Characterization of Particleboard Using the Inner Part of Oil Palm Trunk (OPT) with a Bio-based Adhesive of Sucrose and Ammonium Dihydrogen Phosphate (ADP)

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The effective utilization of the inner part of oil palm trunk (OPT), generally considered a waste product, is desired. In this study, particleboards were manufactured using the inner part of OPT with a bio-based adhesive made of sucrose and ammonium dihydrogen phosphate (ADP). The mixture ratio of sucrose to ADP and the resin content were changed to investigate the optimum condition of the adhesive. The pressing condition was set at 180 °C for 10 min, and the target density was 0.8 g/cm^3. The optimum mixture ratio of sucrose to ADP was 80:20, and the optimum resin content was 20 wt%. The manufactured boards had modulus of rupture (MOR) and modulus of elasticity (MOE) in bending values of 16.4 MPa and 4.3 GPa, respectively. The internal bond strength (IB) was 1.85 MPa, and the thickness swelling (TS) was 9.6%. This indicated that the constructed particleboard was comparable to the 13 types of JIS A 5908 standard (2003). In addition, the particleboard had good termite and decay resistance, similar to those of OPT particleboards made with synthetic adhesives. It was clarified that excellent particleboard could be manufactured from the inner part of OPT and a bio-based adhesive made of sucrose and ADP.

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INTRODUCTION

As the global forest area continues to decline (FAO and UNEP 2020), there are legitimate concerns about diminishing wood resources. This declining forest reserve might affect the supply of wood-based composite products. The utilization of non-wood lignocellulosic resources such as agricultural residue will undoubtedly play a substantial role in the future. As an agricultural plant, the oil palm tree (*Elaeis guineensis*) has become a major contributing crop in Indonesia's growing economy. The total area of oil palm tree plantations in Indonesia in 2018 was approximately 14.3 million ha (Directorate General of Estate Crops 2019).

The palm oil industry usually generates a large amount of waste, estimated to reach 350 million tons by 2020 (Hambali and Rivai 2017). The waste includes the fruit, kernel shell, mesocarp, and fronds of palm trees, as well as the oil palm trunk (OPT), as plantations of oil palms are used only 25 to 30 years before they are razed for another agricultural cycle (Ismail and Mamat 2002). Oil palm trunk is generally underutilized and usually burned because fire is a fast and cheap method for plantation area clearing. Such practices contribute to global warming. In contrast, OPT waste can be left on the plantation field to decompose and become natural fertilizer. However, this activity is poorly managed and impractical for large amounts of waste.

A recent study reported that an environmentally friendly binderless particleboard could be manufactured from the inner part of the OPT and ammonium dihydrogen phosphate (ADP) (Komariah *et al.* 2019). The binderless particleboard showed acceptable mechanical and physical properties and excellent water resistance. It was clarified that ADP changes water-soluble saccharides to water-insoluble components during hot-pressing (Komariah *et al.* 2019, 2021). This means that saccharides have an important role in the properties of particleboards made from the inner part of OPT.

Various recent studies have indicated that sucrose-based adhesives have advantages for composite products. Sucrose is a common disaccharide sweetener in the food and beverage industries and constitutes an abundantly available, renewable chemical resource. Lamaming *et al.* (2014) showed that the addition of sucrose could improve the physical and mechanical properties of binderless particleboard made from OPT. Sucrose reacts well with citric acid (Umemura *et al.* 2013; Kusumah *et al.* 2017; Sun *et al.* 2019; Zhao *et al.* 2019a) and tannin (Zhao and Umemura 2014; Sun and Zhao 2018) to produce good bondability in wood composite products. Previously, Umemura *et al.* (2017) found that with the addition of ADP and treatment with heat, sucrose could be transformed into a high-water-resistance substance and suggested that sucrose with added ADP would likely be a water-resistant wood adhesive. Zhao *et al.* (2018) applied a mixture of sucrose and ADP to recycled wood particleboard manufacturing. The results showed that particleboard achieved good mechanical, physical, and water resistance properties. After heating, structures in the sucrose convert to the substance contains a furan ring and carbonyl group that are predicted to contribute to its bondability as an adhesive for composites. Moreover 5-hydroxymethyl-2-furfural (5-HMF) is considered one of the most important sucrose-derived products responsible for the bonding mechanism of sucrose-base adhesive (Zhao *et al*. 2019b). Furthermore, Zhao *et al.* (2020) stated that the synthesis mechanism of the sucrose-ADP adhesive is a complex reaction; the hydrolysis of sucrose and ammonium ion, the dehydration of monosaccharides, the Amadori rearrangement, caramelization, and the Maillard reaction occurred. The resulting substance is mainly composed of furan ring and nitrogen-containing compounds. In addition, Widyorini (2020) showed that in petung bamboo particleboard manufacturing, the optimal ratio of sucrose to ADP is 95:5 (wt%:wt%).

Considering these previous findings, this study hypothesized that adding sucrose with ADP as an adhesive might improve the properties of OPT particleboard. It was expected that the addition of sucrose would have a synergistic effect with the saccharide components of the OPT. This study investigated the effects of different ratios of sucrose and ADP and different resin contents on the mechanical and physical properties of particleboard made of OPT's inner part. In addition, the termite and decay resistance and the infrared spectra (IR) of the particleboard were examined.

EXPERIMENTAL

Materials

Old OPT (approximate age of 30 years) with a diameter of approximately 60 cm was collected from Bogor, Indonesia. The particles that passed through 10 mesh and were retained on 60 mesh were used as the raw material for the boards. The particles were prepared similarly to the procedures outlined by Komariah *et al.* (2019). Sucrose and ADP of extra-pure grade were purchased from Nacalai Tesque (Kyoto, Japan) and used as-is. Different weight-ratio mixtures of sucrose and ADP (Table 1) were dissolved in distilled water at the concentration of 50 wt%, and those mixture solutions were used as adhesives. The pH and viscosity of the adhesives were measured using a pH meter (D -51 Horiba, Tokyo, Japan) and a viscosity meter (Fungilab, Barcelona, Spain), respectively. The phenol-formaldehyde (PF) resin (B-1370 type) and polymeric diphenylmethane diisocyanate (pMDI) (B-1605 type) were obtained from Oshika Co. Ltd. (Tokyo, Japan) and were used as reference adhesives.

