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ARTICLE

Citric Acid as an Alternative Adhesive: Optimisation of Concentrations on Characteristics of Jabon Plywood

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ABSTRACT: Citric acid adhesive is an alternative to formaldehyde-based adhesives that are more environmentally friendly because they are non-toxic and made from natural ingredients. This study aims to determine the effect of variations in citric acid adhesive concentrations on the physical and mechanical properties of jabon plywood. This study used citric acid adhesive with variations in citric acid (CA) concentrations of 59%, 69%, and 79%. Physical property tests include density, moisture content (MC), water absorption (WA), thickness expansion (TS), and delamination, while mechanical tests include modulus of rupture (MOR), modulus of elasticity (MOE), and shear stress (TSS). The results showed that variations in adhesive concentration did not have a statistically significant effect on the physical and mechanical properties of jabon plywood. However, at CA, 59% had the highest density, and MC, the highest WA was recorded at CA 79%, while the highest TS was at CA 59%, but in this study, no delamination occurred. The highest MOE test result was at a CA concentration of 59%, the highest MOR value was at a CA 79%, and the highest TSS value was at a CA 69%. CA, with a concentration of 69%, is the optimal CA adhesive based on the strength of mechanical properties and water resistance.

KEYWORDS: Citric acid adhesives; jabon plywood; adhesive concentration; water resistance

1 Introduction

Plywood is a panel made of thin layers of wood called veneers glued together using adhesives. Plywood is essential as a raw material for the construction, furniture, and household appliance industries [1]. Generally, the adhesive used for plywood uses formaldehyde-based adhesives, known to have carcinogenic properties that harm humans and the environment. Research [2,3] explains the dangers of using formaldehyde as an adhesive: it can irritate the eyes, nose, and throat and cause respiratory problems. The use of formaldehyde can cause air pollution due to the release of free formaldehyde into the environment.

Finding alternative adhesives to reduce the negative impacts on the environment and health is necessary. One alternative that can be used is citric acid (CA) as an environmentally friendly adhesive. CA is an organic compound commonly found in citrus fruits, is non-toxic, and can decompose naturally [4,5]. Research [6–8] explains that CA can be used as a relatively effective natural adhesive that can be applied to wood-based materials that are more environmentally friendly than synthetic adhesives derived from fossil resources. The use of citric acid adhesive applied to particleboard is known to meet the JIS 5908 standard in several physical and mechanical properties [8]. Research [9] explains that increasing the molar ratio of CA and glucose can produce stronger resin bonds than urea-formaldehyde resin. In addition, research [10] also explained that using CA and starch as adhesives effectively improves the quality of plywood. As an adhesive, CA can reduce dependence on formaldehyde adhesives in plywood manufacturing to produce safe and environmentally friendly adhesives. In addition to these environmental benefits, CA's reactivity as a wood panel adhesive through the formation of ester bonds with lignocellulose has also been extensively studied [11], including CA modification with glucose [9], starch [12], and tannin modification [7], which are known to improve adhesive strength and water resistance. However, research on optimizing CA concentration in jabon plywood is still very limited. Therefore, this study aims to determine the effect of variations in CA adhesive concentrations on the physical and mechanical properties of jabon plywood.

Jabon trees (*Neolamarckia cadamba*) are included in fast-growing trees and are widely planted in Indonesia. Jabon trees can reach a diameter of 34 cm at the age of 5 years, although the tree is still relatively young [13]. Jabon trees in the fast-growing category can be used as plywood to increase the efficiency and economic production. Research [14] shows that plywood from white jabon using citric acid adhesive shows a low delamination rate and produces high shear strength (TSS). In addition, some of the properties of the plywood also meet the SNI 8916.2:2023 standard. The results of functional group analysis using Fourier-transform infrared spectroscopy (FTIR) on jabon plywood glued using CA produced better ester bonds than jabon plywood glued using maleic acid and molasses [15]. The use of CA adhesive in this study examined the effect of variations in optimal CA concentration on the quality of jabon plywood produced based on the results of density analysis, MC, WA, TS, delamination, MOE, MOR, and TSS. By determining the optimal concentration, the resulting plywood will have good mechanical strength and be safe and environmentally friendly. The results of this study are expected to significantly contribute to developing a sustainable plywood industry and support global efforts to reduce negative environmental impacts.

2 Materials and Methods

2.1 Material

The material used was jabon wood veneer (*Neolamarckia cadamba*) with a thickness of 2 mm obtained from the Biomass and Bioproducts Research Center of BRIN-Indonesia. The specific gravity of jabon wood is 0.40 g/cm^3. The adhesive used was citric acid (CA) obtained from PT Telagasakti Sakatautama (Jakarta, Indonesia). To prepare raw materials following [8], the veneer was dried in an oven at 60°C for 24 h until a moisture content of less than 5% was obtained.

2.2 Preparation and Characterization of Adhesive

The preparation of citric acid adhesive used three different concentration variations, namely 59%, 69%, and 79% (w/w). The adhesive characteristics analyses included solids content, acidity (pH), and viscosity.

2.2.1 Solid Content

The solid content of an adhesive measures the number of particles in the adhesive. The more adhesive particles interacting with the wood during the gluing process, the greater the bond strength. 1 g of adhesive sample was placed on aluminium foil and heated in an oven (Memmert, Germany) at 103 ± 3°C for 3 h. After the sample was dried, the aluminium foil was transferred to a desiccator and weighed.

