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Physical, mechanical and thermal properties of composite board based on palm frond fibers and feather clam shells

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ABSTRACT

Research on natural composite boards with polyester has been completed. In this study, composite boards were fabricated using palm frond fiber (PFF) and feather clam shell (FCS) combined with polyester. The mass ratios (%) of PFF:FCS:polyester investigated were 55:20:25, 45:30:25, 35:40:25, 25:50:25, and 15:60:25. The composite board manufacturing process involved pressing for 20 minutes at a pressure of 30 kg/m² and a temperature of 70 °C. Physical parameters observed included density, porosity, and water absorption, while mechanical properties assessed comprised compressive strength, impact resistance, tensile strength, and flexural strength. Additionally, microstructural analysis was conducted using scanning electron microscopy (SEM) and thermal properties were evaluated through differential scanning calorimetry (DSC). The results indicated that the optimum composition of 15% PFF, 60% FCS, and 25% polyester (Sample 5) produced composite boards with a density of 1.511 g/cm³ and a DSC value of 55.03 mW. The mechanical properties at this composition showed a compressive strength of 0.133 kgf/mm², a tensile strength of 0.032 kgf/mm², and an impact resistance of 1.6 J/mm². SEM analysis revealed that the composite board with the 15:60:25 ratio (Sample 5) exhibited the highest distribution and homogeneity of its components. Compared to conventional wood-based materials, the composite boards demonstrated superior strength-to-weight ratios, resistance to water absorption, and thermal stability, making them highly durable and cost-effective. Additionally, the use of PFF and FCS provides a sustainable alternative by utilizing agricultural and marine waste, contributing to environmental conservation. According to JIS A 5905:2003 standards, the fabricated composite board from PFF and FCS combined with polyester in this study are categorized as "Hard Boards," making them a viable alternative to wood for furniture applications such as tables and chairs.

Keywords: composite board, palm frond fiber, feather clam shell, polyester resin, characterization.

INTRODUCTION

In recent years, the development of wood furniture has gained significant attention due to the increasing demand for traditional wood-based products (Laksham and Hitish, 2023). This trend has intensified deforestation, leading to reduced wood availability and rising costs. To address this issue, it is imperative to explore alternative materials that can substitute wood. Fiberboard emerges as a promising alternative, as it can be manufactured from a variety of natural fibers and composite materials (Hasanah et al., 2024; Astari et al., 2024). Composite fiberboards are well-suited as wood substitutes because they are made from lignocellulosic materials like sawdust or natural fibers (Hasanah et al., 2023; Hasanah et al, 2024). These materials, often derived as waste from agriculture, plantations, and forestry, are abundant and cost-effective. Composite boards are reliable due to their good mechanical strength, ease of processing, and lower cost compared to wood (Hongxia Pu et al., 2022). Compared to wood, composite fiberboards offer several advantages, including being free from knots, splits, and cracks, with customizable size

and density that make them easy to work with. Additionally, they exhibit isotropic properties and can be tailored for specific qualities (Cintura et al., 2024). According to Cruz et al. (2023), composite fiberboards are classified into three groups based on density: low density (≤ 0.4 g/cm³), medium density (0.4–0.8 g/cm³), and high density (≥ 0.8 g/cm³).

Several natural fibers have been studied as potential materials, including corn cob (Astari et al., 2024), areca husk fibers (Neelappa et al., 2024), sugarcane bagasse (da Silva Almeida et al., 2024), and palm fiber (Siddiqui et al., 2024). Among these, palm frond fiber (PFF) stands out as an interesting material due to its abundance as a by-product of oil palm harvesting, with waste production reaching up to 10 tons per hectare per year. Despite this large volume, the utilization of palm fronds remains underexplored (Georgiou et al., 2023). Typically, palm fronds are either piled near trees, used as livestock feed, or burned to produce potassium fertilizer. Notably, the lignocellulose content in PFFs is significantly higher than that in empty palm fruit bunches or other plants (Madusari et al., 2023).

Previous studies have shown that the physical properties of palm fiber polymer composites improve as the amount of palm fiber increases. After 168 hours of soaking in cold water, these properties reached acceptable levels, with water absorption at 30% and thickness swelling at 0.9% (Hasanah et al., 2024; Chkala et al., 2024). Similarly, a study on fiberboard made from corn stalks (*Zea mays* L.) and citric acid reported excellent density, achieving 0.7 g/cm³ (Astari et al., 2024). Despite the significant potential of palm fiberboard, its mechanical strength, particularly in terms of tensile and compressive resistance, remains lower than that of traditional wood materials or other composites. This limitation restricts its use in applications requiring high structural strength (Khan et al., 2024). To overcome this issue, incorporating a filler into the fiber composite is necessary (Cai et al., 2024).