Table 1. Viscosity and pH of Sucrose-ADP Adhesives

Mixture Ratio of Sucrose to ADP (wt%)	Concentration (wt%)	Viscosity (mPa•s)	pH
95:5		22.0	3.93
90:10		21.0	3.95
85:15		20.5	3.89
80:20	50	21.0	3.90
75:25		21.5	3.89
70:30		21.0	3.73
60:40		21.0	3.73
50:50		21.0	3.70

Methods

Manufacturing of particleboards

Based on the results of a previous study (Zhao *et al.* 2018), 20 wt% solid content of sucrose-ADP adhesive solution based on the weight of the dried OPT particles was sprayed onto the OPT particles. The sprayed particles were then dried at 90 °C for 24 h until the moisture content was less than 3%. Subsequently, the dried sprayed particles were formed into a mat using a 300 mm × 300 mm forming box. The particleboards were manufactured under two conditions. In the first condition, the mats were mixed with adhesive solutions with various sucrose-ADP ratios and were hot-pressed at 180 °C for 10 min. In the second condition, the mats were mixed with the sucrose-ADP 80:20 adhesive at resin contents of 5 to 40 wt% (solid basis) and were hot-pressed at 180 °C for 10 min. Details of the manufacturing conditions of the two types of particleboards are shown in Table 2.

To prevent blisters, after 1 min of pressing the press pressure was reduced for 30 s. The size of the particleboard was 300 mm × 300 mm × 5 mm, in length, width, and thickness, respectively, and the target density was 0.8 g/cm^3. In addition, particleboards bonded using 15 wt% content (solid base) of PF resin and 8 wt% content (solid base) of pMDI with a size and target density similar to those of particleboards bonded using sucrose-ADP adhesive were manufactured as references. The pressing temperature and time were respectively 140 °C for 6 min for the particleboard bonded using PF resin and

180 °C for 4 min for the particleboard bonded with pMDI. The manufactured particleboards were conditioned for 1 week at 20 °C and approximately 60% relative humidity (RH).

Evaluation of the particleboards

The particleboards were tested according to the JIS A 5908 standard (2003). A static three-point bending test was carried out on 200 mm × 30 mm × 5 mm samples of each type of particleboard. The effective span was 150 mm, and the cross-head speed was 10 mm/min. The modulus of rupture (MOR) and the modulus of elasticity (MOE) values were calculated. The internal bond (IB) test was performed on a 50 mm × 50 mm × 5 mm specimen with a tension loading speed of 2 mm/min. The thickness swelling (TS) after water immersion at 20 °C for 24 h was measured on specimens with dimensions of 50 mm × 50 mm × 5 mm. The water absorption (WA) of the specimens and the pH values of the soaked water were measured. After the TS test, the specimens were subjected to a cyclic aging treatment: drying at 105 °C for 10 h, hot water immersion at 70 °C for 24 h, drying at 105 °C for 10 h, immersion in boiling water for 4 h, and drying at 105 °C for 10 h. The changes in the thickness and weight of the specimens throughout the treatments were observed and recorded. Each test was carried out in five replications, and the average values and standard deviations were calculated. The MOR, MOE, and IB values of the boards were corrected for the target density based on the regression lines between the obtained values and the specimen densities. An analysis of variance (ANOVA) test was used to evaluate the significance in the difference between the factors and levels. The means were compared using a Tukey HSD post hoc test to identify the significance of differences at the 95% confidence level.

Table 2. Particleboard Manufacturing Conditions

Group	Mixture Ratio of Sucrose to ADP (wt%)	Resin Content (wt%)	Hot Pressing Temperature (°C)	Hot Pressing Time (min)
	95:5			
	90:10			
	85:15			
a	80:20	20	180	10
	75:25			
	70:30			
	60:40			
	50:50			
		5		
		10		
b	80:20	15	180	10
		20		
		30		
		40		

Termite and decay resistance tests

The termite and decay resistance of selected particleboards were evaluated. The tested specimens had dimensions of 20 mm × 20 mm × 5 mm. The termite test for the particleboard was performed according to the JIS K 1571 standard (2010). The specimens were exposed to the subterranean termite *Coptotermes formosanus* Shiraki that were obtained from a termite colony developed at Deterioration Organisms Laboratory (DOL), Research Institute for Sustainable Humanosphere (RISH), Kyoto University, Japan. Open acrylic cylinders of 80 mm diameter, 60 mm height, and a 5-mm-thick hard dental plaster (New Plastone, GC Corp., Tokyo, Japan) bottom were used as the containers. A single test specimen was set at the center of the plaster bottom of the test container. A total of 150 worker and 15 soldier termites were introduced into each test container. Small wood blocks (20 mm × 20 mm × 5 mm) of sugi (*Cryptomeria japonica*) were used as the control. Five specimens for each board type were assayed against termites. The assembled containers were set up on damp cotton pads to supply water to the specimens and left at 28 °C and more than 85% RH in darkness for three weeks. The mass loss of the specimens was calculated based on the difference between the initial and final oven-dried (60 °C for 48 h) weights of the specimens.

The decay resistance test was performed according to the JIS K 1571 standard (2010). The specimens were exposed to two wood-degrading fungi, the brown-rot fungi (*Fomitopsis palustris* (Berk. Et Curt) Gilbn. & Ryv. (FFPRI 0507)) and the white-rot fungi (*Trametes versicolor* (L.:Fr.) Pilat. (FFPRI 1030)). The *F. palustris and T. versicolor* isolates were maintained in the potato dextrose agar (PDA) at the laboratory. After measuring their oven-dried (60 °C for 48 h) weights, the specimens were sterilized with gaseous ethylene oxide before exposure. The glass jars were prepared to put potato dextrose broth (PDB) medium and grow the mycelium. Three specimens were placed on top of the growing mycelium when it had entirely covered the medium. Plastic mesh spacers were placed under the specimens. Small wood blocks (20 mm × 20 mm × 5 mm) of sugi (*C. japonica*) were used as a control. The test jars were incubated at 27 °C and 70% RH for 12 weeks. Nine replicates were tested for each decay fungi for each board type. The average mass loss calculated from the oven-dry weights of nine specimens before and after the decay procedure.

Fourier transform infrared spectroscopy (FTIR) analysis

The FTIR analysis was performed on specimens that had been treated to cyclic aging. Using a blender (Vita-mix Absolute 3 ABS-W, Osaka Chemicals, Osaka, Japan), each specimen was ground into powder that could pass through 150-μm size mesh. The obtained powder was vacuum-dried at 60 °C for 15 h. The IR spectra were obtained with an FTIR spectrophotometer (FT/IR-4200, Jasco, Tokyo, Japan) using the potassium bromide (KBr) disk method, and the spectra were recorded after an average of 32 scans at a resolution of 4 cm^{-1} in the 400 to 4000 cm^{-1} range.

