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Development and Investigation of Hybrid Bio-Panels based on Sugarcane Bagasse and Coir Fiber

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ABSTRACT

The widespread availability of bagasse and coir fiber has made them popular choices for use as composite reinforcements. Typically, composites containing bagasse or coir fiber are created using a polymer matrix. However, hybrid composites combining bagasse, coir fiber, tapioca starch, and PVAc matrices have not been identified as innovative aspects of this research. This study aims to develop and analyze a novel hybrid bio-panel by combining sugarcane bagasse (SCB) and coir fiber (CF) with a tapioca starch (TS) and polyvinyl acetate (PVAc) blend as the matrix. The bio-panels were fabricated using a hot press method with three SCB-to-CF fiber ratios (30:70, 50:50, and 70:30) and three fiber-to-matrix ratios (30:70, 40:60, and 50:50). Mechanical and physical properties, including flexural strength, density, water absorption, thermal conductivity, and fractured surface morphology, were thoroughly evaluated. Results showed that higher TS/PVAc matrix content and CF proportions improved water resistance, flexural properties, and thermal stability, though thermal conductivity decreased. Additionally, higher panel density correlated with improved flexural properties and thermal conductivity. Sample BC8, with a density of 0.737 g/cm³, achieved the lowest thermal conductivity at 0.132 W/mK. The highest flexural strength and modulus, 9.18 MPa and 485.48 MPa, were observed with a composition of 30 wt% SCB and 70 wt% CF in a TS/PVAc matrix at 70 wt%. This study concludes that SCB and CF fibers can serve as effective fillers in hybrid bio-panels, offering a sustainable material solution.

1. INTRODUCTION

Throughout nowadays, application of natural fiber-reinforced composites as a replacement for synthetic fiber is observed in various fields. Natural fibers derived from natural resources are gaining increasing popularity due to their abundance, availability, lightweight, high porosity, biodegradability, renewability, environmentally suitability, and cost-effectiveness [1]. Plantation and agricultural biomass, such as sugarcane bagasse, coir, oil palm empty fruit bunch (OPEFB), wheat, rice, banana leaves, pineapple, and many more are the primary sources of natural fibers. Sugarcane bagasse (SCB) is the remainder of sugar production, and coir fiber (CF) derived from coconut husks; both are abundant, low-cost agricultural residues. SCB and CF fiber are natural fiber widely distributed in tropical countries such as Indonesia, India, Philippines, and Thailand. According to Indonesian sugarcane statistics, the area of sugarcane plantations covers 518.183 hectares, with production reaching 2.61 million tons of sugar, and an estimated 1.05 million tons of SCB is produced. Similarly, the potential for coconut fiber is significant. According to the Statistical of National report on Leading Estate Crops Commodity 2021-2023, the area of coconut plantations in Indonesia was 3.34 million hectares, with an estimated production of around 2.8 million tons of coconut [2]. The abundant availability of these two fibers makes them suitable to be used as reinforcement in composite materials.

Numerous studies have explored the physical, mechanical, and thermal characteristics of SCB-reinforced hybrid bio-panels using different matrix types. For instance, Mittal and Sinha [3] and Salatein et al. [4] investigated the mechanical, thermal, and physical properties of wheat straw/SCB and banana fiber/SCB reinforced epoxy hybrid composites. Zafeer et al. and Kusuma et al. reviewed potential and characteristics of SCB fiber-reinforced polymer composites as environmentally friendly composite and sustainable material [5, 6]. Furthermore, recent publications by Mahmud et al. [7], Dos Santos et al. [8], and Asrofi et al. [9] have also studied the mechanical and physical properties of SCB composites using starch matrix. Overall, their reports conclude that SCB composites derived from sugarcane waste have potential applications across various sectors, including furniture, food, automotive, healthcare, and construction. Furthermore, the performance of coir fiber-reinforced composites performance has been reported in several previous studies, with applications coir fiber reinforced various matrix such as thermoplastics, thermoset, and starch. Hasanuddin et al. [10] reported that incorporation CF/E-glass/alumina enhanced the tensile properties of the epoxy composite up to 280%. Development of hybrid composites based on coir fiber for thermal insulation and particle boards has been reported by Wang and Hu [11]. In another study, coir fiber-reinforced bio-panels with polyvinyl acetate matrix [12] was used as composite boards.

In recent years, the use of hybrid composites has grown rapidly for various engineering and non-engineering applications. Hybrid composites combining multiple fibers within a single type of matrix have been widely reported by previous researchers. Generally, thermosetting and thermoplastic polymers as polyester, epoxy, urea-formaldehyde, and polyvinyl acetate are normally used as matrix to bind reinforcement material. This type of matrix is also recognized as non-environmentally friendly since it cannot be easily decomposed. Therefore, the use of natural-based resin presents an opportunity to reduce the domination of synthetic material, which also helps to minimize environmental damage.

Many types of starch are available for use as adhesives in the bio-panels manufacturing process. Starch is a polysaccharide obtained from plant sources such as corn, potatoes, rice, and other carbohydrates. The starch composition generally consist of amylose and amylopectin, with each components playing a distinct role in the binding process. Amylopectin serves as the bonding agent, whereas amylose works as the solidifying component. Among natural resins, tapioca starch has a higher amylopectin content compared to others. The amylopectin content in tapioca is approximately 83%, while in corn, potato, and wheat are 72%, 79%, and 72%, respectively. However, starch presents several disadvantages compared to synthetic polymer materials, such as its high solubility in water, brittleness, low melting temperature, and inferior mechanical performance. On the other hand, polyvinyl acetate (PVAc) is a thermoplastic polymer extensively utilized as a primary material in the adhesive industry. Whether modified or not, and available in the form of a solution, emulsion, homopolymer, or copolymer, PVAc exhibits a diversity that makes it suitable as a binder for various materials, especially wood products and their derivatives. Blending tapioca starch with PVA has proven to be an attractive method for enhancing the mechanical properties of starch matrix-based bio-panels.

