Evaluation of Physical and Mechanical Properties of Particleboard Made from Petung Bamboo Using Sucrose-based Adhesive

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Bamboo is a potential non-wood lignocellulosic material from which to make particleboard. Sucrose-based adhesive is another potential ingredient, but its use in particleboard has been limited. Addition of ammonium dihydrogen phosphate (ADP) can be used to increase the bonding ability of sucrose-based adhesive and to reduce the required pressing temperature. Therefore, this research used different pressing temperatures and sucrose/ammonium dihydrogen phosphate (ADP) composition ratios to optimize the properties of particleboards. The physical and mechanical properties of the boards were analyzed and compared with the JIS A 5908 (2003) standard for particleboard. The results showed that the interaction of the sucrose-ADP composition ratio and the pressing temperature significantly affected the physical and mechanical properties of the particleboards. The particleboard using only sucrose as adhesive had optimum properties at 200 °C; however, after addition of ADP, the intended properties could be achieved at a 160 °C pressing temperature.

Keywords: Petung bamboo; Sucrose; Ammonium dihydrogen phosphate; Particleboard; Pressing temperature

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INTRODUCTION

Bamboo is a lignocellulosic material with great potential, especially in tropical countries, as it is a fast-growing species that starts yielding harvestable material within three or four years of planting. Bambusoideae (bamboos) comprises 1,439 described species in 116 genera (Bamboo Phylogeny Group 2012). China has the greatest bamboo diversity in Asia, with more than 500 species, followed by India, Indonesia, Myanmar, and Malaysia (Nirala *et al*. 2017). In Indonesia, there are 145 bamboo species, of which 63 have economic potential (Widjaja 2000).

In recent years, bamboo has become a main substitute material for wood in construction, parquets, and laminations (Mahdavi *et al*. 2012; Huang *et al.* 2013; Chen *et al*. 2014; Ni *et al*. 2016). One potential type of bamboo for use in materials is petung bamboo, which is found in Indonesia. Its characteristics include a wall thickness of 25 mm to 41 mm, internode lengths of 40 cm to 60 cm, and a diameter that can reach 200 mm (Kusumaningtyas *et al*. 2016). According to Laemlaksakul and Kaewkuekool (2006) and Laemlaksakul (2010), the conversion of bamboo into bamboo strips has an average potential output of up to 34.3%.

Although the potential utilization as laminates is relatively low, the remaining portion could be used as particleboard material (Laemlaksakul 2010; Widyorini *et al*. 2016a). The utilization of biomass byproducts from the bamboo processing industry is yet another way to support environmental sustainability.

In addition to the lignocellulosic material, an important factor in the development of environmentally friendly composites is the adhesive. Synthetic, formaldehyde-based adhesives are mostly used in the composite industry. Urea-formaldehyde is widely used as an adhesive in the manufacture of wood-based composite panels because it is colorless, fast-curing, and inexpensive (Jeong and Park 2019). However, formaldehyde, which is a human carcinogen and not renewable, is emitted during the production and use of such composites. Therefore, many efforts have been made to develop low-formaldehyde-emission synthetic resins or, even, natural adhesives. Many natural adhesives have been studied for composite products, including starch, sucrose, glucose, chitosan, lignin-tannin, tannin, tannin-sucrose, protein, gum, and citric acid (Yang *et al*. 2006; Umemura *et al*. 2009; Lei *et al*. 2010; Moubarik *et al*. 2010; Bertaud *et al*. 2012; Tondi *et al*. 2012; Umemura *et al*. 2012; Lamaming *et al*. 2013; Norström *et al*. 2014; Widyorini *et al*. 2016a; Sun and Zhao 2018; Zhao *et al*. 2018; Sun *et al*. 2019a; Zhao *et al.* 2019a).

Saccharide-based adhesives have potential for composite products. Lamaming *et al.* (2014) showed that addition of sucrose could increase the physical and mechanical properties of binderless particleboard made from oil palm trunk. Sucrose, a saccharide, can react well with citric acid (Umemura *et al*. 2013; Sun *et al*. 2019a; Zhao *et al.* 2019a) and tannin (Zhao and Umemura 2014; Sun and Zhao 2018) to produce good bondability in wood composite products. Widyorini *et al*. (2016b) showed that sucrose adhesive was affected significantly by pressing temperature. Recently, Umemura *et al*. (2017) found that, with the combined presence of ammonium dihydrogen phosphate (ADP) as a phosphate catalyst and a heating treatment, the resulting sucrose was transformed into a highly water-resistant substance. 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 to be one of the most important sucrose-derived products responsible in the bonding mechanism of sucrose-based adhesive. Zhao *et al.* (2019b) stated that the main reactions during the curing process were considered as the dehydration condensation of furan compounds and Maillard reaction. The resulting substance is mainly composed of polyfuran and linked by C-O-C and C=N-C linkages. In addition, Zhao *et al*. (2018) showed that application of ADP in sucrose-based adhesive in the manufacturing of recycled wood particleboard is optimal at 15 wt%. Addition of ADP until 10 wt% in the manufacturing of binderless board improved the board properties and changed water-soluble components of oil palm trunk to water-insoluble components (Komariah *et al*. 2019). Application of sucrose-ammonium dihydrogen phosphate adhesives with a high solids content and suitable viscosities in plywood manufacturing operations was developed by Zhao *et al*. (2019b), Sun *et al*. (2019b), and Zhao *et al*. (2020).

