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Color change and termite resistance of fast-growing tropical woods treated with kesambi (*Schleichera oleosa*) smoke

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Abstract

Smoke treatment can be used to enhance wood resistance to subterranean termite attack. In this study, kesambi (*Schleichera oleosa*) wood was pyrolyzed to produce charcoal. The smoke produced as a by-product of pyrolysis was used to treat sengon (*Falcataria moluccana*), jabon (*Anthocephalus cadamba*), mangium (*Acacia mangium*), and pine (*Pinus merkusii*) wood samples for 1, 2, or 3 weeks. Following the smoke treatment, the wood specimens were exposed to subterranean termites (*Coptotermes curvignathus* Holmgren) according to the Indonesian standard 7207-2014 in a laboratory. The color change caused by smoke treatment was observed, and chemical analysis of smoke was also done. The results showed that chemical compounds of kesambi smoke predominantly consisted of acetic acid, phenol, ketones, amines, and benzene. The color of smoked wood became darker, less yellow, and a little redder, while a longer smoking period produced a darker color which was more resistant to termite attack. Smoke treatment enhanced the resistance of wood to subterranean termite attack, and the resistance levels were not significantly different based on the duration of the smoke treatment.

Keywords: Wood resistance to bio-deterioration, Fast-growing tropical wood, Smoke treatment, Termite attack

Introduction

Log production for the Indonesian wood industry reached 47.9 million m^3 in 2018, with 85% of production being from plantation forests [1]. Forest stands in the country are mostly composed of fast-growing species, which are cut at a young age, generally 6–10 years old. This timber predominantly consists of sapwood and contains juvenile wood, and both types of wood are inferior to mature wood in terms of physical–mechanical properties and resistance to bio-deterioration [2].

In tropical areas, the subterranean termite is a serious problem because these insects attack lignocellulose materials. Nandika [3] reported that subterranean termite attacks on the woody components of buildings, houses, and other structures in Indonesia lead to the need for renovations, with economic losses potentially reaching USD 1 billion per year. To lengthen the service period of wood components, lumber can be preserved by impregnating toxic chemicals into the wood, but these chemicals are harmful for living organisms, including humans.

To reduce or prevent such risks, nontoxic chemicals could be impregnated into the void space of wood or linked with wood tissue via covalent bonds to produce wood with increased resistance to bio-deterioration attacks. Various chemicals have been used for this purpose. Mubarok et al. [4] treated beech wood with different derivatives of glycerol or polyglycerol and maleic anhydride followed by thermal modification, which resulted in wood that was more resistant to subterranean termite during 1-year exposure in a tropical field experiment. Other researchers have developed binder-less particleboard using hydrogen peroxide [5] and citric acid [6]

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for cross-linking agents between wood particles. Particleboards produced in these studies were more resistant to termite attack than conventional particleboards.

In other experiments, wood vinegars produced via pyrolysis of *Vitex pubescens* [7] and oil palm trunk [8] were used for anti-termite activities of *Coptotermes formosanus* workers in the no-choice experiment. The results showed that a 10% (w/w) concentration was required to achieve 100% termite mortality. Yatagai et al. [9] reported that wood vinegars made from mixed chips of *Cryptomeria japonica* and *Pseudotsuga menziesii* (wood vinegar A), *Quercus serrata* (wood vinegar B), and *Pinus densiflora* (wood vinegar C) exhibited high termiticidal activities against *Reticulitermes speratus*. Some chemical modification methods on wood have also been developed, including acetylation [10], furfurylation [11], impregnation with polystyrene [12], impregnation with methyl methacrylate [13], as well as smoked wood [14].

Smoke and heat treatment of mindi (*Melia azedarach*) and sugi (*Cryptomeria japonica*) wood for 12 h was found to enhance wood resistance to attack by subterranean and dry wood termites [14]. Additionally, Hadi et al. [15] explained that smoking sengon (*Falcataria moluccana*), pulai (*Alstonia* sp.), and sugi wood for 2 weeks improved resistance to attack by subterranean and dry wood termites. In the other work, smoke treatment applied to three-layer glued-laminated lumber (glulam) of mangium (*Acacia mangium*), manii (*Maesopsis eminii*), and sengon for 2 weeks was found to improve glulam resistance to subterranean termite attack [16].

In East Nusa Tenggara province, Indonesia, smoke and vinegar from kesambi (*Schleichera oleosa*) wood or leaves are commonly used to add flavor to the meat of tuna fish [17, 18]. Kesambi wood is found in other areas of Indonesia, and it could be used for smoke treatment of wood from fast-growing wood species. The purpose of this study was to enhance the resistance of sengon, jabon (*Anthocephalus cadamba*), mangium, and pine (*Pinus merkusii*) wood to subterranean termite attack. This resistance was assessed via a no-choice test in the laboratory according to the Indonesian standard.

