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Evaluation of Discoloration and Subterranean Termite Resistance of Four Furfurylated Tropical Wood Species after One-Year Outdoor Exposure

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Abstract: The discoloration and resistance to subterranean termite attack of four furfurylated fast-growing tropical wood species were evaluated after outdoor exposure for 1 year in Bogor, Indonesia. For comparison purposes, imidacloprid-preserved and untreated wood samples were also prepared. Discoloration of all treated samples was measured before and after the furfurylation process. The wood specimens were then placed vertically to three-fourths of their length in the ground for 1 year, at which point they were evaluated for resistance to subterranean termite attack. After furfurylation, wood samples were darker in color than untreated wood, while imidacloprid-preserved wood was lighter. After 1-year exposure, furfurylated wood samples appeared to have the highest resistance to subterranean termite attack. These samples had minimal weight loss, indicating a substantial protection level. Imidacloprid-preserved wood had less resistance to termite attack, but was more resistant than untreated wood.

Keywords: discoloration; furfurylation; subterranean termite; weight loss; wood protection level

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1. Introduction

Since 2000, log production in Indonesia has mostly been based on harvesting from plantation forests. In 2019, the wood industry was supplied with 57.9 million m^3 of logs, with more than 85% coming from plantation forests, including 32.6 million m^3 of mangium (*Acacia mangium*), 9.0 million m^3 of eucalypt (*Eucalyptus* spp.), and 5.4 million m^3 sengon (*Falcataria moluccana*) [1]. Mangium, sengon, jabon (*Anthocephalus cadamba*), and pine (*Pinus merkusii*) represent the most common fast-growing plantation species. The trees are cut from young-age stands, mostly less than 10 years old, and the timber has a high portion of juvenile wood. Consequently, it has inferior physical-mechanical properties and is susceptible to wood-destroying organisms, especially termites [2].

As a building material, wood needs to have a long service life, but the timber available on the market is mostly from fast-growing wood species, which are prone to termite attack. The economic losses due to termite damage of wooden buildings in Indonesia has been estimated to reach USD 1 billion per annum [3]. If wood currently on the market is to be used for buildings, it has to be preserved beforehand to obtain a longer service life. Wood preservatives are commonly used in the industry, but they pollute the environment and carry the risk of toxicity for living organisms. To reduce or eliminate these adverse effects, methods based on chemical modification of the wood, including furfurylation, have been developed.

Furfurylation involves the use of furfuryl alcohol (FA) and a catalyst that is used under specific conditions of temperature and curing time to accelerate the polymerization

process [4]. FA can fill the void space in wood and chemically bond to the wood tissue after polymerization, which may change the color of the wood [5]. Various types of catalysts were investigated in previous studies, including citric acid [6], maleic anhydride [5], and tartaric acid [7]. FA is a nontoxic alternative chemical for use in the chemical modification of wood that subsequently has high resistance to decay in laboratory tests [7]. In a 1-year subterranean termite field test, furfurylated specimens of *Pinus sylvestris*, *Agathis dammara*, and sengon with 40% or more weight percent gain had high resistance to termite attack [8]. For Brazilian pine wood, FA, polystyrene, or methyl methacrylate impregnation also enhanced resistance to termite attack [9]. Studies using Indonesian fast-growing tropical wood species showed that furfurylated wood with tartaric acid as the catalyst had better resistance than untreated wood and imidacloprid-preserved wood in 12-week field tests [10] as well as in laboratory tests [11].

Two types of furfurylated wood, Kebony pine (*Pinus Sylvestris* L.) and Kebony beech (*Fagus sylvatica* L.), had excellent resistance to *Teredo navalis* marine borer attack and demonstrated slight or no damage after 16 years of field exposure [12]. In another study, acetylated composite board was tested through ground contact (graveyard test) in seven fields located around the world on four continents (United States, New Zealand, Indonesia, and Sweden); the specimens showed excellent protection against fungal and termite attacks after 3 years of testing [13]. Furthermore, another type of acetylated wood, Accoya wood, underwent 10 years of ground contact testing in central Greece. The specimens with 20% acetyl weight gain were completely free of visible decay; however, the modulus of elasticity and modulus of rupture were significantly reduced by 32.8% and 29.6%, respectively [14]. A different experiment in western Greece tested stakes made from oriented strand board with two levels of acetylation. In that study, ground contact led to total degradation of samples with 11.2% acetyl content in 72 months and for those with 20.4% acetyl content in 102 months [15].

Outdoor exposure for a long period of time can affect wood properties. In spruce cladding panels in Norway, new carbonyl structures and oxidized lignin were detected after 2 years of exposure to natural weathering [16], while 6 years of outdoor exposure showed that brown, white, and soft rot fungi dominated the organisms attacking wooden material specimens in Europe [17]. Another work reported that European beech wood, which was impregnated with polyglycerol maleate and then heat treated, was extremely resistant to termite attack after almost 1 year of field exposure in Bogor, Indonesia [18].

The color of wood is also a matter of importance to buyers in the market. In Slovakia, for example, a greater supply of wood with natural color and color tones of gray, white, and brown is needed [19]. Some treatments can cause discoloration of the wood, typically making it darker. Heat treatment was found to make wood darker as well as to cause chemical changes [20]. Smoking treatment also made wood darker, with a long smoking period resulting in a much darker color [21]. In one study, the color of wood varied through 1–3 weeks of smoking treatment. At 3 weeks, it became a much darker color than the untreated wood; however, it was also much more resistant to subterranean termite attack [22].

Both furfurylation and preservation with imidacloprid can affect wood color and resistance to termite attack. There is currently very little information on how furfurylation with tartaric acid used as the catalyst affects termite resistance of tropical wood species in field tests for long periods of time. Therefore, this study evaluated furfurylated wood resistance to subterranean termite attack after 1 year of exposure in the field and compared results with those from imidacloprid-preserved and untreated wood specimens undergoing the same tests. Discoloration of the samples was also measured following the treatments.