2.2.2 Viscosity

This experiment put 20 mL of adhesive sample into a beaker and mounted it on a rotational rheometer (RheolabQC, AntonPaar, Graz, Austria). Viscosity measurements were performed with a concentric cylinder (cc) no. 27 type spindle at a rotation speed of 50/s. Tests were conducted at 25°C to determine viscosity, and dynamic viscosity was measured for 120 s.

2.2.3 Acidity (pH)

The pH value of the adhesive was measured using a pH meter. Once the pH electrode probe is dipped into the adhesive sample placed in the container, the pH value will be immediately displayed on the screen.

2.3 Plywood Manufacturing

Previous research by [8] became a reference and was slightly modified due to the felt pressure. Jabon wood was cut into 30 × 30 × 0.2 cm for each sheet. The plywood panel consists of 3 layers with adhesive applied as much as 140 g/m^2 for a 3-layer plywood measuring 30 cm × 30 cm × 0.6 cm. The pressing process of the plywood panels was carried out at 190°C and 5 MPa pressure for 10 min. This research used 27 sheets of veneer as raw material, which were then processed into nine boards. The plywood was then conditioned at a room temperature of 20 ± 3°C for 14 days.

2.4 Physical and Mechanical Properties of Plywood Testing

The density, moisture content (MC), delamination, and shear strength (TSS) were carried out referring to the SNI 8916.2:2023 standard [16]. Meanwhile, water absorption (WA), thickness swelling (TS), modulus of elasticity (MOE), and modulus of rupture (MOR) tests were carried out based on procedures referring to BS EN 13986:2004 [17]. Different standards were adopted to align each test with the most suitable and widely accepted procedure. SNI 8916.2:2023 standard was used as the primary reference for testing because it is the most applicable regional standard for tropical plywood, while BS EN 13986:2004 was applied to allow broader comparison to international data.

This test was conducted using three test samples for each type of test with random sample selection. The manufacturing and testing of jabon plywood in this study is shown in Fig. 1. In addition to the test procedures, the performance requirements were referred to the SNI 8916.2:2023 and BS EN 13986:2004 standard with minimum value density ≥ 0.4 g/cm^3, MC ≤ 14%, and TSS ≥ 0.7 MPa. These criteria were used to evaluate whether the plywood met applicable product standards.

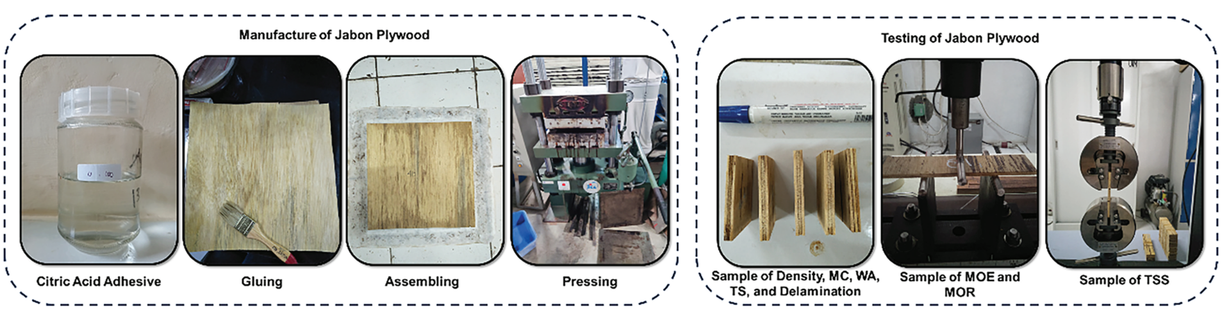

Figure 1: Manufacturing and testing of jabon plywood

2.4.1 Density

Density testing was conducted using 5 × 5 × 0.6 cm^3 samples for length, width, and thickness. Density determination is expressed in terms of the ratio between the weight and volume of the board.

2.4.2 Moisture Content (MC)

Moisture content testing was conducted on 5 × 5 × 0.6 cm^3 samples in length, width, and thickness. After that, the moisture content was calculated by reducing the initial and final weights after drying for 24 h in an oven at 103 ± 2°C.

2.4.3 Water Absorption (WA)

Water absorption was tested on specimens measuring 5 × 5 × 0.6 cm^3. The weight changes before and after immersion in water for 24 h were measured.

2.4.4 Thickness Swelling (TS)

Thickness swelling tests were conducted on samples with dimensions of 5 × 5 × 0.6 cm^3 for length, width, and thickness. Measurements were made by comparing the initial thickness before and after immersion for 24 h.

2.4.5 Delamination

The delamination test process involves immersing the material in hot water at 100°C for 4 h, followed by immersion at room temperature for 1 h. Subsequently, the test samples were oven dried at 70 ± 3°C for 18 h.

2.4.6 Modulus of Elasticity (MOE) and Modulus of Rupture (MOR)

MOE and MOR tests were conducted on samples with 20 × 5 × 0.6 cm^3 dimensions. The universal testing machine used was a Shimadzu AG-IS 50 kN from Japan. The loading speed during MOE and rupture tests was 10 mm/min.

2.4.7 Tensile Shear Strength (TSS)

TSS testing refers [16]. When the test was conducted, the sample size was 7.5 × 2.5 × 0.6 cm^3. The sample was slid using a universal testing machine (Shimadzu AG-IS 50 kN, Kyoto, Japan) with a 2 mm/minute loading speed until the maximum load was reached.

