

Research Article

Formaldehyde-Free Wood Composite Fabricated Using Oil Palm Starch Modified with Glutardialdehyde as the Binder

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Oil palm trunk is a kind of biomass rich in starch content. Oil palm trunk waste was available throughout the year in Malaysia and Indonesia due to continuous felling of nonproductive, over 25-year-old trees. Even though some manufacturers were using it in plywood and veneer production, they are hard to handle which later becomes less favorable raw materials due to a high moisture content where combination with a high starch content quickly attracts fungus and wood-decaying agents. The objective of this work was to evaluate properties of experimental wood composite panels, manufactured using oil palm-extracted starch modified with glutardialdehyde (OPSMG) as a binder. Different analyses were employed to characterize the properties of the samples besides evaluation of bending, internal bonding strength, and dimensional stability of the panels. Characterization on the functional group using the FT-IR analysis showed presence of aldehyde groups and ketone stretching vibrations at 1736.05 cm^{-1} and 1596.25 cm^{-1} , which proves the presence of glutardialdehyde besides formation of bonding between the OPSMG and the woody materials. The XRD analysis showed the starch modification had lowered the crystallinity index which in turn increased the strength of the manufactured wood composites. The OPSMG wood composites were also found to have lower thermal stability, as evaluated using the TGA analysis. It was recorded that the maximum modulus of rupture for OPSMG wood composites was achieved at the 0.80 g/cm^3 density level with an average value of 15.446 N/mm^2 which showed 38.00% increment in strength between those two types of wood composites. Thickness swelling after immersion in water can still be improved by incorporating the moisture-repellent material later. After analyzing the results, it was concluded that modified oil palm starch has the potential to be used as an environment friendly binder for wood composite making.

1. Introduction

Wood composite is one of the most commonly used interior composite panel products manufactured from sawmill waste and fast grown species in many countries for the last 60 years. It is fact that more sustainable use of forest resources triggered development of research projects related to biomass as the raw material for such panels. Trend toward using the forest logging residue and different types of agricultural waste as the raw materials in the wood composite manufacture has been great in the last decades [1]. Urea formaldehyde is most widely used adhesive in this industry due to its low cost, resulting in products with superior

properties [2]. Similar to all formaldehyde-based adhesives such as melamine formaldehyde, phenol formaldehyde, and resorcinol formaldehyde, urea formaldehyde has an issue of formaldehyde emission which could cause hazard to human health including sensory irritation and risk of developing cancer [3]. Therefore, there has been many trials to find alternative ways to reduce the emission by studying the factors that trigger the formaldehyde emission such as wood species, resin type, level of condensation, the initial moisture content of the wood particles, the type of the hardener and amount used, the type of additives and its amount, pressing parameters, and conditioning following the panel manufacture [4]. There are some works that have been carried out

by finding formaldehyde-free binders such as natural latex, modified soy bean flour, tannins resin blended with cashew nut shell liquid, soy protein isolate, wheat gluten, and starch [5–10].

Starch is a carbohydrate polymer consisting of glucose units by α -glycosidic bonds. It can be divided into two groups based on its structure, the linear starch polymer as an amylose, and the branching type called an amylopectin with the portion of unit depending on the source of the starch [11]. Modified starch had been used to manufacture various types of wood composite panels as environmental friendly value-added products. Starch glue or vegetable glue has been modified by different researchers to form various types of modified starches such as starch-polyvinyl alcohol adhesive, corn starch blended with mimosa tannin, and allylglycidyl-ether modified starch to be used in wood composite manufacturing [12–15].

Without modification, starch was used as a binder in their native form by Ozemoya et al. [16], Wang et al. [17], and D'Amico et al. [18]. Some modification trial was done to produce carbamoyl ethylated starch through acrylamide to modify corn starch. As the result, this modification gives good adhesion properties to textile fibers [19]. Other approach was done by Moubarik et al. [20] by mixing native corn starch with tannin in order to bond wood veneers. Another trial by Moubarik et al. [14] was done by using the same mixture with additional urea formaldehyde to improve the binder's properties. The resulted wood composites showed improved properties when compared to urea formaldehyde-bonded wood composite in terms of internal bonding strength (0.57 N/mm^2), modulus of rupture (17.00 N/mm^2), and modulus of elasticity (3090 N/mm^2). Meanwhile, other researchers had crosslinked starch with polyvinyl alcohol which later increases their shear force resistance of the adhesive from 1000 kg of using native starch to 2700 kg [13]. The most recently used modified starches for manufacture of wood composites were epichlorohydrin-modified starch [21, 22], glutardialdehyde-modified starch [23, 24], and carboxymethyl-modified starch [25].

