

Physical and Mechanical Properties of Particle Board from Petung Bamboo-waste using Eco-friendly Chitosan-starch Adhesive

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Abstract

The utilization of bamboo-sawing waste particles as a raw material for particle board manufacturing has been gaining attention due to its waste reduce potential and economic advantages. The effect of starch addition in chitosan adhesive on the physical and mechanical properties of petung bamboo particle board from bamboo-sawing waste was investigated in this work. The results of this study indicated that starch has been proven to enhance the physical and mechanical properties of petung bamboo particle board. Adding only 4% wt. of chitosan/starch adhesive with a chitosan/starch ratio of 7/3 (w/w) has resulted in an improvement in the physical properties of the particle board, such as moisture content, thickness swelling, and water absorption. It has also enhanced the mechanical properties of the particle board, including modulus of elasticity (MOE), modulus of rupture (MOR), and internal bonding (IB), in comparison to chitosan adhesive without starch addition. Overall, these findings provide insights for further developing chitosan/starch adhesive, especially to produce natural-based adhesives with good bonding quality.

Keywords: bamboo, chitosan, particle board, starch, wood adhesive, physical and mechanical properties

Introduction

Timber or non-timber waste processing into useful products is an innovation to address the shortage of wood raw materials in the timber industry in Indonesia. Wood waste processing can also reduce the residue from processing waste and convert it into economically valuable products. One alternative is to process wood waste into particle board. Utilizing wood waste to produce particle board has several advantages, such as optimizing small-sized wood or wood processing residues to produce valuable products, thereby reducing tree cutting to obtain raw materials, reducing the impact of deforestation, and be more economical. However, the current challenge in the particle board manufacturing process is the selection of adhesive type. The particle board industry generally still uses formaldehyde-based synthetic adhesives (Sulaiman *et al.*, 2013). This adhesive has the potential to be harmful to humans because it produces carcinogenic emissions both during production and when the product is used (Sulaiman *et al.*, 2018; Yusof *et al.*, 2020). Therefore, the development of eco-friendly and safe natural adhesives continues to be pursued as an alternative to synthetic adhesives based on formaldehyde.

Chitosan is a polysaccharide compound derived from chitin, originating from the shells of crustaceans which are abundant, non-toxic, biodegradable, and have potential to be used as a sustainable natural adhesive (Ji and Guo, 2018; Zargar *et al.*, 2015). As a renewable and biodegradable natural material, chitosan has advantages in terms of environmental impact compared to chemically-based synthetic adhesives. Even though it is naturally-based, chitosan has shown good adhesive capabilities on substrates like wood chips, making it highly promising for particle board applications (Umamura and Kawai, 2007). The unique

molecular structure of chitosan enables the formation of strong bonds through various adhesive mechanisms, including hydrogen bonding and electrostatic interactions. These adhesive properties, coupled with its biocompatibility and non-toxicity, make chitosan as an ideal candidate for materials and engineering applications such as particle board and plywood manufacturing (Umamura and Kawai, 2008). Despite the good environmental benefits of chitosan, the products produced from chitosan adhesive still exhibit low mechanical and physical properties. These drawbacks can be improved by selecting compatible other natural materials to complement the biopolymers or through chemical modification to create a three-dimensional crosslinked polymeric network with strong bonding ability (El Knidri *et al.*, 2018).

As research continues to explore and optimize its formulation, chitosan stands out as a high-quality, eco-friendly, and versatile composite adhesive with the potential to reshape industries seeking innovative and sustainable bonding solutions. As reported by Umamura *et al.* (2003), the use of chitosan as a plywood adhesive provided better bonding and water resistance compared to previous adhesives. The combination of chitosan and Konjac Glucomannan (KGM) interestingly resulted in increased adhesive strength, particularly associated with wood failure. Furthermore, a series of studies investigated the improvement of film properties and bonding properties of plywood by adding glucose to chitosan adhesive (Umamura *et al.*, 2010). The quality of chitosan adhesion continued to be developed as an environmentally friendly adhesive for composite product manufacturing, such as for the production of composites from sunflower stalks (Mati-Baouche *et al.*, 2014). Reviewing the thermal, mechanical, and acoustical properties of the composite proved a significant improvement

under the influence of compaction pressure. The use of chitosan-based adhesive was also proven to enhance the bonding strength and water resistance of medium-density fiberboard (MDF) (Ji and Guo, 2018). The intention to improve the quality of chitosan adhesion in composite products still to be continue until now.