Materials and methods

Wood sample preparation

Sengon (*Falcataria moluccana*), jabon (*Anthocephalus cadamba*), mangium (*Acacia mangium*), and pine (*Pinus merkusii*) for smoked wood experiments were obtained from Bogor, West Java, Indonesia. The logs were cut from plantation forest at age less than 10 years, and then they were processed for flat-sawn lumbers. After reaching air-dry condition, the lumbers were cut into specimens of 0.5 by 2.5 cm in cross-section and 2.5 cm in the longitudinal direction for the experiments.

Smoking procedure

Wood specimens were divided into four categories: untreated wood and wood smoked for 1, 2, or 3 weeks. Kesambi wood was pyrolyzed to produce charcoal, and the smoke released as a byproduct was used for the smoking process, which lasted 1, 2, or 3 weeks, depending on the treatment group [15]. The smoke produced from pyrolyzed tank flew to another tank for catching the tar and reducing the temperature, and then flew to the smoking chamber. The temperature inside the chamber during smoking process ranged from 18 to 36 °C. After completion of the smoking process, the samples then underwent conditioning for 2 weeks under room temperature of 26 °C (min 21.8, max 30.4 °C) and average relative humidity of 82.5% (range, 61–96%). Six replications were done for each treatment combination.

For analysis of the chemical compounds of the smoke, condensed smoke or wood vinegar was analyzed by gas chromatography–mass spectrometry (GC–MS) type Agilent 7890 before it entered the smoking chamber.

Wood color change determination

Smoke treatment on wood could change the wood color, and the CIELab (Commission International de L'Eclairage, CIE) method was using to determine on it. This method involved directly measuring the values of L^*, a^*, and b^* from a photograph (which was obtained using a CanoScan 4400F scanner) of the wood sample, using the Adobe Photoshop CS5 application. L^* indicates lightness, with a value of 0 to 100 (black to white); a^* indicates colors from green to red, with $+a^*$ from 0 to 80 corresponding to red and $-a^*$ from -80 to 0 corresponding to green; and b^* indicates color from blue to yellow, with $+b^*$ from 0 to 70 corresponding to yellow and $-b^*$ from -70 to 0 corresponding to blue [19].

Each sample was assessed at five points, and the average value was used in the analysis. The color change (ΔE) was calculated regarding to CIELab [20], using the following equation:

$$\Delta E = \sqrt{\left[(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2\right]}, \quad (1)$$

where ΔE = color change, ΔL = difference in L^* values between compared samples, Δa = difference in a^* values between compared samples, Δb = difference in b^* values between compared samples.

According to Hunter Lab [20] and Hrčková et al. [21], the color change can be classified as shown in Table 1.

Subterranean termite test

The laboratory subterranean termite test was based on Indonesian standard SNI 7207-2014 [22]. Each test specimen was placed in a glass container with 200 g of sterilized sand with enough water to reach a

Table 1 Color change classification

Class	Color difference	Color change effect
1	$\Delta E < 0.2$	Invisible changes
2	$0.2 < \Delta E < 2.0$	Very small changes
3	$2.0 < \Delta E < 3.0$	Small changes (color changes visible by high-quality filter)
4	$3.0 < \Delta E < 6.0$	Medium (color changes visible by medium-quality filter)
5	$6.0 < \Delta E < 12$	Big (distinct color changes)
6	$\Delta E > 12$	Different color

moisture content of 7% under water-holding capacity. Two hundred healthy and active subterranean termite (*Coptotermes curvignathus* Holmgren) workers from a laboratory colony were added to each container. The containers were put in a dark room at a temperature of 25 to 30 °C and 80 to 90% relative humidity for 4 weeks and weighed weekly. If the moisture content of the sand decreased by 2% or more, water was added to achieve moisture content standard. At the end of the 4-week test, the wood samples were oven-dried at temperature of 103 ± 3 °C until reaching constant weight. Wood percent weight loss and termite mortality were determined using the following formulae:

$$\text{Percent weight loss (WL)} = (W_1 - W_2)/W_1 \times 100\%, \tag{2}$$

where W_1 = the weight (g) of oven-dried samples before the test, W_2 = the weight (g) of oven-dried samples after the test.

$$\text{Termite mortality} = (T_1 - T_2)/T_1 \times 100\%, \tag{3}$$

where T_1 = the number of live termites before the test, T_2 = the number of live termites after the test.

We assumed that termites died linearly with time, and we calculated the feeding rate according to the following equation:

$$\begin{aligned}\text{Feeding rate(FR)}\,&(\mu\text{g/termite/day})\\ &= (\text{weight of wood eaten; } \mu\text{g})/\\ &\quad(\text{average number of living termites})/\\ &\quad(\text{no of days in the test period}).\end{aligned} \tag{4}$$

Wood resistance class against subterranean termites was determined by referring to SNI 7207-2014 [22] as shown in Table 2. Sengon and pine were included as suitable reference species (comparative reference controls) for inclusion in laboratory tests against subterranean termites [23].

