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Physicochemical Characteristics and Bonding Performance of Cellulose-Starch Based Bio-Adhesives on Medang, Meranti, and Balam Wood

Sumiati Simanullang[1*], Saviska Luqyana Fadia[1], Yunia Frida Adelka[1], & Muhammad Rasyidur Ridho[1]

[1]Departement of Forestry, Faculty of Agriculture, University of Jambi, Jambi, Indonesia

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Abstract

The global shift toward a sustainable economic paradigm is pushing the forest products industry to transition from emission-based petroleum-based adhesives to bio-adhesive alternatives. Cellulose-based adhesives from cardboard waste and starch offer a sustainable solution due to the abundance of hydroxyl groups (-OH) that play a crucial role in the adhesion process. This study aims to determine the physicochemical characteristics of cellulose-starch-based adhesives on three types of wood: medang, meranti, and balam. The research procedure includes measuring the wood density and testing the adhesive characteristics, which encompass appearance tests, acidity (pH), evaporation residue, and pot life. The research results show that medang wood has the highest density (0.47 g/cm³), followed by balam (0.46 g/cm³) and meranti (0.39 g/cm³). On the other hand, the physicochemical characteristics of cellulose-starch-based adhesives have a homogeneous appearance without interfering particles and an acidic nature (pH 3-5). The pot life of the adhesive shows very good stability, ranging from 5 hours 23 minutes to 5 hours 47 minutes.

Corresponding Author:
* Sumiati Simanulang
Departement of Forestry, Faculty of Agriculture, University of Jambi, Jambi, Indonesia
Email: sumiatisimanullang@unja.ac.id

INTRODUCTION

The global transition toward a circular economy demands massive transformation in the forest products industry, particularly in adhesive technology. However, dependence on petroleum-based materials and the issue of chemical emissions pose a unique long-term challenge for the environment. The development of bio-adhesives as environmentally friendly products offers a viable alternative. One approach to achieving sustainable production is by utilizing non-toxic and economical starch as a biodegradable raw material in adhesive manufacturing (Watcharakitti et al., 2022). However, the limitations of pure starch adhesives necessitate modifications, including the addition of cellulose derived from cardboard waste. Adding cellulose is meant to improve the adhesive work. Cellulose can form hydrogen bonds with starch and wood fibers, which makes the bonding network stronger than if only starch were used (Azizah et al., 2020). Cardboard waste is an abundant source of cellulose but has not yet been optimally utilized in the adhesive industry, despite its potential to significantly improve adhesive properties and reduce environmental waste. Adhesives based on cardboard cellulose and starch are a type of natural adhesive composed of biopolymers, namely cellulose and starch, which are rich in hydroxyl groups (-OH). These groups enable the formation of hydrogen bonds between material surfaces, resulting in adhesive strength. The bond strength can be enhanced through modifications such as oxidation or cross-linking to form a stronger and water-resistant network. The main mechanism of this adhesive involves simple yet effective chemical interactions, such as hydrogen bonding and van der Waals forces, which can be enhanced through chemical engineering (Liu et al., 2023; Sun et al., 2025).

The effectiveness of an adhesive is not only determined by its chemical composition but also by the anatomical and physical properties of the wood being bonded. Meranti wood (Shorea spp.), Balam (Palaquium spp.), and Medang (Litsea spp.) are types of wood widely used in the carpentry industry but have different densities, porosities, and extractives. These differences in physical characteristics will significantly affect the absorbency and bond strength of cellulose-starch-based adhesives. The feasibility of using alternative adhesives requires comprehensive testing that compares commercial standards with new innovations. Testing adhesive characteristics such as pH, viscosity, and evaporation residue or solid content is crucial in determining adhesive performance on wood surfaces (Auliata et al., 2021).

The primary focus of this study is to examine the extent to which these environmentally friendly adhesives can be applied to three types of wood with different characteristics, as well as to understand the influence of the adhesive's physical properties on the quality of wood bonds. The results of this study are expected to provide a scientific foundation for the development of economical and environmentally friendly non-formaldehyde adhesive formulations.

METHODS

Tools and Materials

The main materials used in this study were Meranti, Balam, and Medang wood, each measuring 10 cm × 5 cm × 1 cm. A cellulose-based adhesive (a mixture of cardboard and starch) was also used. The equipment used included an analytical balance, an oven, a desiccator, a blender, a sieve, a stove, a pH indicator, a measuring cylinder, test tubes, and a water bath.

Research Procedure

Preparation of Test Samples and Wood Characterization

Test samples were prepared in pairs, with 6 pairs for each type of wood. The samples were dried before being placed in an oven at a temperature of 103ºC ± 2ºC until they reached a constant weight. Physical characterization is carried out by calculating the wood moisture content using the following formula:

$$\textbf{Ka (\%)} = \frac{B0 - B1}{B1} \textbf{ x 100\%}$$

Description: B_0 = Initial weight (g), B_1 = Oven-dry weight (g)

$$\textbf{Density calculation: p} = \frac{m}{v}$$

Description: m = Sample mass (g), v = Sample volume (cm^3)

Synthesis of Cellulose-Based Adhesive

The adhesive used is a cellulose fiber-based adhesive with a starch-based reinforcement. The cardboard is cut into small pieces, blended using a blender, then soaked in hot water and filtered. The filtrate from the soaking is added to starch flour, then heated while continuously stirred until it reaches the gelatinization point and forms a thick mass.

