Application of Maltodextrin-based Adhesive on Particleboard Made from *Salacca* Frond

Greitta Kusuma Dewi, Ragil Widyorini,* and Ganis Lukmandaru

Maltodextrin is a potential natural adhesive for particleboard because it is reactive and freely soluble in water. However, maltodextrin has a low water resistance and a high melting point that hinder its development as a particleboard adhesive. An addition of ammonium dihydrogen phosphate (ADP) as a catalyst of maltodextrin was expected to overcome its weaknesses. The optimal pressing temperature was expected to be affected due to the addition of catalysts. This research aimed to investigate the effect of maltodextrin/ADP ratios and pressing temperatures on particleboard properties made from *Salacca* frond. The maltodextrin/ADP ratios used in this research were 100/0, 90/10, and 80/20 wt%, and the pressing temperatures were set at 200 and 220 °C. The combination of an increased ADP ratio in maltodextrin and an increased pressing temperature improved the particleboard properties. The water resistance was also significantly improved by addition of ADP and increased pressing temperature. Thermal analyses showed that the onset temperature of weight reduction of maltodextrin added particles was lowered by addition of ADP. The results suggested that a maltodextrin/ADP mixture could be a promising particleboard binder.

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Keywords: Maltodextrin; Ammonium dihydrogen phosphate; Particleboard properties; Pressing temperature; Salacca frond

*Contact information: Department of Forest Product Technology, Faculty of Forestry, Universitas Gadjah Mada, Jl. Agro no. 1, Yogyakarta, Indonesia 55281; *Corresponding author: rwidyorini@ugm.ac.id*

INTRODUCTION

The discovery of a new wood adhesive needs to be considered to address the formaldehyde-based adhesive problems. In 2016, formaldehyde was classified as a more toxic compound, from "suspected of causing" to "may cause" carcinogenicity and "suspected of causing" mutagenicity (Axelson 2015). Aside from health issues, formaldehyde is considered less environmental-friendly because its synthesis uses non-renewable and limited-resource compounds, such as petroleum and natural gas. The usage shift of wood adhesives to non-formaldehyde adhesives has now become a concern. However, formaldehyde-based adhesives have supplied more than 60% of the global wood adhesive needs. The need for wood adhesives was predicted to increase year over year as the global production and consumption of wood panels also increases (FAO 2018). Substitutes for formaldehyde-based adhesives must be mass produced or consist of many different types of adhesives.

The exploration of natural adhesives becomes one solution because there are many varieties and the production can be increased through cultivation and biotechnology. Such adhesives also have the potential to be harmless for living things and the environment.

Many natural adhesives have been used and investigated in composite board manufacturing such as soy flour, casein, blood albumin, chitosan, gluten, tannin, lignin, gum, shellac, rubber, citric acid, starch, *etc*. (Umemura *et al*. 2003; Moubarik *et al*. 2009; Lei *et al*. 2010; Umemura *et al*. 2011; Bertaud *et al*. 2012; Kollman *et al*. 2012; Norstrom *et al*. 2014; Widyorini *et al*. 2016). Recently, Umemura *et al*. (2017) found that sucrose/ADP (ammonium dihydrogen phosphate) is a promising wood adhesive because of its bonding ability and high-water resistance, as also reported by Zhao *et al*. (2018) and Widyorini (2020). Sucrose is abundant and available everywhere, but it is widely used as the main sugar in food and drinks, and its usage for commercial wood adhesives may experience obstacles. Another saccharide with potential that only is being used as an additive in the food and drink industry is maltodextrin.

Maltodextrin consists of β-d-glucose oligomers that have a dextrose equivalence (the amount of reducing sugar presented based on total dry substance) of less than 20 (Bemiller and Whistler 1996). It is produced by acid or enzyme hydrolysis of starch, which is abundant. Maltodextrin has better adhesion properties than starch, is easy to obtain, and is freely soluble in water (Clare *et al*. 2002; Rowe *et al*. 2009; Castro-Cabado *et al*. 2016). Compared to sucrose, maltodextrin is cheaper in price. However, development of maltodextrin as a wood adhesive faces challenges, *i.e*. a high melting point and its particleboard has low dimensional stability. The maltodextrin melting point is higher than 225 °C (Mollan and Çelik 1996), which means that the bonding and curing reactions occur at higher temperatures, as well as the optimal pressing temperature in particleboard manufacturing. Santoso *et al*. (2017) states that the thickness swelling (TS) of nipa frond particleboard with 20 wt% maltodextrin does not meet the Japanese industrial standard (JIS) A 5908 (2003) for particleboard at both 180 and 200 °C pressing temperatures but meets the standard only after a minimum 12.5 wt% addition of cross linker citric acid. In addition, Zhao *et al*. (2018) and Widyorini (2020) have successfully improved properties of recycled wood particleboard and bamboo particleboard, respectively, by addition of ADP.

