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Physical and Mechanical Properties of Palm Frond-based Fiberboard Composite

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ABSTRACT

Novel research has been conducted to characterize fiberboards made from palm frond fibers and polyester resin. In this study, polyester resin served as the matrix, and palm frond fibers with a size of 80 mesh were employed as the filler. The fiberboard composites were produced using a hot press at 70°C for 20 minutes, with varying mass compositions of polyester resin to palm frond fibers: S1 (60%:40%), S2 (65%:35%), S3 (70%:30%), S4 (75%:25%), and S5 (80%:20%). Parameters observed include physical properties (density and porosity), mechanical properties (impact, tensile, and flexural strength), and microstructure analysis using scanning electron microscope (SEM) and differential scanning calorimetry (DSC). The results indicate that S5 exhibits optimal properties, including a density value of 1.197 g/mL, low porosity at 0.232%, and mechanical characteristics with an impact strength of 271.251 J/m^2, tensile strength of 23.221 MPa, and flexural strength of 149.837 MPa. However, according to the DSC data, S1 stands out with a higher temperature water evaporating point at 82.48°C, indicating greater thermal stability. In addition, SEM results for the S5 sample reveal minimal voids, enhancing the fiberboard composites' physical and mechanical properties and demonstrating high stability. This fiberboard can be classified as a High-Density Fiberboard (HDF) according to JIS A 5905:2003. It is a viable alternative for household furniture, offering a substitute for traditional wood.

Keywords: Composite, fiberboard, palm frond fiber, polyester resin

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INTRODUCTION

The demand for construction materials is increasing rapidly due to global population growth and expanding infrastructure development (Krausmann et al., 2009). Unfortunately, this trend has led to higher deforestation, resulting in limited availability and higher wood prices (Deininger & Minten, 1999). It is crucial to explore alternative materials that can be used as a substitute for wood to mitigate this problem. One promising option is fiberboard, which can be made from various types of natural fibers and composites (Chaharmahali et al., 2008). The use of fiberboard has gained increasing attention in the field of construction and is expected to play an important role in sustainable development (Vitrone et al., 2021).

Fiberboard is a composite material of lignocellulosic substances, including natural fibers or wood dust, that are compressed with specialized adhesives (Arévalo & Peijs, 2016). Its popularity as a construction material has increased due to its excellent mechanical strength and ease of processing. Numerous research studies have been conducted to improve the quality of fiberboard by using high lignocellulosic materials, such as corn cob waste strengthened with isocyanate resin and fibers from coconut husks and banana stems (Arévalo & Peijs, 2016; Kariuki et al., 2020; Sales et al., 2022; Wang & Hu, 2016). Exploring the use of natural fibers from various sources can expand the range of materials available for fiberboard production and potentially reduce waste in different industries.

Furthermore, using fiberboard can contribute to environmental conservation efforts as it is typically made from recycled materials and can be recycled again after use (González-García et al., 2009). It can help reduce waste and promote a more sustainable construction approach. Moreover, fiberboard has several advantages over traditional wood-based materials, including higher durability, better moisture resistance, and easier maintenance (Yuan et al., 2022). These properties make it a desirable option for various applications, such as furniture, flooring, wall panels, and decorative items.

Utilizing palm leaves as a raw material for fiberboard production provides an eco-friendly solution to waste management and has the potential to produce high-quality products due to its high lignocellulose content (Ali et al., 2022). Lignocellulose is a complex structure found in plant cell walls, composed of cellulose, hemicellulose, and lignin, which provides strength and rigidity to the plant and is highly resistant to degradation. The high lignocellulose content in palm leaves makes them ideal for fiberboard production, providing excellent mechanical properties and durability to the final product.

To further enhance the quality of fiberboard, a suitable adhesive is required to bond the fibers together. The choice of adhesive plays a crucial role in determining the mechanical properties of the composite product (Kazayawoko et al., 1999). Polyester resin, a commonly used adhesive, has several advantages, such as its low cost, ability to withstand extreme conditions like heat, acid, and base, and resistance to deformation (Gao et al., 2019). As demonstrated in recent research, polyester has been recognized for its remarkable resistance to a wide range of chemicals, acids, and solvents (Zhang et al., 2023).