RESULTS AND DISCUSSION

Effects of the Mixture Ratios of Sucrose and ADP

A sucrose-ADP adhesive at various mixture ratios was utilized to manufacture the OPT particleboard, and its bonding properties were assessed. First, particleboards were manufactured using similar hot-pressing conditions, 180 °C for 10 min, and a set resin content of 20 wt.%. Figure 1 shows the bending properties of the particleboards with various ratios of sucrose-ADP. The bending properties decreased gradually as the ADP content increased. The particleboards with a sucrose-ADP ratio of 95:5 had the highest MOR value, 19.02 MPa. However, statistical analysis showed no significant difference (p>0.05) from the particleboards with sucrose-ADP ratios of 90:10, 85:15, or 80:20. The MOE value of particleboards with a sucrose-ADP ratio of 90:10 was the highest, although the statistical analysis showed no significant difference (p>0.05) from those with the 85:15 or 80:20 ratios. The bending properties of the particleboards with the sucrose-ADP adhesive were significantly higher (p>0.05) compared to those of the binderless particleboard and the ADP particleboard (0:100) manufactured in the previous study (Komariah *et al.* 2019). The sucrose-ADP adhesive nearly tripled the MOR and MOE values of the binderless particleboard and the ADP particleboard (0:100), though these were still lower than the MOR and MOE values of PF and pMDI particleboards, with one exception: the MOE value of the PF particleboard was lower than that of the sucrose-ADP-based adhesives.

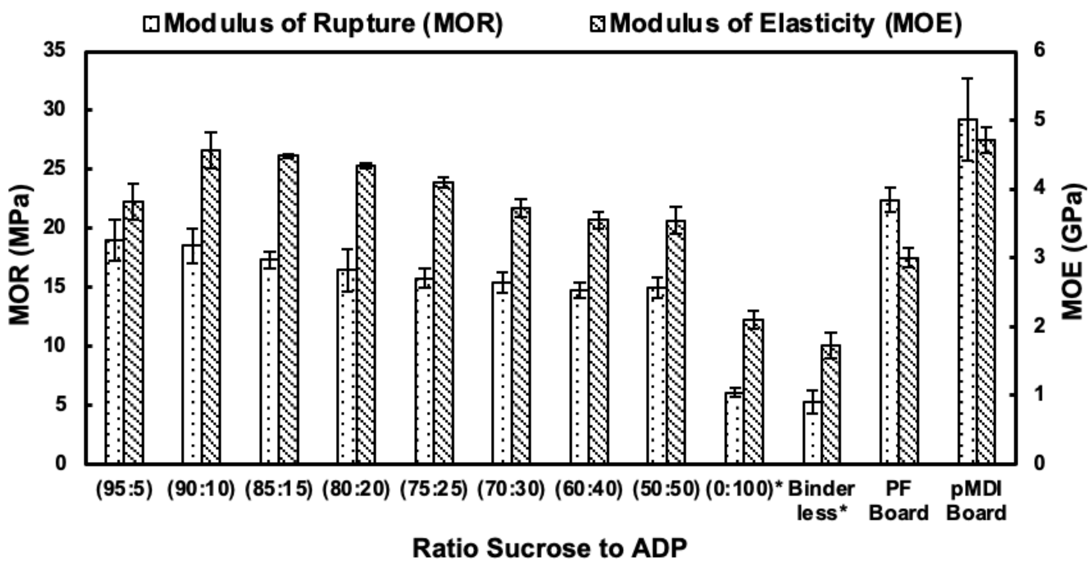

Fig. 1. The bending properties of the particleboards with various ratios of sucrose-ADP (*Adapted from Komariah *et al.* 2019)

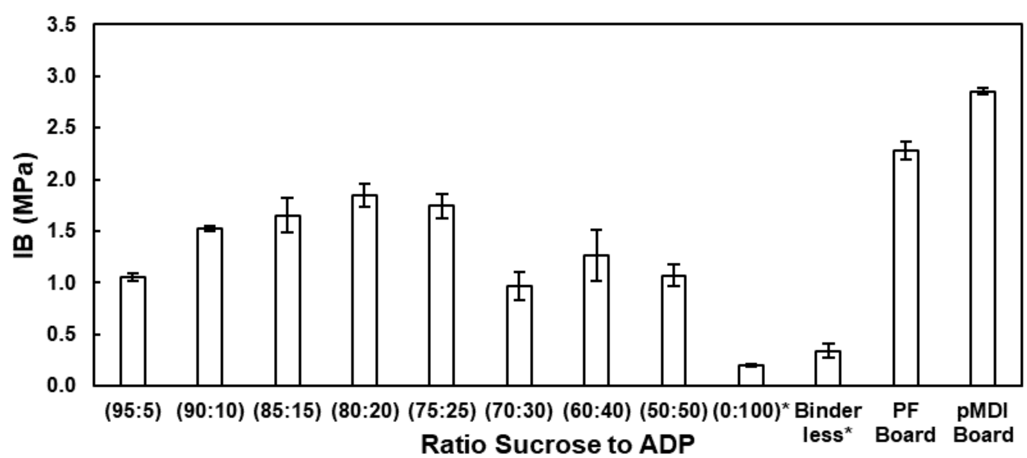

Fig. 2. The IB properties of the particleboards with various ratios of sucrose-ADP (*Adapted from Komariah *et al.* 2019)

The IB values of the particleboards are shown in Fig. 2. The IB strengths of the particleboards continuously increased as the sucrose-ADP ratio decreased to 80:20, where it reached a maximum; from there, it decreased as the sucrose-ADP ratios decreased. The IB strength of the sucrose-ADP particleboards was approximately five times greater than the binderless particleboard and the ADP particleboard (0:100) in the previous study (Komariah *et al.* 2019). However, it was still inferior to the IB strength of the PF and pMDI particleboards. The mechanical properties of all the sucrose-ADP particleboards satisfied the type 13 requirement of the JIS A 5908 standard (2003), 13 MPa, 2.5 GPa, 0.2 MPa, for MOR, MOE, and IB, respectively. These results showed that the addition of sucrose effectively improved the mechanical properties of the OPT particleboard.