Table 2 Resistance class against subterranean termite

Resistance class	Sample condition	Weight loss (%)
I	Very resistant	< 3.52
II	Resistant	3.52–7.50
III	Moderately resistant	7.50–10.96
IV	Poorly resistant	10.96–18.94
V	Very poorly resistant	> 18.94

Precipitated smoke on wood surface

The amount of precipitated smoke on the wood surface could be obtained as follows:

$$\text{Precipitated smoke} = W_3 - W_4, \tag{5}$$

where W_3 = oven-dried weight of wood specimen before smoke treatment (g), W_4 = oven-dried weight of wood specimen after smoke treatment (g).

After the smoking process, the amount of precipitated smoke on wood surface could be interpreted with the color of wood, and the color of wood (L^*, a^*, b^*) would be having a correlation with the weight of precipitated smoke (y), and it could be expressed in an equation as follows:

$$y = a + b\,L* + c\,a* + d\,b*, \tag{6}$$

where a, b, c and d are the constants, L^*, a^* and b^* represent the colors.

The wood color after smoking process could express the wood resistant to termite attack which could be expressed by percent wood weight loss, and the correlation between wood color (L^*, a^*, b^*) and percent wood weight loss (y) could be explained as a multi-regression equation as follows:

$$y = a + b\,L* + c\,a* + d\,b*, \tag{7}$$

where a, b, c and d are the constants, L^*, a^*, and b^* represent the colors.

Data analysis

To analyze the effect of treatments upon all responses (i.e., color change, weight loss, mortality, and feeding rate), a 4 × 4 factorial in a completely randomized design was used for data analysis. The data were analyzed with Microsoft Excel and IBM SPSS Statistics (Statistical Product and Service Solution) version 22. The first factor was wood species (sengon, jabon, mangium, and pine), and the second factor was treatment (untreated, smoked 1-week, smoked 2-weeks, and smoked 3-weeks). Duncan's multiple range tests were used for further analysis if a factor was significantly different at $p \leq 0.05$.

Results and discussion

Wood densities of untreated sengon, jabon, mangium, and pine were 0.31 ± 0.02, 0.45 ± 0.03, 0.51 ± 0.02, and 0.59 ± 0.08 g/cm^3, respectively, with moisture contents of 11.2 ± 0.8, 11.9 ± 0.7, 7.9 ± 0.4, and 8.4 ± 0.6%, respectively. The density and moisture content were affected by wood species, but they were not affected by treatment or an interaction of species and treatment.

Chemical compounds in kesambi liquid smoke

The GC–MS analysis showed that the predominant chemical compounds and mostly had toxicity to the termite of kesambi condensed smoke were acetic acid, followed by phenol, ketones, amines, and benzene, in detail is shown in Table 3. Compared with the findings of Hadi et al. [24] for salam (*Syzygium polyanthum*) and Hadi et al. [16] for mangium smokes as shown in Table 4, the three main components (acetic acid, phenol, and ketones) were the same, but their relative percentages differed each other.

These results indicate that different types of wood produce different smoke compounds, confirming results reported by Toledo [25]. However, the three types of smoke had similar dominant compounds, particularly acetic acid and phenol. Phenolic compounds and acetic acid were previously shown to be effective as wood preservatives against termite attack, and it was also reported that smoke could also protect wood against attack by fungi, termites, and bacteria [26].

Color of wood

The wood color was indicated by values of L^* (lightness, black to white), a^* (green to red), b^* (blue to yellow), and ΔE for the color change, which is shown in Table 5. A summary of the variance analysis is presented in Table 6.

Table 4 Dominant chemical compounds of liquid smokes

Kesambi	Salam	Mangium
Acetic acid	Acetic acid	Acetic acid
Phenol	Phenol	Phenol
Ketones	Ketones	Acetone
Benzene	Benzene	Cyclobutanol
Amines		

In addition, the wood color associated with each treatment for all wood species is shown in Fig. 1.

Based on the data shown in these tables, wood species, smoke treatment, and the interaction of the two factors significantly affected L^* values. Mangium had the darkest color which differed from the other wood species. Smoke treatment resulted in the wood color becoming darker, with a longer smoking period resulting in darker color.

In terms of green to red color, the wood species, smoke treatment, and the interaction of the two factors significantly affected the a^* value. Sengon had the lowest value of red color, and it was significantly different from the other species. Smoke treatment could lead to more of a red color though, as the a^* value was increased.

The color blue to yellow, or b^* value, was significantly affected by wood species, smoke treatment, and the interaction of the two factors. Sengon had the lowest average value for yellow which differed from the other species. Smoke treatment changed the b^* value, and the average values declined or became more blue color.