This research evaluated properties of particleboard made from petung bamboo using sucrose and ADP with varying compositions and pressing temperatures. Bamboo has different characteristics compared with woody materials. This research supports the optimization of the application of sucrose and ADP in the manufacturing of non-wood particleboard and the corresponding bonding properties.

EXPERIMENTAL

Materials

Bamboo petung particles were collected from bamboo-sawing industry in Yogyakarta province, Indonesia. The particles were then screened with a 10-mesh screen, keeping those particles that passed through. The distributions of particle sizes were 75.1% passed through 10 mesh and retained at 40 mesh (10 to 40 mesh), 14.8% (40 to 60 mesh), and 10.1% passed through 60 mesh. After screening, the particles were then kept until they were air-dried (at around 12.3% ± 0.34 %).

Sucrose (Meade-King, Robinson & Co. Ltd., Liverpool, UK) and ammonium dihydrogen phosphate (Merck, Darmstadt, Germany) was used without further purification.

Methods

Preparation of adhesive solution

The sucrose and ADP were dissolved in distilled water at various compositions, and the concentration of solution was set at 50 wt%. The mixture ratios of sucrose/ADP were set at 100 wt% / 0 wt%, 95 wt% / 5 wt%, 90 wt% / 10 wt%, 85 wt% / 15 wt%, and 80 wt% / 20 wt%. The adhesive load was 20 wt% based on dry-weight particles. The weight of particles was calculated from the target density of the particleboard (0.8 g/cm^3), with the target dimensions of the board being 25 cm × 25 cm × 1 cm.

Manufacture of particleboard

The adhesive solution was sprayed onto the particles, which were then oven-dried at 80 °C for 4 h to reduce the moisture content of the particles. The moisture content of the sprayed particles was 26% ± 0.33%, and it decreased to 5% ± 0.34% after oven-drying. The particles were hand-formed into 25-cm × 25-cm mats and then hot-pressed (PCL-700, Riken Seiki Co., Ltd., Ojiya, Japan) using a three-step cycle as done by Widyorini *et al*. (2018) at 3 MPa specific pressure. The target thickness was set at 10 mm. The mat was hot-pressed for 5 min, followed by 1 min for the breathing stage, and then hot-pressed again for 5 min, for a total pressing time of 10 min. The pressing temperatures used were 160 °C, 180 °C, and 200 °C.

Evaluation of board properties

The particleboards were conditioned at room temperature for approximately 1 week, and then their physical and mechanical properties were evaluated according to the Japanese Industrial Standard for particleboard (JIS A 5908 2003). Surface roughness was also evaluated as a means of characterizing the surface quality.

The thickness swelling (TS), water absorption (WA), and internal bonding strength (IB) tests were performed on 5 cm × 5 cm × 1 cm specimens. Thickness swelling and WA were tested by immersing the specimens in water at room temperature for 24 h. The thickness and the weight changes of the specimens that occurred throughout the treatments were then determined. Internal bonding strength was tested by pulling the specimen perpendicularly to its surfaces at a loading speed of 2 mm/min using a universal testing machine (Model 3360, Instron, Norwood, MA, USA).

The static three-point bending strengths under dry and wet conditions were performed on 20 cm × 5 cm × 1 cm specimens from each specimen. The modulus of rupture (MOR) and modulus of elasticity (MOE) were calculated from the bending test. The effective span and the loading speed were 15 cm and 10 mm/min, respectively. The same test was performed for the wet bending strength evaluation (test B) of the specimen after immersion in boiling water for 2 h and further immersion in room temperature water for 1 h. Before the wet bending test, the surface roughness was measured as average roughness (R_a) using a surface roughness tester (SRG 400, Bosworth Instrument, Cleveland, OH, USA) at six random points. The specimen size for the screw-holding power tests of the boards was 10 cm × 5 cm × 1 cm. The pulling-out load speed was approximately 2 mm/min. The MOR, MOE, and IB values were then corrected for target density based on the specimen densities. Each experiment was performed three times, and the average values and standard deviations were calculated. The data were then statistically analyzed using a two-way analysis of variance, followed by Tukey's honestly significant difference (HSD) test.