The addition of ADP is predicted to overcome maltodextrin weaknesses and better optimize its usage as a particleboard wood adhesive. According to Umemura *et al.* (2017), the ADP catalyst lowers the sucrose melting point. Maltodextrin and sucrose have some features in common, *i.e.* they were both dehydrated and rearranged/caramelized in thermal treatment (Claude and Ubbink 2006; Quintas *et al*. 2007). Caramelization basically is a rearrangement process that leads to 5-hydroxymethyl 2-furfural (5-HMF) formation, and there are 4 concepts that lead to the process, *i.e.* 1) thermal treatment of pure saccharides above their melting points, 2) thermal treatment of saccharides in the presence of catalyst, 3) treatment of saccharides in mineral acids or alkali, and 4) treatment with ammonia, ammonium salts, amino acids, protein and polypeptides that cause the Maillard reaction (Tomasik *et al*. 1989). Because maltodextrin acts differently than disaccharides sucrose, the effects of adding ADP and the optimal pressing temperature to product high-quality particleboard could be different. The authors' previous study showed a decrease of the maltodextrin melting point from 272 to 204 °C and an increase of water resistance of the heat-treated maltodextrin after ADP addition (Dewi *et al*. 2020). However, the adhesiveness of maltodextrin and ADP for lignocellulosic materials has not been investigated.

Salacca frond was chosen as the raw material because it works well in citric acid/maltodextrin particleboard (75/25 wt%). The three-layer particleboard with its finer particles or its fibrovascular bundles (length was 25 ± 5 mm) as the face layer was also

successfully produced. The board properties met JIS A 5908 standard (Prasetyo *et al*. 2017; Widyorini *et al*. 2018; Widyorini *et al*. 2020). Those fronds usually are left over to rot in the plantation area during intensive plant maintenance, and the resource has not been used extensively yet (BPPT 2000; Lim 2012; Widyorini *et al.* 2018; Hakim *et al.* 2019). The *Salacca* plant has been widely cultivated in south-east Asia plantation in Indonesia, Malaysia and Thailand, and particularly in Indonesia's agroforestry area for its fruit production (Saleh *et al*. 2018; Hakim *et al*. 2019). Statistic Indonesia (2019) noted that a total number of harvested *Salacca* plant in the fourth quarter of 2018 in Indonesia was 38,024,008 clumps at 27,731 ha plantation area. They usually prune 2 to 3 fronds per clump every 2 months to stimulate the female flower formation for fruit production, so the estimated biomass of the frond is more than 144 million tons/year in Indonesia (the weight of 2 to 3 fronds is about 0.5 to 1 kg). Based on that, it was concluded that the fronds are potential materials to be developed for particleboard industry. This research aimed to utilize *Salacca* frond and investigate the effect of ADP ratios in maltodextrin and pressing temperatures on the properties of particleboard made from it, as well as to find the best manufacturing conditions.

EXPERIMENTAL

Materials

Food grade maltodextrin DE 10-15 was purchased from Zhucheng Dongxiao Biotechnology Co. Ltd, (Zhucheng, China) without further purification. Ammonium dihydrogen phosphate pro analysis (PA) CAS No. 7722-76-1 (Merck, Darmstadt, Germany) was also used as catalyst without further purification and distilled water was used as the solvent.

Salacca (*Salacca zalacca*) fronds were collected from Turi district, Sleman city, Yogyakarta province, Indonesia. Before being processed into particles, *Salacca* fronds were cleaned of thorns, and the tips were cut and discarded (*Salacca* frond length used for particle production was ± 2 m from the frond base). They were then cut with a chipper and air-dried. The particle production used a knife ring flaker. The particles were screened through a 10-mesh screen, and the particles that passed through the mesh were used as the raw material. Roughly 84% were passed through the 10-mesh and 40-mesh was retained. The raw material had a 12.3% moisture content and 0.130 ± 0.002 g/cm³ bulk density.

Method

Adhesive solution preparation

The maltodextrin was dissolved in warm distilled water (80 ± 2 °C) at a 50 wt% concentration because maltodextrin DE 10-15 demonstrates good solubility in the solids range of 45 to 65% (Kenyon and Anderson 1988). After being completely dissolved, certain amounts of ADP catalyst were added. The maltodextrin/ADP mixture ratios were 100/0, 90/10, and 80/20 wt%. The adhesives content used in this research was 20 wt% based on dry weight particles. The viscosity and pH of each adhesive solution is shown in Table 1.

Table 1. Viscosity and pH of Adhesive Solutions at 43 ± 2 °C

Properties	Maltodextrin/ADP Ratio (wt%)		
	100/0	90/10	80/20
Viscosity (cP)	131.2	125.8	106.4
pH	6.22	3.91	3.61

Particleboard manufacturing

The adhesive solutions at warm conditions (43 ± 2 °C) were evenly sprayed onto particles, as reported by Widyorini *et al*. (2017). Solution additions were completed in warm conditions because they had considerably lower viscosity compared to their viscosity at room temperature. The sprayed particles were oven dried at 80 °C for 4 h to reduce moisture content and avoid board delamination (the moisture content of the sprayed particles was reduced from 26.2 to 33% to 4 to 5% after oven drying). The particles were hand formed into mats in 25 cm x 25 cm sizes and then were hot-pressed using a three-step cycle, as reported by Widyorini *et al*. (2018) at 3 MPa specific pressure. The mats were hot-pressed for 5 min, had a 1 min breathing stage, and then hot-pressed again for 5 min. The total pressing time was 10 min. The board dimension was targeted in 25 cm x 25 cm x 1 cm in size with a target density of 0.8 g/cm³. All boards were conditioned for approximately 1 week at room temperature (±27 °C) and a 77% relative humidity before board property evaluations.