2.5 Functional Groups Analysis

Fourier Transform Infrared (FTIR) spectroscopy was conducted to identify functional groups and chemical interactions between citric acid adhesive and Jabon wood. Plywood samples bonded with citric acid at different concentrations were first oven-dried at 60°C for 24 h to remove residual moisture. The dried specimens were then ground into fine powder using a laboratory mill and sieved to pass through a 60-mesh screen. The FTIR spectra were recorded using an FTIR spectrometer (Spectrum Two, PerkinElmer, Waltham, MA, USA) in the wavenumber range of 4000–400 cm^{-1}.

2.6 Statistical Analysis

A simple randomised design with one factor from each stage was evaluated using analysis of variance (ANOVA). Then, Tukey's test was performed to statistically analyse the differences in properties at $\alpha \leq 0.05$.

3 Results and Discussion

3.1 Adhesive Characteristics

In this study, the adhesive characteristics of each sample were measured for viscosity, solid content, and pH (Table 1). Viscosity measures fluid resistance to flow, reflecting how easy or difficult the fluid flows [18]. The viscosity test results produced the highest viscosity in sample B, followed by samples C and A, with 24.18, 21.49, and 11.18 MPa·s values. The low viscosity in A can be influenced by the SC value, where an increase in SC can potentially increase the adhesive's viscosity. This is due to the increase in the number of solid particles in the mixture, increasing the flow resistance [19]. In addition, the viscosity values of the three samples are also lower than those of Urea Formaldehyde (UF) adhesives, which have viscosities of 200 MPa·s [20]. The chemical structure affects the viscosity of the adhesive solution. UF adhesives are formed from the condensation reaction between urea and formaldehyde, forming long polymer chains with amide groups (–NH) and hydroxyl groups (–OH) that can form strong hydrogen bonds. These hydrogen bonds make the polymer structure more rigid and organised, increasing the crystallinity and viscosity of the adhesive solution [21]. In contrast, citric acid-based adhesives have weaker hydrogen bonds as they rely on forming ester bonds, resulting in lower viscosity as the molecules can move more freely [22].

Table 1: Characteristics of citric acid adhesives of varying concentrations

No.	Sample	Viscosity (MPa·s)	SC (%)	pH
1	CA 59 (A)	11.18	58.82	0.22
2	CA 69 (B)	24.18	62.94	0.23
3	CA 79 (C)	21.49	62.38	0.16

The solid content (SC) test showed that sample B had the highest SC, followed by samples C and A with percentages of 62.94%, 62.38%, and 58.52%, respectively. In general, there is a correlation between SC and viscosity. Sample B has the highest SC and viscosity values, which is consistent with previous studies. High SC will produce high viscosity and affect the stability and performance of the adhesive [23]. The higher the SC, the greater the reaction of adhesive molecules with wood during the glueing process and the strength of intermolecular attraction, thereby increasing the adhesive strength of the final product [24]. In this test, the pH value can influence the SC value. Sample C has the lowest pH of 0.16. According to research [25–27], using the right pH in adhesives can increase the formation of cross-links between polymer chains, viscosity, SC, and the quality of the resulting bond. The SC value in this study was slightly lower than the SC in urea-formaldehyde adhesives, ranging from 63.52–64.99% [28].

In this study, the pH value of the CA adhesive is very acidic at <1. Based on the statistical analysis results (α 0.05), there is no significant difference in CA concentration. However, sample C has the lowest pH value (0.16). Citric acid ($C_6H_8O_7$) is a tricarboxylic acid with three carboxylic groups (–COOH). According to [29,30], the CA solution will ionise gradually and release H^+ protons at each ionisation. CA with high concentration will increase H^+ ions, which cause the solution to become very acidic. A very acidic pH can cause wood components such as hemicellulose and lignin to degrade. The study [31,32] explained that pH in acidic conditions can increase the degradation rate of wood components around the adhesive bond line, thereby causing a decrease in bond strength. This is related to the mechanism of the chemical reaction between citric acid and wood. Research [11] explains that the carboxyl group in citric acid reacts with the hydroxyl group in the carbohydrates and lignin of wood, forming an ester bond during the hot pressing process. Several studies have developed self-neutralizing systems to address the problem of low pH. The study [12,33] explains that the use of citric acid-corn starch and tannin-citric acid adhesives has proven effective in maintaining bond strength without compromising adhesive stability. This shows that pH control is very important in adhesive formulation to ensure the structural integrity and durability. This study shows that using the right pH can increase the viscosity and SC of the adhesive. Research [31] shows that higher conditions can increase SC and viscosity of the adhesive, as well as the mechanical strength and stability of the adhesive due to increased cross-linking.

Although no clear linear trend was observed between citric acid concentration and viscosity (Table 1), this behaviour is typical for acid-based bioadhesives. The viscosity of citric acid solutions is influenced not only by concentration but also by the degree of ionization and intermolecular hydrogen bonding among acid molecules. At higher concentrations, excessive free hydrogen ions can interfere with intermolecular interactions, leading to partial molecular dissociation and consequently a reduction in viscosity. Furthermore, preparation factors such as temperature uniformity and mixing homogeneity may also contribute to these variations. The primary objective of varying citric acid concentration in this study was not to establish a linear correlation but to determine the optimum concentration that provides the most balanced combination of adhesive characteristics, mechanical performance, and water resistance of jabon plywood. Based on the overall evaluation, a concentration of 69% CA exhibited the most stable viscosity profile and optimal performance, fulfilling the requirements for exterior-grade plywood.

