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Research Article

Valorization of Corn Husk Agricultural Waste into Particleboard Using Citric Acid Adhesive: Effects of Density, Thickness, and Binder Volume

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Abstract
The valorization of agricultural residues presents an eco-friendly solution to mitigate biomass waste and reduce deforestation. This study investigates the physical, mechanical, thermal, and acoustic properties of particleboard manufactured from corn husk using citric acid as a natural binder. The effects of three key variables board density (0.6 and 0.8 g/cm³), thickness (0.6 and 1 cm), and citric acid content (20%, 25%, and 30%) were systematically analyzed. The novelty of this study lies in the integrated evaluation of board density, thickness, and citric acid content across 12 corn-husk particleboard formulations and their simultaneous effects on physical, mechanical, thermal, and acoustic performance under the same manufacturing conditions. Particleboards were fabricated via hot pressing at 180°C and 15 MPa for 12 minutes. Comprehensive characterization was performed based on JIS A 5908:2003 and ISO 11654:1997, including actual density, thickness swelling, modulus of rupture (MOR), modulus of elasticity (MOE), thermal conductivity, and sound absorption coefficient. Results indicate that higher density and binder content improve mechanical strength and reduce water uptake but may compromise porosity and acoustic absorption. The results revealed trade-offs among the evaluated properties: higher-density boards generally exhibited better mechanical performance, whereas lower-density boards provided lower thermal conductivity and better sound absorption under specific thickness conditions. Therefore, no single formulation was identified as optimal for all evaluated responses. The results demonstrate the potential of corn husk and citric acid for developing bio-based panels; however, further improvement in dimensional stability is required before their use in furniture or building applications.

Keywords: Binder volume, Corn husk, Density, Particleboard, Thickness

1 Introduction

Large volumes of agricultural biomass remain underutilised despite their potential as renewable resources. Corn by-products, such as husk, stalk, and cob, are commonly used as raw material for higher-value-added products [1], [2]. Corn husk, a major lignocellulosic residue from corn *(Zea mays* L.) production, is commonly discarded or incinerated post-harvest, contributing to environmental degradation [3], [4]. In the world, where hybrid corn farming dominates, the abundance of husk waste offers a promising raw material for bio-composite manufacturing [5]. Corn husk consists primarily of cellulose (45%), hemicellulose (21–33%), and lignin (13%), making it suitable for composite panels such as particleboards [6]–[8]. The conversion of such residues into engineered wood products can reduce deforestation pressure and promote circular bioeconomy strategies.

Renewable biofibers and biocomposites have attracted increasing interest as sustainable alternatives to conventional materials because they can reduce

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dependence on non-renewable resources, minimize waste generation, and support the development of environmentally responsible engineering products [9]–[11]. Furthermore, recent studies on natural-fiber composites have demonstrated that fiber–matrix interfacial bonding, material composition, surface modification, and structural configuration strongly influence their mechanical performance and potential engineering applications [12], [13].

Several studies have successfully utilized other natural fibers from agricultural residues such as sorghum stalks, rice husk, and sugarcane bagasse for panel fabrication [14]–[16], though limited attention has been paid specifically to corn husk in combination with natural adhesives. Conventional particleboards are typically bonded using synthetic resins, notably urea-formaldehyde (UF) and phenol-formaldehyde (PF), which emit formaldehyde and are increasingly restricted under international regulations [17]. Citric acid has been investigated as a bio-based adhesive because its carboxyl groups may react with hydroxyl groups in lignocellulosic materials and form ester linkages during thermal curing, as reported in previous studies. However, [18], [19] confirmation of this mechanism requires spectroscopic analysis, such as FTIR.

Its application has been demonstrated in producing binderless boards with sufficient mechanical strength and water resistance [9], [20]. Prior works have optimized pressing temperature (180–200°C), time (10–15 min), and citric acid concentration (10–30%) for bonding various biomass types [21], [22]. However, the combined influence of board density, thickness, and binder volume on both structural and functional performance remains underexplored. These parameters directly affect internal bonding, dimensional stability, pore structure, and the resulting board's suitability for insulation or acoustic applications [12], [13]. This study investigates the effect of board density (0.6 and 0.8 g/cm³), thickness (0.6 and 1.0 cm), and citric acid content (20-30%) on the physical, mechanical, thermal, and acoustic performance of particleboards made from corn husk. The boards were fabricated using a hot-pressing process and characterized according to JIS A 5908:2003 [5], [23]. This study provides preliminary information on the physical, mechanical, thermal, and acoustic properties of laboratory-scale corn-husk particleboards bonded with citric acid.

2 Materials and Methods

2.1 *Materials*

Corn husk was used as the primary lignocellulosic raw material in this study. The husks were obtained as post-harvest agricultural waste from maize (*Zea mays* L.) cultivation in Bogor Regency, West Java, Indonesia. Prior to particleboard fabrication, the corn husks were systematically processed to obtain particles with uniform size and suitable morphology (Figure 1).