Board properties evaluation

The boards were evaluated according to their physical properties, such as density, moisture content, thickness swelling, and water absorption, as well as by their mechanical properties, such as internal bonding strength, bending strength (modulus of rupture and modulus of elasticity), and bending strength under wet conditions. The surface roughness was also evaluated for finishing purposes information. The properties were evaluated according to JIS A 5908 (2003), except that the water absorption was evaluated based on Clarke (1966) and the surface roughness was evaluated based on Hiziroglu and Suzuki (2007).

The density (D), moisture content (MC), thickness swelling (TS), water absorption (WA), and internal bonding strength (IBS) tests were performed on a 5 cm x 5 cm x 1 cm specimen, while the bending strength, bending strength under wet conditions, and surface roughness tests were performed on a 20 cm x 5 cm x 1 cm specimen. The density was determined by dividing the weight sample with its volume. The moisture content was determined as the percentage of weight changes after oven drying based on the constant air-dried weight. The thickness swelling and water absorption were tested by immersing the specimen in water at room temperature for 24 h. The internal bonding strength was tested by pulling the specimen surface perpendicularly at a load speed 2 mm/min before failing force. The bending strength *i.e*. modulus of rupture (MOR) and modulus of elasticity (MOE) were tested by giving load vertically on the board face at rate 10 mm/min and span 15 cm until maximum load before cracking. The same test was performed through a wet bending strength evaluation where the specimen was immersed in warm water at 70 ± 3 °C for 2 h and continued immersed in water at room temperature for 1 h (wet bending test A) prior to the test. Before the wet bending test, surface roughness was measured as the average roughness (R_a) using a surface roughness tester (SRG 4000, Bosworth Instrument, Cleveland, OH, USA) at six random points. The bending strength reduction (%) was calculated by subtracting the wet bending strength from the dry bending strength,

and divided by the dry bending strength. The MOR, MOE, and IBS values were corrected in target density based on specimen densities. Each property was tested in triplicate (except the wet bending strength was tested in duplicate) and the average and standard deviation were determined. A two-ways analysis of variance (ANOVA) with α 1% and 5% was conducted to show the effect of maltodextrin/ADP ratios and pressing temperatures on the board properties.

Fourier Transform Infrared (FTIR) spectroscopy

A FTIR analysis was performed by a FTIR spectrophotometer (IR Prestige-21, Shimadzu, Kyoto, Japan) using a KBr disk method and were recorded by means of a 10 scan average at a 16 cm^{-1} resolution. The wet bending specimen were used as the samples to remove the excess and unreactive maltodextrin in particle bonding for the results. In addition, the materials of heat-treated adhesive after boiling for 4 h (Dewi *et al.* 2020) as well as *Salacca* frond (Widyorini *et al.* 2018) were also analyzed. Each sample was oven-dried at 40 °C overnight and ground into powder (smaller than passed through 100 mesh). Prior to the analysis, the sample was oven-dried again at 60 °C for 15 h.

Thermogravimetry Analysis (TGA)

A thermogravimetry analysis was performed through a simultaneous thermal analyzer (PT 1600, Linseis, Selb, Germany). Maltodextrin with/without ADP catalyst was dissolved in warm distilled water at the maltodextrin/ADP ratios of 100/0 and 80/20 wt% with the concentration of the solution was 50 wt%. Each solution was then sprayed into particles and dried at 80 °C for 4 h. After drying, the samples were pulverized into less than 60 mesh size and served as the TGA samples. In addition, dried mixture of maltodextrin/ADP ratios of 80/20 wt% (Dewi *et al*. 2019) were also added to be analyzed. The samples were scanned from room temperature (± 27 °C) to 400 °C at a rate 10°C/min under nitrogen purging. The flow rate of nitrogen purging is 40 mL/min.

RESULTS AND DISCUSSION

All boards were manufactured without delamination, and the particleboard color became darker as the ADP ratio in the maltodextrin and pressing temperature increased. This phenomenon was also found in citric acid particleboard and binderless particleboard with ADP additions (Widyorini *et al*. 2016; 2018; Komariah *et al*. 2019). Darker colorization of the boards may due to the simple sugar caramelization produced by ADP-hydrolyzed maltodextrin and also a high degree of raw material hydrolysis during high pressing temperatures.

The analysis of variance (ANOVA) of the board properties are shown in Table 2. Interactions between the maltodextrin/ADP ratio and pressing temperature affected board properties related to water, such as thickness swelling, water absorption, modulus of rupture under wet conditions, and modulus of elasticity under wet conditions. Interestingly, those interactions did not affect the modulus of rupture or modulus of elasticity under dry conditions. The maltodextrin/ADP ratios affected internal bonding and modulus elasticity under dry conditions notably but did not affect modulus of rupture under dry conditions.

Table 2. Analysis of Variance

Properties	Significance (p-value)		
	Maltodextrin/ADP Ratios	Pressing Temperature (°C)	Maltodextrin/ADP Ratios* Pressing Temperature
Thickness Swelling	1.133×10^{-8} **	1.188×10^{-8} **	5.277×10^{-3} **
Water Absorption	3.926×10^{-8} **	3.921×10^{-7} **	0.034*
Surface Roughness	0.006**	4.704×10^{-7} **	0.866 ns
Internal Bonding Strength	1.776×10^{-4} **	2.850×10^{-6} **	0.159 ns
Modulus of Rupture under Dry Conditions	0.055 ns	0.159 ns	0.346 ns
Modulus of Elasticity under Dry Conditions	0.009**	0.342 ns	0.264 ns
Modulus of Rupture Under Wet Conditions	2.829×10^{-5} **	1.251×10^{-4} **	0.012*
Modulus of Elasticity under Wet Conditions	2.525×10^{-5} **	1.556×10^{-5} **	0.003**

