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Water Resistance Ability and Mechanical Strength of Eco-Friendly Particleboard Made from Bamboo Waste and Maltodextrin-Based Adhesive

Vodootpornost i mehanička čvrstoća ekološki prihvatljive iverice izrađene od bambusova otpada i ljepila na bazi maltodekstrina

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ABSTRACT • *Bamboo waste from the handicraft and furniture industry is an excellent source of lignocellulose with significant potential for use as raw material in particleboard production. The bamboo particleboard, when paired with a natural adhesive such as maltodextrin-based adhesive, potentially provides an eco-friendly waste management solution, aligning with Sustainable Development Goals (SDGs) 12 and 13. The optimal manufacturing conditions for maltodextrin/ammonium dihydrogen phosphate (M/ADP)-based particleboard are still under investigation. In this study, our aim was to assess the quality of bamboo-M/ADP particleboard, focusing on its water resistance and mechanical properties, the crucial factors in determining particleboard quality. Various M/ADP ratios were used, namely 100/0, 90/10, and 80/20 wt%. The pressing conditions used a temperature of 200 °C at 3 MPa, with pressing times of 1, 3, 5, 7.5, and 10 minutes. The results showed that particleboard with a M/ADP ratio of 90/10 and 80/20 wt% demonstrated satisfactory water resistance, as supported by the results of thickness swelling and aging evaluations. Overall, the M/ADP 80/20 wt% at 10 minutes of pressing time exhibited optimal particleboard properties, i.e., thickness swelling 5.08 %, thickness change after aging treatment 5.29 %, water absorption 38.47 %, surface roughness 8.92 μm, internal bonding strength 0.21 N/mm², modulus of rupture 4.8 MPa, modulus of elasticity 1.72 GPa, and brittleness 41.7 %.*

KEYWORDS: *maltodextrin; ammonium dihydrogen phosphate; bamboo waste; particleboard*

SAŽETAK • *Bambusov otpad iz radionica rukotvorina i industrije namještaja odličan je izvor lignoceluloze s velikim potencijalom za iskorištenje u proizvodnji ploča iverica. Bambusova iverica, u kombinaciji s prirodnim ljepilom kao što je ljepilo na bazi maltodekstrina, potencijalno je ekološki prihvatljivo rješenje za gospodarenje otpadom u skladu s ciljevima održivog razvoja (SDGs) 12 i 13. Optimalni uvjeti proizvodnje iverice na bazi malto-*

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dekstrin/amonijeva dihidrogen fosfata (M/ADP) još su u fazi istraživanja. Cilj ovog istraživanja bio je procijeniti kvalitetu bambus-M/ADP iverice, s fokusom na njezinoj otpornosti prema vodi i na mehaničkim svojstvima, što su najvažniji pokazatelji kvalitete iverice. Primijenjeni su različiti M/ADP omjeri: 100/0, 90/10 i 80/20 težinskih postotaka. Za prešanje je odabrana temperatura od 200 °C pri 3 MPa, a vremenima prešanja iznosila su 1, 3, 5, 7,5 i 10 minuta. Rezultati su pokazali da je iverica s M/ADP omjerom od 90/10 i 80/20 težinskih postotaka pokazala zadovoljavajuću otpornost na vodu, što je potkrijepljeno rezultatima ocjene debljinskog bubrenja i promjene debljine nakon tretmana ubrzanog starenja iverice. Zaključno, optimalna svojstva iverice dobivena su s M/ADP 80/20 težinskih postotaka, pri prešanju od 10 minuta, i iznosila su: debljinsko bubrenje 5,08 %, promjena debljine nakon tretmana ubrzanim starenjem 5,29 %, upijanje vode 38,47 %, hrapavost površine 8,92 µm, unutarnja čvrstoća na raslojavanje 0,21 N/mm², modul loma 4,8 MPa, modul elastičnosti 1,72 GPa i krtost 41,7 %.

KLJUČNE RIJEČI: *maltodekstrin; amonijev dihidrogen fosfat; otpad od bambusa; iverica*

1 INTRODUCTION
1. UVOD

Solid waste from the forestry sector and industry has many potential uses due to its lignocellulosic substance and other chemical substances. These solid wastes generally consisted of wood bark, wood chips, and other wooden materials chips, e.g., bamboo waste (Millati *et al*., 2019). Bamboo waste was predicted to increase in linearity with the increased use of bamboo worldwide, especially in construction and interior design, handicrafts, and furniture industries (Dlamini *et al*., 2022). About 30-50 % of bamboo chip waste was usually generated in handicrafts and furniture; meanwhile, 14.6-33.5 % was generated in building/construction components of the total production (Wiwoho *et al*., 2017; Fadillah *et al*., 2022). Furthermore, in Indonesia, which has the third-largest bamboo plantation area after China and India, the volume production of bamboo surprisingly increased five times from 2020 to 2021 (Statistics Indonesia, 2020, 2021; Park *et al*., 2021). The total business unit recorded in the handicraft industry in Bali, Indonesia, was 3655 units. In Anji, China, the total bamboo waste was around 0.16 million tons/year in 2015 (Tong *et al*., 2021), uncountable yet for other areas. The waste was huge and might pollute the environment if not handled or processed for reuse. Furthermore, the processing and utilization of bamboo/wooden waste into some products support the sustainable development goals (SDGs) 12 and 13, which is consistent with responsible consumption and production as well as with the requirements for controlling climate change (Pinho and Calmon, 2023).