Initially, the husks were manually separated from the corn stalks to remove non-fibrous components and isolate the fibrous fraction (Figure 1a). The separated husks were subsequently cut into smaller fragments using a table saw to facilitate further mechanical processing (Figure 1b). These fragments were then milled using a ring flaker to produce finer lignocellulosic particles (Figure 1c). Finally, the milled particles were screened using a horizontal vibrating sieve equipped with a 14-mesh screen, corresponding to an opening of approximately 1.40 mm. Only particles passing through this sieve were used. No lower-size sieve was applied; therefore, the resulting material contained particles smaller than 1.40 mm, including a proportion of fine particles. The complete particle-size distribution, particle aspect ratio, and fines content were not quantitatively determined in this study, which is acknowledged as a limitation (Figure 1d). Only particles passing through the 14-mesh sieve were used in this study. Citric acid ($C_6H_8O_7$) was employed as a bio-based adhesive. The citric acid solution was prepared by dissolving citric acid powder in distilled water at a weight ratio



Figure 1: Systematic preparation of corn husk particles: (a) manual separation from corn stalks, (b) size reduction using a table saw, (c) milling with a ring flaker, and (d) sieving through a 14-mesh vibrating screen.

of 59:41 (citric acid: water), following formulations commonly adopted for citric acid-bonded particleboards. The citric acid contents of 20%, 25%, and 30% were defined on a dry-mass basis relative to the oven-dry mass of corn-husk particles, rather than to the total mass of the adhesive solution. Thus, citric acid contents of 20%, 25%, and 30% corresponded to 20, 25, and 30 g of dry citric acid, respectively, per 100 g of oven-dry corn-husk particles. The amount of water required for each formulation was calculated from the dry citric acid-to-water mass ratio of 59:41. The target board density was calculated using the combined oven-dry mass of corn husk and dry citric acid divided by the nominal board volume. Water was excluded from the target-density calculation because it was removed during oven drying and hot pressing [23]. All materials and chemicals used in this study were of analytical grade and used without further purification.

2.2 *Board fabrication*

Particleboard fabrication was carried out following a controlled hot-pressing procedure, as illustrated in Figure 2. Corn husk particles prepared in Section 2.1 were first blended with a citric acid–based adhesive to achieve homogeneous distribution. The adhesive solution was applied using a spray gun connected to an air compressor while the particles were continuously mixed in a rotary drum mixer, ensuring uniform coating of the particle surfaces (Figure 2).

After adhesive application, the treated particles were oven-dried at 80 °C for 24 h to reduce moisture content and minimize vapor formation during hot pressing, which could otherwise lead to internal defects in the boards (Figure 2b). The dried furnish was then manually formed into a mat and placed into a steel mold with target board dimensions of 300 mm × 300 mm. Board thicknesses of 0.6 cm and 1.0 cm were applied according to the experimental design, and the mat was evenly distributed to ensure uniform density across the panel (Figure 2c). Hot pressing was performed using a hydraulic press with the platen temperature set at 180 °C. A single-stage pressure of 15 MPa was applied and maintained throughout the 12 min pressing cycle. The pressing time was counted after the target pressure had been reached. Both the 6 and 10 mm boards were pressed for the same duration to maintain consistent nominal processing conditions among the formulations. Accordingly, the press factors were 2.0 min/mm for the 6 mm boards and 1.2 min/mm for the 10 mm boards. The press-closing rate, platen-temperature accuracy, and internal board core temperature were not independently recorded. Therefore, possible differences in heat transfer and citric acid curing between the two board thicknesses are acknowledged as limitations of this study. These pressing conditions were selected based on previous studies of citric acid-bonded lignocellulosic particleboards, in which thermal curing under comparable conditions was associated with possible esterification between the carboxyl groups of citric acid and the hydroxyl groups of lignocellulosic materials [24]–[26]. Because FTIR analysis was not performed in the present study, ester-bond formation in the corn-husk particleboards could not be directly confirmed [27]. After pressing, the boards were allowed to cool under pressure to minimize spring-back and internal stress development. The produced particleboards were demolded and conditioned at 25 ± 2°C and 65 ± 5% relative humidity for seven days prior to specimen preparation and testing. Each formulation was fabricated in triplicate to ensure reproducibility of the results.

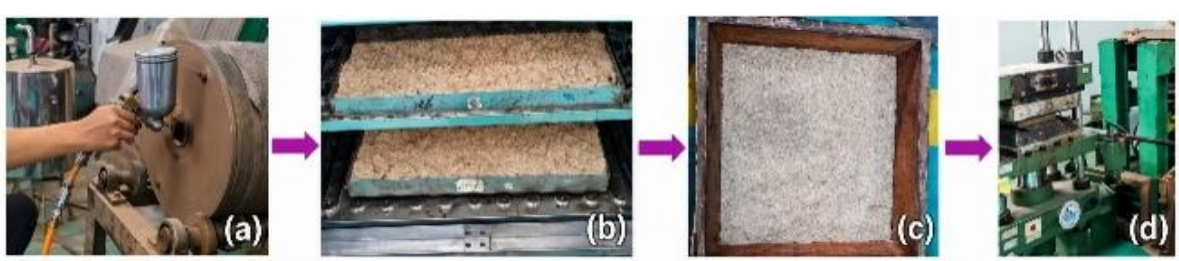


Figure 2: Particleboard production process: (a) adhesive application using a spray gun and rotary mixer, (b) oven drying at 80 °C, (c) mold forming with target dimensions, and (d) hot pressing at 180 °C and 15 MPa.