Note: ns: non-significant, *: significant at 5% test level, **: significant at 1% test level

Physical Properties and Surface Roughness of Boards

Table 3 shows the physical properties and surface roughness of the boards. All boards had densities ranging from 0.74 to 0.78 g/cm³, although the target density was 0.8 g/cm³. The lower density compared to the target density was likely due to board widening (2 to 5%) after hot-pressing process. All moisture contents (MC) of the boards met the requirement of JIS A 5908 (5 to 13%) as the MC range was 5.75 to 7.59%. An increase of the maltodextrin/ADP ratio and the pressing temperature resulted in a decreased moisture content of the board. Two causes could have led to these results, *i.e*. the bonding formation between maltodextrin and particles that was accelerated by ADP additions could have reduced the free OH-groups in particles to bond with moisture in its surroundings, and severe dehydration of the raw material during hot pressing caused a hysteresis effect. Higher temperatures caused greater chemical structure changes in the wood, such as lignocellulose decomposition and cellulose crystallinity increases, which led to the equilibrium moisture content to become lower, known as wood hysteresis (Akyildiz and Ates 2008; Esteves and Pereira 2009).

The TS and WA values ranged from 6.25 to 73.16% and 35.5 to 151.8%, respectively (Table 3). Only the boards with an 80/20 wt% maltodextrin/ADP ratio and a 220 °C pressing temperature met the TS standard of JIS A 5908 requirement (max. 12%), while the 80/20 wt% maltodextrin/ADP boards at both pressing temperatures and the 90/10 wt% maltodextrin/ADP boards at 220 °C had WA values that met the WA values range of particleboard stated by Clark (1966) (20 to 75%). The 100/0 wt% maltodextrin/ADP boards at both pressing temperatures had low dimensional stability and water resistance. The bonding system of maltodextrin 100% and particles might not have been formed entirely, as the melting point of maltodextrin is higher than 225 °C (higher than the pressing temperature used); in addition, maltodextrin has properties, *i.e*. freely soluble in water and high wettability (Mollan and Çelik 1996; Wang and Wang 2000; Rowe *et al*. 2009) that make the bonding system easy to break in the presence of excess water. Hydrogen bonds formed by maltodextrin and lignocellulose is also easily broken by water. Breakages in the adhesives bond network and potential thickness recovery of densified particles are factors affecting TS values of resin-bonded particleboard (Sekino *et al*. 1999).

Table 3. Density (D), Moisture Content (MC), Thickness Swelling (TS), Water Absorption (WA), and Surface Roughness (SR) of Maltodextrin/ADP-based Particleboard

Properties	Maltodextrin/ADP Ratio (wt%)					
	100/0		90/10		80/20	
	200 °C	220 °C	200 °C	220 °C	200 °C	220 °C
D (g/cm³)	0.74 ± 0.00	0.78 ± 0.02	0.75 ± 0.02	0.78 ± 0.01	0.77 ± 0.01	0.78 ± 0.02
MC (%)	7.59 ± 0.1	7.01 ± 0.1	7.13 ± 0.1	6.16 ± 0.4	5.99 ± 0.9	5.75 ± 0.3
TS (%)	73.16 ± 8.6	35.61 ± 3.8	48.30 ± 3.2	17.73 ± 1.5	23.23 ± 4.1	6.25 ± 0.8
WA (%)	151.8 ± 14.1	93.1 ± 6.4	97.5 ± 4.1	66.3 ± 12.0	68.8 ± 7.6	35.5 ± 2.7
SR (µm)	8.14 ± 0.5	6.16 ± 0.1	7.77 ± 0.8	5.63 ± 0.3	7.21 ± 0.6	4.94 ± 0.2

Results showed a downward trend of TS and WA values with increased maltodextrin/ADP ratios and pressing temperatures. At 220 °C pressing temperature, the TS value was 35.61% and decreased to 17.73% and 6.25% after addition of 10% and 20% ADP in maltodextrin, respectively. The WA decreased from 93.1% to 66.3% and 35.5%, respectively. There was a greater decrease in values at a 220 °C pressing temperature than 200 °C. Umemura *et al.* (2017) states that ADP can lower the melting point of sucrose and change sucrose to a high water-resistant substance containing a furan ring and carbonyl group by heat treatment. High pressing temperature and the presences of ADP in the maltodextrin bonding system might also turn maltodextrin into a high water-resistant substance, although maltodextrin could require a higher amount of ADP and higher heating temperature. Stofko (1980) states that the transformation of polymeric starches, such as potato starch, into furan-type compounds requires a somewhat higher proportion of catalyst than simpler sugars, such as glucose and sucrose, for a given reaction rate. Therefore, the lowest TS and WA values of maltodextrin-based particleboard was achieved at higher catalyst contents and pressing temperatures, *i.e.* 20 wt% at 220 °C, while the same TS value could be achieved at 180 °C for sucrose-based particleboard (Widyorini 2020).

