Article

Potential of Oil Palm Wood Thermally Modified via Hot Press Machine for Eco-Friendly Wall Insulation Applications

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Abstract: To utilize a huge amount of oil palm trunk (*Elaeis guineensis*) biomass as wall
insulation, its dimensional stability and insulation properties need to be improved. Thermal
modification (TM) (without compression or densification) is one of the efficient methods
widely used for improving insulation properties and dimensional stability of wood material,
but such an existing method requires a complex system. In this work, the TM of oil palm
wood with an initial density of 219 ± 34 kg/m^3 was performed at 200 °C using a hot press
machine. The optimum heat-treatment durations (2 h, 4 h, and 6 h) for their potential for
insulation wall applications were explored. TM improved dimensional stability, sound-
absorption coefficient, and thermal conductivity by approximately 66.7%, 26.7%, and 24.6%,
respectively, but increased volatile organic compound (VOCs) emission compared with
the control. Heat-treatment duration notably affected mass loss, density, and thermal
conductivity. Compared with available natural material-based insulation walls, TM oil
palm showed better insulation performance for all treatment durations. Thus, the heat-
treatment duration of 2 h is suggested to save the energy consumption in the heat-treatment
process while still achieving the same level of sound absorption, dimensional stability, and
VOC emission performance as that of the long heat-treatment duration.

Keywords: oil palm wood; thermal modification; hot press machine; insulation wall;
sound/thermal insulation; volatile organic compounds (VOCs)

1. Introduction

Walls are commonly used to divide the floor space of a building into separate rooms
for various purposes, such as bedrooms, meeting rooms, office rooms, etc. Besides their role
as a room divider, they are sometimes used as insulation for energy and sound-absorption
efficiency inside a building [1–4]. Walls also play an important role in controlling indoor
air quality because they are one of the main sources of volatile organic compounds (VOCs)

that could be emitted during their service life [5–7]. Excessive emissions of some VOCs can be seriously harmful to human health, and thus, they should be controlled appropriately.

There are various kinds of wall systems used in buildings, such as frame-based walls sheathed with thin panel products, including cement board, gypsum plasterboard, plywood and oriented strand board (OSB) [8], masonry walls [9], sandwich panels [10,11], wood-based composites; i.e., cross laminated timber [12], etc. These walls can be categorized into two main types based on their mechanical performance: load-bearing and non-load-bearing walls. In many countries, non-load-bearing walls are commonly used for most buildings. Following environmental concerns raised globally, many attempts have been made to replace these walls, which are typically derived from cement/petroleum-based materials, with natural materials [13,14].