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The dry furnish mass required for each board was calculated from the target density and nominal board volume using equation (1):

$$m_f = \rho_t \times L \times W \times T \quad (1)$$

where m_f is the calculated dry furnish mass (g), ρ_t is the target density (g/cm³), and L, W, and T are the nominal board length, width, and thickness (cm), respectively [28]. The dry furnish mass included both oven-dry corn husk and dry citric acid, whereas water was excluded from the target-density calculation. Based on a mould size of 30 × 30 cm, the calculated dry furnish masses for all formulations are presented in Table 1. Material losses during adhesive spraying, oven drying, mat formation, and specimen trimming were not separately quantified. Therefore, the furnish masses reported in Table 1 represent the calculated initial masses before processing losses. These losses may have contributed to the differences between the target and actual board densities and are acknowledged as a limitation of this study [29].

Table 1: Calculated dry furnish mass for each board.

Target density (g/cm³)	Thickness (cm)	Mould size (cm)	Dry furnish mass (g)
0.6	0.6	30 × 30	324
0.6	1	30 × 30	540
0.8	0.6	30 × 30	432
0.8	1	30 × 30	720

2.3 *Experimental design*

The experimental design was developed to evaluate the effects of board density, board thickness, and citric acid content on the properties of corn husk-based particleboards. Three independent variables were considered in this research: target board density, board thickness, and binder content [30], [31]. Two target densities were selected, namely 0.6 and 0.8 g/cm³, representing medium-density particleboards commonly used for interior and non-structural applications (Table 2).

Board thickness was varied at two levels, 0.6 cm and 1.0 cm, to investigate the influence of panel geometry on mechanical integrity, moisture resistance, and functional performance [32]. Citric acid content was applied at three levels, 20%, 25%, and 30%, based on the dry weight of corn husk particles, to assess the effect of binder dosage on interparticle bonding and overall board performance. The combination of these variables resulted in twelve different particleboard formulations.

CA content was calculated based on the oven-dry mass of corn husk. The citric acid-to-water mass ratio was 59:41. Total furnish mass represents the combined mass of dry corn husk, dry citric acid, and water before oven drying. The calculations were based on a nominal board size of 300 × 300 mm. Water was excluded from the target-density calculation because it was removed during oven drying and hot pressing. Each formulation was fabricated in triplicate to ensure reproducibility and statistical reliability of the experimental results [33].

Table 2: Formulations of corn-husk particleboards at different target densities, thicknesses, and citric acid contents.

Dens (g/cm³)	Thic (cm)	CA (%)	Husk (g)	CA (g)	Water (g)	Total furnish (g)	Dry binder (%)
0.6	0.6	20	270	54	37.53	361.53	16.67
0.6	0.6	25	259	64.8	45.03	369.03	20
0.6	0.6	30	249	74.77	51.96	375.96	23.08
0.6	1	20	450	90	62.54	602.54	16.67
0.6	1	25	432	108	75.05	615.05	20
0.6	1	30	415	124.6	86.6	626.6	23.08
0.8	0.6	20	360	72	50.03	482.03	16.67
0.8	0.6	25	346	86.4	60.04	492.04	20
0.8	0.6	30	332	99.69	69.28	501.28	23.08
0.8	1	20	600	120	83.39	803.39	16.67
0.8	1	25	576	144	100.1	820.07	20
0.8	1	30	554	166.2	115.5	835.46	23.08

The produced boards were subsequently characterized in terms of their physical, mechanical, thermal, and acoustic properties in accordance with relevant testing standards [34], [35].

2.4 *Physical properties testing*

The physical properties of the particleboards were evaluated in accordance with the Japanese Industrial Standard (JIS) A 5908. The evaluated parameters included density and thickness swelling (TS), which are commonly used to assess dimensional stability and moisture resistance of lignocellulosic particleboards [36]. Board density was determined by measuring the mass and dimensions of each conditioned specimen and calculated as the ratio of specimen mass to its volume. The measured density values were used to verify the consistency between the target and actual board densities, as density is known to strongly influence the physical and mechanical performance of particleboards [37], [38].

Thickness swelling tests were conducted to evaluate the hygroscopic behavior of the particleboards. Test specimens were immersed in distilled water at room temperature, and water absorption was calculated as the percentage increase in specimen mass after immersion relative to the initial dry mass. Thickness swelling was determined as the percentage increase in specimen thickness measured at the centre point before and after immersion. These parameters are critical indicators of board durability under humid conditions and are closely related to porosity, binder distribution, and interparticle bonding quality [39], [40]. All physical property measurements were performed on conditioned specimens, and the reported values represent the average of three replicates for each formulation.