The bamboo chip waste has been studied as a versatile material for bioenergy (biopellet, bioethanol, charcoal briquette), pulp and paper, advanced material (cellulose nanofiber, green adhesive, activated carbon), biocomposite, etc (Zaia *et al*., 2015; Kaur *et al*., 2022). This is due to the similar chemical composition between the bamboo waste and the raw bamboo, namely the holocellulose (69-82 %) and lignin (21-30 %) (Maulana *et al.,* 2020). For biocomposite application, bamboo chip waste was proven as a good reinforced/raw material with many adhesives/matrices, such as urea formaldehyde, polystyrene, polyurethane, etc. (Biswas *et al.,* 2011; Zaia *et al.,* 2015; Abdulkareem and Adeniyi, 2017). Nowadays, due to increasing sustainability awareness and demand for eco-friendly products, this waste was studied as the raw material of binderless particleboard and the particleboard with some natural adhesives such as tannin, citric acid, citric acid/starch, sucrose/ammonium dihydrogen phosphate (ADP), etc (Aini *et al*., 2020; Widyorini *et al*., 2020; Guan *et al*., 2022; Santoso *et al*., 2022). The particle board had excellent properties, and some properties were similar to some synthetic adhesives. Furthermore, the exploration of natural adhesives for particleboard production focused on substituting the formaldehyde-based adhesives that constituted more than 90 % of particleboard adhesives globally with a potentially harmful emission and the issue of non-renewability (Flores *et al.,* 2011).

Recently, our studies found that maltodextrin/ADP could be a promising natural adhesive for salacca frond particleboard with excellent dimensional stability (Dewi *et al.,* 2022). Maltodextrin is a hydrolysis product of starch that is abundant, widely available globally, and one of the major agricultural commodities (Whistler *et al.,* 1984). Meanwhile, ADP could catalyze the dehydration of sugar (sucrose) into 5-hydroxymethyl furfural (5-HMF), which is responsible for increasing the physical and mechanical properties of particleboards (Umemura *et al.,* 2017; Zhao *et al.,* 2018). The composition of maltodextrin/ADP was known to affect the physical and mechanical properties of particleboard, identically with sucrose/ADP (Zhao *et al.,* 2018; Dewi *et al.,* 2022). Due to the catalysis effect of ADP, the optimal pressing time of the particleboard might be affected. Lehmann *et al.* (1973) stated that the addition of a catalyst into urea-formaldehyde adhesive could reduce up to a certain level the pressing time.

This research aimed to investigate the effect of maltodextrin/ADP ratio and pressing time on the properties of particleboard made from bamboo waste. Some physical and mechanical properties of the particleboard were evaluated, along with the chemical fingerprint (Fourier transform infrared analysis) of the particleboard and thermal properties of the sprayed particles to clarify the possible scenario during particleboard production.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Petung bamboo particle waste was obtained from bamboo crafts central in Cebongan, Yogyakarta, Indonesia. The characteristics of bamboo particles after being ground in a knife ring flaker are presented in Table 1. Maltodextrin (DE 10-15 %, powder, food grade) was purchased from Zhucheng Dongxiao Biotechnology Co. Ltd. (Zhucheng, China), meanwhile ammonium dihydrogen phosphate (ADP) (powder, pro-analysis grade) was obtained from Merck, Darmstadt, Germany. The solvent used was distilled water (pH 7).

2.1 Adhesive solution preparation
2.1. Priprema ljepila

The maltodextrin-based adhesive solution was prepared at 50 wt% concentration, as reported by Dewi *et al.* (2022). The maltodextrin was dissolved in the distilled water at 80°C. Three maltodextrin/ADP ratios were used, namely 100/0, 90/10, and 80/20 wt%. The adhesive content was 20 wt% based on the air-dried particle's weight. The adhesive solution was cooled and used at ±43 °C in order to maintain the easiness of glue spreading.

2.2 Analysis of sprayed particles and particleboard manufacturing
2.2. Analiza iverja i proizvodnja iverice

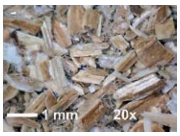
The warm adhesive solution was spread into the particles evenly, and then oven-dried at ±2.5 cm bulk height at 80 °C for 4 h. The intended moisture content of the sprayed particles was ±6 %. One gram of each sprayed particle was analyzed for its thermal properties using thermogravimetry analysis. Prior to the test, it was ground, screened into a 100-mesh screen, then oven-dried at 60 °C for 12 h. The analysis was performed using TGA801 (Leco, Michigan, USA). It was subjected to heat subsequently at 27-400 °C at a rate of 10 °C/min under a 35 mL/min nitrogen purging. For the comparison, the thermal analysis of the bamboo raw material and maltodextrin was also conducted.

The remaining sprayed particles were hand-formed into a mat with a 25 cm × 25 cm size. The mat was hot-pressed at 200 °C at 3 MPa specific pressure into 1 cm thickness. The targeted density of the particleboard was 0.7 g/cm³. The pressing time and the pressing method are presented in Table 2, and the board was manufactured in triplicate. Particleboard with 1 min pressing time at 100/0 M/ADP ratio failed to be manufactured. The particleboards were then conditioned at room condition (±27 °C, 77 % relative humidity) for 7 days prior to the board properties test.

