EFFECT OF ADHESIVE VARIATIONS: TAPIOCA, PVAC, MOLASSES AND CITRIC ACID ON THE PHYSICAL PROPERTIES OF PARTICLEBOARD

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ABSTRACT
Sustainability issues and the need for environmentally friendly materials prompted the utilization of biomass waste as an alternative raw material in composite panel manufacturing. The development of biomass-based composite boards not only reduced dependence on natural wood but also provided added value to agricultural and forestry organic waste. One of the main challenges was the application of safe and effective natural adhesives to replace formaldehyde-based synthetic adhesives, which are known to be harmful to the environment and human health. This study employed three adhesive formulations: citric acid with polyvinyl acetate (PVAc/Lem Fox), citric acid with molasses, and citric acid with tapioca, to investigate their effects on the physical and mechanical properties of composite boards. The panels were produced by hot pressing at 160°C and 3 MPa, then conditioned at room temperature for five days to ensure even moisture distribution. Property tests included measurements of moisture content (MC), density, modulus of elasticity (MOE), and modulus of rupture (MOR), all following the relevant SNI standards. The results showed that variations in adhesive formulation significantly affected

board strength and stiffness. The combination of citric acid and PVAc yielded the lowest MOE and MOR values at 15.14 MPa and 1.0 MPa, respectively, indicating that these panels were less stiff and more susceptible to fracture due to suboptimal interparticle bonding and high moisture content. In contrast, the citric acid and molasses formulation achieved the highest MOE and MOR values at 41.25 MPa and 2.90 MPa, respectively, followed by citric acid and tapioca at 39.78 MPa and 2.60 MPa, along with more stable density and moisture content values.

Keywords: *Citric acid, density, molasses, particle board, PVAc, tapioca*

INTRODUCTION

The issue of sustainability and biomass waste reduction is increasingly a global concern in facing the challenges of limited natural resources and efforts to reduce carbon emissions. The demand for eco-friendly materials continues to increase in line with the need for the construction, automotive, and furniture industries to switch from conventional raw materials to more sustainable alternative sources. Biomass from agricultural and forestry waste is now recognized as a raw material for particle board, which can not only reduce the generation of organic waste, but also support the conservation of forest resources. The use of biomass waste for particle boards has been proven to produce materials with competitive performance, especially when combined with innovative process technologies and adhesive formulations. One of the main aspects that determine the physical and mechanical qualities of particleboard is the use of adhesives. Properties such as MC, density, MOE, and MOR are greatly influenced by the type and composition of the adhesive used. However, until now, the particleboard industry still relies heavily on formaldehyde-based synthetic adhesives, such as urea formaldehyde (UF) and phenol formaldehyde (PF), which are known to have a negative impact on human health and the environment due to formaldehyde emissions which are toxic and carcinogenic. As the demand for safe and environmentally friendly products increases, innovations in natural adhesives and modifications to their formulas continue to be the focus of research in the field of materials engineering.

Citric acid is one of the natural adhesives that has stood out in recent years, thanks to its ability to form ester bonds with hydroxyl groups in biomass cellulose, thereby increasing the strength of the bonds between particles and resistance to water. In addition to citric acid, molasses and tapioca flour are also widely researched as natural adhesives because of their biodegradable properties, abundant availability, and ability to reduce carbon emissions from industry. Recent studies have found that the combination of citric acid with other natural adhesives such as molasses, PVAc, and tapioca is able to produce particleboards with physical and mechanical characteristics that meet or even exceed national and international standards.

However, there are still challenges in optimizing mechanical properties, especially MOR and MOE, which are greatly influenced by the composition variables and the adhesive application method. This has prompted recent research to test different variants of adhesive materials, both single and combination, as well as mixing and pressing methods to ensure that the resulting particleboard truly meets the demands of performance and sustainability. This innovation is the key to increasing the competitiveness of biomass waste-based materials in the global market.