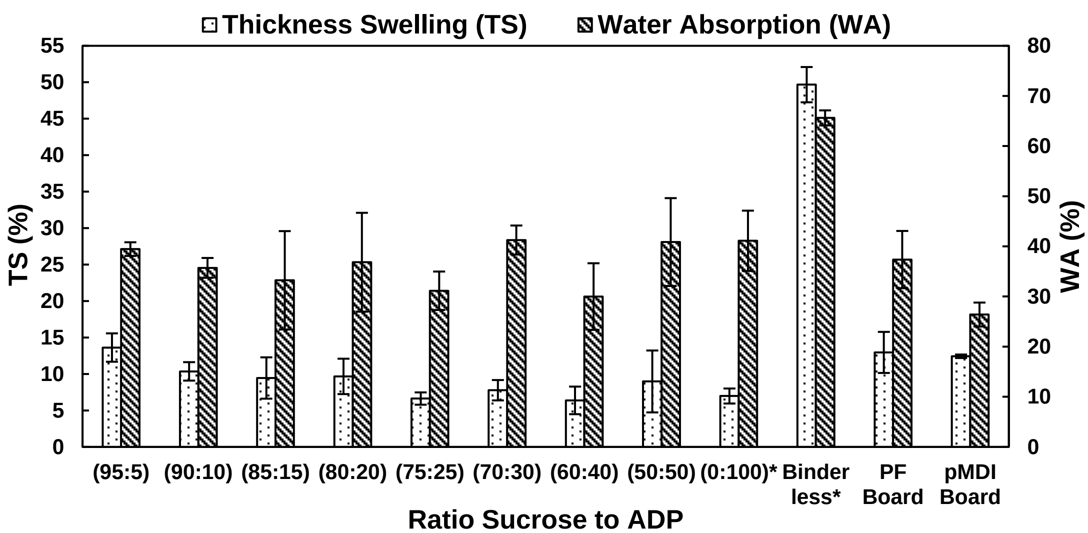

Fig. 3. TS and WA values of the particleboards with various ratios of sucrose-ADP (*Adapted from Komariah *et al.* 2019)

Figure 3 shows the TS and WA values of the particleboards made with adhesive of various ratios of sucrose to ADP. The TS value of the sucrose-ADP particleboards was in the range of 6.38% to 13.62%, with the lowest value recorded for the 60:40 sucrose-ADP particleboard. Statistically, the TS value of the sucrose-ADP particleboards did not significantly ($p>0.05$) change between the mixture ratios of 90:10 to 50:50 sucrose-ADP, except for the ratios of 75:25 and 60:40, which were significantly lower than some of the others ($p>0.05$). The TS value of the sucrose-ADP particleboards satisfied the type 13 requirement of the JIS A standard 5908 (2003) (less than 12%), except for the 95:5 sucrose-ADP particleboard. The TS value of the sucrose-ADP particleboard was also superior to that of the binderless particleboard and similar to the particleboards bonded with PF and pMDI. The WA value of the sucrose-ADP particleboards was in the range of 29.98% to 41.26%. This was similar to the WA value of the PF and pMDI particleboards, but lower than the binderless particleboard. This result indicates that ADP addition ratios from 10 wt.% to 50 wt% maintain the excellent water resistance level of sucrose-ADP particleboards. It is known that wood is degraded by acid and heating (Saeman 1945). Acidity causes the material to seem brittle, which improves the stiffness and decreases the strength of particleboard (Kusumah *et al.* 2017). The pH values of the soak water from the TS tests were determined to verify the acidity of the particleboards. As shown in Fig. 4, increases in the ADP content decreased the pH values of the soak water.

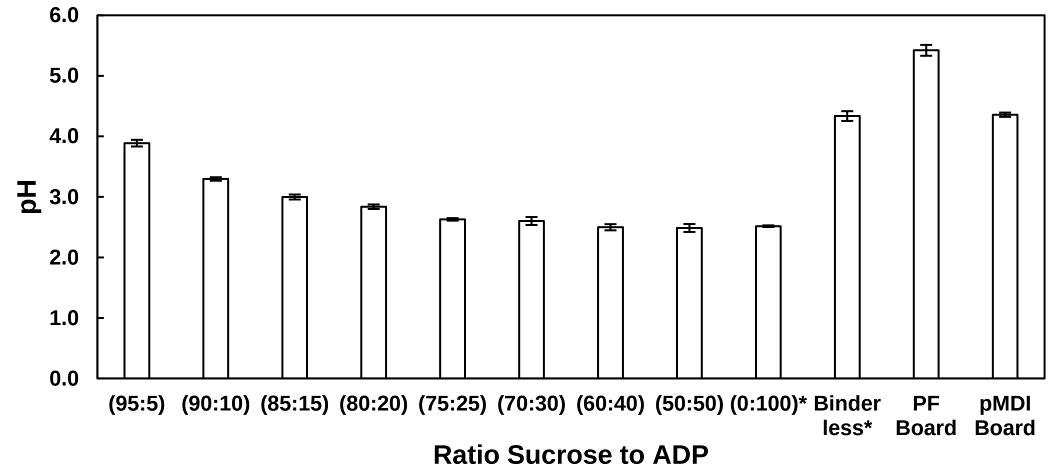

Fig. 4. pH of the soaking water after TS treatment of the particleboards with various ratios of sucrose-ADP (*Adapted from Komariah *et al.* 2019)