2.3 Evaluation of particleboard properties
2.3. Ocjena svojstava iverice

The properties of bamboo particleboard were tested according to the modified Japanese Industrial Standard (JIS) A 5908 (2015). The thickness swelling and water absorption (TSWA) tests were conducted simultaneously by immersing the 5 cm × 5 cm sample horizontally for 24 hours at room temperature. The percentage of thickness and the weight changes based on the initial thickness and weight were TSWA values. A

Table 1 Characteristics of bamboo particle waste
Tablica 1. Svojstva iverja od bambusova otpada

	Particle distribution, % *Distribucija iverja, %*	**Particle appearance** *Izgled iverja*	***MC**, %**	**Bulk density, g/cm³** *Nasipna gustoća, g/cm³*	**CWAH*, mm**
-10+40 mesh (0.42 – 2 mm)	77.1		12	0.136±0.003	1040.4±22.0
-40+60 mesh (0.25 – 0.42 mm)	8.4				
-60+100 mesh (0.15 – 0.25 mm)	7.8				
-100 mesh (max 0.15 mm)	6.7				

**MC* – moisture content, CWAH – corrected water absorption weight by Bodig (1962)
**MC – sadržaj vode, CWAH – korigirana težina upijene vode prema Bodigu (1962.)*

Table 2 Preparation of bamboo particleboards
Tablica 2. Priprema bambusove iverice

	Pressing time / *Vrijeme prešanja*				
	1 min	3 min	5 min	7.5 min	10 min
MADP/mixture ratios, wt% *MADP/omjeri miješanja,* težinski postoci	-	100/0	100/0	100/0	100/0
	90/10	90/10	90/10	90/10	90/10
	80/20	80/20	80/20	80/20	80/20
Pressing methods *Metoda prešanja*	Single step	Single step	Three-step (2.5 min – 1 min – 2.5 min)	Three-step (3.75 min – 1 min – 3.75 min)	Three-step (5 min – 1 min – 5 min)

cyclic accelerated aging treatment was also conducted subsequently after TSWA test to investigate the dimensional stability of the bamboo particleboard bonded with maltodextrin/ADP adhesive. The test was carried out according to Kusumah *et al.* (2017). Following the 24 h-water immersion at room temperature, the samples were oven-dried at 105 °C for 10 h, immersed in warm water (70±2) °C for 24 h, oven-dried at 105 °C for 10 h, immersed in boiling water for 4 h, and oven-dried at 105 °C for 10 h, respectively. The thickness change was measured after each of those treatments compared to the initial thickness. The moisture content (*MC*) was measured in a 5 cm × 5 cm sample. The surface roughness (*SR*) was measured using SRG4000 (Bosworth Instrument, Ohio, USA) at 6 random points in each 20 cm × 5 cm sample. Furthermore, the color testing of particleboard was carried out using a Color Reader CR-10 (Konica Minolta Sensing Inc., Japan) after SR test.

Internal bonding (*IB*) was tested by applying a tension load vertically to the board surface at 2 mm/min speed using UTM3369 (Instron, Massachusetts, USA) until the bonding failed. Three-point bonding strength (BS) test was carried out by applying a load with 10 mm/min speed perpendicular to the board surface of a 20 cm × 5 cm sample in a 15 cm span until cracking. Based on the load-deflection curve of the bending test, the brittleness was calculated by dividing the elastic area to the total area of the curve. The elastic area and the total area up to the maximum load were measured with the ImageJ software.

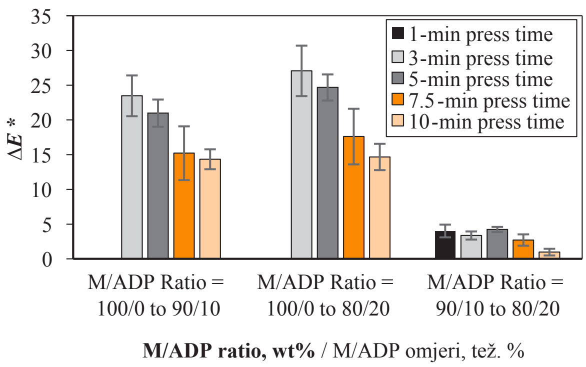
2.4 Fourier Transform Infrared (FTIR)
2.4. Fourierova infracrvena spektroskopija (FTIR)

The samples chosen for FTIR analysis were particleboards with a press time of 10 minutes at all compositions (100/0, 90/10, and 80/20 wt%) and particleboards with a M/ADP composition of 80/20 wt% at all press times (1 min, 3 min, 5 min, 7.5 min, and 10 min). The particleboard sample was boiled for 2 h, followed by water immersion at 27 °C for 1 h, then ground into a powder size (less than 100 mesh) and oven-dried at 60 °C for 15 h prior to the test. The boiling and the immersion were conducted to eliminate the unreacted adhesive. The analysis used KBr disk methods and was recorded at a 10 scan with a 16 cm^{-1} resolution in FTIR spectrometer IR-Prestige 21 (Shimadzu, Kyoto, Japan).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

All the bamboo particleboards were successfully manufactured without any defects. The surface color of the particleboards was darkened visually from light brown to dark brown in accordance with the higher ADP ratio and longer pressing time. The same result has been observed in binderless particleboards made from the inner part of oil palm trees with an additional ratio of ADP (Komariah *et al.,* 2019). The brightness (L^*) level measurement also proves the phenomenon. The L^* value of the board with 100/0 M/ADP ratio at 3 to 10 minutes press time was 33 – 45.54, while in 90/10 and 80/20 boards, the L^* values were 25.03 – 28.93 and 25.50 – 27.23, respectively. The decreased trend of the L^* value of particleboards with the increase in ADP content and press time showed that the boards color became dark.

