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An investigation of thermal conductivity and sound absorption from binderless panels made of oil palm wood as bio-insulation materials

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ABSTRACT

Oil palm wood is one of the solid wastes available in large quantities, which has been used as non-structural material. Many researchers focus on their material strength and binder selection. However, limited studies investigate oil palm wood as insulation materials. Therefore, this study aimed to evaluate the thermal and sound characteristics of oil palm wood binderless panels as insulation materials. Panels were manufactured from oil palm wood using hot presses with different particle sizes and pressing times. The results indicated that the particle size had a significant effect on the characteristics of the binderless panels but not on pressing times. The coarser particle size enhanced the thermal and sound resistance but decreased density, water resistance, and flexural strength. In addition, the panels with large particles had the least thermal conductivity (0.050 W/mK) and the highest sound absorption coefficient of 0.33. The study also showed that the flexural strength and water absorption of the panels ranged from 4.21 to 8.18 MPa and 84.51%–119.06%, respectively. The findings of this study indicate the feasibility of binderless panels from oil palm wood as insulation materials.

1. Introduction

Since the early twentieth century, insulation materials have been widely employed in buildings. These materials are generally synthetic, such as extruded polystyrene, polyurethane foam, polyisocyanurate, and expanded polystyrene. Some thermal and acoustic insulators in commercial construction have been previously reviewed [1–4]. Synthetic materials have high performance in resistance to thermal and sound but impact the environment and health [1,5]. Therefore, the use of natural materials is essential in creating a sustainable and healthy environment.

In recent years, many studies have investigated natural-based insulation materials as a replacement for synthetic materials. The natural fibers from natural resources are becoming increasingly popular because they are abundant, low density, highly porous, environmentally friendly, renewable, low cost, and suitable isolators [6–8]. Some researchers studied the utilization of natural fibers as a raw material for thermal insulation, such as wood fiber [9,10], bamboo fiber [11], sunflower and vermiculite fiber [12], and banana fiber [13]. Furthermore, some previous studies have reported the performance of natural fibers as acoustic absorbers. Hemp fiber [14], sunflower [15], sisal, coconut husk, sugar cane, banana [16], coir [17], date palm empty fruit [18], bamboo [19], and jute [20] from natural sources have also been investigated. In addition, the thermal properties and acoustic performance of different particle sizes of the Washingtonia palm tree were also examined [21,22]. Overall, their reports have concluded that natural materials have good thermal resistance and sound absorption performance, an alternative to synthetic fibers.

The present study proposes oil palm wood particles as raw materials for thermal and sound insulation panels. Currently, Indonesia is the largest producer of palm oil globally, 48.42 million tons, with an oil palm plantation area of 14.59 million hectares [23]. Each tree generates about 10% of palm oil, and 90% of the remaining is biomass waste [24]. The trunks and fronds were the primary biomass wastes produced by plantations, around 70% and 20.5%, respectively [25]. In 2020, Indonesia was expected to produce approximately 44 million tons of felled trunks [26]. These appreciable amounts of felled are potential as a wood-based product. Some previous researchers have explored oil palm trunks as a raw material for wood-based products, such as lumber, plywood, particleboard [27–29], compreg wood [30], and biomass [31,32]. Furthermore, efforts to develop oil palm wood (OPW) for acoustic

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Table 1
Chemical, starch, and sugar content of the oil palm wood [36].

Composition	Content
Alpha cellulose	50.21%
Holocellulose	72.60%
Lignin	20.15%
Starch	12.19 (mg/ml)
Glucose	5.97 (mg/ml)
Xylose	6.61 (mg/ml)
Arabinose	1.09 (mg/ml)

Table 2
Panel manufactured design.