Natural fiber-based hybrid bio-panels are environmentally friendly substitutes for various technical uses. Several previous studies have explored the effects of bagasse or coconut fiber separately on the characteristics of composites with polymer matrices. In addition, some researchers have published the effect of hybridization on polymer matrix blends for various composite applications [13, 14]. However, hybrid bio-panels reinforced SCB and CF with a matrix blend of tapioca starch with PVAc polymer remain limited. In this study, the hybrid technique was used to produce a novel hybrid bio-panel, aiming to evaluate its flexural strength, thermal, physical properties, and morphology. SCB and CF fiber were chosen as reinforcements, with a mixture of TS and PVAc used as the matrix. The fabrication process employed a hot press at a fixed temperature and pressure. Various analyses were conducted using analytical equipment such as universal testing machine for bending, TGA, and insulation box.

2. MATERIALS AND METHODS

2.1 Materials

In this work, hybrid bio-panels were produced using sugarcane bagasse (SCB) and coir fiber (CF) as reinforcement and tapioca starch (TS) and polyvinyl acetate (PVAc) as a matrix. The sugarcane bagasse and coir fiber were collected from sugarcane and coconut milling in North Aceh, Aceh, Indonesia. Tapioca starch (TS) and polyvinyl acetate (PVAc) (Fox brand, made in Indonesia) were purchased from a local supplier. Additionally, natrium hidroksida (NaOH) served as the pretreatment substance for SCB and CF fiber, while maleic anhydride was utilized as a constituent for matrix formation. Table 1 shows a comprehensive overview of the chemical composition, mechanical, and physical properties of the reinforcement and matrix employed in composite production [15-17].

2.2 Treatment of coir and sugarcane bagasse fiber

Both fibers were pretreated before use. SCB fiber was cut into small pieces, dried, and reduced to particles to pass through a 20-mesh sieve using a disc mill. Meanwhile, CF was sorted with a diameter of <0.5 mm and cut into 5-10 mm lengths. Next, SCB and CF fibers were soaked in 5% NaOH solution for 4 hours and then neutralized by washing with water until they reached a neutral pH. Furthermore, both fibers were dried to a moisture content of 10-15% using an oven at a temperature of 80°C for 24 hours. Figure 1 shows the stages of pretreatment of fibers before use.

Table 1. Chemical composition, physical and mechanical characteristics of the reinforcement and matrix

Description	Coir Fiber	Bagasse Fiber	Tapioca Starch	PVAc
Chemical constituents (%)				
Cellulose	32-43	55.2	-	-
Hemi cellulose	0.15-0.25	16.8	-	-
Lignin	40-45	25.3	-	-
Amylose	-	-	-17	-
Amylopectin	-	-	83	-
Physical & mechanical properties				
Density (g/cm^3)	1.25-1.5	0.4-0.55	-	1.10-1.20
Glass transition Temp. (°C)	-	-	-	30-45
Tensile strength (MPa)	105-175	20-50	-	23.35
Young's modulus (GPa)	4-6	2.7	-	-

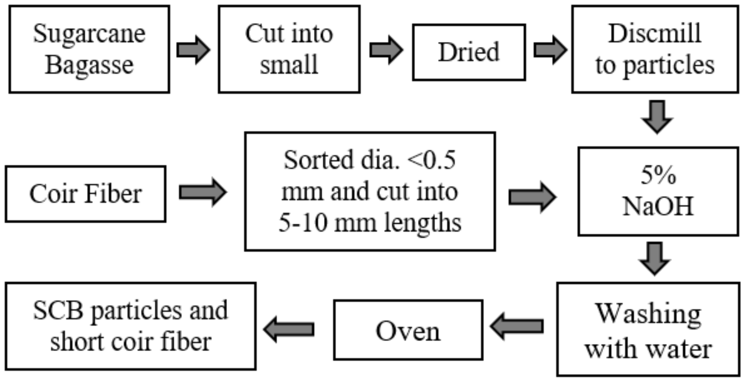

Figure 1. Stages of fiber treatment

Table 2. Hybrid bio-panels formulation of fibers and matrix

Code of Specimen	Fibers		Fibers Incorporation (wt%)	Matrix		Blend PVAc/TS (wt%)
	SCB (wt%)	CF (wt%)		TS (wt%)	PVAc (wt%)	
BC1	30	70		80	20	
BC2	70	30	30	80	20	70
BC3	50	50		80	20	
BC4	30	70		80	20	
BC5	70	30	40	80	20	60
BC6	50	50		80	20	
BC7	30	70		80	20	
BC8	70	30	50	80	20	50
BC9	50	50		80	20	

Note: BC1, BC2, and BC3 are hybrid bio-panels with SCB and CF fibre ratios of 30:70, 70:30, and 50:50, respectively, with a fiber-to-matrix ratio of 30:70. BC4, BC5, and BC6 are hybrid bio-panels with SCB and CF fibre ratios of 30:70, 70:30, and 50:50, respectively, with a fiber-to-matrix ratio of 40:60. BC7, BC8, and BC9 are hybrid bio-panels with SCB and CF fibre ratios of 30:70, 70:30, and 50:50, respectively, with a fiber-to-matrix ratio of 50:50.