3.2 Physical and Mechanical Properties of Plywood

The research data in Table 2 shows the test results of several parameters with various treatments, including density, moisture content, water absorption, thickness expansion, and delamination. The research data in Table 2 shows the density test results of three adhesive samples with varying concentrations of citric acid: CA 59 (A), CA 69 (B), and CA 79 (C). Samples A and B showed similar density of 0.43 g/cm^3, although with different standard deviations, indicating that the small variation in citric acid concentration between these samples did not significantly affect density. Sample C showed a lower density of 0.38 g/cm^3. Sample C was significantly different from A and B in producing material density, which was shown through statistical analysis using Tukey Honestly Significant Difference (HSD) and Duncan's method.

Table 2: The physical properties of plywood

Parameter	Density (g/cm^3)	MC (%)	WA (%)	TS (%)	Delamination (%)
CA 59 (A)	0.43 (0.03)^b	9.70 (1.33)^b	60.93 (1.05)^a	4.35 (0.48)^a	0.00 (0.00)
CA 69 (B)	0.43 (0.02)^b	7.15 (0.09)^a	64.82 (1.39)^{ab}	3.25 (0.52)^a	0.00 (0.00)
CA 79 (C)	0.38 (0.02)^a	7.07 (0.13)^a	68.90 (3.82)^b	3.87 (0.66)^a	0.00 (0.00)
ANOVA	**	**	**	ns	–

Note: Values in parentheses are standard deviations. The superscript alphabet above describes the interaction between each factor using Tukey's multiple distance test; ns describes not significant, while ** describes significant at $p \leq 0.05$.

This lower density can be attributed to the lower pH of 0.16, compared to pH 0.22 and 0.23 in the other samples. A highly acidic pH increases the chemical reactivity of citric acid, which can lead to increased cross-linking between molecules in the adhesive. However, this increase may not always be beneficial. If there is too much cross-linking, the structure may become more porous, lowering the total density of the material. At lower pH, the ionisation of citric acid increases, which can disrupt the molecular arrangement of the polymer and lead to pore formation. These pores make the polymer network less dense, reducing its density. Research [34] showed that increasing citric acid concentration and low pH can reduce particleboard density. This is due to the formation of a porous network and ineffective cross-linking, which weakens the structure. Research by [35] explains that although citric acid can increase cross-linking, excessive concentrations can increase porosity in the polymer network, reducing density.

The results of the water content (MC) test listed in Table 2 show that sample A has the highest value of 9.70%, followed by sample B with 7.15% and sample C reaching 7.07%. Sample A produces a significantly different MC from samples B and C, as shown by the Tukey HSD and Duncan analysis results. All three samples have a water content below 14%, meaning all meet the SNI 8916.2:2023 standard [16]. From the analysis, it can be seen that viscosity and solid content play a significant role in determining water content. Low viscosity and solid content can increase water content, which has the potential to reduce bond strength. Adhesives with low solid content tend to contain more water or solvents than the solid material needed to form a bond. In contrast, adhesives with low viscosity will spread and penetrate the wood's pores more easily. This may increase the amount of water carried by the adhesive absorbed by the wood [32,36].

The water absorption (WA) test results showed that sample C had the highest value of 68.90%, followed by sample B with 64.82%, and sample A, which reached 60.93%. The concentration of CA did not significantly affect WA, because there was no statistically significant difference using the Tukey HSD and Duncan methods. This finding indicates that sample C has the best ability to absorb water compared to the other samples. The high WA in sample C can be caused by a suboptimal reaction due to the high citric acid concentration. Research by [8] explains that the esterification reaction between citric acid and hydroxyl groups in wood can be less efficient when the citric acid concentration is too high. This can cause suboptimal bond formation, so some plywood parts remain susceptible to water, causing increased water absorption. In addition, the viscosity of the adhesive used also influences WA. Research [32,37] shows that adhesive viscosity can affect the ability of the adhesive to spread and adhere to the plywood surface. Adhesives with low viscosity tend to have better WA because they are easier to spread and adhere to wood. Conversely, adhesives with high viscosity take longer to spread, resulting in lower WA values. Compared to other samples, the high WA value in sample C is closely related to density. According to [38], plywood with a lower density can cause an increase in WA value, due to a more porous and rougher surface. This allows the adhesive liquid to spread better and strengthen the bond between the wood layers.

The test results on the TS value showed that sample A had the highest percentage of 4.35%, followed by sample C with 3.87% and sample B, which reached 3.25%. The CA concentration did not significantly affect TS, because there was no statistically significant difference using the Tukey HSD and Duncan methods. Based on previous analysis of the adhesive's viscosity and solid content (SC), sample B showed better viscosity, contributing to a more even distribution of the adhesive and more effective penetration into the wood pores. In addition, increasing SC in the adhesive can strengthen the bond and reduce thickness swelling. The viscosity of the adhesive plays an important role in influencing thickness swelling, where adhesives with high viscosity tend to be more effective in adhering to the wood surface and filling the cavities of the wood [18]. According to research by [19,39], the solid content of the adhesive affects the bond strength between wood particles and the adhesive. Adhesives with higher solid content will produce stronger bonds, thus reducing water absorption and lowering the TS value. Water content also affects the TS value; in sample C, which has the lowest TS value, the water content is lower than in sample A. The lower water content indicates that the material absorbs less water from the environment, reducing the potential for thickness swelling due to water absorption. The water content of plywood also affects thickness swelling, where plywood with low water content tends to experience less thickness swelling because it reduces the space between wood particles [18]. In addition, the TS value is also affected by density. Although sample B's density is equivalent to sample A's, the TS value in sample B is lower, which may be due to better adhesive distribution or higher homogeneity, so that the bond between the wood layers becomes stronger and more stable against water absorption. The density of plywood affects thickness swelling [18].