2. Materials and Methods

2.1. Materials

Small logs with less than 20-cm diameter of sengon (*Falcataria moluccana*), jabon, mangium, and pine (*P. merkusii*) wood were harvested in Bogor, Indonesia. Wood specimens

that were 2 cm × 0.8 cm × 20 cm (width, thickness, and length, respectively) were kiln-dried to reach 12% moisture content (MC) [23], weighed, and then vacuumed at 0.80 bars for 30 min in a tank. For the impregnation process, tartaric acid as catalyst was added to FA (1:20; *v/v*), and the solution was inserted into the tank when the vacuum was released. Afterward, pressure at 9.81 bars was applied for 30 min.

Following the impregnation process, each wood specimen was wrapped with aluminum foil and then put in the oven at 100 °C for 24 h. The foil was then removed, and the specimen was weighed to calculate polymer loading. Conditioning of the specimens was conducted at room temperature for 3 weeks. For comparison purposes, untreated (control) and imidacloprid-preserved wood specimens were also prepared. For imidacloprid preservation, a 3% imidacloprid solution was used in the same vacuum-pressure treatment as described for wood furfurylation. Ten replications of test samples were done for each wood species and treatment combination.

To identify chemical molecules in the jabon wood before and after furfurylation, also after 1-year outdoor exposure, pyrolysis gas chromatography-mass spectrometry (Py-GCMS; Shimadzu® GCMS-QP2010) was used. Energy dispersive X-ray detector (EDX) analyses (Zeiss evo 50 Bruker 133 eV) were also carried out to identify the different chemical components in the wood before and after the exposure. The other collected data were weight percent gain (WPG), retention, density, and MC, with the MC calculation following Thybring [24].

2.2. Discoloration Determination of the Samples

Color for all wood specimens was determined according to the CIELab method by measuring L* (lightness), a* (red to green), and b* (blue to yellow) values [25], and using a scanner machine (CanoScan 4400F) and the Adobe Photoshop CS5 application. The color change of wood specimens was also calculated by referring to CIELab, while classification was according to Hunter Lab [26] and Hrčková et al. [27].

2.3. Termite Resistance of the Samples

A 1-year field test was carried out in an arboretum of IPB University, Bogor, Indonesia. Bogor has a tropical climate with an average total rainfall of 4617 mm·year^{-1} and an average rainfall of 14.4 mm·day^{-1} (range, 0–140 mm·day^{-1}). The average relative humidity (RH) is 84% (range, 65%–95%), average temperature is 26.4 °C (range, 24.2–28.6 °C), and average amount of sunlight is 5.4 h·day^{-1} (range, 0.0–10.6 h·day^{-1}) [28]. An ombrothermic diagram during the test period is shown in Figure 1.

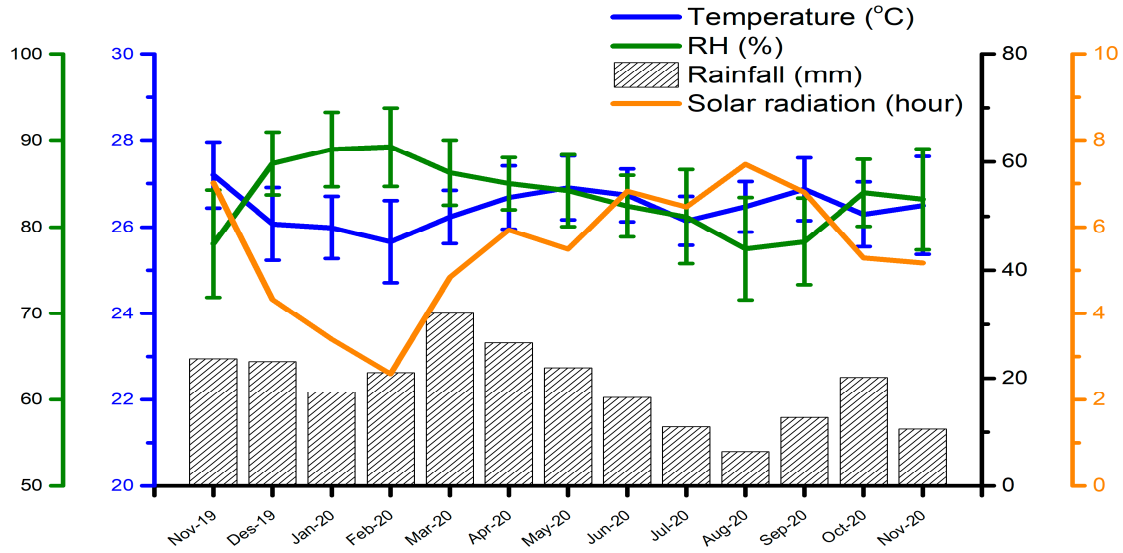


Figure 1. Ombrothermic diagram of the test site.

Each wood specimen was vertically inserted to three-fourths of its length into the ground in a 1-year graveyard test. The conditions of the test location are shown in Figure 2. After 1 year, the weight loss percentage [29] of each specimen and its protection level against subterranean termite attack [30] were determined. The protection level values varied from 0 to 10, where lower values meant less resistance to termite attack.



(a) **(b)**

Figure 2. Subterranean termite field test in the beginning (**a**) and at the end (**b**) of 1-year of exposure.

2.4. Analysis of the Data

The data were analyzed in a completely randomized block design using two factors, wood species and treatment. The wood species as a block factor consisted of sengon, jabon, mangium, and pine, while the factor of treatment consisted of untreated wood (control), imidacloprid-preserved wood, and furfurylated wood. Duncan's multiple range test was carried out for further analysis when the main factor was significantly different at $p \leq 0.05$.