The source of starch, the oil palm tree, initially originated from West Africa [26]. Both Malaysia and Indonesia have the advantage of location within 10 degrees latitude of the equator which is ideal for oil palm cultivation without having a serious drought problem that could adversely influence the overall yield of the crops [27]. Oil palm plantation generates a large amount of biomass waste. As the world's first and second largest oil palm production country, over 55 million hectares and 5 million hectares of the land area are palm oil plantation areas in Indonesia and Malaysia, respectively [28]. For each kilogram of palm oil produced, roughly another 4 kg of dry biomass was generated where one-third was generated from fruit bunches while another two-thirds were produced from the trunk and frond material [29]. Unfortunately, such biomass is not used as efficiently as it should be. In a previous research, it was also found that starch can be extracted to a yield of 7.15% from oil palm biomass [30].

Considering the potential of the huge amount of oil palm biomass available, this work investigates the suitability of oil

palm starch modified using glutardialdehyde as a binder for wood composite manufacturing. Glutardialdehyde (GDA) was obtained in colorless organic compound with the formula $\text{CH}_2(\text{CH}_2\text{CHO})_2$. It is commonly used as the chemosterilizing agent for different medical equipment [31]. Glutardialdehyde or also called glutaraldehyde was chosen in this work as many researchers had successfully utilized it in improving the properties of chitosan/corn cob bio-composite films [32] and thermoplastic starch [33, 34], where the improvement in tensile strength, tensile modulus, tear, and burst of the starch film happened [35].

2. Materials and Methods

2.1. Raw Material Preparation and Extraction of Oil Palm Starch. Rubberwood particles for wood composite making were obtained from Heveaboard Sdn Bhd, in Negeri Sembilan, Malaysia, for panel manufacture. Raw material was dried at a temperature of 50°C in an oven until the moisture content of the particles reaches 2%. Oil palm trunks were obtained from Kuala Lumpur Kepong oil palm plantation in Kedah, Malaysia. Freshly cut oil palm trunks were stored in large freezers to keep their freshness before further use. The glutardialdehyde 25% used for starch modification was purchased from Merck chemical company.

Fresh oil palm trunks were chipped into smaller pieces with an approximate dimension of $2 \text{ cm} \times 2 \text{ cm} \times 4 \text{ cm}$. Sodium metabisulphite of 0.5% concentration was prepared for the extraction process. Chipped oil palm trunks of 100 g were soaked in 1000 mL of 0.5% sodium metabisulphite for 24 h [22]. The extraction solution was filtered through a $125 \mu\text{m}$ sieve to remove impurities before it was kept to settle for 60 min. The supernatant of the starch suspensions was removed carefully by tilting the container without removing the starch at the bottom of the container. Later 100 ml of distilled water was added to the remaining solid before it was centrifuged at 4000 rpm for 20 minutes employing Beckman Coulter Allegra X-15R centrifuge. A Buchner funnel fitted with $1.6 \mu\text{m}$ pore-size fiber-glass filter was used to expel excess moisture by suction. Finally extracted starch was dried in an oven at a temperature of $45 \pm 5^\circ\text{C}$ overnight [30].

2.2. Modification of Oil Palm Starch and Panel Manufacture. The oil palm starch powder was dissolved in distilled water at a temperature of $30 \pm 5^\circ\text{C}$ and stirred. The temperature was increased slowly up to 50°C . After addition of glutardialdehyde solution 25%, the temperature was further increased up to 90°C [24].

Based on the literatures, the suitable target densities of the manufactured wood composites will be set between 0.60 g/cm^3 and 0.90 g/cm^3 . Most works choose one to three different density levels to study its effect on the performance of the wood composites [22, 36–39]. Therefore, wood composite panels were made using oil palm starch modified using glutardialdehyde (OPSMG) as a binder in three density levels, namely, 0.60 g/cm^3 , 0.70 g/cm^3 , and 0.80 g/cm^3 . A set of wood composite samples was manufactured using native oil palm starch (OPS) as control samples.

A total of 30 panels were produced with 5 replicates for each density levels. Fifteen percent of modified oil palm starch was weighed and mixed manually as homogeneous as possible with rubberwood particles. The formed mat was cold pressed for 5 seconds before being hot pressed using Carver hot press using 5 MPa pressure at a temperature of 165°C for 20 min. Manufactured wood composites were conditioned in a climate room with a temperature of 20°C and a relative humidity of 65% for 2 weeks before they were cut into test samples according to the required dimension for each test. Replicates of 30 were prepared for density measurement, and 15 replicates were used for other tests including moisture content, thickness swelling, water absorption, bending strength, and internal bond strength evaluations [40].

