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Exploring the physical, mechanical, and thermal properties of oil palm trunk and ramie fiber hybrid bio composites as building insulation materials

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Abstract

Agricultural waste has attracted the attention of researchers as a high potential reinforcement material for green thermal insulation. This study aimed to investigate the use of hybrid bio composites from oil palm trunks (OPTs) and ramie fibers as new raw materials for thermal insulation in buildings. In this paper, OPTs and ramie fibers were used as fillers in different particle sizes to fabricate hybrid bio composites using hot pressing, with tapioca starch biopolymer serving as a matrix. The bio composite was produced using a hot pressing machine at 9.8 MPa for 25 minutes, with pressing was conducted in two stages, namely 5 and 20 minutes. The physical, mechanical, and thermal properties of the OPTs and ramie fiber hybrid bio composites developed in this study and those of a pure OPTs bio composite as comparison were determined. The study found that the hybrid bio composites showed better performance and properties than the pure oil palm trunk bio composite. The results further showed that the HC200 hybrid bio composite sample had the lowest water absorption and thickness swelling (54.73 and 19.57, respectively), the HC40 hybrid bio composite sample had the highest moduli of rupture and elasticity (19.59 MPa and 2.95 GPa, respectively), and the HC20 hybrid bio composite sample had the lowest thermal conductivity coefficient (0.0807 W/mK). Thermogravimetric analysis showed that the hybrid bio composites had higher thermal stability at 309°C than the pure OPTs bio composite. From the research results, it can be concluded that the hybrid bio composites have the potential as thermal insulation materials for use in the construction sector.

1. Introduction

Oil palm is one of the main commodities from the agricultural sector that has an essential role in Indonesia's economy. Indonesia produced 48.42 million tons of palm oil, with an oil palm plantation area of 14.59 million hectares and a growth rate in the range of 2–4% per year [1].

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According to Abnisa, each palm oil tree produces approximately 10% palm oil, while the remaining 90% becomes biomass waste. The waste generally is derived from the milling process and plantation activities. The milling process, in particular, mostly generates waste from empty fruit bunches, accounting for about 22% of all waste, followed by waste from mesocarp fibers (13.5%) and palm kernel shells (5.5%). Furthermore, the fronds and trunks are found as the primary biomass waste produced from plantations, constituting up to 70% and 20.5% of all biomass waste, respectively [2].

The volume of trunks is the main contributor to palm oil solid waste. Currently, only 25% of the trunks are utilized, while the remaining are still dumped as untreated waste. Oil palm trunks (OPTs) have the potential to be used as a bio composite board material for building panel structures. Some previous research has investigated their applications, including as particleboard, lumber, and laminated wood materials [3], [4], [5]. Most of the research mainly focused on the matrix selection and material strength, but none has investigated the thermal insulation property of bio composite boards produced from oil palm trunks. It is essential to examine this property as it can help improve the thermal insulation of the panels produced and increase their durability.

Generally, thermal insulation is provided by synthetic materials, such as glass wool, rock wool, styrofoam, fiberglass, extruded polystyrene, and expanded polystyrene. These materials have good thermal insulation, but their use brings harm to the environment, especially during processing and disposal in landfills [6]–[10]. Various innovations have been made to replace the synthetic with natural materials, including by using natural-fiber-based materials, such as wood [11], wheat and sunflower stalks [12], bamboo [13], oil palm empty fruit bunches [14], and corn cobs [15]. To bind reinforcement materials, thermosets such as polyester, epoxy, and urea-formaldehyde (UF) are normally used as resins. However, these types of resin are known to be non-environmentally friendly since they cannot be decomposed easily. Therefore, the use of natural resins will open up an opportunity to reduce the profuse use of synthetic materials, which also helps minimize environmental damage.

Many natural resins are available to be used as adhesives in the bio composite manufacturing process. A good resin must have a high starch content, which is an essential ingredient as an adhesive. The starch composition generally consists of amylose and amylopectin, which play different roles in the binding process; while amylopectin serves as an adhesive, amylose does as a hardener. Tapioca starch is acknowledged for its high amylopectin content, measuring 85%, compared to 72% in corn, 79% in potato, and 72% in wheat. However, the amylose content, which is basically responsible for slow recrystallization, brittleness improvement, and mechanical strength reduction, was found to be as low as 17% [16].

Besides thermal insulation, bio composites must also have high strength and low water absorption. The strength of a bio composite can be improved by adding a reinforcement mixture or additive materials. Using materials as a hybrid will increase their effectiveness because it can increase the cellulose content of the reinforcement and maximize the amount of waste utilized. High cellulose content can in turn improve the mechanical and physical properties of the bio composite board. Several researchers have previously reported the potential of oil palm trunks as an environmentally friendly insulation material [17]–[19]. These studies examined the thermal insulation properties of oil palm trunks by focusing on the characteristics of a single material, without integrating a hybrid bio composite approach. Combining oil palm trunks (OPTs) with other materials may enhance thermal and mechanical performance and expand its applications in environmentally friendly insulation. Ramlee et al. [20] produced bio composite boards of OPTs mixed with empty fruit bunches (EFBs). They reported that using solely OPTs tended to yield lower strength than when mixed with EFBs. Another study reported that the tensile property of pure sugarcane composite was improved by hybridizing with EFB fibers until 18.8% [20]. Furthermore, a bio composite board with low water absorption capacity is preferrable since it reduces the defect caused by natural moisture. High moisture absorption will lead to bio composite board swelling, matrix instability and cracking, and reduced mechanical properties [21].