Panel type	Particle size (mm)	Temp (^{O}C)	Pressing Parameter	
			Stage 1	Stage 2
L1	0.84–0.42	200	p = 15 MPa	p = 10 MPa
L2	0.42–0.07		t = 10 min	t = 5 min
L3	<0.07			
L4	0.84–0.42		p = 15 MPa	p = 10 MPa
L5	0.42–0.07		t = 20 min	t = 5 min
L6	<0.07			

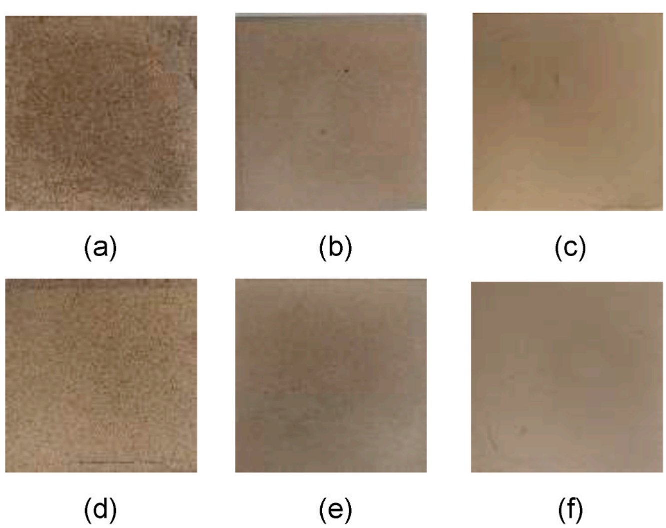

Fig. 1. The physic of bindreless panels (a) L1, (b) L2, (c) L3, (d) L4, (e) L5, (f) L6.

Table 3
The average physical properties of binderless panels and different literature.

Particle size (mm)	Density (g/cm^3)	WA (%)	TS (%)	Ref.
0.84–0.42	0.58 ± 0.05	119.06 ± 8.18	73.33 ± 4.50	Present study
0.42–0.07	0.65 ± 0.06	93.90 ± 6.80	56.00 ± 3.30	
<0.07	0.70 ± 0.07	84.51 ± 2.49	43.24 ± 2.49	
0.84–0.42	0.62 ± 0.07	117.97 ± 6.60	72.50 ± 2.87	
0.42–0.07	0.65 ± 0.04	92.75 ± 5.25	54.41 ± 3.09	
<0.07	0.68 ± 0.03	85.88 ± 2.62	41.33 ± 2.05	
0.3–5	1	42.92	17.96	[43]
0.5–1	0.8	211.03	111.1	[44]
fine	0.65	100.40	59.34	[45]
0.25–2	0.8	65.6	49.70	[27]

insulation materials in buildings have been made [33].

In this study, the binderless panels were made of oil palm wood particles to evaluate the thermal and acoustic insulation properties. Oil palm wood was prepared to particles, boiled, dried, and formed using hot pressing. Various analyses were undertaken, including water absorption, thickness swelling properties, flexural properties, thermal conductivity, and sound absorption performance.

2. Material and methods

2.1. Materials

Oil palm wood with an approximate age of 25–30 years was examined from one of the oil palm plantations in Aceh, Indonesia. In this study, only the inner part of felled oil palm logs was used as the raw materials. Oil palm wood was chopped to the tiny chip manually and then reduced to three particles size using a disc mill: large (0.84–0.42 mm), medium (0.42–0.07 mm), and small (<0.07 mm). Particles were boiled in hot water at a temperature of 100 ^{O}C for 30 min. Pre-treatment oil palm wood particles in hot water for 30 min increased the mechanical properties and thermal stability of the final particleboard [34,35]. Later, particles were dried in an oven at a temperature of 80 ^{O}C for 24 h to a moisture content of 10–12%. Table 1 presents the chemical value of the oil palm wood.

2.2. Panel fabrication

In this work, the panels were manufactured using a two-stage pressing process. First, they were pre-pressed for 10 and 20 min at a pressure of 15 MPa at 200 ^{O}C and continued the cooling process for 5 min at 100 ^{O}C under the 10 MPa pressure. The panels were manufactured from different particle sizes with a target density of 0.70 g/cm^3. Three samples of each type with dimensions of 150 mm × 150 mm x 10 mm and Ø 100 mm × 10 mm were prepared for thermal conductivity and sound absorption testing, respectively. Table 2 summarizes the manufacturing design of the binderless panels, and Fig. 1 shows the physic of binderless panels. Before undergoing tests, the panels were conditioned for seven days at 25 ^{O}C and approximately 60% relative humidity.