Incorporating palm frond fibers, which are emerging as a promising reinforcement agent for polymer composites, introduces the potential for our fiberboard to serve as an innovative thermal insulation material in construction applications (Mlhem et al., 2022). Therefore, this study aims to produce a novel fiberboard composite using palm frond fibers and polyester resin. The resulting fiberboard product is expected to possess desirable properties such as high strength, low density, and good dimensional stability, making it a viable wood alternative for construction needs and various equipment such as furniture (table or chair) and interior design. Eventually, this research will contribute to developing sustainable composite materials and provide an eco-friendly solution to address the environmental impact of wood used in the construction industry.

MATERIALS AND METHODS

The materials used were palm frond fibers (Figure 1), NaOH, polyester resin, methyl ethyl ketone peroxides (as a catalyst), and mirror glaze wax. The equipment includes an 80-mesh sieve, digital balance, hot press, two iron plates, a 100 × 20 × 10 mm sample mold, a 500 mL glass beaker, aluminum foil, spatula, blender, stopwatch, vernier caliper, Universal Tensile Machine (UTM; GOTECH AI-7000M), Wolpert Impactor, Scanning Electron Microscope (SEM; JEOL-JSM-6510LV), and Differential Scanning Calorimetry (DSC; Linseis STA PT 1600). The production of fiberboard composites was carried out in the Basic Chemistry Laboratory of Universitas Sumatera Utara. In contrast, the characterization of the physical, mechanical, and microstructural properties of the fiberboard composites was conducted in the Integrated Research Laboratory of Universitas Sumatera Utara, Indonesia.

Figure 1. Palm frond fiber raw material

Preparation of Palm Frond

The preparation of palm frond fibers was carried out in several stages. First, palm frond fibers were cleaned with water and soaked in 2% NaOH for 24 hours. This stage was done to separate the fibers from organic materials and other debris that were still attached to the fibers. Next, the soaked fibers were immersed in 12% NaOH and heated to 130°C for 120 minutes on a hotplate. The purpose of this stage was to break the bonds between cellulose, lignin and hemicellulose, facilitating the easy separation and refinement of the fibers (Cai et al., 2016). The processed fibers were then cleaned with water and sun-dried. After complete drying, the fibers were ground and sieved through an 80-mesh screen to ensure homogeneity in size.

Manufacturing of Fiberboard Composites from Palm Frond Fiber with Polyester Resin Matrix

The procedure for making fiberboard composites from palm frond fibers with polyester resin matrix began with weighing the fibers and polyester resin. The composition of the polyester resin matrix used for palm frond fibers is presented in Table 1. The polyester resin was then mixed with methyl ethyl ketone peroxides as a catalyst in a ratio of 100:1 to ensure a homogeneous mixture. Next, the mold was cleaned to prevent the mixture from sticking. An aluminum foil was placed on the iron plate as a base and cover for the mold. A mirror glaze was used to coat the mold, and an iron plate was used to prevent the sample from sticking when it was removed. The mold used complies with ASTM D256 standards and is sized at 100 × 20 × 10 mm.

The previously processed polyester resin mixture was then mixed with the palm frond fibers using a blender. The mixture was poured into the mold and leveled using a spatula. The mold was covered with an iron plate covered in aluminum foil and pressed for 20 minutes at a temperature of 70°C. Afterward, the sample was slowly removed from the mold. The appearance of the produced fiberboard composites can be seen in Figure 2. The sample was then subjected to physical and mechanical property testing. In this stage, tests such as density, porosity (Raza et al., 2023), impact strength (Ghori & Rao, 2021), tensile strength, and flexural strength (Patil et al., 2023) were performed to determine the quality of the fiberboard composites produced.

