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Characteristics of Fast-Growing Wood Impregnated Using Monoethylene Glycol and SiO_2 Nanoparticles Against Fungal Attacks

Karakteristik Kayu Cepat Tumbuh Terimpregnasi Monoetilen Glikol dan Nanopartikel SiO_2 terhadap Serangan Jamur Pelapuk Kayu

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ABSTRACT

Jabon (*Anthocephalus cadamba*) and Sengon (*Falcataria moluccana*) were fast-growing wood species widely planted in the community forest. Both kinds of wood have low durability even though they can potentially be used in the carpentry material industry. Therefore, this research aimed to analyze the vacuum-pressure impregnation effect using monoethylene glycol *($C_2H_6O_2$) or* MEG and silica dioxide (SiO_2) nanoparticles on wood resistance to fungal decay. The results showed that impregnation treatment with MEG and SiO_2 nanoparticles significantly improved the durability of Jabon and Sengon against fungal attacks. Furthermore, $MEGSiO_2$ with 24-hour polymerization had a better impact on durability compared to both the control and $MEGSiO_2$ with 12-hour polymerization. The 24-hour polymerization using 1% SiO_2 nanoparticles resulted in the lowest weight loss for Jabon (5.86%) and Sengon (5.21%). In addition, the variation of SiO_2 nanoparticle concentration did not significantly affect the weight loss and durability of Jabon and Sengon against fungal decay.

KATA KUNCI
impregnasi vakum-tekan, monoetilen glikol, nanopartikel SiO_2*, polimerisasi, schizophyllum commune*

INTISARI

Jabon (Anthocephalus cadamba) dan Sengon (Falcataria moluccana) adalah spesies kayu cepat tumbuh yang banyak ditanam di hutan rakyat. Kedua jenis kayu tersebut mempunyai potensi untuk dimanfaatkan dalam industri pertukangan, namun memiliki ketahanan yang rendah. Pengaruh impregnasi vakum-tekan menggunakan monoethylene glycol ($C_2H_6O_2$) atau MEG dan nanopartikel SiO_2 pada ketahanan kayu terhadap jamur pelapuk menjadi fokus pada penelitian ini. Hasil penelitian menunjukkan bahwa perlakuan impregnasi dengan MEG dan nanopartikel SiO_2 meningkatkan ketahanan kayu Jabon dan Sengon dari serangan jamur. Perlakuan $MEGSiO_2$ dengan polimerisasi 24 jam memberikan pengaruh yang lebih baik terhadap ketahanan kayu dibandingkan perlakuan kontrol dan $MEGSiO_2$ dengan polimerisasi 12 jam. Polimerisasi dengan SiO_2 1% selama 24 jam menghasilkan kehilangan berat yang paling rendah pada kayu Jabon dan Sengon, masing-masing sebesar 5.86% dan 5.21%. Variasi konsentrasi nanopartikel SiO_2 tidak berpengaruh nyata terhadap kehilangan berat dan ketahanan kayu Jabon dan Sengon dari jamur pelapuk.

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Introduction

Jabon and Sengon are fast-growing wood species harvested from community forests in Indonesia. However, these types of wood had unfavorable characteristics, such as low density, specific gravity, high juvenility, and a low portion of heartwood, which led to poor physical and mechanical properties as well as durability (Dewi et al. 2024). According to Martawijaya et al. (2005), Sengon specific gravity ranged from 0.24-0.49, while Jabon ranged from 0.29-0.56. A common issue with using fast-growing wood as a building material is its susceptibility to fungal attack. This issue is compounded by the tropical climate of Indonesia, which has high precipitation levels, temperature, and humidity.

Wood decay due to fungus needs an immediate solution, considering the significant damage and associated losses it causes. According to Kirker (2018), many cases of wood damage due to fungal attacks occur in residential and industrial sectors, leading to material losses of up to one billion USD. Therefore, it is necessary to improve wood quality, specifically through preservation. Several methods have been developed, including kiln drying, preservation, and modification (Elustondo et al. 2023; Kusumaningsih 2017; Teng et al. 2018). Wood modification is a technology that has recently attracted considerable interest from experts because it can produce promising new materials by modifying the molecular structure of the cell wall components (Hill 2006). In this context, Sandberg et al. (2017) reported that modification enhanced the fundamental properties of wood, such as durability, dimensional stability, and hardness.