Overall, kesambi smoke treatment changed the color (ΔE) of wood, causing it to become much darker. Wood species and smoking treatment factors significantly affected the color change, but the interaction between these factors did not. Mangium had the lowest average color change (24.6), which was different from sengon,

Table 3 Dominant compounds of kesambi smoke

Peak#	Retention time (min)	%	Library/ID	Ref#	CAS#	Qual
1	1.956	49.49	Acetic acid (CAS)	971	000064-19-7	91
2	2.207	3.42	2-Isopropylimidazole	17,658	036947-68-9	47
3	2.568	14.01	2(3H)-Furanone, dihydro-	5115	000096-48-0	87
4	2.964	1.76	Pyridine, 3-methoxy-	16,618	007295-76-3	64
5	3.117	2.92	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	18,873	000080-71-7	96
6	3.339	10.52	Phenol, 2-methoxy-	30,859	000090-05-1	97
7	4.152	3.76	Creosol	50,893	000093-51-6	96
8	4.889	2.60	Benzeneethanol, 2-methoxy-	76,699	007417-18-7	95
9	5.556	7.00	Phenol, 2,6-dimethoxy-	81,474	000091-10-1	97
10	6.327	2.56	3,5-Dimethoxy-4-hydroxytoluene	113,861	006638-05-7	95
11	6.953	1.97	4-Ethyl-syringol	150,897	2000150-89-7	87

Table 5 Wood color before and after smoke treatment (ΔE)

Wood	Treatment	L^*	a^*	b^*	ΔE
Jabon	Control	75.9 (4.3)	3.7 (1.0)	25.5 (1.6)	
	Smoked-1W	42.6 (1.0)	8.0 (0.3)	21.3 (0.6)	33.9 (3.7)
	Smoked-2W	32.0 (1.7)	6.8 (0.6)	13.8 (1.0)	45.6 (3.3)
	Smoked-3W	30.3 (4.4)	6.8 (0.6)	14.8 (1.0)	47.0 (5.7)
	Average	45.2 (1.8)	6.3 (0.3)	18.9 (0.4)	36.3 (7.3)
Sengon	Control	77.5 (2.9)	3.6 (0.3)	14.1 (1.9)	
	Smoked-1W	46.6 (1.6)	6.1 (0.2)	20.7 (1.6)	31.8 (2.7)
	Smoked-2W	31.8 (3.6)	5.4 (0.9)	11.2 (4.0)	45.9 (6.5)
	Smoked-3W	26.5 (2.4)	6.4 (0.7)	9.7 (1.1)	51.3 (3.4)
	Average	45.6 (0.8)	5.4 (0.3)	14.0 (1.3)	35.8 (2.2)
Mangium	Control	58.7 (3.1)	6.8 (0.4	22.0 (0.7)	
	Smoked-1W	39.4 (1.3)	7.5 (1.0)	18.8 (0.9)	19.6 (3.8)
	Smoked-2W	31.0 (2.7)	5.6 (0.8)	11.5 (1.3)	29.7 (4.6)
	Smoked-3W	27.3 (3.7)	5.8 (0.7)	11.9 (1.3)	33.0 (4.8)
	Average	39.1 (1.0)	6.4 (0.3)	16.1 (0.3)	24.6 (2.1)
Pine	Control	75.6 (1.1)	7.5 (1.7)	26.2 (2.8)	
	Smoked-1W	38.8 (2.1)	8.6 (0.4)	19.7 (0.6)	37.5 (3.0)
	Smoked-2W	30.6 (1.3)	6.3 (0.2)	11.1 (1.3)	47.6 (2.0)
	Smoked-3W	27.6 (4.1)	6.5 (0.5)	14.2 (1.4)	49.5 (3.4)
	Average	43.1 (1.4)	7.2 (0.7)	17.8 (0.9)	38.1 (1.1)
All species	Control	71.9 (8.4)	5.4 (2.0)	22.0 (5.2)	
	Smoked-1W	41.8 (3.5)	7.6 (1.1)	20.1 (1.3)	30.7 (7.5)
	Smoked-2W	31.3 (2.4)	6.0 (0.8)	11.9 (2.3)	42.2 (8.5)
	Smoked-3W	27.9 (3.7)	6.4 (0.7)	12.7 (2.3)	45.2 (8.5)

1W = 1 week; 2W = 2 weeks; 3W = 3 weeks

Values in parentheses are standard deviations

Table 6 Summary of analysis of variance

Color value	Wood species (A)	Treatment (B)	Interaction (A x B)
L^*	**	**	**
a^*	**	**	**
b^*	**	**	**
ΔE	**	**	ns

** Highly significant difference ($p \leq 0.01$); ns = not significantly different ($p \leq 0.05$)

jabon, and pine, with values of 35.8, 36.3 and 38.1, respectively. The values for these three species were not significantly different from each other. In other words, smoke treatment for each species resulted in different colors (ΔE more than 12) compared with untreated wood, and the smoked wood becoming darker, a little redder, and less yellow. These findings had the same result in mangium and sengon wood as reported by Hadi et al. [24], and also was in line with Ishiguri et al. [27] who found that smoke-heated wood for 200 h had a total color change, with a deeper color developing with 200 h of treatment compared with 100 h.