2.3. Physical properties

Three samples were cut from each panel with the dimension of 50 mm × 50 mm X 10 mm to evaluate their physical properties. Before testing, all samples had been pre-conditioned to reach the constant weight. For the thickness swelling (TS) and water absorption (WA) testing, the sample thickness and weight were measured before and after being soaked in water for 24 h. SNI 03-2105-2006 standard [37] was used to determine the physical properties.

2.4. Flexural test

The flexural strength test using a three-point flexural test was performed on an MTS EXCEED Model E43 universal testing machine with a crosshead speed of 2 mm/min. The five samples with the dimension of 150 mm × 30 mm x 10 mm from each panel were placed between two supports at a distance of 100 mm, based on the standard ASTM D790 [38].

2.5. Thermal conductivity

An insulated box model PHYWE SYSTEME GMBH 37070 Göttingen, Germany, was used for thermal conductivity testing. Three samples of each type were prepared for heat resistance testing was (150 × 150 x 10) mm, following ASTM C177-9 [39] at a steady-state condition. Temperature measurements using four thermocouples were installed inside and

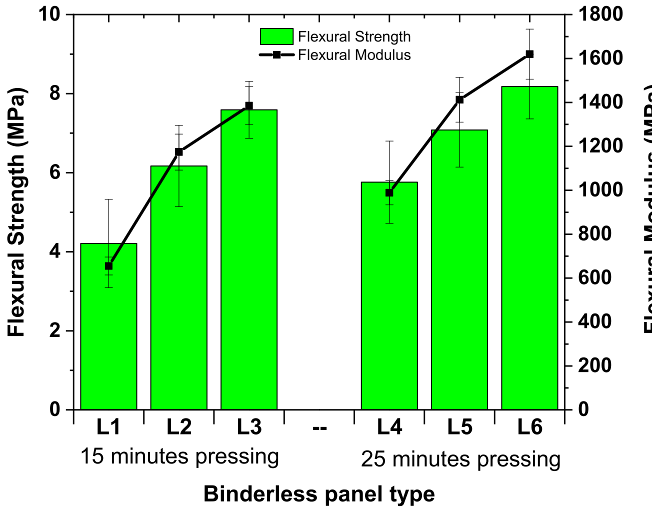

Fig. 2. Flexural properties of binderless panels.

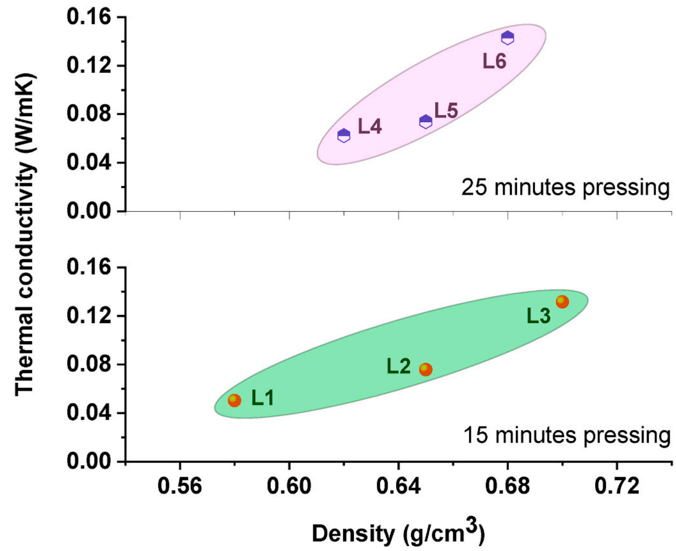

Fig. 3. Correlation of thermal conductivity with different particle sizes and densities.

outside the box and on the interior and exterior of the sample walls.

