Vol. 10(3): 426-438, September 2022

DOI: https://doi.org/10.23960/jsl.v10i3.574

Jurnal Sylva Lestari

P-ISSN: 2339-0913
E-ISSN: 2549-5747

Journal homepage: https://sylvalestari.fp.unila.ac.id

Full Length Research Article

Characteristics of Particleboard from Sorghum and Nypa Fruit Skin Fiber Bonded with Citric Acid-Sucrose Adhesive

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ARTICLE HISTORY:

Received: 17 December 2021
Peer review completed: 24 January 2022
Received in revised form: 19 July 2022
Accepted: 4 September 2022

KEYWORDS:

Citric acid-sucrose
Nypa fruit skin
Particleboard
Sorghum

ABSTRACT

Sorghum (*Sorghum bicolor* L.) and nypa fruit skin fiber (*Nypa fruticans* Wurmb.) can be used as raw materials in the manufacture of eco-friendly particleboard (PB) using natural adhesives based on citric acid and sucrose. This study aimed to determine the characteristics of PB from sorghum and nypa fruit skin fiber using citric acid-sucrose adhesive and also to determine the optimum composition of raw materials and adhesives in the manufacture of PB. The PB panel was made by mixing raw materials and adhesives with variations in the composition of nypa fruit skin fiber:sorghum raw materials 100:0, 25:75, 50:50, and 0:100, and variations in the concentration of citrate-sucrose adhesive were 20% and 30%. The target dimensions and density of PB were 25 cm × 25 cm × 0.9 cm and 0.8 g/cm^3, respectively. The PB was hot-pressed for 10 min at 200°C with a pressure of 11 MPa. The physical and mechanical properties of PB were determined using the Japanese Industrial Standard (JIS) A 5908:2003 standard. The results showed that the PB has average values of moisture content of 11.94%, density of 0.79 g/cm^3, water absorption of 52.96%, thickness swelling of 13.21%, modulus of elasticity of 1029.55 N/mm^2, modulus of rupture of 6.46 N/mm^2, internal bonding of 0.18 N/mm^2, and screw holding power of 43.12 N. Variation of raw materials composition has a significant effect moisture content, water absorption, thickness swelling, modulus of elasticity, and modulus of rupture. Applying 30% adhesive content significantly affected water absorption, thickness swelling, and screw holding power.

1. Introduction

Particleboard (PB) is a panel manufactured from wood particles containing lignocellulosic compounds bonded together with adhesives. PB made of wood has several advantages over the original wood, such as better appearance or free of knots, breaks, cracks, size, uniform density, ease to work with, isotropic properties, and ease of adjustment. Types of non-wood materials that can also be used include straw, bagasse, reeds, bamboo, cotton fibers, and kenaf (Maloney 1993).

In 2018, industrial PB production reached a record of 97 million m^3 worldwide (FAO 2020). It shows that PB products are in great demand among the public. PB is a composite panel product with several advantages compared to other panels. Besides that, the raw material can come from various lignocellulosic materials derived from forestry industry waste, including the plywood industry and agricultural waste, such as sorghum stalks (Sutiawan 2018).

Putra et al. (2017) reported that sorghum is the third food cereal crop after rice and corn. The potential of sorghum in several provinces in Indonesia in 2011-2013 include South Sulawesi (3,405 ha), Southeast Sulawesi (4 ha), East Nusa Tenggara (11,415 ha), West Nusa Tenggara (68 ha), Lampung (25 ha), West Java (258 ha), Central Java (45 ha) and East Java (211 ha). Kusumah et al. (2016) used sorghum stalks as raw material for PB with citric acid adhesive to produce PB that meets the JIS A 5908:2003 standard.

In Indonesia, the area of the nypa forest reaches 4,237,000 ha (Herfayati et al. 2020). Dalming et al. (2018) stated that nypa leaves could be used to make house roofs, broomsticks, baskets, mats, and hats. Several studies on the manufacture of PB used nypa palm fronds (Santoso et al. 2016, 2017; Widyorini et al. 2012;). In addition, nypa fruit skin fiber has been used in the manufacture of charcoal briquettes (Anizar et al. 2020) and PB combined with urea-formaldehyde (UF) adhesive (Rosidah et al. 2019).

PB products are generally prepared using formaldehyde-based adhesives, such as UF adhesive (Hidayat et al. 2022; Sutiawan et al. 2022; Syahfitri et al. 2022). However, industries often face problems where the formaldehyde emissions from the PB are still very high. Therefore, to reduce formaldehyde emissions, natural adhesives have been developed recently. Natural adhesives that have the potential to be developed are citric acid and sucrose. Research from Umemura et al. (2015) stated that citric acid acts as an adhesive agent through chemical bonds and has potential as an environmentally friendly natural wood adhesive. Meanwhile, adding sucrose increases the number of hydroxyl groups that can bind to the carboxyl groups of citric acid to form ester bonds. Kusumah et al. (2016) used citric acid with a concentration of up to 30%, and the results showed that concentrations of 20% and 30% produced better mechanical properties and water resistance on PB. Therefore, this work conducted research combining two types of lignocellulosic materials: sorghum (*Sorghum bicolor* L.) and nypa fruit skin fiber (*Nypa fruticans* Wurmb.) bonded with citric acid-sucrose adhesive.