One alternative is by adding starch to chitosan solution. The addition of starch proposed to the improving on bonding strength, enhanced water resistance, dimensional stability, and cost-effectiveness (Li *et al.*, 2023). The previous research has explored the improvement of physical and mechanical properties of particle board using starch adhesive. The result showed that the addition of starch to citric acid adhesive has higher mechanical properties compared to the citric acid only bonded particle board (Widyorini *et al.*, 2017). However, the influence of chitosan-starch adhesive on the physical and mechanical properties of bamboo particle board has not been investigated so far. Therefore, this study investigated the physical and mechanical properties of petung bamboo particle board using chitosan-starch adhesive. Based on the previous research, maranta starch showed the higher mechanical properties of particle board compared to corn and canna starch, thus maranta starch was chosen for further investigation regarding its influence on the quality of chitosan adhesive bonding.

Materials and Methods

Materials

The materials used in this study were chitosan (deacetylation degree 98%), acetic acid, maranta starch, and deionized water. All of the chemicals were analytical grade and used directly without further treatment. Petung (*Dendrocalamus asper*) bamboo particles were collected from bamboo-sawing industry in Yogyakarta province, Indonesia. The particles are then screened with a 10-mesh sieve and used for particle board manufacturing. After screening, the particles are stored to air dry and the moisture content of 11%.

Methods

Preparation of chitosan-starch adhesive. Starch was dissolved in distilled water with a various composition to provide a solution with a concentration of 50%wt. These starch solutions were then mixed with chitosan solution in acetic acid to obtain a wide variety of chitosan adhesives with a solid content of 4%wt. based on dry-weight particles. The chitosan/starch (C/S) ratio was set at 10/0, 9/1, 8/2, and 7/3 (w/w), referred to Umemura *et al.* (2010) with some modifications. The weight of the particles was calculated from the target density of the particle board (0.8 g/cm³), and the target dimensions of the board were 25.5 x 25.5 x 1 cm. The detailed research formulation can be seen in Table 1.

Particle board manufacturing. The prepared chitosan/starch adhesive was applied and mixed onto the petung-bamboo particles uniformly, and then dried in an oven at 60°C for 5 h to reduce the moisture content of the particles to around 12%. The target density of particle board was set at 0.8 g/cm³. The particles were then hand-formed into 25.5 x 25.5 cm mats and subsequently pressed at 200°C for 12 minutes under a specific pressure of 3 MPa. The target thickness of the board was set at 1 cm, and all treatments were repeated 3 times. After hot-pressing, the particle boards were then conditioned at room temperature for approximately a week, followed by specimen preparation for particle board testing. The detailed dimensions of the specimen prepared for testing were illustrated in Fig. 1.

Particle board properties tests. The physical and mechanical properties of the particle board were evaluated following the Japanese Industrial Standard A 5908 (2015) for Particle board, which were density, moisture content, thickness swelling (TS), water absorption (WA), modulus of elasticity (MOE), modulus of rupture (MOR), and internal bond strength (IB).

The TS and WA test were conducted by immersing a sample sized of 5 x 5 x 1 cm in water at 20°C for 24 h then the changes of the samples were measured. The static three-point bending strength of the particle board was evaluated using 20 x 5 x 1 cm specimens. The bending test was used to determine the modulus of rupture (MOR) and modulus of elasticity (MOE). The MOR, MOE, and IB values were adjusted for the target density according to the specimen densities. Each experiment was repeated three times, and the average values along with the standard deviations were computed.

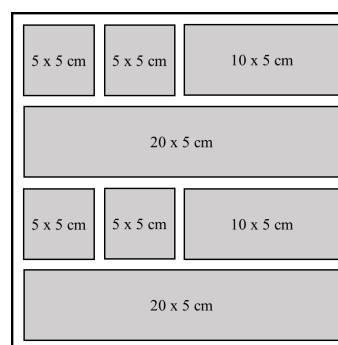


Figure 1. Cutting pattern of the particle board test sample

Results and Discussion

The particle boards from petung bamboo with chitosan/starch adhesive were successfully manufactured. After a week of conditioning, the particle board was cutting based on pattern and was evaluated for the physical and mechanical properties.