In addition to brightness measurement, Figure 1 shows the color change (ΔE^*) in the particleboard as the effect of addition of ADP and press time variation. The ΔE^* values of the particleboard due to the addition of ADP and variation of press time ranged from 1.11 to 27.39 and 0.77 to 16.45. Based on ΔE values, the effect of ADP addition on the particleboard color was more notable than the effect of press time. Similar to the wood heating treatment, the darkening of the surface color of the particleboard was allegedly expected due to the increased chromophores formed by oxidation and dehydration of lignin or carbohydrates (Srinivas and Pandey, 2012) and also by the increased dehydration and caramelization of maltodextrin at high temperature for a time duration. The ADP existence is also



Colour Change/ ΔE	M/ADP ratio (wt%)		
	100/0	90/10	80/20
ΔE from 1-min to 3-min press time	-	0.90±0.72	0.77±0.34
ΔE from 1-min to 5-min press time	-	1.62±0.58	1.09±0.75
ΔE from 1-min to 7.5-min press time	-	3.30±1.06	1.86±0.78
ΔE from 1-min to 10-min press time	-	6.33±1.26	2.88±0.62
ΔE from 3-min to 5-min press time	4.06±1.52	1.45±0.06	1.58±0.77
ΔE from 3-min to 7.5-min press time	12.59±5.40	3.48±0.18	2.23±0.69
ΔE from 3-min to 10-min press time	16.45±2.42	6.52±0.35	3.29±0.80
ΔE from 5-min to 7.5-min press time	8.74±5.03	2.72±0.62	1.05±0.22
ΔE from 5-min to 10-min press time	12.69±1.96	5.60±0.39	2.01±0.12
ΔE from 7-min to 10-min press time	8.93±1.24	3.25±0.34	1.14±0.25

Figure 1 Effect of (a) ADP addition and (b) pressing time on color change (ΔE^*) level of bamboo particleboards
Slika 1. Utjecaj (a) dodavanja ADP-a i (b) vremena prešanja na razinu promjene boje (ΔE^*) bambusove iverice

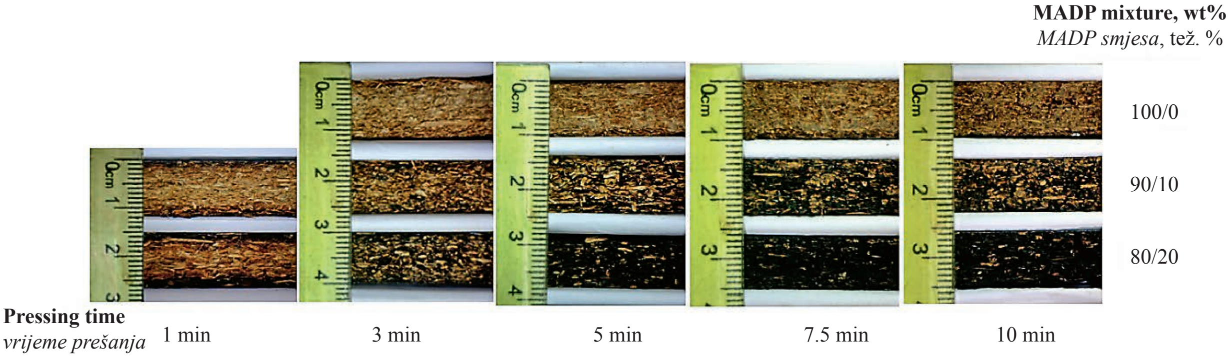


Figure 2 Thickness of bamboo particleboards
Slika 2. Debljine bambusovih iverica

Table 3 Physical properties and surface roughness of bamboo particleboards
Tablica 3. Fizička svojstva i hrapavost površine bambusove iverice

M/ADP mixture ratios, wt% *M/ADP omjeri miješanja, tež. %*	**Pressing time, min** *Vrijeme prešanja, min*	**Physical properties and surface roughness** *Fizička svojstva i hrapavost površine*		
		***TS*±*SD*, %**	***WA*±*SD*, %**	***Ra*±*SD*, µm**
90/10	1	Uncountable values (board destroyed)		13.41 ± 2.81
80/20				13.36 ± 3.50
100/0	3	104.57 ± 26.86	240.54 ± 7.29	14.63 ± 1.73
90/10		81.49 ± 7.10	189.22 ± 1.17	12.24 ± 2.00
80/20		48.48 ± 7.33	131.69 ± 11.15	10.96 ± 1.42
100/0	5	53.34 ± 7.85*	197.03 ± 11.83*	14.97 ± 1.86*
90/10		20.13 ± 0.66*	110.57 ± 11.30*	11.98 ± 1.97*
80/20		8.58 ± 2.23*	69.26 ± 12.42*	10.10 ± 1.74*
100/0	7.5	52.91 ± 10.72	160.92 ± 30.73	14.02 ± 1.41
90/10		7.44 ± 0.99	62.44 ± 14.92	10.70 ± 1.72
80/20		7.02 ± 1.27	50.40 ± 4.04	10.20 ± 1.85
100/0	10	38.96 ± 5.65	103.78 ± 2.19	11.52 ± 1.42
90/10		6.65 ± 1.24	64.33 ± 11.04	9.60 ± 1.80
80/20		5.08 ± 0.92	38.47 ± 1.15	8.92 ± 1.38