2. Materials and Methods

2.1. Board Materials

Materials used were nypa fruit skin fiber and sorghum with the size stuck in 32 mesh. The natural adhesives used were citric acid and sucrose with a ratio of 10:90. The tools used consisted of a ring flaker, disk mill, hammer mill, oven, spray gun, rotary blender, mold measuring 25 cm × 25 cm with a thickness of 0.9 cm, aluminum foil, Teflon paper, hot-pressing machine, Universal Testing Machine (UTM), caliper, analytical balance, water bath, thermometer, and hotplate.

2.2. Board Manufacturing and Evaluation

This study used a two-factorial Completely Randomized Design (CRD) experimental method. The first factor was the variation of the composition of nypa fruit skin fiber with sorghum with four treatment levels, namely:

A1: Nypa 100%
A2: Nypa 50%: Sorghum 50%
A3: Nypa 25%: Sorghum 75%

A4: Sorghum 100%

The second factor was the difference in the concentration of adhesive with two treatment levels, namely:

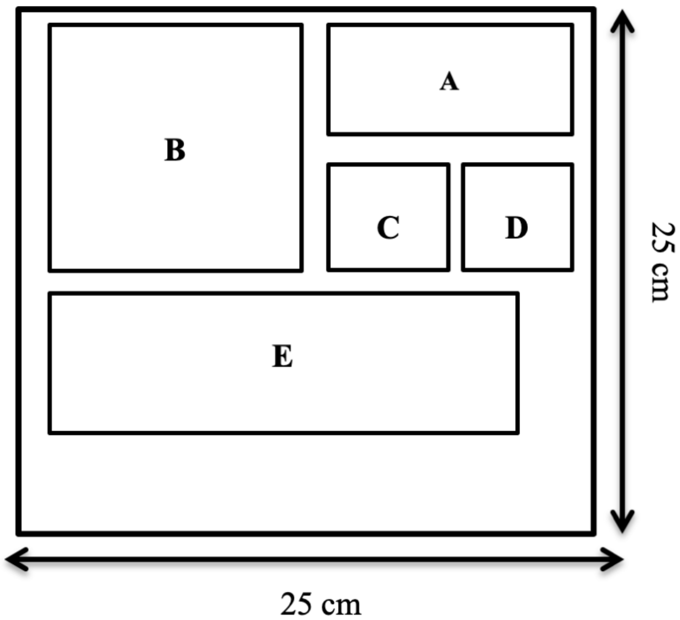
B1: 20%

B2: 30%

The adhesive composition was made with a ratio of 10:90 citric acid and sucrose with pH 3 stirred at room temperature and an agitation speed of 200 rpm (Kusumah et al. 2017). The adhesive was then sprayed onto the raw material using a spray gun in a rotary blender until evenly distributed.

The PB was fabricated with a size of 25 cm × 25 cm × 0.9 cm with a target density of 0.8 g/cm^3. The test board was hot pressed for 10 min at a temperature of 200°C with a pressure of 11 MPa. After the compression process, the boards were conditioned for 7-14 days at room temperature to free the residual stress from the compression process until the weight was constant.

Based on the results of a combination of variations in the composition of raw materials (factor A) and differences in adhesive concentration (factor B), eight treatments were obtained with three repetitions resulting in 24 examples of test boards. Test according to JIS A 5908:2003 with the cutting pattern shown in **Fig. 1**.



Notes:
A : Specimen for screw holding power test (5 cm × 10 cm)
B : Specimen for density and moisture content test (10 cm × 10 cm)
C : Specimen for internal-bonding test (5 cm × 5 cm)
D : Specimen for water absorption and thickness swelling test (5 cm × 5 cm)
E : Specimen for bending test (MOE and MOR) (5 cm × 20 cm)

Fig. 1. Cutting pattern of the test sample.

2.3. Research Procedure

2.3.1. Moisture content

Moisture content was calculated by measuring the initial and oven-dry weight of the PB sample using Equation 1.

$$Moisture\ content\ (\%) = \frac{BB - BKT}{BKT} \times 100\% \quad (1)$$

where *BB* is sample weight before drying (g) and *BKT* is sample weight after oven-drying (g).

2.3.2. Density

Density was calculated by measuring the weight and dimensions of PB using Equation 2.

$$Density\ (g/cm^3) = \frac{M}{V} \qquad (2)$$

where M is the weight of PB (g), and V is the volume of PB (cm^3).