2.6. Acoustical characteristic

The sound absorption coefficient of the panels determined the acoustical characteristic. The sound absorption coefficient was set based on ISO 10534–1:1996 [40], using an impedance tube [41] with a two-channel and a frequency ranging from 250 to 2000 Hz. Three (Ø 100 × 10) mm samples of each type were prepared for sound absorption testing.

3. Results and discussion

3.1. Physical properties of the binderless panel

Table 3 shows the average density, water absorption (WA), and thickness swelling (TS) of oil palm wood binderless panels from this works and other literature. The density of binderless panels ranges from 0.58 to 0.70 g/cm^3, with the lowest density in panels made of larger OPW particles. The decrease in density due to particle size was also reported in previous studies [22,42]. Their studies evaluated the effect of the wood particle size on composites, and large particles showed a lower density of composites than small ones. The panel made of larger-sized wood particles may have more and larger pores, whereas smaller particles resulted the mat with better structure compactness.

WA and TS are the keys parameters for the dimensional stability of wood-based products. The binderless panel exhibited a high water absorption (from 84.51% to 119.06%). As reported in the literature, the poor water resistance would be due to the hygroscopic characteristic of oil palm wood. It has more hydroxyl groups in the parenchyma tissue that facilitates more hydrogen bonds. In addition, the parenchyma behaved like a sponge, making it easier for the oil palm wood to absorb water [28]. In addition, the poor water resistance of oil palm wood could be attributed to the chemical components of the substance, which are rich in sugars, starch, and saccharides in the parenchyma tissue [27]. The performance of water uptake decreases based on the particle geometry, following small < medium < large. The water uptake capacity of the panels depends on the particle size; the large particle has a higher percentage of water uptake. This work exhibited an extra to 40% reduction when small particles used. Other authors have reported that boards' water resistance increased when using finer particles [44]. Similarly, the water resistance of particleboards from oil palm trunks (OPT) increased with finer particles [44]. Other researchers have also observed a decrease in the WA of panels with smaller particles [22,46].

The absorbed water influences the thickness swelling (TS); the higher the water content, the higher the panel dimension changes. This study obtained the highest thickness swelling for sample L1 (73.33%) and the lowest (41.33%) for L6. Previous studies [47,48], has reported similar findings, where the swelling thickness decreases with the increasing water resistance. The findings of this work prove that particle size can influence physical properties. Nevertheless, it was no significant effect pressing times on the physical properties.

3.2. Flexural strength properties

Fig. 2 depicts the flexural properties of the panels as a function of particle size and pressing time. The highest flexural strength and modulus values were 8.8 MPa and 1620 MPa, respectively, for the binderless panel made of small particles (L6 sample). Using small particles better improves flexural properties compared to other panel particle sizes in all conditions. Fine particles can produce better compatibility to increase the bonding between individual particles [21,44]. The fine and ratio particle size fractions had a significant impact on the internal bonding strength of the panels [49]. Similar findings from the previous study [21,44] reported that large particles reduced the flexural properties of board manufactured oil palm trunks and Washingtonia palm trees. The particle size significantly impacts the flexural properties due to its effect on the interlocking mechanism between the particles [50,51]. These findings are better than bio-composites made of rice husk, wheat husk, wood fibers, and textile waste fibers with PLA as a binder; their flexural strength is 0.80–2.25 MPa [52]. Furthermore, similar results were obtained in another research study [27], reaching 8.9 MPa when adding 10% ammonium dihydrogen phosphate to the binderless board from oil palm trunks.

The binderless board could be produced by hot-press without adding any adhesives due to chemical components, such as sugar and starch, which act as the particles' self-bonding. However, a longer press time was insufficient to create strong bonding between the particles in the panels [53], so it did not significantly influence the bending strength [54]. The flexural properties of the binderless panels with a pressing time of 15 min differed by about 7% compared to 25 min.