This was carried out by utilizing a certain mesh-sized biomass powder with a moisture content of less than 10%, which was then mixed with three variations of adhesives, namely citric acid + Fox Glue/PVAc, citric acid + molasses, and citric acid + tapioca. The pressing process is carried out at a temperature of 160°C and a pressure of 3 MPa, then the board is conditioned for five days before being tested for its physical and mechanical properties (MC, density, MOE, MOR) referring to the latest SNI standards. This study aims to examine the effect of variations in natural adhesive composition on the physical and mechanical properties of biomass particle board and produce optimal formulations that meet national standards, so that it can be an environmentally friendly material alternative that is applicable and sustainable.

A. ADHESIVE FORMULATION AND PARTICLEBOARD MANUFACTURING

To achieve uniformity in particle size and enhance bonding performance, wood-based biomass powder is first prepared through drying and sieving processes. The raw material is conditioned to a moisture content of less than 10%, then filtered using a 20-mesh sieve. This ensures consistent particle distribution and optimal adhesion during pressing.

Three types of adhesives were applied, combining natural and synthetic components. These include tapioca flour, polyvinyl acetate (PVAc or fox glue), and molasses. Each adhesive is mixed with citric acid in a fixed ratio of 1:4 (citric acid to adhesive), which acts as a natural cross-linking agent. The role of citric acid is not only to improve internal bond strength but also to reduce emissions from synthetic adhesives. The formulation ratio for all variations consisted of 40% adhesive by weight relative to oven-dried biomass, a proportion chosen based on prior studies that demonstrated its efficiency in binding and resulting board properties. Water was added in moderate amounts to aid the homogenization of the mixture.

The adhesive-biomass blend is shaped in a square mold and compressed using a hydraulic press at 160 °C under 3 MPa of pressure. This temperature and pressure combination facilitates the activation of citric acid and enhances the polymerization or gelatinization process depending on the adhesive used. After pressing, the boards are conditioned at room temperature (25–34 °C) for five days, ensuring even humidity distribution and full adhesive curing. Flowchart of this process shown in Figure 1.

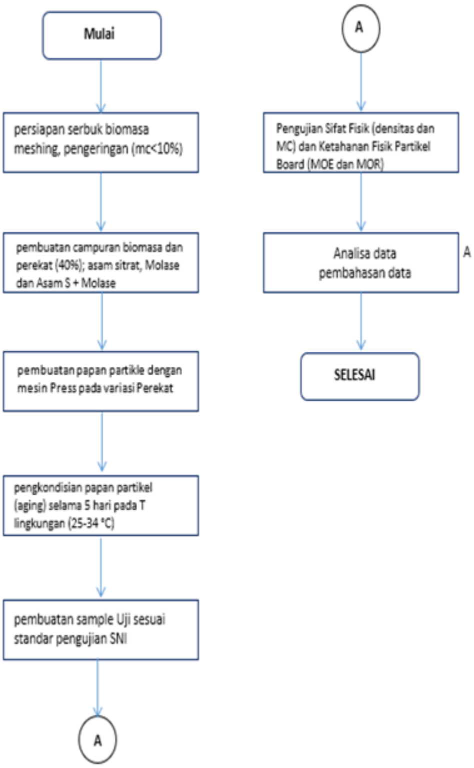

Figure 1. Research Flow

B. INSTRUMENTATION AND MATERIALS OVERVIEW

The process utilized standard laboratory equipment, including analytical balances, mesh strainers, mixers, thermoguns, and hydraulic pressing tools. Precision tools like jigsaws were used for sample preparation, while mechanical tests were conducted using a Universal Testing Machine (UTM) to evaluate properties such as compressive strength, MOE, and MOR. This uses various laboratory tools to support the process of preparation, manufacturing, and testing of particle boards. The tools used include analytical scales to weigh materials precisely, mesh strainers to ensure the size of biomass powder according to the standard (passes mesh 20), so that the binding process is more optimal. Furthermore, a measuring cup and mixer mixer to mix adhesive materials, as well as a thermogun to monitor temperature. In addition, jigshaw machines are used for board cutting, hydraulic presses are used for pressing processes at certain temperatures and pressures, and UTM used for testing the mechanical properties of particleboards, such as compressive strength, MOE, and MOR.