Wood resistance to termite attack

Termite mortality

The termite mortality, wood percent weight loss, wood resistance class, and termite feeding rate of each wood species and smoke treatment are shown in Table 7. The summary of the analysis of variance is presented in Table 8, and further data analysis based on Duncan's multiple range testing is shown in Table 9. Termite mortality for untreated wood ranged from 14.6% to 22.3%.

Wood species, treatment factors, and the interaction of the two factors had a highly significant effect on mortality. Each wood species has particular characteristics in terms of anatomy, density, and extractive content, among others. Sengon and mangium were associated with average mortalities of 22.1 and 22.3%, respectively, which were higher than those for pine and jabon, with 14.6 and 16.2%, respectively. Pine belongs to the conifer family, which has more simple anatomical characteristics compared with hardwood or the three other wood species; therefore, the wood is more susceptible to attack by termites. Jabon wood also had low termite mortality in this study, which signaled lower resistance to termite attack. As stated by Arango et al. [28], a significant inverse association exists between the percentage of mass lost and specific gravity, and wood with a higher specific gravity has more resistance to termite attack.

Sengon wood has a low density, but the wood contains extractives that may discourage insect attack. Pari [29] found that sengon wood contained 19.6% extractive substances soluble in NaOH, including cellobiose, glucose, xylose, arabinose, ribose, oligosaccharide, pentasaccharide, capriate, myristic acid, myristoleic acid, pentadecanoic acid, palmitic acid, margaric acid, stearic acid, oleic acid, linoleic acid, and arachidonic acid. Such extractives would reduce termite attack on the wood, such as palmitic acid [30]. Mangium, which has a higher density and extractive content, would be even more resistant to termite attack. In the case of pine and sengon, Arinana et al. [23] reported that both species could be suitable reference species (comparative reference controls) for inclusion in laboratory tests against subterranean termites. That study was conducted under the Indonesian standard SNI 01.7207-2006 [31], which was revised to create SNI 7207-2014 [22].

Smoke treatments significantly affected termite mortality, but mortality was not significantly different between smoke treatments of different duration and all periods were associated with 100% termite mortality. These results are in line with Hadi et al. [24], who used smoke from salam wood to treat mangium and sengon wood.