Table 1
Composition of polyester resin and palm frond fiber in composite

Sample Code	Composition	
	Polyester Resin (%)	Palm Frond Fiber (%)
S1	60	40
S2	65	35
S3	70	30
S4	75	25
S5	80	20

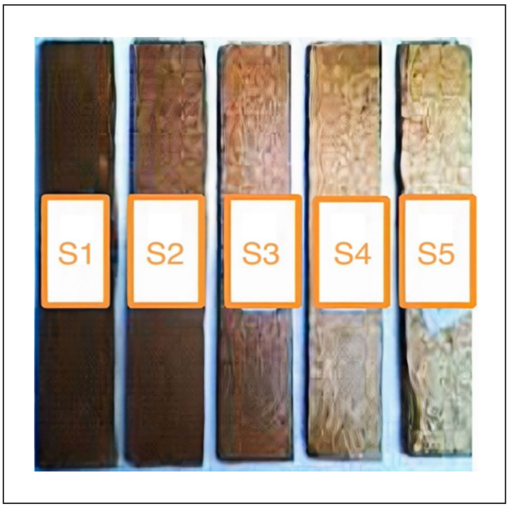

Figure 2. The produced fiberboard composites

Density and Porosity Assessment

The density and porosity of the composites were determined by dividing the mass of the cylindrical samples by their volume. Three replicates were tested, and the averages of these measurements were reported. A digital balance and vernier caliper were used to measure the mass and dimensions by ASTM C134 (Raza et al., 2023).

Impact Strength Measurement

All samples were cut and prepared by ASTM D256, resulting in six replicas with 100 × 20 × 10 mm dimensions. Subsequently, the specimens were conditioned at 22°C with a humidity level of 50% for 48 hours before conducting the tests. The impact test used the Wolpert Impactor instrument (Ghori & Rao, 2021).

Tensile Strength Measurement

The composites' tensile test was carried out using the UTM, following the standard test method ASTM D3039. The crosshead movement was set at 0.02 mm per minute to ensure consistent testing conditions (Patil et al., 2023).

Flexural Strength Measurement

ASTM D790, utilizing the UTM, assessed the flexural characteristics of the test specimens. The specimens were supported at both ends during the test, and a load was applied to the center until failure occurred, following a predetermined rate. The crosshead speed was 1 mm/min (Patil et al., 2023).

RESULTS AND DISCUSSION

Density and Porosity Testing

In this study, composite materials underwent density and porosity testing to determine the ratio of pore volume to the total composite volume. Typically, porosity is expressed as open porosity. The results of these tests are presented in Figure 3.

Figure 3 shows that the highest density was obtained by S5 (sample with the highest polyester resin percentage), which is 1.197 g/mL because polyester resin was used as the matrix in the highest proportion, resulting in the fiberboard composites having the highest density. Additionally, optimal use of resin during molding will result in physical and mechanical properties values with excellent stability of a composite when it is molded (Romanzini et al., 2013). Fiberboard composite made from palm frond fibers using polyester resin as the matrix can be used as a composite board according to JIS (Japanese Industrial Standard) A 5905:2003, which requires a fiber or particle board density value higher than 0.80 g/mL in the High-Density Fiberboard (HDF). Therefore, all fiberboard composites produced with variations in polyester resin and palm frond fibers have met the established requirements.

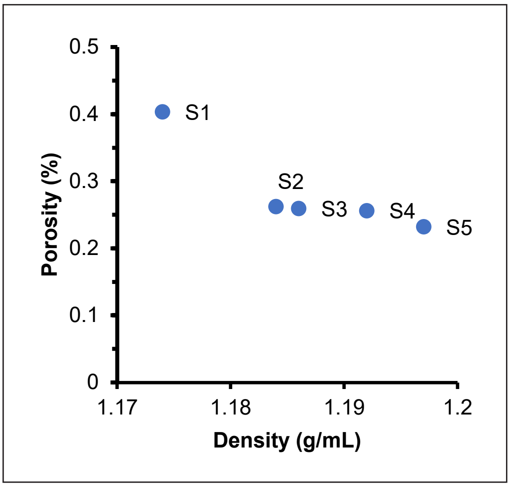

Figure 3. Density and porosity of palm frond-based fiberboard composite

The highest porosity value was observed in S1, with a composition of 60% polyester resin and 40% palm frond fiber, reaching a porosity value of 0.403%. It can be attributed to the uneven distribution of raw materials, particularly due to the hydrophilic properties of palm frond fibers, which tend to absorb more resin (Essabir et al., 2016). Consequently, areas where the fibers were inadequately mixed with the resin resulted in an uneven surface, increasing the presence of open pores in the fiberboard composites. Conversely, the lowest porosity was achieved with S5, yielding a porosity value of 0.232%. The raw materials were easily and evenly mixed in these compositions, resulting in a fiberboard composite with a sufficiently low percentage of pores.