FCS are another waste material that can serve as a bio-composite filler. These shells are available in large quantities and, if unprocessed, can contribute to environmental pollution. As global population increases, especially from consumption-based sources, the volume of this waste continues to grow. Utilizing FCS not only reduces the environmental burden by repurposing a waste material but also helps minimize landfill waste and pollution. Additionally, this practice aligns with the growing need for sustainable materials in the manufacturing industry. FCS contains 66.70% CaO and 22.28% MgO, making them an excellent filler material for strengthening composite boards (N. Wang et al., 2021). Previous research has demonstrated that incorporating 5% crab shell powder into a hybrid composite increased tensile, flexural, and impact strengths by 21%, 52%, and 50%, respectively. Furthermore, the hardness of the hybrid composite improved by 33% (Kocharla et al., 2024). Another study found that fiberboard bonded with a citric acid/shrimp shell adhesive exhibited dry and wet shear strengths of 2.1 MPa and 1.1 MPa, respectively, exceeding the China National Standard (GB/T 9846-2015, ≥ 0.7 MPa). The adhesion mechanism involved mechanical interlocks and cross-linking between the citric acid/chitosan in the adhesive and components within the cell wall (Cai et al., 2024).

In addition to matrix and filler, adhesive material such as polyester resin are essential for producing bio-composites. Polyester resin, a low-viscosity liquid that cures room temperature with a catalyst, is not only affordable but also possesses advantageous properties such as stiffness, brittleness, good weather resistance, moisture resistance, transparency, and resistance to acids, except oxidizing acids (Prabhuram et al., 2023). These properties make it suitable for use in composite materials. Furthermore, PFFs, FCS, and polyester offer additional benefits, including low cost, low density, renewability, and biodegradability, which make them attractive as reinforcing agents in fiberboard composites.

Despite these advantages, there remains a need for sustainable and cost-effective alternatives to traditional wood-based boards, which often face challenges such as high production costs, limited renewability, and environmental concerns. This study addresses this gap by investigating the feasibility of using PFFs, FCS, and polyester as raw materials for composite boards. Specifically, this research aims to explore how variations in composite loading affect the mechanical, physical, and microstructural properties of the boards. It provides a detailed analysis of compressive and flexural strength, water absorption, density, and porosity, alongside thermal and microstructural evaluations using differential scanning calorimetry (DSC) and scanning electron microscopy (SEM).

METHODS

Materials and instruments

The materials used include PFF and FCS powder. The chemical materials include polyester resin adhesive (Sigma-Aldrich, USA), methyl ethyl ketone peroxides (Sigma-Aldrich, USA) as the catalyst, NaOH (analytical grade; Merck, Germany), and wax mirror glaze (TR Industries,USA). Additionally, several instruments were employed, including a compressive testing machine (Heico, India), a Universal Tensile Machine (UTM; GOTECH AI-7000M), a density meter (MH-300A), Differential Scanning Calorimetry (DSC; Linseis STA PT 1600), and a Scanning Electron Microscope (SEM; JEOL-JSM-6510LV).

Sample preparation

The PFFs were first cleaned and soaked in a 2% NaOH solution for 24 hours. After soaking overnight, the fibers were immersed in a 12% NaOH solution and heated at 130 °C for 120 minutes on a hotplate. The fibers were then washed with clean water, dried in the sun, and cut into 0.5 cm lengths. The selected FCS were cleaned, washed with water, and dried in the sun. Once dried, the shells were crushed into powder and sieved using a 200-mesh sieve.

Composite board fabrication

A total of 10 g of PFFs, FCS powder, and polyester resin were measured according to specific composition ratios (%w:%w:%w): (55%:20%:25%), (45%:30%:25%), (35%:40%:25%), (25%:50%:25%), and (30%:60%:25%) using a digital balance (Hasanah et al., 2024). The ratio was developed to evaluate how varying the amounts of PFF, FCS powder, and polyester resin affects the composite's properties. PFF content was varied from 25% to 55% to study its impact on strength. FCS powder content was adjusted from 20% to 60% to assess its role as a filler. Polyester resin was kept constant at 25% to maintain a consistent adhesive matrix. This approach helps identify the optimal balance for improved composite performance. The polyester resin was mixed with the catalyst in a 100:1 ratio (100 g of polyester resin and 1 g of catalyst). This mixture was then stirred until a homogeneous dough was formed. After mixing, the dough was placed into a mold, which was covered with an iron plate coated with aluminum foil and pressed using a hot press with a pressure of 30 kg/m² for 20 minutes at 100 °C. Afterward, the sample was carefully removed from the mold and left to rest for about 3 hours to allow the adhesive to harden before it was fully removed. Finally, the sample was dried for 7 days to achieve uniform moisture content distribution and relieve any residual stress in the board caused by the pressing process. The biocomposite was then prepared for characterization (Choi et al., 2022).