Various modifications commonly used are chemical, thermal, surface, and impregnation. According to Hill (2006), impregnation is done by infusing chemicals into the lumens to enhance wood properties. Previous research on impregnation using nanoparticles showed significant improvements in wood properties (Dong et al. 2014; Rahayu et al. 2022; Wahyuningtyas et al. 2022). Dirna et al. (2020) reported that modifying sengon with monoethylene glycol (C_2H6O_2) or MEG and silica dioxide (SiO_2) nanoparticles improved the physical properties and characteristics. However, further investigation regarding the resistance to fungal decay is still needed. MEG has been widely used in many industrial sectors and can be found in antifreeze materials, pharmaceuticals, and cosmetics applications (Haque et al. 2022; Islam et al. 2017).

MEG has a molecular weight of 62.07 g/mole, is colorless, odorless, and dissolves perfectly in water (ATSDR 2020). Additionally, it has a sweet taste, is hygroscopic, non-volatile, and 100% lethal to animals at a dose of 1.4 mL/kg (Danish Environmental Protection Agency 2013; Fowles et al. 2017). Using chemicals alone is only effective in improving physical properties, and new characteristics that make wood more advanced and multifunctional cannot be produced. Therefore, SiO2 nanoparticles were added to the MEG solution to prevent wood damage from fungal decay and wood stain fungal attacks while synthesizing a hydrophobic material that is resistant to flammability. The chemical combination was infused into Jabon and Sengon wood to asses their durability against fungal decay attacks.

Methods

Materials

This research used two types of 5-year Sengon (*Falcataria moluccana*) and Jabon (*Anthocephalus cadamba*) woods obtained from the community forest in Ciherang, Bogor. Sengon had the lowest branch height of approximately 8 m, with a breast height diameter of 29.29 cm, while Jabon had the lowest branch height of 10 m and a breast height diameter of 29.93 cm. This research used MEG from Merck, SiO2 nanoparticles with a particle size of 15 ± 5 nm (Anhui Elite Industrial. Co. Ltd. China) and demineralized water. Potato Dextrose Agar (PDA) was used with 70% alcohol and a pure white rot *Schizophyllum commune* culture to isolate the fungus (Figure 1).

Methods

Wood Sample Preparation

According to SNI 01-7207:2006, the size of wood samples was 5 cm × 2.5 cm × 1.5 cm. The samples were coded and oven-dried at 103 ± 2°C for 48 hours and subsequently weighed to obtain an initial weight (W_0).

Figure 1. The fruiting body of *Schizophyllum commune*

Figure 2. The pure culture of *S. commune* in a 14 cm petri dish

Fungus Culture Preparation

The fungus culture preparation followed the SNI 01-7207:2006 and was modified using PDA as a medium. Each liter of PDA consisted of 200 g potatoes, 20 g agar flour, and 20 g granulated sugar. Firstly, PDA was synthesized by boiling potatoes that had been cleaned and cut into pieces approximately 1 cm × 1 cm × 1 cm until the texture was soft. The boiled potato mixture was filtered to remove all the pieces, the water was reheated, and 20 g of agar flour and 20 g of granulated sugar were added. After boiling, 250 mg of the antibiotic chloramphenicol was added. The boiled solution was then transferred into a 250 ml Erlenmeyer tube and covered, then autoclaved at a temperature of 121°C and pressured at 1.5 atm for 30 minutes.

S. commune was cultivated in Petri dishes with a diameter of 14 cm (Figure 2). Furthermore, aseptic propagation activities were performed in an isolation room using a laminar flow instrument. Daily monitoring was conducted at room temperature to ensure no contamination occurred during incubations. This stage continued until fungal mycelium covered the PDA medium, producing a pure fungal culture.