This study aims to determine the physical, mechanical, thermal conductivity, and thermal stability characteristics of hybrid bio composites composed of OPTs and ramie fiber as thermal insulation

materials. The effect of OPTs particle size and ramie fiber addition were evaluated. Bio composites were produced using tapioca starch as the matrix and fabricated through hot pressing at a constant temperature and pressure. Various analyses were conducted, including water absorption, thickness swelling, flexural strength, tensile strength, thermal conductivity, and thermal stability.

2. Materials and Methods

2.1. Material

This study used oil palm trunks (OPTs) and ramie fibers as hybrid bio composite reinforcement materials. The oil palm trunks used in this study were collected from local oil palm plantations in Aceh, and the ramie fibers were obtained from ramie plantations in Yogyakarta, Indonesia (Fig. 1). Tapioca starch biopolymer bought from a local market was used as a matrix. This resin consisted of 15% amylose and 85% amylopectin [22]. The chemical compounds found in the oil palm trunks, ramie fibers, and tapioca starch are presented in Table 1. Furthermore, the mechanical and physical properties are listed in Table 2. In this study, physical and mechanical properties are reviewed because these two aspects determine the performance, reliability, and application of insulation materials. Physical properties affect thermal insulation capability and environmental resistance, while mechanical properties are important to ensure that the material is sufficiently strong and stable enough during installation and throughout its service life.

(a) (b)

Fig. 1. Materials (a) oil palm trunk and (b) ramie fiber

Table 1. The chemical compounds contained in OPTs, ramie fibers, and tapioca starch

Filler	Cellulose (wt%)	Holocellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Amylose (%)	Amylopetin (%)
OPTs	29-37	42-45	12-17	18-23	-	-
Ramie	68.6-76.2	-	13-16	0.6-0.7	-	-
Tapioca starch	-	-	-	-	15	85

Table 2. The mechanical and physical properties of OPTs and ramie fibers

Properties	OPTs [23] [17]	Ramie fiber [24]
Tensile strength (MPa	300-600	290-1060
Young Modulus (GPa)	8-45	5-128
Elongation (%)	5-25	1.2-4.6
Density (g/cm^3)	0.28	1.5-1.6
Thermal Conductivity (W/mK)	0.05-0.143	0.072-0.152

2.2. Preparation of OPTs and Ramie Fiber

OPTs ware cut into small pieces, dried, and milled using a ball mill (Planetary Mill, Fritsch, P6) using 20 mm diameter sintered corundum balls at 100 rpm to pass through 0.42–0.84 mm (20 mesh), 0.07–0.42 mm (40 mesh), and <0.07 mm (200 mesh) sieves. Variations in OPTs particle size and the addition of ramie fibers aim to produce bio composites with low thermal conductivity, improved mechanical strength, and enhanced structural stability. The ground OPTs were then

boiled in water at a temperature of 100°C for 30 minutes and dried in an oven at a temperature of 80°C for the next 24 h until reaching 10–15% moisture content. Pre-treatment of OPTs particles in hot water aims to remove starch granules from the parenchymatous tissue, which can enhance the mechanical properties and thermal stability of the bio composites [25]. Furthermore, ramie fibers were cut to a length of approximately 5 mm and subsequently treated with 5% NaOH (1000 g of water and 50 g of NaOH flake) for one hour. The fibers were then washed repeatedly to reach a neutral pH and dried in an oven at a temperature of 80°C for 24 h. NaOH treatment of OPTs fiber aims to reduce lignin and hemicellulose content. Previous studies have shown that soaking oil palm fiber in 5% NaOH for 1 hour can improve the mechanical properties of the bio composite. However, higher NaOH concentrations may lead to excessive lignin and hemicellulose, thereby diminishing fiber properties and the quality of the bio composite [26]. Fig. 2 depicts the preparation processes of OPTs and ramie fibers.

(a)

(b)

Fig. 2. The preparation processes of OPTs (a) and ramie fibers (b)

2.3. Fabrication of Hybrid Bio Composites

Hybrid bio composites were fabricated with the formulation as shown in Table 3 using hot pressing with a mold size of 150 mm × 150 mm × 30 mm and a target density of 0.70 g/cm^3. The target density of the bio composite was set at 0.7 g/cm^3 to balance lightness and structural integrity. This value also corresponds to the middle value of the JIS A 5908: 2003 standard [27] for particleboard, which is 0.4-0.9 g/cm^3. The density allows for the development of a material that is relatively

lightweight yet sufficiently strong for various applications. Lower density tends to increase pore space, which can reduce thermal conductivity, but it may also compromise mechanical properties.