Composite board evaluation

The performance of the boards was assessed following the ASTM D 1037-93 standard procedures. Water absorption was evaluated using samples measuring 5×5 cm, which were immersed in water at room temperature for 2 hours and 24 hours to analyze short- and long-term changes. The weight gain and thickness of the samples were recorded immediately after immersion. Prior to testing, all samples were conditioned at 65% relative humidity and 20 °C for 7 days. Mechanical tests, including tensile, flexural, and compressive strength tests, were conducted using a UTM equipped with a 10 kN load cell with 0.2% accuracy. Rectangular strips measuring 50×190 mm were used for the mechanical tests. Tensile strength tests were performed at a crosshead speed of 4 mm/min, while flexural strength tests were conducted at a crosshead speed of 2.9 mm/min with a 140 mm span (Nicolao et al., 2020). The density and porosity of the composites were obtained by dividing the mass by the volume of the cylindrical samples. Three replicates were tested, and their averages were reported (Hasanah et al., 2024; Raza et al., 2023; Gashawtena et al., 2024).

RESULTS AND DISCUSSION

Density

Density testing is a key physical property that measures the ratio of an object's mass to its volume, or the mass of a substance per unit volume (Zhang et al., 2023). Figure 1 illustrates the relationship between the density of composite boards made from PFF and FCS using polyester resin, with variations in the composition of PFF, FCS, and polyester resin.

Figure 1 shows the densities of composite boards with different compositions as follows: 55:20:25 with 0.814 gr/cm³, 45:30:25 with 1.137 gr/cm³, 35:40:25 with 1.478 gr/cm³, 25:50:25 with 1.388 gr/cm³, and 15:60:25 with 1.511 gr/cm³. The data indicate that as the proportion of FCS increases in the composite boards, their density generally increases. However, in the 25:50:25 composition (Sample 4), where a higher of density was expected, a decrease was observed. This anomaly may result from an uneven mixing process during the preparation of the sample dough. Additionally, air trapped during the pressing process may have hindered adequate particle bonding, contributing to the decreased density (Yang et al., 2023). The highest density, 1.511 gr/cm³, was achieved by Sample 5, which contained the highest proportion of FCS. This higher density can be attributed to the increased shell content, which enhances the compactness of the composite board, along with the optimal use of resin during the molding process. These factors contribute to improved physical and mechanical properties (Chrispin Das et al., 2023).

Furthermore, the fabricated composite boards complies with the Japanese Industrial Standard (JIS) A 5905:2003 for fiber/particle boards. This standard specifies a minimum density of 0.80 gr/cm³ for classification as a "hard board." Therefore, all composite boards produced with varying compositions meet the established standards (Homkhiew et al., 2020).

Porosity

Porosity refers to the percentage of void space within a material and is closely related to its density. Porosity testing was performed to determine the ratio of pore volume to the total volume of the composite (Rao et al., 2023). Figure 2 illustrates the porosity of the composite boards produced.

Based on Figure 2, the porosity results are as follows: 55:20:25 with a porosity of 0.322%, 45:30:25 with 0.174%, 35:40:25 with 0.103%, 25:50:25 with 0.239%, and 15:60:25 with 0.047%. The highest porosity value, 0.322%, was observed in the 55:20:25 composition (Sample 1), which can be attributed to the low proportion