Table 1. Research formulation of chitosan/starch (C/S) adhesive.

| Chitosan/starch (w/w) | Solid content of adhesive (% wt.) | Hot-press temp (°C) | Pressing time (min) | Repetition | | |
|-----------------------|-----------------------------------|---------------------|---------------------|------------|----|----|
| | | | | 1 | 2 | 3 |
| 10/0 | 4 | 200 | 12 | A1 | A2 | A3 |
| 9/1 | | | | B1 | B2 | B3 |
| 8/2 | | | | C1 | C2 | C3 |
| 7/3 | | | | D1 | D2 | D3 |

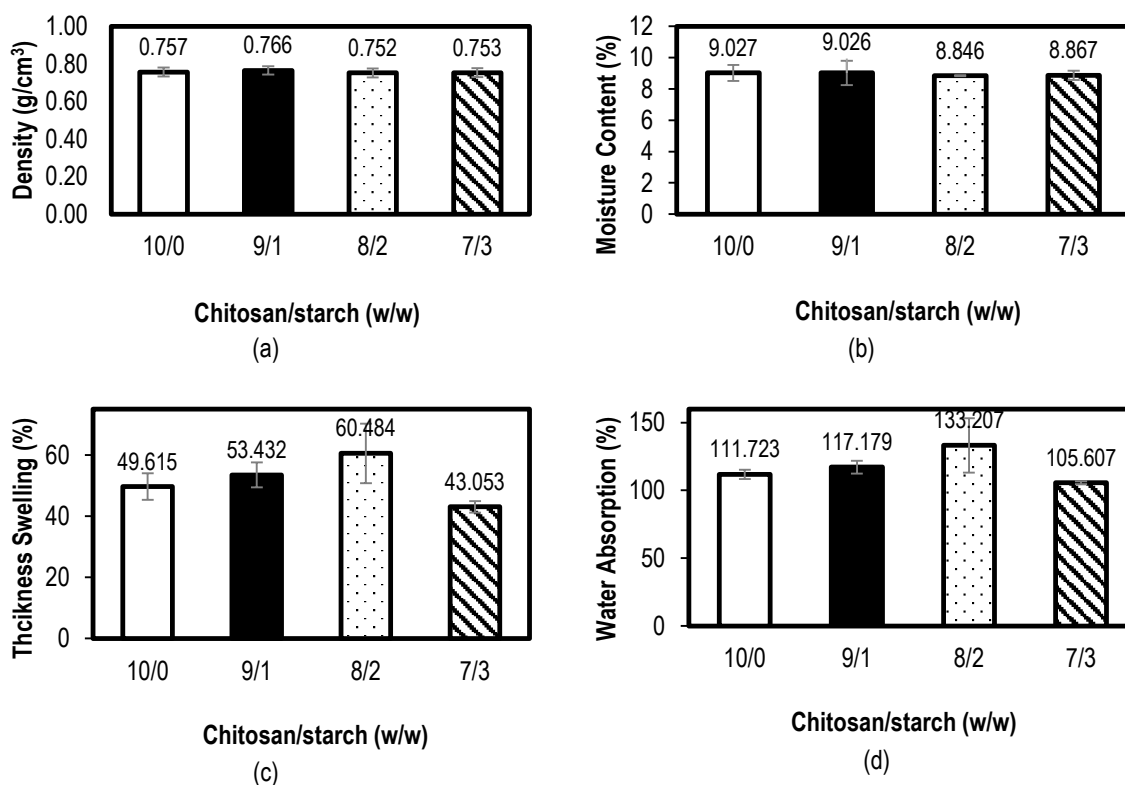


Figure 2. The effect of C/S adhesive ratio on the physical properties of petung bamboo particle board: (a) density of particle board; (b) moisture content of particle board; (c) Thickness Swelling of particle board; (d) Water Absorption of particle board.

Density. Particle boards were manufactured with a target density of 0.8 g/cm³. Data on the density of petung bamboo particle boards with C/S adhesive was presented in Fig. 2(a). The average density values of the particle boards produced ranged from 0.752 to 0.766 g/cm³. The density values were closed to the target density of particle board and met the JIS A 5809 (2015), which ranged from 0.4 to 0.9 g/cm³.

The highest density was given by the particle board with a C/S ratio of 9/1 (w/w), which was 0.766 g/cm³. The smallest density was found in the particle board with a C/S ratio of 8/2 (w/w), which was 0.752 g/cm³. Statistical analysis showed that the composition of C/S did not have a significant impact on particle board density.