The average surface roughness of the boards ranged between 4.94 to 8.14 µm (Table 3). The lowest surface roughness was obtained from the 80/20 wt% maltodextrin/ADP ratio and 220 °C pressing temperature. This was the only surface roughness found within average roughness values of commercial particleboard in Japan, which range from 3.67 to 5.46 (Hiziroglu and Suzuki 2007). Compared to Santoso *et al*. (2017), who also used maltodextrin, the surface roughness of *Salacca* frond particleboard with a 100/0 wt% maltodextrin/ADP ratio at 200 °C had lower values than Nipa frond particleboard with the same treatment (± 8.5 µm). Differences in particle size distribution and raw material type could be the reason for the different values (Nemli *et al*. 2005; Hashim *et al*. 2010). Increasing the ADP ratio and pressing temperature decreased the surface roughness values (a smaller R_a resulted in better board quality) which may be due to increased density board and decreased moisture content. Increased density and decreased moisture content lowered the surface roughness values of the particleboard (Hiziroglu and Suchland 1993; Nemli *et al*. 2005).

Mechanical Properties of Boards

The IBS values of the boards are shown in Fig. 1. All boards satisfied JIS A 5908 requirement type 18 (min. 0.3 MPa), except the 100/0 wt% maltodextrin/ADP ratio at 200 °C, which satisfied JIS requirement type 13 (min. 0.2 MPa). The IBS value of the maltodextrin-bonded *Salacca* frond particleboard was 0.25 MPa, while that of the

maltodextrin-bonded nipa frond particleboard was 0.16 MPa (Santoso *et al.*, 2017) at 200 °C pressing temperature. These results indicated that maltodextrin is potential material for adhesive. Based on Fig 1., it shows that to utilize maltodextrin as an adhesive, it needs at least 200°C pressing temperature. After the pressing temperature was increased to 220°C, the IBS value of maltodextrin-based particleboard could increase to 0.5 MPa. The higher pressing temperature approached the melting and curing point of maltodextrin better than lower pressing temperatures, and also the bonding occurred between maltodextrin and particles and produced higher IBS values. The melting point of maltodextrin is higher than 225 °C (Mollan and Celik 1996), while that of ADP is around 203 to 208 °C (Umemura *et al.* 2017). With addition of 10% ADP, an endothermic peak was observed at around 204 °C (Dewi *et al.* 2020). Figure 1 shows that addition of 20% ADP caused the increasing of IBS values until around 0.43 MPa (200°C) or 0.62 MPa (220 °C). Widyorini *et al.* (2018) showed that maltodextrin and citric acid could provide the optimum IBS value of *Salacca* frond particleboard (0.67 MPa) when the ratio citric acid/maltodextrin ratio was 75/25 with a 180 °C pressing temperature. It was clearly shown that the bonding properties of maltodextrin can be improved by cross-linking agent, such as citric acid (Widyorini *et al*. 2018), or addition of a catalyst, such as ADP in this research.

The IBS values increased remarkably with increased pressing temperatures, and a 10 wt% ADP addition in the maltodextrin increased IBS values remarkably compared to the maltodextrin without ADP. However, further addition (20 wt% ADP) had similar IBS values compared to 10 wt% ADP. This result was similar to Zhao *et al*. (2018) and Widyorini (2020), but the effect of increasing pressing temperatures from 180 and 200 °C to 220 °C in the sucrose/ADP (85/15 wt%) particleboard did not increase the IBS value remarkably. As mentioned above, the curing mechanism of maltodextrin-based adhesive was expected to be related to caramelization and the forming of furan-type compounds/furan derivative, *i.e.* 5-hydroxymethyl 2-furfural (5-HMF), that is produced by the dehydration of saccharides-based materials/carbohydrates with/without catalyst in heat treatment (Tomasik *et al.* 1989; Chheda *et al.* 2007).

The range of MOR and MOE values was 8.5 to 10.4 MPa and 2.37 to 3.15 GPa, respectively (Fig. 2). All boards met MOR and MOE requirements of JIS A 5908 type 8 (min. 8 MPa and min. 2 GPa). Some boards even met the MOE requirement of the JIS A 5908 type 18 (min. 3 GPa). Results showed the boards exhibited moderate MOR values but had high elasticity. The MOR values were not particularly affected by the maltodextrin/ADP ratios and pressing temperatures due to the same value in all treatments. The interaction between the pressing temperature and adhesive composition also did not notably affect the MOR values of the *Salacca* frond particleboard with acid citric/maltodextrin 100/0 to 50/50 wt% at 180 and 200 °C (Widyorini *et al*. 2018). The use of the same particle size and the treatment type could be the reasons for inconsequential MOR value changes because particle size affected the MOR values (Widyorini *et al*. 2016).