Coating and Assembly Procedure

The investment technique is carried out using the single spread and double spread methods with a target coating weight of 300 g/m² and a sample size of 10 cm x 5 cm x 1 cm. The adhesive requirement for the samples is calculated as follows: Single spread: 1.5 g/pair. Double spread: 0.75 g/surface. After the application, the sample goes through the open assembly time stage until the adhesive reaches the optimal concentration level, followed by the close assembly time when both surfaces are contacted. The sample was then clamped for 24 hours. The test sample was stored in a sealed plastic bag to prevent changes in moisture content.

Testing of Adhesive Characteristics

The testing of adhesive characteristics is conducted through six main parameters:

a. Appearance Test: Visual observation of the object glass to detect the presence of solid particles or contaminants.
b. Acidity Test (pH): Measurement of acidity levels using a universal pH indicator.
c. Evaporation Residue Test (S%): Determination of solid content by drying approximately ± 1.5 g of adhesive (W1) in an oven until a constant weight (W2) is achieved. S (%) = W_2/W_1 x 100

Pot Life: Observation of the duration of time required for the adhesive to harden and become unusable (shelf life)

RESULTS AND DISCUSSION

Analysis of Wood Density in Various Species

The density of each wood sample for cellulose-starch-based adhesive applications is shown in Figure 1, which illustrates the variation in density values among the three types of wood tested. Medang wood has the highest density, with an average of nearly 0.47 g/cm³, followed by balam wood at 0.46 g/cm³ and meranti wood with the lowest value of approximately 0.39 g/cm³. In general, an increase in wood density correlates with an increase in adhesive bond strength due to a larger contact surface area and a greater amount of cell wall material. This allows for more effective load transfer at wood joints. However, in high-density wood, adhesive penetration can be more difficult, thereby reducing mechanical interlocking, which under certain conditions can actually decrease bond strength (Follrich et al., 2008; Plaster et al., 2008).

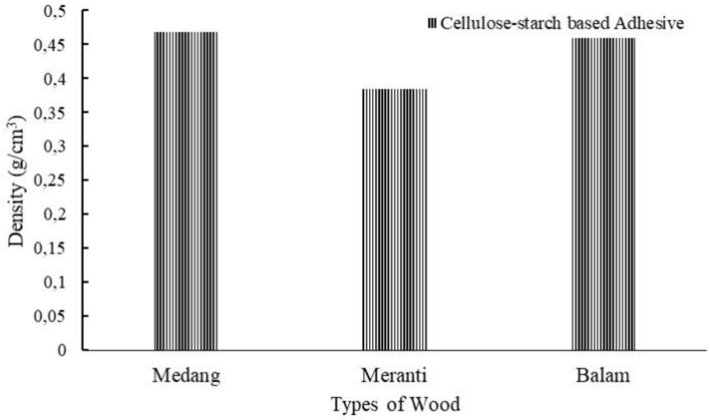

Figure 1. Average density values of medang, meranti, and balam wood.

Wood with higher density generally requires a longer pressing time or stronger pressure for the adhesive to penetrate. The wood density of the medang, meranti, and balam species shows variations influenced by anatomical and environmental factors. Medang wood has a density of about 0.47 g/cm³, a value lower than the research findings (Anggraini et al., 2022) on Medang Sereh, which reached 0.62–0.69 g/cm³. Meanwhile, the density of Meranti wood at 0.39 g/cm³ also shows a lower value compared to the findings (Wahyudi & Sitanggang, 2016), which reported a density of 0.65 g/cm³ for small diameters and 0.90 and 0.87 g/cm³ for medium- to large-diameter trees. Meanwhile, specific density data for Balam are still limited, but as part of the genus Shorea, its value is estimated to vary depending on growth conditions and wood anatomical characteristics (Adi et al., 2020). Wood density is a fundamental parameter that determines the surface area of contact between the adhesive and the wood cell walls. In wood with higher density, such as balam, the mechanical strength of its constituent wood is indeed stronger, but the effective penetration area of the adhesive tends to be more limited. Conversely, in Medang and Meranti wood, the larger pore spaces provide a broader mechanical interlocking for cellulose-based adhesives containing microfibers from cardboard (Ruhendi et al., 2007).

Physicochemical Characteristics of Cellulose–Starch-Based Adhesive on Various Wood Species

The results of the physical and chemical property tests of the cellulose-starch-based adhesive applied to medang, meranti, and balam wood show characteristics that meet the functional criteria as a wood adhesive. Complete data regarding the test results are presented in Table 1.