2.3.3. Water absorption

Water absorption of PB was determined by measuring the difference in weight before and after immersion in water for 24 h. Then, the water absorption was calculated using Equation 3.

$$Water\ absorption\ (\%) = \frac{B_2 - B_1}{B_1} \times 100\% \qquad (3)$$

where B_1 is the weight before water immersion (g) and B_2 is the weight after water immersion (g).

2.3.4. Thickness swelling

Thickness swelling was determined by immersing the PB sample in water for 24 h, then calculating the expansion of the thickness of the board using Equation 4.

$$Thickness\ swelling\ (\%) = \frac{T_2 - T_1}{T_1} \times 100\% \qquad (4)$$

where T_1 is thickness before soaking (mm) and T_2 is thickness after soaking (mm).

2.3.5. Modulus of elasticity

The value of the modulus of elasticity (MOE) was determined by using a Universal Testing Machine, Shimadzu AG-IS 50 kN, to test the sample by placing a load on the center of a 15 cm long span and a load speed of 10 mm/min. The MOE was then calculated using Equation 5:

$$MOE\ (N/mm^2) = \frac{\Delta PL^3}{4\Delta Ybh^3} \qquad (5)$$

where ΔP is the load below the limit of proportion (N), Y is deflection at load P (mm), b is the sample width (mm), and h is the sample thickness (mm).

2.3.6. Modulus of rupture

The modulus of rupture (MOR) was performed by placing a load on the center of the span of the board. The test was carried out until the test sample was broken. Then, the MOR value was calculated using Equation 6.

$$MOR\ (N/mm^2) = \frac{3PmaxL}{2bh^2} \qquad (6)$$

where P_{max} is the maximum load (N), L is the span length (mm), b is the sample width (mm), and h is the sample thickness (mm).

2.3.7. Internal bonding strength

The internal bonding (IB) strength testing was carried out by measuring the test sample under air-dry conditions. The test sample was glued with an epoxy adhesive between two iron blocks measuring 5 cm × 10 cm, then left for 24 h for a perfect gluing process. The test sample was placed on the testing machine, and the iron block was pulled upright until the maximum load value was known. The value of the IB was calculated using Equation 7.

$$Internal\ Bond\ (N/mm^2) = \frac{P}{A} \quad (7)$$

where P is the maximum load (N) and A is the sectional area (mm^2).

2.3.8. Screw holding power

The screw holding power test was carried out by installing the screws on the left and right sides of the sample and then pulling the screw up to the maximum load until the screw was pulled out using a UTM.

2.4. Data Analysis

Data analysis was done using a two-factorial, completely randomized design (CRD). Data processing was performed using SPSS with a 95% significance level to determine the treatment effect (variations in the ratio of nypa fruit skin fiber to sorghum composition and differences in the concentration of adhesive used). Analysis of the variance of the calculated F test was also performed. If the calculated F value < F table 5% or the significance value is ≤ 0.05, the results showed a significant difference, then proceed with further testing using Duncan's New Multiple Range Test (DNMRT).

3. Results and Discussion

3.1. Moisture Content

The highest moisture content was produced at 100% nypa fruit skin fiber composition, namely 20% adhesive (13.39%) and 30% adhesive (14.36%). On the other hand, the lowest moisture content value was obtained at 100% sorghum composition with 20% adhesive (9.82%). Overall, the use of adhesive with a concentration of 30% had a higher water content except for the composition of nypa fruit skin fiber:sorghum (50:50). The moisture contents of the PB are shown in **Fig. 2**.

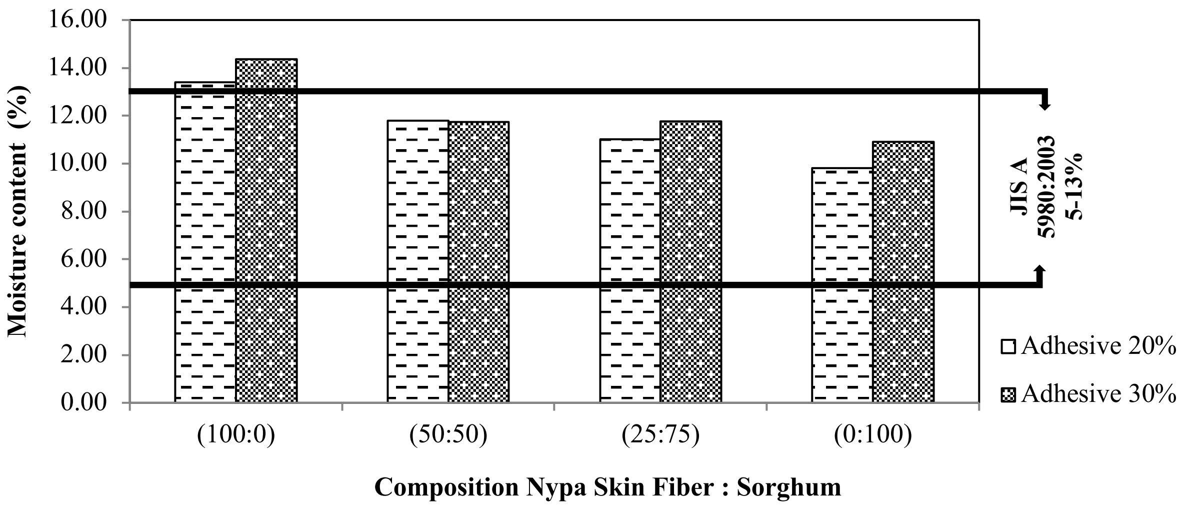


Fig. 2. Moisture content of particleboard at different adhesive contents and particle compositions.