In addition, the material used in this study is biomass powder as the basic material for particle board. Biomass powder is obtained from the process of crushing and sifting wood waste until it passes a 20 mesh sieve, then dried until the moisture content is less than 10%. As an adhesive, three types of materials are used, namely tapioca flour, polyvinyl acetate (PVAc/fox glue), and molasses. All three types of adhesives are combined with citric acid as an additive, with a ratio of citric acid to adhesive ratio of 1:4. The use of citric acid has been shown to increase bond strength and reduce emissions of harmful substances on particleboard. The composition of the adhesive used in each mixture is 40% of the dry weight of the biomass. The adhesive dose of 40% of the dry weight of the biomass was taken based on the binding efficiency and good final properties of the particle board according to previous research. Furthermore, enough water is also used to help the mixing process so that the mixture is homogeneous. All materials used are sourced from the same source to maintain the consistency and quality of the materials during the research process. The list of research materials and their use can be seen in Table 1.

Table 1. Research Materials

No	Material	Use of Adhesive
1	Biomass Powder	Particleboard main material, moisture content <10%, pass mesh 20
2	Tapioca Flour	Natural adhesive, mixed with citric acid (1:4 ratio)
3	PVAc/ Fox Glue	Synthetic adhesive, mixed with citric acid (1:4 ratio)
4	Molasses	Natural adhesive, mixed with citric acid (1:4 ratio)
5	Citric Acid	Additives, combined on all adhesives
6	Water	Used moderately for homogeneous mixtures

C. DEFLECTION BEHAVIOR AND LOAD RESPONSE

Three combinations of citrate-based adhesive formulations each of which are combined with different additives, namely citric acid, molasses, and tapioca flour. The test was conducted to evaluate the quality of the relationship between the adhesive concentration to MOE, as well as the stability of the resulting data. The test results of the citrate and fox glue formulations are shown in Figure 2.

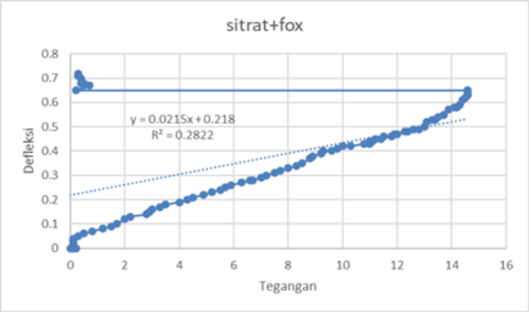

Figure 2. Deflection and Stress Curves of Citrate + Fox Glue Formulation

The deflection curve and voltage of the particle board with citrate adhesive + Fox glue (PVAc) tend to show considerable voltage fluctuations at the time the load is raised. This nonlinear and unstable curve indicates that the material tends to undergo uneven deformation and that the ability to withstand elastic loads is relatively low. This is in line with the low MOE and MOR values and suggests that the bonds between biomass particles produced by the combination of citric acid and PVAc are less effective, making the panels more susceptible to fracture or damage when subjected to bending loads.

Furthermore, the curve in Figure 3 shows a more linear and stable pattern, indicating a more even load distribution and the ability of the panel to withstand the load to the breaking point more consistently.

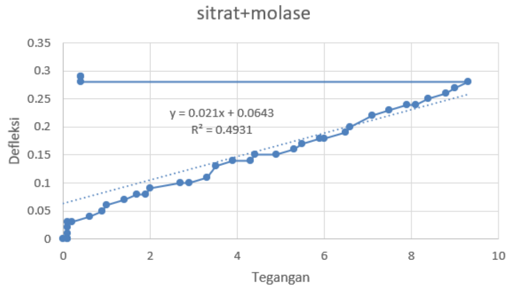

Figure 3. Deflection Curve and Tension of Citrate + Molasses Formulation

The citrate + molasses formulation produce a tension-deflection curve that gradually increases until it reaches the maximum load before failure occurs. This characteristic reflects the chemical interaction between citric acid and molasses which can form strong cross-bonds and binding matrices, so that the resulting particle board becomes stiffer and can maintain its mechanical strength to peak loads.

The test results of the citrate and tapioca formulations are shown in Figure 4. The deflection curve and tension of the particle board with citrate + tapioca adhesive show a stable pattern and tend to be linear. This curve shows that the panel can withstand elastic deformation well and that the stress distribution takes place evenly until it is close to the breaking point.