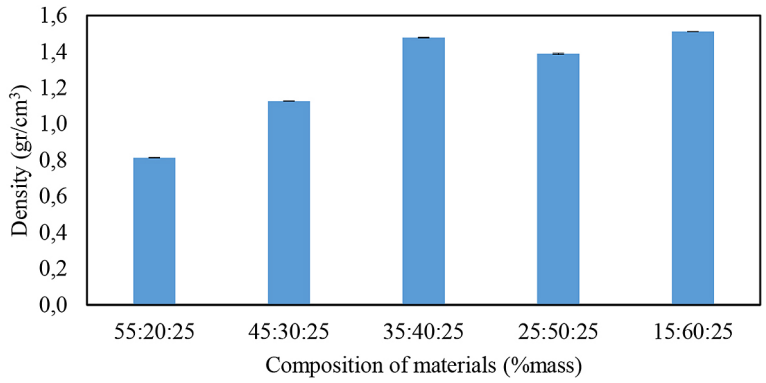

Figure 1. Density of the composite boards

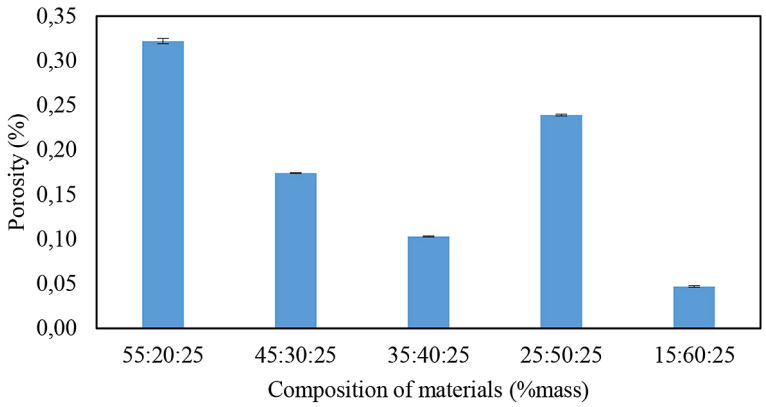

Figure 2. Porosity of the composite boards

of FCS, the primary filler material in the composite board. Conversely, the lowest porosity value, 0.047%, was recorded in the 15:60:25 composition (Sample 5). This composition contains the highest proportion of FCS powder, significantly reducing the number of pores in the composite board. However, in the 25:50:25 composition (Sample 4), the porosity increased despite expectations of lower values. This anomaly is likely due to the observed decrease in density, which may have resulted in the formation of more pores within the composite board (Haider et al., 2022).

Water absorption

Water absorption testing is a method used to evaluate a key physical property of composite boards: their ability to absorb water after immersion for 2 or 24 hours. This test is crucial for assessing the board's water resistance, particularly when the board is designed for outdoor use and exposure to environmental conditions. Figure 3 presents the results of the water absorption test. The results show that the 55:20:25 composition (Sample 1) has the highest water absorption at 0.396%, due to the higher proportion of PFF, which is hydrophilic and absorbs water easily. In contrast, the 15:60:25 composition (Sample 5) has the lowest water absorption at 0.034%, thanks to its high FCS content, which is water-resistant and creates a denser, less porous structure. As the FCS content increases, water absorption decreases, improving water resistance. However, the 25:50:25 composition (Sample 4), with 0.172% absorption, shows slightly higher water uptake than expected, likely due to uneven mixing or trapped air increasing porosity. In summary, higher FCS content enhances water resistance, making Sample 5 ideal for moisture-prone applications.

Compressive strength test

Compressive strength testing is conducted to evaluate the mechanical properties of composite materials under pressure or compressive forces. The results of the compressive strength test for the fabricated composite materials made are shown in Figure 4.

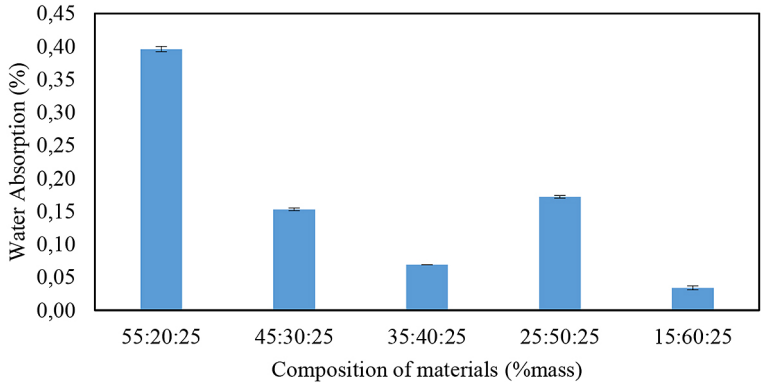

Figure 3. Water absorption of composite boards

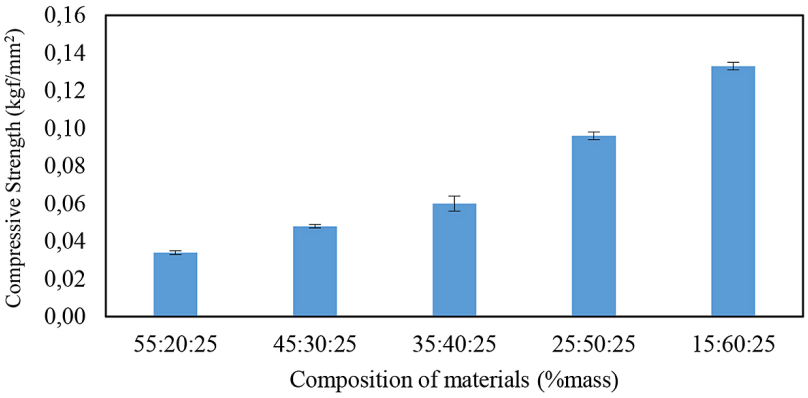

Figure 4. Compressive strength test results

The measured compressive strengths are as follows: 55%:20%:25% at 0.034 kgf/mm², 45%:30%:25% at 0.048 kgf/mm², 35%:40%:25% at 0.060 kgf/mm², 25%:50%:25% at 0.096 kgf/mm², and 15%:60%:25% at 0.133 kgf/mm². The highest compressive strength (0.133 kgf/mm²) was achieved with the 15%:60%:25% composition (Sample 5), indicating that compressive strength improves as the proportion of FCS powder increases, up to an optimum value. Consequently, the mechanical strength of the composite board improves with the increased concentration of FCS powder in the mixture.