Moisture content. Moisture content affects the physical and mechanical properties of particle board. Excessive moisture

content will produce poor quality boards and cause defects (Gul *et al.*, 2023). The moisture content of petung bamboo particle boards with various C/S adhesive is presented in Fig. 2(b). The moisture content of petung bamboo particle boards with chitosan/starch adhesive was found to range from 8.84 - 9.02%. The highest moisture content was given by the chitosan particle board without the addition of starch (C/S 10/0), while the lowest moisture content was showed by the C/S 8/2 (w/w) particle board. All of the particle boards met the moisture content standards according to JIS A 5809 (2015), with a range of 5 - 13%. Based on previous studies which used chitosan-based adhesive on particle board, the used of chitosan-lignin on sunflower-stalks composite boards produced a moisture content of approximately 8% (Mati-Baouche *et al.*, 2014). Therefore, the results of our research

show a better moisture content value compared to the other research (Lindangan et al., 2019), whose moisture content ranges from 11.9 – 15.8%.

The analysis of variance result showed that the composition of chitosan and starch did not affect the moisture content of petung bamboo particle board. However, aside from adhesive composition, the moisture content of particle board is influenced by several factors such as raw materials (initial moisture content, hygroscopic properties of particles), moisture content in the adhesive, and the amount of evaporating moisture during the compression process (Lindangan et al., 2019).

Thickness swelling. Thickness swelling of particle board represents the stability and bond strength properties of particle board. The data on the thickness swelling (TS) of

petung bamboo particle boards with various C/S adhesive is presented in Fig. 2(c).

Petung bamboo particle boards with C/S adhesive exhibited the TS values ranging from 43.05-60.48%. None of these particle boards met the TS standards of JIS A 5809 (2015), which are $\leq 12\%$. However, the used of C/S adhesive with a 7/3 (w/w) ratio was successfully reduced the thickness swelling of particle board to 43.05%, compared to bare chitosan which the TS value was 49.15%. These results indicated that the adding starch to chitosan adhesive with a 7/3 (w/w) of C/S ratio was effectively improved the dimensional stability properties of particle board, resulting in the lowest TS compared to chitosan without starch or chitosan with other ratios of starch.

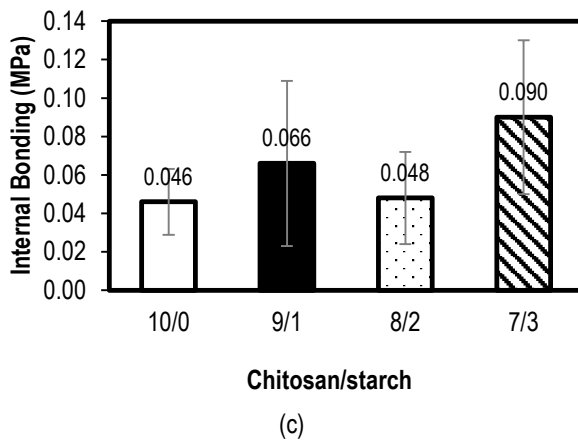
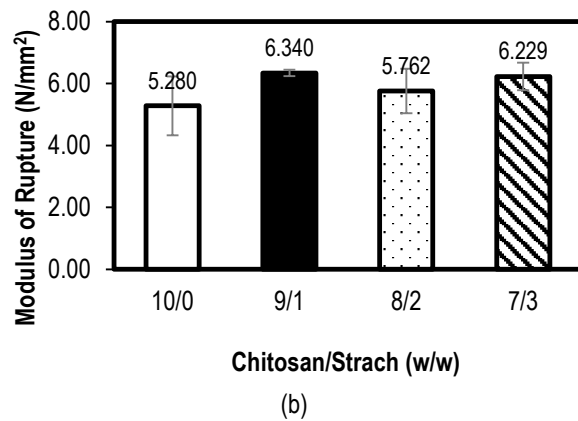
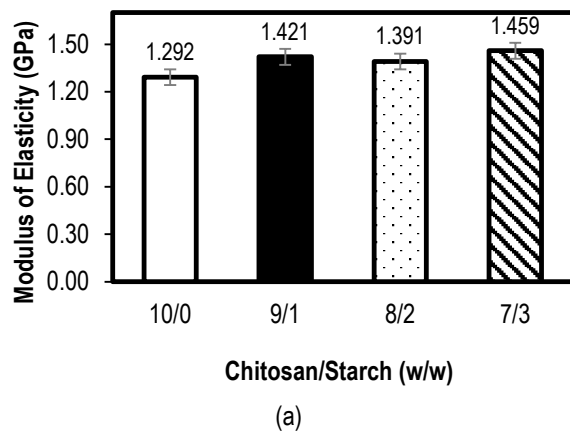


Figure 3. The effect of C/S adhesive ratio on the mechanical properties of petung bamboo particle board: (a) MOE of particle board; (b) MOR of particle board; (c) IB of particle board.