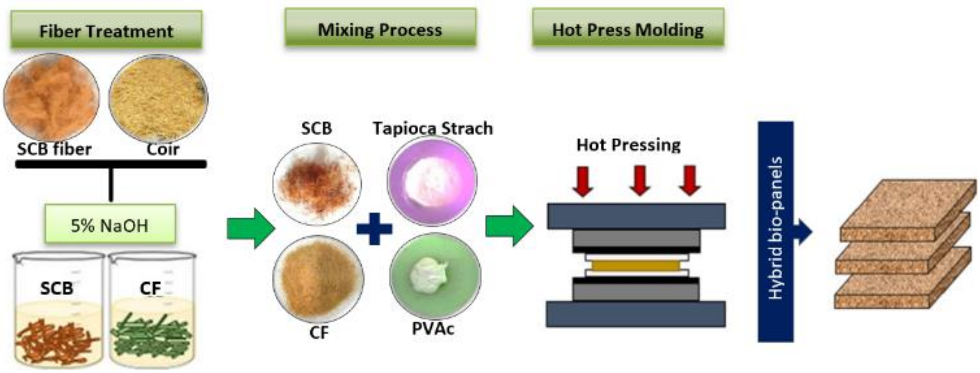

Figure 2. Schematic diagram SCB/CF hybrid bio-panels manufacture using hot-press

Figure 3. The physic of SCB/CF hybrid bio-panels (a) BC1, (b) BC2, (c) BC3, (d) BC4, (e) BC5, (f) BC6, (g) BC7, (h) BC8, (i) BC9

2.3 Fabricating of hybrid bio-panels

The hybrid bio-panels with the formulation in Table 2 were produced using a laboratory-type hydraulic hot-press (Indonesia) with a pressure capacity of 150 MPa. CF dan SCB as reinforcement, were mixed with TS. PVAc with a solid content 55% was dissolve in 100 ml of hot water, then sprayed into the fiber and TS mixture using a spray gun. The solution was then stirred until completely mixed using a mechanical mixer (model HM-620, Miyako, Indonesia) for 5 min. The mat was then poured into a mold measuring 200 mm × 200 mm × 30 mm and placed at a hot-press machine. The mats were pressed at a pressure of 9.8 MPa for 20 minutes at a temperature of 150℃ to achieve 700 kg/m^3 as the target density and a thickness of 10 mm. In this study, the hybrid bio-panels were manufactured using a two-stage pressing process: pre-pressed at a pressure of 5 MPa for 5 minutes at 150℃, followed by full pressing for 15 minutes at 150℃ under 9.8 MPa. As stated by Savov et al. [18], the primary purpose of the initial heating is to remove water from the adhesive mixture. The manufactured hybrid bio-panels were conditioned in a dry room with 65% relative humidity for seven days before being put to the test. Figures 2 and 3 show the overall scheme of SCB/CF hybrid bio-panels manufacturing process and the physical of SCB/CF hybrid bio-panel.

2.4 Thermal conductivity testing

Thermal conductivity testing uses the principle of heat transfer. Thermal conductivity was determined using an insulated box fitted with the PHYWE SYSTEME GMBH 37070 model (Göttingen, Germany), following the ASTM C177-97 standard [19] with a thermocouple in and out of the box. The specimen is placed on one side of the box. Temperature measurements of sample (150×150×10 mm) were taken using two thermocouples were installed inside and outside the box and two at the sample walls, on the interior and exterior. Heat transfer measurements are performed by measuring the temperature difference between the specimen's inner and outer walls. The measurement was started when the temperature absorbed by the sample reached a steady-state condition. The thermal conductivity value of the hybrid bio-panels sample was calculated using Eq. (1) [20].

$$Q_{c,wall} = -kA\frac{T_1 - T_2}{\Delta x}\ (W) \quad (1)$$

where, T_1 represents the temperature on the inner surface, T_2 denotes the temperature on the outer surface, Δx is the thickness or distance separating the two surfaces of the wall, and A refers to the area of the wall surface.

2.5 Thermogravimetric testing

Thermogravimetric analysis (TGA) testing following the ASTM E1131-08 standard was performed using a SHIMADZU Thermal Analyzer model DTG-60. The principle of TGA testing is to measure a material's mass change against temperature or time in a particular atmosphere (air, inert, or oxidizing). The sample undergoes controlled heating, during which weight changes are monitored to evaluate decomposition, thermal stability, or the composition of elements like water, carbon, and residue. A sample weighing approximately 5 mg was scanned from 30 to 700℃ with a heating rate of 40℃/minute under nitrogen purging with a flow rate of 20 ml/minute.

2.6 Flexural property testing

The flexural strength of the hybrid bio-panels was tested using a three-point flexural test performed on an the Tensilon Universal Testing Instrument Model RTF 1350 (Japan), employing a crosshead speed of 2 mm/minute. Five samples, each with the dimension of 150 mm × 25 mm × 10 mm were tested from each hybrid bio-panel. The samples were placed between two supports at a distance of 100 mm, in accordance to the standard ASTM D790 [21]. The flexural strength of the hybrid bio-panels was determined using he flexural strength of the hybrid bio-panels was tested using Eq. (2).

$$\text{Flexural Strength (MPa)} = \frac{3PL}{2bd^2} \quad (2)$$

where, P is the max. load (N), L is the support distance (mm), and b and d are the specimen's width and thickness (mm), respectively.