Tensile strength test

Tensile testing is a process used to evaluate the mechanical properties of composite materials under tensile stress. This testing is essential for determining a material's or composite's ability to resist tensile forces without failing or breaking. It is crucial because it reveals the material's capacity to endure tensile stresses that may occur in practical applications, particularly in situations where the material must support applied forces or loads on its surface (Hadini et al., 2024). The tensile test for the composites was conducted in accordance with the standard test method ASTM D 1037-93 (Nicolao et al., 2020). During this test, a sample of the composite material is subjected to a gradually increasing tensile force while its response to the applied force is measured. The tensile test results for the composite materials are shown in Figure 5. The tensile test results are as follows: 55%: 20%: 25% of 0.0017 kgf/mm², composition of 45%: 30%:25% of 0.0020 kgf/mm², 35%:40%:25% of 0.0030 kgf/mm², 25%:50%:25% of 0.0031 kgf/mm², and 15%:60%:25% of 0.0032 kgf/mm². The highest tensile strength was obtained from Sample 5 (15%:60%:25%) with a value of 0.0032 kgf/mm². This finding is consistent with previous studies, which reported an increase in tensile strength as the palm fiber content decreased in palm fiber epoxy composites (Hasanah et al., 2024; Hadini et al., 2024).

Impact test

Impact testing is a method used to assess the response of composite materials to impact loads. This evaluation provides critical insights into the strength and ductility of materials when subjected to impact forces, which are often encountered in real-world applications. The impact test results are presented in Figure 6. The impact strength of each variation of composite boards is as follows: 55%:20%:25% at 1.2 J/mm², 45%:30%:25% at 1.0 J/mm², 35%:40%:25% at 1.2 J/mm², 25%:50%:25% at 1.4 J/mm², and 15%:60%:25% at 1.6 J/mm². The highest impact strength was obtained from Sample 5 (15%:60%:25%) with a value of 1.6 J/mm². However, the decrease in impact strength observed in the composition of 45%:30%:25% (Sample 2) is associated with insufficient pressing treatment during the molding of the brittle composite board. This study found that both the volume fraction and pressing treatment affect the composite's strength in the impact test (Jing et al., 2023).

DSC analysis

The DSC thermal analysis method is widely used to analyze the thermal properties of a material. This analysis was conducted to determine the thermodynamic behavior of the base material, as the production of thermal insulation materials

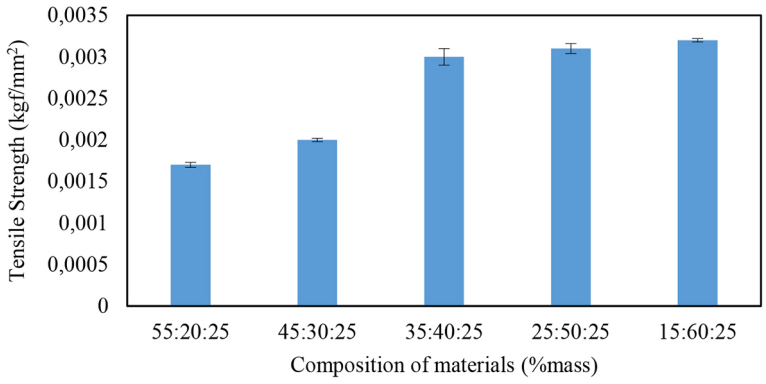

Figure 5. Tensile strength of composite boards

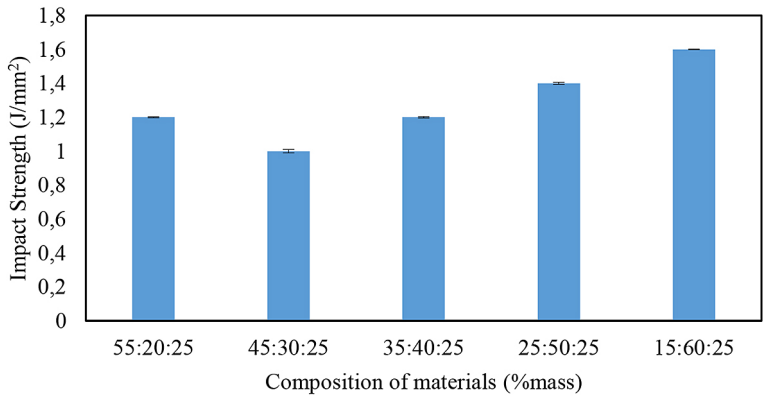

Figure 6. Impact strength of composite boards

involves hot pressing, which can affect the quality of the material, particularly its physical properties. Therefore, it is essential to analyze the thermal properties of the base material to assess its ability to withstand the applied heat load, both before and after the production process (Jennings et al., 2024). The results of the DSC testing on composite boards are shown in Figure 7.