2.3. Characterization of Starch. The solubility and swelling power determination were carried out following the method by Builders et al. [41]. Oil palm trunk starch was diluted in distilled water at 5% w/w. The starch suspensions were heated at temperature levels of 50, 60, 70, 80, and 90°C for 30 min. The hot dispersions were cooled to room temperature before being centrifuged at 2000 rpm using GS-15 Centrifuge, Beckman, Germany, for 10 min. The supernatant formed was removed. The solubility and swelling of oil palm trunk starch were also determined as the weight of sediment over the dry weight of starch based on the following equation:

$$\text{solubility (\%)} = \frac{\text{mass of starch in supernatant (g)}}{\text{mass of starch in aliquot (g)}} \times 100,$$

$$\text{swelling power (\%)} = \frac{\text{mass of wet residue (g)}}{\text{mass of dry residue (g)}} \times 100.$$

(1)

2.4. Microcharacterization of the Panels. Scanning electron microscopy (SEM) analysis was done to determine the distribution of the binder between the wood particles. The infrared spectra of the wood composite were measured using the FT-IR spectrophotometer (Nicolet, AVATAR FT-IR-360) equipped with Omnic software. Wood composite ground particles were mixed with KBr fine powder to produce the pellets. The samples were scanned in the range of 4000–470 cm⁻¹ to characterize the functional group inside the wood composite.

The X-ray diffraction analysis was carried out using Diffractometer D5000 Kristalloflex, Siemens. Powdered wood composites samples were evaluated for their crystallinity by step scan measurements using X-rays (Cu-Ka) set at 40 kV and 40 mA. Scanning of 2θ was done from 10.0° to 40.0°. Scanning speeds were adjusted to 2°/min [42]. The crystallinity index (CrI) was calculated as follows:

$$\text{CrI (\%)} = \frac{(I_{200} - I_{\text{am}})}{I_{200} \times 100}, \quad (2)$$

where I_{200} is the peak intensity corresponding to crystalline fraction and I_{am} is the peak intensity of the amorphous fraction.

The thermal decomposition of the manufactured wood composites was evaluated using Mettler Toledo TGA/SDTA 851 thermogravimetric analyzer. Approximately about 5–10 mg was placed in an aluminum pan with a heating rate of 20°C min⁻¹ under a nitrogen atmosphere. The weight changes of the samples were recorded by heating samples from a temperature of 30 to 800°C [43].

The differential scanning calorimeter (DSC) Pyris 1 PerkinElmer was used to evaluate the behavior of the samples towards temperature at a heating rate of 10°C/min. About 7 mg of the grounded wood composite sample was added to an aluminum pan and sealed entirely, and an empty sealed aluminum pan was used as a reference. The aluminum pan with the sample was heated from -10°C to 280°C at the respective heating rate.

2.5. Evaluations of Physical and Mechanical Properties of the Panels. The flexural strength and internal bond strength of the samples were tested using Instron Machine Model 5582 equipped with a load cell having 1,000 kg each. The cross-head speeds were set at 10 mm/min and 2 mm/min for bending and internal bonding strength test, respectively. Thickness swelling and water absorption of the samples were also evaluated to determine dimensional stability of the samples. They were carried out by soaking 50 mm × 50 mm × 5 mm samples in distilled water for 2 hours and 24 hours. Increment of thickness and weight of the specimens were measured at each time period and expressed in percentage. All tests were done based on Japanese Industrial Standard [44].

3. Results and Discussion

3.1. Characterization of Starch and the Panels. Table 1 displays the solubility and swelling power of OPS and OPSMG. Solubility and swelling power of both types of starches increased with increasing temperature. It was also found that crosslinking had reduced the solubility and swelling power of starch, suggesting that wood composites made with oil palm starch modified with glutardialdehyde as the binder will have better dimensional stability towards moisture.

Micrographs taken from the samples on SEM are illustrated in Figures 1(a) and 1(b). The high compactness of the wood fiber at a density level of 0.80 g/cm³ can be seen in Figure 1(a), while Figure 1(b) shows the modified starch in the samples. Images were taken at 1000x and 3000x magnification, respectively.