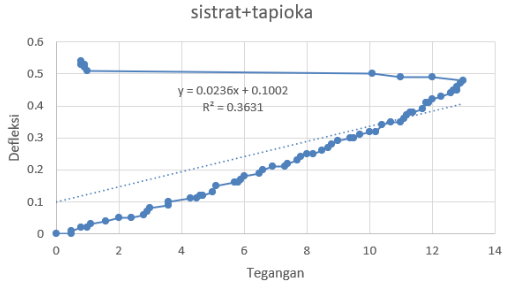

Figure 4. Deflection and Stress Curves of Citrate + Tapioca Formulations

The viscoelastic properties of the tapioca gel matrix formed during the citric acid co-pressing process contribute to the increased rigidity and durability of the board. This is in line with the relatively high MOE and MOR values, as well as good moisture content stability, indicating that the citrate + tapioca formulation is effective in producing a strong, flexible, and dimensionally stable particleboard.

The physical and mechanical properties of the particleboard resulting from various adhesive variations were tested to determine the effect of each formulation on the quality of the final product. The main parameters measured included density, MC, MOE, MOR. Each particle board is manufactured by a pressing method at 160°C and a pressure of 3 MPa, using biomass particles that pass a 20 mesh as well as an adhesive dose of 40% of the dry weight of the biomass. The use of different types of adhesives, both citric acid, molasses, or a combination of citric acid and molasses, results in particleboards with different mechanical and physical properties.

D. COMPARATIVE PERFORMANCE OF ADHESIVE FORMULATIONS

The values MOE and MOR in this study are based on a formula used as a standard in the testing of wood-based materials. The MOE value is calculated using Equation (1). While the MOR value is calculated by Equation (2).

$$MOE = \frac{\Delta P L^3}{4 \Delta y b h^3} \quad (1)$$

$$\mathrm{MOR} = \frac{3\mathrm{PL}}{2\mathrm{bh}^3} \quad (2)$$

Where

L = the spacing distance (cm)

b = the width of the test sample (cm)

h = the thickness of the test sample (cm)

ΔP = the change in load (kg)

Δy = the deflection change (cm)

p = the maximum load (kg)

The calculation of these two parameters refers to the particle board testing standard to obtain an accurate picture of the rigidity and maximum flexural strength of the research material. The results of the calculation of density, moisture content, as well as MOE and MOR of all adhesive variations used are presented in Table 2.

Table 2. Average Density, MC, MOE, and MOR of Particleboard by Adhesive Type

Adhesive	Density (g/cm³)	MC (%)	MOE (MPa)	MOR (MPa)
Citric Acid + Fox Glue (PVAc)	0,489	8,25	15,14	1,0
Citric Acid + Molasses	0,519	5,42	41,25	2,9
Citric Acid + Tapioca	0,540	6,83	39,78	2,6

All particle boards in this study were produced by a pressing method at a temperature of 160°C, a pressure of 3 MPa, and a biomass particle size that passed a mesh sieve of 20, as well as an adhesive dose of 40% of the dry weight of the biomass. The type of adhesive used consists of a combination of citric acid with Fox/PVAc Glue, citric acid with molasses, and citric acid with tapioca. The test results showed that particle boards with citric acid and tapioca adhesives had the highest average density values of 0.540 g/cm^3, followed by citric acid with molasses of 0.519 g/cm^3, and citric acid with PVAc of 0.489 g/cm^3. DIn terms MC, boards with citric acid and molasses adhesives also have the lowest MC values of 5.42%, while citric acid with tapioca is 6.83%, and citric acid with PVAc is 8.25%. In the mechanical aspect, the highest MOE value was achieved by boards with citric acid and molasses adhesives of 41.25 MPa, followed by citric acid with tapioca of 39.78 MPa, and citric acid with PVAc of 15.14 MPa. Similarly, the MOR of boards with citric acid and molasses was recorded at 2.90 MPa, higher than boards with citric acid and tapioca (2.60 MPa) and citric acid with PVAc (1.00 MPa).