2.5 *Mechanical properties testing*

The mechanical properties of the particleboards were evaluated in accordance with the Japanese Industrial Standard **(**JIS) A 5908 to assess structural integrity and bonding performance. The evaluated parameters included modulus of rupture (MOR) and modulus of elasticity (MOE), which are key indicators of load-bearing capacity and interparticle adhesion in particleboard materials [41]. The modulus of rupture (MOR) and modulus of elasticity (MOE) were determined using a three-point bending test configuration.

Test specimens were loaded until failure using a universal testing machine, and the resulting load-deflection data were used to calculate MOR and MOE values. These parameters reflect the flexural strength and stiffness of the particleboards and are strongly influenced by board density, particle geometry, and adhesive effectiveness [42], [43]. Mechanical tests were conducted on conditioned specimens, and the reported values represent the average of three replicates for each formulation [16], [44].

2.6 *Thermal properties testing*

Thermal conductivity was measured using the guarded hot-plate method at the Propellant and Quality Testing Laboratory, BRIN KST B.J. Habibie. The measurement principle was consistent with ISO 8302, which describes the determination of steady-state thermal resistance and related properties using a guarded hot-plate apparatus [5], [23]. Nominal specimens measuring 150 × 50 mm with thicknesses of 6 and 10 mm were positioned between the hot and cold plates, with heat flow applied perpendicular to the board surface. The temperature difference between the plates was maintained at 10°C at a mean test temperature of 10°C, corresponding to nominal hot- and cold-side temperatures of 15 and 5°C, respectively [9].

Measurements were recorded after steady-state conditions had been reached, as indicated by a constant heat flow through the specimen. Thermal conductivity (k) was calculated using equation (2), based on the heat-transfer rate, specimen thickness, heat-transfer area, and temperature difference, and was reported in W/(m·K) [11].

$$k = \frac{Qd}{A(T_h - T_c)} \quad (2)$$

where k is the thermal conductivity [W/(m·K)], Q is the heat-transfer rate (W), d is the specimen thickness (m), A is the heat-transfer area (m²), and ΔT is the temperature difference between the hot and cold plates (K). The instrument manufacturer and model, calibration material, applied contact pressure, and quantitative steady-state tolerance and duration were not documented in the available testing records. This incomplete documentation is acknowledged as a limitation of the study. The experiment followed a $2 \times 2 \times 3$ factorial design consisting of two target

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densities (0.6 and 0.8 g/cm³), two board thicknesses (0.6 and 1.0 cm), and three citric acid contents (20%, 25%, and 30%). Each formulation was fabricated in triplicate. The experimental results are expressed as mean ± standard deviation [17]. Factorial analysis of variance (ANOVA) was performed to evaluate the effects of target density, board thickness, and citric acid content on the measured properties. Statistical significance was determined at p-value < 0.05. Probability values lower than 0.001 are reported as p-value < 0.05, rather than p-value = 0.0000.

2.7 *Acoustic properties testing*

The normal-incidence sound absorption coefficient was measured at the Adhiwijogo Acoustics Laboratory, Institut Teknologi Bandung, using two impedance tubes. Circular specimens with nominal diameters of 150 and 30 mm were prepared to match the internal diameters of the respective tubes. Measurements were conducted at one-third-octave centre frequencies of 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1000, 1250, 1600, 2000, 2500, 3150, 4000, 5000, and 6300 Hz. The measurement principle was consistent with the two-microphone transfer-function method described in ISO 10534-2:2023 [5], [17], in which the normal-incidence absorption coefficient is determined from the incident and reflected acoustic waves inside an impedance tube. However, the microphone spacing, specimen-backing condition, and detailed transfer-function processing parameters were not documented in the available test records and are acknowledged as methodological limitations [45]. Because the measurements represented normal-incidence absorption in an impedance tube, the weighted sound absorption coefficient (α_w) specified in ISO 11654 was not calculated [29], [46].

3 Results and Discussions

The results are interpreted in relation to the fabrication parameters and material characteristics, with comparisons to relevant literature to highlight performance trends and underlying mechanisms. Emphasis is placed on evaluating the trade-offs among structural integrity, dimensional stability, thermal conductivity, and sound absorption rather than identifying a single optimum without a formal multi-response optimization procedure.

3.1 *Physical properties*

3.1.1 Density

Figure 3 shows the density of particleboards made in this experiment. The densities are in the range of 0.58 g/cm³ to 0.85 g/cm³. Particleboard with the targeted density of 0.8 g/cm³ is more likely to result in a more accurate actual density compared to particleboard with a targeted density of 0.6 g/cm³. In terms of particleboard with a 0.8 g/cm³ density, the highest actual density reached by particleboard with a combination of thickness 0.6 cm with 30% CA was 0.85 g/cm³. Those values were higher compared to particleboard with 20% and 25% CA, either 0.6 cm and 1 cm thickness, which were 0.73-0.79 g/cm³. Particleboard with 0.6 g/cm³ of targeted density showed an actual density between 0.58 and 0.63 g/cm³.