Table 3. Hybrid bio composite formulation

Bio Composite Type	Sample Code	Size of OPTs (mm)	OPTs particle (%)	Ramie fiber (%)
Bio Composite	BC20	0.42-0.84	70	0
	BC40	0.07-0.42	70	0
	BC200	<0.07	70	0
Hybrid Bio Composite	HC20	0.42-0.84	50	20
	HC40	0.07-0.42	50	20
	HC200	<0.07	50	20

In this study, pure OPTs bio composite was used as a comparison. Ramie fibers as fillers were mixed with tapioca starch, and 100 mL of hot water was then added to the mixture. Tapioca starch was used as a biopolymer matrix in an amount of 30% for all variations. The solution was stirred until completely mixed using a mechanical mixer (HM-620 Miyako, Indonesia) for 5 minutes at 200 rpm. The mixed solution was then poured into a mold and placed in a hot-press machine at a temperature of 150°C. To achieve a hybrid bio composite thickness of 10 mm, the hot-press machine was adjusted at 9.8 MPa for 25 min, and the pressing was performed in two stages: a temperature of 120°C was applied for 5 min in the first stage, and a temperature of 150°C was applied for 20 min in the second stage. After the hot-pressing process, the bio composite was kept in a dry room for seven days before use for testing. Figures 3 depict the different stages of the fabrication process of the hybrid bio composites.

Fig. 3. Stages of the fabrication process hybrid bio composites

2.4. Characterization of Hybrid Bio Composites

All the produced bio composite samples were characterized using physical tests (water absorption, thickness swelling, and scanning electron microscopy), mechanical tests (modulus of rupture, modulus of elasticity, tensile strength, and Young's modulus), and thermal analysis (thermal conductivity and thermogravimetric analysis).

2.4.1 Physical Test

For the water absorption and thickness swelling tests, three specimens were prepared with the size of 50 mm × 50 mm × 10 mm. Prior to the tests, the weight and thickness of the specimens were measured, followed by re-measurement after 24 h of an immersion process. Equation 1 was used

to calculate the water adsorption capacity, and Equation 2 was used to determine the thickness swelling.

$$\mathrm{WA} = \left(\frac{\mathrm{W_2} - \mathrm{W_1}}{\mathrm{W_1}}\right) x\ 100\ (\%) \tag{1}$$

$$\mathrm{TS} = \left(\frac{\mathrm{t_2} - \mathrm{t_1}}{\mathrm{t_1}}\right) x\ 100\ (\%) \tag{2}$$

where W_1 is the initial mass of specimen before immersion in water, W_2 is the mass of specimen after immersion in water, t_1 is the initial thickness of specimen before immersion in water, and t_2 is the thickness of specimen after immersion in water.

2.4.2 Flexural Test

The modulus of rupture (MOR) and modulus of elasticity (MOE) were determined using the three-point bending approach. The tests involved five specimens measuring 150 mm × 20 mm × 10 mm, in accordance with the ASTM D790 standard [28], using the MTS EXCEED Model E43 universal testing machine with a crosshead speed of 2 mm/min and a load cell of 10 kN. The same setting of the machine was also applied to evaluate the tensile strength. The bending data obtained were used to determine the MOR and MOE using Equations 3 and 4.

$$\mathrm{MOR} = \left(\frac{3PL}{2bh^2}\right)\ (\mathrm{MPa}) \tag{3}$$

$$\mathrm{MOE} = \frac{\Delta PL^3/4\Delta Ybh^3}{1000}\,(\mathrm{GPa}) \tag{4}$$

where P is the maximum loading, L is the span, b is the width of specimen, h is the thickness of specimen, ΔY is the deflection, ΔP is the difference between the upper and lower loading.

2.4.3 Tensile Test

The tensile properties sample was cut into rectangular strips using the ASTM standard D3039 [29] with a dimension of 250 x 25 mm x actual thickness for each type of composite. Five samples were prepared for each variant, and the tests were conducted using an MTS EXCEED Model E43 (Japan) with a load cell of 10 kN and a crosshead speed of 2 mm/minute. The tensile properties data obtained were used to determine the tensile strength and modulus of elasticity using Equations 5 and 6.

$$\sigma = \frac{\mathrm{P}}{\mathrm{A}}\ (\mathrm{MPa}) \tag{5}$$

$$\mathrm{E} = \frac{\sigma}{\varepsilon}\ (\mathrm{MPa}) \tag{6}$$

where P is the maximum loading, A is the cross-sectional area, σ is the stress, and ε is the strain.

The modulus of elasticity (E) is obtained from the linear (elastic) region of the load-displacement curve resulting from a tensile test. The slope ΔP/ΔY is used to calculate Δσ/Δε, considering the test specimen's dimensions.

2.4.4 Thermal Conductivity Test

The thermal conductivity test was conducted using an instrument from PHYWE Systeme GmbH (37070 Göttingen, Germany) in reference to the ASTM C177-97 standard [30]. The method was run in an insulated box equipped with a thermocouple in and out of the box. Thermal conductivity test specimens were prepared for each variation with dimensions of 150x150x10 mm. The test was conducted with the room temperature conditioned to 24°C. Measurements were started when the temperature inside the box reached 60°C, which was maintained for 30 minutes before data collection. The measurement data were then used to determine thermal conductivity values by applying Equation 7 below [31].

$$Q_{c,wall} = -kA\frac{T_1 - T_2}{\Delta x}\ (W) \quad (7)$$

where T_1 is the temperature of the inside surface, T_2 is the temperature of the outside surface, Δx is the distance between the two surfaces, and A is the surface area.

2.4.5 Thermogravimetric Analysis (TGA)

Thermogravimetric analysis (TGA) was carried out using the SHIMADZU model DTG 60 instrument. A sample weighing about 5 mg was scanned from room temperature to a temperature of 700°C with a heating rate of 40°C/min under nitrogen purging with a flow rate of 20 mL/min.