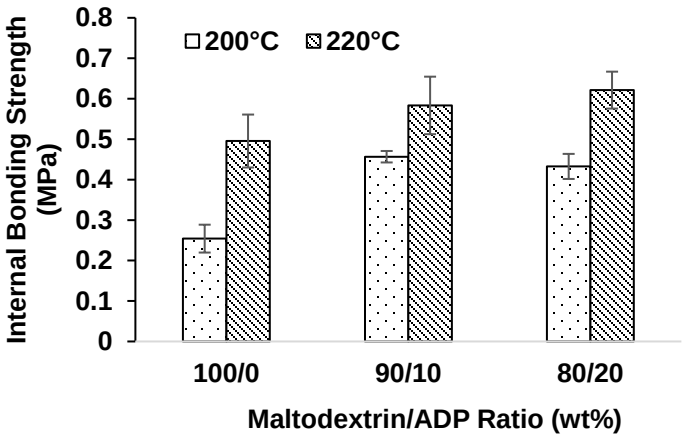
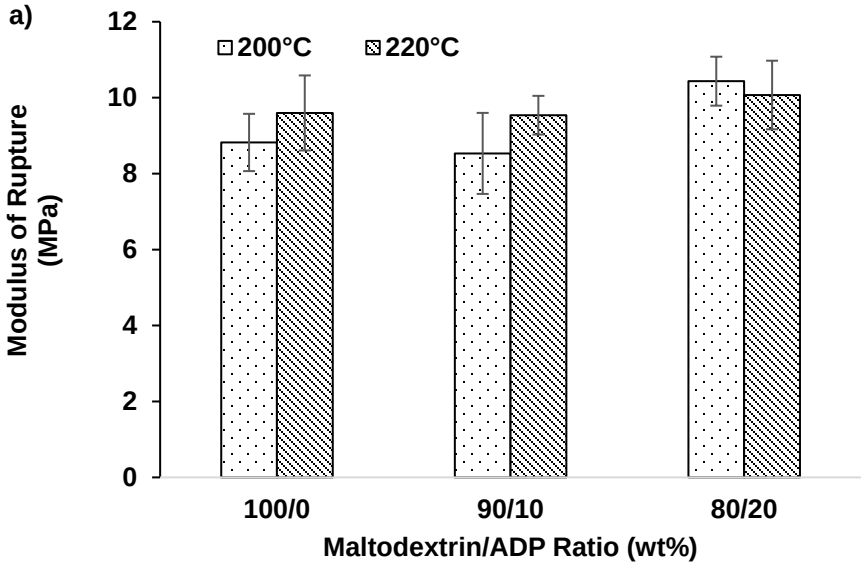


Fig. 1. IBS of particleboard at various maltodextrin/ADP ratios and pressing temperatures; vertical line through the bars represents standard deviation from the mean

Figure 3 shows the reduction of bending strength after hot water treatment. Particleboards made with the 100/0 wt% maltodextrin/ADP ratio and 90/10 wt% maltodextrin/ADP ratio at 200 °C had a 100% strength reduction because the sample was damaged after hot water treatments. However, the reduction of the MOR and MOE values after treatments decreased remarkably with increased ADP additions and pressing temperatures. Interestingly, it clearly showed that the increasing of IB values and decreasing of the TS and WA values correlated to the improving wet bending strength of the boards.



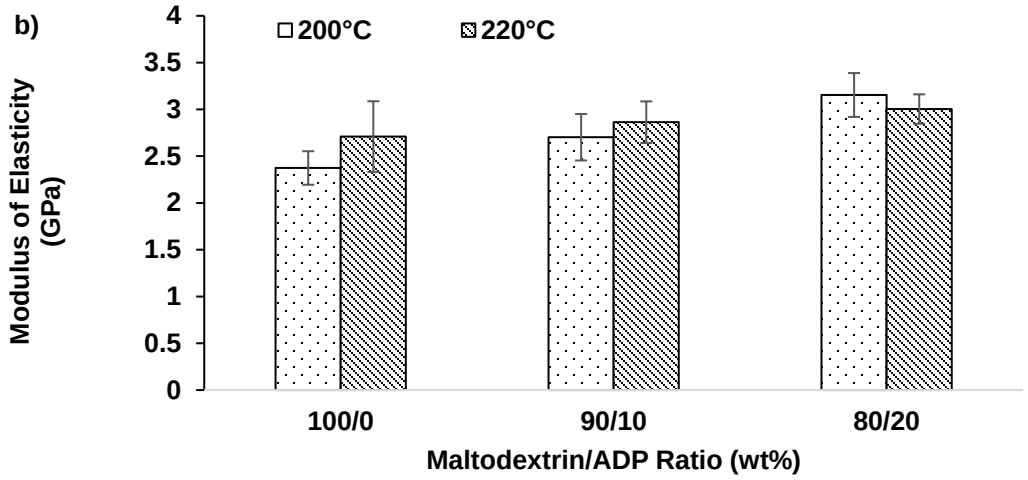


Fig. 2. a) MOR and b) MOE of particleboard under dry conditions at various maltodextrin/ADP ratios and pressing temperatures; vertical line through the bars represent standard deviation from the mean

Fourier Transform Infrared (FTIR)

The FTIR spectra of *Salacca* frond particle, the adhesive of maltodextrin /ADP (80/20), as well as the particleboards at different ADP ratios and pressing temperatures, are shown in Fig. 4. The peak at 2924 cm^{-1} was attributed to C-H stretching of CH_2 (Parikh and Madamwar 2006). Figure 4 shows that the absorbance of the peak of 2924 cm^{-1} for maltodextrin-bonded particleboard was stronger compared other boards. The peaks at around 1705 and 1636/1620 cm^{-1} would be attributed to carbonyl groups. The peaks at 1512 and 794 cm^{-1} were attributed to C=C and CH=CH of furan ring (Beta *et al*. 2001; Billes *et al*. 2004; Umemura *et al*. 2017). Those absorption bands increased with increasing pressing temperature, indicating promotion of the curing process along the polymerization of the furan compounds, as mentioned by Zhao *et al*. (2019). Meanwhile, the peak at around of 1512 cm^{-1} can be attributed to C=C stretching vibration furan ring (Umemura *et al*. 2017; Zhao *et al*. 2019), as well as to C=C stretching of the benzene ring in lignin (Kubovsky *et al*. 2020) as shown at *Salacca* frond and the particleboards. The FTIR spectra showed that the maltodextrin/ADP based particleboard and maltodextrin/ADP dried adhesive had the peak of 794 cm^{-1}, while the maltodextrin-based particleboard and *Salacca* frond had not. Based on the results, ADP seemed act as catalyst for maltodextrin, in presence of heat treatment, to caramelize and lead to 5HMF formation, as mentioned by Tomasik *et al*. (1989).