This fact was previously found by Melo *et. al.,* [47], who attributed it to variations in the specific mass and moisture content of the particles, as well as loss of adhesive during the application time due to adherence on the drum's edges. As is well known, particleboard quality can also be impacted by the kind and quantity of glue employed. Increasing the amount of adhesive improves the distribution of adhesive on the particles and increases the sites of compatibility and connection between the particles and adhesive, which raises the quality of particleboard [6], [24], [48].

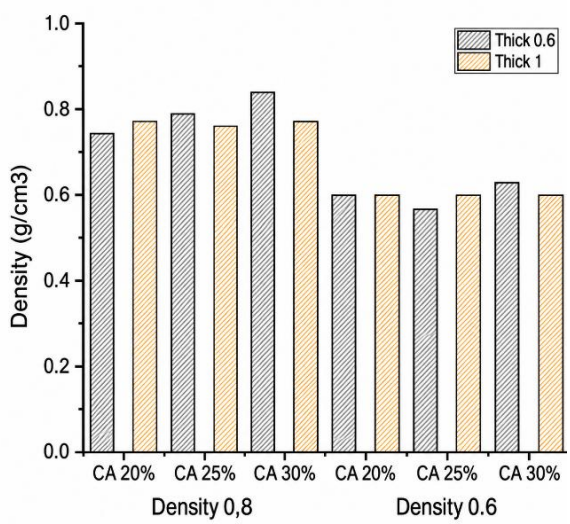


Figure 3: Actual density of particleboard.

3.1.2 Thickness swelling

Thickness swelling of the board showed the value of dimensional change in particleboard due to immersion in water. The values of TS of particleboard in this study are depicted in Figure 4. Thickness swelling values in this study are in the range of 25% to 52%, depending on the combination of targeted density, thickness of the board, and the percentage of adhesive (citric acid). For particleboard with a targeted density of 0.6 g/cm^3, the highest value of TS was recorded by particleboard with 1 cm thickness and 20% CA (±48%). The lowest thickness swelling was ±27%, performed by particleboard with a thickness of 0.6 cm and CA 30%.

The thickness-swelling values obtained in this study, ranging from approximately 25% to 52%, exceeded the maximum limit of 12% specified in JIS A 5908:2003. Therefore, the developed boards did not satisfy the dimensional-stability requirement of the standard [49]. These results indicate that further improvements in binder distribution, particle-size control, and moisture resistance are required before the boards can be considered for applications involving exposure to humid conditions [49]. According to Maraghi *et. al.,* [50], the dimensional stability of particleboard made of poplar wood mixed with citrus branches and beech twigs particles improved somewhat as the adhesive percentage increased. Particleboard's water absorption dropped as its density grew, but its thickness swelled.

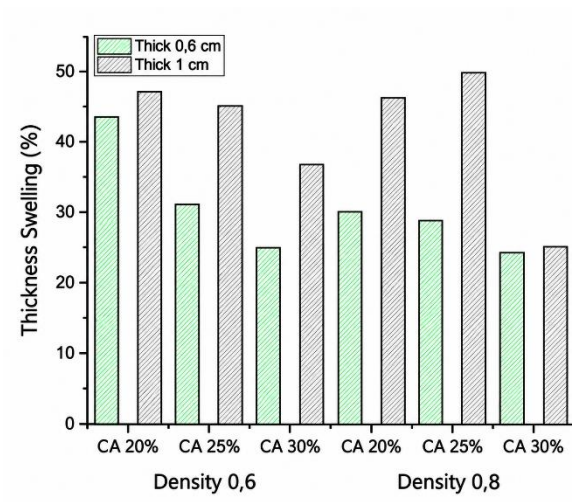


Figure 4: Thickness swelling of particleboard.

The TS characteristics may also be impacted by the tiny maize husk particles. According to Bazzetto *et. al.,* [51], [52], compared to the bigger particles with a higher coating capacity, the adhesive content may not completely cover the surface area of the smaller particles, thus, they do not effectively create a barrier to water absorption by the fiber cell wall. Prasetiyo *et. al.,* [4], [53] stated that high porosity in particleboard increases thickness swelling and affects the long-term properties of the particleboard. Furthermore, Astari *et. al.,* [31], mentioned that the type of adhesive and relative humidity affect the hygroscopicity of the board.

Because the particle-size distribution, aspect ratio, and fines content were not quantified, the influence of particle geometry on adhesive coverage, compaction, pore structure, and thickness swelling could not be independently determined. Consequently, interpretations related to particle size should be regarded as qualitative. Future studies should employ multi-sieve fractionation and image-based morphological analysis to establish quantitative relationships between particle geometry and board performance.

3.2 *Mechanical properties*

3.2.1 Modulus of rupture (MOR)

Modulus of rupture (MOR) is a critical mechanical property of particleboard to reflect the maximum load-bearing capacity before breaking. A higher MOR value indicates an improved load-bearing response under bending. However, the corresponding changes in interparticle bonding, adhesive distribution, and internal structure could not be directly confirmed because microstructural characterization was not performed [54], [55]. The results of the MOR investigation of this research are presented in Figure 5.