2.4.6 Scanning Electron Microscopy (SEM)

SEM was used to observe the surface morphology of the bio composites with an EVO MA10 model (ZEISS, Germany). Prior to SEM analysis, the samples were gold-coated with sputtering. The bio composites were characterized using the SEM EVO MA10 (ZEISS, Germany) with a working distance of 13-14 mm and a voltage of 20 kV during operation.

3. Results and Discussion

3.1. Water Absorption and Thickness Swelling

Water absorption test is an essential aspect in determining the quality of natural fiber composite materials. Table 4 and Figure 4 shows the percentage of water absorption and thickness swelling of the hybrid bio composites developed in this study after 24 h. The percentage of water absorption for all samples were found in the range of 54.73–74.40%. BC20 was found to absorb the highest amount of water (74.40%), which was similar to the percentage for HC20 (65.54%). Both samples were composed of OPTs with a particle size of 20 mesh. A larger particle size allows more water absorption compared to smaller particles. Large particles create open pores, enabling water to easily enter the material. Smaller particles tend to fill these open pores, reducing the pathway for water to enter. In addition, systems with narrower particle distribution (small particles) are more likely to form compact structures.

Table 4. Water absorption and thickness swelling value of hybrid bio composites

Bio composites sample	WA (%)	SD of WA	TS (%)	SD of TS
BC20	74.46	5.22	26	2.83
BC40	61.84	5.77	23.08	3.82
BC200	59.8	3.99	22.5	3.39
HC20	65.54	5.98	28.85	4.35
HC40	56.76	4.41	22.86	3.07
HC200	54.73	3.02	19.57	1.79

SD : standard deviation

Similar results were reported by previous research [32], which measured the water absorption of a particleboard made from palm oil wood. The study showed that the particleboard with a larger particle size (0.5–1 mm) had a water absorption capacity of 41.43%, compared to the 17.19% value for the particleboard with a particle size in the range of 0.1–0.5 mm. The same trend was also found for bio composite made from composite materials. Mawardi et al. noted that composite materials with larger particle sizes absorbed more water compared to materials with smaller particle sizes [33]. Hybridization with ramie fibers was expected to help reduce water absorption, which was proved by this study. It was found in this study that using OPTs and ramie fibers in a mixture resulted in a 5% reduction in water absorption. Ramlee et al. reported that the addition of co-reinforcement materials has the possibility to reduce water absorption due to compatible characteristics of mixed materials, which reduces void and porosity of the exposed surface area on

composites [20]. The phenomenon of decreased pore number due to the use of small particles and hybridization of ramie fibers, which increases density, is also illustrated by SEM scanning results (Fig. 12). Furthermore, reinforcement materials from natural fibers normally have a tendency to absorb more water due to their natural hydrophobic characteristic [23]. The absorbed water will in turn affect the thickness swelling of the hybrid bio composite s if it remains for a certain period of time. This study showed that after 24 hours of immersion, the highest thickness swelling was obtained where the thickness swelling was obtained at 29% when urea-formaldehyde (UF) was used to bind the natural reinforcement material (oil palm fronds). To improve the adhesive level, Pan et al. [34] tried to mix UF and polymethylene diphenyl isocyanate (PMDI), which is known as a common adhesive in the particleboard industry. However, their results showed that the thickness swelling of their produced hybrid bio composite was above 30%, which was higher compared to the result obtained from using tapioca starch as an adhesive in this experiment. UF and PMDI are the most commonly used binders in the particleboard industry, but they are known to cause health concerns and pose emission issues to the environment. The results of this study proved that tapioca starch can be an option to be used as an alternative natural adhesive to the widely used thermoset-based resins.

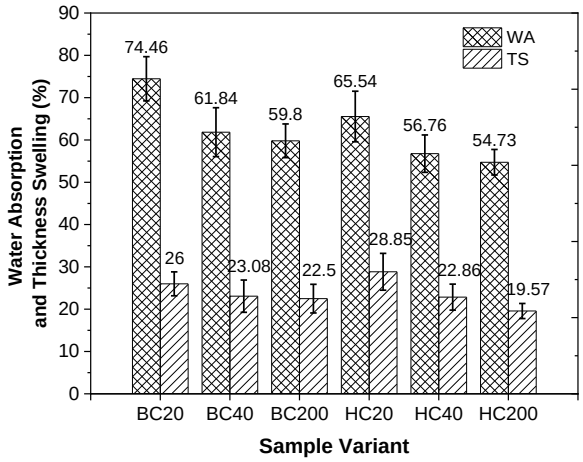


Fig. 4. Water absorption and thickness swelling of hybrid bio composites

3.2. Mechanical Properties of Hybrid Bio Composites

Figure 5 shows the load versus displacement curves for various bio composites: BC20, BC40, BC200, HC20, HC40, and HC200. The curves indicate that all specimens experience an increasing force until reaching a peak, after which the force gradually decreases, reflecting plasticity or flexural failure characteristics. The HC20 sample shows the highest flexural performance, while the BC200 sample shows the lowest flexural force value.