3. Results and Discussion

3.1. Furfurylation of the Samples

The results from Py-GCMS are presented in Tables 1 and 2 for untreated and furfurylated jabon woods, respectively. Based on the findings, the furfurylated wood contained new chemical compounds, such as methyl furfuryl compounds, in some peak numbers. The compounds were likely created through reactions between FA and wood components, especially lignin [30]. Furthermore, Gérardin [31] reported that FA molecules could polymerize with each other and generate poly-furfural or poly-furfurylated compounds that fill the void space and bind to the cell wall. These compounds could affect the weight gain and color change of wood.

The density of each wood species according to treatment is shown in Figure 3. The variance analysis is summarized in Table 3, and the results of Duncan's multiple range test are presented in Table 4. Based on the variance analysis, wood density varied by wood species and treatment. Sengon and jabon wood were classified as low-density woods, while mangium and pine wood were medium-density woods. In terms of the treatment, furfurylation significantly increased the wood density, with the average weight percent gain of all wood species reaching 49.1%, and retention reaching 9.9 kg·m^{-3} (0.01 g·cm^{-3}). The density of furfurylated wood was the highest, and it was significantly different from untreated and imidacloprid-preserved woods. However, the two latter types of wood were not different from each other based on the small density increment (0.01 g·cm^{-3} only) of imidacloprid-preserved wood compared with untreated wood.

Table 1. Chemical compounds in untreated jabon based on Py-GCMS.

Peak no.	Retention Time (min)	Conc.% rel	Name	Chemical American Standard
1	4.011	8.72	Carbamic acid, monoammonium salt	Ammonium carbamate
2	5.465	0.53	2,3-Pentanedione	2,3-Pentadione
3	6.049	11.70	Acetic acid	Ethylic acid
4	6.669	3.74	2-Propanone, 1-hydroxy-	Acetol
5	8.584	2.84	2-Propanone, 1-hydroxy-	Acetol
6	9.007	2.76	2-Propanone	Acetone
7	11.954	4.36	Cyclohexanone	Hexanon
8	13.521	1.31	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	Corylone (Hydroxy methyl furfural)
9	14.045	2.13	Phenol, 2-methoxy-	Guaiacol
10	14.158	2.06	n-Valeric anhydride	Pentanoic anhydride
11	14.400	9.71	Cyclopropyl carbinol	
12	15.190	2.12	2-Methoxy-4-methylphenol	4-Methyl guaiacol
13	15.824	1.18	2-(2′-Nitro-2′-propenyl)-1-cyclohexanone	
15	16.450	6.32	3-Methoxyacetophenone	
16	16.802	5.22	Phenol, 2,6-dimethoxy-	2,6-Dimethoxyphenol
17	17.279	1.08	Phenol, 2-methoxy-4-(1-propenyl)-	Isoeugenol
18	17.659	5.39	3-Acetylpyridine-*N*-oxide	
20	18.241	0.93	Benzene, 1,2,3-trimethoxy-5-methyl-	Toluene, 3,4,5-trimethoxy-
21	18.518	0.72	2-Propanone, 1-(4-hydroxy-3-methoxyphenyl)-	1-(4-hydroxy-3-methoxy-phenyl)
22	18.607	6.74	Phenol, (1,1-dimethylethyl)-4-methoxy-	Butylated hydroxyanisole
23	18.834	3.39	Phenol, 2,6-dimethoxy-4-(2-propenyl)-	4-Allyl-2,6-dimethoxyphenol
24	19.274	0.42	Phenol, 2,6-dimethoxy-4-(2-propenyl)-	4-Allyl-2,6-dimethoxyphenol
25	19.658	5.84	Phenol, 2,6-dimethoxy-4-(2-propenyl)-	4-Allyl-2,6-dimethoxyphenol
26	20.119	0.90	Ethanone, 1-(4-hydroxy-3,5-dimethoxyphenyl)-	Acetosyringone
27	20.296	1.59	2,4-Hexadienedioic acid, 3,4-diethyl-, dimethyl ester	
28	20.363	3.30	3-(p-hydroxy-*m*-methoxyphenyl)-2-propenal	
29	21.199	0.66	Hexadecanoic acid	Palmitic acid
30	22.061	1.50	3-(3′,5′-dimethoxy-4′-hydroxyphenyl)-E-2-propenal	

Table 2. Chemical compounds in furfurylated jabon based on Py-GCMS.