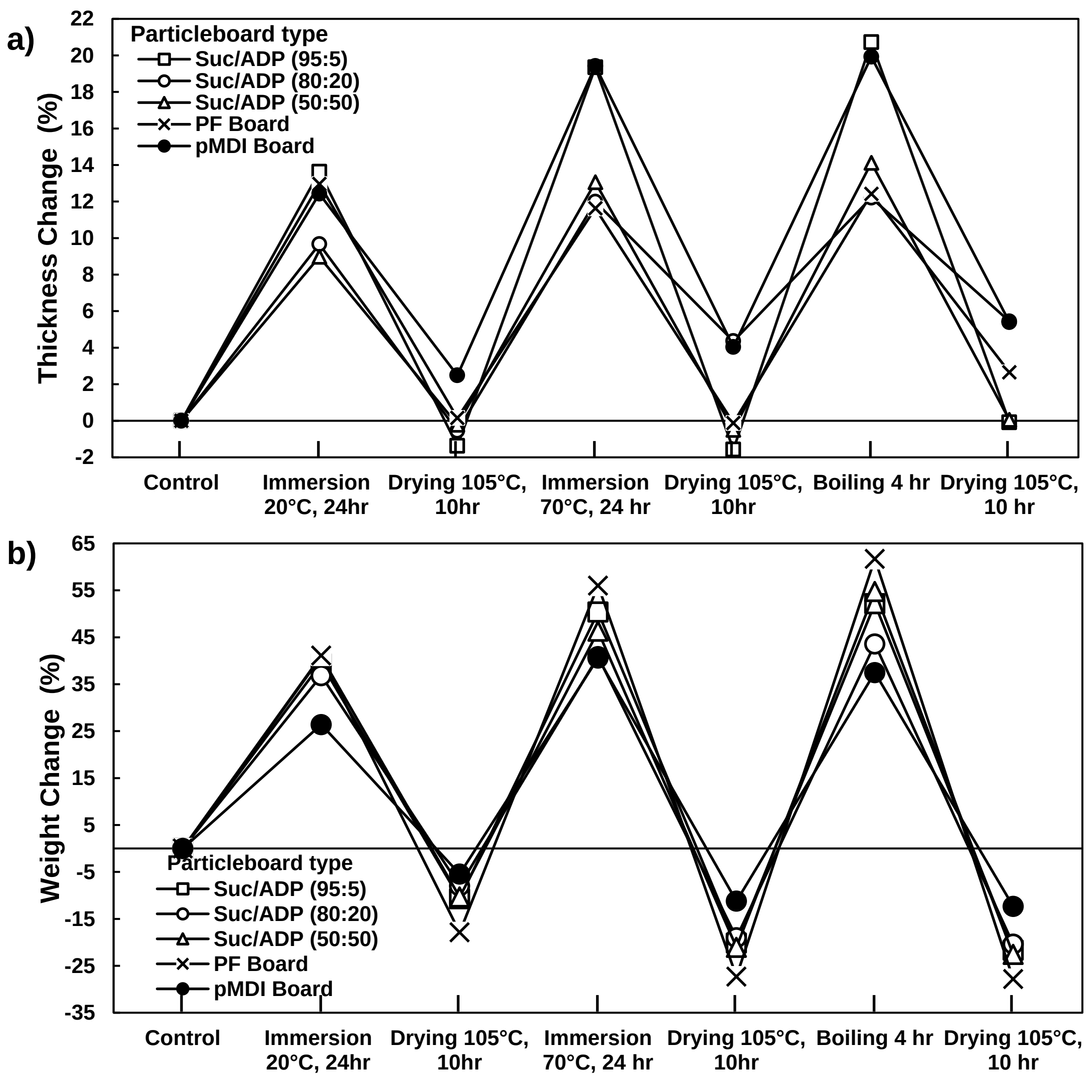

Fig. 5. The a) thickness and b) weight changes of the particleboards with various ratios of sucrose-ADP on the cyclic aging treatment test

This means that the acidity of the particleboard increased with each addition of ADP. It is known that ADP decomposes into ammonia, phosphoric acid, diammonium dihydrogen diphosphate, and water (Abdel-Kadeer *et al.* 1991; Pardo *et al.* 2017) at approximately 200 °C. Therefore, the pH value would decrease due to the formation of phosphoric acid. This also could explain why the mechanical properties worsened as the ADP content increased.

The thickness and weight changes of the particleboards were measured continuously by the cyclic aging treatment test to clarify the water resistance under severe conditions in greater detail. Based on the results shown in Fig. 3, particleboards with sucrose-ADP ratios of 95:5, 80:20, and 50:50 were used as representative specimens of particleboard to investigate the thickness and weight changes in response to water exposure. The thickness and weight changes of the PF and pMDI particleboards were also measured as references. The results of the thickness and weight changes of cyclic aging treatment are shown in Fig. 5. In the thickness changes, the extent of thickness changes from immersion at 20 °C to immersion at 70 °C were relatively higher compared to the change from immersion at 70 °C to that at the boiling point. Moreover, the change at each stage of the cyclic aging treatment decreased as the ADP content increase. The thickness changes of the sucrose-ADP particleboards at ratios of 80:20 and 50:50 were less than the thickness changes of the sucrose-ADP particleboards at a 95:5, and they were similar to the thickness changes of the PF board. However, the pMDI board showed a remarkable increase in the thickness change after hot-water immersion at 70 °C. This indicates that the sucrose-ADP particleboards exhibited excellent water resistance, comparable to synthetic adhesives. Remarkably, the 80:20 sucrose-ADP particleboard inhibited thickness swelling better than the pMDI board. The weight changes of the sucrose-ADP particleboards were similar at each stage, regardless of the ADP content. The final dried weight changes for the sucrose-ADP particleboards were approximately -20.38% to -22.58%. The pMDI particleboard showed the lowest final dried weight changes at approximately -12.33%, and the lowest weight changes similarly to the 80:20 sucrose-ADP particleboard. Moreover, the PF particleboard showed the greatest weight changes during the immersion and drying treatment, with the final weight change recorded at -27.83%.

From the comprehensive results of the tests of mixture ratios on the particleboard properties, the sucrose-ADP ratio of 80:20 was the most effective for particleboard, with relatively high MOR, MOE, and lower TS values compared to other mixture ratios. Therefore, this adhesive condition was utilized in the second part of this study.

Effects of the Resin Content

The effects of the resin content on the mechanical and physical properties of the OPT particleboard were investigated using sucrose-ADP adhesive at the ratio of 80:20. Figure 6 shows the bending properties of the sucrose-ADP-adhesive OPT particleboards with various resin contents (wt%). The MOR values gradually increased with increasing resin content, while the MOE values tended to increase with increasing resin content up to 20 wt.%, after which they decreased slightly. The statistical analysis showed no significant difference ($p>0.05$) among the MOR values of particleboards with resin contents of 10 wt.% to 30 wt.%. However, the MOE values for the 20 wt.% sample were significantly higher ($p>0.05$) than the MOE values of the particleboards with other resin contents. This means that 20 wt.% of resin content was effective in obtaining good bending properties. All the tested particleboards satisfied the bending strength type 13 JIS A 5908 standard (2003). This is in line with Lamaming *et al.* (2014), who found that the addition of sucrose at rates as high as 20 wt% improved the properties of OPT binderless particleboard. Moreover, Stark *et al*. (2010) noted that resin contents of 4 wt% to 15 wt% are needed for synthetic adhesive particleboard. Then, a resin content more than double the synthetic adhesive particleboard for sucrose-ADP particleboard was needed to obtain satisfactory properties.