3.3. Thermal conductivity properties of the panel

Using the thermal insulation materials of buildings is the most effective way to reduce energy consumption in buildings [55]. Thermal conductivity is the primary quality indicator of the thermal insulation

Table 4
The thermal conductivity and different insulation materials.

Panel type	Density (g/cm^3)	Thermal Conductivity (W/mK)	Ref.
L1	0.58 ± 0.05	0.050 ± 0.009	Present study
L2	0.65 ± 0.06	0.075 ± 0.015	
L3	0.70 ± 0.07	0.132 ± 0.029	
L4	0.62 ± 0.07	0.062 ± 0.013	
L5	0.65 ± 0.04	0.074 ± 0.017	
L6	0.68 ± 0.03	0.143 ± 0.016	
Wood waste binderless	0.17	0.055	[9]
Bamboo binderless	0.63	0.10	[11]
Banana/Polypropylene	0.98	0.157	[13]
Washingtonia tree/UF	0.75	0.062	[21]
Wood fiber/PLA	0.45	0.110	[52]
Sunflower/Gypsum	0.22–0.30	0.134–0.219	[12]
Hybrid bio-panel	0.66–0.79	0.067–0.148	[59]

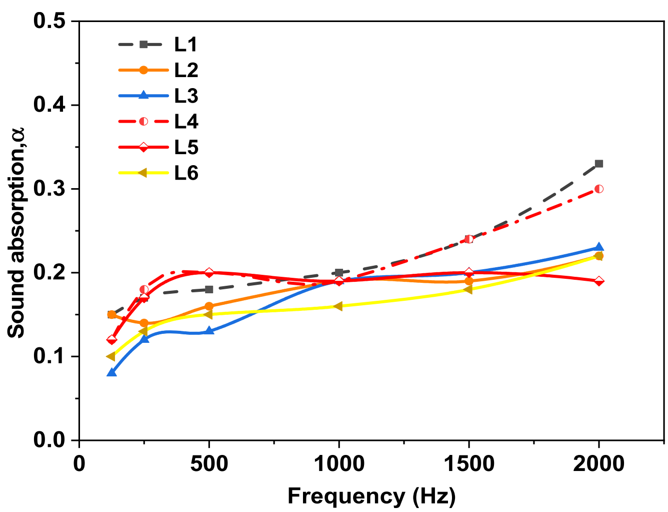

Fig. 4. Sound absorption of binderless panels.

material, with a lower value indicates good resistance. The average thermal conductivity coefficient is between 0.050 and 0.132 W/mK for 15 min pressing and 0.062–0.143 W/mK for 25 min pressing. The samples L1 and L6 showed the lowest and highest thermal conductivity produced from the largest and smallest particles.

Fig. 3 shows the relationship between the thermal conductivity of panels and particle size and density. The panels decreasing order of thermal conductivity and density are as follows: (L1, L6) < (L2, L5) < (L3, L4). Overall, the particle size and density affected the thermal conductivity coefficients of panels. However, it seems there is no significant effect for pressing time. An increase in particle size decreases the thermal conductivity of the panel and the larger particle size leads to decreased density or compactness. As the panel density decreases, the voids increase, and the solid substances reduce; so, the panels contain more air in their structures, leading to the enhanced heat resistance of the panels [11]. A similar finding has been published by some previous researchers [9,12,56,57], measuring thermal conductivity on boards made of natural fiber. Their study showed a positive relationship between thermal conductivity and density.

Table 4 summarizes the thermal conductivity and density of the produced panels and other insulation materials made of natural fiber. The thermal conductivity in the present work is comparable to the wood waste particleboard binderless [9] and the boards of Washingtonia palm tree with additive UF [21]. The result of this work showed that the panels produced have better thermal performance than particleboards made of a synthetic polymer as an adhesive, such as banana/polypropylene [13], wood fiber/PLA [52], and sunflower/gypsum [12]. According to the Wood Handbook [58], the thermal conductivity ranging from 0.1 to 0.14 W/mK is suitable for a thermal insulator for buildings. Overall, all binderless panels in this work fall into that range. Therefore, the panels are potentially used as thermal insulation material for buildings.