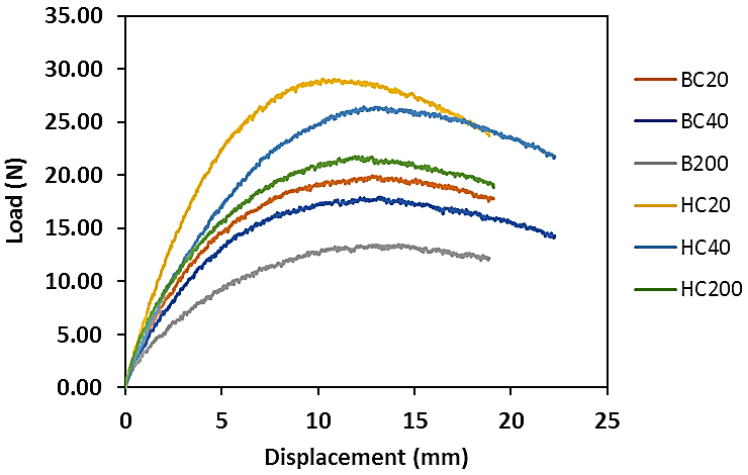


Fig. 5. Load vs displacement curves of hybrid bio composites' flexural properties

Figure 6 shows the results of the MOR and MOE tests for all the produced hybrid bio composite s, with decreasing MOR and MOE for smaller particle sizes. This finding was evident for both scenarios, with and without co-reinforcements. The single reinforcement was recorded to yield reduced MOR from 14.41 to 12.35 MPa, while the co-reinforcements used in the bio boards yielded a reduction in MOR from 18.89 to 16.65 MPa. Similar trends were also reported by several researchers, who used different reinforcement materials, such as wood, rice straws, and bamboo, with bio-resins used as binders [13], [15], [35] highlighting the role of such factors as particle size, porosity, density, and bending strength that might come into play (see Figure 7). Smaller particle sizes produce lower porosity [36], and low porosity in turn tends to increase the bio board density [15]. As density increases, the result of bending analysis will tend to drop, as revealed by MOR tests [13]. In this work, the density of the pure OPTs bio composite and the hybrid bio composite s ranged between 0.69 and 0.79 g/cm^3, as shown in Table 5.

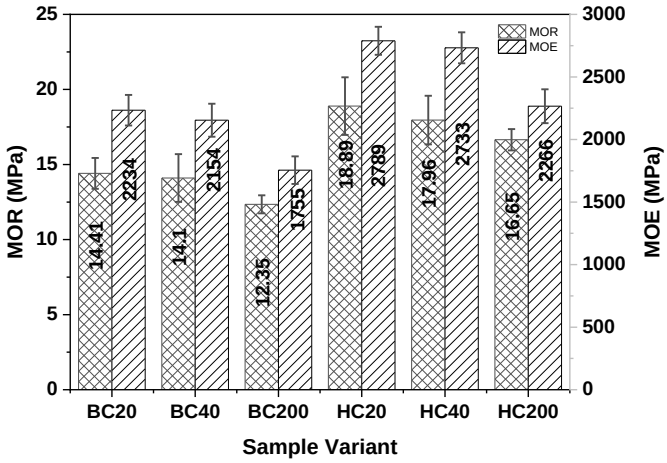


Fig. 6. MOR and MOE hybrid bio composites

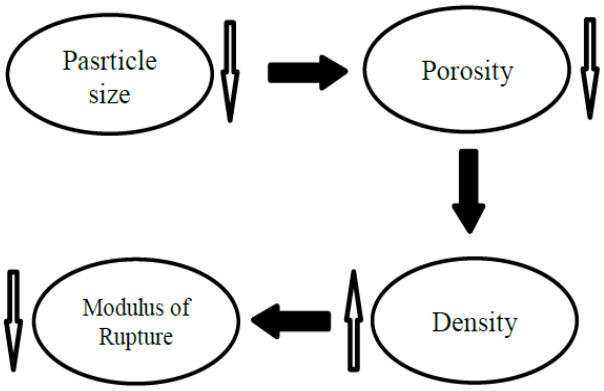


Fig. 7. Correlation of particle, porosity, density, and flexural strength

Figure 8 shows the tensile force versus displacement curve for bio composite variations: BC20, BC40, BC200, HC20, HC40, and HC200. In general, the curve shows an increase in tensile force with increasing displacement until reaching a peak, after which the force decreases sharply, indicating material failure. The HC200 sample showed the highest tensile performance, followed by HC40 and HC20, while BC20 showed the lowest performance. The results indicate that variations in the type and number of reinforcing materials significantly affect the mechanical characteristics, especially tensile strength and deformation resistance.

The tensile strength and modulus of elasticity of the hybrid bio composites are presented in Figure 9. As depicted in the figure, particle size and the addition of co-reinforcements had a positive effect on the tensile strength property. A smaller particle size with the addition of 20% ramie fibers yielded a higher tensile strength, increasing from 2.33 to 7.92 MPa, and a higher modulus of

elasticity, increasing from 55.68 to 157.20 MPa. In addition, the results of this study indicate that increased density is positively correlated with tensile strength. This is likely due to increased adhesion between the fiber and the matrix, which improves stress transfer efficiency from the matrix to the fiber. Conversely, at low density, numerous pores are formed, which act as sites for crack initiation and contribute to the decrease in bio composite strength.