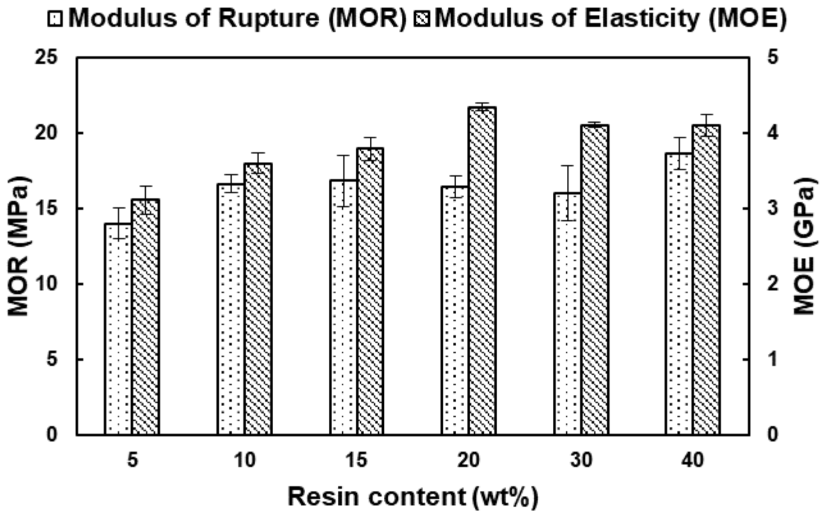

Fig. 6. MOR and MOE values of the particleboards with sucrose-ADP 80:20 with various resin contents (wt%)

The IB strengths of the tested particleboards are shown in Fig. 7. The results showed that the IB strength has a similar trend to the bending strength, with the IB value gradually increasing with the resin content. The IB value reached a maximum at 20 wt% resin content, after which it gradually decreased. The average IB value at 20 wt% was 1.84 MPa, which was almost two times higher than that at 5 wt%. Compared to the increase of the bending properties, a remarkable increase was recognized. The IB strength required in the 13 types of the JIS A 5908 standard (2003) is more than 0.2 MPa. Therefore, the adhesion system composed of sucrose and ADP developed a good dry-bond strength.

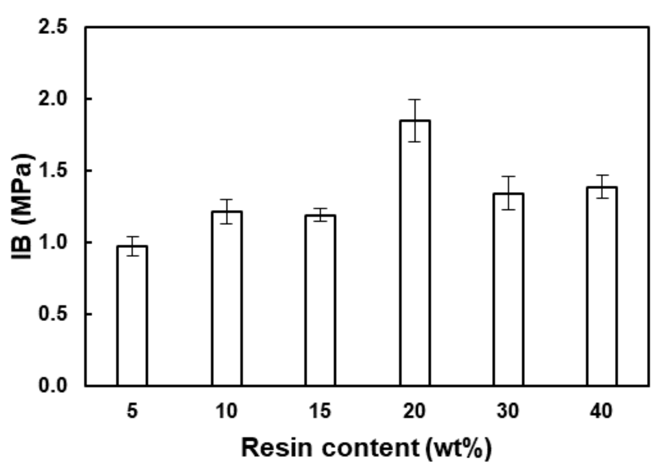

Fig. 7. IB values of the particleboards with sucrose-ADP 80:20 with various resin contents (wt.%)

Figure 8 shows the TS and WA values of the particleboards with various resin contents (wt%). The results showed trends of decreasing TS and WA values with the increasing resin content. The TS value was approximately 12% or less when the resin content was 20 wt% or more. Generally, the main factors that affect the TS are the compressibility of the board, the adhesive type, and the resin content. In this study, the target density of the particleboard was constant, irrespective of the resin content. This means that an increase in the resin content leads to a decrease in the quantity of particles. The decrease of the relation-force of compressed particles and the coating of particles with the adhesive decreased the TS value. Furthermore, the pH values of the soaking water from the TS test are shown in Fig. 9. Increases in the resin content decreased the pH of the soaking water. In other words, increased adhesive content led to increased acid formation.

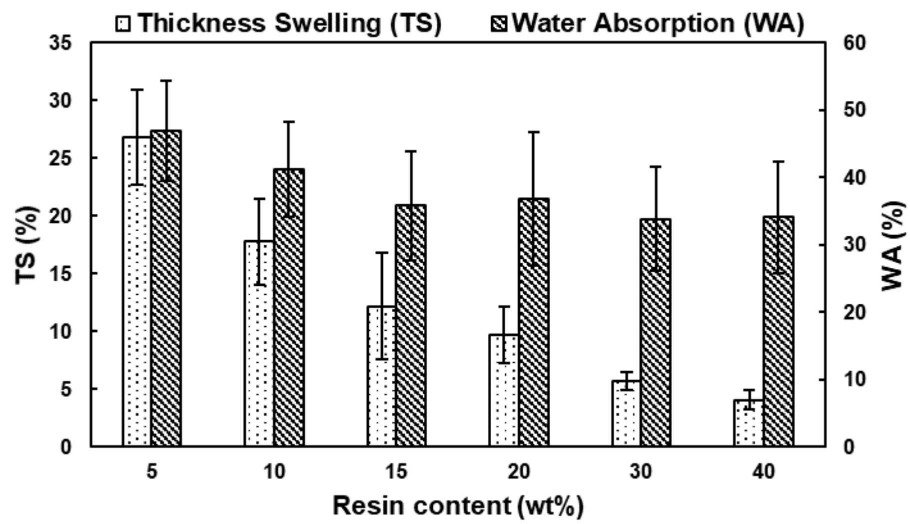

Fig. 8. The TS and WA properties of the particleboards with sucrose-ADP 80:20 with various resin contents (wt%)

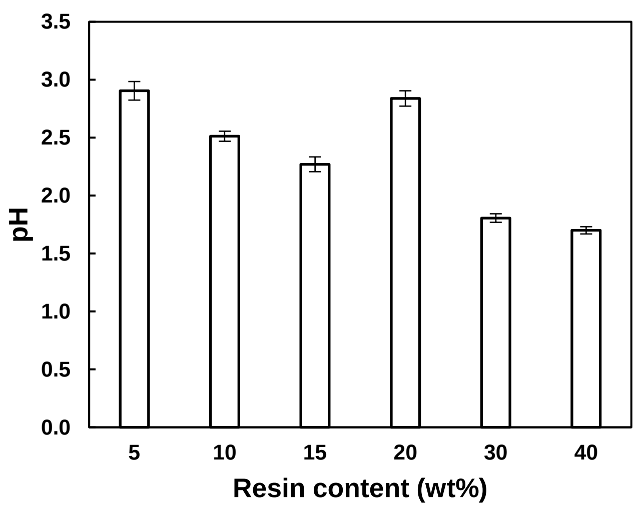

Fig. 9. pH of the soaking water after the TS treatment of the particleboards with sucrose-ADP 80:20 with various resin contents (wt%)

The thickness and weight changes of particleboards with different resin contents (wt%) in a cyclic aging treatment are shown in Fig. 10. In the cyclic aging treatments, the thickness of all types of particleboards increased in each immersion treatment. The degree of thickness change decreased as the resin content increased. The degree of thickness was remarkably suppressed when 20 wt% and higher resin contents were applied. The final dried thickness changes of the sucrose-ADP particleboards with resin contents of 20 wt% to 40 wt% were between -0.35% and 5.44%. Furthermore, the weight changes in the first water immersion treatment exhibited decreasing values as the resin content increased. This indicated that increasing resin content inhibits water absorption.