The high moisture content in the 100% nypa fruit skin fiber composition was probably due to the hygroscopic raw materials used and having different lignocellulose content from sorghum.

Tamunaidu (2010) stated that the cellulose content in nypa was 36.5% and lignin 27.3%, while Kusumah et al. (2016) stated that the cellulose content in sorghum was 34.87% and lignin 23.02%.

Sutiawan (2018) stated that the moisture content of PB is influenced by the moisture content of the raw materials. The higher the moisture content of the raw material, the higher the moisture content of the PB. Another thing that affects the moisture content is that the adhesive was made by dissolving citric acid and sucrose with water, thereby increasing the moisture content in the PB.

The analysis of variance showed that the comparison factor of the raw material composition was significantly different from the water content value. In contrast, the adhesive concentration factor and the interaction of the two did not significantly affect the water content value. DNMRT analysis showed that PB with 100% nypa composition had significantly different results from other PBs. Overall the value of the moisture content of the PB meets the JIS A 5908:2003 standard, which requires a moisture content value of 5-13% except for the composition of 100% nypa fruit skin fiber.

3.2. Density

The average density values produced ranged from 0.70-0.85 g/cm^3 (**Fig. 3**). It was presumably due to the different raw materials and adhesives compositions. Various compositions of raw materials can cause different density values, and variations in the adhesive composition can cause different densities. The highest density value was in the composition of 50% nypa fruit skin fiber and 50% sorghum using 20% adhesive. In contrast, the lowest density value was obtained at 100% nypa fruit skin fiber composition using 20% adhesive.

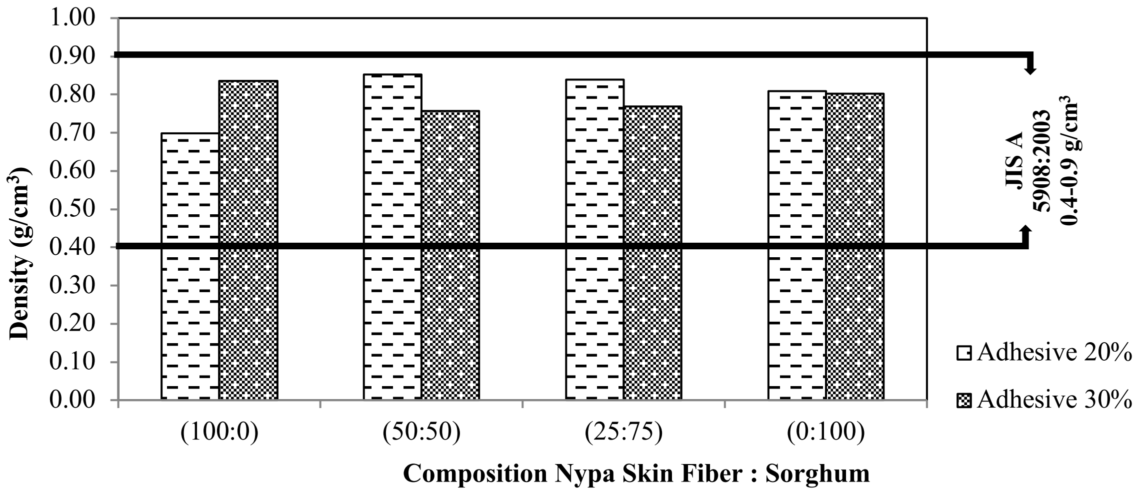


Fig. 3. Density of particleboard at different adhesive contents and particle compositions.

This study showed that high density tends to result from using 20% adhesive compared to 30% adhesive. It was presumably due to the uneven distribution of the adhesive during the blending process, causing parts of the raw material not to be covered by the adhesive. This statement was in line with Aini et al. (2009), reporting that when making sheet boards manually, it can result in uneven distribution of particles and adhesives in the formation of sheets in the mold, even though efforts have been made to be as uniform as possible. Endriani et al. (2019) stated that adding adhesive to the manufacture of PB would cause an increase in the total weight of the board produced at the same volume so it will cause an increase in the density of the PB. However, the analysis of variance in this study showed that the composition of the raw material and the concentration of the adhesive did not significantly affect the value of the PB density. This condition supports the hypothesis that the different density values in each treatment are due to the manual mattress forming, causing an uneven distribution of particles. The results of this study were similar to those of Bekhta et al. (2021), showing a slight difference in density values caused by the conditions of manual mattress forming. No significant differences were observed between the boards bonded by MgLS or NaLS and UF adhesive system.