2.7 Physical testing

The density and water absorption tests were conducted using the standard method of ASTM D792 [22] and ASTM D570 standard [23], respectively. Five specimens, each with the dimension of 50 mm × 50 mm × 10 mm squares were prepared. For the water absorption (WA) performance, the samples weight were measured before and after being soaked in water for 24 hours. The density and percentage of absorbed water was calculated using the formula in Eqs. (3) and (4). Where, W_1 is the initial mass of the sample before water immersion, W_2 is the mass of specimen after immersion in water.

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}\left(\frac{g}{cm^3}\right) \quad (3)$$

$$\text{WA (\%)} = \left(\frac{W_2 - W_1}{W_1}\right) \quad (4)$$

2.8 Observation scanning electron microscopy

Scanning electron microscopy (SEM) images of hybrid bio-panels were obtained using Hitachi SU-3500 scanning electron microscope from Japan. Prior to SEM analysis, the samples were coated with gold sputtering using Jeol JSM-IT200. The surface of the hybrid bio-panels sample was observed using scanning electron microscopy with 20 kV accelerating voltage.

3. RESULTS AND DISCUSSION

3.1 Thermal conductivity analysis of hybrid bio-panels

The thermal conductivity properties are crucial for thermal insulation materials, as material with lower conductivity are suitable as isolator material. Figure 4 shows the variation in thermal conductivity of SCB/CF hybrid bio-panels with TS/PVAc matrix blend. The data indicate a positive correlation between thermal conductivity and density. The average thermal conductivity coefficient SCB/CF hybrid bio-panels for fiber-to-matrix ratio 30:70 (Figure 4(a)), 40:60 (Figure 4(b)), and 50:50 (Figure 4(c)) is between 0.165 to 0.175 W/mK, 0.143 to 0.162 W/mK, and 0.132 to 0.138 W/mK, respectively. The samples BC2, BC5, and BC8 which correspond to fiber-to-matrix ratios of 30:70, 40:60, and 50:50, respectively, exhibited the lowest thermal conductivity values.

This works indicates that a combination ratio of 70 wt% SCB and 30 wt% CF fibers results in lower thermal conductivity and lower density. This phenomenon is likely due to the morphology of the fibers, as SCB fiber has a lower density and is lighter compared to CF fiber. Additionally, the matrix ratio also contributes to the decrease in thermal conductivity of composite. Lower matrix ratio results in low density and ultimately lower thermal conductivity coefficient. In this work, the thermal conductivity coefficient indicates a positive correlation for density. A similar finding was reported by Ramlee et al., who found that increasing the amount of OPEFB at OPEFB/SCB hybrid composites with biophenolic matrix decreases the thermal conductivity [16]. Previous studies on various natural fibers have also found that specimens with higher fiber content exhibit greater total porosity, which results in lower density composites [24]. The test results demonstrate that the thermal conductivity of the hybrid bio-panel is influenced by factors such as the density of the forming material, the matrix quantity, and the overall density of the hybrid bio-panel. The thermal conductivity of SCB/CF hybrid bio-panels in the present study is comparable with different insulation materials (Table 3).

3.2 Thermogravimetric properties of hybrid bio-panels

Understanding the thermal properties of a material is crucial for assessing its application potential. Its behavior in response to varying temperatures indicates its quality. Figure 5 exhibed the TGA and DTG thermograms of the SCB/CF hybrid bio-panels, illustrating the weight loss of hybrid bio-panels temperature up to 600°C at a rate of 20 ml/ml. The results indicate a decrease in the weight loss value of hybrid bio-panels, which can be categorized into three regions (Figure 5(a)). Region 1 is characterized by temperatures range of 30-250°C. Region 2 is spans temperatures between 250°C and 400°C. Region 3 involves temperatures exceeding 400°C. Region I corresponds to the water evaporation stage at hybrid bio-panel. In this region, TS/PVAc and cellulose SCB/CF fiber experience a mass loss of approximately 10%-16%, primarily due to moisture removal. Previous studies generally accepted that loss of weight at region 1 is due to the water vaporization heat in the composites. This phase indicates the initial phase of the decomposition of cellulosic components, predominantly occurring in the amorphous regions, facilitating the removal of water molecules [16].

Table 3. The thermal conductivity of different insulation materials

Composite	Density (g/cm^3)	Thermal Conductivity (W/mK)	Ref.
BC1	0.82	0.176	This study
BC2	0.78	0.165	
BC3	0.79	0.171	
BC4	0.80	0.162	
BC5	0.79	0.143	
BC 6	0.78	0.151	
BC7	0.77	0.138	
BC8	0.73	0.132	
BC9	0.76	0.136	
Wood fiber/PLA	0.45	0.110	[25]
OPEFB/SCB/Phenolic	0.54	0.089	[16]
SCB/Newspapers	0.65-0.68	0.116-0.118	[26]
SCB/Coir/PU	0.69	0.176	[27]
SCB/Bambo/PU	-	0.084 - 0.124	[28]