Peak#	Retention Time (min)	Conc.% rel	Name	Chemical American Standard
1	5.862	2.69	Acetic acid	Ethylic acid
2	11.910	3.87	Cyclohexanone	Hexanon
4	13.453	1.41	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	Corylone (Hydroxy methyl furfural)
5	**13.628**	**1.25**	**Furan, 2,2′-methylenebis-**	**2-Furfurylfuran**
6	14.008	1.00	Phenol, 2-methoxy-	Guaiacol
8	**14.713**	**7.20**	**Furan, 2-(2-furanylmethyl)-5-methyl-**	**5-METHYL-2-FURFURYLFURAN**
9	15.142	2.54	2-Methoxy-4-methylphenol	**5-METHYL-2-(5′-METHYL-2′-URFURYLFURAN**
10	**15.688**	**3.67**	**Furan, 2,2′-methylenebis [5-methyl-**	**5-METHYL-2-(5′-METHYL-2′-FURFURYL)FURAN**
11	16.009	0.91	Phenol, 4-ethyl-2-methoxy-	p-Ethylguaiacol
12	**16.100**	**1.57**	**Furan, 2,2′-[oxybis(methylene)]bis-**	**Difurfuryl ether**
13	16.433	4.19	Phenol, 2-methyl-5-(1-methylethyl)-	Carvacrol
14	16.781	4.41	Phenol, 2,6-dimethoxy-	2,6-Dimethoxyphenol
15	**17.206**	**2.78**	**2(5H)-Furanone, 5-(2-furanylmethyl)-5-methyl-**	**4-FURFURYL-2- PENTENOIC ACID- γ-lactone**
16	17.484	0.89	2-Furanmethanol, acetate	Furfuryl acetate
17	17.579	2.48	Benzene, 1,2,3-trimethoxy-	1,2,3-Trimethoxybenzene (CAS) Methylsyri
18	17.634	3.08	Phenol, 2-methoxy-4-(2-propenyl)-	Eugenol
19	**18.075**	**0.58**	**Cyclohexanone, 6-furfurylidene-2,2-dimethyl-**	**2-FURFURYLIDENE-6,6-DIMETHYLCYCLOHEXANONE**
20	18.213	2.35	Benzene, 1,2,3-trimethoxy-5-methyl-	Toluene, 3,4,5-trimethoxy-
22	18.604	3.60	Phenol, (1,1-dimethylethyl)-4-methoxy-	Butylated hydroxyanisole
23	**18.717**	**0.70**	**Furan, 2,2′-methylenebis[5 -methyl-**	**5-METHYL-2-(5′-METHYL-2′-FURFURYLFURAN**
24	18.829	5.06	1-(P-TOLUIDINO)-1-DEOXY-B-D-IDOPYRANOSE	
25	**19.082**	**2.04**	**Furan, 2,5-bis(2-furanylmethyl)-**	**2,5-Difurfurylfuran**
26	19.638	4.00	Phenol, 2,6-dimethoxy-4-(2-propenyl)-	4-Allyl-2,6-dimethoxyphenol
27	**19.721**	**5.50**	**Furan, 2-(2-furanylmethyl)-5-methyl-**	**5-METHYL-2-FURFURYLFURAN**
28	20.095	0.86	Ethanone, 1-(4-hydroxy-3,5-dimethoxyphenyl)-	Acetosyringone
29	**20.313**	**4.09**	**Furan, 2,2′-methylenebis[5-methyl-**	**5-METHYL-2-(5′-METHYL-2′-FURFURYLFURAN**
30	20.694	1.27	Cyclohexene, 3-(2-propynyl)- (	3-(2-PROPYNYL)CYCLOHEXENE
31	21.182	0.73	Octadecanoic acid	Stearic acid
33	22.032	1.83	3-(3′,5′-dimethoxy-4′-hydroxyphenyl)-E-2-propenal	
34	22.232	0.75	1-Acetyl-3-methylenecyclopentane	
35	**23.232**	**4.77**	**Furan, 2,5-bis(2-furanylmethyl)-**	**2,5-Difurfurylfuran**
36	**23.881**	**3.40**	**Furan, 2-(2-furanylmethyl)-5-methyl-**	**5-METHYL-2-FURFURYLFURAN**
37	**24.584**	**0.71**	**Furan, 2,2′-methylenebis[5-methyl-**	**5-METHYL-2-(5′-METHYL-2′-FURFURYLFURAN**
38	24.964	0.77	BENZENEMETHANOL, α-1-PENTYNYL-	
39	25.260	0.64	CYCLOHEXENE, 1-BROMO-	

Remarks: Bold letters refer to compounds from furfurylation.

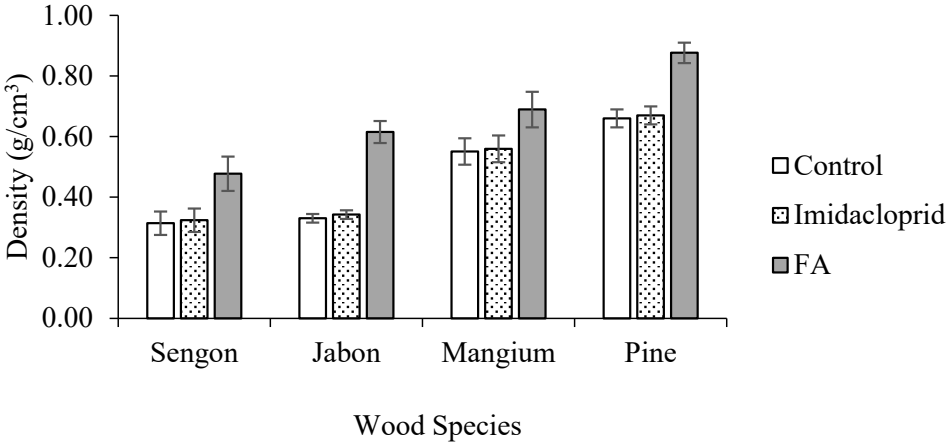


Figure 3. The density of each wood specimen according to treatment.

Table 3. Variance analysis summary of density, WPG, retention, and MC.

Parameter	Density	Retention	WPG	MC
Wood species	**	**	**	**
Treatment	**	-	-	**

Remarks: ** Highly significantly different ($p \leq 0.01$); ns = not significantly different; WPG is weight percent gain; MC is moisture content.

Table 4. Duncan's multiple range test of density, WPG, retention, and MC.

Parameter	Sengon	Jabon	Mangium	Pine	Untreated	Imidacloprid	FA
Density	a	b	c	d	e	e	f
Retention	b	c	a	a	—	—	—
Weight% gain	c	d	a	b	—	—	—
MC	a	b	ab	a	f	f	e

Remarks: Cells in a row with the same letter are not significantly different; FA is furfurylated wood.