In this study, no delamination was found in the three samples analysed. Although low pH can usually affect the stability and strength of adhesives, research by [40] showed that citric acid-based adhesives can form significant ester bonds with wood fibres. This ester bond is formed through a reaction between citric acid's carboxyl group (–COOH) and the hydroxyl group (–OH) found in wood components, such as cellulose and hemicellulose. This process is strengthened by heating during the hot-pressing stage, which produces a strong and stable bond in the plywood structure. The ester bonds formed contribute to increasing the adhesion strength of plywood and reducing the possibility of delamination, even when using adhesives with low pH. Research by [41] also revealed that stable covalent bonds can be formed even under low pH conditions. Using citric acid adhesives at high concentrations can create cross-bridges between adhesive molecules and wood fibres, increasing bond strength and reducing the risk of delamination, even at low pH. The functional groups in citric acid act as stabilising agents that maintain the structure and integrity of the adhesive, thereby preventing the decrease in bond strength usually caused by acid hydrolysis [6]. The absence of delamination at all three CA concentrations indicates that the CA adhesive can form stable bonds even under conditions that would normally cause adhesive failure. This indicates that the adhesive performance remained consistent across all samples, providing strong evidence of its stability.

Table 3 presents data on the mechanical properties of plywood treated with citric acid adhesive, which are distributed in various sample codes A, B, and C. The mechanical properties analysed include Modulus of Elasticity (MOE), Modulus of Rupture (MOR), and TSS. MOE measures the material's stiffness and ability to withstand elastic deformation when subjected to a load. The analysis results show that variations in CA concentration do not significantly affect the MOE, MOR, and TSS values, as evidenced by statistical analysis using the ANOVA method. The analysis results showed that varying citric acid concentrations had no significant effect on MOE, MOR, and TSS values, as confirmed by statistical analysis using the ANOVA method. The ANOVA results in the study by [42] also had similar findings. Although increasing the CA concentration up to 50% increased wet shear strength, statistical analysis did not show a significant difference. This suggests that the effect of concentration on mechanical properties is not always linear and may be influenced by other variables, such as adhesive distribution or wood material properties. The MOE values obtained ranged from 5.12 to 6.54 GPa, while the MOR ranged from 26.06 to 50.16 MPa. Although no significant direct correlation was found between CA concentration and the mechanical properties of plywood, the TSS, MOE, and MOR test results indicated that the 69% concentration produced the best combination of mechanical strength and water resistance. The TSS value at 69% CA reached 0.87 MPa, which exceeded the minimum requirement of SNI 8916.2:2023 [16] for exterior plywood (≥0.7 MPa), thus it can be considered the optimum concentration. Furthermore, all MOE values at each CA concentration met the standards for exterior plywood use (grade 2 or 3), while the MOR values were only met at 69% and 79% CA [17]. Although the TSS did not reach the 1.0 MPa standard, the results at 69% CA still demonstrated adequate performance for plywood applications, while ensuring a balance of water resistance and mechanical strength. When compared with previous research on Mempisang plywood, there are differences in MOE, MOR, and TSS values. The MOE value in this study was lower than the MOE value (10.85 GPa) of Mempisang plywood using CA adhesive. However, the MOR value obtained in this study was higher than that of Mempisang plywood (44.37 MPa) [8]. In this study, the TSS value ranged from 0.70 to 0.87 MPa, which is lower than previous studies [8], which recorded the TSS value of Mempisang plywood at 1.06 MPa. Generally, high MOE and MOR values correlate with material density [43].

Table 3: The mechanical properties of plywood

Parameter	MOE (GPa)	MOR (MPa)	TSS (MPa)
CA 59 (A)	6.54 (0.30)^{b}	26.06 (10.18)^{a}	0.70 (0.14)^{a}
CA 69 (B)	5.93 (0.36)^{b}	49.75 (16.46)^{a}	0.87 (0.05)^{a}
CA 79 (C)	5.12 (0.23)^{a}	50.16 (1.36)^{a}	0.77 (0.04)^{a}
ANOVA	**	ns	ns

Note: Values in parentheses are standard deviations. The superscript alphabet above describes the interaction between each factor using Tukey's multiple distance test; ns describes not significant, while ** describes significant at $p \leq 0.05$.

3.3 Functional Group Analysis

Fourier Transform Infrared (FTIR) spectroscopy was conducted to identify functional groups and chemical interactions between citric acid adhesive and Jabon wood. For comparison, the FTIR spectrum of untreated jabon wood was also recorded. The spectrum of pure wood showed characteristic –OH stretching (3340 cm^{-1}) and C–O stretching of cellulose and lignin (1050–1150 cm^{-1}). In contrast, the spectra of citric-acid-bonded plywood displayed a new strong absorption peak at 1725 cm^{-1}, corresponding to C=O stretching of ester linkages, indicating a chemical reaction between citric acid's carboxyl groups and the hydroxyl groups of lignocellulose. The FTIR graph presented shows the absorption spectrum of three samples of jabon plywood bonded with different percentages, namely 79%, 69%, and 59% (Fig. 2). The FTIR wavenumber range between 500–1500 cm^{-1} is often called the "fingerprint region." This area has particular and unique characteristics for each molecule, so it is often used to identify and differentiate different molecules. At a wavenumber of 1725 cm^{-1}, this peak is generally associated with the carboxylate (C=O) stretching vibration of the carbonyl group found in esters, aldehydes, and ketones [44,45].