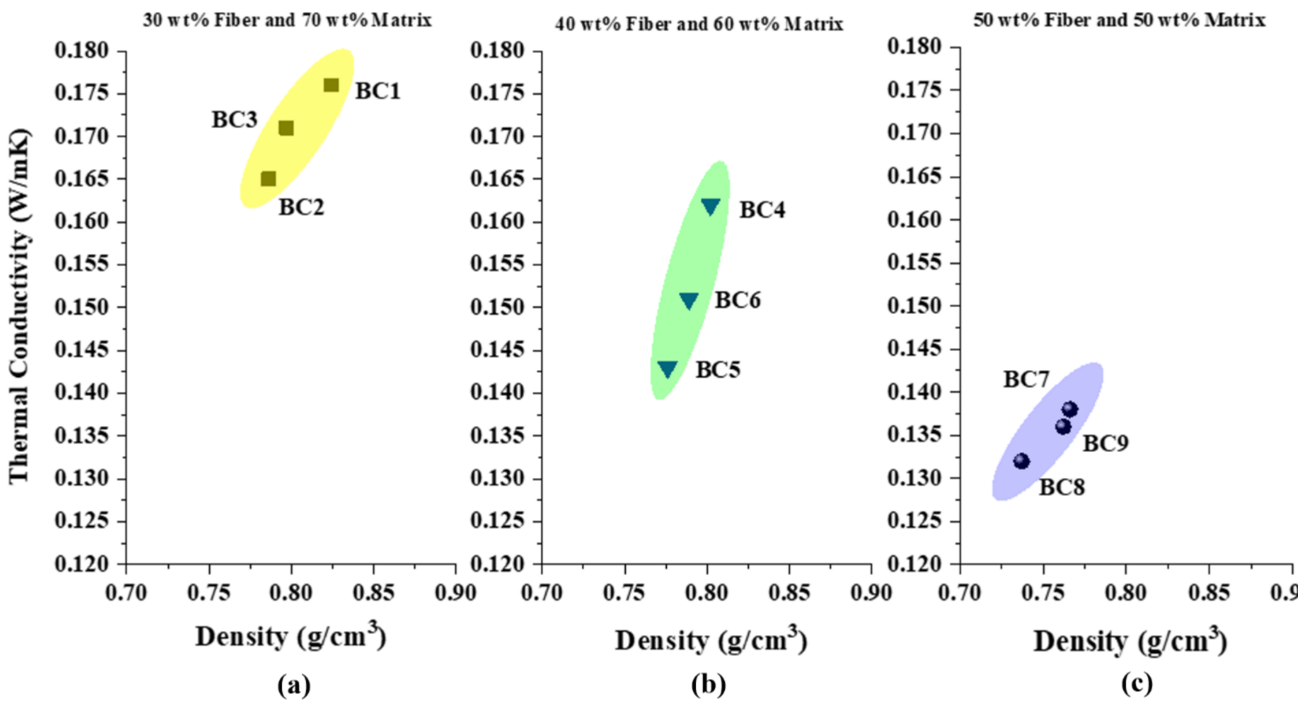

Figure 4. Correlation of thermal conductivity with different density: (a) 30 wt% Fiber and 70 wt% Matrix, (b) 40 wt% Fiber and 60 wt% Matrix, (c) 50 wt% Fiber and 50 wt% Matrix

