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Physical Characterization of Non-Woven Treated and Untreated Palm Empty Fruit Bunch Layered by Fibreglass as an Interior Insulation Material

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ABSTRACT

Palm empty fruit bunch (PEFB) fibres hold potential as a natural material for insulation, offering an alternative to the commonly used fibreglass in HVAC system ducting. Fibreglass (FG) in commercial insulation materials contributes to issues such as unpleasant environmental noise, which can have harmful effects on communication, health and overall quality of life. This study aims to prepare nonwoven untreated and treated PEFB with FG at different ratios using a silane coupling agent treatment. The nonwoven materials are produced through a combination of a needle punching machine and hot compress technique and various characteristics, including thermal decomposition, functional groups, thermal conductivity and water contact angles, are examined. The thermal decomposition analysis of treated PEFB reveals a shift in the decomposition temperature to a higher value of 25 °C after the silane coupling agent treatment, indicating improved thermal stability. The examination of functional groups confirms the presence of peaks corresponding to cellulose, hemicellulose and lignin in PEFB, along with a new peak of Si-O-C due to the silane coupling agent treatment. Furthermore, the thermal conductivity of treated PEFB samples decreases after treatment, with the PEFB (70): FG (30) ratio displaying the lowest thermal conductivity value of 0.05 W/m °C. The composition of treated PEFB (70): FG (30) achieves the highest contact angle of 135°, signifying superior water repellence. Moreover, an increased treated PEFB ratio consistently demonstrates improved water repellence. Therefore, enhancing treated PEFB with a silane coupling agent holds promise as an insulation duct material, offering improved thermal stability and water repellence and serving as a sustainable alternative to conventional FG in heating, ventilating and air-conditioning (HVAC) systems.

1. Introduction

The palm oil and fibre sectors generate significant waste, including empty fruit bunches (EFB), which are not utilized efficiently and can result in negative environmental effects. These solid wastes

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are not commercially utilized and are primarily used as compost or fuel in oil palm farms, mulch, fertilizer and animal feed [1-3]. The oil palm plantation constitutes a significant worldwide industry sector, contributing to economic growth and providing Malaysia's largest agricultural sector [4]. The phrase "palm empty fruit bunch" (PEFB) refers to the fibrous waste product produced following oil extraction from oil palm fruits. PEFB is a valuable biomass resource used for a variety of uses, including the manufacturing of biodegradable products, animal feed, fertilizer and renewable energy. PEFB fibre waste is a significant issue because of the incorrect use of fibrous material from oil palm plants. PEFB fibre has the potential to be a useful biomass resource for a variety of uses, but poor management may result in its disposal as waste [5].

The construction industry, which relies mostly on non-renewable resources, has noticed an increase in demand for environmentally friendly insulation materials. Converting waste into efficient insulation materials can address environmental concerns and meet the growing need for sustainable building materials. A solution could be to use biomass refuse from these sectors to produce sustainable insulation materials, reducing waste and offering a renewable alternative to conventional insulation materials [6]. Suppose fibreglass is the only material used for insulation, during installation or maintenance. In that case, small particles may be released into the air, causing skin irritation and respiratory problems in those who encounter the fibres. Furthermore, especially in humid situations, fibreglass can absorb moisture, which could reduce its insulating qualities and perhaps encourage the formation of mould. However, the danger of mould development will be decreased, helping to control moisture levels and preserving the integrity of the insulation when natural fibre and fibreglass are combined.

Oil palm processing by-products, such as empty fruit bunches, serve as effective fermentation raw materials owing to their cellulose and hemicellulose content. The EFB fibres, also utilized as mulch for palm oil mills, represent a rich source of lignocellulosic material. Consequently, the treatment of PEFB has been addressed through chemical processes. The chemical alteration of natural fibres is a method that permanently changes the surface of fibre cell walls through polymer grafting [7]. This chemical treatment enhances physical properties, reduces hygroscopic potential and imparts resistance to fungal blight in fibres [8]. Coupling agents such as silanes, acetylation and graft copolymerization is applied on lignocellulosic fibres to enhance the chemical bonding of the fibre surface, which contains oxide groups with the polymer molecules [9]. Silanes, featuring micro-pores on their surface, act as coupling agents, modifying the fibre surface through processes such as hydrolysis, condensation, adsorption and chemical grafting. This modification enables the formation of bonds with fibre surfaces [10].

Silane can serve as a silane coupling agent due to its possession of two functional groups with varying reactivity [11]. The first functional group reacts with organic molecules, while the second reacts with inorganic elements. When applied between organic polymers and inorganic fillers, silane coupling agents offer significant benefits, enhancing resin and filler compatibility [12]. The extermination groups of hydroxyls that contribute to strong interfacial bonding are achieved through the synthetic modification of fibres using silane coupling agents [13]. This process can also improve filling capacity, reduce swelling and mitigate water vapor penetration [14]. There are several types of silanes coupling agents, namely 3-arninopropyl (diethoxy) methyl-silane [14], 3 methacryloxypropyltrimethoxysilane (3-MPS) [15], Hexadecyltrimethoxysilane polysiloxane [16], 3-glycidoxypropyltrimethoxy silane [17] and 3- ureidopropyltrimethoxy silane [18]. On the other hand, the non- functional silanes have a reactive functional group that may react with inorganic substances and are frequently employed for some surface modification materials [19,20].

Therefore, in this study, converting waste PEFB into an efficient insulation material addresses the issue of environmental concerns and meets the increasing demand for sustainable building materials.