In the tropical zone, a large amount of the relatively low-density and -strength oil palm trunk (*Elaeis guineensis*) waste could be considered as a potential source of material for producing non-load-bearing insulation walls in the form of laminated products [15]. To be competitive with available natural material-based insulation walls [16–19], the low dimensional stability and low insulation performance of oil palm wood need to be improved. Previously, Srivaro et al. [20] succeeded in using thermal compression to improve the mechanical and dimensional stability of oil palm wood (wood was densified under pressure and heat), but its density was also increased, which negatively affected its insulation properties. Thermal modification (TM) without compression (or densification) at relatively high temperatures is one of the efficient methods that has been successfully used to improve both the dimensional stability and insulation properties of softwood and hardwood species [21–26]. It has been reported that the dimensional stability and thermal and sound-insulation properties of the thermally modified wood are improved with increased temperature, but TM could also affect the volatile organic compound (VOC) emission as well. However, such a thermal modification method requires a complex system, as it needs to be done under inert or low-oxygen conditions to prevent combustion during the thermal modification process at relatively high temperatures (~160–260 °C). In such a system, the heat was transferred to wood material through media such as steam, air, or vegetable oils, which is generally a time-consuming process [21–26]. To be more convenient in practice, in this work, thermal modification of oil palm wood was undertaken via a heated plate in a hot press machine under an ambient environment, so that the heat could be directly transferred to the oil palm wood material, and the heat-treatment duration was expected to be shortened.
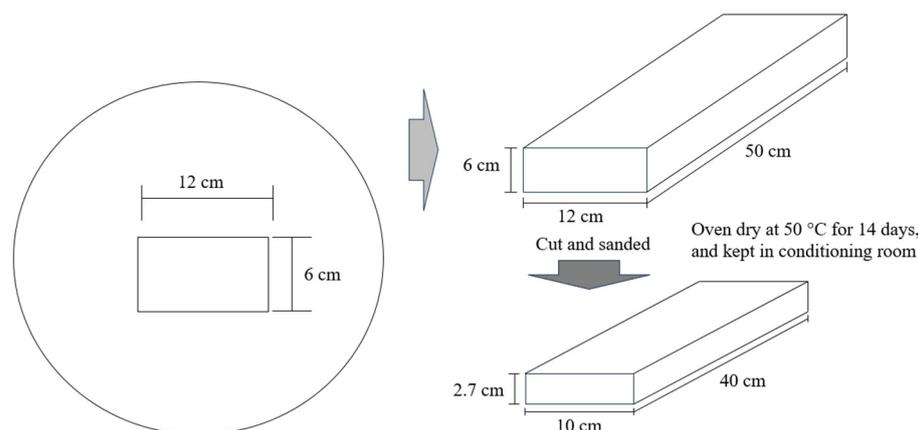
The objective of this study was to explore the potential of oil palm wood thermally modified (without compression or densification) via a hot press machine in an ambient environment, which can be easily done in practice, for use as raw material for producing non-load-bearing insulation walls in the form of a laminated product. Based on the work reported in the literature [23–25] and the preliminary work, a temperature as high as 200 °C was used for the heat treatment of oil palm wood to achieve an efficient insulation performance and avoid self-ignition (the preliminary work showed that if the temperature was higher than 200 °C, it caused ignition). The main focus was on determining the optimum heat-treatment duration (2 h, 4 h, and 6 h) regarding the examined properties (physical, dimensional stability, thermal and sound-insulation properties, and VOC emission) of TM oil palm wood.
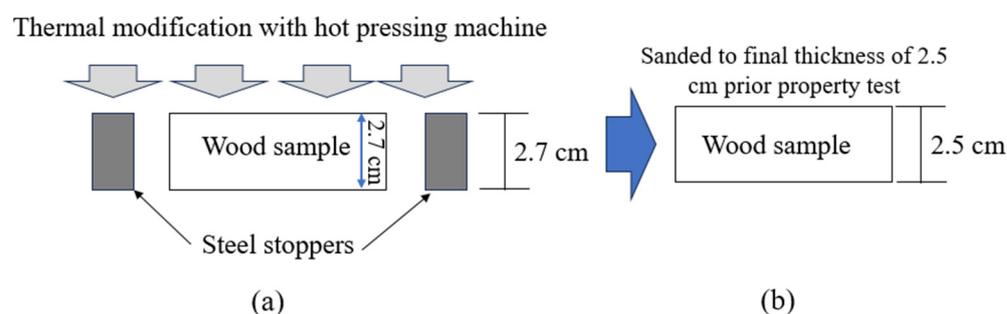
2. Materials and Methods

2.1. Preparation of TM Oil Palm Wood

The oil palm trees used in this study were harvested from the plantation area of Thasala district, Nakhon Si Thammarat province, Thailand. The age of the oil palm trees was approxi-

mately 30 years. After being felled, the trunks were cut into 50.0 cm logs, and each log was cut to obtain oil palm wood lumber in dimensions of 12.0 cm × 6.0 cm × 50.0 cm using a circular saw, as shown in Figure 1. Only the central parts were used for the experiment. The lumber was then oven-dried at 50 °C for 14 days, and the dried lumber was kept in a conditioning room at 20 °C with a relative humidity of 65% for about 1 month to equilibrate its moisture content to 12%. The density of the oil palm wood samples at this moisture content was then determined. The average density of the oil palm wood specimens was 219 ± 34 kg/m^3. These samples were cut and sanded to obtain the specimens in dimensions of 10.0 cm × 2.7 cm × 40.0 cm. These wood samples were then thermally modified using a hot press, which consisted of two heated plates (upper and lower plates), so that the heat was applied to the top and bottom surfaces of wood material simultaneously during the heat-treatment process. During thermal modification, two steel stoppers with the same thickness of 2.7 cm (equal to wood sample thickness) were placed between the wood samples to prevent the densification of wood, which could result in lowering its insulation properties (Figure 2). The wood samples were thermally modified at a temperature of 200 °C and three heat-treatment durations of 2 h, 4 h, and 6 h, respectively. The mass and moisture content of the wood samples before and after heat treatment were recorded for further analysis of mass losses described in the next section. A total of 69 TM oil palm wood samples were produced. Prior to the property tests (density, dimensional stability, thermal conductivity, and sound absorption), the wood sample was sanded to the final thickness of 2.5 cm (Figure 2b).

Figure 1. Preparation of oil palm wood specimens for heat treatment in a hot press machine.