Fourier transform infrared (FT-IR) spectroscopy of powdered samples from wood composite made using OPSMG and OPS as the binder is shown in Figure 2. In the case of wood composite powder made using OPS, most of the peaks revealed the presence of hydroxyl and hydrocarbon groups, detected at 3377.52 cm⁻¹, 2919.39 cm⁻¹, 1374.77 cm⁻¹, and 1330.82 cm⁻¹. For OPSMG wood composite powder, peaks at 3395.48 cm⁻¹ and 1331.63 cm⁻¹ showed the presence of hydroxyl groups, detected from wood and starch polymers. Peaks at 1736.05 cm⁻¹ and

TABLE 1: Solubility and swelling power of OPS and OPSMG.

Starch	Temperature (°C)	Solubility (%)	Swelling power (g/g)
OPS	50	5.60	7.80
	60	9.51	19.32
	70	16.35	19.51
	80	24.26	25.57
	90	28.50	33.83
OPSMG	50	4.93	5.21
	60	5.98	7.56
	70	13.04	8.65
	80	16.97	19.38
	90	21.77	23.68

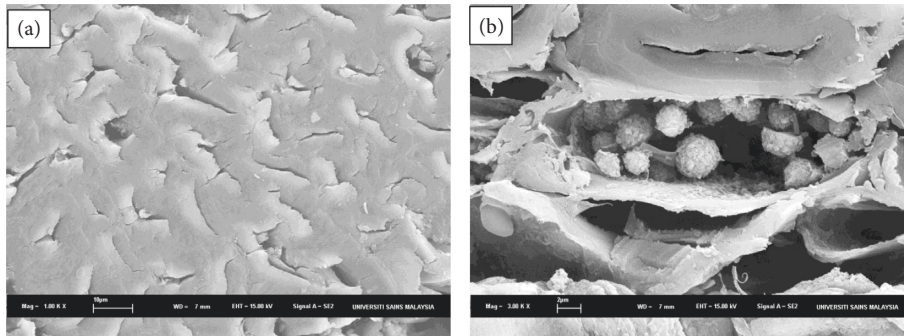


FIGURE 1: SEM image of wood composite made using oil palm starch modified with glutardialdehyde at 1000x (a) and 3000x (b) magnification.

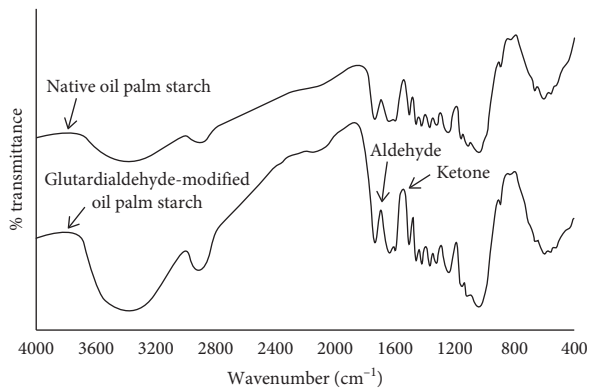


FIGURE 2: FT-IR spectra of powdered samples from wood composite made using OPSMG and OPS.

1596.25 cm^{-1} prove the presence of aldehyde groups and ketone stretching vibrations, respectively [45]. Detection of aldehyde groups showed the presence of glutardialdehyde in the powdered sample, while ketone group detection showed formation of bonding between the oil palm starches modified using glutardialdehyde and the woody materials [46].

3.2. X-Ray Diffraction Analysis (XRD). Figure 3 illustrates the X-ray diffraction pattern of powdered samples made using OPSMG and those manufactured using OPS as the binder. The X-ray diffraction pattern of powdered OPS wood composite shows higher peaks, reflecting higher crystallinity of the wood composite powder compared to those of

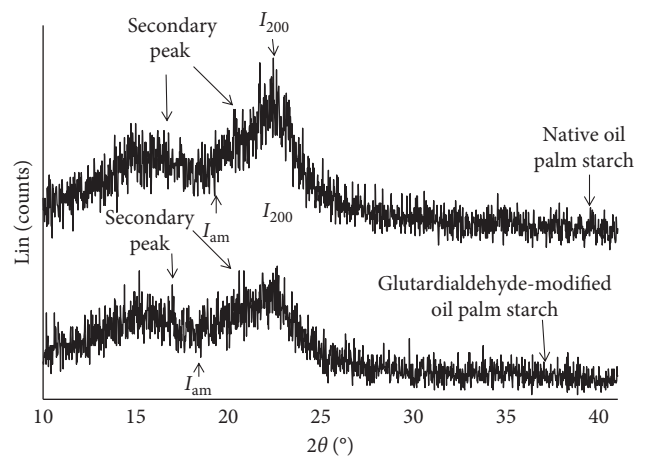


FIGURE 3: X-ray diffraction pattern of powdered samples from wood composite made using OPSMG and OPS.