To decrease waste and offer a renewable option to conventional insulation materials, an alternative that uses biomass refuses from these sectors to produce sustainable insulation materials. Therefore, this study investigated the physical characteristics of untreated and treated waste PEFB fibre by thermalgravimetric analysis (TGA), Fourier-Transform Infrared Spectroscopy (FTIR) Analysis, water contact angle and thermal conductivity.

2. Methodology

2.1 Materials

The waste PEFB fibre was obtained from a factory located in Bukit Pasir, Muar, Johor. The diameter of waste PEFB fibre is about 0.4mm and the average length is about 15cm. The fibres may need to be cut in the size range of 6 to 8cm. The silane coupling agent and fibreglass were obtained from Syarikat Saintifik Bersatu Sdn Bhd.

2.2 Sample Preparation of Nonwoven Untreated and Treated PEFB Reinforced with Fibreglass

The waste PEFB was treated with a silane coupling agent. A mixture of ethanol and distilled water in a weight ratio of 80:20 was mixed with 0.1 g 3-aminopropyl (diethoxy) methylsilane hydrolyzed. The combination of the mixture was stirred at a constant rate until it reached the homogenous solutions. Then, 10 g of waste PEFB fibres were added into the solution and continually agitated (silane-filler ratio of 1: 100). The bamboo fibres were immersed in the silane solution for 3 hours before adjusting the pH to 4.00 using the modified method of acetic acid. After that, the waste PEFB fibres were oven-dried for 24 hours at 80°C. Figure 1 depicts the waste PEFB fibre treatment procedure using a silane coupling agent.

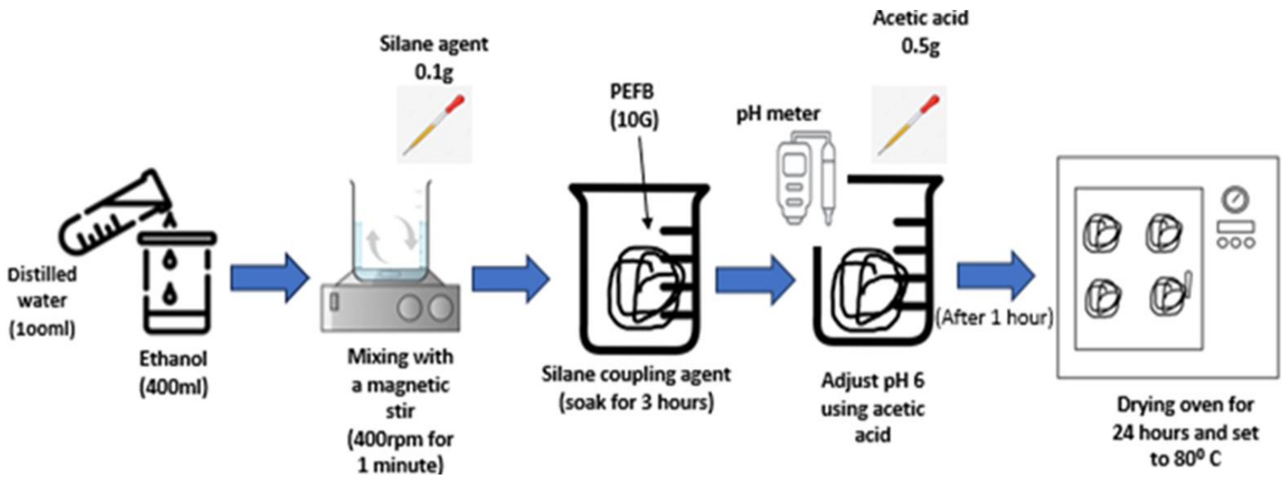


Fig. 1. The waste PEFB fibres treated with a silane coupling agent

The untreated and treated nonwoven waste PEFB fibres were prepared using Needle Punching Nonwoven Machine GM2350 Jute Fibre Needle Punching Machine of Geotextile Jinan Xingsai Machinery Manufacturing Co at textile laboratory UTHM, Pagoh Campus, Johor followed by ISO 9001 internationally recognized standard for creating, implementing and maintaining a Quality Management System (QMS). The thickness of both the untreated and treated waste PEFB fibres was observed to be approximately 3 mm. The needle-punching machine has a capacity of 2,000 needles/m^2, operating at a speed of 300 m/min. Nine samples were prepared with the following PEFB fibres and fibreglass (PEFB: FG) ratios: 100:0, 70:30, 50:50, 30:70 and 0:100. Subsequently, the samples were arranged in layers and assembled onto a hot press machine at a temperature of 50°C and a pressure of 1 MPa for 1 hour.

2.3 Physical Characterization

2.3.1 Thermalgravimetric analysis (TGA)

The thermal study of materials provides fundamental information on their thermal stability. In this study, TGA was conducted better to understand the PEFB degradation characteristics for temperature. The samples were analysed using the TA Instruments TGA Q500 and TGA 550 thermogravimetric analysers, following the ASTM E1131 TGA Analysis Testing Services standard. All measurements were conducted at a nitrogen flow rate of 25 ml/min, with a constant heating rate of 10 °C/min in the ranges of 40 to 900°C. The specimens, weighing approximately 10 mg, were placed in ceramic crucibles and the tests were carried out under a nitrogen atmosphere.

2.3.2 Fourier-transform infrared spectroscopy (FTIR) analysis

FTIR is a rapid, suitable, non-destructive and cost-effective technique for identifying the functional groups present in fibreglass, untreated PEFB and treated PEFB. FTIR analysis was carried out using the Agilent Cary 630 FTIR Spectrometer, following the ASTM D6342-12 (Standard Practice for Polyurethane Raw Materials: Determining Hydroxyl Number of Polyols by Near Infrared (NIR) Spectroscopy). The purpose was to determine the chemical functional groups present in both untreated and treated PEFB fibres. To measure the spectra of the compounds, present in the samples, the wavelength range was set from 650-4000 cm^{-1}, with the maximum resolution at 4 cm^{-1}.