The results of the DSC testing of composite boards with varying compositions are as follows: for the composition 55%:20%:25%, endothermic activity occurs at temperatures ranging from 28.99 °C to 120.75 °C, while exothermic activity occurs between 459.21°C and 548.72 °C, with a peak heat of 52.60 mW at 499.45 °C. For the composition 45%:30%:25%, endothermic activity occurs at temperatures from 54.68 °C to 110.74°C, with exothermic activity between 463.09 °C and 534.27 °C, and a peak heat of 46.24 mW at 505.08 °C. For the composition 35%:40%:25%, endothermic activity is observed from 162.24 °C to 273.24 °C, while exothermic activity occurs between 462.47 °C and 504.73 °C, with a peak heat of 42.66 mW at 491.62 °C. For the composition 25%:50%:25%, endothermic activity occurs at temperatures ranging from 113.94 °C to 236.9 °C, while exothermic activity is observed between 469.63 °C and 511.64 °C, with a peak heat of 30.07 mW at 499.92 °C. Finally, for the composition 15%:60%:25%, endothermic activity occurs between 133.26 °C and 286.73 °C, while exothermic activity is observed from 469.63 °C to 507.14 °C, with a peak heat of 55.03 mW at 493.32 °C.

These findings indicate that increasing the palm fiber content reduces the thermal stability of the composites. According to Ahmad et al. (2023), the different temperatures required for fibers to release their water content are due to the

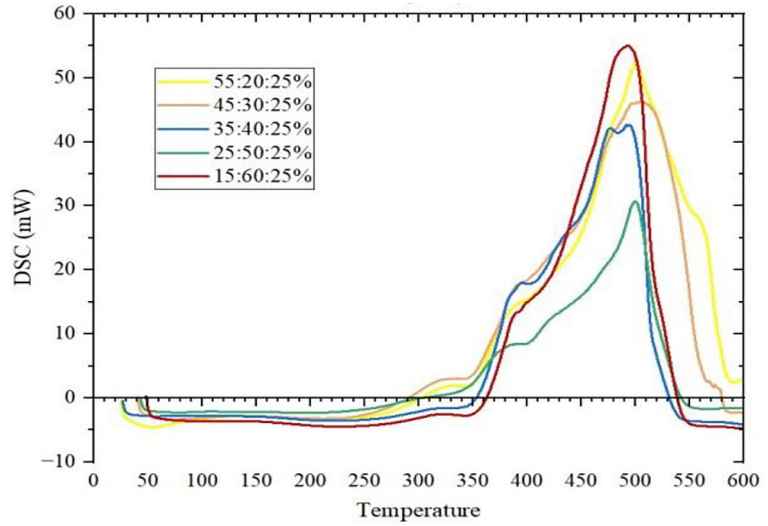

Figure 7. The effect of thermal conditions on board composites with various mass of PFF, FCS, and polyester

varying non-substituted hydroxyl groups present on their surfaces. Fibers with a greater affinity for water molecules require higher temperatures for water evaporation. This study also observed similar results, demonstrating that an increase in the polyhydroxybutyrate percentage within composite materials lowers their thermal stability (Hachaichi et al., 2021). Based on the data presented, it can be concluded that the composite board composition of PFF and FCS using polyester adhesive, which exhibits good thermal stability, is the composition of 15%:60%:25%, with a DSC value of 55.03 mW (Pardi et al., 2024).

SEM morphology

The microstructure testing was conducted to examine the pores of the composite boards at 500× magnification using SEM, as shown in Figure 8.

In general, the composite exhibits uneven mixing, leading to unfilled gaps or voids within the matrix, which contribute to the formation of voids on the composite's surface (Khallaf et al., 2024). Based on SEM results, the microstructure of the composite boards varied significantly with changes in composition. Sample A (55%:20%:25%) exhibited a high density of voids and irregularities, with poor interfacial adhesion between PFF, FCS particles, and polyester resin, along with uneven fiber distribution. Sample B (45%:30%:25%) showed reduced porosity compared to Sample A but still displayed visible voids, uneven dispersion of FCS particles, and fiber pull-out, indicating suboptimal bonding. In Sample C (35%:40%:25%), the dispersion of FCS particles improved; however, small gaps between the matrix and reinforcement, as well as particle aggregation, were observed, potentially creating stress concentration points. Sample D (25%:50%:25%) demonstrated better FCS particle distribution, but voids remain in some points. Sample E (15%:60%:25%) exhibited the most uniform dispersion of FCS particles, minimal voids, strong interfacial bonding, and a compact structure with reduced fiber pull-out. This well-integrated morphology enhances the composite's mechanical and physical properties, as seen in its superior tensile, compressive, and impact strengths, as well as its thermal stability. The compact and cohesive structure of Sample E supports its designation as the optimum composition, with SEM analysis directly correlating its microstructural features to its superior overall performance.