The analysis of variance showed that the comparison factor of raw material composition and adhesive concentration factor had no significant effect on the density value. In contrast, the interaction between the two significantly affected the density value. All boards produced have met the JIS A 5908:2003 standard which targets a density value of 0.4-0.9 g/cm^3.

3.3. Water Absorption

The water absorption of the PB is shown in **Fig. 4**. The highest water absorption value (90.28%) was found in the composition of nypa fruit skin fiber 100% with a concentration of 20% adhesive. The lowest value (42.96%) was found in the composition of nypa fruit skin fiber 25%:sorghum 75% with a concentration of 20% adhesive. The addition of adhesive concentration tended to produce lower water absorption values. Likewise, with the ratio of the composition of raw materials, adding the amount of sorghum tended to produce PB with a lower water absorption value.

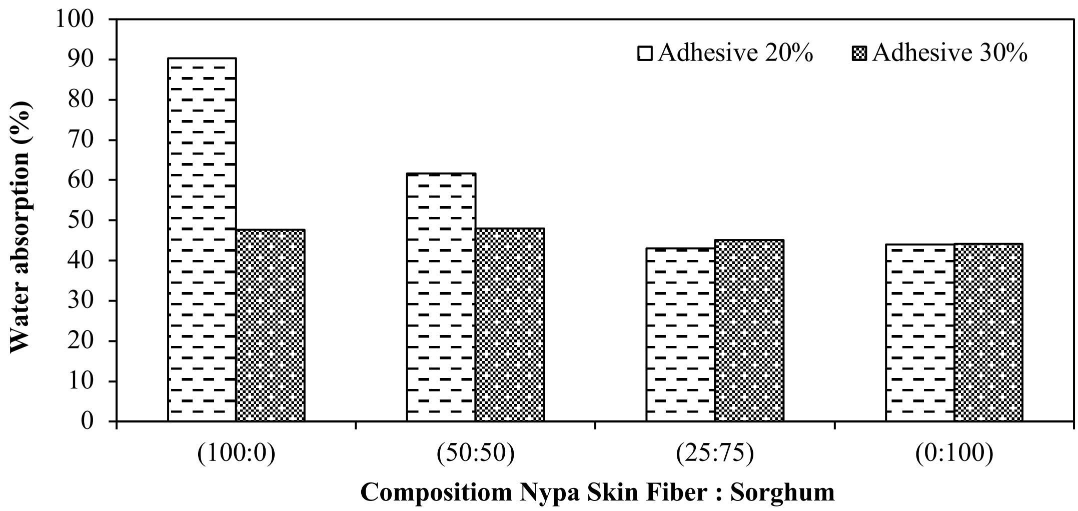


Fig. 4. Water absorption of particleboard at different adhesive contents and particle compositions.

Overall, the comparison of the composition of raw materials shows that the value of water absorption decreases with the increase in the composition of sorghum or the decrease in the composition of nypa fruit skin fiber. It could be caused by the nypa having a higher lignocellulose content than sorghum, so it is easy to absorb water. Likewise, Sutiawan (2018) also reported the decrease in water absorption of PB with the combination of sengon and sorghum as raw materials in PB manufacture. They explained that the higher the addition of sorghum particles, the lower the water absorption value of the resulting PB. The water absorption value diagram shows that with the addition of 10% adhesive, the water absorption value tends to decrease. The addition of citric acid and sucrose concentrations increased the resistance of PB to water. This condition occurred because citric acid plays a significant role in reducing the hydroxyl group on the PB with an ester bond formation so that it can form a hydrophobic PB with good dimensional stability and water resistance (Umemura et al. 2015).

The analysis of variance showed that the comparison factor of raw materials, adhesive concentration factor, and the interaction of the two factors significantly affected the water absorption value. The DMRT analysis showed that PB with a composition of 100% sorghum and 25% nypa fruit skin fiber:75% sorghum had significantly different results from other PBs.

3.4. Thickness Swelling

Thickness swelling values ranged from 8.61-20.08% (**Fig. 5**). The highest thickness expansion of 12% was found in adhesive with a concentration of 20%. In comparison, at an adhesive concentration of 30%, the thickness development value tended to be lower, reaching 12%. It was presumably because the bond between the particles becomes tighter with the addition of adhesive content so that less water enters the board.