2.3.3 Thermal conductivity

The untreated and treated PEFB-FG samples were prepared in 300 mm (length) x 300 mm (width) x 20 mm (thickness) sizes for the thermal conductivity test. The test was performed using a Heat Flow Apparatus following ASTM E1530–19 Standard, with a measurement range of 0.01 to 0.50 W/mK and measuring accuracy of approximately 1%. The temperature difference between the measurements was maintained at 20°C. The thermal conductivity was calculated by multiplying the heat transfer rate by the thickness of the sample, divided by the area and then multiplied by the temperature difference of the samples.

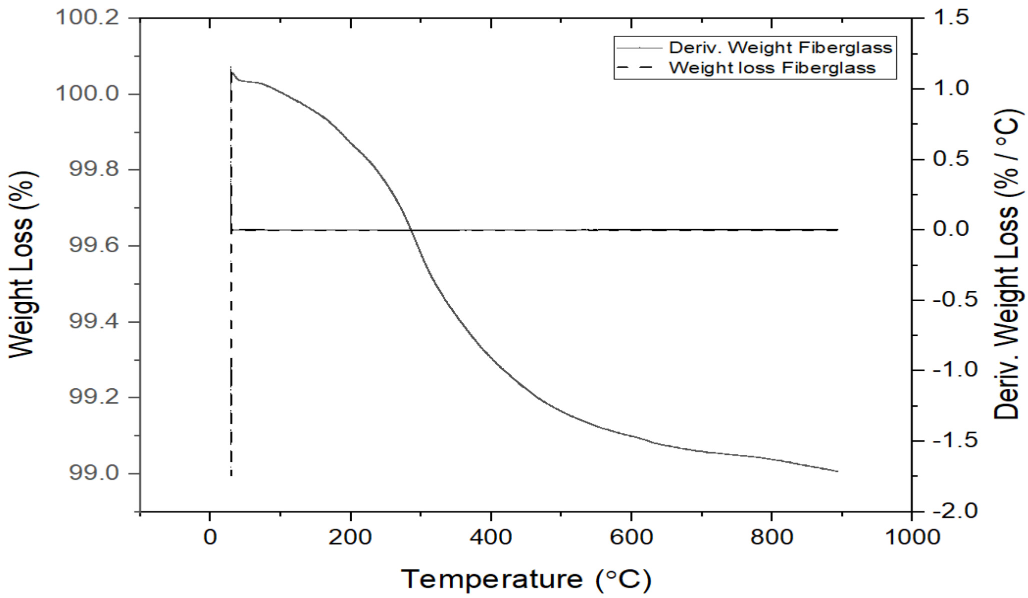
2.3.4 Water contact angle

To measure the wetting behaviour of the PEFB, the untreated and treated waste PEFB fibres were prepared in dimensions of 15 mm x 15 mm and the double-sided tape was affixed to a glass slide. The fibre sample was then placed on the contact angle setup holder platform substrate using a syringe with a size of 100 microlitres (µL). To measure the contact angle, five µL of distilled water was applied to the fibre surface areas using a micropipette attached to the VCA Optima contact angle measurement tool, following the ASTM D7334-8 Standard Practice for Surface Wettability of Coatings, Substrates and Pigments by Advancing Contact Angle Measurement.