Understanding the porosity of the board is crucial as this property plays a key role in hot-pressing simulation models (Rebolledo et al., 2018). The porosity of fiberboard significantly influences transfer mechanisms and the development of density profiles. Analyzing how fiber size and density impact the material's porosity can help determine optimal conditions for the vertical density profile, ultimately enhancing the overall quality of the fiberboard. The data in this study reveals a clear relationship between porosity and density (Rebolledo et al., 2018). Similarly, Shinoj et al. (2010) also observed a consistent trend: An inverse relationship between density and porosity. In other words, as porosity increases, density decreases, and vice versa. For instance, in the case of the S1 composite, an increase in porosity leads to more void spaces within the material, resulting in a lower overall density due to a reduced amount of solid material per unit volume. On the contrary, materials with lower porosity exhibit fewer void spaces, contributing to higher density.

Impact Strength

The impact strength test was conducted to determine the toughness of a sample under dynamic loading and whether the tested material was brittle or strong. It was performed using the Wolpert Impactor instrument. In this test, both ends of the sample were placed on supports, and then the impactor was quickly released towards the sample with dynamic load. The results of the impact strength test for the fiberboard composites are displayed in Figure 4.

Figure 4 shows that the highest impact strength of the composite was obtained by S5, with an impact strength value of 271.251 J/m^2. The results indicate that the impact

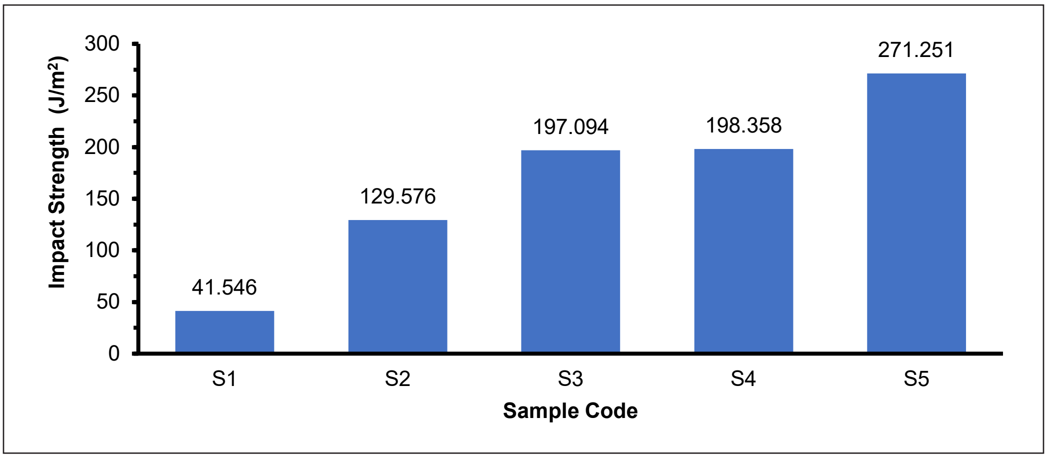

Figure 4. Impact strength of palm frond-based fiberboard composite

strength increases as the composition of polyester resin as the matrix increases because the mechanical properties of polyester resin improve resistance to deformation when it is evenly mixed with other base materials and, therefore, increasing the composition of polyester resin will affect the impact strength value of the fiberboard composite. In previous studies, Raju and Balakrishnan (2020) reported that palm fiber modified with epoxy and glass fiber yielded the highest impact strength, measured at 116 J. However, in this present study, it has been observed that palm frond fiber modified with polyester resin demonstrates a significantly higher impact strength. This substantial difference in impact strength can be attributed to using polyester resin. Known for its excellent resistance to stress-induced deformation, polyester resin substantially increases the impact strength upon its incorporation into the composite, as evidenced by the findings of Daramola et al. (2023). Additionally, polyester is recognized as a shatter-proof material, making it a viable alternative to glass in the production of containers (Seixas et al., 2023).