Preparation of Solution

The solution, which consisted of MEG and SiO_2 nanoparticles, was mixed using a Cole Parmer sonicator and homogenized with an amplitude of 40% for 60 minutes. Various concentrations were used to obtain the optimal result for wood resistance against fungal decay. Specifically, the research included a control, 50% MEG, and 50% MEG with the addition of SiO_2 nanoparticles at 0.5%, 1%, and 1.5%.

Impregnation Process

Wood samples that had been weighed (W0) were arranged in an impregnation tube to initiate the process, and the solution was poured until perfectly immersed. According to Dong et al. (2014) and Rahayu et al. (2020), the impregnation process was conducted under a vacuum of 0.5 bar for 60 minutes, followed by 2.5 bar pressure for 120 minutes. After this process, wood samples were drained of the remaining solution and wrapped in aluminum foil for polymerization. Two types of polymerization duration were used in this research. The first underwent a 12-hour polymerization process at room temperature, while the second involved two stages, namely 12 hours at room temperature followed by another 12 hours at 100°C. Subsequently, the weight of the samples after impregnation treatment (W_1) was determined for weight percent gain (WPG) calculation. The WPG was calculated using the following formula (Eq. 1).

$$WPG\ (\%) = \frac{W0 - W1}{W1} x\ 100 \qquad \text{(Eq. 1)}$$

Testing on Wood Resistance Against Fungal Decay

Based on SNI 01-7207:2006, these wood samples were first conditioned for 14 days, then oven-dried at 103 ± 2°C until a constant weight was reached, and then weighed (W_2). Subsequently, wood samples were placed into Petri dishes inoculated with *S. commune*. The isolation process was performed aseptically using a laminar flow instrument, followed by incubation for 12 weeks at ambient temperature. At the 12-week point, wood samples were taken out of Petri dishes, and the attached mycelium was removed. In the final step, wood samples were oven-dried at 103 ± 2 ºC and weighed to a constant weight condition (W_3) to calculate the weight loss (WL) of Jabon and Sengon. The decay resistance test was carried out in three repetitions and the weight loss was determined using Eq. 2. Wood resistance classification based on weight loss value referred to SNI 01-7207:2006.

$$WL\ (\%) = \frac{W2 - W3}{W2} x\ 100 \qquad \text{(Eq. 2)}$$

Data Analysis

Linear regression analysis was used to calculate the coefficient of determination (R^2) of the concentration level of SiO_2 nanoparticles in MEG with WPG and the weight loss value of Jabon and Sengon with variations in polymerization duration (12 hours and 24 hours). In addition, the data were analyzed using ANOVA, followed by Duncan's test at a 5% significant level using IBM SPSS (Statistical Package for the Social Sciences) version 25**.**

Result and Discussion

Weight Percent Gain (WPG)

A vacuum-pressure impregnation process was successfully carried out to increase the weight of Jabon and Sengon, with results presented in Table 1. The t-test results showed that the interaction between treatments and polymerization times was only statistically significant for the WPG of Jabon, as indicated by the t-stat value being larger than the t-critical and the *p*-value being lower than α (Table 2). This result was supported by the significantly increased WPG of Jabon after impregnation and polymerization. WPG of the control sample for both woods was not tested because it did not show any weight gain after being impregnated with water. However, MEG and MEGSiO_2-treated wood samples showed an increasing trend in the weight of Jabon. Although there was only a slight improvement in the WPG for various treatments of Jabon and Sengon in 12 and 24 hours of polymerization, the differences were evident, as shown by the different alphabet letters following the average numbers in Table 1.

MEG was suspected of penetrating deeply into wood cell walls, specifically after adding SiO_2 nanoparticles, which continued to improve WPG.