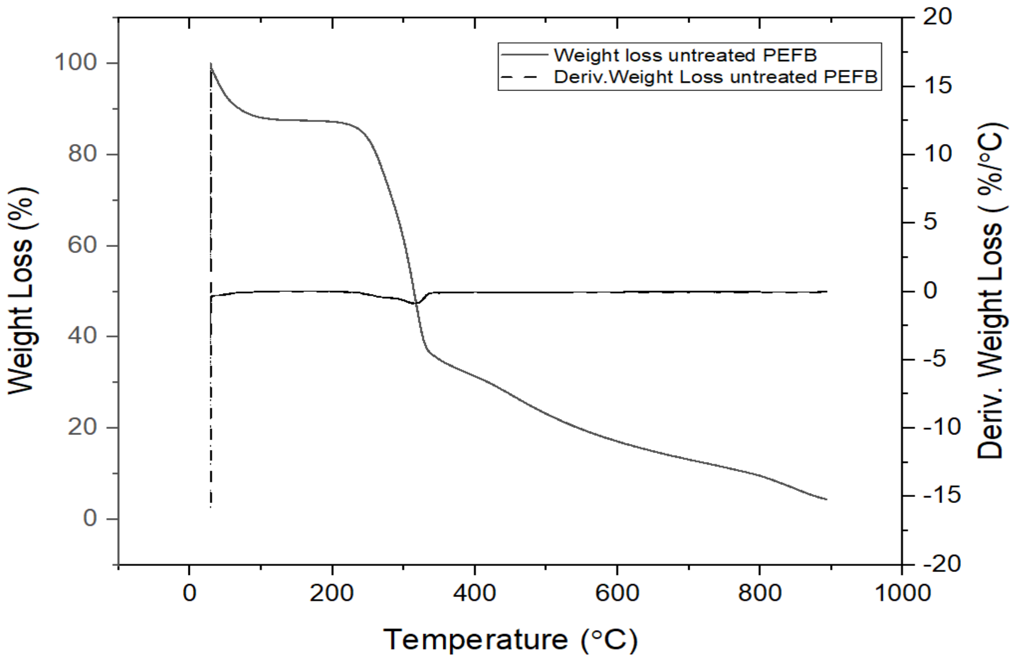
3. Results

3.1 Thermalgravimetric Analysis (TGA)

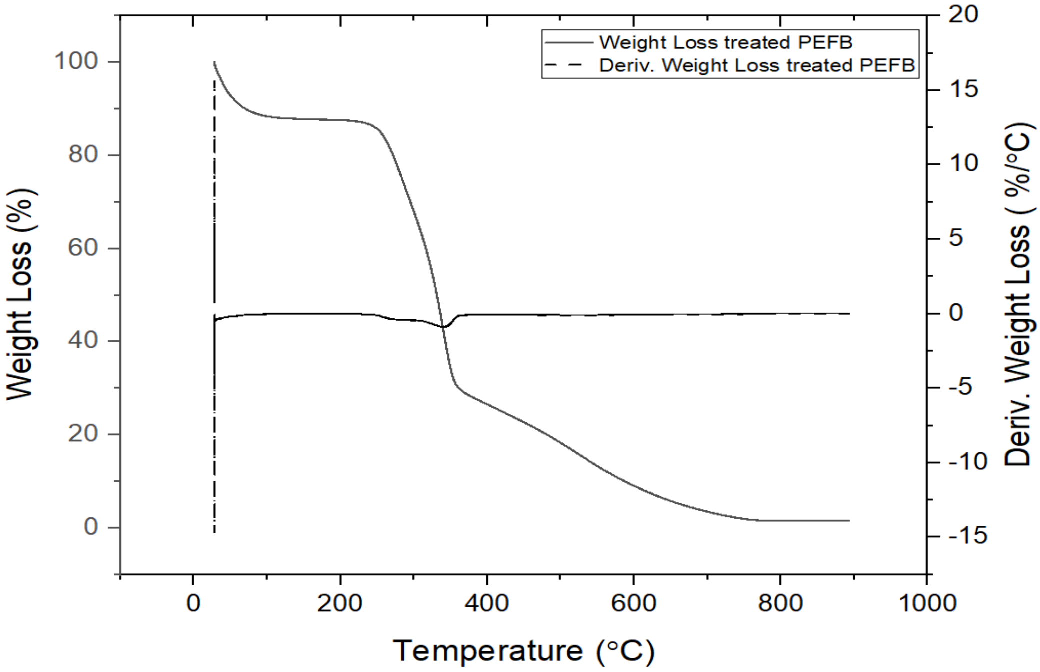
The results of the TGA of fibreglass, untreated PEFB and treated PEFB are presented in Figure 2, covering a temperature range of around 30°C to 900°C. The TGA diagrams of fibreglass depict the weight loss and derivative weight loss curves at the first stage, up to 100 °C, corresponding to the evaporation of water or solvent (if any) in fibreglass. This stage appears as a plateau before the onset of the first decomposition. The decomposition temperature of fibreglass is not evident until 900°C, as there is no weight loss and the materials reach stability.



(a)



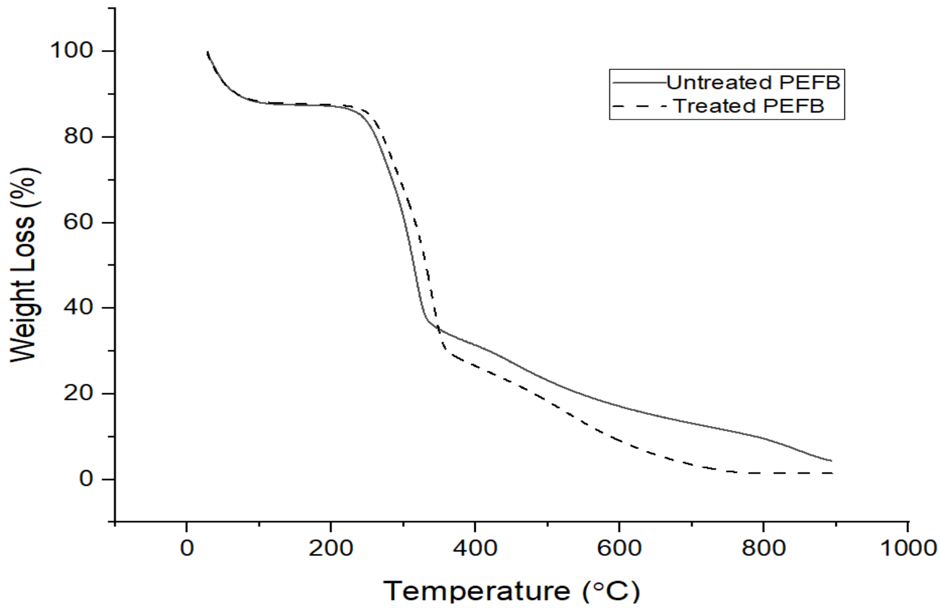
(b)