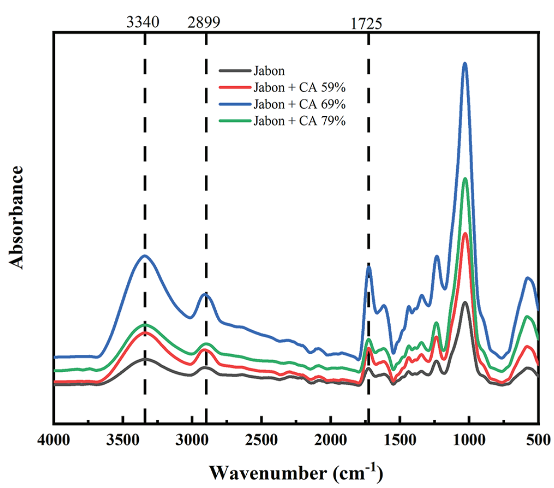

Figure 2: FTIR of jabon plywood bonded with citric acid adhesives at varying concentrations

Meanwhile, at a wavelength of 3344 cm^{-1} it is usually associated with the hydroxyl functional group (–OH) or hydrogen bound to oxygen in the molecule. Strong absorption in the 3200–3600 cm^{-1} range is generally used to identify hydroxyl groups, which can appear in various forms such as water, alcohol, and phenol [45]. The presence of an ester group in the IR spectrum indicates that the carboxyl group of citric acid reacts with the hydroxyl group of the lignocellulose chemical compound derived from jabon wood, forming an ester bond. This finding is in line with previous studies showing the presence of an ester bond between citric acid and lignocellulose chemical compounds due to the reaction between the carboxyl group of citric acid and the hydroxyl group of corn stalks [46].

4 Conclusion

The results showed that different CA concentration variations (59%, 69%, and 79%) did not significantly impact most of the physical and mechanical properties of plywood. The modulus of rupture (MOR), modulus of elasticity (MOE), and shear strength (TSS) all increased at 79% CA concentration, but these differences were not statistically significant. The 69% CA concentration met the standards for exterior plywood and provided the best combination of mechanical strength and water resistance. Overall, citric acid, at 69% concentration, is a good environmentally friendly adhesive for making plywood.

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Author Contributions: Muhammad Ilham Aulia: data curation, methodology. Alifah Syahfitri: data curation, methodology. Imam Busyra Abdillah: data curation, methodology. Abdus Syukur: data curation, methodology. Dede Hermawan: supervision, writing—original draft, writing—review and editing. Rita Kartika Sari: writing—review and editing. Mahdi Mubarok: writing—review and editing. Muhammad Adly Rahandi Lubis: writing—review and editing. Sukma Surya Kusumah: writing—review and editing. Sarah Augustina: writing—review and editing. Jajang Sutiawan: supervision, writing—original draft, writing—review and editing. All authors reviewed the results and approved the final version of the manuscript.

Availability of Data and Materials: The data that support the findings of this study are available from the corresponding authors, Dede Hermawan and Jajang Sutiawan, upon reasonable request.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest to report regarding the present study.

References

1. De Araujo V, Alves L, Jardim P, Švajlenka J, Christoforo A. Massive plywood panels and manufacturers: a comprehensive systematic literature review and case study. Discov Civ Eng. 2025;2(1):54. doi:10.1007/s44290-025-00213-z.
2. Kang DS, Lee N, Shin DY, Jang YJ, Lee SH, Lim KM, et al. Network-based integrated analysis for toxic effects of high-concentration formaldehyde inhalation exposure through the toxicogenomic approach. Sci Rep. 2022;12(1):5645. doi:10.1038/s41598-022-09673-0.
3. Tesfaye S, Hamba N, Gerbi A, Negeri Z. Occupational formaldehyde exposure linked to increased systemic health impairments and counteracting beneficial effects of selected antioxidants. Alex J Med. 2021;57(1):157–67. doi:10.1080/20905068.2021.1926172.