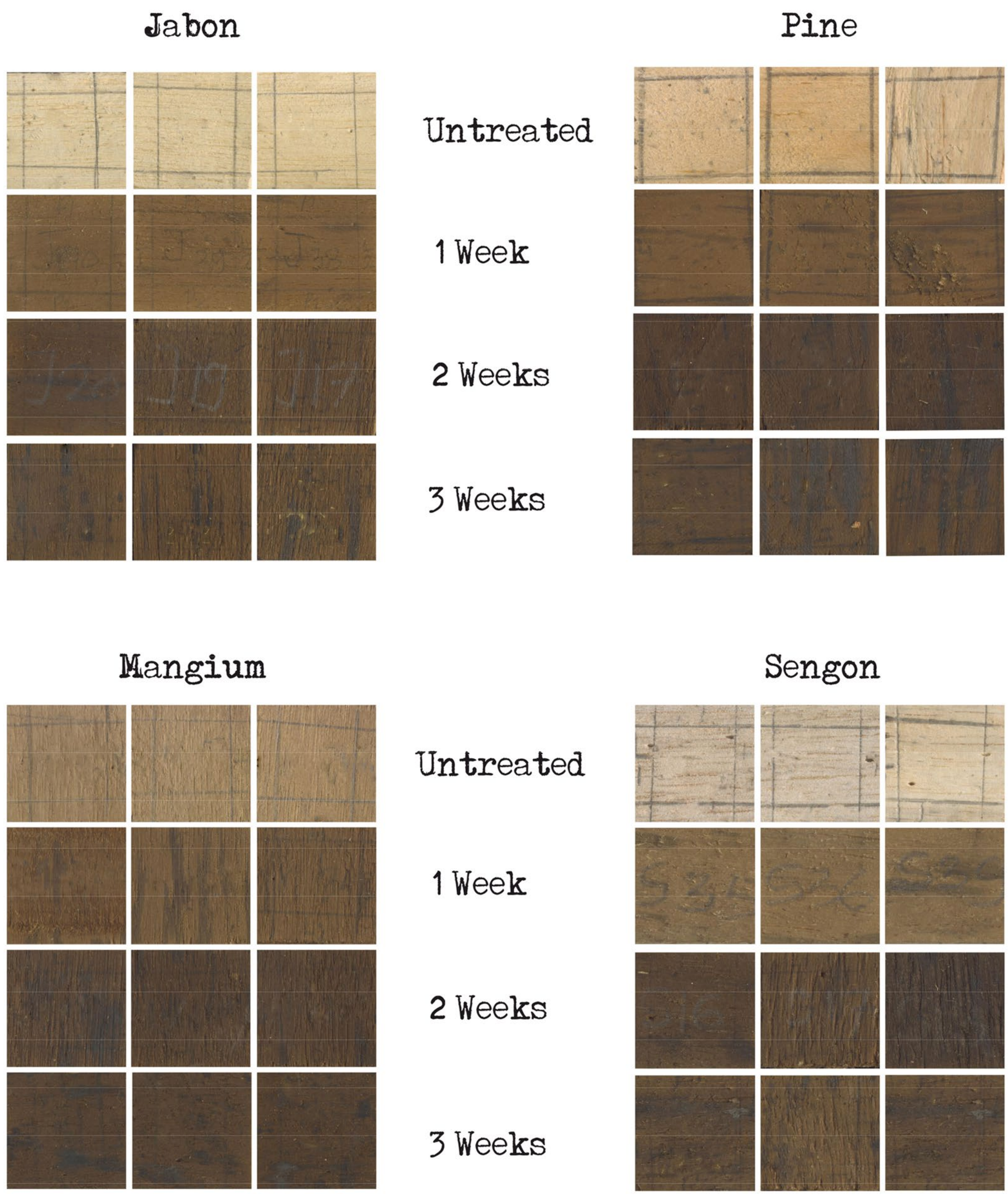

Fig. 1 Wood color of each species and treatment

Notably, smoke from salam wood and kesambi wood contains the same dominant compounds, namely, acetic acid, phenol, ketones, and benzene. For future work, a possibility could be to develop a biocide that contains these compounds so that the preservation process could be accomplished in a much shorter time period, as opposed to 1 to 3 weeks.

Percent weight loss

Wood species and smoke treatment significantly affected wood percent weight loss, but the interaction of the two factors did not. Untreated sengon wood with lowest density had the highest average percent weight loss, followed by pine, jabon, and mangium. Hadi et al. [15] previously reported that a lower wood density tends to result in lower resistance to subterranean termite attack, as indicated by the higher wood percent weight loss. With regard to the Indonesian standard [22], untreated sengon, jabon, mangium, and pine could be classified into average resistance classes 4.7, 4.3, 3.5, and 4.4, respectively.

Table 7 Mortality, percent weight loss, resistance class, feeding rate, and precipitated smoke based on wood species and treatment

Wood species	Treatment	Precipitated smoke (mg)	Mortality (%)	Weight loss (%)	Resistance class		Feeding rate (µg/termite/day)
Sengon	Untreated	0	22.1 (3.3)	21.7 (4.6)	V[a]	4.7 (0.5)[b]	33.2 (7.4)
	Smoke-1W	32.1 (8.5)	100.0 (0.0)	9.9 (2.3)	III	3.1 (0.3)	29.8 (9.6)
	Smoke-2W	50.7 (5.6)	100.0 (0.0)	9.7 (2.3)	III	3.0 (0.7)	28.9 (6.1)
	Smoke-3W	47.2 (6.6)	100.0 (0.0)	8.5 (2.1)	III	2.8 (0.8)	26.4 (7.2)
	Average smoke	43.3 (6.9)	100.0 (0.0)	8.7 (1.6)	III	2.8 (0.5)	27.6 (7.9)
Jabon	Untreated	0	16.2 (5.0)	21.1 (9.7)	V	4.3 (0.7)	47.5 (21.7)
	Smoke-1W	38.3 (3.0)	100.0 (0.0)	8.1 (1.7)	III	2.6 (0.7)	35.7 (8.9)
	Smoke-2W	60.9 (5.0)	100.0 (0.0)	7.9 (2.5)	III	2.7 (0.9)	34.8 (12.3)
	Smoke-3W	57.8 (4.9)	100.0 (0.0)	6.9 (1.0)	II	2.1 (0.3)	29.9 (5.9)
	Average smoke	52.3 (4.3)	100.0 (0.0)	6.8 (1.2)	II	2.2 (0.5)	28.9 (4.9)
Mangium	Untreated	0	22.3 (5.5)	13.5 (7.7)	IV	3.5 (1.2)	39.4 (21.6)
	Smoke-1W	59.0 (8.0)	100.0 (0.0)	6.6 (2.9)	II	2.4 (0.8)	34.1 (13.4)
	Smoke-2W	74.5 (5.4)	100.0 (0.0)	6.6 (3.7)	II	2.2 (0.6)	35.6 (18.6)
	Smoke-3W	70.7 (5.9)	100.0 (0.0)	5.5 (1.0)	II	2.1 (0.3)	29.5 (6.2)
	Average smoke	68.1 (6.4)	100.0 (0.0)	5.1 (0.3)	II	2.0 (0.0)	27.5 (3.0)
Pine	Untreated	0	14.6 (5.3)	20.8 (8.9)	V	4.4 (0.8)	73.4 (37.0)
	Smoke-1W	94.9 (28.7)	100.0 (0.0)	7.0 (2.9)	II	2.6 (0.8)	48.2 (18.8)
	Smoke-2W	116.6 (47.4)	100.0 (0.0)	8.0 (3.2)	III	2.6 (0.8)	52.1 (20.9)
	Smoke-3W	115.3 (17.8)	100.0 (0.0)	5.9 (1.8)	II	2.2 (0.4)	40.7 (12.4)
	Average smoke	108.9 (19.4)	100.0 (0.0)	5.5 (1.4)	II	2.1 (0.3)	37.5 (9.7)