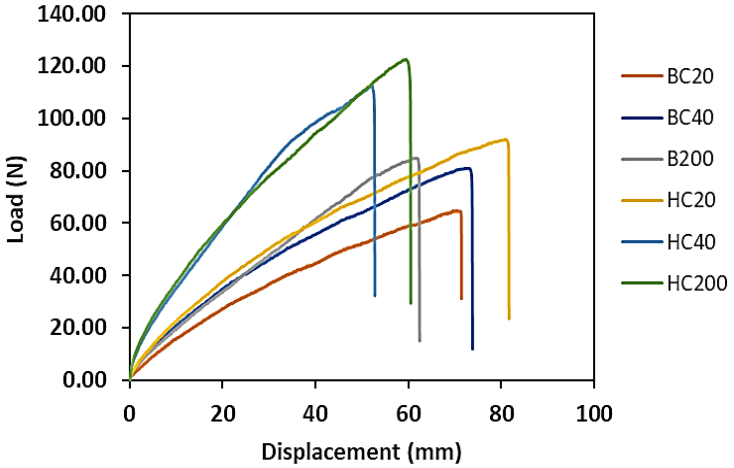


Fig. 8. Load vs displacement curves of hybrid bio composites' tensile properties

Mawardi et al. [37]) posited that the smaller particle size of a filler exhibits higher tensile strength because of better filler dispersion and filler-matrix interaction compared to fillers with larger particle sizes. This filler-matrix interaction is mainly influenced by the presence of lignocellulosic properties, where the presence of cellulose and hemicellulose will specifically improve the composite strength [38]. This study clearly showed that the addition of ramie fibers significantly improved the tensile strength, with a significantly greater amount of them (71.8 wt%) used than that of cellulose-containing OPTs (30.2 wt%) used. In this experiment, ramie fibers were incorporated into the hybrid samples (HC20, HC40, and HC200). The increasing trend of tensile strength linearly affected the modulus of elasticity, which was observed for all samples.

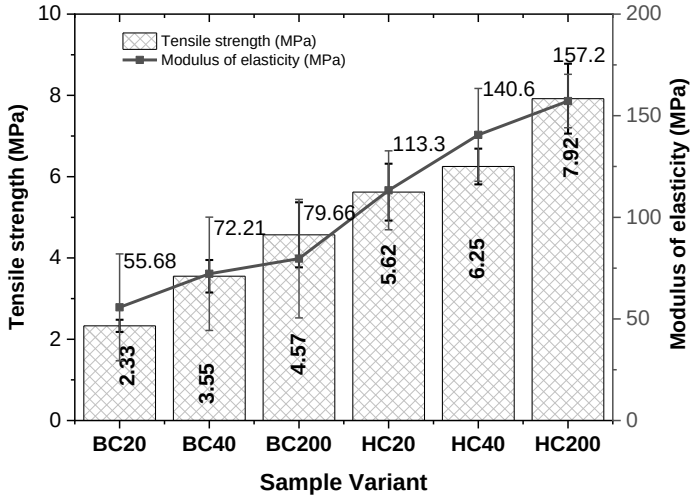


Fig. 9. Tensile properties of hybrid bio composites

3.3. Thermal Conductivity Coefficients

Thermal conductivity coefficients were used to determine the thermal insulation performance of the composites. As shown in Table 5, the highest coefficient was obtained by BC200. This indicates that the board was easy to transfer heat, which means it provided low insulation. According to Mati-Baouche, a bio board can be qualified as an insulator if its thermal conductivity measures 0.1 W/mK or lower [39]. Of the bio composite s produced in this study, BC20, HC20, and HC40 fell into the

category defined by Mati-Baouche. Thermal conductivity coefficients are an essential aspect to consider in choosing building materials for different weather conditions. Various factors affect the thermal insulation performance of a composite material, including fiber type, fiber-adhesive interface structure, density, particle size, and porosity. Of all the samples in this study, only BC200 and HC200 were observed to be out of the standard range, valued 0.18 and 0.17 W/mK, respectively (Table 5).

Table 5. Density and thermal conductivity of hybrid bio composites

Bio composite Type	Sample	Density (g/cm^3)	Thermal Conductivity (W/m.K)	Standard Deviation
Bio composite	BC20	0.69	0.0914	0.022
	BC40	0.75	0.1311	0.032
	BC200	0.77	0.1811	0.026
Hybrid Bio composite	HC20	0.71	0.0807	0.018
	HC40	0.77	0.0849	0.016
	HC200	0.79	0.1705	0.021

The thermal insulation values obtained in this study were better than not only those of vermiculite, sunflower stalks, and wheat stalks (0.063–0.334 W/mK) [12], but also that of corn cobs (0.101 W/mK) and they were comparable to the value for OPTs (0.055–0.091 W/mK) [6]. In addition, this study's thermal conductivity coefficients were relatively higher than those reported for wood waste [11] and synthetic fibers, such as glass and rock wool (0.032 to 0.045 W/mK) and polyester fabric (0.09 to 0.45 W/m K) [40]. Overall, the hybrid bio composites were better than the pure OPTs bio composite in terms of thermal conductivity coefficients. Hybridization with ramie fibers lowered the thermal conductivity value of the bio composites. This result is supported by a previous study [41], according to which thermal conductivity is influenced by fiber type and fiber structure.