Retention and the weight percent gain (WPG) values of each wood species are shown in Figure 4. According to the variance analysis, retention and WPG were affected by wood species. Mangium and pine wood had smaller retention and WPG values than the other two wood species. Untreated mangium and pine wood had higher densities, implying less void space and more cell wall components, consequently these types of wood had lower preservative retention and WPG than sengon and jabon. These results were in line with Hadi et al. [32]. Nevertheless, the level of preservative retention was satisfactory in all wood samples; that is, it was more than 8 kg·m^{-3} and fulfilled the Indonesian standard, which requires 8–14 kg·m^{-3} [33]. Sengon wood had lower retention and WPG than jabon wood, despite having lower density. This finding could be attributed to sengon wood having an interlocked grain [34]. Furthermore, sengon heartwood was previously found to contain 19.6% extractive substances soluble in NaOH, including carbohydrate derivatives (glucose, ribose, xylose, cellobiose, oligosaccharide, arabinose, and pentasaccharide), and long-chain fatty acids (myristic acid, capriate, pentadecylic acid, myristoleic acid, palmitic acid, stearic acid, margaric acid, linoleic acid, oleic acid, and arachidonic acid) [35].

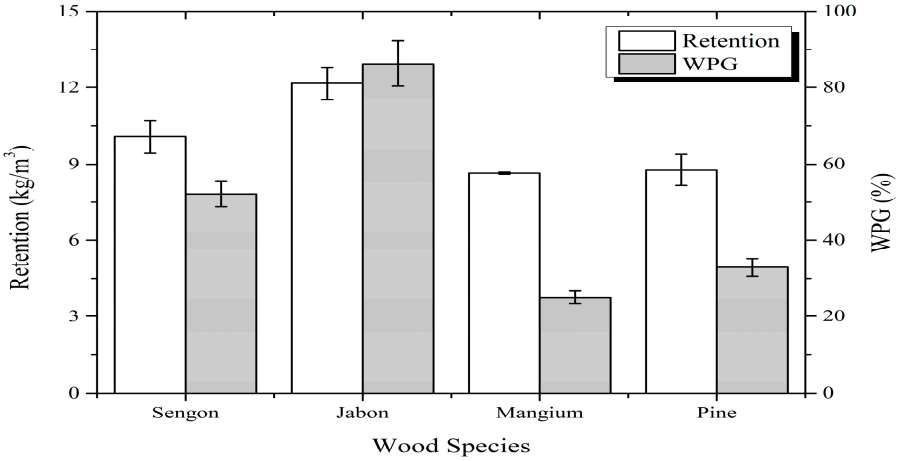


Figure 4. Retention and WPG of each species according to treatment.

The moisture content (MC) of each type of wood specimen according to treatment is shown in Figure 5. The variance analysis presented in Table 3 showed that the MC of the wood was affected by the wood species as well as the treatment. The average MC of the four wood species varied between 8.59% and 9.35%, and for untreated woods, the range in average MC was between 11.19% and 12.61%. These values were not significantly different and were still in ambient moisture content in the Bogor area.

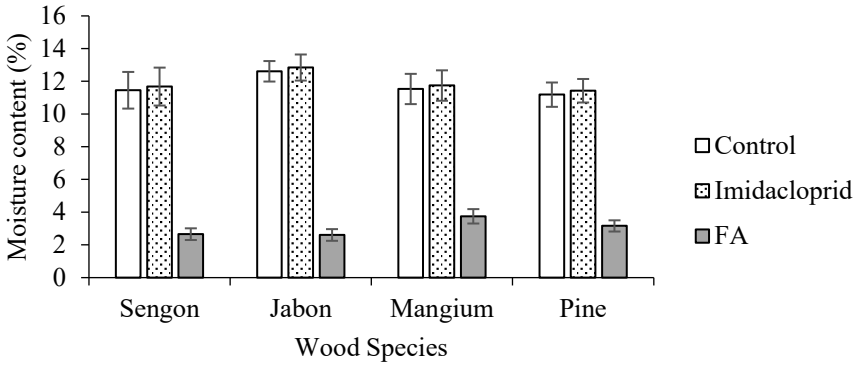


Figure 5. Moisture content of each wood species according to treatment.

The MC values of untreated and imidacloprid-preserved wood did not differ from each other, but they were different from furfurylated wood, which had very low MC. In addition to furfurylated wood having poly-FA in the void, FA could also react with wood components, especially lignin, leading to a reduction of hydroxyl compounds and creating methyl furfuryl. These changes could cause the wood to become more hydrophobic [31]. These outcomes were in line with other works reporting that furfurylated wood had a much lower MC and its equilibrium MC decreased by 40% compared with untreated wood [11,36].

3.2. Discoloration of Wood Specimens

Wood color was measured before and after the furfurylation process based on ColorHexa [37]. Wood colors are indicated quantitatively with L*, a*, and b* values, while discoloration is indicated by ΔE [37]. The values of all wood species according to treatment before and after furfurylation are presented in Table 5.

Table 5. The color of untreated and treated wood samples.

Wood sp.	Treatment	Color			ΔE
		L*	a*	b*	
Sengon	Untreated	81.2 (0.8)	5.8 (0.8)	18.2 (1.8)	
	Imidacloprid	90.7 (2.2)	3.7 (0.6)	9.0 (1.2)	13.5 (3.3)
	Furfurylated	56.2 (2.2)	8.5 (0.9)	11.1 (2.2)	26.2 (2.5)
Jabon	Untreated	82.4 (1.4)	1.6 (0.5)	24.2 (2.3)	
	Imidacloprid	87.4 (3.4)	4.3 (0.7)	15.6 (2.8)	10.7 (4.3)
	Furfurylated	54.3 (2.2)	7.7 (0.9)	6.8 (1.6)	33.7 (2.9)
Mangium	Untreated	50.8 (3.7)	5.6 (0.8)	26.4 (2.7)	
	Imidacloprid	73.9 (3.2)	6.0 (1.0)	16.8 (1.7)	25.3 (4.7)
	Furfurylated	60.0 (3.0)	7.8 (1.6)	11.8 (4.5)	18.5 (3.1)
Pine	Untreated	77.4 (3.6)	7.0 (0.9)	33.2 (2.4)	
	Imidacloprid	86.4 (1.6)	5.8 (0.7)	16.8 (2.4)	18.9 (4.3)
	Furfurylated	59.1 (1.6)	7.3 (1.2)	6.9 (2.2)	32.3 (3.6)
Total	Untreated	72.9 (13.3)	5.0 (2.1)	25.5 (5.8)	
	Imidacloprid	84.6 (6.9)	4.9 (1.2)	14.5 (3.9)	17.1 (6.9)
	Furfurylated	57.4 (3.2)	7.8 (1.2)	9.2 (3.5)	27.7 (6.7)

Remarks: Values in parentheses are standard deviations; L* is lightness, a* is red to green, and b* is blue to yellow.

