Comparative Effects of Alkali Treatment on the Physical, Mechanical, and Morphological Properties of Natural Fiber for Preliminary Insulation Material Screening

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The effects of alkali treatment were studied relative to the physical, mechanical, and morphological properties of oil palm empty fruit bunch (OPEFB) and banana fibers to evaluate their potential as insulation materials. Both fibers were subjected to several concentrations of sodium hydroxide (3, 6, and 9 wt%). The impact of altered fibers was assessed using image analysis, scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), tensile testing, and thermal characterisation. The diameters of both fibers were decreased post-treatment, along with reductions in lignin and hemicellulose contents inside the fibers. Tensile strength was enhanced by 29% to 177% with 3% alkaline treatments for both fibers, while 6% alkali treatment yielded superior results for both fibers. The NaOH-treated OPEFB and BF exhibited increased residual content after thermogravimetric analysis and enhanced thermal stability. SEM analysis revealed that 3% alkali treatment eliminated silica bodies from OPEFB fiber, but 6% alkali treatment consistently filled the porosity of BF. The results implied that alkali treatment of OPEFB fiber significantly enhanced compatibility and mechanical properties, whereas treated BF had improved thermal stability for the manufacture of composite materials. Thus, alkali treatment effectively enhanced OPEFB and banana fibers, making them promising candidates for insulation material applications.

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Nomenclature

BF	= Banana fiber	**CH_3COOH**	= Acetic acid
OPEFB	= Oil palm empty fruit bunch	**DTG**	= Derivative thermogravimetry
SEM	= Scanning electron microscopy	***T***	= Temperature (°C)
FTIR	= Fourier-transform infrared	**wt%**	= Weight percentage
NaOH	= Sodium hydroxide	***F***	= Applied force (N)
TGA	= Thermogravimetric analysis	***A***	= Cross-sectional area (mm^2)

INTRODUCTION

In recent years, an escalating focus on the utilization of biodegradable composites reinforced with natural fibers, driven by economic incentives and environmental considerations, has stimulated significant research (Diyana *et al*. 2024). Natural fibers are increasingly recognised as a viable alternative for reinforcement in petroleum-based polymers. Global societies are being encouraged to utilize biomass wastes as an alternative material in the development of green technology in the era of globalization because of the depletion of synthetic resources such as petroleum (Asyraf *et al*. 2022). Plant-based fibers offer several benefits compared to traditional synthetic fillers, including their lightweight nature, cost-effectiveness, distinct mechanical properties, and outstanding biodegradability (Taharuddin *et al*. 2024). Evidence indicates that incorporating natural fiber into polymeric materials can improve the characteristics of virgin materials. The natural fibers, including kenaf, jute, sisal, coir, hemp, bamboo, flax, and rice husk, offer numerous benefits to composite materials, characterised by their favourable specific strength, lightweight nature, effective thermal insulation, biodegradability, excellent acoustic properties, and cost-effectiveness (Kabir *et al.* 2012). Natural fibers from agricultural biowaste have been shown in earlier research to have potential uses in the construction, automobile, food packaging, and aerospace industries (Sari *et al.* 2020). Concerns of the upcoming exhaustion of petroleum-based products and other non-renewable energy reserves due to their escalating rates of depletion, new government policies and regulations on climate change, and the world's rapid population growth have sparked intense research efforts to develop environmentally friendly and economically viable natural products for industrial applications (Marichelvam *et al.* 2019).

One of the natural fibers that has garnered significant interest from researchers in Malaysia is oil palm empty fruit bunch (OPEFB) fiber. In addition to oil palm fronds (OPF) and oil palm trunks (OPT), OPEFB constitute 40 million tons of biomass generated by the palm oil industry in Malaysia. These materials are available in abundance after extraction of the oil, but they are evidently underutilised (Latip *et al.* 2018). In the past, OPEFB was utilised as a fuel for steam production *via* incineration; nevertheless, this practice faced criticism for its detrimental effects on the surrounding environment, particularly high emissions of white smoke (Chang 2014).

Meanwhile, in Malaysia's agriculture sector, bananas are among the most sought-after crops in terms of economic value and production. Banana fiber possesses intriguing mechanical characteristics; composites derived from the agricultural by-products of banana agriculture create valuable industrial components (Sivaranjana and Arumugaprabu 2021). Banana fiber (BF) presents significant drawbacks, notably its lack of dimensional stability and hydrophilic properties. Deficiencies in the characteristics have led to inadequate bonding with the polymer matrix, adversely affecting the composite surface and hindering effective stress transmission (Sharan *et al*. 2021). These deficiencies, can be mitigated by treating banana fibers using various physical and chemical surface modification approaches.