3.4. Sound absorption performance of the panel

Fig. 4 depicts the sound absorption coefficient of the panels with different particle sizes and pressing times in the low-frequency region, 125–2000 Hz. Panels with large particles (L1 and L4) at a frequency of 2000 Hz showed a high sound absorption coefficient of 0.33 and 0.30, respectively. The study exhibited that the sample manufactured with a lower density absorbed more sound than the small particles [18]. In this case, the pressing time of the binderless panel did not have a significant effect on sound absorption.

The finding is in line with previous studies [60,61], examining the effect of particle size on the sound absorption of panels made of natural fiber. They showed that low-density panels have more porosity and are therefore suitable for sound insulating materials. As the porosity of the material increases, tortuosity also increases, and the distance sound waves travel improves. Hence, increasing the amount of sound energy lost in the material results in high sound absorption [62]. Overall, the sound absorption property of the panels produced is poor; however, they better than oil palm trunk panels [33] and empty fruit bunch with a density of 0.701 g/cm^3 [63]. Furthermore, the comparison of the sound absorption performance of binderless panels with some different boards made of OPW is given in Table 5.

4. Conclusions

This study investigated the thermal and sound resistance performance of binderless panels manufactured from oil palm wood.

Table 5
Sound absorption of panels and different boards made from OPT.

Panel type	Density (g/cm^3)	Frequency (Hz)						Ref.
		125	250	500	1000	1500	2000	
L1	0.58 ± 0.05	0.15	0.17	0.18	0.20	0.24	0.33	Present study
L2	0.65 ± 0.06	0.15	0.14	0.16	0.19	0.19	0.22	
L3	0.70 ± 0.07	0.08	0.12	0.13	0.19	0.20	0.23	
L4	0.62 ± 0.07	0.12	0.18	0.20	0.19	0.24	0.30	
L5	0.65 ± 0.04	0.12	0.17	0.20	0.19	0.20	0.19	
L6	0.68 ± 0.03	0.10	0.13	0.15	0.16	0.18	0.22	
OPT cross-cut	0.34	–	~0.11	~0.10	~0.15	~0.18	~0.16	[33]
OPT + UP	0.10	–	~0.30	~0.60	~0.52	~0.42	~0.50	[64]
OPT+25% UP5	–	–	~0.05	~0.10	~0.18	~0.15	~0.22	[65]
OPEFB	0.58	–	–	~0.22	~0.34	~0.38	~0.46	[63]
Oil palm frond	0.30	–	~0.39	~0.60	~0.39	–	~0.38	[66]

Generally, the results showed that particle size had a significant influence on the characteristics of the binderless panel, but not the pressing duration of 15 and 25 min. These implied that 15 min pressing time is sufficient from the view of the practical and economic practice. The use of large particles increased the thermal and sound resistance, decreased flexural properties, and absorbed a higher volume of water. The L1 sample showed the best values for thermal conductivity (0.050 W/mK) and sound absorption (0.33) at 2000 Hz, while the L6 sample had the highest flexural strength and thickness swelling at 8.18 MPa, and 41.33%, respectively, and the L3 sample had the highest water resistance (84.51%). Based on the results, the binderless panel from oil palm wood is feasible as an insulating product for building. In addition, effective utilization of the oil palm wood would be beneficial from environmental and socio-economic aspects.

Credit author statement

Samsul Rizal: Conceptualization, Methodology, Supervision. **Indra Mawardi**: Data curation, Writing – original draft preparation. **Sri Aprilia**: Visualization, Investigation. **M. Faisal**: Writing-Reviewing and Editing. **Ikramullah**: Validation, Reviewing and Editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Samsul Rizal reports financial support was provided by Ministry of Education, Culture, Research and Technology, Indonesia. Samsul Rizal reports a relationship with Universitas Syiah Kuala that includes: board membership.

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