RESULTS AND DISCUSSION

All of the particleboards were successfully produced. The color of the boards became darker with increasing ADP content and pressing temperature. The moisture content of the particleboards ranged from 5.35% to 9.08%. Table 1 shows the analysis of variance of the factors corresponding to each board property. Clearly, the interaction of the pressing temperature and the sucrose/ADP ratio significantly affected all of the board properties. During heat treatment, ammonium catalyzed the hydrolysis of sucrose to glucose and fructose, and the ammonium ion from ADP also was hydrolyzed to ammonium hydroxide (Zhao *et al*. 2019b). It has been found that there was a positive correlation between the temperature and curing of sucrose/ADP (Zhao *et al*. 2020), and those combinations affected board properties. The interaction analysis is important for predicting the optimum manufacturing condition of the board, considering that the board properties were simultaneously affected by many factors. In addition, Zhao *et al*. (2018) showed significant effects for each factor, *i.e*., pressing temperature and sucrose/ADP ratio.

Table 1. Analysis of Variance

Board Property	Significance of Factors		
	Pressing Temperature	Sucrose/ADP Ratio	Pressing Temperature*Sucrose/ADP Ratio
TS	1.4×10^{-14} **	3.7×10^{-17} **	1.7×10^{-13} **
WA	5.2×10^{-17} **	8.2×10^{-22} **	3.7×10^{-16} **
Surface roughness	1.6×10^{-13} **	5.8×10^{-10} **	1.1×10^{-13} **
MOR	1.4×10^{-11} **	5.1×10^{-12} **	9.1×10^{-15} **
MOE	1.5×10^{-16} **	4.2×10^{-21} **	3.9×10^{-17} **
IB	3.0×10^{-9} **	3.3×10^{-12} **	1.0×10^{-6} **
Screw holding strength	1.6×10^{-7} **	1.2×10^{-10} **	1.8×10^{-7} **
** Significant at $p < 0.01$			

After conditioning, the thickness of particleboards that used only pure sucrose as an adhesive and pressed at 160 °C was 1.18 ± 0.03 cm or increased around 18% compared to targeted thickness. The boards looked not as dense as other boards, since the densities of those particleboards were only 0.64 ± 0.02 g/cm^3. It seemed that the bondability of the boards was lower compared to other boards. Figure 1 shows the conditions of particleboards before and after water immersion for 24 h at room temperature. The color of particleboards became more darker after water immersion. Interestingly, all of the particleboards were not destroyed during water immersion test.

Figure 2 shows the TS and WA of the sucrose-ADP-based particleboard made from bamboo. When only sucrose was used as an adhesive, and the board was pressed at 160 °C, the TS of the board was 60% based on the thickness after conditioning or 91% based on the target thickness. The average TS values of the boards decreased to 18% at a pressing temperature of 180 °C, indicating that increasing pressing temperature contributed to the improvement of bonding performance of the board. Compared to Widyorini *et al*. (2016a), binderless particleboard made from petung bamboo has a TS value 35% when it pressed at 180 °C. Lamaming *et al.* (2014) showed that the TS values of old and young oil palm trunk binderless particleboards that pressed at 180 °C were 39.6 % and 22.7% and decreased to 15.2 % and 15.9%, respectively, after addition of 20 wt% of sucrose. It has been stated by Lamaming *et al.* (2013) that the particleboard made with the addition of sucrose consisted of short chain polymers with a large amount of branching with other monosaccharides, that it might possibly to contribute to its bondability. Other results from Widyorini *et al*. (2016b) showed that the TS of boards made from teak wood was 62% (180 °C) with the same adhesive. Those results were better than that of Zhao *et al*. (2018), in which the particleboard sample made from recycled wood and sucrose adhesive pressed at 180 °C could not be measured due to its destruction. It seemed that the chemical components of raw material also affected the board properties. In addition, if only sucrose is used as the adhesive and a pressing temperature of at least 200 °C, the particleboard made from bamboo has TS value of 11.7 ± 2.2%, that approached value for the requirement of JIS A 5908 (2003).

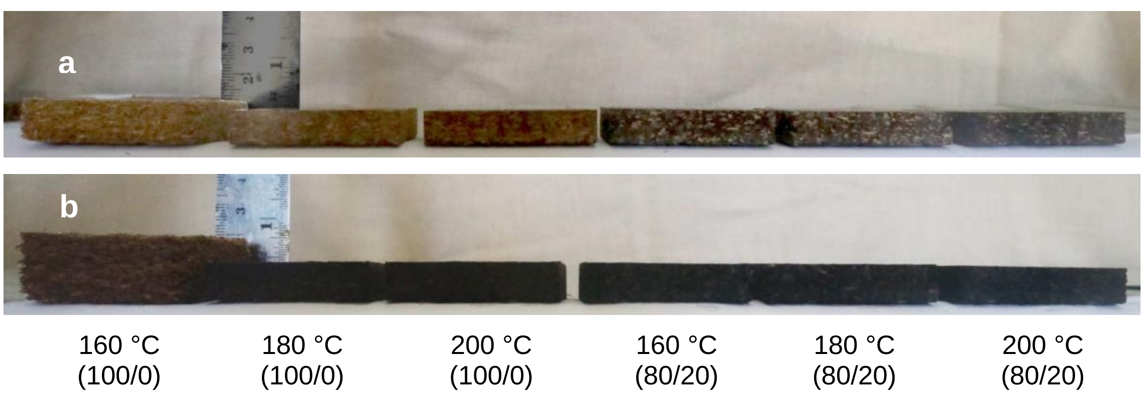

Fig. 1. Conditions of particleboards at various pressing temperature and sucrose/ADP ratios, before (a) and after (b) water immersion for 24 h at room temperature