Values in parentheses are standard deviations. Values followed by the same letter within the same column are not statistically different according to Duncan's multiple range tests

1W = 1 week; 2W = 2 weeks; 3W = 3 weeks

[a] Classified based on weight loss average

[b] Average of six tested wood specimens

Table 8 Analysis of variance for mortality, percent weight loss, feeding rate, and precipitated smoke

Source	Mortality	Percent weight loss	Feeding rate	Precipitated smoke
Wood species	**	**	**	**
Treatment	**	**	**	**
Interaction	**	ns	ns	ns

** Highly significant difference ($p \leq 0.01$); ns = not significantly different

Smoke treatment enhanced wood resistance to termite attack, as indicated by all smoked wood having much lower percent weight loss compared with untreated wood. With regard to the Indonesian standard, all smoked sengon, jabon, mangium, and pine wood samples had average resistance classes of 3.0, 2.5, 2.2 and 2.5, respectively. In other words, smoke treatment enhanced resistance class to be 1.7 classes higher. We speculate that the chemical compounds in the smoke coated the wood and protected it from attack by termites.

Table 9 Duncan's multiple range test

Factor	Mortality	%weight loss	Feeding rate	Precipitated smoke
Wood species				
Sengon	q	q	q	r
Jabon	p	q	q	r
Mangium	q	p	q	q
Pine	p	q	p	p
Treatment				
Untreated	a	a	a	–
1-week	b	b	b	a
2-week	b	b	b	b
3-week	b	b	b	b

The same letter in a column for each factor indicates no significant difference at $p \leq 0.05$

Feeding rate

Wood species and smoke treatment factors significantly affected the termite feeding rate, but the interaction of the two factors did not. Untreated pine wood had the highest feeding rate, followed by mangium, jabon, and sengon, with average values of 73.4, 47.5, 39.4, and 35.7 µg/termite/day, respectively. Compared with results reported by Arinana et al. [23] and Hadi et al. [16, 24], the feeding rates for untreated sengon, mangium, and pine were smaller. These differences were likely due to variations in wood densities and the exposure environments in Forest Products Research and Development Center for this research and in Faculty of Forestry, IPB University (Bogor Agricultural University).

The average feeding rate was the highest for pine, a conifer wood, compared with the other three species, all of which were hardwoods. This result aligned with termite mortality, with pine having the lowest termite mortality. Because more termites survived, there were more termites consuming the wood, which led to the resulting feeding rate being higher. The other three wood species were not significantly different from each other.

Smoke treatment reduced the feeding rate, as shown by the data in Table 7. Untreated wood had the highest feeding rate and differed from the treated wood, but the three types of wood based on smoke treatment were not significantly different from each other. In other words, the termite feeding rate did not differ if the smoking period was 1, 2, or 3 weeks, so a 1-week smoking period would be enough for these results; however, if the resistance needs to be better, a longer smoking period would be recommended.

Precipitated smoke on wood surface

The amount of precipitated smoke on wood surface (mg) of each wood species and smoking period are shown in Table 7, the analysis of variance is figured in Table 8, and Duncan's multi-range tests are presented in Table 9. Factors of wood species and smoking period highly affected the amount of precipitated smoke, but the interaction of both factors did not.

Further analysis showed that the precipitated smoke weight on pine was different from the other species, and pine had the highest value (108.9 mg), while mangium (68.1 mg) was smaller than pine. The precipitated smoke on jabon (52.3 mg) and sengon (43.3 mg) were not different from each other, and both weights were smaller than mangium. Pine belonged to coniferous wood and having the highest wood density, these factors might be affecting as pine could retain the precipitated smoke more than the other species.

Regarding the smoking period, 2- and 3-week smoking periods were not different from each other, but these periods were different from the 1 week period. Even though 2- and 3-week smoking periods were not different, but the 2-week period had a smaller precipitated smoke, it could be happened because of the wood specimen position in the chamber during smoke treatment, and also it was an indication that the 2-week smoke was optimal for the smoke to precipitate. Furthermore, 1-week smoking period had the lowest amount of the precipitated smoke and the wood color was less dark compared the other smoking periods. If we look at the relationship between wood color (L^*, a^*, b^*) and the weight of precipitated smoke (y), the regressions of each wood species and all species are figured in Table 10.