E. EFFECT OF ADHESIVE VARIATIONS ON PARTICLE BOARD DENSITY

The difference in density values based on the type of adhesive used shown in Figure 5. Particle board density is an indicator that indicates the density between particles and the level of cohesiveness of the board structure. Based on the test results, the particle board with a combination of citric acid and tapioca adhesive had the highest density value, which was 0.540 g/cm^3, followed by citric acid + molasses of 0.519 g/cm^3, and citric acid + Fox Glue (PVAc) of 0.489 g/cm^3. The high-density value indicates that the biomass particles are more tightly arranged and the binding process between the particles runs optimally. Tapioca-based adhesives, when heated together with citric acid, can form a gel matrix that penetrates the cavities between wood fibers and strengthens the density of the structure. Meanwhile, citric acid + molasses also produces a high density due to the chemical cross-reaction between the adhesive molecules, although it is slightly lower than tapioca. Citric acid + Fox Glue adhesive has the lowest density, allegedly due to PVAc character which tends to be more flexible and less effective in filling gaps between particles during high temperature pressing processes.

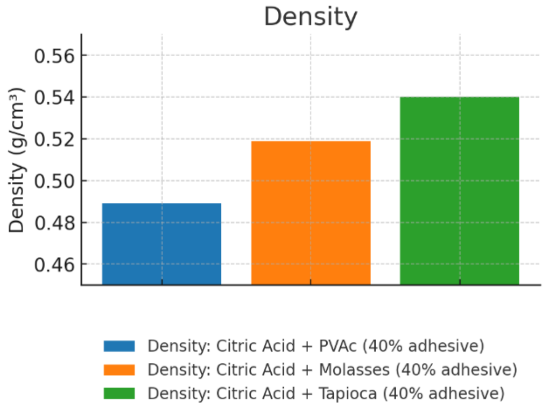

Figure 5. Density Graph by Adhesive Type

F. EFFECT OF ADHESIVE VARIATIONS ON MC

MC greatly affects the dimensional stability and durability of the particle board in the face of environmental changes. The test results showed that particle board with citric acid + Fox Glue (PVAc) adhesive had the highest moisture content, which was 8.25%, followed by citric acid + tapioca at 6.83%, and citric acid + molasses at 5.42%. The high MC in Fox Glue-based boards is likely due to PVAc's properties that tend to absorb and retain moisture, as well as a suboptimal drying process. On tapioca-based boards, the moisture content tends to be lower due to the starch gel structure that binds water strongly and slows down the process of moisture diffusion into the board shown in Figure 6. However, the combination of citric acid + molasses provides the lowest MC value, indicating that the chemical cross-reaction between citric acid and sugars in molasses is able to suppress water absorption and produce more stable and moisture-resistant ester bonds.

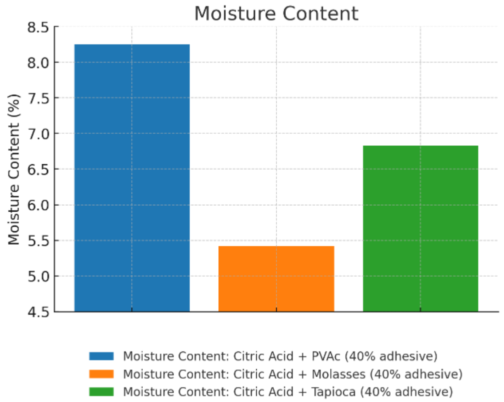

Figure 6. MC Graphics By Adhesive Type

G. EFFECT OF ADHESIVE VARIATION ON MECHANICAL PROPERTIES (MOE AND MOR)

The mechanical properties of particle boards, MOE and MOR are indicators of the rigidity and flexural strength of the board shown in Figure 7 and 8. Based on the tests, particle boards with citric acid + molasses adhesives showed the highest MOE and MOR values, namely 41.25 MPa and 2.90 MPa, followed by boards with citric acid + tapioca of 39.78 MPa and 2.60 MPa, and the lowest on boards with citric acid + Fox Glue of 15.14 MPa and 1.00 MPa. A high MOE value signifies the rigidity and ability of the board to resist elastic deformation, while the MOR value indicates the board's maximum strength before breakage. The combination of citric acid and molasses chemically forms a more effective cross-bond, strengthening the interaction between molecules and wood fibres so that the load distribution is more even and the board is not easily broken. The starch gel structure formed during heating also acts as a binding matrix that increases the bending strength. Meanwhile, in Fox Glue-based boards, the weak bond between particles causes the board to be less rigid and easily broken under bending loads. These findings suggest that the combination of citric acid and molasses is the most recommended formulation in producing particleboards with the best mechanical strength.