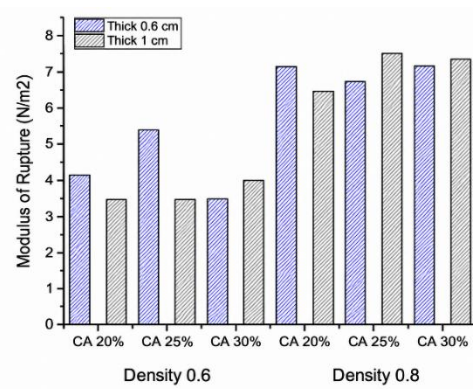


Figure 5: MOR values of the particleboard.

The graph shows that the MOR values of the particleboard are in the range of ±3,5 N/mm² to ± 7,8 N/mm². The increasing trend of MOR values is in line with the increase in targeted densities and adhesive (citric acid) percentage. For the particleboard with a thickness of 0.6 cm, the highest MOR was obtained from those with targeted densities of 0.6 g/cm³ and CA 30%, which was ±7.2 N/mm². The lowest MOR value was recorded by particleboard with CA 25%, which was ±3.5 N/mm². For particleboard with a thickness of 1.00 cm, the highest values were from particleboard with a targeted density of 0.6 g/cm^3 and percentage of CA 25%, which was ± 5.5 N/mm², and the lowest MOR value was from particleboard with CA 0% (±3.7 N/mm²) [56]. Particleboard with the targeted density of 0.8 g/cm³ showed a more consistent pattern of increase. The particleboard with a thickness of 0.6 cm showed an increment from ± 6.5 N/mm² (CA 20%) to ±7.5 N/mm² (CA 30%). The condition also occurred on particleboard with the thickness of 1 cm, which recorded high MOR values on particleboard after treatment with the maximum value of ±7.8 N/mm² on particleboard with CA 25%. According to Brito *et. al.,* [51], [57], an increase in the compaction rate promotes a larger particle contact area, while a decrease in vacant spaces promotes a better slenderness ratio. These findings suggested that corn husk might be produced as a substitute raw material for particleboard that was bonded with WSC as an adhesive to improve the bending properties.

The measured MOR values of approximately 3.5-7.8 MPa were below the minimum requirement of 8 MPa for Type 8 particleboard specified in JIS A 5908:2003. Therefore, the developed boards cannot currently be classified as Type 8 particleboard or recommended for load-bearing, furniture, or construction applications. Although the MOE values ranged from approximately 400 to 900 MPa, these results should be regarded as preliminary because long-term creep, screw-withdrawal resistance, impact resistance, and ageing performance were not evaluated [58].

3.2.2 Modulus of elasticity (MOE)

Modulus of elasticity (MOE) is a mechanical parameter that determines the ability of particleboard to deform before breaking. A high value of MOE shows that particleboard is stiff and not easy to bend. The MOE values of particleboard in this research are presented in Figure 6. The MOE values ranged from approximately 390 to 890 MPa and also exhibited non-monotonic responses to CA content. At a target density of 0.6 g/cm³, the MOE of the 6 mm boards increased markedly from approximately 420 MPa at 20% CA to 860 MPa at 25% CA, but subsequently decreased to approximately 390 MPa at 30% CA. The corresponding 10 mm boards showed relatively limited variation, with values of approximately 410-450 MPa. At a target density of 0.8 g/cm³, the 6 mm boards had their highest MOE at 20% CA, followed by lower values at 25% and 30% CA [59].

Conversely, the 10 mm boards decreased from approximately 800 MPa at 20% CA to 640 MPa at 25% CA and then increased to approximately 890 MPa at 30% CA. Therefore, higher CA content did not consistently increase board stiffness, indicating an interaction between adhesive content, density, and board thickness [60]. The non-monotonic MOE trends may reflect differences in adhesive distribution, mat consolidation, particle arrangement, moisture removal, and the degree of curing achieved during hot pressing [61]. Although additional CA may strengthen some particle contacts, excessive or uneven adhesive distribution can create local heterogeneity and may not contribute effectively to board stiffness [62], [63]. Thickness-dependent heat transfer during pressing may further produce differences in curing and internal structure between the 6 and 10 mm boards. These interpretations remain tentative because the internal morphology and chemical bonding were not directly characterized in the present study.

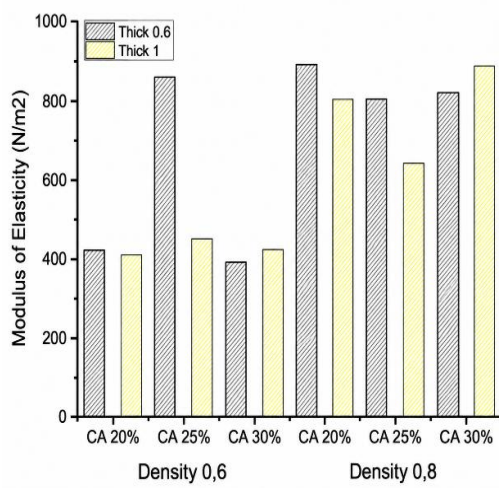


Figure 6: MOE value of particleboard.