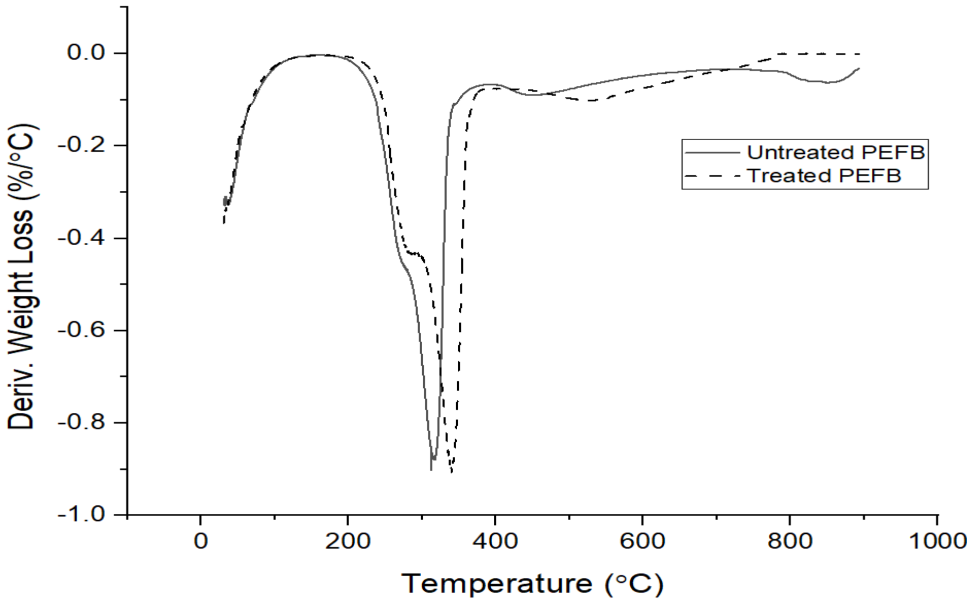
(c)

Fig. 2. Overlay thermogram and derivative weight of (a) Fibreglass (FG), (b) Untreated PEFB and (c) Treated PEFB fibre

The thermal degradation of untreated and treated PEFB fibres exhibits a similar trend in decomposition temperature, as illustrated in Figure 3. The decomposition of PEFB fibres typically transpires in three stages: the drying process, degradation process and evaporation of light components (phase one); devolatilization of cellulose and hemicellulose (phase two); and decomposition of lignin (phase three). The initial phase, involving the drying and evaporation of light components such as moisture and volatile organic compounds, spans from 30°C to 100°C. During this phase, the drying and evaporation of untreated and treated PEFB lead to a mass reduction of 12.0%, with weight losses occurring at 94°C and 114°C, respectively. Consequently, the degradation of PEFB fibres initiates at approximately 230°C and 246°C.



(a)



(b)

Fig. 3. Overlay thermogram of (a) Untreated PEFB and treated PEFB and (b) Derivative weight of untreated PEFB and treated PEFB fibre

In this study, a noteworthy weight loss in untreated and treated PEFB was observed within the temperature range of 230 to 350°C, indicative of phase two, involving the devolatilization of cellulose and hemicellulose. The weight percentage of untreated PEFB decreased from 86 to 48%, resulting in a total weight loss of 38% during the devolatilization process. Similarly, treated PEFB exhibited a decrease from 86 to 42%, with a weight loss of 44% at the temperature of 340°C. In phase three, a gradual yet consistent weight loss was observed as the temperature reached approximately 350°C, with a heating rate of 10 °C/min. This weight loss is attributed to the degradation of lignin compounds and other chemically bound compounds that persisted at the high degradation temperature range for an extended period. At the end of phase three, the weight of untreated PEFB decreased from 48 to 7.6%.

In comparison treated PEFB corresponds with the decomposition temperature at 340°C higher than untreated at 315°C. This result observed that, after being treated with a silane coupling agent, the decomposition temperature was shifted to increase by 25°C. This exhibited that the degradation of the cellulosic material in treated PEFB was stronger than in untreated PEFB due to the cellulosic is a major factor in the degradation of PEFB fibre. The treatments with silane coupling agent had a considerable effect on the thermal degradation behaviour of the PEFB fibres, promoting an increase in the temperatures at which the thermal degradation took place. The thermal stability of PEFB fibres increased due to the chemical degradation of hemicelluloses, lignin and part of silica during silane coupling agent treatment. Hence, the PEFB fibre starts degrading at about 232°C and 246°C. Structural constituents of the PEFB fibre (cellulose, hemicelluloses, lignin, etc.) are sensitive to the different ranges of temperatures. Thermal stability can be enhanced by removing a certain proportion of hemicelluloses and lignin constituents from the fibre by silane coupling agent treatment.

3.2 Fourier-Transform Infrared Spectroscopy (FTIR) Analysis

The fibreglass exhibited a dominant peak at 1000 and 3800 cm^{-1}, attributed to the O-H groups. In a recent study, FTIR was successfully employed to examine the bonding interactions of PEFB before and after being treated by a silane coupling agent, as illustrated in Figure 4. The absorption peaks of the untreated PEFB fibre at 3400, 2906, 1620 and 1150–1050 cm^{-1} were associated with the stretching vibrations of the –OH groups, C–H groups, H–C–H rings and C–O groups of cellulose, respectively. Peaks at 2851 and 897 cm^{-1} were attributed to the stretching and rocking vibrations, respectively, of the C–H groups of cellulose. The peak at 1238 cm-1 was ascribed to the stretching of the C–C groups of hemicellulose and the peaks at 1639 and 1512 cm^{-1} corresponded to the stretching of the C=O and C=C bonds of the aromatic ring of lignin. This functional group was similar to previous research of bamboo fibre [21].

For the treated PEFB fibre, it was observed that the trend of peaks was similar to the untreated PEFB fibre. The absorbance in the range of 1000 to 1 100 cm^{-1} after treatment indicated a sharp peak corresponding to the deformation of the Si-O-C bond stretching. The peak at 3300 cm^{-1} indicated the O-H hydrogen bonding stretching of cellulose in treated PEFB. In the treated PEFB fibre, stronger peaks were observed from 3010 to 3040 cm^{-1} after treatment, which could be related to Si-O-Si and Si-O-C stretching vibrations. These observations suggest the formation of new chemical bonds between the PEFB fibres and the silane coupling agent. However, the absorption at 1638 to 1648 cm^{-1} assigned to the C=C stretching bond appeared with high absorption intensity in this FTIR analysis. The reason for this is presumably due to the silane coupling agent being present in too low a concentration to display all the peak changes in the FTIR spectra. Consequently, the silane coupling agent treatment improved the crystallinity of the fabricated cellulose PEFB.