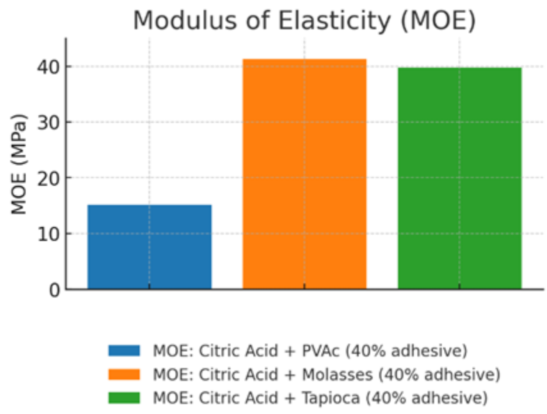

Figure 7. MOE Graph by Adhesive Type

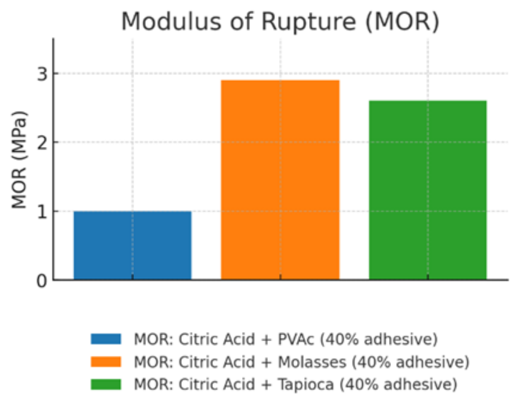

Figure 8. MOR Graph by Adhesive Type

H. RELATIONSHIP BETWEEN PHYSICAL AND MECHANICAL PROPERTIES

There is a close correlation between the physical properties (density, moisture content) and mechanical (MOE, MOR) properties of particleboards. High-density boards generally have better mechanical strength because the biomass particles are tightly arranged and the bonds between particles are stronger, so they can distribute the load evenly. In addition, the low moisture content favors increased mechanical strength, as excess water in the board structure can lead to the formation of microcavities, delamination, and decreased adhesive bond effectiveness. On boards with citric acid + molasses and citric acid + tapioca, the combination of high density and low MC provides optimum mechanical strength (high MOE and MOR). In contrast, on Fox Glue-based boards, lower density and high MC contribute to a decrease in MOE and MOR values. These results prove the importance of managing the physical properties of the board to support overall mechanical performance.

CONCLUSION

Based on the results of the study, the variation in adhesive formulation has a significant influence on the physical and mechanical properties of biomass-based particleboards. Particleboard with Citric Acid + Fox Glue (PVAc) adhesive showed the lowest MOE and MOR values, namely 15.14 MPa and 1.00 MPa, and the highest moisture content of 8.25%, indicating poor stiffness and flexural strength due to suboptimal particle bonding and PVAc's tendency to absorb moisture. In contrast, the combination of Citric Acid + Molasses produced a board with the highest MOE of 41.25 MPa, MOR of 2.90 MPa, the lowest moisture content of 5.42%, and a density of 0.519 g/cm^3, while Citric Acid + Tapioca also showed competitive mechanical performance with a MOE of 39.78 MPa, MOR of 2.60 MPa, a moisture content of 6.83%, and the highest density of 0.540 g/cm^3. The improvement in the mechanical properties of molasses and tapioca-based boards is related to the ability of both to form cross-bonds with citric acid and produce a dense matrix structure, so that the load can be distributed more evenly and the bonds between particles become stronger. In addition, the more controlled moisture content of the panels with molasses and tapioca favors the formation of a more stable structure that is resistant to environmental influences. Overall, the combination of natural adhesives such as molasses and tapioca with citric acid has been proven to be able to produce composite boards with better strength and stability than citric acid with fox glue, making it an environmentally friendly and highly competitive alternative material.

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