Figure 2. (**a**) Thermal modification (without compression or densification) of oil palm wood using a hot press machine, and (**b**) wood sample sanded to the final thickness of 2.5 cm prior to property tests (density, dimensional stability, thermal conductivity, and sound absorption).

2.2. Property Tests of TM Oil Palm Wood

The mass loss, density, dimensional stability, sound-absorption coefficient, thermal conductivity, and volatile organic emission of the TM oil palm wood specimens were measured.

Mass Loss (*ML*)

Mass loss (*ML*) was calculated from the dried mass of the samples before and after heat treatment using the following equation:

$$ML(\%) = \frac{DM_b - DM_a}{DM_b} \times 100 \tag{1}$$

where DM_b: dried mass of the wood sample before heat treatment, DM_a: dried mass of the wood sample after heat treatment.

Density (ρ)

The density of the original and thermally modified oil palm wood was measured using small specimens in dimensions of 2.5 cm $\times$ 2.5 cm $\times$ 2.5 cm in accordance with ISO 13061 [27]. A total of nine samples were randomly selected for density measurement for each sample type. Before the test, the samples were kept in a conditioning room at 20 °C and relative humidity of 65% for about 2 weeks. The mass (*m*) and volume (*V*) of the wood specimens were measured for the determination of density using the following equation:

$$\rho = \frac{m}{V} \tag{2}$$

Dimensional Stability

Thickness swelling (*TS*) of the TM oil palm wood was examined. TS measurement was conducted on the specimens in dimensions of 2.5 cm (width, tangential direction) $\times$ 2.5 cm (length, longitudinal/fiber direction) $\times$ 2.5 cm (thickness, radial direction) in accordance with ISO 13061 [27]. The specimens were soaked in distilled water at 20 °C for 24 h. The thickness of the wood samples was measured before (TS_b) and after (TS_a) being soaked in water to determine the TS of the wood samples using the following equation
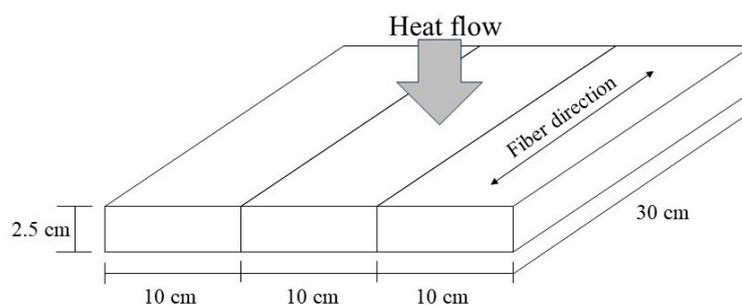
$$TS(\%) = \frac{TS_a - TS_b}{TS_b} \times 100 \tag{3}$$

Thermal Conductivity (*k*)

The thermal conductivity (*k*) of the original and TM oil palm wood samples was determined using a guarded hot-plate instrument. Three wood samples in dimensions of 10.0 cm $\times$ 30.0 cm $\times$ 2.5 cm were prepared and bonded at the edge using polyurethane to form a panel with dimensions of 30.0 cm $\times$ 30.0 cm $\times$ 2.5 cm for the measurement of thermal conductivity (see Figure 3), which was calculated using the following equation.

$$k = -\frac{q}{dT/dx} \tag{4}$$

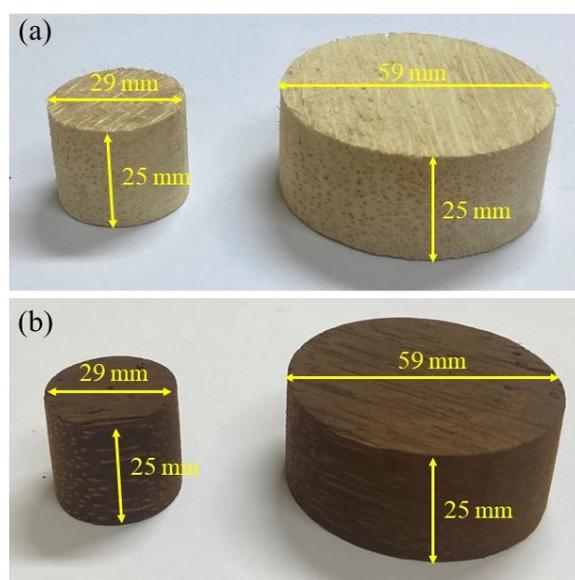where q = heat flux (W/m^2), dT/dx = temperature gradient (K/m).

Figure 3. Preparation of wood sample for thermal conductivity measurement.