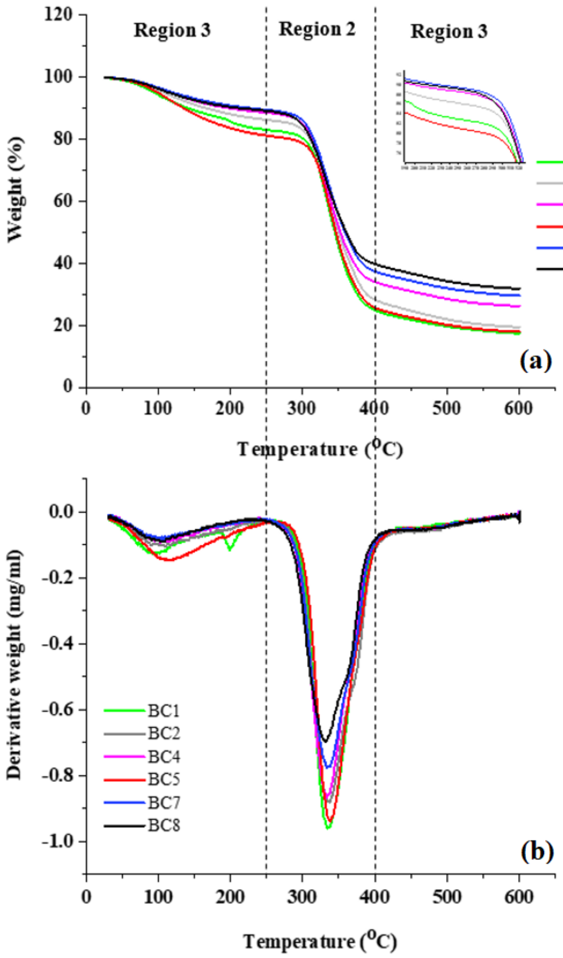

Figure 5. The thermograms depicting (a) TGA and (b) DTG of hybrid bio-panels

Region 2 shows the onset temperature and main weight loss of SBC/CF hybrid bio-panels. The thermal stability of the hybrid bio-panels decreases with increasing SCB fiber and reduced matrix ratio, although the effect is not significant. Among the hybrid bio-panels sample, the BC1 sample exhibited the highest T_{onset} (BC1 > BC2 > BC4 > BC5 > BC7 > BC8). Conversely, the weight loss value of the hybrid bio-panels decreased as higher percentage composition CF fiber and ratio matrix. This result suggests that at high temperature, CF fibre in hybrid bio-panels is more thermally stable compared to SCB fibre. A Similar observation previously for the SCB/OPEFB hybrid bio-panel, where OPEFB fibre with high cellulose content in hybrid bio-panels, exhibited greater thermal stability compared to SCB fibre [29]. During this stage, the weight reduction of the hybrid bio-panels sample ranged from 58.16 to 58.25%, for a 30:70 fiber-to-matrix ratio, from 54.51 to 55.48% for a 40:60 ratio, and from 49.25 to 52.11% for the fibers to matrix ratio 50:50. The increased weight loss is caused by the degradation of fiber and decomposition of matrix, likely exacerbated by the flammable nature of SCB fiber and tapioca starch. Furthermore, Figure 5(b) illustrates the DTG thermogram, which highlights the primary degradation phase. The data suggests that increasing the percentage of CF fiber and PVAc/TS matrix did not significantly influence the midpoint temperature. The hybrid bio-panels produced a maximum degradation temperature between 330°C and 335°C. A similar observation by Indra et al., where the major degradation of fiber-reinforced composites occurs around 340°C, corresponding to the degradation of both cellulose and polymer matrix. Region 3 represents the final degradation stage of the hybrid bio-panel, during which residues ranging from 8.81% to 7.75%.

Overall, the thermogravimetric analysis results suggests that incorporation of SCB/CF fiber and TS/PVAc at different volumetric fractions leads to a slight increase in the thermal stability of the hybrid bio-panels, though the change is not significant. Table 4 presents detailed information regarding onset, midpoint, endset temperature, and endpoint weight loss of hybrid bio-panels samples.

3.3 Flexural strength properties of hybrid bio-panels

The initial mechanical evaluation included a flexural test to determine key strength parameters such as deformation at maximum force, flexural strength, and flexural modulus. The findings of this investigation are depicted in Figures 6 and 7. Figure 6 exhibits the curves recorded during the static flexural test, showing the relationship between deflection and force. It was observed that the increase of TS/PVAc matrix blend and CF into the hybrid bio-panels improved the potential for deflection in the panels, and required more force to fracture the materials.

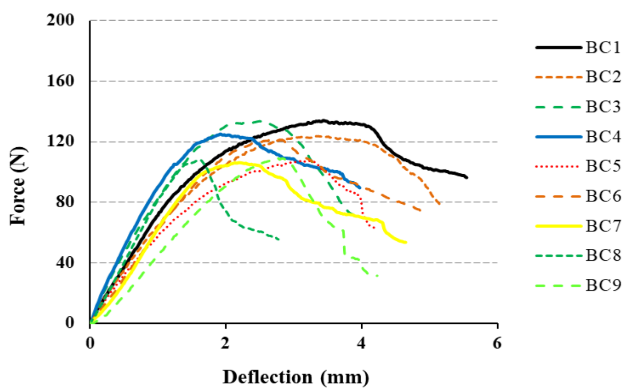

Figure 6. Flexural curves of SCB/CF hybrid bio-panels

Table 4. The temperature and mass weight loss of the SCB/CF hybrid bio-panels at various region

Samples	T Onset (°C)	T Mid Point (°C)	T Endset (°C)	Weigth Loss (%)		
				Region 1	Region 2	Region 3
BC1	296	335	378	16.87	58.16	8.81
BC2	289	333	380	13.58	58.25	7.44
BC4	288	332	374	15.92	54.51	7.91
BC5	287	331	376	11.44	55.48	7.71
BC7	286	331	377	11.12	49.25	7.84
BC8	282	330	379	10.46	52.11	7.75

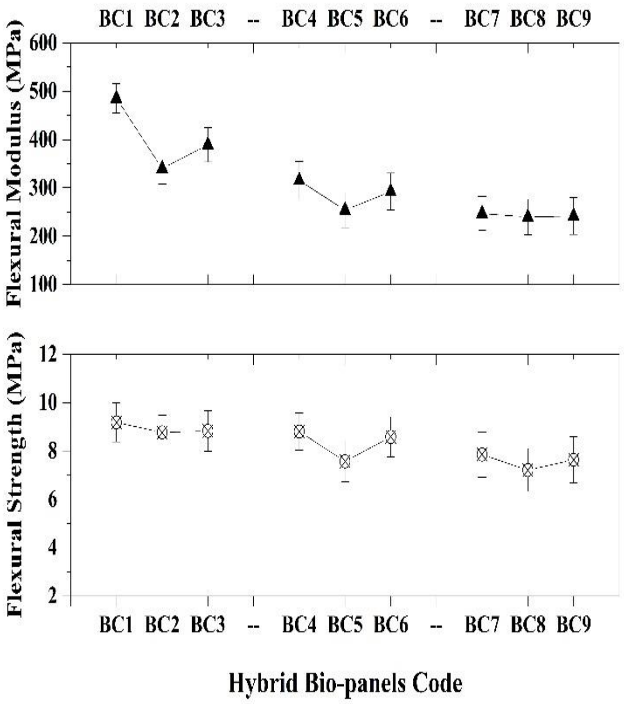

Figure 7. Average values of flexural parameters of SCB/CF hybrid bio-panels

Figure 7 depicts the average values of the fundamental flexural parameters. The hybrid bio-panels with fibers to matrix ratio of 70:30 show the highest flexural strength, with BC1 at 9.18 MPa, followed by BC3 (8.83 MPa), and BC2 (8.77 MPa), respectively. For a fibers-to-matrix ratio of 60:40, the flexural strength are 8.81 MPa for BC4, 8.58 MPa for BC6, and 7.57 MPa for BC5. For a fibers-to-matrix ratio of 50:50, the flexural strength are 7.85, 7.64, and 7.21 MPa for BC7, BC9, and BC8, respectively. The ratio 70 wt% CF and 30wt% SCB fiber into 70 wt% TS/PVAc matrix blend provide the maximum flexural strength of hybrid bio-panels compared the other ratio composition up to 27.32%. This increase is likely due to enhanced adhesion between the SCB/CF fiber and the matrix, with TS/PVAc matrix acting as a bridge between the fibers. This interaction occurs when the fiber surface is well coated by the matrix [30].