modified starch wood composite powder. Major intensity peaks at 2θ were observed near 23° for both wood composite powders, related to their crystalline structure. Secondary peaks were found at $2\theta = 14.74^\circ$ and $2\theta = 21.69^\circ$ for OPS wood composite powder, while for OPSMG, wood composite powders were found at $2\theta = 15.19^\circ$ and $2\theta = 20.58^\circ$. For the peak intensity of the amorphous fraction (I_{am}), peaks were found at $2\theta = 19.26^\circ$ and $2\theta = 18.5^\circ$ for native and modified oil palm starch wood composite powder, respectively. The calculated crystallinity indexes yielded 68.60% and 24.56% for native and modified oil palm starch

wood composite powder, respectively. Amorphous condition of OPSMG powder resulted in better binding properties of the adhesive, supported by the results in the mechanical strength properties where OPSMG wood composite had a higher mechanical strength than those made from OPS.

3.3. Thermal Gravimetry Analysis (TGA). The thermal gravimetry analysis was done to determine the effect of temperature towards decomposition of wood composite. Figure 4 shows the thermal gravimetric analysis (TGA) and derivative thermal gravimetric analysis (DTGA) curves for OPS wood composite powder and OPSMG wood composite powder.

Initial weight reduction of both samples at low temperature could be due to the evaporation of moisture, breaking of water linkage, while the second step may correspond to the degradation of the whole wood composite polymer [47]. Thermal decomposition of cellulose materials was taking place between 200°C and 400°C [48]. It could be observed from the DTGA curves that fastest degradation of samples were at 354.43°C and 354.52°C for native oil palm wood composite and OPSMG wood composite, respectively. Between the two temperatures of 185.2°C and 482.8°C, samples made with starch modified using glutardialdehyde showed a higher decomposition of 70.88% of weight reduction compared to that of native oil palm wood composite sample having only 67.34% reduction within the same temperature range. At the end of the experiment which was 700°C of temperature, the OPS wood composite sample still had higher residue than the OPSMG wood composite sample which were 21.12% and 17.09%, respectively. This phenomenon could be explained using the X-ray diffraction pattern. It was suggested in [49, 50] that material with a higher crystallinity index had a higher thermal stability. Consequently, samples manufactured with starch modified using glutardialdehyde degraded more, as they have a higher amorphous portion than those made from virgin oil palm starch.

3.4. Differential Scanning Calorimetry (DSC). Figure 5 showed the differential scanning calorimetry curves of the OPS wood composite powder and OPSMG wood composite powder. DSC is an instrument to estimate the thermal transition of modified starch and wood composite made using modified starch which reflects the quality of chemical bonding [51, 52]. It was observed that the OPSMG wood composite powder has a higher melting point temperature which is 88°C compared to 80°C for the OPS wood composite powder, where the melting point is the point polymer melt or the energy per mass unit released when an amorphous portion of a crystalline polymer crystallizes, and the OPSMG wood composite powder also required higher energy for the melting process which was 6.37 mW compared to 5.41 mW for the OPS wood composite powder. This was because higher energy was needed to break the linkages in the OPSMG wood composite powder.

3.5. Physical Properties of the Samples. Table 2 displays moisture content and density of the samples made using

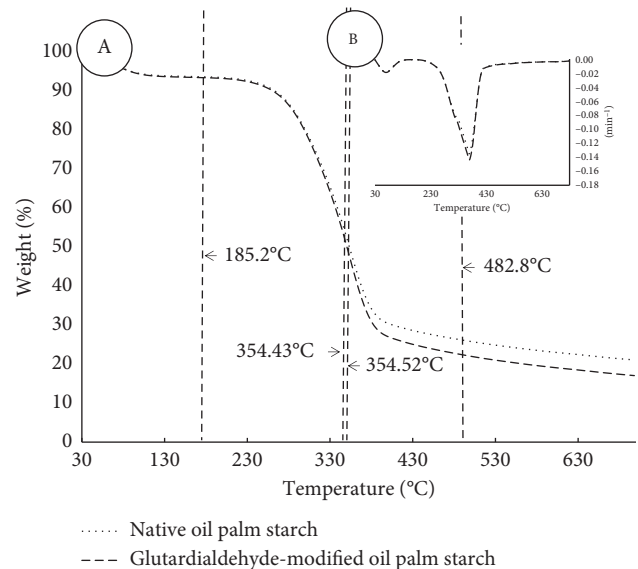


FIGURE 4: Thermal gravimetric analysis (A) and derivative thermal gravimetric analysis (B) curve for OPS wood composite powder and OPSMG wood composite powder.