In all regressions, the lightness (L^*) with negative value of a constant significantly affected the weight of the precipitated smoke, and the interpretation from these regressions could be mentioned that a darker wood color or lower L^* value had a higher weight of precipitated smoke (y). In jabon and sengon the constants of L^* were smaller than pine and mangium, which means that for a certain increment of precipitated smoke weight, the degradation of darker color in jabon and sengon was smaller compared to the other wood species. Jabon and sengon had lower wood densities compared to the wood species, and also a smaller amount of precipitated smoke weights, so the darkness changes were also less than other species.

Regarding the above regressions, the darker color had more precipitated smoke weight, and it could be presumed that the wood had better resistance to the termite attack because more chemicals could enhance the wood resistance. Concerning this observation, there could be a correlation between the color of the wood (L^*, a^*, b^*) and its resistance to termite attack which is represented by the percent wood weight loss (y), and the regressions of each color and color change are shown in Table 11.

Table 10 Relation between wood color (L^*, a^*, b^*) and precipitated smoke weight (y)

No.	Wood species	Regression	R^2
1.	Sengon	$y = 79.952 - 1.069L^*$ (**) $- 0.870a^* + 0.427b^*$	0.898
2.	Jabon	$y = 99.779 - 0.633L^*$ (**) $+ 1.714a^* - 2.271b^*$ (**)	0.970
3.	Mangium	$y = 137.787 - 2.642L^*$ (**) $+ 0.686a^* + 0.747b^*$	0.899
4.	Pine	$y = 180.924 - 2.357L^*$ (*) $+ 1.413a^* - 0.440b^*$	0.743
5.	All species	$y = 111.537 - 1.520L^*$ (**) $+ 2.152a^* - 0.502b^*$	0.573

y = weight of precipitated smoke; L^*, a^*, and b^* are representing color; (**) highly significant ($p \leq 0.01$); R^2 = determination coefficient

Table 11 Relation between wood color (L^*, a^*, b^*) and percent wood weight loss (y)

No.	Wood color	Regression	R^2
1.	*L*	$y = -2.035 + 0.289L^*$ (**)	0.560
2.	*a*	$y = 22.030 - 1.825a^*$ (**)	0.135
3.	*b*	$y = 1.413 + 0.543b^*$ (**)	0.176
4.	*L, a, b*	$y = 1.261 + 0.327L^*$ (**) $- 0.227a^* - 0.209b^*$	0.582
5.	ΔE	$y = 6.515 + 0.026\Delta E$ (ns)	0.09

y = percent wood weight loss; L^*, a^*, and b^* are representing color; (**) highly significant ($p \leq 0.01$); ns = not significantly different ($p \leq 0.05$); R^2 = determination coefficient

Referring to Table 11, the highest correlation coefficient (R^2, 0.582) was the three colors together (L^*, a^* and b^*) predicting the percent wood weight loss, but in that correlation the colors of a^* and b^* were not significant. For simplifier prediction, the lightness (L^*) could be used to predict percent wood weight loss, because this regression had a little lesser correlation coefficient (R^2, 0.56) than all colors. In terms of L^* only as prediction factor, from that regression could be predicted that a lighter wood color or higher L^* value resulting a higher percent wood weight loss or the wood was less resistant to termite attack.

Conclusion

We conclude that the predominant chemical compounds of kesambi liquid smoke are acetic acid, phenol, ketone, amine, and benzene. Smoke treatment caused wood color to become darker, less yellow, and a little redder, while a longer smoking period produced a darker color which was more resistant to termite attack. Smoke treatment enhanced wood resistance to subterranean termite attack, and the improvement was 1.7 classes higher from untreated wood for all smoking periods (1, 2, and 3 weeks).

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Authors' contributions
YSH contributed to conceptualization, writing the manuscript, supervision, and funding acquisition. MYM contributed to validation and supervision. DN contributed design methodology and supervision. WOMA and IBA contributed to formal analysis, data curation, reviewing and editing manuscript. LS, YA contributed to research material procurement. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate
All authors agree that the manuscript is submitted to *Journal of Wood Science*, and we will follow the rule that the journal decided.

Consent for publication
This manuscript was carried out to out-break for inferior properties of fast-growing wood species that cut at young age (mostly less than 10 years), especially in bio-deterioration attack. The subterranean termite very severely attacks wooden construction and causes huge amount of economic loss.Manufacturing of charcoal is still conducted and the smoke is away to the air. This research tries to utilize smoke for wood preservation. In other sectors, especially fishery and meat processing, the smoke is already used intensively.We hope the manuscript will pursue in the future perspective as one choice in the preservation subject.

Competing interests
The authors declare that they have no conflict of interest.

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