In this study, increasing TS/PVAc matrix and CF fiber content in the hybrid bio-panels improved the flexural strength the panels. The improvement is due to a higher degree of cross-linking at the contact surface, leading to stronger bonding between the matrix and the fiber. Furthermore, the presence of CF fiber has also contributed to the flexural strength in the hybrid bio-panels. The superior properties of CF fiber compared to SCB fiber positively impact the flexural load resistance of the panels. Previous study have found that fiber hybridization, fiber loading, and proportional matrix ratio can increase flexural strength [31]. This finding suggests that the flexural properties of the composite are significantly influenced by the type of fiber, fiber ratio, and matrix, which share a directly proportional relationship.

The modulus of elasticity reflects the capability of composite materials to undergo elastic deformation. Figure 6 depicts the flexural modulus of SCB/CF hybrid bio-panels with the TS/PVAc matrix blend. The results show that the flexural modulus behavior exhibits similar trend to the flexural strength property hybrid bio-panels. As the CF ratio increases to 70 wt%, the flexural modulus of the hybrid bio-panels rises from 340.18 MPa for BC2 to 389.29 MPa for BC3 and 485.48 MPa for BC1. A similar trend is observed with increasing TS/PVAc matrix ratio of 60 wt% and 50 wt%. The flexural property of the hybrid bio-panels produced are superior to those of sugarcane bagasse and polyvinyl acetate composite [32]. Previous research conducted by the author also found that increasing the styrofoam matrix in the bagasse fiber composite improved the bending modulus of the bagasse composite [30]. Several researchers have concluded that type of fiber, the matrix, and the stiffness of the fiber may influence the modulus of the bio-panels [11, 29]. This work demonstrates that increasing CF fiber and TS/PVAc matrix blend loading positively effects the flexural strength and modulus of the hybrid bio-panels. The ratio of fiber and matrix plays crucial roles in influencing the flexural characteristic of hybrid bio-panels.

3.4 Physical properties of hybrid bio-panels

Figure 8 shows the correlation between density and percentage of water absorption of SCB/CF hybrid bio-panels for 24 hours of immersion. The data indicates that the water absorption capacity of composites is inversely proportional to its density. In other words, when the density increases, the water absorption capacity decreases. Furthermore, increasing the matrix positively affects water absorption resistance.

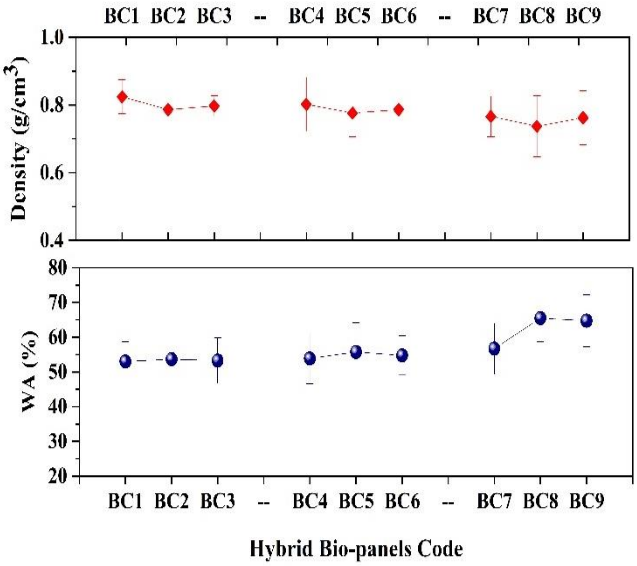

Figure 8. Relationship density and water absorption of hybrid bio-panels

The density of hybrid bio-panels ranges from 737 kg/m^3 and 824 kg/m^3, with BC1 exhibits the highest and BC8 exhibits the lowest density. The findings reveal that hybrid bio-panels containing a higher proportion of TS/PVAc matrix and CF exhibits a higher density compared to those made from more SBC and little TS/PVAc matrix. The increased presence of TS/PVAc matrix and CF in the hybrid bio-panels contributes to better compaction of the mat structure, whereas a decrease in the matrix content leads to the formation of more and larger pores in the mat. Previous researchers has also indicated that reducing the matrix can lower the density of the composite [30]. Additionally, the raw material density plays a crucial role in determining the overall density of the hybrid bio-panel. For instance, the density of SBC is 0.4-0.55 g/cm^3, and CF is 1.25-1.5 g/cm^3.