Figure 2 shows that, with the addition of at least 5 wt% of ADP and pressing temperatures of 180 °C, the TS values of the boards were less than 12%. Interestingly, with the addition of at least 15 wt% of ADP, the average TS values of the boards met the requirement of JIS A 5908 (2003) even when pressed at 160 °C. The addition of ADP noticeably reduced the required pressing temperature for producing boards that met the TS standard. Compared to Zhao *et al* (2018), at the same temperature and sucrose/ADP ratio, the TS of particleboards made from recycled wood was around 26 to 27%. This result is supported by Umemura *et al*. (2017), in the presence of 5 wt% of ADP, the sucrose reached insolubility more than 40% at heating temperatures of 160 °C or more. In addition, the insoluble matter rate increased with increasing temperature with different trends for each sucrose/ADP ratio, indicating that sucrose was polymerized to a highly water-resistant substance with heating and the presence of ADP as a catalyst. Based on the Zhao *et al.* (2018), the insoluble mass proportion of sucrose-ADP adhesive (85/15 wt%) after boiling treatment for 4 h was increased, exceeded 60% when the heating temperature was or more than 160 °C for 10 min. Based on thermal analysis, this indicated that the main curing behavior of SADP adhesive occurred near 145 °C and the majority of SADP seemed have already cured at these temperatures (150 to 170 °C) (Zhao *et al*. 2020).

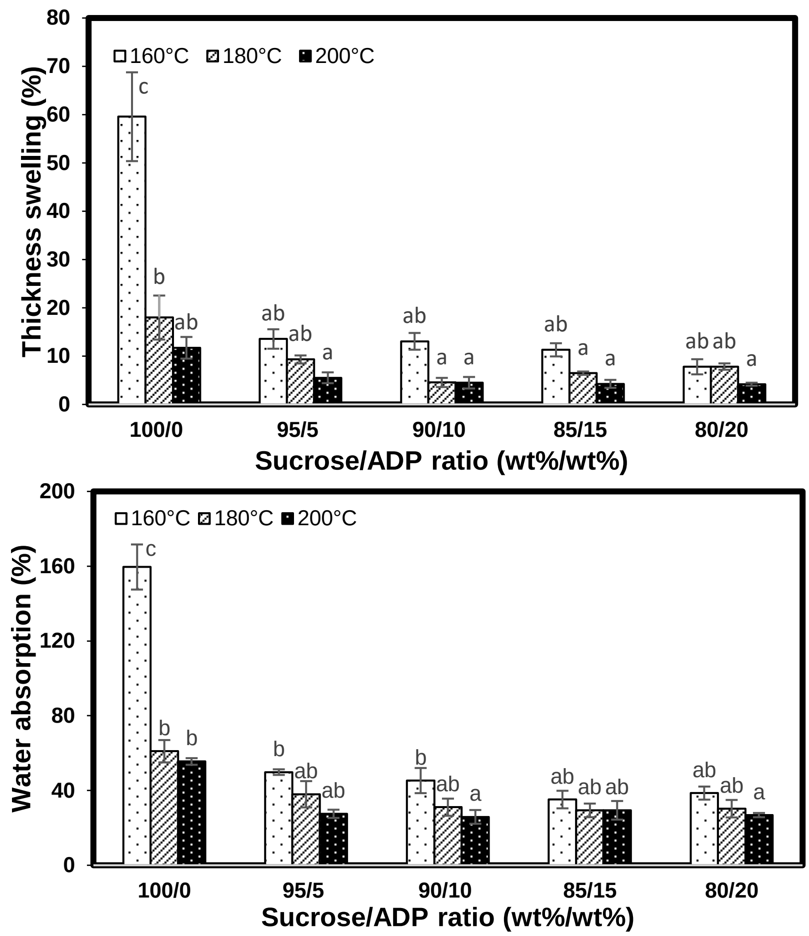

Fig. 2. TS and WA of sucrose-based particleboards made from bamboo. Error bars indicate the standard deviations. Different letters indicate significant differences between factors at $p < 0.01$.

The same trend was found for the WA of the particleboards. All particleboards had WA values less than 60%, except for those particleboards that used only sucrose as adhesive and were pressed at 160 °C (160%) or 180 °C (61%). The same results were found by Lamaming *et al.* (2014); the WA values of old and young oil palm trunk particleboards that were bonded with sucrose and pressed at 180 °C were 59.9% and 56.18%, respectively. Based on Table 1 and Fig. 2, this research clearly showed that the interaction between sucrose/ADP ratio and pressing temperature significantly affected the TS and WA values of the bamboo boards. Increasing the ADP portion of the sucrose/ADP ratio decreased the required pressing temperature for achieving optimum board properties.