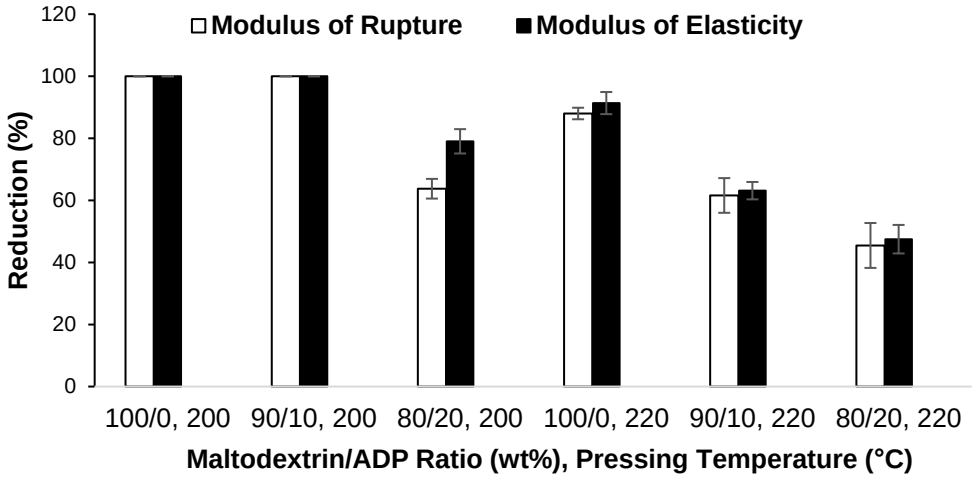


Fig. 3. MOR and MOE reductions after hot water treatment; vertical line through the bars represent standard deviation from the mean

Thermogravimetry Analysis (TGA)

Figure 5 shows the TGA of dried mixtures of maltodextrin/ADP added *Salacca* frond particles and maltodextrin/ADP (Dewi *et al.* 2019). The dried mixture of maltodextrin/ADP added particles was composed of maltodextrin, ADP, and *Salacca* frond, that reflect the composition of the mat. Based on Dewi *et al*. (2019), the onset temperature of weight reduction of dried mixtured of only maltodextrin (100/0 wt%) at around 270 °C, which is similar with Castro *et al.* (2016), *i.e.* 266 °C. It can be seen that the preliminary weight loss temperatures of maltodextrin added particles was around 204 °C, as shown in Fig. 5. This behavior of the decomposition is principally attributed to the three main components of the lignocellulosic material (hemicellulose, cellulose, and lignin) of *Salacca* frond, considering that the dried mixture was around 83 wt% composed of the biomass.

Figure 5 shows that when ADP of 20 wt% was added to maltodextrin, the onset temperature of weight reduction was around 188 °C. Umemura *et al*. (2017) showed that the onset temperature of weight reduction of ADP was around 170 °C. When that mixture was added to the *Salacca* frond particles, the preliminary weight loss temperatures was approximately 156 °C. Those phenomena showed that ADP addition caused lowering the onset temperature of weight reduction. Komariah *et al*. (2019) also resulted that when ADP was added to oil palm trunk (OPT) particles, the degradation of OPT shifted to lower temperature. These findings indicated that the thermal degradation and caramelization reactions of maltodextrin shifted at a lower temperature with the addition of ADP, as also has been occurred on sucrose, as mentioned by Zhao *et al.* (2019). Shorter chain saccharides and 5-HMF have a lower melting point than longer chain saccharides (Shallenberger and Birch 1975; Rosatella *et al*. 2011), which may be one of the reasons the onset degradation temperature occurred at lower temperatures.