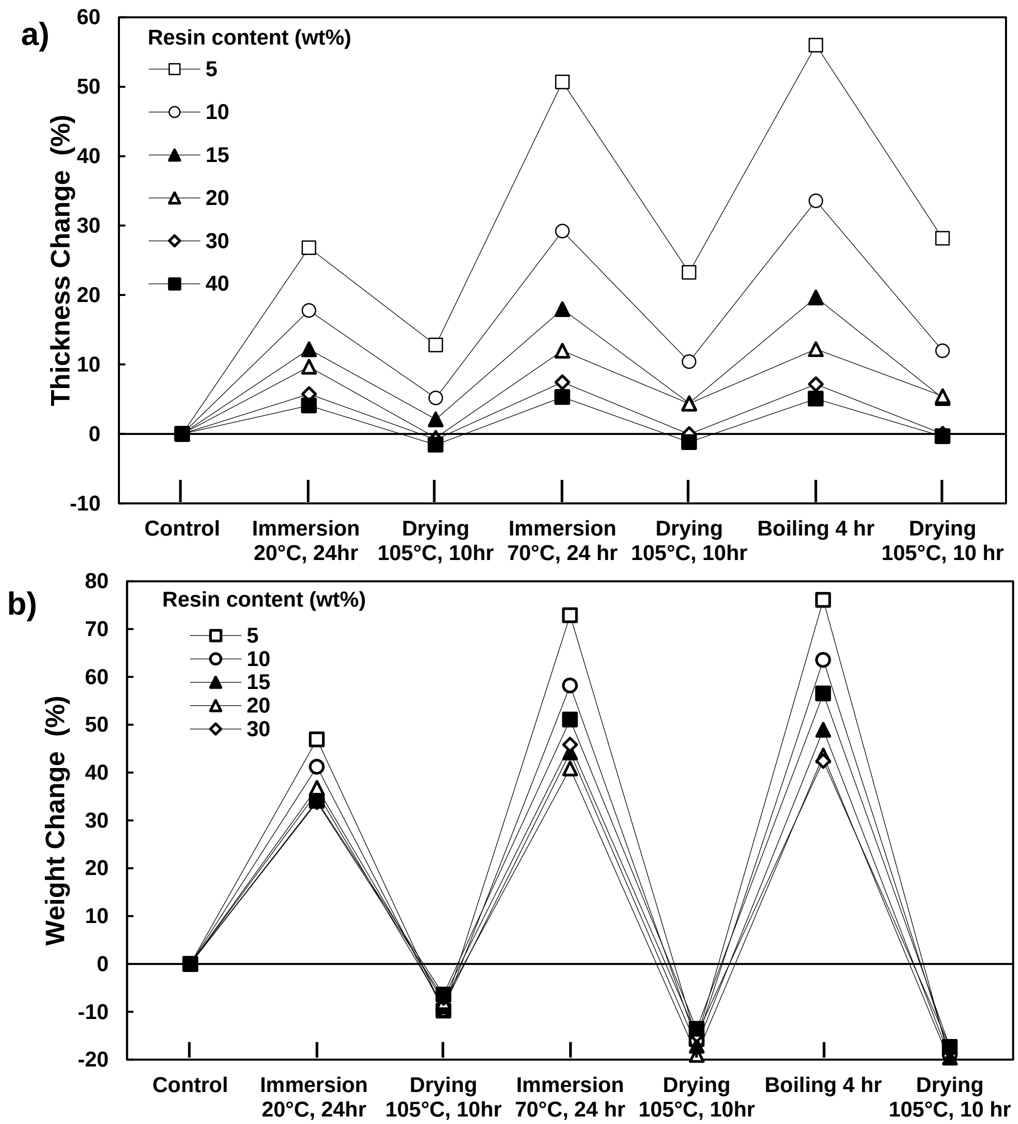

Fig. 10. The a) thickness and b) weight changes of the 80:20 sucrose-ADP particleboards with various resin contents (wt%) on the cyclic aging treatment test

The overall weight increase in the subsequent warm water immersion treatment was higher than that in the first treatment. This could be attributed to the lowering of the water resistance of the adhesive and the penetration of water into the particleboards. However, no marked change in weight with the subsequent boiling water treatment was observed, and the final dried weight changes recorded were between -17.34% and -20.12%. The weight changes of the particleboards with resin content of 20 wt% and 30 wt% were remarkably smaller than those of other conditions.

Termite and Decay Resistance

The biological durability against termites and decay of the 80:20 sucrose-ADP particleboard with a resin content of 20 wt% was investigated. The biological durability of the binderless, ADP, PF, and pMDI particleboards were also investigated as references. Table 3 shows the average mass loss and mortality in the particleboards exposed to termite attack. The particleboard that was bonded with sucrose-ADP showed a mass loss and termite mortality of 13.61% and 19.55%, respectively. These values were similar to the mass loss and termite mortality of the ADP and PF particleboards. Meanwhile, the pMDI particleboard showed a lower mass loss and termite mortality than the sucrose-ADP particleboard, and the binderless particleboard showed similar mass loss but lower termite mortality compared to the sucrose-ADP particleboard. This indicated that chemicals derived from sucrose and ADP might have inhibitory properties against termites.