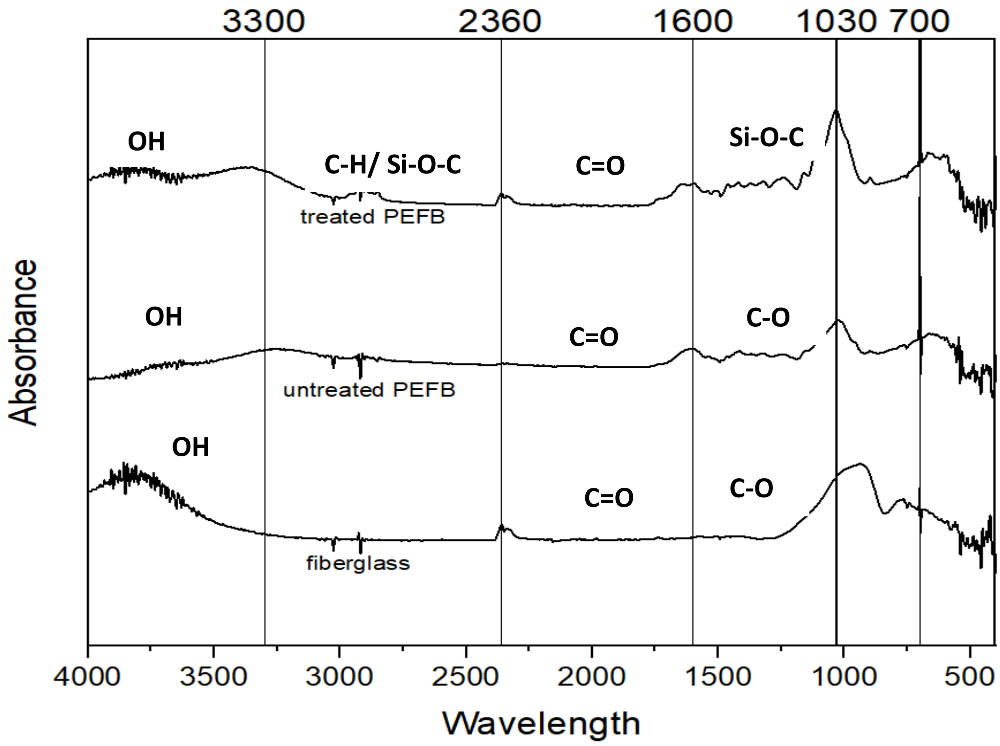


Fig. 4. FTIR of untreated, treated PEFB and fibreglass

3.3 Thermal Conductivity

The thermal conductivity results for treated and untreated PEFB and FG composites are shown in Figure 5. At the 30:70 PEFB:FG ratio, the untreated sample displayed a thermal conductivity of 0.079 W/mK indicating moderate heat transfer characteristics. The treated sample at the same ratio demonstrated a reduced thermal conductivity of 0.05 W/mK. The reduction shows that the treatment technique had a positive impact on the composite's thermal characteristics, resulting in increased insulation capabilities. The silane coupling agent used as a treatment PEFB has been prevented to decrease heat transfer in the fibre-reinforced composite. The untreated samples with a 50:50 PEFB: FG ratio have an average heat transmission rate of 0.082 W/mK, which is shown by their thermal conductivity. On the other hand, the treated sample with the same ratio showed a 0.084 W/mK slightly lower thermal conductivity. The minimal variation in thermal conductivity for treated and untreated samples at a 50:50 ratio reveals that the silane coupling agent treatment has a small impact on the PEFB fibre's overall thermal properties. The results might have been impacted by additional factors including the distribution and orientation of the fibres inside the composite. When compared with the untreated sample, the treated samples' thermal conductivity gradually increased as the ratio of PEFB in the 70:30 and 100:0 ratios. The treated sample showed a slightly greater thermal conductivity of 0.07 W/mK in the 70:30 ratio than the untreated sample, which had a thermal conductivity of 0.053 W/mK. Additionally, at a 100:0 ratio, the treated sample exhibited a thermal conductivity of 0 W/mK, whereas the untreated sample had 0.027 W/mK. These results suggest that the treatment method significantly influenced the thermal properties, especially at higher PEFB ratios where the heat transfer characteristics of the composite may have been influenced by the silane coupling agent.