TS – thickness swelling, *SD* – standard deviation, *WA* – water absorption, *Ra* – arithmetic average of absolute values of roughness profile ordinates, *Dewi *et al*. (2023)
*TS – debljinsko bubrenje, SD – standardna devijacija, WA – upijanje vode, Ra – aritmetička sredina apsolutnih vrijednosti ordinata profila hrapavosti, *Dewi et al. (2023.)*

likely to act as a catalyst for the dehydration and caramelization of maltodextrin. Ammonium phosphate effectively catalyzes the sugar and starch transformation/caramelization into furan compounds and generates a dark color (Stofko, 1980; Liu *et al.,* 2013).

The effect of pressing time and ADP ratio on the particleboard was clearly shown with respect to thickness (Figure 2). A shorter duration of hot-pressing time turned out to merely harden/cure the adhesive on the surface; meanwhile, the core is still not cured due to low heat transfer on the core part. It was particularly obvious in 1 minute pressing time. Heat transfer during hot pressing was easily seen by a color change of maltodextrin caramelization and lignocellulose dehydration in the presence of ADP. A longer hot-pressing time was anticipated to improve heat transfer to the core. In the shorter hot-pressing time, the addition of ADP was expected to enhance the caramelization and the hardened reaction of maltodextrin in all areas of the board. It was apparently seen that a dark particleboard color could be obtained by the 5-minute pressing time with 20 % ADP. Meanwhile, a darker particleboard color with 100 % maltodextrin would be obtained by the 10-minute pressing time or more.

Table 3 shows the physical properties and surface roughness (*SR*) of bamboo particleboard with various M/ADP mixtures and pressing times. The *TS* and *WA* values of particleboards ranged from 5.08 % to 104.57 % and 38.47 % to 240.54 %, respectively. After the addition of ADP, the thickness swelling decreased notably by 22-87 %, while the water absorption decreased by 21-69 %. This decrease tended to get bigger with the longer pressing time. Good dimensional stability and water resistance of particleboards were achieved with longer pressing time and in the presence of ADP. Particleboards with M/ADP 90/10 and 80/20 at pressing times of 7.5 and 10 minutes met the TS standard of JIS A 5908 (2003) that required a maximum *TS* of 12 %. Interestingly, the 5-minute pressing time could also meet the standard only with 20 % ADP. Dewi *et al.*

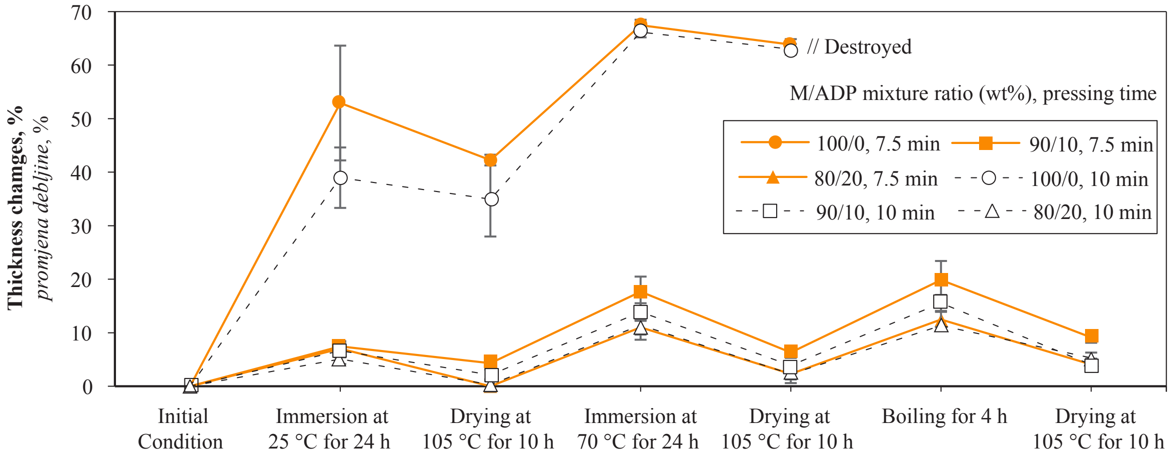


Figure 3 Thickness change of bamboo particleboard after accelerated cyclic aging treatment at pressing time of 7.5 and 10 minutes
Slika 3. Promjena debljine bambusove iverice nakon tretmana ubrzanim cikličnim starenjem pri vremenu prešanja od 7,5 i 10 minuta

(2022) mentioned that the addition of ADP promoted maltodextrin into highly water-resistant substances involving furan that might be generated by caramelization and dehydration.