Table 2 shows the average surface roughness (R_a) values of the particleboards made from bamboo. Surface roughness is an important point in determining the quality of final products, especially when the particleboard is used for thin overlays in the wood manufacturing industry. In this research, R_a ranged from 7.43 µm ± 0.31 µm to 17.33 µm ± 1.87 µm, which is greater than that of commercially manufactured composite board (Hiziroglu and Suzuki 2007). The particleboard that used only sucrose as adhesive and was pressed at 160 °C had a rough surface. This result was consistent with the TS and WA values and indicated that the sucrose had not yet polymerized at 160 °C, as mentioned by Umemura *et al*. (2017). However, increasing the pressing temperature and fraction of ADP simultaneously significantly affected the surface roughness of the boards. Compared to commercial particleboard made from rubber wood (Hiziroglu *et al*. 2004), the particleboard made using sucrose/ADP (90 wt% / 10 wt%) with a pressing temperature of 180 °C had a smoothest surface. The degree of surface roughness is affected by raw material characteristics (such as particle size, species, and fiber distribution) and manufacturing variables (such as pressing parameters, adhesive content, densification of face layers, and sanding) (Hiziroglu and Suzuki 2007).

Table 2. Surface Roughness, MOR, MOE, and Screw Holding Strength of the Sucrose/ADP-based Particleboard

Pressing Temperature (°C)	Sucrose/ADP Ratio (wt%/wt%)	R_a (µm)	MOR (MPa)	MOE (GPa)	Screw Holding Strength (N)
160	100/0	17.33 ± 1.87^c	0.78 ± 0.03^a	0.15 ± 0.01^a	52 ± 5^a
	95/5	11.33 ± 0.90^b	13.97 ± 0.02^b	3.76 ± 0.02^c	393 ± 8^b
	90/10	11.35 ± 0.97^b	12.21 ± 1.77^b	3.51 ± 0.27^{bc}	385 ± 47^b
	85/15	8.42 ± 0.86^{ab}	12.47 ± 0.94^b	3.32 ± 0.12^{bc}	400 ± 16^b
	80/20	9.58 ± 1.79^b	12.59 ± 0.97^b	3.74 ± 0.29^c	400 ± 98^b
180	100/0	8.50 ± 0.84^{ab}	13.46 ± 0.23^b	3.11 ± 0.28^b	330 ± 49^b
	95/5	8.48 ± 0.75^{ab}	14.32 ± 0.76^b	4.20 ± 0.15^c	412 ± 10^b
	90/10	7.43 ± 0.31^a	13.44 ± 0.78^b	3.95 ± 0.11^c	442 ± 44^b
	85/15	9.18 ± 0.92^{ab}	13.13 ± 0.66^b	3.65 ± 0.14^{bc}	401 ± 14b
	80/20	9.60 ± 1.35^b	12.61 ± 1.05^b	3.73 ± 0.14^c	416 ± 55^b
200	100/0	10.03 ± 0.95^b	13.75 ± 0.28^b	3.36 ± 0.07^{bc}	384 ± 16^b
	95/5	9.32 ± 0.64^{ab}	14.08 ± 1.12^b	4.14 ± 0.07^c	433 ± 58^b
	90/10	9.48 ± 2.02^{ab}	12.23 ± 0.11^b	3.68 ± 0.19^c	455 ± 38^b
	85/15	10.83 ± 1.80^b	12.66 ± 0.43^b	3.88 ± 0.14^c	425 ± 28^b
	80/20	9.44 ± 1.30^b	13.83 ± 0.98^b	3.84 ± 0.10^c	418 ± 34^b

Different letters indicate significant differences between factors at $p < 0.01$.

The MOR values are shown in Table 2. The particleboard with only sucrose as adhesive and pressed at 160 °C had the lowest MOR (0.78 ± 0.03 MPa). Interestingly, when the pressing temperature increased, the MOR increased dramatically to greater than 13 MPa, as required for JIS A 5908 (2003) type 13. The MOR of young and old oil palm trunks particleboards with the addition of 20% sucrose and pressed at 180 °C also passed the requirement for type 13 (Lamaming *et al*. 2014). At the same pressing temperature, sucrose-based particleboard made from recycled wood had MOR of 1.17 MPa (Zhao *et al*. 2018). This indicated that the chemical components of the raw materials also influenced the bonding properties of the sucrose-based particleboards. When ADP was added to the sucrose, the MOR values were more than 12 MPa, with half of the particleboards meeting the requirement of JIS A 5908 (2003) type 13.

The same trend was also found for the MOE values. In addition, except for that with the sucrose-only adhesive, all of the particleboards in this research had MOE values greater than 3 GPa, meeting the requirement of JIS A 5908 (2003) type 18. Zhao *et al.* (2018) found the same result, whereby the MOE exhibited a rising trend as the ADP content was increased by 5 to 15 wt% when pressed at 180 °C. In addition, when the pressing temperature equal or more than 160 °C and the ADP content was 15%, the mechanical properties of the particleboard made from recycle wood fulfilled the requirement of JIS A 5908 type 18.