4. Zafar M, Arshad F, Faizi S, Anwar Z, Imran M, Mehmood RT. HPLC based characterization of citric acid produced from indigenous fungal strain through single and co-culture fermentation. Biocatal Agric Biotechnol. 2020;29(1):101796. doi:10.1016/j.bcab.2020.101796.
5. Salihu R, Abd Razak SI, Ahmad Zawawi N, Rafiq Abdul Kadir M, Izzah Ismail N, Jusoh N, et al. Citric acid: a green cross-linker of biomaterials for biomedical applications. Eur Polym J. 2021;146(Pt 2):110271. doi:10.1016/j.eurpolymj.2021.110271.
6. Ando D, Umemura K. Bond structures between wood components and citric acid in wood-based molding. Polymers. 2020;13(1):58. doi:10.3390/polym13010058.
7. Li J, Lei H, Xi X, Li C, Hou D, Song J, et al. A sustainable tannin-citric acid wood adhesive with favorable bonding properties and water resistance. Ind Crops Prod. 2023;201(1):116933. doi:10.1016/j.indcrop.2023.116933.
8. Sutiawan J, Syahfitri A, Purnomo D, Sudarmanto, Narto, Akbar F, et al. Characterization and application of non-formaldehyde binder based citric acid, maleic acid, and molasses adhesive for plywood composite. Polymers. 2023;15(19):3897. doi:10.3390/polym15193897.
9. Li C, Lei H, Wu Z, Xi X, Du G, Pizzi A. Fully bio based adhesive from glucose and citric acid for plywood with high performance. ACS Appl Mater Interfaces. 2022;14(20):23859–67. doi:10.1021/acsami.2c02859.
10. Kusumah SS, Jayadi, Wibowo DT, Pramasari DA, Widyaningrum BA, Darmawan T, et al. Investigation of eco-friendly plywood bonded with citric acid-starch based adhesive. IOP Conf Ser Earth Environ Sci. 2020;460(1):012009. doi:10.1088/1755-1315/460/1/012009.
11. Del Menezzi C, Amirou S, Pizzi A, Xi X, Delmotte L. Reactions with wood carbohydrates and lignin of citric acid as a bond promoter of wood veneer panels. Polymers. 2018;10(8):833. doi:10.3390/polym10080833.
12. Xu D, Li C, Pizzi A, Xi X, Wang Z, Du G, et al. Self-neutralizing citric acid-corn starch wood adhesives. ACS Sustainable Chem Eng. 2024;12(35):13382–91. doi:10.1021/acssuschemeng.4c05590.
13. Arisandi R, Ihda FV, Nirsatmanto A, Sunarti S, Lukmandaru G. Characterization of chemical components in the wood and bark of *Anthocephalus cadamba* and *Anthocephalus macrophyllus* from progeny trial in wonogiri, Indonesia. BIO Web Conf. 2025;167(5):06001. doi:10.1051/bioconf/202516706001.
14. Sutiawan J, Hermawan D, Massijaya MY, Kusumah SS, Lubis MAR, Marlina R, et al. Influence of different hot-pressing conditions on the performance of eco-friendly jabon plywood bonded with citric acid adhesive. Wood Mater Sci Eng. 2022;17(6):400–9. doi:10.1080/17480272.2021.1884898.
15. Sutiawan J, Mardhatillah S, Hermawan D, Syamani FA, Subyakto S, Kusumah SS. Pengaruh jenis perekat terhadap sifat papan partikel Dari campuran limbah vinir sengon Dan bagas Sorgum. J Ilmu Dan Teknologi Kayu Trop. 2021;18(1):1–10. doi:10.51850/jitkt.v18i1.539.
16. SNI 8916.2:2023. Light wood—part2: plywood. Jakarta, Indonesia: National Standardization Agency of Indonesia; 2023.
17. BS EN 13986-2004. Wood-based panels for use in construction-characteristics, evaluation of conformity and marking. London, UK: British Standards Institution; 2015.
18. Arninda A, Junianti F, Perdana MA. Pemanfaatan tepung kulit singkong pada pembuatan glue di industri plywood. J Agro Ind Eng Res. 2022;1(2):35–9. doi:10.61844/jaier.v1i2.359.
19. Supriadi A, Santoso A, Pari R. Keteguhan rekat kayu lapis sengon menggunakan perekat lignin-formaldehida dengan dua macam bahan pengisi (bonding strength of sengon plywood using lignin-formaldehyde adhesive with two types of fillers). J Ilmu Dan Teknol Kayu Trop. 2021;17(2):134–43. doi:10.51850/jitkt.v17i2.466.
20. Dermawan D, Al Ghani L, Prawidya AB. Melamine acetate preparation as a urea-formaldehyde resin additive for particleboard production. ASEAN J Chem Eng. 2023;23(2):178. doi:10.22146/ajche.79192.
21. Wibowo ES, Lubis MAR, Park BD, Kim JS, Causin V. Converting crystalline thermosetting urea-formaldehyde resins to amorphous polymer using modified nanoclay. J Ind Eng Chem. 2020;87(3):78–89. doi:10.1016/j.jiec.2020.03.014.
22. Mohamad Amini MH, Hashim R, Sulaiman NS, Mohamed M, Sulaiman O. Citric acid-modified starch as an environmentally friendly binder for wood composite making. BioResources. 2020;15(2):4234–48. doi:10.15376/biores.15.2.4234-4248.