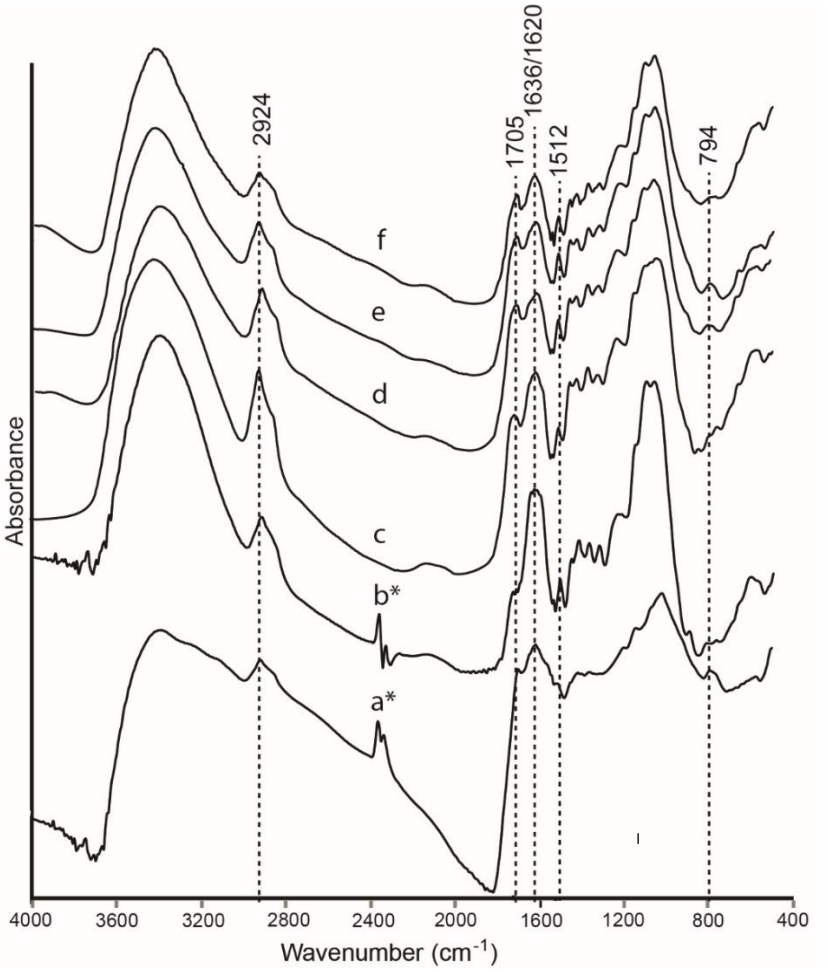


Fig. 4. FTIR spectra of several samples a*) dried mixture of maltodextrin/ADP (80/20 wt%, 220 °C) (Dewi *et. al*. 2020), b*) *Salacca* frond particles (Widyorini *et al*. 2018), c) particleboard (maltodextrin/ADP: 100/0 wt%, 220 °C), d) particleboard (maltodextrin/ADP: 90/10 wt%, 220 °C), e) particleboard (maltodextrin/ADP: 80/20 wt%, 220 °C), f) particleboard (maltodextrin/ADP: 80/20 wt%, 200 °C)

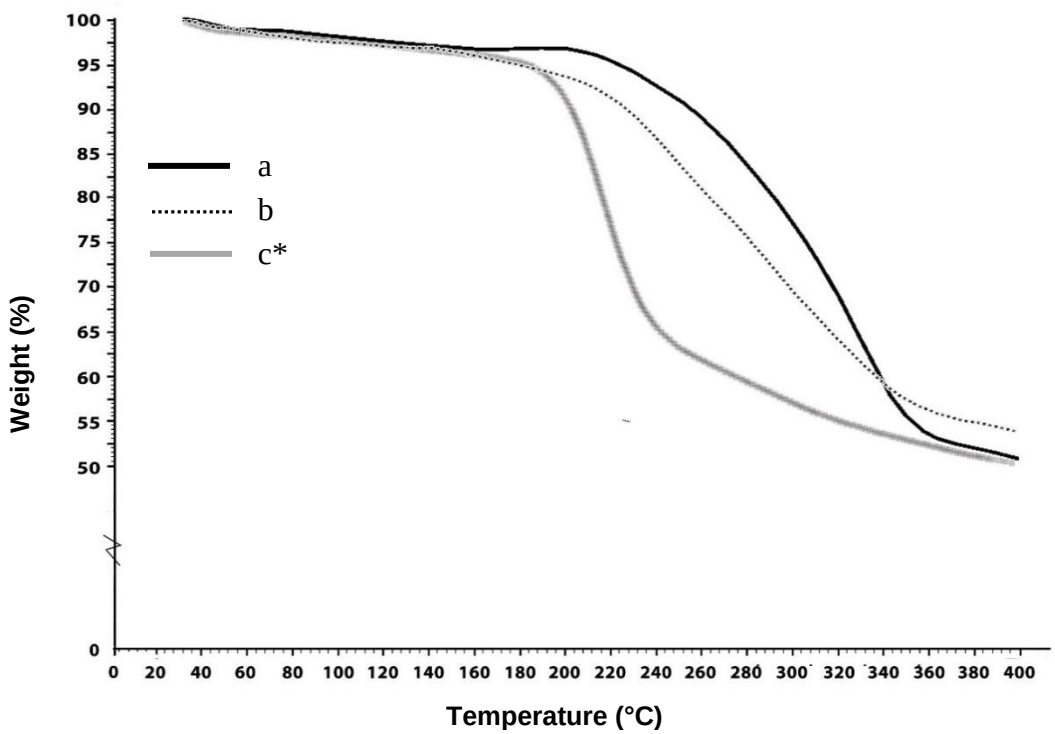


Fig. 5. Thermogravimetry curve of a) the maltodextrin/ADP (100/0 wt%)-added *Salacca* frond particles, b) the maltodextrin/ADP (80/20 wt%)-added *Salacca* frond particles, and c*) dried mixture adhesive of maltodextrin/ADP (80/20 wt%) (Dewi *et. al*. 2019)

CONCLUSIONS

1. A combination of increased ammonium dihydrogen phosphate (ADP) ratio in maltodextrin and increased pressing temperature improved the properties of *Salacca* frond particleboard, especially the properties related to water treatment. This result was consistent with a catalytic effect of ADP in caramelization/the rearrangement of maltodextrin into a high-water resistance substance, *i.e.* 5-hydroxymethyl 2-furfural (5-HMF).
2. The best particleboard manufacturing condition found in this research was the 80/20 wt% maltodextrin/ADP ratio at a 220 °C pressing temperature, and the properties met the requirement of JIS A 5908.

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