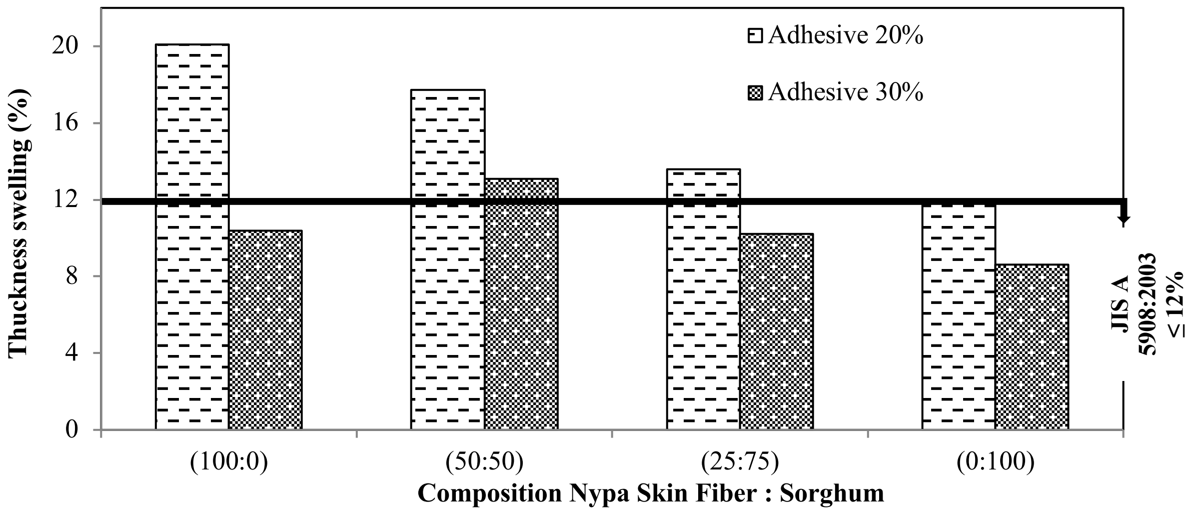


Fig. 5. Thickness swelling of PB at different adhesive contents and particle compositions.

The high thickness swelling value was also thought to be due to the influence of the adhesive composition. The concentration of sucrose used was higher than the concentration of citric acid, causing a lot of dissolved substances in the water. These results were in line with the previous studies (Santoso et al. 2016; Widyorini and Nugraha 2015), stating that the sucrose on PB results in a high thickness expansion value because sucrose was converted to caramel which contains a relatively high amount of dissolved substances in water.

3.5. Modulus of Elasticity

Modulus of elasticity (MOE) value range between 845.53–1319.01 N/mm^2 (**Fig. 6**). Overall, these results did not meet JIS A 5908:2003 type 8, which requires a MOE value of 2000 N/mm^2. Using 100% nypa fruit skin fiber composition, the MOE value increases with the addition of adhesive content. Suroto (2010) stated that the use of the amount of adhesive in PB affects the properties of the resulting PB. The greater the use of adhesive, the more significant the increase in the strength of the resulting PB. However, when the nypa material was mixed with sorghum, the flexural strength of the PB was reduced. On the other hand, the MOE value in the 100% sorghum composition increased with increasing the adhesive content. However, the MOE value decreased when nypa and sorghum were mixed.

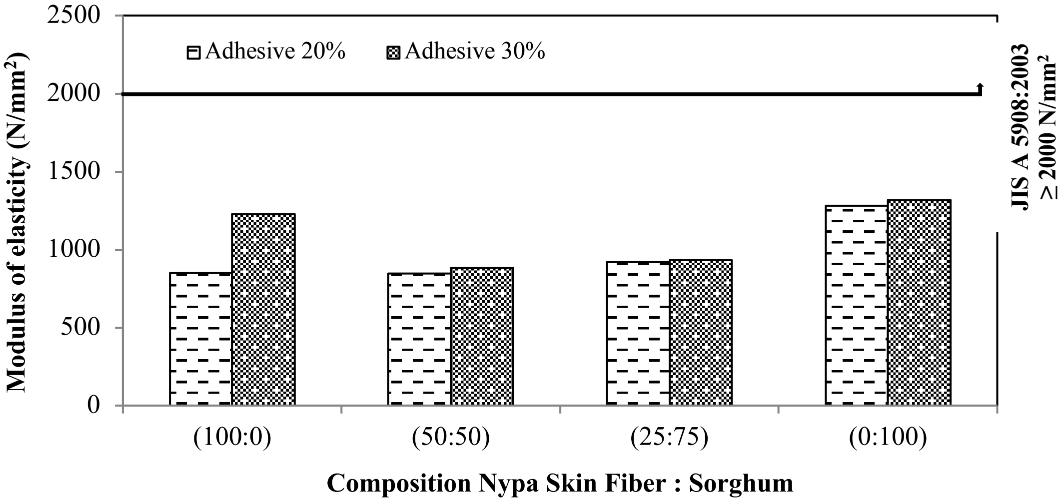


Fig. 6. Modulus of elasticity of particleboard at different adhesive contents and particle compositions.