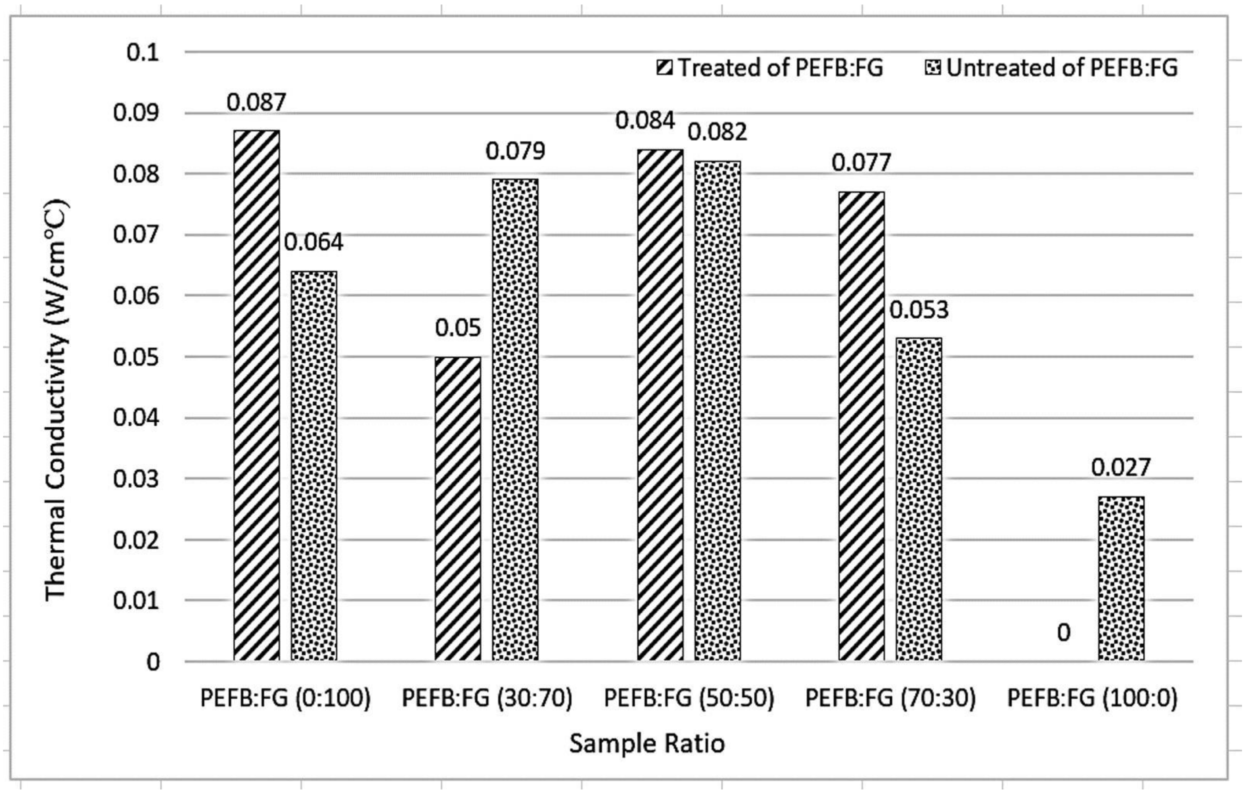


Fig. 5. Thermal conductivity of treated and untreated Palm Empty Fruit Bunches (PEFB) layered by Fibreglass (FG) composites as insulation applications

The observed decrease in thermal conductivity in composite materials treated with a silane coupling agent can be identified by a number of interconnected treatment-related phenomena. A silane coupling agent's main function is to improve PEFB's adherence to the FG matrix material. A more homogeneous composite structure with fewer voids or gaps at the fibre-matrix interface is the result of this improved interfacial bonding, which reduces thermal conductivity and decreases heat transmission. The silane coupling agent controls the surface properties of the natural fibres, leading to a more uniform distribution of thermal within the PEFB-FG composite. The modification could involve filling up the fibres' porous structures, which would lower the composite's total amount of porosity. Reducing porosity decreases the possibility of affecting heat transport, which contributes to the thermal conductivity reduction that has been observed.

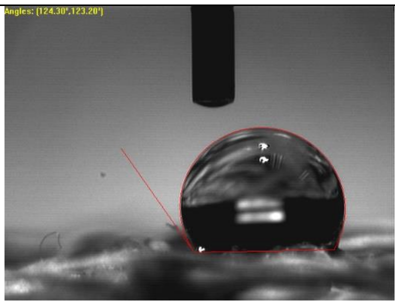
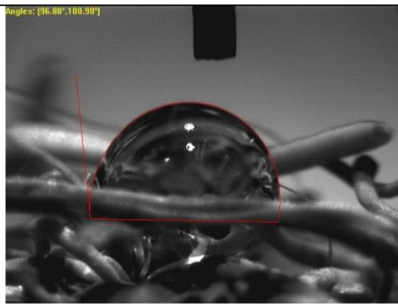
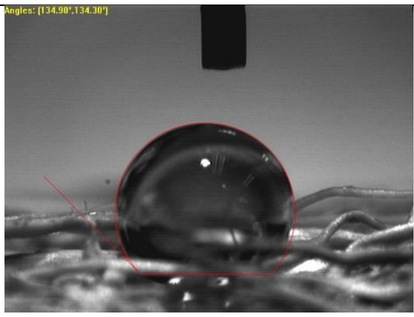
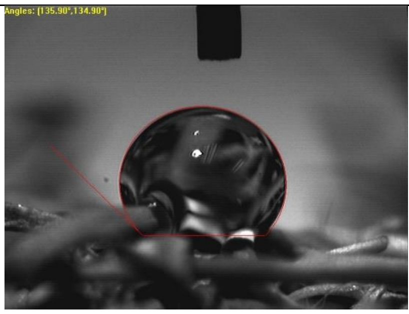
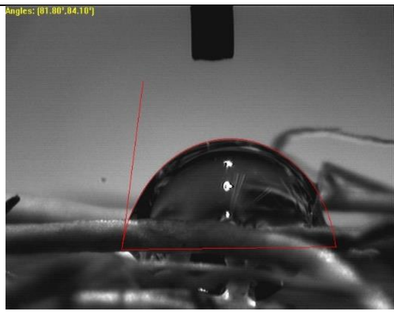
The hydroxyl groups on the surfaces of PEFG and FG may form a chemical bridge as a result of the treatment procedure. This improved contact lowers thermal resistance at the PEFB-FG interface while simultaneously increasing the composite's thermal conductivity. The improved bonding between PEFB and FG facilitates efficient heat transfer within the material. Silane coupling agents often exhibit hydrophobic properties, preventing moisture absorption by the PEFB-FG composites. As moisture can act as a thermal conductor, the treatment's ability to minimize water absorption helps maintain lower thermal conductivity in the composite. Moreover, the modification of the matrix properties by the silane coupling agent plays a role in the observed reduction in thermal conductivity. The study analyses thermal conductivity data for non-woven palm fibre mats reinforced with fibreglass at different ratios. The treated samples show lower thermal conductivity, indicating that the treatment enhances insulating characteristics. The 70:30 ratio is the most promising for efficient insulation, exhibiting the lowest heat transfer capability. This balanced ratio supports the research objective of reducing heat loss and increasing energy efficiency in ducting systems.