Table 1. Testing of Properties of Cellulose–Starch-Based Adhesive

No	Test	Test Result		
		Medang	Meranti	Balam
1	Appearance	No foreign matter	No foreign matter	No foreign matter
2	Acidity	pH 3 (Acidic)	pH 5 (Acidic)	pH 4 (Acidic)
3	Evaporation Residue	8.04%	1.30%	7,83%
4	Pot Life	5 hours 23 minutes	5 hours 25 minutes	5 hours 47 minutes

Appearence

Cellulose-starch-based adhesives applied to medang, meranti, or balam wood show the same appearance, which is free of contaminants. This indicates that the process of making cellulose-starch adhesive produces a solution that is clean, homogeneous, and free from dirt or foreign particles. The uniformity of this appearance indicates that the extraction and formulation processes of the adhesive have been successful even when applied to the three samples. Surface preparation plays a crucial role in producing strong bonds and optimal appearance (Marceau & Thrall, 2017; Naat et al., 2023).

Acidity (pH) and Surface Interactions

The acidity and basicity of the adhesive are determined by its chemical composition, specifically by the presence and type of functional groups that are acidic or basic in its molecular structure. The adhesive testing results on the three types of wood show adhesive properties in the acidic range, with pH values ranging from 3 to 5. The acidity of cellulose-based (cardboard) and starch glues is related to the acid-base properties of their constituent biopolymers and the modification processes carried out. Acidity affects the cross-linking density and chemical interactions between the adhesive and the wood substrate, thereby determining the quality of adhesion at the microscopic level (Ando & Umemura, 2021; Zhang et al., 2011). Medang wood shows the highest acidity level (pH 3), followed by balam (pH 4) and meranti (pH 5). According to Ribawa et al. (2025), the acidic properties of the adhesive can trigger the activation of hydroxyl groups on the wood surface, facilitating the formation of hydrogen bonds between the adhesive and the wood cell walls, thereby enhancing the adhesive strength. However, excessive acidity in medang wood needs to be monitored to prevent fiber degradation in the adhesive line area in the long term, in line with the research by Vnučec et al. (2017), which states that excessively low pH values pose a significant risk to wood fiber degradation due to the phenomenon of acid hydrolysis in the long term. On the other hand, an acidic environment and the addition of acid are very beneficial for accelerating the curing process in certain types of adhesives that require catalytic activation in a low-pH atmosphere (Park et al., 2023). The optimization of this pH becomes a determining factor in whether the adhesive will form stable covalent bonds or damage the strength of the wood cell walls.

Evaporation Residue and Solids Content

The evaporation residue reflects the solid content remaining after the solvent evaporates. The evaporation residue test results show values of 8.04% for medang wood, 7.83% for balam wood, and 1.30% for meranti wood. These evaporation residue values are much lower compared to the findings of Medynda et al. (2012), who used liquid adhesives from outer and inner cocoa pod husk waste, with values of 42.33% and 44.66%, respectively. This significant difference indicates different solid content characteristics between cellulose-starch-based adhesives and liquid adhesives. Cellulose-starch-based adhesives work through the mechanism of forming extensive polymer networks where the liquid phase is mechanically trapped.

Cardboard fibers (cellulose) and starch have a very high-water holding capacity, the hydroxyl groups (–OH) in starch and cardboard cellulose form hydrogen bonds with water molecules, which explains why water is mechanically trapped, resulting in low evaporation but a very thick texture. Cellulose from cardboard waste has a relatively high-water holding capacity, reported to be around 12.6 g/g. This value is influenced by the more dominant amorphous structure and the presence of lignin and hemicellulose, which enhance water-binding capacity (Raclavská et al., 2025). Meanwhile, starch flour (tapioca) also shows good water-binding capacity, with a range of 182–199%, especially after gelatinization, which allows starch granules to absorb water and swell (Bishnoi et al., 2023; Izzi et al., 2023). In cellulose cardboard, the amorphous regions provide space for water molecules to enter and bind through hydrogen bonds. Whereas in starch, the gelatinization process causes the crystalline structure to break down, exposing more hydroxyl groups and allowing for more intensive interaction with water (Rakhshi et al., 2022).

Pot Life

The pot life or lifespan of the adhesive shows very good stability, ranging from 5 hours 23 minutes to 5 hours 47 minutes. This stability indicates that the polymerization of the cellulose-starch-based adhesive occurs in a controlled manner at room temperature. The pot life of wood adhesives is the period from the moment the adhesive is mixed until it is no longer effective for use, which plays a crucial role in determining the quality of adhesion to wood. The duration of pot life varies depending on the type of adhesive; for example, epoxy adhesives generally have a working time of about 30–45 minutes, while other types of adhesives may have shorter or longer durations depending on their chemical composition (Rudawska et al., 2026

CONCLUSION

starch have a homogeneous appearance, an acidic pH (3-5), and a low evaporation residue (1.30%-8.04%). The high density of hydroxyl groups within the cross-linked polymer network grants the adhesive excellent water-binding capacity, establishing a strong chemical foundation for sustainable bonding applications. Furthermore, compatibility testing across various timber species revealed that medang wood yielded the highest density (0.47 g/cm^3), followed by balam (0.46 g/cm^3) and meranti (0.39 g/cm^3).

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