The addition of starch in C/S ratio from 10/0 to 8/2 resulted in an increase in the TS value of the particle board. This is because starch is easily soluble in water. This results are in correlation with the previous study by Widyorini et al. (2017), that the addition of starch to the adhesive apparently

increased the TS value. However, despite the increase in the TS value, the higher of starch ratio in adhesive proved to enhanced the MOR, MOE, and IB values of the particle board. This indicates that the more starch composition, the higher the bonding strength of the particle board, leading to

an improvement in its mechanical properties. Furthermore, the C/S ratio of 7/3 resulted in a decreased in the TS value due to the increasing number of hydrogen bonds formed between the chitosan-starch adhesive as well as hydroxyl chemical reactions on the surface of the petung bamboo particles, resulting in an increase in the bond strength properties of the particle board (Li et al., 2023). This may affect to the increasing of the particle board dimensional stability and decreasing the TS value.

Based on the analysis of variance, the factor of C/S adhesive composition had an influence on the TS values of particle board. This was indicated by a significant reduction in the TS when using 7/3 (w/w) of C/S adhesive. The use of chitosan as an adhesive was found to reducing the TS of particle boards (Ji & Guo, 2018). On the other hand, the presence of starch in the adhesive was proven to decrease the TS value because starch enhanced the strength of hydrogen, covalent, and ionic bond interactions (Boussetta et al., 2023).

Water absorption. The relationship between the composition of C/S adhesive on the water absorption (WA) is shown in Fig. 2(d). According to Fig. 2(d), the WA of particle boards were found in range from 105.607% to 133.207%. The highest water absorption value was found in the 8/2 ratio of C/S adhesive and the lowest water absorption value was provided by the 7/3 ratio of C/S adhesive. This results indicates that adjusting the starch composition in chitosan adhesive to 7/3 (w/w) successfully improved the bonding strength, thereby reducing the hygroscopic properties of the particle board. The WA values were in correlated with the TS values. The lowest WA value of 7/3 C/S indicated the better dimensional stability (Boussetta et al., 2023; Mayilswamy & Kandasubramanian, 2022).

The results in analysis of variance showed that the composition of C/S adhesive had no effect on the WA values. Furthermore, the JIS A 5809 (2015) standards do not specify water absorption values for particle boards.

Modulus of elasticity. The quality of C/S bonding on petung bamboo particle board was also evaluated through the mechanical properties of the particle board, one of which is the modulus of elasticity (MOE). The MOE data of particle board are presented in Fig. 3(a).

The MOE of petung bamboo particle boards using C/S adhesive ranged from 1.292 to 1.459 GPa. The highest MOE was found in the 7/3 of C/S particle board, which was 1.459 GPa. Without the addition of starch, the lowest MOE was obtained at 1.292 GPa. This indicates that adding starch to the chitosan adhesive successfully increased the bonding strength, thus enhancing the flexural modulus values of the particle board. The addition of starch with a chitosan/starch ratio of 7/3 (w/w) was the best composition for improving bonding strength, as evidenced by the highest MOE compared to other adhesive compositions. This results much higher than the previous research by Lindangan et al. (2019) using bare chitosan as an adhesive. The bare chitosan adhesive showed the MOE as 1.04 GPa, smaller than the

MOE of C/S 7/3 in our work, which was 1.459 GPa. The increase in the MOE value was caused by strong bonding interactions formed between chitosan and starch, as well as the chitosan-starch adhesive and active groups on the surface of petung bamboo particles. This is also confirmed by Widyorini et al. (2017), where starch has a significant effect on improving the mechanical properties of particle board. The presence of starch contributed numerous hydroxyl groups that could form strong hydrogen bond interactions with chitosan, as mentioned by Boussetta et al. (2023).

The results of the variance analysis indicated that the composition of C/S did not affect the MOE of the particle board. Furthermore, the petung bamboo particle boards with C/S adhesive did not meet the standard flexural modulus values according to JIS A 5809 (2015). However, the chitosan/starch (7/3) (w/w) particle board satisfied the MOE standards of ANSI A208.1-1999 for LD-1 (≥ 550 N/mm²) and LD-2 (≥ 1025 N/mm²) for particle board types.