Tensile and Flexural Strengths

When subjected to a pulling force, the internal bond strength, or the tensile strength test, assesses a material's maximum load-bearing capacity. Meanwhile, the flexural strength test is designed to evaluate the composite's resistance to loading at three flexure points and to measure its elasticity. Tensile and flexural strength tests were performed using a UTM, with the test conducted by applying a load to both ends of the sample. The obtained values can be observed in Figure 5.

Based on Figure 5, S5 demonstrates the highest tensile and flexural strength among the composites, with values of 23.221 MPa and 149.837 MPa, respectively. This composite's tensile and flexural strengths are higher than the compressive strength. It can be attributed to the composite's composition of resin and palm fiber, where the fiber orientation

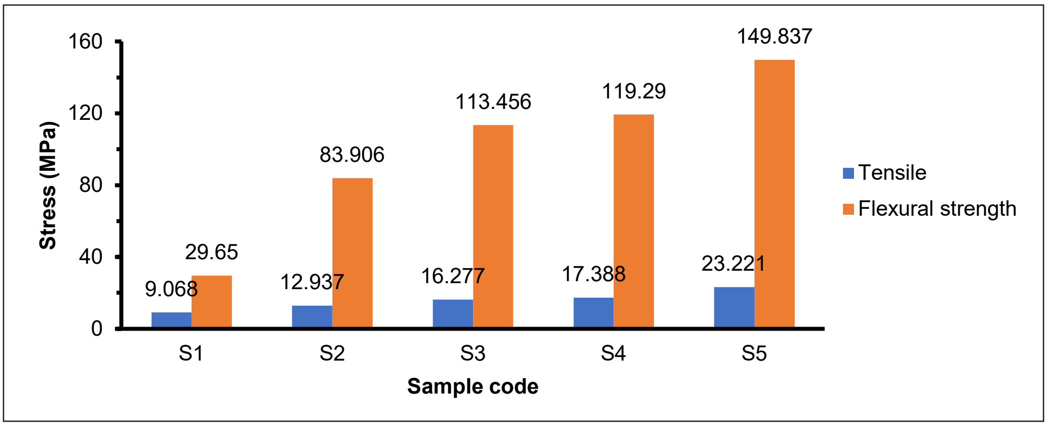

Figure 5. Tensile and flexural strength of palm frond-based fiberboard composite

contributes to enhanced stability in tensile and flexural strength (Hachaichi et al., (2021). The results indicate an impact and flexural strength increase as the matrix's polyester resin composition increases. It aligns with Kalam et al. (2005), who found a decrease in tensile strength with higher palm fiber content in palm fiber epoxy composites. Additionally, as noted by Ramlee et al. (2021), several factors contribute to the lower tensile strength of palm composites, including poor adhesion capability, the hydrophilic nature of the fibers, and the random orientation of palm fibers within the matrix, resulting in inefficient stress transfer. Furthermore, decreased flexural strength with increasing palm fiber content leads to fiber failure and reduced composite strength (Karina et al., 2007).

The fiberboard produced in this study can be a viable alternative to wood, particularly for crafting furniture (Rosli et al., 2024). Moreover, because this fiberboard falls under the category of HDF, it can be used for furniture and other applications such as laminate flooring and siding (Rowell, 2014; Tang et al., 2017).

SEM Morphology

Surface analysis of the fiberboard composites was conducted using SEM on samples S1 and S5. Sample S1 was chosen because it had poor mechanical properties, while sample S5 had the highest mechanical properties compared to the other samples. Figure 6 shows the surface analysis results obtained using SEM.