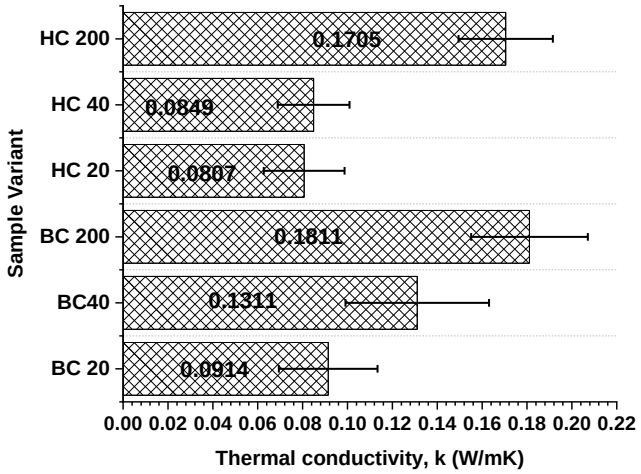


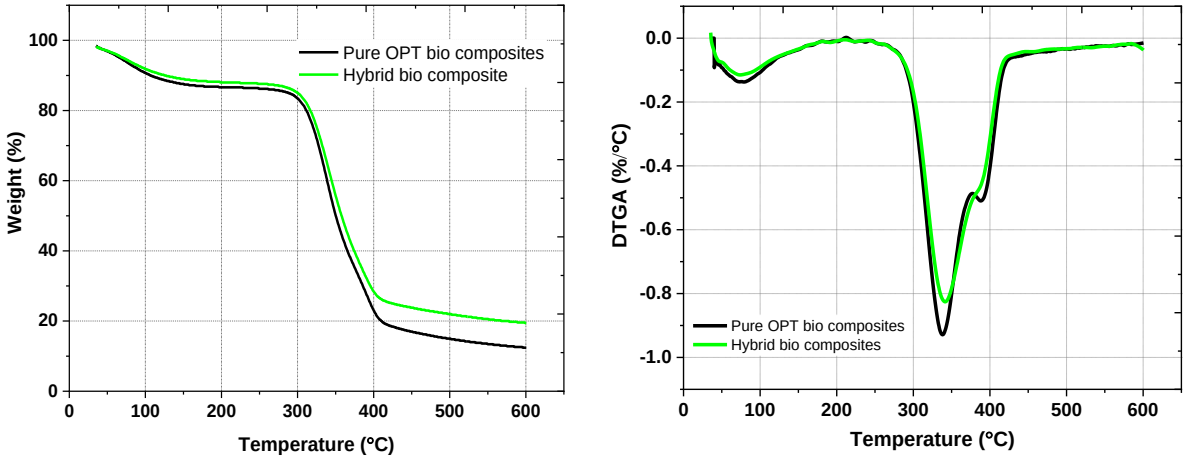
Fig. 10. Thermal conductivity of hybrid bio composites

Figure 10 depicts the effect of particle size on the thermal conductivity coefficient. HC20 and HC40 had thermal conductivity coefficients of 0.080 and 0.084 W/mK, respectively, making them suitable to be used as insulators. HC20 showed the lowest thermal conductivity coefficient (0.080 W/mK) among the bio composite samples. The thermal conductivity coefficient decreased with the increasing particle size, likely due to the higher density and reduced porosity of the bio composites. Pores within the bio composites contain gas, which hinders the flow of heat. This finding is supported by [37], who stated that porosity in wood composites serves as a burst center for phonons, thus reducing the thermal conductivity coefficient. A decrease in particle size within a specific range may decrease the thermal insulation property but not the mechanical properties.

3.4. Thermogravimetric Analysis

Figure 11 shows the thermogravimetric analysis (TGA) and derivative thermogravimetric analysis (DTGA) curves for the pure OPTs bio composite and hybrid bio composite samples. Overall, the TGA and DTGA curves for both types of bio composites have similar patterns, with three stages of degradation and weight loss (Fig. 11a). The first stage of degradation took place from 36 to 137°C and from 35 to 133°C for the pure OPTs bio composite and hybrid bio composite samples, respectively. The initial decreases of sample weight of up to 10% were due to evaporation of water from the samples. From 308 to 412°C and from 309 to 406°C, there was another major degradation, with weight losses reaching 65% and 59% for the pure OPTs bio composite and hybrid bio composite samples, respectively. This finding was relatively similar to that of a previous study [42], which reported decomposition of palm tree fibers at a temperature of 300°C by 50%. A final decomposition occurred within the temperature range of 391–600°C, with mass losses of up to 12%. The weight loss may happen due to the thermal decomposition of hemicellulose, carbon dioxide, water, and microfibrils.

The hybrid bio composite samples had higher initial degradation temperatures and lower weight losses compared to the pure OPTs bio composite sample. The initial degradation temperatures of the hybrid bio composites occurred at a minimum of 309°C and a maximum of 341°C (Fig. 11b). This results were better when compared to those for binderless particleboards from OPTs [43], and particleboards from OPTs added with ammonium dihydrogen phosphate (ADP) [19]. These findings showed that hybridization with ramie fibers improved the thermal stability of OPTs bio composites. The results of thermogravimetric analysis indicated that the hybrid bio composites have the potential to be used as thermal insulation materials.



