z,Z)-9,12-Octadecadienoic acid	43.564	0.26	280.2	Fatty acid
1,1,1-trichloro-2-Propanol	9.407	0.26	161.9	Secondary alcohol
(E,Z)- 2,4-Dodecadiene	20.504	0.24	166.2	Unsaturated aliphatic diene

In addition, some compounds belonging to the alkyl halide group have been used as insecticides and medical applications (particularly veterinary medicine). As insecticides, these compounds primarily act as fumigants, effective in controlling stored-product pests and wood-destroying insects (Proquin et al. 2024).

Other compounds found in neem oil also belong to the alkene group. Previous studies have reported that alkene-based compounds exhibit significant biological activity. Recent evidence demonstrated strong antibacterial effects against *E. coli*, *Pseudomonas aeruginosa*, *Staphylococcus aureus*, and *Salmonella enteritidis* (Sogan et al. 2021). Indicating that the alkene constituents in neem oil may contribute to its biological protection potential for bamboo. Overall, the identified chemical constituents demonstrate relevant biological activities that could enhance bamboo resistance against termite attack. Although each compound exhibits different mechanisms, their combined toxic, repellent, and biological effects support the effectiveness of neem oil as an impregnating agent within the present treatment system.

4. Conclusions

Impregnation with BAE, heating treatment, and vegetable oil can significantly increase the resistance of gombong bamboo to termite attacks, including drywood termites. High-temperature treatment (150 °C and 180 °C) can increase the resistance of gombong bamboo, especially when combined with BAE and neem oil, as evidenced by reduced weight loss and an increase in resistance class from IV to II–III. In addition, heat treatment caused a change in bamboo color, which tended to become darker and redder as the temperature increased. Using neem oil gives the bamboo a shiny surface. Neem oil contains dominant fatty acid compounds and other components that can increase the resistance of bamboo to attacks by termites. The combination of BAE treatment, heating at 180 °C, and neem oil treatments resulted in the greatest increase in gombong bamboo resistance to termites in termite testing.

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Author Contributions

L.C.P.: Conceptualization, Methodology, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft Preparation, Writing – Review and Editing; T.P.: Conceptualization, Methodology, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft Preparation, Writing – Review and Editing; Y.H.P.: Conceptualization, Methodology, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft Preparation, Writing – Review and Editing.

Conflict of Interest

The authors declare no conflict of interest.

Declaration of Generative AI And AI-Assisted Technologies in the Manuscript Preparation

During the preparation of this manuscript, the authors used Grammarly for grammar and language checking to improve clarity and readability. The tool was not used to produce original content, perform data analysis, or contribute to the development of scientific ideas. All authors have reviewed and approved the final version of the manuscript for publication.

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