Particleboards produced by a higher ADP ratio and longer pressing time exhibited lower surface roughness (Table 3). Tabarsa *et al.* (2011) also found that the particleboard surface was smoother with a longer pressing time, from 6 to 8 minutes. The improvement of the surface smoothness related to pressing time and the addition of ADP may be due to the fact that both parameters facilitated the good curing process of the adhesive and compression of the board. The surface roughness (*SR*) of this bamboo particleboard was close to the *SR* of the sanded and unsanded commercial Indonesian particleboard made from rubberwood (6.13-14.20 µm) (Hiziroglu *et al.,* 2008).

Figure 3 shows the thickness change of bamboo particleboard in the 7.5 minutes and 10 minutes pressing time after accelerated cyclic aging treatment. The most notable thickness change in the first immersion (25 °C for 24 h) was earned in the 100/0 M/ADP in both pressing times. The thickness change increased with further severe aging treatment, and it was damaged after the boiling treatment for 4 hours. It showed that the bonding of maltodextrin was susceptible to water. The thickness change was decreased with the addition of ADP and pressing time. Even the thickness change of the particleboard bonded with maltodextrin/ADP 80/20 at both pressing times is still in the range of 12.5-13.4 % after all of the cycles till the boiling step. At the same manufacturing condition (pressing temperature, pressing time, and adhesive content), our particleboard quality was better than some particleboards bonded with citric acid/sucrose 100/0-15/85 (Kusumah *et al.,* 2017) and tannin/sucrose 25/75 (Zhao and Umemura, 2014). It demonstrated that ADP addition into maltodextrin accompanied by heat (temperature and duration) enhances the dimensional stability of the particleboards against water. Dewi *et al.* (2021) showed that the insoluble matter rate of maltodextrin apparently increased with the increase of ADP addition accompanied by higher heating temperature and longer heating time, causing a change in maltodextrin and making it a high-water resistance substance.

The mechanical properties were also in line with the physical properties that showed an improvement in increasing the ADP ratio and pressing time. IB, MOR, MOE and brittleness increased with the increasing ADP ratio and pressing time (Figure 4-5). Increasing the ADP ratio could increase the mechanical properties of both the sucrose and maltodextrin-based particleboard (Dewi *et al.,* 2022; Komariah *et al.,* 2022). Meanwhile, increasing the pressing time was known to increase the mechanical properties of particleboard (Nemli *et al.,* 2007). In 1-minute pressing time, ADP ratio seemed to not affect the IB, but affected the IB at 3-10– minute pressing time, especially between with and without ADP. ADP would perform its catalyzing effect on sugar-based components deformation into furan-type components in the presence of heat (Umemura *et al.,* 2017), and 1-minute pressing time might be a relatively short time to provide heat for the entire section of the board. The board with a 5-minute pressing time and 20 % ADP had an IB value that almost met the JIS standard. Furthermore, the IB value of the board with 10 and 20 % ADP at 7.5– and 10-minutes pressing time met the JIS type 8 (0.15 N/mm^2). The IB value of the board with 20 % ADP and 10-minute pressing time even met the JIS type 13 (0.2 N/mm^2).

None of the *MOR* and *MOE* values met the JIS requirement. Some improvements had to be made in order to increase the *MOR* and *MOE* values, e.g., the use of particles with high slenderness/aspect ratio, as

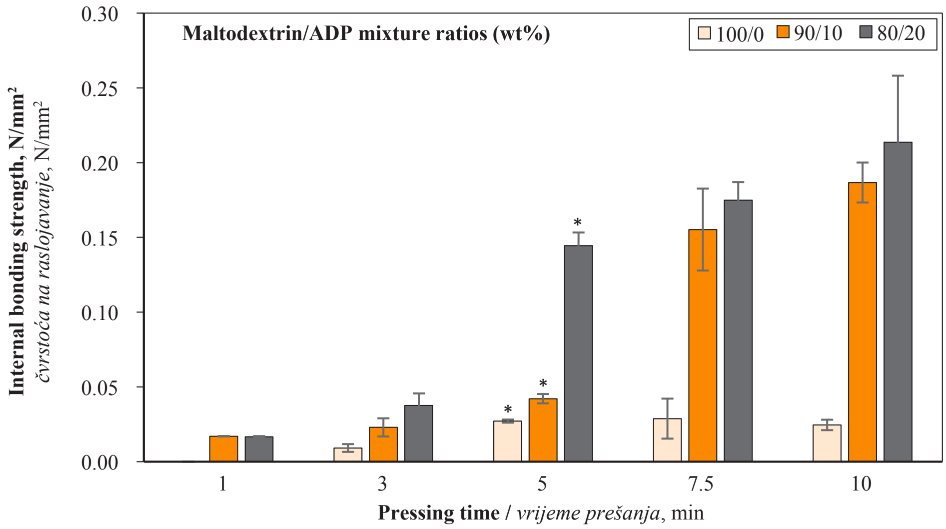


Figure 4 Internal bonding strength of bamboo particleboards, *Dewi *et al*. (2023)
Slika 4. Čvrstoća bambusove iverice na raslojavanje, * Dewi *et al*. (2023.)