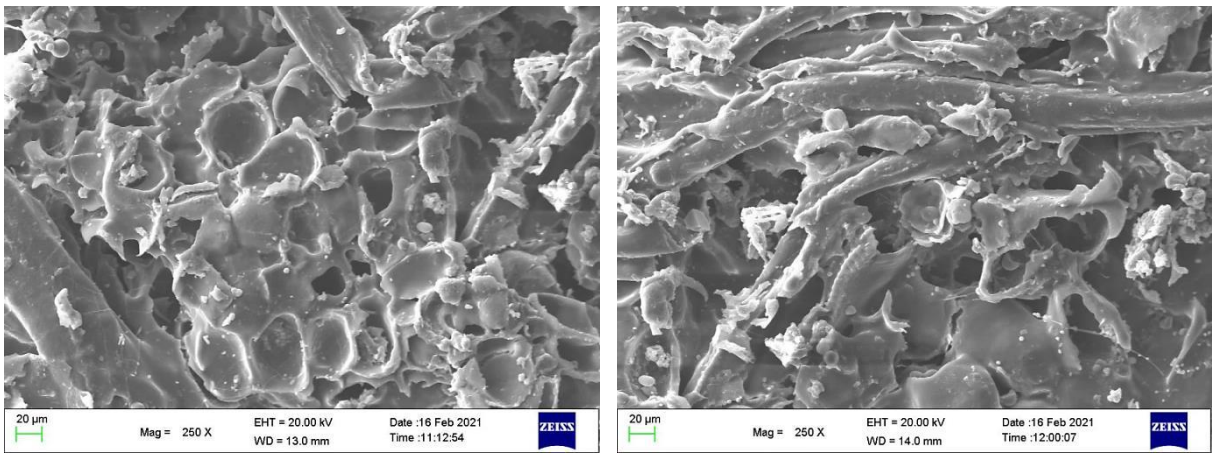
(a) (b)

Fig. 11. Thermal analysis of bio composites and hybrid bio composites (a) TGA and (b) DTGA

3.5. Analysis of Scanning Electron Microscopy (SEM)

Figure 12 shows the microscopic observations of the cross-sections of pure OPTs bio composite and hybrid bio composite samples under a scanning electron microscope (SEM). SEM micrographs of the pure OPTs bio composites and hybrid bio composite s are presented in Figure 12a and Figure 12b, respectively. Figure 12(a) shows that some fibers are well embedded in the matrix, while others show gaps or cavities around the fibers. The pure OPTs fibers are prone to detachment from the matrix, which impacts the composite's density, as higher void content results in lower density. The presence of voids in the bio composite indicates weak adhesion, which reduces the efficiency of stress transfer from the matrix to the fibers. This condition directly contributes to the decrease in the mechanical properties of the bio composite. The SEM image supports the results of the mechanical test, which shows low flexural and tensile strength. However, conversely, the voids serve as spaces for trapped air, which has low thermal conductivity. This phenomenon hinders heat flow through the material, as the air-filled pores act as insulators. In addition, the pores create

numerous interfaces between the solid and gas phases, each introducing thermal boundary resistance that further impedes heat flow.



(a) (b)

Fig.12. SEM images of a cross section of composites (a) pure OPTs bio composite and (b) hybrid bio composite

Meanwhile, Figure 12b shows that additional ramie fibers produce a different morphology, where ramie fibers partially cover the parenchyma tissue. This tissue must be minimized due to its high water absorption capacity, which can reduce the mechanical properties of the bio composite . In some areas, ramie fibers appear well embedded in the matrix, while in other places, gaps between the fibers and the matrix indicate debonding. This debonding phenomenon has an impact on the decrease in the strength of the bio composite. However, overall, the presence of ramie fibre still positively contributes to increasing the elastic modulus and strengthening the structure, especially in composites with small particle sizes.

4. Conclusions

This study successfully developed a bio composite based on pure oil palm trunk and a hybrid bio composite combining oil palm trunk and ramie fiber. Overall, the results demonstrated that the addition of ramie fiber significantly improved the physical, mechanical, and thermal properties of the bio composite. Smaller oil palm trunk particle sizes improved water absorption resistance, thickness swelling, modulus of rupture (MOR), and modulus of elasticity (MOE), although not the thermal conductivity coefficient. The hybrid bio composite samples, especially types HC200, HC40, and HC20, exhibited good mechanical strength, water absorption resistance, dimensional stability, and thermal conductivity performance. The controlled water absorption and thickness swelling values, combined with adequate mechanical strength, indicate potential of this material for building insulation applications that require resistance to humidity fluctuations and light mechanical stress. In addition, the low thermal conductivity coefficient indicates the material capability to inhibit heat transfer, making it a strong candidate for energy savings by reducing indoor cooling or heating needs. The increased thermal stability with the presence of ramie fiber also expands the potential application of this material in higher-temperature environments.

Based on the results obtained, the hybrid bio composite of oil palm trunk and ramie fibers exhibits great potential for development as a renewable and environmentally friendly thermal insulation material. This result supports initiatives towards sustainable building materials and contributes to climate change mitigation through energy efficiency. Future research may explore several important directions. First, experiments with other types of natural fibers (such as kenaf, abaca, or bamboo fibers) or combinations with environmentally friendly synthetic fibers could further enhance the material's properties. Second, the use of various matrix materials, such as bio-based resins or natural polyurethanes, can be explored to improve the thermal and environmental performance. Third, long-term durability tests, including weathering, freeze-thaw cycles, and exposure to microorganisms, are important to validate the material's service life. Finally, a production cost analysis and a feasibility study for large-scale manufacturing should be conducted

to ensure the potential for widespread commercial application of this bio composite in the industrial sector.

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