Table 3. Termite and Decay Resistance of the OPT Binderless particleboard and OPT Particleboard Bonded with Sucrose, ADP, PF, and pMDI

Specimen Types	Biological Durability			
	Termite Resistance		Decay Resistance	
	Termite Mortality (%)	Mass loss (%)	Mass Loss of the Brown-rot Fungi (%)	Mass Loss of the White-rot Fungi (%)
S-ADP Board	19.55 (3.58)	13.61 (1.44)	16.80 (1.28)	16.31 (0.83)
ADP Board	21.82 (3.78)	12.53 (0.54)	21.61 (0.89)	16.67 (0.33)
Binderless particleboard	3.03 (0.43)	14.35 (2.62)	63.93 (5.77)	76.15 (8.27)
PF Board	15.39 (4.45)	12.97 (0.67)	26.21 (0.47	24.48 (0.41)
pMDI Board	8.61 (0.66)	9.89 (0.63)	13.47 (1.83)	12.42 (0.29)
Sugi (Control)	3.27 (1.64)	25.80 (3.08)	58.46 (3.99)	22.20 (6.87)

The mass losses of particleboards exposed to fungal decay is also presented in Table 3. The mass loss values for the white-rot fungi and the brown-rot fungi on the sucrose-ADP particleboard were similar, at approximately 16%. The pMDI particleboard showed the lowest mass loss values for the white-rot fungi and the brown-rot fungi at 13% and 12%, respectively. The binderless particleboard showed the highest mass loss values, at 63% and 76%, respectively. Compared to the PF particleboard, the sucrose-ADP particleboard caused a lower mass loss in the fungal decay test. These results suggest that the sucrose-ADP adhesive system in the particleboard tested in this study protects against fungal decay. In a previous study, Kusumah *et al.* (2017) found that sorghum bagasse particleboard with sucrose-citric acid adhesive at weight ratios of 85:15 and 90:10 had good termite resistance and effectively inhibited decay. Moreover, based on the FTIR analysis it found that the formation of the furan ring and carbonyl group was significant in the sucrose-ADP particleboard. And it was found that furan ring is a key pharmacophore for many active natural-products insecticidal agents such as toosendanin and limonin (Xiang *et al.* 2018). In addition, furfuryl alcohol significantly impacted the resistance against the termite of fast-growing tropical wood (Hadi *et al.* 2020) and also resistance to decay fungi of Masson pine wood (Li *et al.* 2015). It can be concluded that the sucrose-ADP particleboard has good biological durability against deterioration organisms such as termites and wood decay fungi, similar to that of particleboards made with synthetic adhesives.

FTIR Analysis

The IR spectrum of the particleboard with a sucrose-ADP ratio of 80:20 and a resin content of 20 wt% was taken to clarify the chemical changes of the OPT particleboard. Figure 11 shows the results of the IR spectra of the binderless particleboard and sucrose-ADP particleboard after cyclic aging treatment.

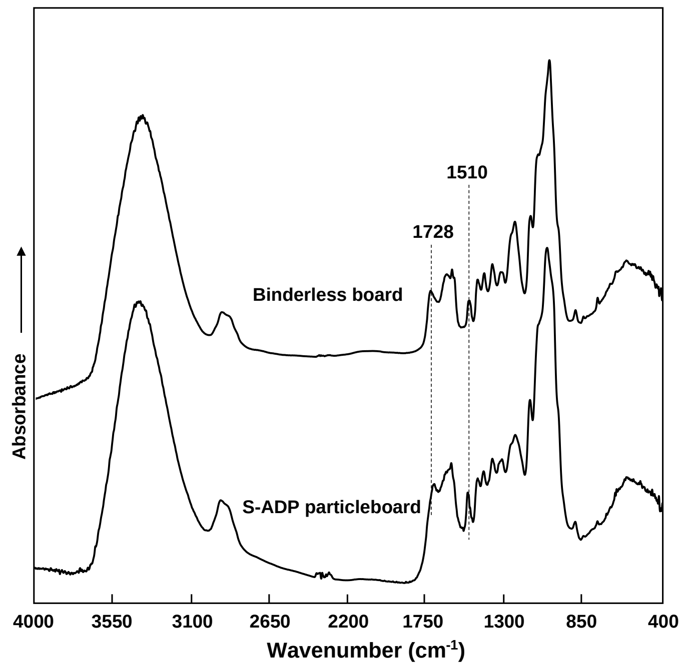

Fig. 11. FTIR spectra of the OPT binderless particleboard and the sucrose-ADP particleboard (80:20, resin content of 20 wt%) after the cyclic aging treatment test

Two absorption peaks at approximately 1728 and 1510 cm^{-1} were observed in both specimens. The peak at 1728 cm^{-1} is typically ascribed to the stretching vibrations of carbonyl C=O bonds (Lee *et al.* 2018), which are formed upon heating of sucrose. The peaks at 1510 cm^{-1} have been attributed to both the C=C of the aromatic ring vibrations in lignin (Sun *et al.* 1999) and the furan ring from sucrose heated with ADP (Umemura *et al.* 2017; Zhao *et al.* 2018; Komariah *et al.* 2021). Therefore, the peak at approximately 1510 cm^{-1} likely combines the vibrations of two different functional groups. These two peaks (at 1728 cm^{-1} and 1510 cm^{-1}) in the sucrose-ADP particleboard spectra were higher than those of the binderless particleboard. This indicates that the furan ring and carbonyl group formation was significant in the sucrose-ADP particleboard. This would be reasonable because their formation is derived from both sucrose and the saccharides of OPT. The addition of a furan ring contributes to improved bondability. Consequently, the furan ring improved the mechanical and physical properties of the particleboard by adding sucrose. These results align with Zhao *et al.* (2020), which found pyrolysed products containing a furan ring that participated in the curing reaction of sucrose-ADP adhesive.

CONCLUSIONS

1. The mechanical properties and water resistance of the particleboard made from the inner part of oil palm trunk (OPT) increased as the sucrose ratio increased. The optimum sucrose-ammonium dihydrogen phosphate (ADP) mixture ratio was 80:20 and the optimum resin content was 20 wt%. The modulus of rupture (MOR), modulus of elasticity (MOE), and thickness swelling (TS) values were 16.45 MPa, 4.34 GPa, and 9.67%, respectively. The internal bond (IB) strength was 1.85 MPa, and the board exhibited good bond performance.
2. The particleboard manufactured under the optimum condition was comparable to the type 13 of board described in the JIS A 5908 standard (2003). The particleboard also had good water resistance under cyclic aging treatment.
3. The sucrose-ADP adhesive in the particleboard provided good protection against termite and decay, similar to that of particleboards with synthetic adhesives.
4. Excellent particleboard could be manufactured from the inner part of OPT and a bio-based adhesive made of sucrose and ADP.

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