Modulus of rupture. The modulus of rupture (MOR) data of petung bamboo particle boards with various C/S adhesives are presented in Fig. 3(b). The MOR of particle boards were 5.280 - 6.340 N/mm². The addition of starch to the chitosan adhesive to be 9/1 of C/S produced the highest MOR at 6.340 N/mm². In addition, the 7/3 of C/S particle board resulted in MOR that were not significantly different from the 9/1 of C/S particle board, at 6.229 N/mm². Particle boards with chitosan adhesive without the addition of starch (10/0 of C/S) showed the lowest flexural strength, which was 5.280 N/mm². This indicates that the addition of starch to chitosan can enhance the bonding quality, resulting in improved MOR of particle boards (Xi et al., 2022).

The analysis of variance indicated that the composition of C/S adhesive did not affect the MOR of the particle board. However, it was evident that adding starch to the chitosan adhesive successfully increased the MOR. Although all of C/S adhesive particle boards did not meet the MOR standards of JIS A 5809 (2015), the particle boards met the MOR standards established by ANSI A208.1-1999 for LD-1 (≥ 3.0 N/mm²) and LD-2 (≥ 5.0 N/mm²) types.

Internal bonding strength. The particle board with a 7/3 (w/w) C/S displayed the highest IB compared to other particle boards, as shown in Fig. 39(c). The addition of starch to chitosan, has proven to increasing the IB value to 0.090 MPa when compared to other C/S particle boards and chitosan without the addition of starch (0.046 MPa). This confirmed that the starch addition to chitosan was successfully improved the mechanical quality of particle boards, lead to the increasing in the IB value. However, all of these particle boards still did not meet the IB standards of JIS A 5809 (2015). The IB of particle boards is influenced by the appropriate pressing temperature, not too low or too high (Widyorini, 2020). Therefore, it is important to evaluate the influence of various pressing temperatures in the production of petung bamboo particle boards with chitosan/starch adhesive.

The enhanced mechanical properties MOE, MOR, and IB of the particle board with chitosan/starch adhesive are caused by the strong interaction between chitosan and the -OH groups of starch, resulting in strong cross-linked network macro-molecules with a large of molecular weight. This strong macro-molecular interaction also occurs between chitosan/starch and the -OH groups on the surface of petung bamboo particles. Chitosan macro-molecules have -OH and -NH groups which can form strong hydrogen bond interactions with the -OH groups which are abundant in starch (Boussetta et al., 2023). Both chitosan and starch contain hydroxyl groups (-OH), which can establish hydrogen bonds with each other. These hydrogen bonds contribute to the adhesive strength between chitosan and starch, resulting in a strong bond between wood particles in the particle board (Xi et al., 2022; Zargar et al., 2015). Additionally, the enhancement in mechanical properties is associated with the unique characteristics of good chemical reactivity from both chitosan and starch, resulting in an interconnected network between the adhesive and particles. The results indicate that the presence of starch in the chitosan-starch adhesive enhances the physical and mechanical properties of petung bamboo particle board.

The increased amount of starch in chitosan adhesive results in an improvement in the physical and mechanical properties of particle board. This is because a higher amount of starch provides more hydroxyl groups, leading to increased hydrogen bonds between starch and the -OH and -NH₂ groups from chitosan, as well as the active groups on the particle surface. This aligns with Umemura et al. (2010), that adding saccharides such as glucose to chitosan adhesive enhances its physical and chemical properties. The enhancement is attributed to the Maillard reaction, which strengthening the interaction between chitosan and saccharides. In our study, the improvement of physical and mechanical properties may also be due to the facilitated Maillard reaction occurring after the addition of starch, resulting in strong bonding properties. This results is in line with the findings of Xi et al. (2022) indicating that an increased starch ratio in chitosan adhesive positively impacts to the dry shear strength of plywood. Thus, from the findings we obtained, it has been proven that increasing the amount of starch in chitosan adhesive resulted in an increase in the physical and mechanical properties of particle board.

Conclusions

The use of starch in chitosan adhesive has been proven to successfully enhanced the physical and mechanical properties of petung bamboo particle boards compared to the physical and mechanical properties of particle boards with chitosan adhesive without starch. The C/S adhesive ratio of 7/3 (w/w) resulted in the best moisture content, TS, and WA values. Similarly, in terms of mechanical properties, this 7/3 of C/S adhesive led to the highest MOE, MOR, and IB values

compared to other adhesive compositions. Petung bamboo particle boards with C/S adhesive met the standards of JIS A 5809 (2015) and ANSI A208.1-1999. However, further studies are needed to examine the influence of various pressing temperatures on petung bamboo particle boards with chitosan/starch adhesive.

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