The analysis of variance showed that the ratio of raw materials significantly affected the MOE value. At the same time, the adhesive concentration factor and the interaction of the two factors did not significantly affect the MOE value. The DMRT analysis showed that PB with 100% sorghum composition had significantly different results from other PBs.

3.6. Modulus of Rupture

The modulus of rupture (MOR) from the results of this study ranged from 5.07-9.16 N/mm^2. **Fig. 7** shows that the PB in this study did not meet the JIS A 5908:2003 standard, which requires a MOR value of 8 N except for the composition of 100% nypa fruit skin fiber with 30% adhesive with a value of 9.16 N/mm^2. In addition, the MOR value decreased when the nypa material was mixed with sorghum.

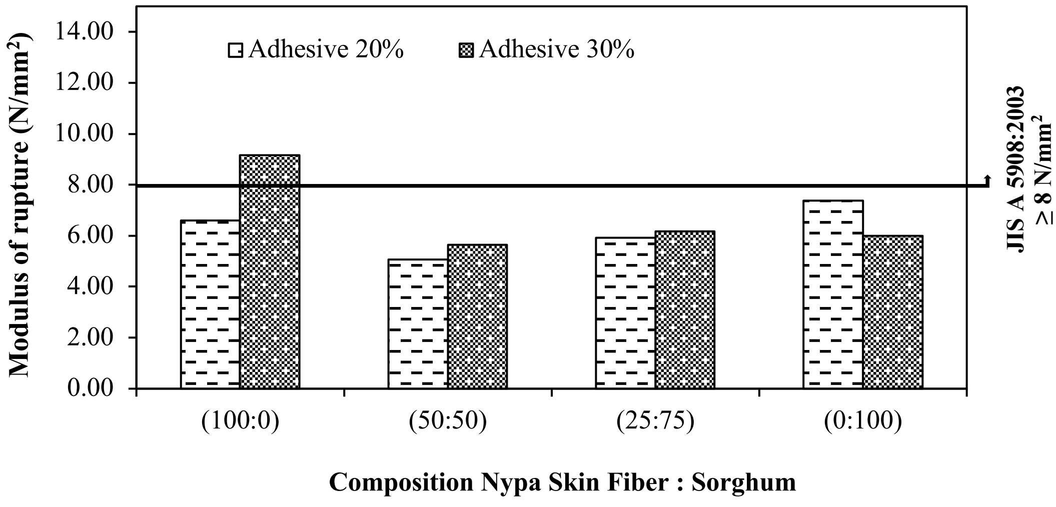


Fig. 7. Modulus of rupture of particleboard at different adhesive contents and particle compositions.

The low value of MOR was also presumably because of the difference in particle size, so the bonding power between particles is much less. Suroto (2010) also reported the PB made of rattan and explained that the higher the adhesive concentration and the longer the particle size, the higher the MOR.

The analysis of variance showed that the comparison factor of raw material composition and the interaction of the two factors had a significant effect on fracture toughness. In contrast, the adhesive concentration factor had no significant effect on the MOR value. The DMRT analysis showed that 100% nypa fruit skin fiber composition was significantly different from other PBs.

3.7. Internal Bonding Strength

The internal bonding (IB) strength value ranges from 0.07–0.35 N/mm^2 (**Fig. 8**). JIS A 5908:2003 standard requires the value for IB strength of 0.15 N/mm^2. The value of IB strength produced in this study varied widely.

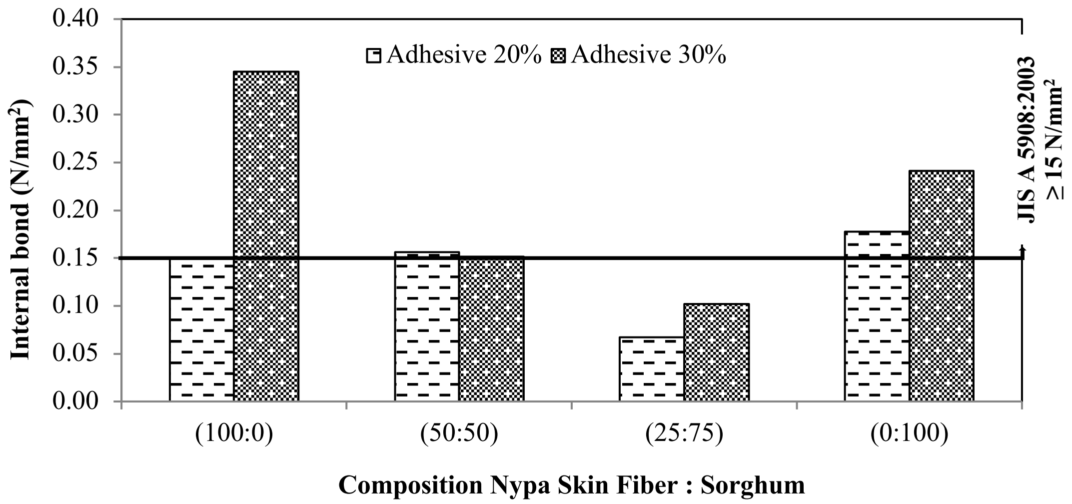


Fig. 8. Internal bonding strength of particleboard at different adhesive contents and particle compositions.