Sound-Absorption Property

The sound-absorption coefficient (*SAC*) was determined using the impedance tube method in accordance with ASTM E 1050 [28], utilizing an SW466 model tube from BSWA. Measurements were taken from 25.00 mm-thick cylindrical specimens (See Figure 4), with diameters of 29.00 mm for sound absorption in the 2500–6000 Hz range, and 59.00 mm for the 400–2000 Hz range. The *SAC* was calculated by comparing the absorbed sound energy (*E*) to the total incident energy (E_0) using Equation (5). The average sound-absorption coefficient (α_{avg}) was determined by averaging the sound-absorption coefficient values at the frequencies of 500, 1000, 2000, and 4000 Hz (see Equation (6)), enabling a comparison of sound-absorption performance between different materials.

$$\alpha = \frac{E}{E_0} \tag{5}$$

$$\alpha_{avg} = \frac{\alpha_{500} + \alpha_{1000} + \alpha_{2000} + \alpha_{4000}}{4} \tag{6}$$

Figure 4. Oil palm wood specimens used for measuring sound-absorption coefficient: (**a**) Original oil palm wood, and (**b**) Thermally modified oil palm wood.
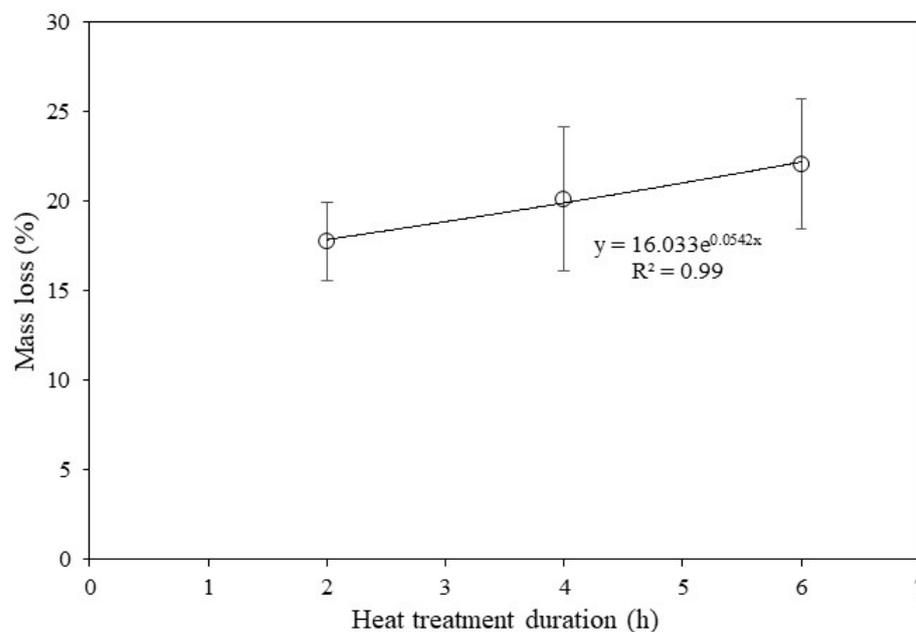
VOC Emissions

VOC emissions were measured using the static headspace method. Wood samples were cut into wood chips (size ~2–4 mm × 2–4 mm × 2–4 mm) using a knife, and 1 g of wood chips was placed in a 20 mL glass vial. The wood chip sample was incubated at 80 °C for 30 min, and 1 mL of headspace gas was injected (inlet temperature = 200 °C) into the gas chromatograph–mass spectrometer (GC-MS) (CG model: Agilent 7890B GC system, MS model: Agilent 7000C GC/MS Triple Quad, Ion source: EI, Agilent Technologies, Santa Clara, CA, USA). The CG column (HP-INNOWAX part no. 19091N-133 (30 m × 0.25 mm, 0.25 μm), Agilent Technologies, Santa Clara, CA, USA) was heated from 40 °C to 230 °C with the following steps: heated at 40 °C for 5 min and then raised to 230 °C at the rate of 10 °C/min and held for 5 min. The MS was scanned over the mass range of m/z 29–400. The detected VOCs were then analyzed and compared with those listed in the National Institute of Standards and Technology mass spectral library. Three replicates were performed for each sample type. The effect of lamination on VOC emissions was not evaluated in this study.