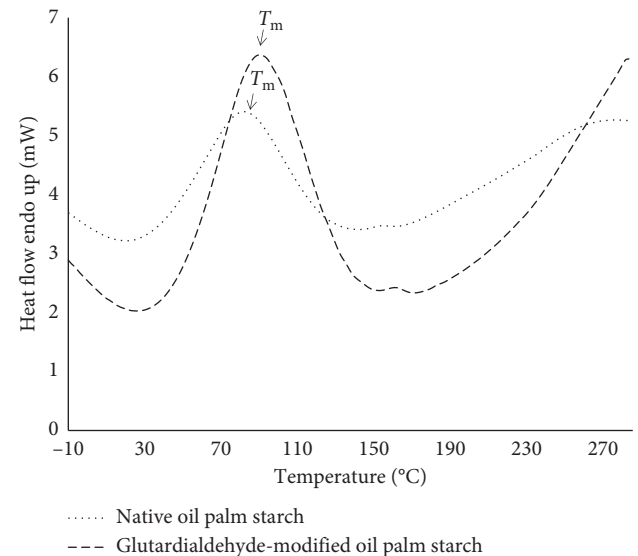


FIGURE 5: Differential scanning calorimetry curves of the OPS wood composite powder and OPSMG wood composite powder.

native and modified oil palm starch as a binder, respectively. The moisture content of the wood composites was around 5% to 6.4%. The measured densities of the wood composites satisfied the required value of density for the wood panels. Statistical analysis in Table 2 showed a significant difference existed between different density levels of wood composites, which reflect that the panels were manufactured according to their respective, predetermined density levels.

Thickness swelling and water absorption of wood composites after immersion in water were carried out for the 2 h and 24 h period. Table 2 showed the results for thickness swelling and water absorption of the manufactured wood composites, sorted according to their density levels. The

TABLE 2: Statistical analysis for wood composites made using OPS and OPSMG as a binder.

Panel type	Target density (g/cm ³)	Measured density (g/cm ³)	Moisture content (%)	Thickness swelling (%)		Water absorption (%)		Bending test (N/mm ²)		Internal bonding strength (N/mm ²)
				2 h	24 h	2 h	24 h	Modulus of elasticity	Modulus of rupture	
OPS	0.60	0.56 (0.07) ^a	5.72 (0.02) ^a	70.20 (17.32) ^a	78.93 (21.61) ^a	140.17 (15.92) ^a	213.26 (47.68) ^a	661.20 (192.73) ^a	2.80 (0.75) ^a	0.08 (0.02) ^a
	0.70	0.67 (0.07) ^b	5.54 (0.07) ^b	83.98 (20.74) ^{ab}	89.44 (24.03) ^a	145.51 (10.15) ^a	177.32 (6.23) ^b	1860.06 (450.77) ^b	8.15 (2.86) ^b	0.10 (0.01) ^b
	0.80	0.76 (0.12) ^c	6.10 (0.14) ^c	100.69 (19.07) ^b	109.07 (13.53) ^b	146.02 (28.29) ^a	178.79 (32.36) ^b	2569.77 (409.38) ^b	9.58 (1.25) ^c	0.22 (0.01) ^c
OPSMG	0.60	0.57 (0.10) ^a	6.40 (0.44) ^a	57.38 (19.84) ^a	67.95 (24.78) ^a	130.38 (7.26) ^a	165.47 (8.28) ^a	2057.54 (345.90) ^a	7.15 (2.15) ^a	0.43 (0.05) ^a
	0.70	0.67 (0.10) ^b	5.27 (0.20) ^b	60.88 (14.67) ^a	72.46 (17.84) ^{ab}	121.84 (11.96) ^b	162.18 (15.88) ^a	2354.23 (175.51) ^a	7.78 (1.66) ^a	0.45 (0.06) ^a
	0.80	0.75 (0.10) ^c	5.56 (0.06) ^b	80.89 (13.99) ^b	97.60 (10.08) ^b	128.79 (4.40) ^b	163.49 (9.99) ^a	3944.62 (957.70) ^b	15.45 (5.56) ^b	0.59 (0.06) ^b

*Different letters in a same column and same panel type show a significant difference at α value of 0.05; **values in parenthesis are the standard deviation.