As its MOR and MOE values were very low, the specimen of particleboard that used only sucrose as adhesive and was pressed at 160 °C was destroyed after the boiling treatment for 2 h, as shown in Fig. 3. This result was consistent with the TS and WA values of the boards and indicated that, with only sucrose used as adhesive, greater pressing temperatures were needed to cause adhesive curing. Based on Zhao *et al*. (2018), insoluble materials of heated sucrose were hardly observed after boiling treatment for 4 h, irrespective of heating temperature. However, in this research, results for wet bending strength after boiling treatment for 2h were still obtained at pressing temperatures of at least 180 °C.

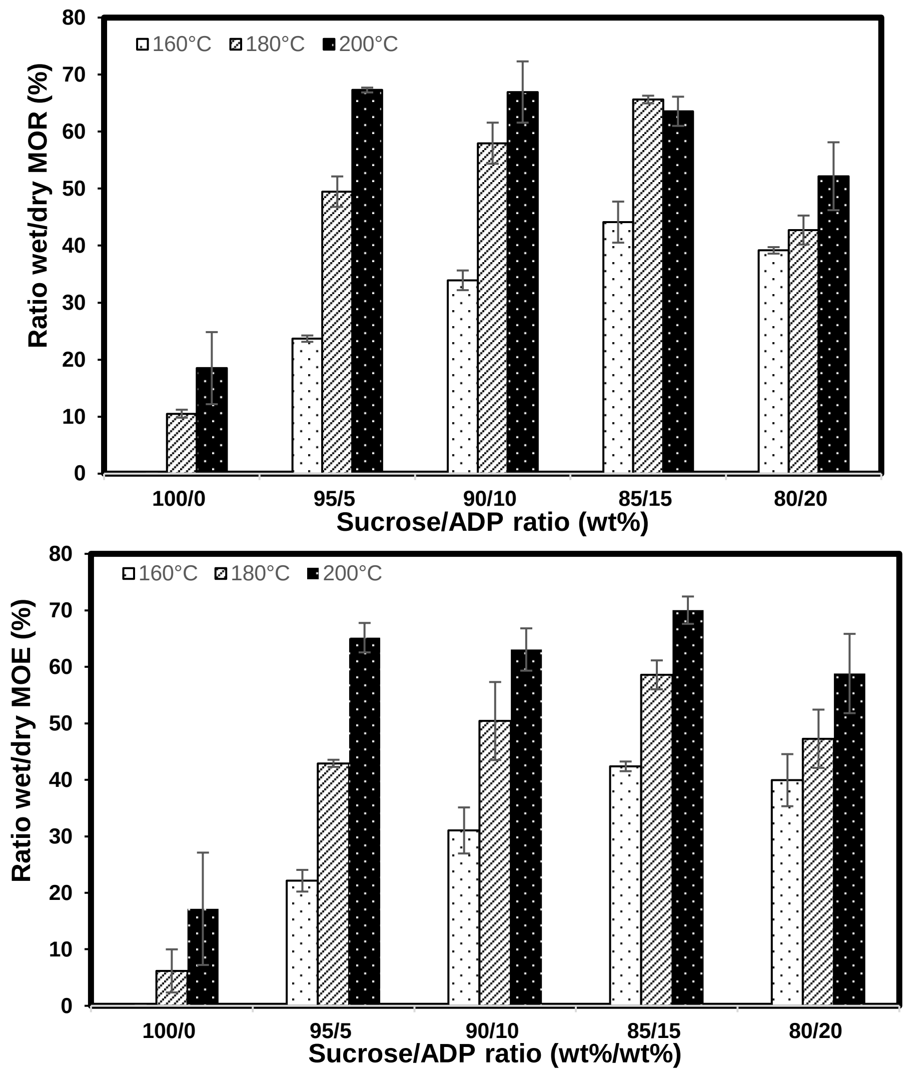

Fig. 3. Ratios of wet/dry MOR and MOE of sucrose-based particleboards made from bamboo. Error bars indicate standard deviations.

The ratios of the wet/dry MOR values of the particleboards that used only sucrose as adhesive and were pressed at 180 °C and 200 °C were only 10.5% and 18.5%, respectively. Even though the water resistance of the boards was relatively low, it indicated that the particleboard had still sufficient bondability that might be due to short-chain polymers with a large amount of branching with other monosaccharides (Lamaming *et al.* 2013). In another study, teak particleboard bonded with sucrose as adhesive and pressed at 180 °C was destroyed after boiling treatment for 2 h (Widyorini *et al*. 2016b). These results indicated that, in addition to sucrose acting as adhesive, the chemical components of the raw materials also contributed to the bonding mechanism. Future research is needed to make clear the influence of chemical components of the raw materials to the bonding mechanism of sucrose/ADP adhesive.