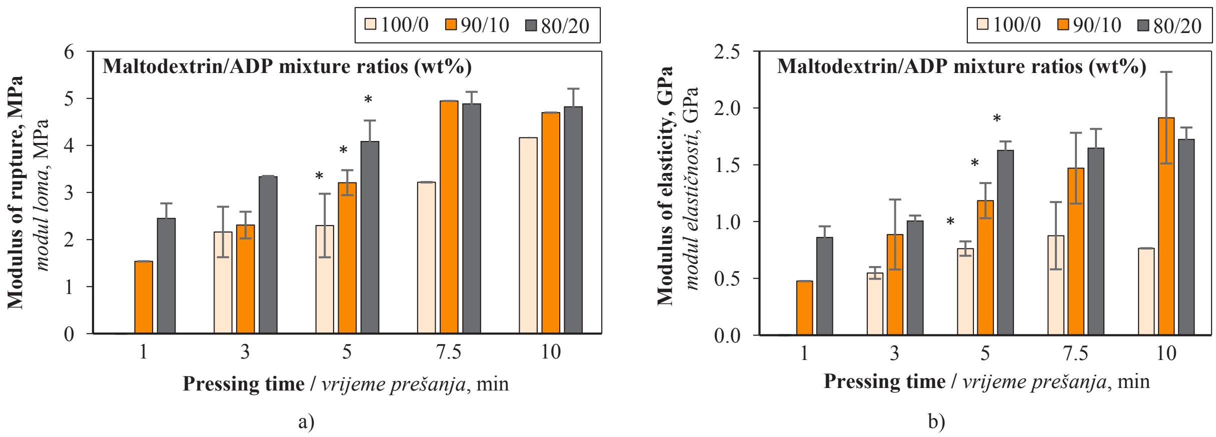


Figure 5 a) *MOR*, b) *MOE* of particleboard, *Dewi *et al*. (2023)
Slika 5. a) *MOR*, b) *MOE* iverice, * Dewi *et al*. (2023.)

well as increasing the board density and resin content. Jin-shu *et al.* (2006) summarised that the density was a significant factor that affected the *MOR*, *MOE*, and IB. But, Arabi *et al.* (2011) showed that the use of particles with a high slenderness ratio could compensate for the reduction of density and resin content in intending to increase the MOR and *MOE* while significantly saving the production cost. Due to low *MOR* and *MOE* value, the brittleness was also low (namely 4.6-41.7 %) compared to sorghum bagasse particleoard bonded with citric acid (namely 90 %) by Kusumah *et al*. (2017). Similar to *MOE*, the brittleness was increased on the increasing of ADP ratio and pressing time.

The effect of M/ADP ratios and pressing time on the chemical properties of the bamboo particleboard is shown in Figure 6. The higher ADP ratios on the maltodextrin adhesive and the higher pressing time, the more clearly visible the absorbance of 1705 cm^{-1} (carbonyl of ketone) and 1620 cm^{-1} (carbonyl of the aromatic ring) (Umemura *et al.,* 2017). However, the absorbance of the carbohydrate fingerprint (1458-833 cm^{-1}) (Sritham and Gunasekaran, 2017) was more invisible. This showed that increasing the ADP ratio and increasing the pressing time was expected to assist the carbohydrate dehydration/hydrolysis (either from the maltodextrin or the hemicellulose of the raw material) into other substances, i.e. 5-hydroxymethyl 2-furfural (5-HMF). Tomasik *et al.* (1989) and Chheda *et al.* (2007) stated that carbohydrates were hydrolyzed into 5-HMF at high temperatures. The 1705 cm^{-1} peak was expected from carbonyl (C=O groups) of 5-HMF.

The thermogravimetry analysis of the maltodextrin, petung bamboo, and dried mixtures at M/ADP 100/0 wt% and 80/20 wt% could be shown in Figure 7. The onset temperature of weight loss was rather different in each component and showed a different reactivity toward the heat treatment. The maltodextrin has the highest onset temperature of weight loss (266 °C). The preliminary weight loss temperatures were around 240 °C when the maltodextrin 100/0 wt% was mixed with bamboo. Dewi *et al.* (2022) also found that when ADP was added to maltodextrin and mixture with Salacca