lowest thickness swelling of wood composites made using OPSMG as the binder was 57.38% and 67.95% for 2 h and 24 h of immersion, respectively, while the highest was 80.89% and 97.60%, respectively. This is lower than the lowest thickness swelling of wood composites made using OPS as the binder which was 70.20% and 78.93% for 2 hours and 24 h of immersion, respectively. Meanwhile, the highest thickness swelling of wood composites made using OPS as the binder was recorded at 100.69% and 109.07% for 2 h and 24 h of immersion, respectively. The water absorption was also lower for wood composites made using OPSMG as the binder, which were 121.84% and 162.18% for 2 h and 24 h of immersion, respectively, while the highest was 130.38% and 165.47%, respectively. Wood composites made using OPS, on the contrary, had the lowest water absorption of 140.17% and 177.32% for 2 h and 24 h of immersion, respectively, while the highest was 146.02% and 213.26%, respectively. Thickness swelling properties of both types of wood composites did not satisfy the Japanese Industrial Standard, which allow only 25% thickness swelling for panels with a thickness of 12.7 mm and below [44]. This drawback of using starch as the raw material for making wood binder warrant further investigation.

The results also showed increments of thickness swelling as the density level were increased from 0.60 g/cm³ to 0.80 g/cm³. This happened because of a higher amount of wood particles in higher density wood composites. More wood will absorb more moisture, so the panel will expand more in the water because of hygroscopicity of wood and breakage of the binder system. Water absorption showed a different trend, except for 2 h thickness swelling for wood composites made using OPS as a binder. The results of water absorption properties did not follow the trend because the amount of water that penetrates into the test pieces is not uniform throughout the surface and small particles may be disintegrated from the test piece. The results also revealed that the thickness swelling and water absorption for 24 h are always higher than the thickness swelling and water absorption for 2 h. This could occur because a longer exposure

to water gives more time for the moisture to penetrate into the test piece and a higher binder breakage and leads to more expansion of the dimensions of test pieces. The more crucial finding from the test results were the thickness swelling and water absorption of wood composites made using OPSMG are always lower than wood composites made using OPS. Figure 6 showed a normalized chart, representing the reduction of thickness swelling and water absorption when using OPSMG as the binder for the wood composites, compared to wood composites made using OPS as the binder. From the results, it was found that using OPSMG as the binder for wood composite reduces the thickness swelling for at least 10.98% and water absorption at a minimum of 9.80%. Reduction of 24 h water absorption for wood composites of 0.60 g/cm³ density level was remarkably high. This is probably because the wood composites made using OPS as the binder with a low-density level has many voids that could hold so much water or the native starch itself was highly hydrophilic material that leads to a higher water absorption value. Therefore, when calculated, the difference of water absorption, compared to the wood composites made using OPSMG as the binder, becomes so high. Statistical values in Table 1 showed the results of thickness swelling and water absorption were not quite significant to each other.

3.6. Mechanical Properties Evaluations. Flexural strength testing of the wood composites yielded two beneficial results which are the modulus of elasticity and modulus of rupture, expressed in N/mm². Flexural strength is an essential characteristic of a wood panel as it reflects the ability of the composite material to withstand a certain amount of load before it breaks. This is crucial for wood panels involved in application for furniture and wall paneling industries.

The first result is the modulus of rupture which reflects the maximum load or capacity of a material could withstand before failure. It is well accepted to use modulus of rupture as an evaluation of strength of wood panels. From the results in

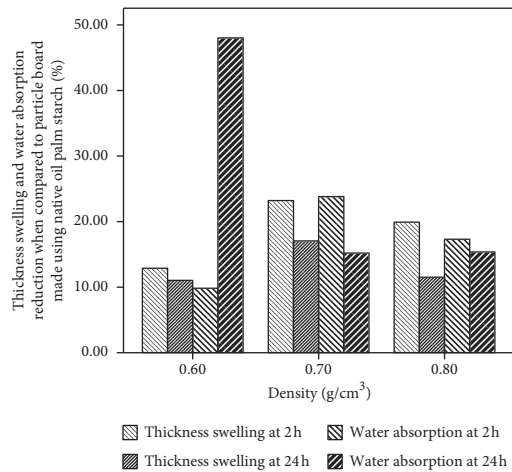


FIGURE 6: Normalized chart of thickness swelling and water absorption when using OPSMG as a binder compared to wood composites made using OPS as a binder.

Table 2, it is well seen that the wood composite made using OPSMG as the binder has better strength than the OPS wood composite at a density level of 0.60 g/cm^3 and 0.80 g/cm^3 , recorded as 7.154 N/mm^2 and 15.446 N/mm^2 , respectively. It was a 60.84% and 38.00% increment in strength between those two types of wood composites. Wood composite made using OPS at a density level of 0.70 g/cm^3 had higher modulus of rupture compared to the wood composite using modified oil palm starch as the binder. The result is unexpectedly high, comparable to wood composite using modified oil palm starch as the binder, maybe because the test pieces had more woody material or starch than the other parts. Both types of wood composites made at a density level of 0.80 g/cm^3 passed the requirement of Japanese Industrial Standard [44] for modulus of rupture. For wood composites made at the 0.70 g/cm^3 density level, wood composite made using OPS as the binder was only narrowly above the standard, while wood composite made using OPSMG as the binder was only a bit below the par, which required a minimum modulus of rupture of 8.0 N/mm^2 .