The SEM test results on sample S1 suggest that many strands of palm frond fibers are not evenly distributed, resulting in clumps. It indicates that the composite is not homogeneously mixed, resulting in many unfilled spaces or voids not covered by the matrix, causing voids on the composite surface. Meanwhile, the SEM test results on sample S5 show that only a few palm frond fiber powders are unevenly mixed, and it is evident that the smooth surface reveals that the polyester resin binds the palm frond fibers evenly. It demonstrates that this composition's composite components with lower palm fiber are

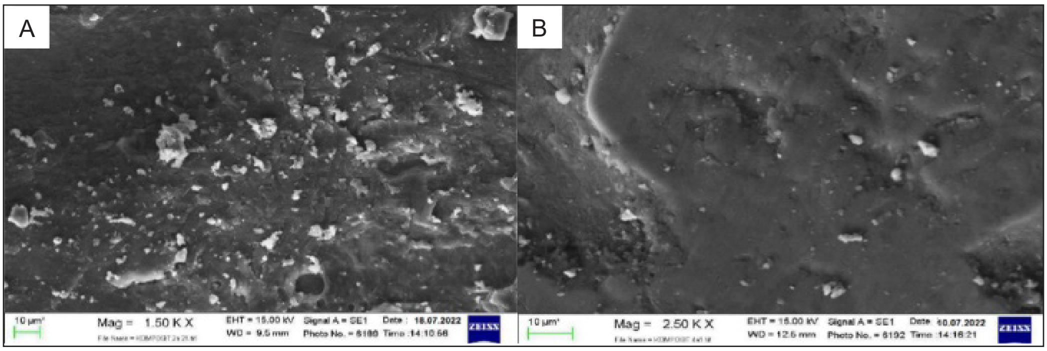

Figure 6. SEM morphology of palm frond-based fiberboard composite with a magnification of 1500× (A=S1 and B=S5)

more homogeneous (Chiromito et al., 2019). Similarly, as suggested by Raza et al. (2023), the homogeneity of the composite is influenced by the proportion of the polymer matrix. Composites with a higher proportion of polystyrene matrix compared to date surface palm fibers (DSF) exhibited no significant cleavage. This observation suggests DSF had a well-dispersed homogeneous distribution within the polystyrene matrix. Notably, voids within a composite can reduce mechanical strength, act as stress concentrators, and contribute to reduced stiffness. In addition, the image of sample S5 presented in this study indicates a relatively lower formation of voids, resulting in the fiberboard composite exhibiting the most optimal physical and mechanical properties.

DSC Analysis

We conducted a DSC analysis on the palm fronds-based fiberboard composite to compare the heat required to raise the sample's temperature. The analysis focused on the time- and temperature-dependent heat flow. Figure 7 displays the DSC thermogram.

The results of the DSC analysis were quantified in terms of degradation temperature values. The graph shows that the degradation of the materials began around 250°C. As depicted in Figure 7, during the heating phase lasting 5 to 10 minutes, an exothermic peak was observed in both the palm frond fiber raw material and composite thermograms. This peak indicates the evaporation of water, occurring at approximately 76.09°C. In the case of the palm frond fiber composite, a curing peak was also observed, which significantly decreased with a reduction in the percentage of palm fiber addition. As for samples S1 to S5, with decreasing percentages of palm frond fiber in the composites, there was a corresponding decrease in the water evaporation temperature, ranging from 82.48 to 67.82°C (Table 2). Notably, S1, containing the lowest polyester resin, exhibited the highest evaporation temperature.

These results suggest that an increase in palm fiber content has a diminishing effect on the thermal stability of the composites. As Ahmad et al. (2023) reported, the varying