Color characteristics of untreated wood in this study were similar to those in a previous study [21]. Table 5 shows that the furfurylated wood had lower values for L* and b* compared with the untreated wood. The L* value was decreased after the furfurylation process, but the inverse happened with the imidacloprid preservation process. The increased lightness after perseveration using imidacloprid was similar to Hadi et al. [22]. The color of wood specimens after 1-year test for each wood species and treatment is shown in Figure 6.

According to the variance analysis shown in Table 6, the wood species and treatment affected the values of L*, a*, and b*. Based on the Duncan's multiple range test presented in Table 7, mangium had the darkest color compared with the other three wood species, while sengon wood had more green and blue than the other woods. With regard to the treatment factor, furfurylated wood had the darkest color, as well as more red and blue, compared with untreated and imidacloprid-preserved woods, while imidacloprid-preserved wood was lighter and had more blue compared with untreated wood.

Table 6. Variance analysis summary of wood discoloration after furfurylation.

Factor	L*	a*	b*	ΔE
Wood species	**	**	**	ns
Treatment	**	**	**	**

Remarks: ** Highly significantly different ($p \leq 0.01$); ns = not significantly different. L* is lightness, a* is red to green, and b* is blue to yellow.



Figure 6. Wood specimens after 1-year of exposure in the field.

Table 7. Duncan's multiple range test for color values after furfurylation.

Parameter	Sengon	Jabon	Mangium	Pine	Untreated	Imidacloprid	FA
L*	b	b	a	b	d	e	c
a*	a	b	b	b	c	c	d
b*	a	b	c	c	f	e	d
ΔE	a	a	a	a	—	b	c

Remarks: Cells in a row with the same letter are not significantly different.

Furfurylated wood specimens had the lowest L* value, indicating that they had the darkest color. According to the results of py-GCMS in Table 8 and those of the EDX analysis in Table 9, the furfurylated samples contained the element bromine that could cause a darker color. The discoloration of furfurylated wood was in line with findings from previous work, which stated that furfurylated wood is characterized by a darker color than untreated wood [11].

Table 8. Chemical compounds in furfurylated jabon after 1 year test based on Py-GCMS.

Peak no.	Retention Time (min)	Conc.%rel	Name	Chemical American Standard
1	**3.900**	**3.62**	**Cyclopropane, 1,1-dibromo-2-chloro-2-fluoro-**	**1,1-DIBROMO-2-CHLOR-2-FLUORO**
2	5.477	1.29	4H-Pyran-4-one, 2,6-dimethyl-	2,6-Dimethyl-4-pyrone
3	6.248	1.12	Acetic acid	Ethylic acid
4	8.692	0.83	2-Propanone, 1-hydroxy-	Acetol
5	9.036	1.09	Propanoic acid, 2-oxo-, methyl ester	Methyl pyruvate
6	9.442	1.37	3-METHOXYBUTA-1,2-DIENE	3-Methoxy-1,2-butadiene
7	11.831	2.50	2-Furanmethanol	Furfuryl alcohol
8	12.375	1.03	Pyrazine, methoxy-	2-Methoxypyrazine
9	12.742	0.81	3-Cyclobutene-1,2-dione, 3,4-dihydroxy-	Squaric acid
10	13.092	0.47	3-Acetoxypyridine	3-Pyridinol,acetate
11	13.246	0.82	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	Corylon
12	13.416	1.21	Furan, 2,2′-methylenebis-	2-Furfurylfuran
13	13.777	1.42	1,5-Hexadiene-3,4-diol, 3,4-dimethyl-	
14	13.947	0.98	Oxirane, (2-methylpropyl)-	1,2-Epoxy-4-methylpentane
15	14.225	3.31	Acetic acid, heptyl ester	n-Heptyl acetate
16	14.475	3.63	Furan, 2-(2-furanylmethyl)-5-methyl-	5-METHYL-2-FURFURYLFURAN
17	14.748	0.82	4H-Pyran-4-one, 2,3-dihydro-3,5-dihydroxy-6-methyl	3,5-DIHYDROXY-2-METHYL-5,6 PYRAN
18	14.878	2.51	2-Methoxy-4-methylphenol	
19	15.121	2.73	1-Octene	Caprylene
20	15.440	4.50	Furan, 2,2′-methylenebis[5-methyl-	(5-METHYL-2-(5′-METHYL-2′-FURFURYL)FURAN
21	15.749	1.60	Phenol, 4-ethyl-2-methoxy-	p-Ethylguaiacol
22	15.873	2.13	2-Furancarboxaldehyde, 5-(hydroxymethyl)-	5-Oxymethylfurfurol
23	16.177	2.97	Ethanone, 1-(2-hydroxy-5-methylphenyl)-	1-Hydroxy-2-acetyl-4-methyl
24	16.545	2.11	Phenol, 2,6-dimethoxy-	2,6-Dimethoxyphenol
25	16.675	1.98	3-Heptanol	3-Hydroxyheptane
26	16.937	1.24	Ethanone, 1-[5-[(5-methyl-2-furanyl)methyl]-2-furanyl]-	5-ACETYL-2-FURFURYL-(5′METHYL
27	17.321	5.98	4-Methoxy-3-(methoxymethyl)phenol	
28	17.691	1.15	4,5-Heptadien-2-one, 3,3,6-trimethyl-	
29	17.817	1.10	GERMACRENE-D	
30	17.962	2.13	Benzene, 1,2,3-trimethoxy-5-methyl-	Toluene, 3,4,5-trimethoxy-
31	18.232	1.59	2-Propanone, 1-(4-hydroxy-3-methoxyphenyl)-	1-4-HYDROXY-3-METHOXY-PHENYL
32	18.361	2.26	4-METHYL-2,5-DIMETHOXYBENZALDEHYDE	
33	18.593	6.51	CYCLOPROPANEMETHANOL, DIMETHYL-2-METHYLEN α.	
34	18.825	7.57	Furan, 2,5-bis(2-furanylmethyl)-	2,5-Difurfurylfuran
35	18.994	10.14	1,6-ANHYDRO-β-D-GLUCOPYRANOSE (LEVOGLUCOSAN)	
36	19.408	3.98	Phenol, 2,6-dimethoxy-4-(2-propenyl)-	4-Allyl-2,6-dimethoxyphenol
37	19.525	0.88	Androst-5-ene-3,19-diol, 3-acetate, (3. β.)-	
38	19.846	1.71	Ethanone, 1-(4-hydroxy-3,5-dimethoxyphenyl)-	Acetosyringone
39	20.058	2.02	2H-FURAN-2-ON, 3-CYCLOHEXYLIDEN-5-(4-HEPTANOYLOXYPHENYL)	
40	20.173	0.67	(+,−)-9-(3,5-dinitrobenzoyloxy)-2,3,6,7-tetramethyl-1,4,4.alpha.,5,8,8a. α.9.	
41	20.414	0.68	Ethanone, 1-(4-hydroxy-3,5-dimethoxyphenyl)-	Acetosyringone
42	20.608	0.26	Androst-5-en-7-one, 3-(acetyloxy)-, (3. β.)-	Androst-5-en-7-one