Table 1. WPG obtained in Jabon and Sengon with two ways of polymerization

Wood	Treatments	WPG (%) in two ways of Polymerization	
		12 hours	24 hours
Jabon	MEG	13.39^{ab}	13.61^{ab}
	MEGSiO_2 0.5%	14.95^{b}	13.01^{a}
	MEGSiO_2 1%	19.41^{d}	13.89^{ab}
	MEGSiO_2 1.5%	17.76^{c}	13.10^{a}
Sengon	MEG	8.77^{a}	11.17^{bc}
	MEGSiO_2 0.5%	10.07^{abc}	10.49^{abc}
	MEGSiO_2 1%	11.81^{c}	10.31^{abc}
	MEGSiO_2 1.5%	9.70^{ab}	10.43^{abc}

Note: $^{a-c}$ values: Duncan's test result that explains the significance among the different alphabets

Table 2. T-test results on WPG of Jabon and Sengon

T-test Parameters	Wood Species	
	Jabon	Sengon
t-stat	13.160	9.977
p-value (T≤t) one-tail	0.00	0.5111
t-critical one-tail	12.71	2.71
α value	0.05	0.05

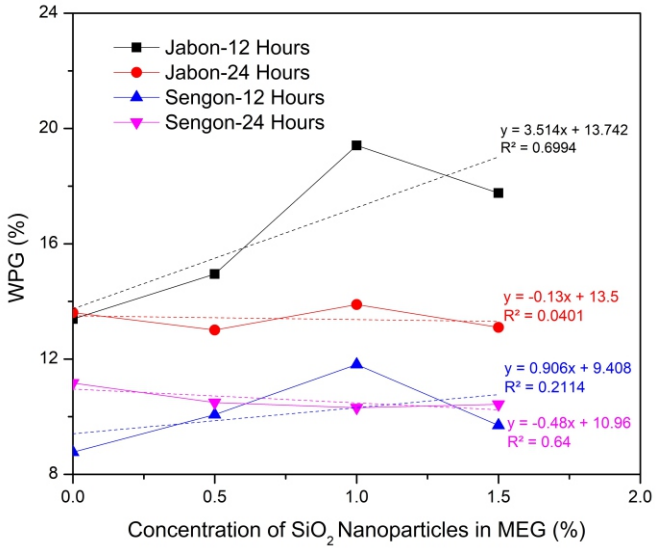

Figure 3. The correlation between WPG and SiO_2 nanoparticle concentration in MEG

However, there was a decline in WPG for the MEGSiO_2 1% wood. The high concentration of SiO_2 nanoparticles might have caused the solution to form a cracked layer, preventing proper cross-linking between the solution and wood polymer (Hadiyawarman et al. 2008). In addition to WPG, Dirna et al. (2020) also mentioned that combining MEG and SiO_2 nanoparticles could enhance the bulking effect, anti-swelling efficiency, and wood density while reducing water absorption. This was due to SiO_2 nanoparticles being deposited and well distributed inside wood cavities with the help of MEG.

Based on the statistical analysis, Sengon experienced an enhancement in WPG (Table 1), although the concentration treatments and polymerization durations did not significantly affect WPG (Table 2). This might be due to the agglomeration and aggregation of SiO_2 nanoparticles on wood surfaces, preventing the solution from fully saturating wood (Prihatini et al. 2023; Rahayu et al. 2021). Additionally, 24-hour polymerization did not significantly affect the enhancement of WPG, which may also be related to other potential physical properties of wood. Overall, Jabon showed a superior WPG to Sengon (Table 1). This difference was likely due to the wood's pore-size characteristics. Sengon had a pore size of 140-200 µm, which was primarily solitaire and amounts to 1-3 pores/mm^2, while Jabon

had a pore diameter of 130-220 µm, which may overlap and amounts to 2-5 pores/mm^2.