Elasticity could be defined as the recoverability of a material from a low stress deformation under the proportional limit to its original state after load is removed. Flexural modulus of elasticity is a measure of the resistance of a material to bending deflection, which is in contrast to the stiffness. The modulus of elasticity can be obtained from the slope of the stress-strain curve of the wood composite flexural strength result [53]. Modulus of elasticity of wood composite made using OPSMG was also higher, read as 2057.54 N/mm^2 , 2354.23 N/mm^2 , and 3944.62 N/mm^2 for 0.60 g/cm^3 , 0.70 g/cm^3 , and 0.80 g/cm^3 density levels, respectively. Meanwhile, wood composites made using OPS as the binder showed 661.20 N/mm^2 , 1860.06 N/mm^2 , and 2569.77 N/mm^2 at the same density levels, respectively. These results showed that the wood composites made from OPSMG are less stiff than wood composites made using OPS as the binder. All of the wood composites passed the Japanese Industrial Standard requirement for modulus of elasticity [44], except for wood composite made using OPS as the binder at 0.60 g/cm^3 and

0.70 g/cm^3 density levels, where they did not meet the minimum 2000 N/mm^2 value.

Another evaluation is the internal bonding strength which reflects the strength of binder to hold woody materials together when load is applied towards two different directions. The results in Table 1 showed that using OPSMG as the binder greatly increased the internal bond strength of the wood panels. The maximum internal bond strength was achieved at the 0.80 g/cm^3 density level which were 0.22 N/mm^2 and 0.59 N/mm^2 for wood composite made using OPS and wood composite made using modified oil palm starch, respectively. All of wood composites made using modified starch as the binder had higher internal bond properties with their increments recorded at 81.40%, 77.78%, and 62.71% for 0.60 g/cm^3 , 0.70 g/cm^3 , and 0.80 g/cm^3 density levels, respectively. All of the wood composites passed the Japanese Industrial Standard requirement for internal bonding strength which is over 0.15 N/mm^2 [44], except for wood composite made using OPS as the binder at 0.60 g/cm^3 and 0.70 g/cm^3 density levels.

4. Conclusions

Wood composites had been fabricated using OPS and OPSMG as the binder at three density levels. Characterization of the functional group using the FT-IR analysis showed presence of aldehyde groups and ketone stretching vibrations at 1736.05 cm^{-1} and 1596.25 cm^{-1} which proves the presence of glutardialdehyde in the powdered sample, while the ketone group detection showed formation of bonding between the oil palm starches modified using glutardialdehyde and the woody materials. The XRD analysis showed the starch modification had lowered the crystallinity index which in turn increased the strength of the manufactured wood composites. The OPSMG wood composites were also found to have a lower thermal stability as evaluated using the TGA analysis. From the test results, the highest and lowest modulus of rupture values were determined from the OPSMG wood composite recorded at 15.45 N/mm^2 and achieved by the 0.80 g/cm^3 density level, while the highest value of modulus of rupture for wood composite made using OPS was 9.58 N/mm^2 at the same density level. Internal bonding strength showed a higher value for the OPSMG wood composite which was 0.59 N/mm^2 for 0.80 g/cm^3 , compared to 0.22 N/mm^2 for wood composite made using OPS as the binder. Both types of wood composite satisfy requirements of Japanese Industrial Standard for the mechanical strength properties at the 0.80 N/mm^2 density level. The thickness swelling, however, for both types of wood composites, did not meet the requirement in Japanese Industrial Standard. However, this drawback could be improved by incorporating water-repellent materials such as wax into the formulation or applying surface coating to protect it from moisture. To the very less extent, it could be limited for usage in dry conditions.

Abbreviations

OPS: Oil palm starch
 OPSMG: Oil palm starch modified with glutardialdehyde

CrI: Crystallinity index
 SEM: Scanning electron microscopy
 FT-IR: Fourier transform infrared
 TGA: Thermal gravimetry analysis
 DSC: Differential scanning calorimetry analysis.

Data Availability

The characterisation data used to support the findings of this study are available from the corresponding author at hazimamini@gmail.com upon request. Other than that, the physical and mechanical test data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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