3. Results
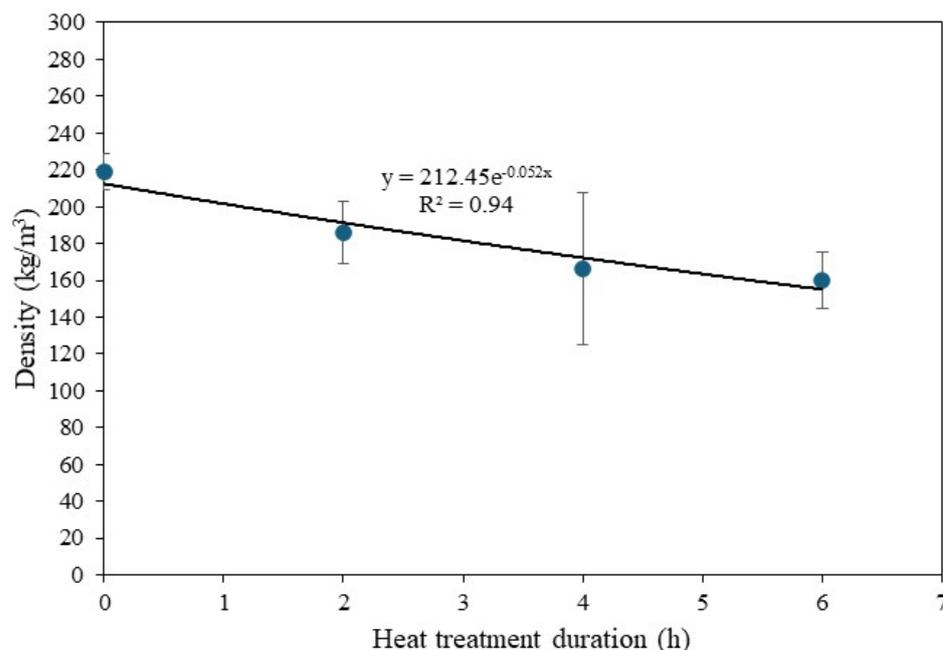
3.1. Properties of Thermally Modified Oil Palm Wood

3.1.1. Mass Loss and Density

Figure 5 shows the mass loss of the wood samples after heat treatment plotted against the heat-treatment duration. As expected, the mass of oil palm wood decreased after heat treatment due to the thermal degradation of the wood substance (i.e., hemicellulose depolymerizes when the temperature is higher than 160 °C [21]), and it tended to increase exponentially with the heat-treatment duration. The results were consistent with other studies in the literature, which found that longer heat-treatment duration resulted in more mass loss [25].

Figure 5. Mass loss of thermally modified oil palm wood at various heat-treatment durations.
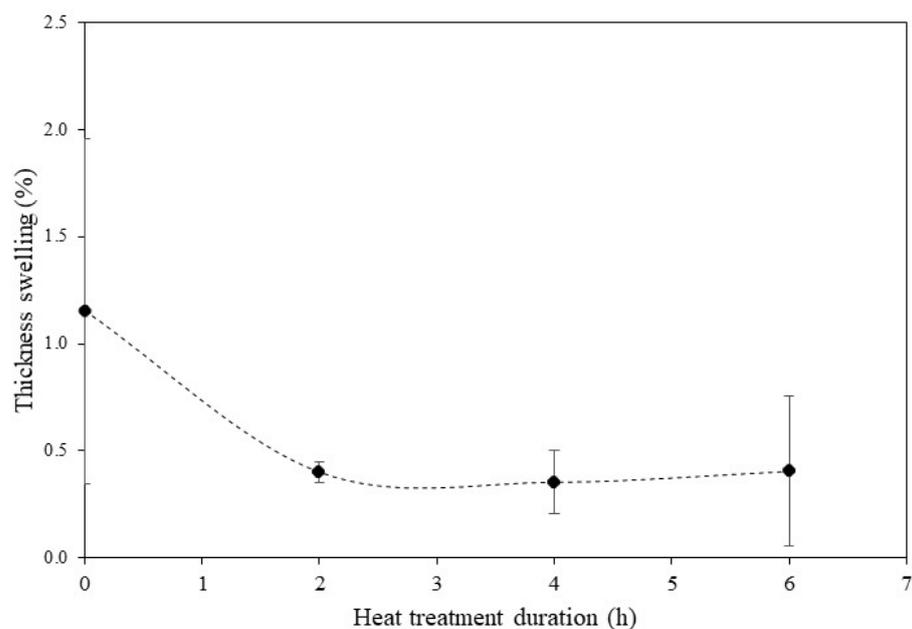
The densities of the TM oil palm wood were lower than those of the control (see Figure 6), consistent with the trend of the observed mass loss in TM oil palm wood mentioned earlier. It was also noticed that the TM oil palm wood densities tended to decrease exponentially with heat-treatment duration. This trend corresponded with other wood species heat-treated under a vacuum environment [25]. However, the decreasing rate of TM oil palm wood density was found to be higher. This was due to the heat from the hot plate being directly transferred to the wood sample, resulting in a more rapid degradation of the wood substance. The density of TM oil palm wood decreased by approximately 15%, 24%, and 27% at 2 h, 4 h, and 6 h, respectively, with respect to the control. The density of TM oil palm wood (ranging from 160 to 180 kg/m^3) was found to be relatively low compared with that of other natural materials such as low-density fiberboard, cork composites, and natural rubber foam (densities ranging from 260 to 520 kg/m^3) developed for use as insulation materials for wall applications [17–19]. Thus, it is expected that this material can provide better insulation performance, and this will be discussed in the next section.