The result was supported by the correlation between SiO_2 concentration treatments and WPG (Figure 3). Hair et al. (2013) stated that an R^2 value of about 0.75 was considered strong, 0.50 was moderate, and 0.25 was considered weak. Based on the graph, a moderate positive correlation appeared in Jabon after 12 hours of polymerization and Sengon after 24 hours of polymerization. Conversely, a weak positive correlation was observed in Sengon after 12 hours of polymerization. Meanwhile, Jabon, with 24 hours of polymerization, showed a very weak or almost no correlation. Furthermore, the impregnation process did not affect the wood's physical characteristics, such as discoloration. Combining MEG and SiO_2 nanoparticles could enhance the mechanical properties of wood (Rahayu et al. 2021).

Weight Loss of Decaying Wood

The average weight loss of Jabon and Sengon after the incubation process was outlined in Table 3. The results showed that both Jabon and Sengon were attacked by wood-decaying fungi, as evidenced by the reduction in weight compared to the WPG. The interaction between concentration treatments and polymerization durations significantly affected Jabon weight loss, as shown by the ANOVA with α p-value less than 0.05 and t-Stat greater than the t-critical value. However, the effects on Sengon were not statistically significant (Table 4). Both wood species experienced a reduction in weight after the incubation process compared to the control wood. For comparison, Martha et al. (2021) showed that the highest weight loss percentage was observed in control teak wood against wood-decaying fungi.

In Jabon, which had been polymerized for 12 hours, the least weight loss was observed in the $MEGSiO_2$ 1.5% wood sample, while the most significant weight loss occurred in the $MEGSiO_2$ 1% wood sample and did not differ from the control wood sample. On the other hand, the addition of SiO_2 nanoparticles in Jabon led to fluctuating results across both polymerization durations. Polymerization at higher temperatures and for longer duration should have allowed MEG and SiO_2 to remove excess water from wood, making it more resistant to decaying fungi (Badi et al. 2020). The weight loss in Jabon polymerized for 24 hours showed a linear relationship with WPG in Table 1. However, the weight loss in Jabon polymerized for 12 hours did not correlate with initial expectations. It was observed that the highest WPG led to Jabon's highest weight loss value after the fungal attack. This reduction was suspected to be due to the loss of cellulose and lignin in wood caused by fungal decomposition. Moreover, the nonlinear weight loss of $MEGSiO_2$ 1% wood sample compared to other concentration levels in 24-hour polymerization was thought to result from the small amount of SiO_2 binding to the cell wall components and covering only a particular area of the wood surface. The high rate of fungal activity led to a lighter color in wood (Stange and Wagenführ 2022).

A tendency for weight loss to decrease with the addition of SiO_2 nanoparticles was observed in Sengon. Since the T-test result stated that neither factor had a significant effect on weight loss in Sengon, further observations were conducted to assess the effect of each single factor. However, these observations also concluded that both factors had no significant effect, with t-stat values for concentration treatments and polymerization times being -3.223 and

Table 3. The weight loss of wood caused by fungi after the incubation process

Wood	Treatments	Weight Loss (%) in two ways of Polymerization	
		12 hours	24 hours
Jabon	Control	11.46^{a}	11.46^{b}
	MEG	10.51^{a}	5.90^{c}
	$MEGSiO_2$ 0.5%	10.66^{a}	6.74^{bc}
	$MEGSiO_2$ 1%	11.94^{a}	5.86^{c}
	$MEGSiO_2$ 1.5%	8.32^{b}	5.89^{c}
Sengon	Control	11.69^{a}	11.69^{a}
	MEG	9.49^{b}	6.56^{b}
	$MEGSiO_2$ 0.5%	7.43^{b}	7.03^{b}
	$MEGSiO_2$ 1%	10.36^{b}	5.21^{b}
	$MEGSiO_2$ 1.5%	8.04^{b}	6.78^{b}

Note: $^{a-c}$ values are Duncan's test result that explains the significance among the different alphabets

Table 4. Results of the T-test on the weight loss of Jabon and Sengon

T-test Parameters	Wood Species	
	Jabon	Sengon
t-stat	14.350	9.515
p-value (T≤t) one-tail	0.00	0.00
t-critical one-tail	12.71	112.71
α value	0.05	0.05