Table 8. *Cont.*

Peak no.	Retention Time (min)	Conc.%rel	Name	Chemical American Standard
43	20.930	0.98	Hexadecanoic acid	Palmitic acid
44	21.389	0.40	SPIRO[7H-BENZ[E]INDENE-7,1′-[2]CYCLOPENTENE]-4′,9(8H)-DIONE, 1,2,3	
45	21.558	0.32	5,9-Dimethyl-2-(1-methylethyl)-1-cyclodecanone	
46	21.780	0.48	3-(3′,5′-dimethoxy-4′-hydroxyphenyl)-E-2-propenal	
47	21.958	0.22	Estra-1,3,5(10)-trien-17-one, 3-methoxy-	Estrone methyl ether
48	22.924	0.26	N′-[1-(4-AMINOPHENYL)ETHYLIDENE]-2-(2-CYANOPHENOXY)ACETHYDR	
49	23.938	0.18	Murrialongin	
50	24.154	0.46	9-Octadecenamide, (Z)-	OLEOAMIDE

Remarks: Bold letter refers to Brom compound.

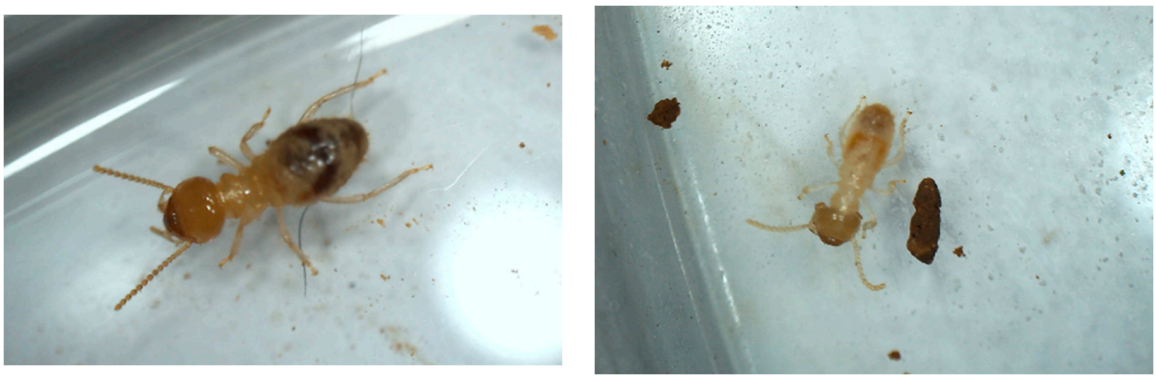
Table 9. Chemical content of jabon wood according to EDX analysis.

Chemical Content	Before Exposure			After Exposure		
	Untreated	Imidacloprid	FA	Untreated	Imidacloprid	FA
Oxygen	55.26	44.72	47.48	47.79	47.90	47.26
Carbon	43.27	33.95	46.92	48.40	28.43	46.78
Nitrogen	1.48	16.73	2.94	1.90		2.91
Aluminum			1.95	1.90	7.90	1.49
Bromine			0.70			1.55
Chlorine		3.01				
Silicon					5.94	
Fluorine					9.82	
Sodium		1.58				

Regarding the color change classification, the treated wood samples were different colors that the untreated wood, which were indicated by the ΔE value of imidacloprid-preserved wood being 17.1 and that of furfurylated wood being 27.7. According to Table 6, the color change was significantly affected by the treatment, but not by the wood species.

3.3. Weight Loss

Representative termites that attacked wood specimens during the field test are shown in Figure 7. The two species were identified as *Microtermes inspiratus* Kemner and *Coptotermes curvignathus* Holmgren.