Figure 6. Density of the original and thermally modified oil palm wood at 200 °C plotted against heat-treatment durations.

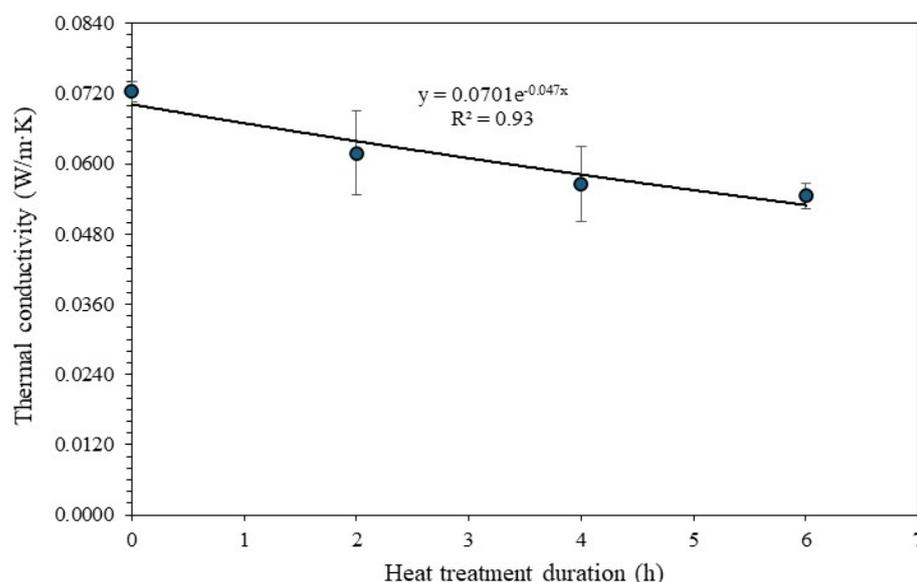### 3.1.2. Dimensional Stability

Figure 7 shows the thickness swelling (*TS*) of TM oil palm wood plotted against heat-treatment duration. It was found that thermal modification improved the dimensional stability of oil palm wood by approximately 66.7%. As can be seen in Figure 7, the TS of TM oil palm wood was lower compared with that of the control due to the reduced hygroscopic property of TM oil palm wood, which was a result of the chemical change in the wood cell walls during the thermal modification process [21]. However, the average *TS* at 2 h, 4 h, and 6 h varied by approximately 0.40%, indicating that heat-treatment duration did not affect the TS of TM oil palm wood.

Figure 7. Thickness swelling of 200 °C heat-treated oil palm wood at heat-treatment durations of 2 h, 4 h, and 6 h compared with that of the control (0 h).