23. Qu Y, Guo Q, Li T, Zhang Y, Gao Q, Liu H, et al. A novel environmentally friendly hot-pressed peanut meal protein adhesive. J Clean Prod. 2021;327(1):129473. doi:10.1016/j.jclepro.2021.129473.
24. Santoso A, Basri E, Balfas J. Kualitas kayu laminasi dengan perekat tanin Dari ekstrak kulit kayu mahoni. J Penelit Has Hutan. 2020;38(3):151–60. doi:10.20886/jphh.2020.38.3.151-160.
25. Radabutra S, Khemthong P, Saengsuwan S, Sangya S. Preparation and characterization of natural rubber bio-based wood adhesive: effect of total solid content, viscosity, and storage time. Polym Bull. 2020;77(5):2737–47. doi:10.1007/s00289-019-02881-1.
26. Del Valle Raydan N, Richter K, Charrier B, Hartwig A, Robles E. Cold-set, crosslinker-free wood adhesives: a comparative study of ultrasound-extracted duck feather keratin and traditional food proteins. Mater Today Sustain. 2024;27(15):100905. doi:10.1016/j.mtsust.2024.100905.
27. Tene Tayo L, Dönni F, Euring M. Preparation of a canola-based polyethyleneimine-crosslinked bioadhesive for particleboards production. BioResources. 2025;20(3):5262–78. doi:10.15376/biores.20.3.5262-5278.
28. Danielli D, Pires MR, da Silva Araujo E, Lorenço MS, Mori FA. Application of Myrcia splendens tannins in the composition of urea-formaldehyde adhesive for sustainable wood bonding. Res Soc Dev. 2021;10(12):e370101220543. doi:10.33448/rsd-v10i12.20543.
29. Burel C, Kala A, Purevdorj-Gage L. Impact of pH on citric acid antimicrobial activity against Gram-negative bacteria. Lett Appl Microbiol. 2021;72(3):332–40. doi:10.1111/lam.13420.
30. Wang Z, Deng Y, Zhang Y, Wei Z, Wan Z, Li C, et al. Impacts of citric acid concentration and pH value on mechanism and rheological properties of cold-set whey protein fibrils hydrogels. LWT. 2023;183(5):114872. doi:10.1016/j.lwt.2023.114872.
31. Xi X, Pizzi A, Lei H, Zhou X, Du G. Self-neutralizing melamine-urea-formaldehyde-citric acid resins for wood panel adhesives. Polymers. 2024;16(13):1819. doi:10.3390/polym16131819.
32. Silva E, Gonçalves F, Segundinho P, Paes J, Chaves I, Lopez Y, et al. Effect of adhesive on shear strength in young wood glued of *Anadenanthera peregrina*. Sci Rep. 2025;15(1):15833. doi:10.1038/s41598-025-98775-6.
33. Zhou Y, Xu D, Li C, Pizzi A, Du G, Lei H. Self-neutralizing tannin-citric acid wood adhesives. Int J Biol Macromol. 2025;310(Pt 2):143419. doi:10.1016/j.ijbiomac.2025.143419.
34. Saad S, Augustina S, Sutiawan J, Surya Kusumah S, Adly Rahandi Lubis M, Syahfitri A, et al. Feasibility of bio-based molasses and citric acid for the manufacturing of oil palm frond particleboard. BioResources. 2025;20(2):2656–69. doi:10.15376/biores.20.2.2656-2669.
35. Lee C, Kang SW. Influence of citric acid concentrations on the porosity and performance of cellulose acetate-based porous membranes: a comprehensive study. Int J Biol Macromol. 2024;263(Pt 1):130243. doi:10.1016/j.ijbiomac.2024.130243.
36. Tran A, Konnerth J, Gindl-Altmutter W. Adhesive strength and micromechanics of wood bonded at different moisture contents. Int J Adhes Adhes. 2024;132:103688. doi:10.1016/j.ijadhadh.2024.103688.
37. Sapenti AD, Sari RK, Hermawan D, Antov P, Dudeva V, Lubis MAR. Formaldehyde-free plywood composites bonded with polyurethane adhesive derived from lignin-polyvinyl alcohol-based polyol. Discov Sustain. 2025;6(1):112. doi:10.1007/s43621-025-00880-z.
38. Salca EA, Bekhta P, Seblii Y. The effect of veneer densification temperature and wood species on the plywood properties made from alternate layers of densified and non-densified veneers. Forests. 2020;11(6):700. doi:10.3390/f11060700.
39. Nuryawan A, Ritonga LA, Basyuni M, Risnasari I. Properties of tannin formaldehyde adhesive made of part of branches. J Penelit Has Hutan. 2023;41(3):149–56.
40. Augustina S, Marbun SD, Sudarmanto, Narto, Trisatya DR, Santoso EB, et al. Dimensional stability and mechanical properties of citric acidimpregnated samama wood (*Anthocephalus macrophyllus* (Roxb.) Havil.) at high curing temperatures. J Korean Wood Sci Technol. 2023;51(6):431–46. doi:10.5658/wood.2023.51.6.431.
41. Kawalerczyk J, Kuliński M, Majlingová A, Dukarska D, Mirski R. The effect of wood particles polyesterification with sorbitol and citric acid on the properties of particleboard produced with the use of PF/pMDI adhesive. Eur J Wood Prod. 2024;82(5):1725–37. doi:10.1007/s00107-024-02124-9.

42. Sun S, Zhao Z, Umemura K. Further exploration of sucrose-citric acid adhesive: synthesis and application on plywood. Polymers. 2019;11(11):1875. doi:10.3390/polym11111875.
43. Bekhta P, Pizzi A, Kusniak I, Bekhta N, Chernetskyi O, Nuryawan A. A comparative study of several properties of plywood bonded with virgin and recycled LDPE films. Materials. 2022;15(14):4942. doi:10.3390/ma15144942.
44. Alauhdin M, Tirza Eden W, Alighiri D. Aplikasi spektroskopi inframerah untuk analisis tanaman dan obat herbal. Inov Sains Dan Kesehat. 2021:84–118.
45. Nandiyanto ABD, Ragadhita R, Fiandini M. Interpretation of Fourier transform infrared spectra (FTIR): a practical approach in the polymer/plastic thermal decomposition. J Sci Technol. 2022;8(1):113–26. doi:10.17509/ijost.v8i1.53297.
46. Song S, Su D, Xu X, Yang X, Wei L, Li K, et al. Using citric acid to suppress lignin repolymerization in the organosolv pretreatment of corn stalk. Ind Crops Prod. 2023;200(1):116881. doi:10.1016/j.indcrop.2023.116881.