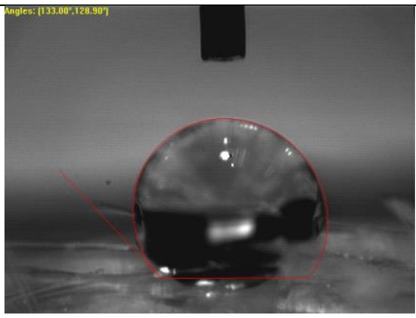
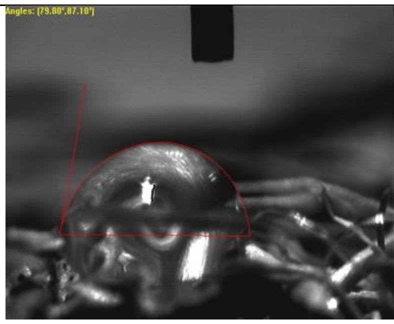
3.4 Water Contact Angle

The water contact angle results of treated and untreated PEFB and FG composite surfaces are shown in Table 1. In the sample ratio of PEFB:FG (0:100), water contact angles for untreated samples were 0°, while treated samples exhibited angles of 37°. This inconsistency implies a significant impact of the treatment process on the wettability of the composite material when the treatment dominates the composition. In the 30:70 PEFB:FG ratio, a difference emerged between untreated and treated samples. The treated sample showed a water contact angle of 124°, which suggests that its hydrophobicity is relatively high. The untreated sample, on the other hand, showed a lowered contact angle of 100°, indicating a definite improvement in water contact angle resistance upon application of the treatment procedure. The surface became more hydrophobic as a result of the treatment. The treated sample showed a water contact angle of 134° at a 50:50 PEFB:FG ratio, indicating its fundamental hydrophobic characteristics. The untreated sample, in contrast, showed a significantly reduced contact angle of 87°, highlighting how effectively the treatment performed in making the surface more hydrophobic. This significant difference indicates that the composite's wettability was considerably altered by the treatment procedure. A steady trend developed as the percentage of PEFB rose in the 70:30 and 100:0 ratios. When compared to treated counterparts, the untreated samples consistently showed lower water contact angles. The treated sample shows a contact angle reduction to 81° at the 70:30 ratio, compared to 135° for the untreated sample. Similarly, the treated sample showed a contact angle of 133° in the 100:0 ratio, while the untreated sample showed even more improvement with a contact angle of 79°.

These findings indicate that the treatment procedure enhanced the composite's water resistance while also successfully reducing the hydrophobicity of PEFB and FG. In the untreated PEFB and FG materials, the reduced contact angle may be due to the presence of free hydroxyl groups correlated with hemicellulose and lignin, representative hydrophilic surfaces. Besides, the treated FG material and PEFBs show higher contact angles indicating a reduction in free hydroxyl groups during the treatment process, improving their water repellence. The result of the PEFB surface modification is that the composite exhibits enhanced hydrophobic behaviour. Both the structural strengthening and the hydrophobic properties have been remarked for further enhanced by the addition of fibreglass to both formulations. The findings of this investigation show that the silane coupling agent treatment has a significant effect on the water contact angles of FG and PEFB composite materials. For all PEFB: FG ratios, the treatment continuously resulted in greater water contact angles, demonstrating improved hydrophobicity. Increasing the PEFB ratio led to the biggest improvements, indicating that the silane coupling agent was successful in modifying the composites surface characteristics.

Table 1
Water contact angle for treated and untreated Palm Empty Fruit Bunches (PEFB) layered by Fibreglass (FG) composites as insulation applications

Samples	Treated of PEFB-FG	Untreated of PEFB-FG
PEFB:FG 0:100	 37°	 37°
PEFB:FG 30:70	 124°	 100°
PEFB:FG 50:50	 134°	 87°
PEFB:FG 70:30	 135°	 81°

PEFB:FG 100:0	 133°	 79°

4. Conclusions

The fabrications of untreated and treated PEFB with fibreglass at different ratios resulted in better decomposition temperature, functional group composition, thermal conductivity and water contact angle, making these PEFB composites suitable for insulation applications. FTIR results revealed chemical compositions by identifying peaks corresponding to various functional groups in treated and untreated PEFB and fibreglass. A function group of samples was observed following treatment with a silane coupling agent, indicating a change in the functional group of each sample. The decomposition temperature of untreated and treated PEFB showed decreased mass losses in lignin and hemicellulose degradation, demonstrating that PEFB was more thermally stable upon treatment. The PEFB treatment with silane coupling agents consistently increased water contact angles, indicating improved hydrophobicity at different PEFB:FG ratios. Notably, the PEFB(70): FG(30) ratio was identified as the most potential for effective insulation, with the lowest thermal conductivity capability and the maximum hydrophobic surface property. Overall, the work demonstrates the effectiveness of the silane coupling agent in modifying the surface properties of composites, giving useful insights for applications that require good thermal stability and hydrophobic characteristics in insulation materials.

Acknowledgment
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