Particleboard with a density of 0.8 g/cm³ showed higher MOE compared to those with 0.6 g/cm³. The highest MOE on particleboard with a density of 0.8 g/cm³ was from those with a thickness of 1 cm and a CA percentage of 30%, which was ± 900 N/mm². For particleboard with a thickness of 0.6 cm, the highest MOE was from particleboard with CA 20%, which was ±880 N/mm². Related to Sekaluvu *et. al.,* [38], stated that particle size and adhesive content have an impact on board density, MOE, and MOR from particleboard made from maize cobs [64]. Because of the weak adherence between the adhesive and the particles, the use of particles with a high moisture content produced particleboards with poorer mechanical qualities [65].

The mechanical performance of natural-fiber composites is governed not only by the inherent properties of their constituents but also by interfacial bonding and structural arrangement. Ratna *et. al.,* [66] demonstrated that improved fiber-matrix adhesion through fiber surface modification enhanced the mechanical properties of areca-banana fiber composites [65]. Similarly, Ayyappan *et. al.,* showed that constituent arrangement and hybrid configuration influenced the quasi-static, cyclic, and fatigue performance of natural-fiber-containing laminates [67]. Although the material systems differ from the particleboards investigated in the present study, these findings support the importance of particle–binder interaction and structural configuration in determining composite mechanical performance.

3.3 *Thermal properties*

3.3.1 Thermal conductivity

Thermal conductivity is an intrinsic material property that describes heat conduction through the particleboard. The area-specific thermal resistance (R) depends on the specimen thickness (d) and thermal conductivity (k), as expressed in Eq. (3):

$$R = \frac{d}{k} \tag{3}$$

Therefore, when material composition, density, moisture content, and microstructure are identical, increasing specimen thickness increases thermal resistance but should not independently change thermal conductivity [68], [69]. T The measured thermal conductivity values in this study ranged from approximately 0.17 to 0.29 W/(m·K). The 6 mm boards generally exhibited higher measured thermal conductivity than the 10 mm boards across the evaluated density and citric acid levels [70].

The differences between the 6 and 10 mm boards should not be interpreted as a direct intrinsic effect of thickness [6]. Although the boards had comparable target formulations, applying the same pressing time to different board thicknesses may have produced differences in heat penetration, moisture removal, citric acid curing, compaction, density profile, and pore structure [71]. Specimen heterogeneity and thermal contact resistance between the board surfaces and the measurement plates may also have influenced the measured values. Because these factors were not independently quantified, the lower measured thermal conductivity of the 10 mm boards cannot be attributed solely to their greater thickness [69].

Figure 7 shows that thermal conductivity generally increased with increasing particleboard density. Higher-density boards contain less pore volume and a lower proportion of trapped air, while closer particle-to-particle contact creates more continuous solid pathways for heat transfer [72], [73]. In contrast, the stagnant air retained within the pores of lower-density boards acts as an insulating phase because its thermal conductivity is considerably lower than that of the solid lignocellulosic components. Therefore, reducing porosity through board densification can increase the effective thermal conductivity, whereas a greater proportion of closed, air-filled pores generally improves thermal-insulation performance [74]–[76].

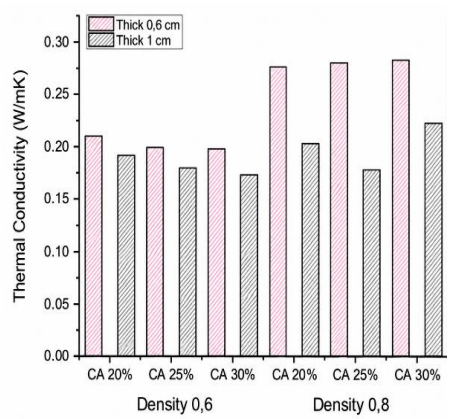


Figure 7: Thermal conductivity of particleboard.

Several formulations exhibited thermal conductivity below 0.25 W/(m·K); however, their suitability as thermal-insulation materials requires further validation using fully documented standardized testing conditions. This suggests that the material is safe to use, as the measured thermal conductivity indicates preliminary thermal-insulation potential; however, practical use cannot be recommended without additional evaluation of fire behaviour, moisture durability, ageing, and environmental safety [77], [78]. A substantial amount of trapped air is naturally present in the structures of both wood and non-wood particles or fibers, which enhances their insulating qualities [79], [80].