The composition of 100% nypa fruit skin fiber and 100% sorghum increased the value of adhesive strength with increasing levels of adhesive used. The increase in the amount of adhesive used positively affected the value of adhesive strength in the composition of 100% nypa fruit skin fiber and 100% sorghum raw materials. The combination of sorghum with nypa did not have a positive effect on the mechanical properties of PB. The value of IB strength decreased when the material was mixed; even increasing the use of adhesive content did not give good results on the value of the internal bond of PB. It was in line with the analysis of variance results, showing that the comparison factor of raw material composition, adhesive concentration factor, and the interaction of the two factors did not significantly affect the value of the internal bond. Kusumah et al. (2017) reported that the PB with a composition ratio of citric acid: sucrose (10:90) using raw materials sorghum produced particle bonding strength of the value of 1.17 N/mm^2.

The difference in value in the research results using the same adhesive as in the study of Kusumah et al. (2017) was allegedly due to differences in the types of raw materials, sizes, and chemical content contained in the materials used. Likewise, Santoso et al. (2016) stated that the possibility of differences in the chemical composition of the raw materials, especially the content of extractive substances, is thought to play a role in producing different values, as well as differences in particle geometry sizes affect on differences in research results. Hashim et al. (2010) also reported that the internal bonding strength of oil palm PB with a rough geometry and size of 49% is better than that of the finer particles.

3.8. Screw Holding Power

Standard JIS A 5908: 2003 required a minimum screw holding power of 300 N. The results show that screw holding power increased with the increase in the adhesive content used (**Fig. 9**). These results indicate that adding adhesive content effectively increased the screw holding power of PB. Rowell et al. (2005) stated that screw holding power is influenced by the cellulose content. Tamunaidu (2010) stated that the cellulose content in nypa is 36.5%, while the cellulose content in sorghum is 34.87% (Kusumah et al. 2017). The cellulose content affects the cell wall. A thick cell wall will produce a large screw holding power value (Sutiawan 2020).

The analysis of variance results revealed that the comparison factor of raw material composition and the interaction of the two factors had no significant effect on the value of the screw holding strength. In contrast, the adhesive concentration factor significantly affected the value of the screw holding power. The results indicated that adding adhesive content effectively increased the value of PB screw holding strength.

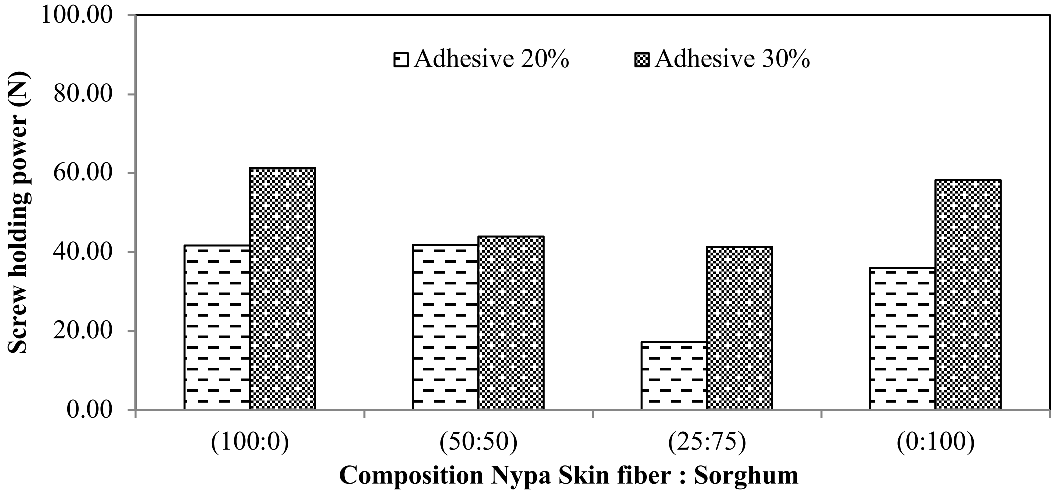


Fig. 9. Screw holding power of particleboard at different adhesive contents and particle compositions.

4. Conclusions

The PB from a mixture of sorghum and nypa fruit skin fiber using citric acid and sucrose adhesives could meet the JIS A 5908:2003, particularly for the moisture content, density, water absorption, and adhesive toughness. In contrast, the thickness expansion, MOE, and MOR of the PB did not meet the JIS A 5908:2003 standard. Combining nypa fruit skin fiber and sorghum with small particle sizes was ineffective in improving PB characteristics because mixing the two materials will result in inferior characteristics.

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