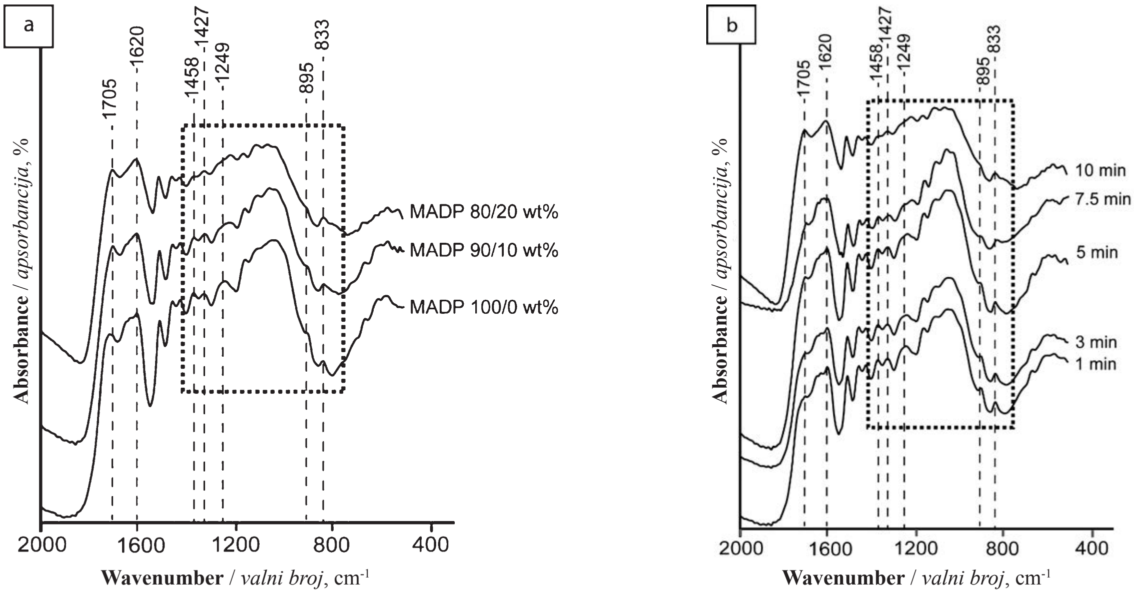


Figure 6 The infrared spectrum of the bamboo particleboards on various a) M/ADP mixture ratios at 10 minutes pressing time, b) pressing temperatures at M/ADP 80/20 wt%

Slika 6. Infracrveni spektri bambusove iverice s obzirom na (a) M/ADP omjere pri vremenu prešanja od 10 minuta i (b) na temperature prešanja pri M/ADP omjeru 80/20 tež. %

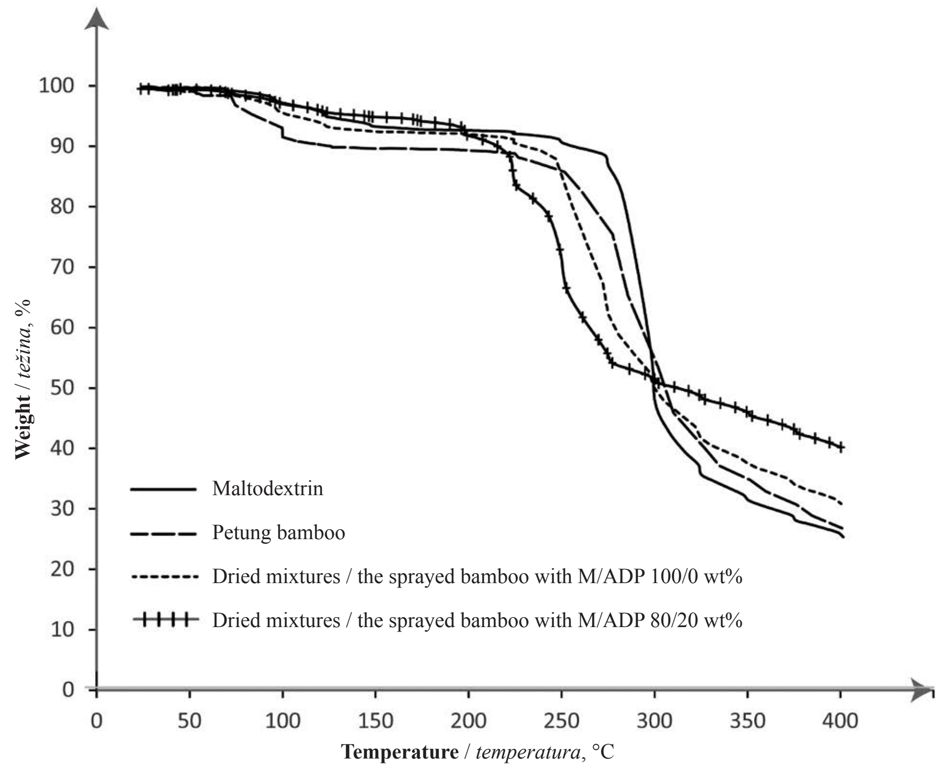


Figure 7 Thermogravimetry of the maltodextrin adhesives, the bamboo raw material, and the adhesive-sprayed bamboo particle

Slika 7. Termogravimetrija maltodekstrinskih ljepila, sirovine od bambusa i oblijepljenog iverja bambusa

frond particle, the weight loss temperature was around 156 °C. These findings demonstrated that the addition of ADP resulted in a drop in the weight-reduction onset temperature. The onset temperature of weight reduction shifted to 200 °C for the dried mixture of bamboo with M/ADP 80/20 wt%, and then the bamboo raw material tended to be stable on heating at room temperature to 230 °C with 10 % weight reduction at 80 °C. Ardhyananta *et al.* (2019) also stated that the onset weight loss of Petung bamboo at 267 °C.

4 CONCLUSIONS
4. ZAKLJUČAK

This research aimed to utilize bamboo particle waste, combined with a maltodextrin/ADP natural adhesive, to produce an environmentally friendly particleboard. Based on the research results, increasing the M/ADP ratio and pressing time improved the physical and mechanical properties of the bamboo particleboard. However, the modulus of rupture and modulus of elasticity still required enhancement. A M/ADP ratio of 90/10 and 80/20 wt% with a pressing time of 7.5 and 10 minutes achieved satisfactory water resistance, as indicated by thickness swelling and aging evaluations. The best particleboard properties were obtained with a M/ADP ratio of 80/20 wt% at a pressing time of 10 minutes, making it suitable for water-related applications. FTIR spectra revealed the presence of a furan-type component in the treatment, which may contribute to the improved properties. This method of particleboard production could serve as an alternative for managing bamboo waste effectively.

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