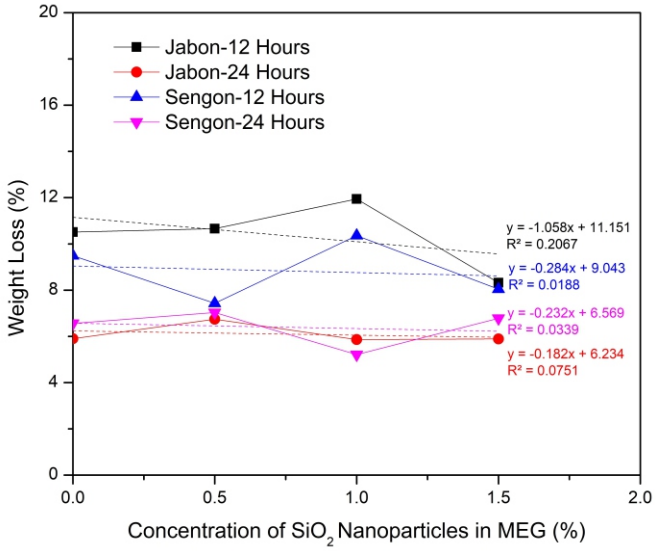

Figure 4. The correlation between the concentration of SiO_2 nanoparticles in MEG and weight loss

-2.524, respectively, less than the t-critical value of 12.71 (Table 4).

After 12 hours of polymerization, the lowest weight loss percentage was achieved with MEGSiO_2 at 0.5%. MEG and SiO_2 nanoparticle concentrations affected weight loss differently than the control wood. In contrast, 24-hour polymerization showed the lowest weight loss in MEGSiO_2 1%, indicating that Sengon was more durable against decaying fungi than 12-hour polymerization. This differed from the initial hypothesis, as a high WPG led to high weight loss, even in both polymerization treatments. Among these treatments, 24-hour polymerization time proved to be more effective in reducing the weight loss of Jabon and Sengon, although WPG did not differ significantly. The correlation between concentration treatments had a weak positive correlation with weight loss in Jabon with 12 hours of polymerization, while the other samples showed a very weak positive or almost no correlation, as indicated by low R^2 (Figure 4). A value of R^2 less than 0.25 is considered a weak correlation (Hair et al. 2013).

Dong et al. (2014) reported that wood impregnation using SiO_2 nanoparticles with 24-hour polymerization increased wood crystallinity. This improvement was due to the polymerization reaction between SiO_2 nanoparticles and wood polymers, which turned the amorphous area of Sengon into a crystalline area. Furthermore, the reduction in wood crystallinity after MEG and SiO_2 nanoparticles impregnation also reduced the water absorption capacity of wood polymers and created an unfavorable condition for fungi, thereby making 24-polymerized wood more resistant to decay. This result correlated with Ghosh et al. (2008), who reported that silicon could improve wood durability against decaying fungi because silicon altered wood characteristics, making it appear poisonous to fungus. According to SNI 01-7207:2006, Sengon was moderately durable and could last a long service life, categorized in durability classes III-IV. On the other hand, Jabon's weight loss showed less resistance than Sengon's. Therefore, Jabon was classified as having weak to moderate durability and included in durability classes IV-V (Martawijaya et al. 2005).

Conclusion

In conclusion, vacuum-pressure impregnation treatment of MEG and SiO_2 nanoparticles significantly impacted the resistance of Jabon and Sengon to the attack of wood-decaying fungi *S. commune*. Specifically, 24-hour polymerization produced better penetration in Jabon and Sengon, evidenced by the higher WPG. Varying the concentration levels of SiO_2 nanoparticles used in the impregnation process of Jabon and Sengon samples also significantly affected the resistance to wood-decaying fungi attack, as shown by the lower weight loss. As a result of these treatments, the durability class of the impregnated Jabon was classified as IV-V, while the impregnated sengon was classified into durability classes III-IV. Therefore, this research determined that the best composition for producing high physical properties and durable modified wood was MEGSiO_2 1% for each wood species with 24 hours of polymerization duration.

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