3.1.3. Thermal Conductivity

The thermal conductivity of TM oil palm wood and the control are shown in Figure 8. It was found that the thermal conductivity of TM oil palm wood was lower than that of the control and tended to decrease with heat-treatment duration. They were 0.0724 ± 0.0017 W/m·K, 0.0618 ± 0.0072 W/m·K, 0.0565 ± 0.0064 W/m·K, and 0.0546 ± 0.0022 W/m·K for the control and TM oil palm wood at 2 h, 4 h, and 6 h heat-treatment durations, respectively. This was because the density of TM oil palm wood was lower than that of the control, so that its heat conduction capability was lower. It should be noted that the value of TM oil palm wood was approximately half that of typical wood species [29]. Compared to TM paulowna wood with the similar original density (237 kg/m^3) to original oil palm wood used in this work (219 kg/m^3), which was heat-treated at the same temperature of 200 °C with typical heat-treatment process (heat-treated in a vacuum environment) [25], it was found that the decrease in amount of thermal conductivity of TM oil palm wood at 6 h heat-treatment duration (24.6%) was approximately 9.5 times higher than that of paulownia heat-treated for 35 h (~2.6%). This indicates that the thermal modification of oil palm wood in a hot press machine could effectively improve thermal insulation with a relatively short heat-treatment duration.
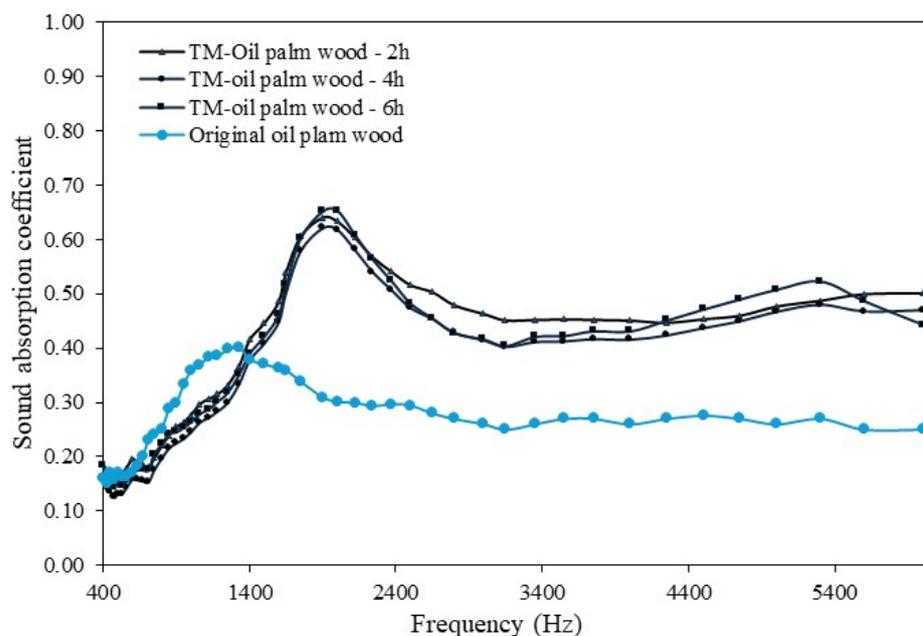

Figure 8. Thermal conductivity of heat-treated oil palm wood at temperature of 200 °C and heat-treatment durations of 2 h, 4 h, and 6 h compared with that of the control (0 h).

Compared with other natural materials developed for use as insulation walls, it was found that thermal conductivity of TM oil palm wood at 6 h heat-treatment duration (0.0546 W/m·K) was approximately 0.6–0.7 times lower than that of low-density fiberboard (0.078 W/m·K) [17], cork composites (0.072 W/m·K) [18], and natural rubber foam (0.09 W/m·K) [19]. Thus, the walls made of TM oil palm wood could provide a more energy-efficient solution.

3.1.4. Sound-Absorption Coefficient

The sound-absorption coefficient (averaged from three samples) of the original and TM oil palm wood plotted against frequency is shown in Figure 9. They are similar to each other in shape. Sound absorption is a phenomenon in which the sound wave energy is converted into thermal energy through a friction mechanism within the cavities [30,31]. Thus, more sound energy is anticipated to be absorbed as wood porosity increases through TM. The average sound-absorption coefficient (α_{avg}) of TM oil palm wood ranged from 0.35 to 0.38, which was higher than that of the original wood (0.30), indicating that the sound-
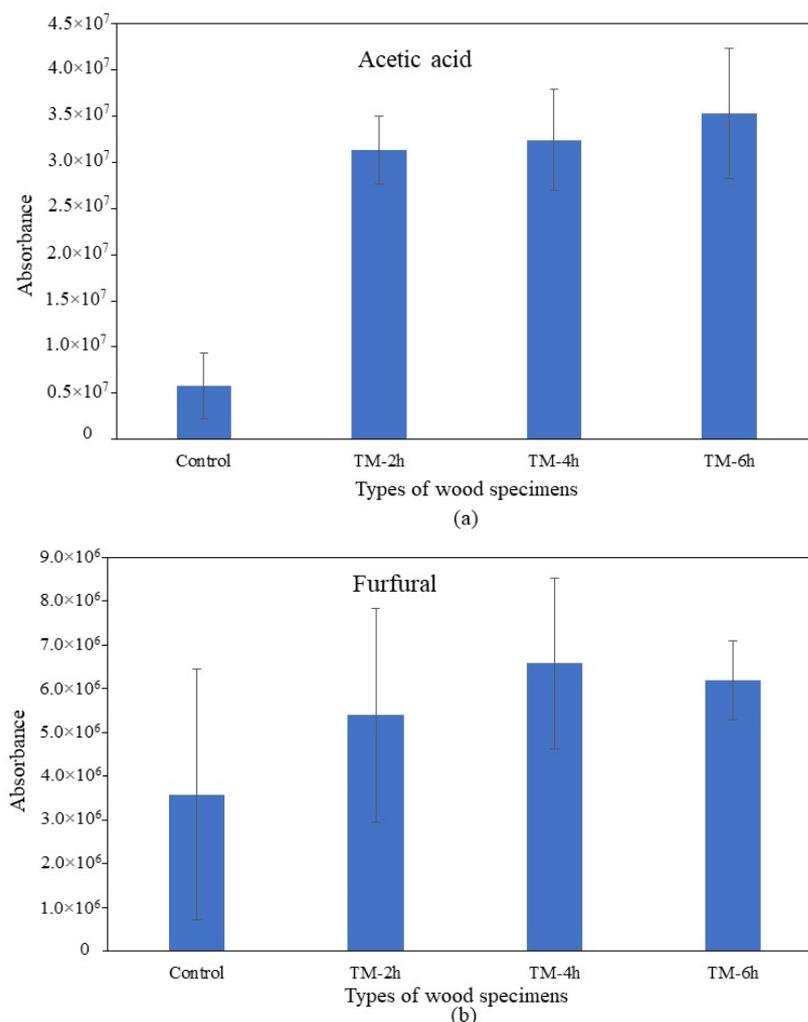
absorption performance of oil palm wood was improved after heat treatment; however, the heat-treatment duration did not affect the sound-absorption performance. Specifically, TM oil palm wood outperformed the control in absorbing high-frequency sound ranging from 2000 Hz upwards. These observations suggest that this material can be attractive for applications in environments where controlling noise is essential for privacy, comfort, or performance, such as classrooms and meeting rooms. Additionally, the average sound-absorption coefficient (α_{avg}) of TM oil palm wood (0.35–0.38) was comparable to that of a coconut fiber sound absorber ((α_{avg})~0.37) at a thickness of 20 mm [31], indicating TM oil palm wood's strong sound-insulation performance.