(a) **(b)**

Figure 7. Subterranean termites found during the field test: *Microtermes inspiratus* Kemner (**a**) and *Coptotermes curvignathus* Holmgren (**b**).

The weight loss percentages of the wood specimens after 1-year of exposure in the field for each wood species according to treatment are presented in Table 10. The variance analysis in Table 11 shows that wood species and treatment significantly affected the weight loss of wood specimens. Jabon had the highest weight loss, indicating greater susceptibility to termite attack and poor resistance, which translates to the lowest class, V, with regard to the Indonesian standard [34]. According to the Duncan's multiple range test in Table 12, jabon differed from the other wood species, which did not differ from each other.

Table 10. Weight loss percentage of wood specimens.

Treatment	Wood Species			
	Sengon	Jabon	Mangium	Pine
Untreated	62.6 (30.3)	96.3 (6.9)	47.8 (28.0)	54.9 (23.2)
Imidacloprid	47.6 (30.3)	57.5 (21.0)	25.2 (11.3)	22.5 (16.9)
Furfurylated	2.6 (0.7)	2.8 (0.9)	9.9 (3.6)	5.5 (1.1)

Remarks: Values in parentheses are standard deviations.

Table 11. Variance analysis of weight loss percentage.

Source	Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	88,210.23	5	17,642.05	39.66	0.000
Intercept	163,297.27	1	163,297.27	367.13	0.000
Wood species	10,938.58	3	3646.19	8.20	0.000
Treatment	77,271.65	2	38,635.83	86.86	0.000
Error	50,706.78	114	444.80		
Total	302,214.29	120			

Table 12. Duncan's multiple range test of percent weight loss and protection level based on wood species and treatment.

Parameter		Weight Loss	Protection Level
Wood species	Sengon	37.6 a	6.0 ab
	Jabon	52.2 b	5.4 a
	Mangium	27.6 a	7.1 bc
	Pine	30.2 a	7.7 c
Treatment	Untreated	67.3 c	3.1 d
	Imidacloprid	38.2 d	7.2 e
	FA	5.2 e	9.3 f

Remarks: Values in a column followed by the same letter are not significantly different.

In terms of treatment, imidacloprid preservation and furfurylation appeared to enhance wood resistance to subterranean termite attack. This interpretation is supported by the weight loss (Table 12) of untreated wood being 67.3% compared with 38.2% for imidacloprid and 5.2% for furfurylated wood, or only 8% that of untreated wood. Both treatments effectively enhanced the wood resistance to subterranean termite after exposure for 1 year in the field.

In comparison with previous work [10], the furfurylated wood showed very consistent resistance to termite attack, as indicated by weight loss being 3.4% in the 3-month test and 5.2% in the 1-year test, an increase of about 1.5 times only. In comparison, imidacloprid-preserved wood had a weight loss of 6.6% at 3 months and 38.2% at 1 year (5.8 times), and untreated wood had a weight loss of 12.9% at 3 months and 65.4% at 1 year (5.1 times). Compared with previously reported findings, the furfurylated wood had similar resistance to subterranean termite attack as European beech wood that was impregnated with poly glycol-maleic anhydride and then heat treated [18].

3.4. Protection Level

Protection levels for each type of specimen are presented in Table 13 Analysis of variance results are summarized in Table 14, and Duncan's multiple range test outcomes are shown in Table 12. Wood species and treatment significantly affected the protection level. Further analysis showed that jabon had the lowest protection level (value of 5.4, refers to Table 12), which was significantly different from the other three wood species. Sengon, mangium, and pine wood had protection levels of 6.0, 7.1, and 7.7, respectively.

Table 13. Protection level of specimens.

Treatment	Wood Species			
	Sengon	Jabon	Mangium	Pine
Untreated	2.3 (3.2)	0.0 (0.0)	5.4 (3.1)	4.7 (2.0)
Imidacloprid	5.8 (3.3)	6.6 (2.8)	7.7 (0.5)	8.8 (0.6)
Furfurylated	9.9 (0.3)	9.6 (0.5)	8.2 (3.2)	9.6 (0.5)

Table 14. Variance analysis of protection level.

Source	Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	899.85	5	179.97	32.47	0.000
Intercept	5148.30	1	5148.30	928.87	0.000
Wood species	97.50	3	32.50	5.86	0.001
Treatment	802.35	2	401.18	72.38	0.000
Error	631.85	114	5.54		
Total	6680.00	120			

Remarks: df is degree of freedom; F is from calculation; sig. is significant level.

In terms of treatment, after 1 year of exposure in the field, furfurylation had the highest protection level (value of 9.3, refers to Table 12), and the value was slightly smaller than that at 3 months (9.6). Imidacloprid-preserved wood had a value of 7.2 at 1 year and 8.7 at 3 months, while untreated wood had values of 3.1 and 7.4 at 1 year and 3 months, respectively. In other words, the furfurylated wood was the most resistant and had the smallest decrease in protection level over time with regard to subterranean termite attack.

4. Conclusions

Based on the findings in this work, it could be concluded that the density and moisture content of untreated and imidacloprid-preserved wood samples were found to be not significantly different from each other. However, they were significantly different from furfurylated wood, which had a much higher density and a much lower moisture content. In terms of wood color, mangium wood had a darker color compared with the other three wood species, which had lighter colors. After treatment, imidacloprid-preserved wood had a lighter color, but furfurylated wood had a darker color compared with untreated wood. Concerning termite attack, untreated jabon wood had the lowest resistance to subterranean termite attack, while untreated sengon, mangium, and pine had almost the same resistance. After 1-year exposure in the field in Bogor, Indonesia, furfurylated wood showed superior resistance to subterranean termite attack, followed by imidacloprid-preserved wood, and untreated wood which had the lowest resistance.

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