The microstructure of the sample above demonstrates that the greater the material mixture and the pressure applied during molding significantly influence the characteristics of the composite board (Er Yusuf et al., 2024). Additionally, studies by Hasanah et al. (2024) and Raza et al. (2023) report similar findings, highlighting that the homogeneity of the composite is affected by the proportion of the polymer matrix. Composites with a higher proportion of polystyrene matrix

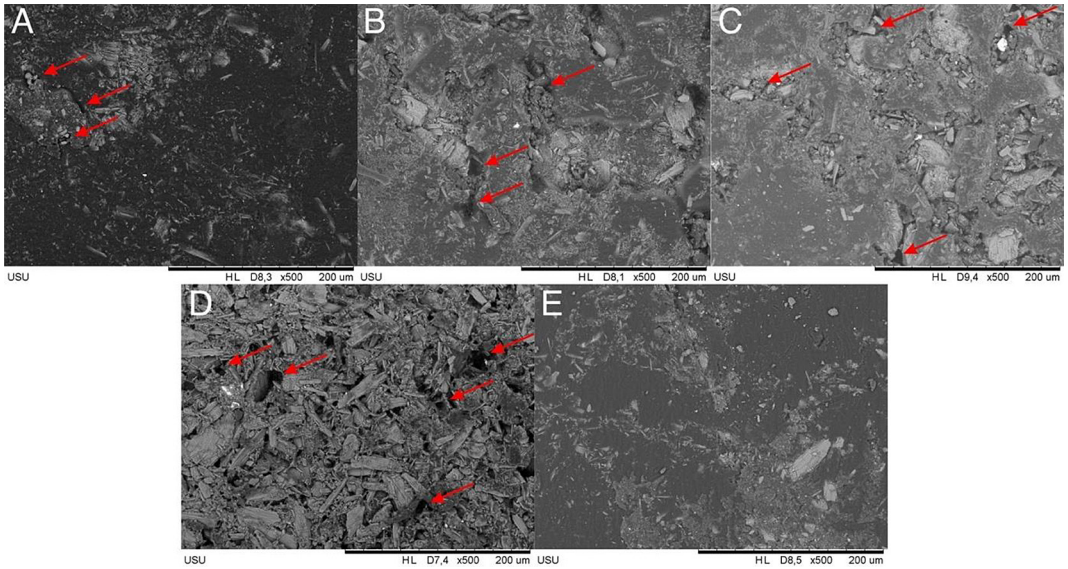

Figure 8. SEM morphology of composite boards with variations in PFF:FCS:polyester resin composition: (A) 55%:20%:25%, (B) 45%:30%:25%, (C) 35%:40%:25%, (D) 25%:50:25%, and (E) 15%:60%:25% (red arrows indicate voids)