Almost all of the particleboards that used ADP and were pressed at 180 to 200 °C had wet/dry MOR ratios greater than 50%, though there was a decrease at the sucrose/ADP ratio of 80/20. Interestingly, the wet bending strengths of the particleboards using sucrose/ADP ratios of 95/5, 90/10, and 85/15 and pressed at temperatures of 180 °C and 200 °C met the requirement of JIS A 5908 (2003) type 13, *i.e*., at least 6.5 MPa. The resulted particleboards had relatively high-water resistance and could have potential as a furniture material. In general, the wet bending strengths of sucrose/ADP based particleboards that were pressed at 160 °C were lower compared than other pressing temperatures. Based on this study, to meet the requirements for water-resistant particleboards, at least 180 °C of pressing temperature was needed. Umemura *et al*. (2017) showed that the insoluble matter rate of sucrose/ADP materials against boiling water was more than 70% when pressed at 180 °C and 200 °C with the addition of ADP 5 to 20 wt%. Zhao *et al.* (2019b) found that application of synthesized sucrose/ADP as plywood adhesive resulted the optimum wet shear strength for sample that hot pressed at 170 °C.

Similar to the trends in MOR and MOE, the screw holding strength was very low for particleboard that used only sucrose as adhesive and was pressed at 160 °C (Table 2). Other particleboards had screw holding strengths greater than 300 N, meeting the requirement of JIS A 5908 (2003) type 13. Notably, more than 60% of the particleboards had a screw holding strength greater than 400 N, meeting the requirement of JIS A 5908 (2003) type 18. High screw holding strengths were achieved by particleboards produced at a pressing temperature of 160 °C with an ADP proportion of at least 15 wt% or produced at a pressing temperature of 180 °C or greater with an ADP proportion of at least 5 wt%. Overall, the sucrose-ADP based particleboards made from bamboo had high bonding strengths and the potential to be used in furniture.

Figure 4 shows that the sucrose/ADP ratio and pressing temperature significantly affected the IB strength of the particleboards. As with the other physical and mechanical properties, the IB strength of the particleboard that used only sucrose as adhesive and was pressed at 160 °C was the lowest, indicating that the greater pressing temperatures are needed if using only sucrose as adhesive. Thermogravimetric analysis by Zhao *et al*. (2018) showed that sucrose starts to exhibit rapid mass loss at 195 °C, due to caramelization reactions. When the pressing temperature increased to 180 °C and 200 °C, the IB strength increased to 0.65 MPa and 0.79 MPa, respectively. In other studies, the IB strengths of sucrose-based particleboards that were pressed at 180 °C and made from old oil palm trunk, teak wood, and recycled wood particleboards, were 0.91, 0.11 MPa, and 0 MPa (not measurable), respectively (Lamaming *et al.* 2014; Widyorini *et al*. 2016b; Zhao *et al*. 2018). Those results indicated that the bonding mechanisms were affected by many factors, such as pressing time, adhesive content, or even the raw materials used. The chemical components of raw materials that synergize with sucrose to produce good bondability and the corresponding bonding mechanisms are interesting topics for future research.

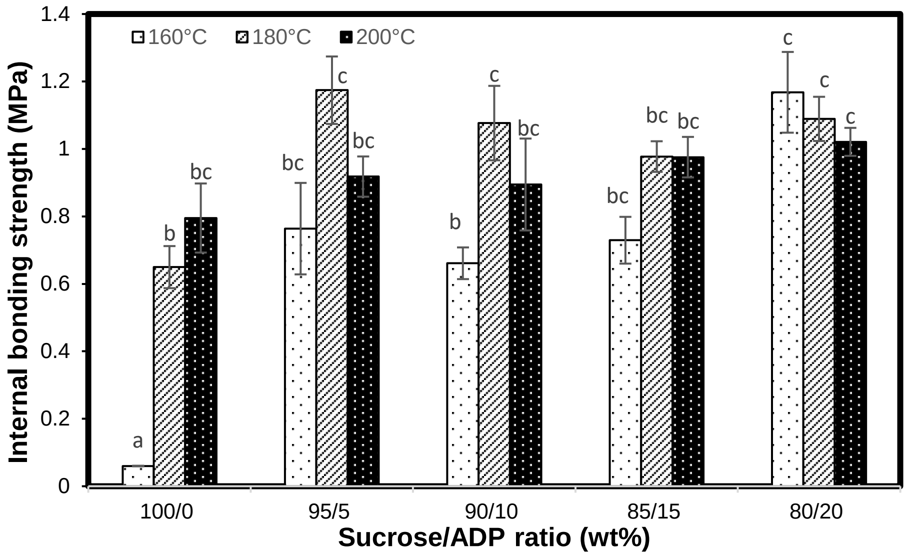

Fig. 4. The IB strength of sucrose-based particleboards made from bamboo.Error bars indicate the standard deviation.

This research also showed that the addition of ADP could reduce the required pressing temperature. By adding 5 wt% of ADP in the adhesive mixture, the IB strength increased to 1.2 MPa with a 180 °C pressing temperature, which met the requirement of the JIS A5908 type 18 standard. However, if the pressing temperature was set at 160 °C, at least 20 wt% of ADP was needed in the adhesive to achieve the same IB strength. The results clearly showed that ADP acted as catalyst, and the pressing temperature significantly affected the reaction. Zhao *et al*. (2018) showed that when the hot-pressing temperature was equal to or greater than 160 °C, the mechanical properties of particleboards with sucrose/ADP ratios of 85/15 fulfilled the requirement of JIS A5908 type 18 standard.