3.4 *Acoustic properties*

The normal-incidence sound absorption coefficients measured at one-third-octave centre frequencies from 63 to 6300 Hz are presented in Figure 8. Generally, the SAC ranged from 0.01 to 0.77. All values also fluctuated; however, they were higher and better than those at low frequencies. The board with a target density of 0.6 g/cm³ and a thickness of 0.6 cm exhibited the highest normal-incidence sound absorption coefficient, reaching approximately 0.76 at 100 Hz. A secondary peak of approximately 0.67 was observed at 500 Hz. These results indicate that this board formulation provided the highest sound absorption performance, particularly in the low- to medium-frequency range. Therefore, the previous statement identifying a peak near 630 Hz has been corrected [23]. This result indicates that the combination of thickness and lower density allows effective sound absorption for low frequencies. The SAC at medium frequency showed a variation with particleboard thickness, and 0.6 cm and 0.8 cm remain dominant, especially at a frequency of 630 Hz.

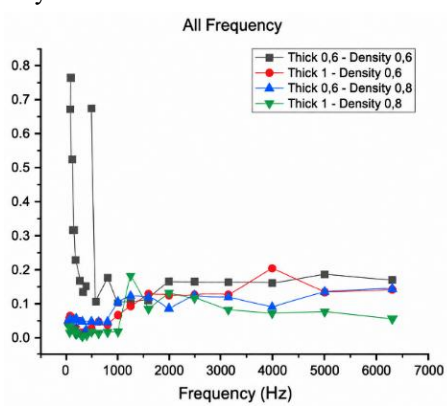


Figure 8: Sound absorption value of particleboard.

However, the increase in sound absorption on particleboard with a density of 0.8 g/cm³ and a thickness 1.0 cm showed a potency on its capability as sound absorber for medium to high frequencies. At high frequencies, all particleboard types showed absorption values that varied, with no single type dominating. Some type of particleboard such as thickness of 1 cm with density of 0.6 g/cm³ showed dramatically increased on a certain frequency (approximately 4,000 Hz).

Another variation of particleboard, such as a thickness of 0.6 cm and density of 0.8 g/cm³ had a lower sound absorption value yet was more consistent to this range of frequency. This indicates that thickness and density affect sound absorption on high frequency with more complex and non-linear. Based on the test results, the increase in density and thickness of particleboard significantly improved the sound absorption coefficient, particularly on medium and high frequencies. These findings are in line with results from Karlinasari *et. al.,* [55], which reported that the sound absorption coefficient increased with the increase in density and binder content of particleboard made from Betung bamboo.

Microstructural and spectroscopic characterizations were not performed in this study. Therefore, the proposed effects of density and citric acid content on pore structure, particle–binder interaction, interparticle bonding, adhesive distribution, and esterification should be regarded as interpretations based on the measured macroscopic properties and previously published studies rather than as direct experimental observations. Future work should include SEM examination of representative cross-sections and fracture surfaces to quantify pore structure and evaluate particle–binder interfaces. FTIR analysis should also be conducted to investigate changes in hydroxyl, carbonyl, and ester-related absorption bands and thereby assess the proposed esterification mechanism.

4 Conclusions

Based on the investigation and determination in this research, the density of particleboard (0.6 g/cm³ and 0.8 g/cm³) significantly affects the physical and mechanical properties of particleboard. Particleboard with higher density has better MOR and MOE values and lower values for thickness swelling. The thickness variation in particleboard (0.6 cm and 1.00 cm) affects the distribution of pressure during the hot-pressing process. Particleboard with a thickness of 1.00 cm

showed more stable performance and a lower thermal conductivity value compared to particleboard with a thickness of 0.6 cm. The variation in citric acid percentage (20%, 25%, and 30%) has a critical effect on the solidity of particleboard. Particleboard with 30% citric acid resulted in the highest MOR, MOE, and thermal resistance.

The evaluated properties showed different performance trends, and no single formulation provided the best results for all responses. Higher-density boards generally exhibited better mechanical performance, whereas the lowest thermal conductivity was obtained from the board with a target density of 0.6 g/cm³, a thickness of 1.0 cm, and 30% citric acid. In contrast, the highest normal-incidence sound absorption coefficient was observed for the board with a target density of 0.6 g/cm³ and a thickness of 0.6 cm. These findings demonstrate trade-offs among mechanical, thermal, dimensional, and acoustic performance. Therefore, the preferred formulation should be selected according to the intended application. A formal multi-response optimization procedure using predefined response priorities is required to establish an overall optimum formulation. Nevertheless, the thickness-swelling values of approximately 25–52% exceeded the maximum limit specified in JIS A 5908:2003. Therefore, the developed boards cannot yet be classified as compliant particleboards for furniture or construction applications, particularly under humid conditions. Further optimization of particle geometry, binder distribution, pressing conditions, and moisture resistance is required.

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Author Contributions

K.W.P.: conceptualization, investigation, reviewing and editing, funding acquisition; L.A.: investigation, methodology, writing an original draft; B.S.: writing-reviewing and editing. K.: research design, data analysis; R.H.: conceptualization, data curation, writing-reviewing. I.M.S.: writing-reviewing and editing. D.A.I.: writing-reviewing and editing. M. K.: writing-reviewing and editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors utilized the ChatGPT tool to enhance the language and readability of the manuscript.

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