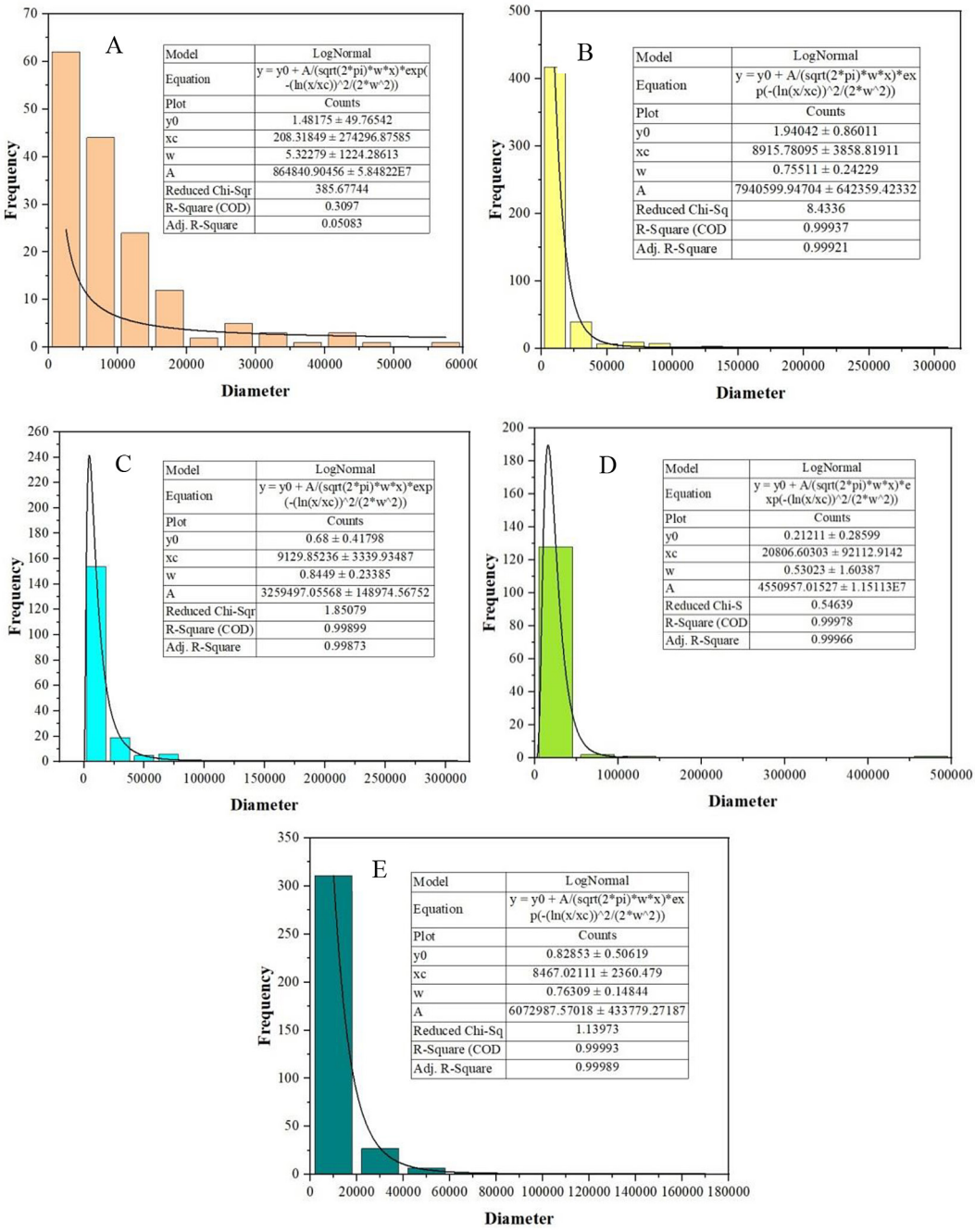

Figure 9. Particle size distribution of composite boards: (A) 55%:20%:25%, (B) 45%:30%:25%, (C) 35%:40%:25%, (D) 25%:50%:25%, and (E) 15%:60%:25%

relative to surface PFFs exhibited no significant separation, indicating that the fibers were well-dispersed and homogeneously distributed within the polystyrene matrix (Patil et al., 2023). Furthermore, the microstructure of the 15%:60%:25% composition in this study shows minimal void formation, contributing to the composite board's optimal physical and mechanical properties.

Figure 9 presents the average particle size of the composite boards, measured using ImageJ and OriginLab software. The results indicate that the average particle size for Sample 1 (55%:20%:25%) is 208.32 ± 274296.88 µm, for Sample 2 (45%:30%:25%) is 8467.02 ± 2360.48 µm, for Sample 3 (35%:40%:25%) is 9129.85 ± 3339.93 µm, for Sample 4 (25%:50%:25%) is 8915.78 ± 3858.82 µm, and for Sample 5 (15%:60%:25%) is 20806.60 ± 92112.91 µm. As the composition of FCS increases, the composite board exhibits improved mechanical strength, with the optimal value achieved in Sample 5, which has an Adj R-Square value of 0.99978 µm (Abir et al., 2023).

CONCLUSIONS

This study demonstrated that composite boards made from PFF, FCS, and polyester resin exhibit promising properties for various applications, particularly in the furniture industry. The optimal composition of 15% PFF, 60% FCS, and 25% polyester (Sample 5) produced composite boards with excellent physical and mechanical properties, including compressive strength, tensile strength, and impact resistance. SEM microstructure analysis revealed a high degree of distribution and homogeneity of the components within the composite. According to JIS A 5905:2003 standards, the composite is classified as a "Hard Board," underscoring its potential as a sustainable alternative to traditional wood products. These findings suggest that combining PFF, FCS, and polyester resin can create an eco-friendly and durable material for furniture manufacturing, helping reduce environmental impact and utilize waste materials.

Future research could explore using other parts of the palm tree, such as leaf fibers and stems, to create composites with varied properties for specific applications. The impact of different particle sizes of FCS powder on composite performance could also be investigated. Developing bio-based or eco-friendly adhesives as alternatives to polyester resin would enhance sustainability. Long-term testing under different environmental conditions, such as humidity, UV exposure, and temperature changes, could assess durability for outdoor use. Adding flame-retardant treatments or other additives could broaden applications to construction materials. Scaling up production and performing cost analyses would help evaluate industrial feasibility, while a life cycle assessment could highlight environmental benefits.

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