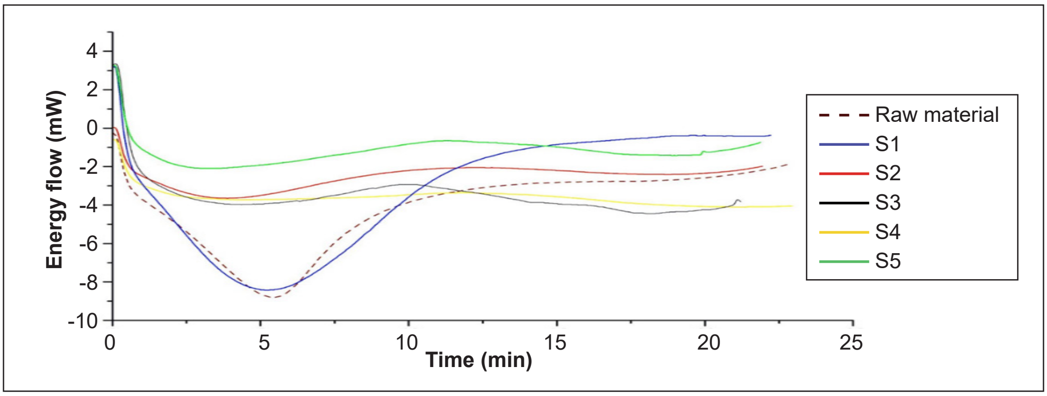

Figure 7. The DSC peaks for temperature degradation of palm fronds-based fiberboard with various composition

Table 2
Water evaporation temperature peaks (°C) from DSC analysis

Code	Peak of glass temperature (°C)
Raw material	76.09
S1	82.48
S2	72.36
S3	71.66
S4	67.45
S5	67.82

temperatures required for fibers to evaporate their water content can be attributed to the different non-substituted hydroxyl groups on their surfaces. Fibers with a higher affinity for water molecules require higher temperatures to evaporate their water content (Hachaichi et al., 2021). This study also found similar results, demonstrating that an increase in the percentage of polyhydroxybutyrate (decrease in degree of polymerization/ DPF) in composite materials reduced their thermal stability. It was attributed to weakened hydrogen bonding and reduced mobility of cellulose chains in DPF, particularly after the composite's dehydration process (Mlhem et al., 2022).

CONCLUSION

Mixing palm frond fibers with a polyester resin matrix resulted in the production of a fiberboard composite that can serve as a substitute for wood. The material fulfilled the JIS A 5095:2003 assessment requirements with a "hard board" classification and underwent physical and mechanical testing. S5 demonstrated the best physical and mechanical properties, indicating an optimal mass ratio composition of 80% polyester resin and 20% palm frond fibers, as shown by the microstructure of the fiberboard composite. Testing resulted in the highest density of 1.197 g/mL, the lowest porosity of 0.232%, the optimal impact strength of 271.251 J/m^2, tensile strength of 23.221 MPa, and flexural strength of 149.837 MPa. The SEM microstructure analysis showed the least number of voids formed, supporting the fiberboard composites' maximum physical and mechanical properties. However, based on the DSC analysis, S1 emerges with a notably higher temperature for water evaporation, recorded at 82.48°C. These results imply that while S5 may excel in specific mechanical and physical properties, S1 exhibits superior thermal characteristics.

This study has several limitations that merit consideration. While essential for controlled experimentation, the controlled laboratory conditions may not entirely replicate the variability encountered in real-world applications, thereby introducing a limitation regarding the study's external validity. Moreover, the study did not address the long-term durability of the fiberboard composite, leaving uncertainties about its performance in real-world environments over extended periods. Furthermore, the study predominantly focused on one manufacturing method—hot pressing—and did not explore alternative production techniques, limiting the understanding of potential material properties variations. Lastly, the evaluation of thermal stability was confined to the temperature of water evaporation, neglecting a broader exploration of other thermal properties and responses to diverse environmental conditions.

Future research should explore various avenues to enhance the understanding and applicability of the developed fiberboard composites. Investigating alternative fiber types or sizes beyond palm frond fibers would contribute to a more comprehensive understanding of the material's versatility. Similarly, exploring diverse resin types, including bio-based or environmentally friendly options, can open avenues for creating more sustainable composite materials. Long-term durability studies under real-world conditions are essential to assess the material's performance over extended periods and under varying environmental factors. A more thorough exploration of thermal properties, encompassing a broader range of temperatures and conditions, would provide valuable insights into the material's behavior. Environmental impact assessments, including recyclability and biodegradability, are essential to determine the ecological footprint of the composite. Furthermore, future research should address variability in manufacturing conditions, such as temperature, pressure, and curing time, to ensure robust and consistent material properties.

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