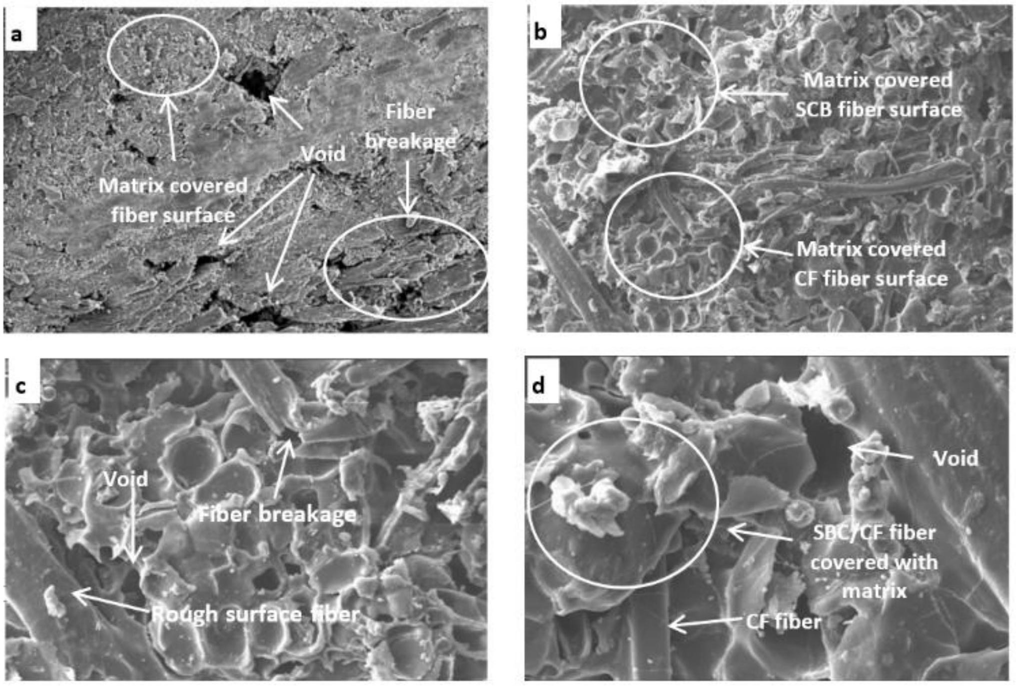

Figure 9. SEM of the hybrid bio-panels

The water absorption test is essential for evaluating the quality of natural fiber composite materials. In this study, the percentage of water absorption ranged from 52.99 to65.47%. Specifically, the BC1 sample, which has 50 wt% fiber and 50wt% TS/PVAc matrix, exhibited the highest water absorption at 65.47%. Similarly, BC5 sample showed 55.75% water absorption and BC2 absorbed 53.65%. In the third case, samples with a higher SCB content (70 wt%) and lower CF content (30 wt%). exhibited greater water absorption compared to those with more CF. Apart from that, the effect of CF incorporation will help to reduce water absorption of composites. The incorporation of co-reinforcement like CF improves the compatibility of the mixed materials, reduces surface voids, and ultimately reduces water absorption [29]. An increased percentage of the TS/PVAc matrix in the hybrid bio-panels enhances the bonding between fibers, reducing the likelihood of water infiltration. Conversely, a lower matrix weakens interfacial bond between fiber and matrix, making it easier for water molecules to diffuse to materials. This effect leads to higher water absorption in composites with less matrix. Previous researchers have also reported similar findings [33, 34]. Additionally, the consistently high water absorption capacity of the composites is inherently associated with the natural hydrophobic properties of SCB and CF.

The compatibility of natural fibers with the matrix influences the strength, density, and water absorption of the composite. Poor adhesion due to the hydrophobic nature of the matrix and hydrophilic fibers causes porosity, mechanical weakness, and high water absorption, thus reducing the performance and physical properties of the composite. Chemical modification of the fiber or matrix is necessary to improve the physical properties of the composite.

3.5 Morphological of the hybrid bio-panels

The SEM micrographs (Figure 9), captured at magnifications ranging from 50x to 500x, were utilized to examine the morphology and assess the potential interfacial adhesion between the matrix and the fibers in the hybrid bio-panels. Figure 9 (a) and (b) reveal the cross section of hybrid bio-panelsat 50× and 100× magnification. The image indicates that the matrix covers the fibers well, but there are still some voids present in the structure. This phenomenon impacts the composite's density, as increased void content leads to lower density. Additionally, it reveals fiber breakage from the matrix when a load is applied to the composites. Figure 9 (c) and 9 (d) depict surface fracture of hybrid bio-panels at 500× magnification. SEM images reveal that a higher ratio of matrix and CF fiber resulted panels to become more ductiles due to high strength of CF fiber properties on flexural. A large matrix ratio can cover the fiber well and closed the void. This phenomenon contributes to good flexural properties and water absorption resistance performance.

4. CONCLUSIONS

This study explored the physical, thermal, and flexural properties of hybrid bio-panels reinforced with sugarcane bagasse (SCB) and coir fiber (CF) using a tapioca starch (TS) and PVAc blend resin as the matrix. The findings demonstrate a positive correlation between coir fiber content and the TS/PVAc matrix ratio with water absorption resistance, flexural strength, and thermal stability of the bio-panels. Conversely, thermal conductivity decreased as the density of the composites increased. The BC8 sample exhibited the lowest thermal conductivity (0.132 W/mK) and the lowest density (0.737 g/cm³). The hybrid bio-panel containing 30% SCB and 70% CF with a 70 wt% TS/PVAc matrix achieved the highest flexural strength (9.18 MPa) and modulus (485.48 MPa). This research underscores the potential of SCB and CF fibers as sustainable fillers in hybrid bio-panels, paving the way for environmentally friendly material solutions. Future studies could focus on optimizing fiber-matrix interactions, developing eco-friendly resins, and enhancing environmental resistance. Applications of SCB and CF composites include lightweight automotive components, sustainable building panels, and eco-friendly packaging for the green industry.

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