Figure 9. Sound-absorption coefficient of original and thermally modified oil palm wood at a frequency range of 400–4000 Hz. TM oil palm-2 h: Thermally modified oil palm wood with heat-treatment duration of 2 h; TM oil palm-4 h:Thermally modified oil palm wood with heat-treatment duration of 4 h; and TM oil palm-6 h: Thermally modified oil palm wood with heat-treatment duration of 6 h.

3.1.5. Volatile Organic Compound Emission

Major VOCs in softwood, such as terpenes and hexanal, can easily evaporate during thermal treatment. However, new VOCs may form due to the thermal degradation of wood components like cellulose, hemicellulose, and lignin at high temperatures [26,32]. Since oil palm wood was thermally modified at 200 °C, this research focused on furfural and acetic acid emissions, which the thermal degradation of hemicellulose could generate [26,32]. As shown in Figure 10, the acetic acid and furfural emissions from oil palm wood increased after thermal modification, which followed the trend reported for thermally modified softwood and hardwood species [26,32]. The increased amount of acetic acid and furfural in TM oil palm wood resulted from deacetylation and decomposition, respectively, of hemicellulose [26,32]. In addition, it was also found that the increased amount of acetic acid seemed to be higher than that of furfural, and both VOCs tended to be similar for all heat-treatment durations.

Figure 10. Volatile organic compound (VOCs) emission of original (control) and 200 °C thermally modified oil palm wood at 2 h (TM-2h), 4 h (TM-4h), and 6 h (TM-4h) (**a**) acetic acid and (**b**) furfural.

4. Conclusions

Conclusions can be drawn as follows:

1. The thermal modification (TM) of oil palm wood via a hot press machine improved dimensional stability and thermal and sound-insulation properties but triggered more volatile organic compound (VOC) emissions, suggesting that it should be reduced or prevented to avoid the impact on human health.

2. Heat-treatment duration exponentially decreased density and thermal conductivity but increased mass loss due to the thermal degradation of wood substance. The sound-absorption coefficient, thickness swelling, and VOC emission appeared to be similar at all heat-treatment durations.

3. Compared with the available natural materials developed for use as wall insulation, the TM oil palm wood showed superior insulation performance for all heat-treatment durations. Thus, it had potential for an insulation-efficient and dimensionally stable wall application.

4. Regarding the benefit of the heat-treatment duration, the heat-treatment duration of 2 h is suggested to save energy consumption during the heat-treatment process while still achieving the same level of dimensional stability, sound absorption, and VOC emission performance as that of the long heat-treatment duration. However,

if the thermal conductivity is the major performance criterion to achieve, a long heat-treatment duration is recommended.

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