Interestingly, Fig. 4 shows that with a 200 °C pressing temperature, the IB strength was not significantly affected by the addition of ADP. However, a slight increase in board properties was observed with increase in ADP content. A possible reason is that sucrose was the main source of bonding strength in this adhesion system. However, the added ADP was responsible for increasing the water resistance properties, as shown by the TS and wet bending strength values. In addition, it was mentioned by Zhao *et al*. (2019b) that the addition of ADP improved the thermal stability of sucrose at high temperature.

A comparison of the properties of the boards produced in this study and in other related studies is shown in Table 3. Sucrose could be used as an effective adhesive with high pressing temperatures and longer pressing times (Lamaming *et al*. 2014, Widyorini *et al*. 2016b). Results shown in Table 3 indicate that the chemical components of the raw materials influenced the bond strength of sucrose-based particleboard. Addition of sucrose lowered the xylose/arabinose ratio, which indicates the degree of linearity of branching of hemicelluloses (Lamaming *et al.* 2013). The presence of ADP was supposed to be a catalyst in the sucrose-based adhesive system. Infrared analysis of sucrose-ADP adhesive showed peaks that indicated furan rings, carbonyl groups, and dimethylene ether bridges, which were possibly formed by the dehydration of sucrose (Zhao *et al*. 2018). The addition of ADP promoted the conversion of sucrose to 5-HMF (Sun *et al*. 2019b). Other reactions that also took place such as hydrolysis of sucrose and ammonium ion, the dehydration of monosaccharides, the Amadori rearrangement, caramelization, and the Maillard reaction (Zhao *et al*. 2020), continued by the dehydration condensation of furan compounds and Maillard reaction during curing process (Zhao *et al*. 2019b).

In addition, at high temperatures, hemicellulose and part of cellulose degrade to produce simple sugars and other decompositions products (Widyorini *et al*. 2005). The sugar components of the raw materials also support the bonding mechanism, while ADP may be acting as a catalyst in the degradation of sucrose and other sugar components. Komariah *et al*. (2019) stated that addition of ADP improved the bond strength between oil palm trunk particles. It seems that all the decomposition products then polymerize and arrange into a stable network during hot pressing, resulting in good properties of the particleboards.

Table 3. Comparison of the Properties of the Particleboards of this Study and of Other Related Studies

Characteristic of Particleboard	This Research	This Research	Lamaming *et al*. (2014)	Widyorini *et al*. (2016b)	Zhao *et al*. (2018)	Komariah *et al*. (2019)
Raw material	Petung Bamboo	Petung Bamboo	Old & young oil palm trunk	Teak wood	Recycled wood	Oil palm trunk
Adhesive/binder/ catalyst type	Sucrose	Sucrose/ ADP (95/5)	Sucrose	Sucrose	Sucrose/ ADP (85/15)	ADP
Adhesive content	(20 wt%)	(20 wt%)	(20 wt%)	(10 wt%)	(20 wt%)	(10 wt%)
Pressing condition	200 °C 10 min	180 °C 10 min	180 °C 20 min	200 °C 10 min	200 °C 10 min	180 °C 10 min
Target density (g/cm^3)	0.8	0.8	0.8	0.9	0.8	0.8
MOR (MPa)	13.7	14.3	13.6 & 10.7	9	25	8.9
MOE (GPa)	3.4	4.2	-	2.5	5	2.5
Wet MOR (MPa)	3.8	7.8	-	3.8	-	-
IB (MPa)	0.8	1.2	1.9 & 2.1	0.22	1.4	0.53
TS (%)	11.7	9.3	15.2 & 15.9	9	9.2	5.9

CONCLUSIONS

1. The interaction of the pressing temperature and the ratio of sucrose to ammonium dihydrogen phosphate (ADP) significantly affected all of properties physical and mechanical properties of the particleboard made from petung bamboo. The addition of ADP decreased the required pressing temperature for producing boards with properties that met the standard.

2. At 200 °C pressing temperature, the TS value, bending strength, screw holding strength, and IB strength were not significantly affected by the addition of ADP. However, the WA value and wet bending strength were noticeably affected by the addition of ADP, indicating that ADP can be regarded as an important catalyst to increase the water resistance of the sucrose adhesive.
3. In this research, optimal conditions were achieved with a 180 °C pressing temperature and a sucrose/ADP ratio of 95/5 (wt%/wt%). The properties of the particleboard at these conditions were as follows: The TS, WA, surface roughness, MOR, MOE, wet MoR, wet MoE, IB strength, and screw holding strength were 9.3%, 38%, 8.48 μm, 14.3 MPa, 4.2 GPa, 7.8 MPa, 2.2 GPa, 1.2 MPa, and 412 N, respectively.

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