Researchers have investigated several treatment approaches for fiber modification, including chemical, physical, and mechanical techniques, to identify high- and low-performance fiber compositions and processes for diverse applications. Research indicates that fiber type, treatment, and extraction method are the primary factors for producing natural fiber-reinforced polymer matrix composites to enhance properties, particularly mechanical and thermal stability (Fiore *et al*. 2015). Surface treatment of natural fibers can

significantly improve the tensile and flexural strengths of polymer-based composites reinforced with banana, jute, and sisal fibers, according to previous findings (Sepe *et al*. 2018). An earlier study by John *et al.* (2008) examined the impact of chemical treatment on sisal/oil palm-reinforced natural rubber hybrid composites *via* alkaline and silane treatments, concluding that composites with chemically treated fibers exhibit better mechanical properties compared to those with untreated fibers. Alkali treatment is widely recognized for improving the mechanical properties of these fibers by modifying their surface chemistry. Previous studies have demonstrated the effectiveness of alkali treatment in enhancing the fiber characteristics, including increased tensile strength and improved compatibility with matrix materials (Ilyas *et al*. 2020). This process uses an alkali solution at a specific concentration and under particular conditions on a natural fiber, aimed at removing lignin and a portion of hemicellulose while also improving enzyme accessibility to cellulose (Pakarinen *et al*. 2012). The chemical treatment of alkali alters the fiber surface chemical properties and porosity, and it may increase or decrease the capacity to absorb oil or moisture (Asadpour *et al*. 2021).

The research gap addressed by this study is the comparative evaluation of OPEFB and banana fibers under identical alkali treatment conditions. While the treatment of each fiber type has been widely reported, a direct side-by-side analysis remains scarce. This comparative study not only provides insight into the behavior of these fibers but also offers a broader perspective on their relative performance in potential applications, particularly in insulation panels. The novelty of this work lies in its systematic evaluation, in which both fibers are subjected to alkali treatment under identical conditions, enabling a direct comparison of their properties. Unlike prior studies that typically focus on a single-fiber system, this work provides comparative screening data to support material selection for building insulation applications. The results reveal differences in treatment sensitivity and optimal NaOH concentration, offering insight beyond confirmatory alkali-treatment effects.

This study is particularly relevant for the preliminary screening of fibers for use in insulation panels, where mechanical strength and matrix compatibility are key considerations. Although alkali treatment of OPEFB and banana fibers has been reported, direct comparison across the literature is difficult because treatment conditions (NaOH concentration, time, temperature), fiber preparation, and testing methods vary substantially. This study addresses that gap by conducting a controlled, side-by-side evaluation of OPEFB and banana fibers under identical treatment conditions and the same characterization suite. Treatment with alkali also changes the crystallinity of fibers and the thermal decomposition trends, which are key to insulation units that are subject to temperature changes (Abioye *et al*. 2024). Recent reviews and comparative studies have emphasized that natural fiber composites can offer good thermal resistance, low density, and sustainability for building applications (Alazzawi *et al*. 2024). Understanding the comparative performance of OPEFB and banana fibers will help inform decisions on their potential use in sustainable building applications, supporting the ongoing demand for eco-friendly, cost-effective materials. The concept of valorization fits well with the sustainable concept for waste utilization for the production of high-performance insulation materials through optimization techniques (Kuppusamy *et al*. 2024). The acquired structural and chemical data, along with the thermomechanical properties of both untreated and treated fibers, provide a framework for the surface modification of OPEFB and BF for potential reinforcement in advanced composite applications, specifically for wall insulation panels.

The resulting comparable dataset supports material screening for wall insulation panel reinforcement by identifying treatment conditions that improve surface characteristics and thermal stability while avoiding excessive degradation that can reduce tensile performance. It is hypothesized here that moderate alkali treatment removes surface impurities and a portion of the hemicellulose/lignin fraction, increasing surface roughness and thermal stability, whereas overly aggressive treatment can damage the fiber structure and reduce strength.

EXPERIMENTAL

This section presents the materials used, the procedure for alkali treatment, and the characterization techniques used to assess the physical, mechanical, and morphological properties of the fibers.

Materials

This study employed oil palm empty fruit bunch (OPEFB) fibers sourced from HK Kitaran Sdn. Bhd., Pulau Pinang, Malaysia, and banana fibers (BF) supplied by Bambusoideae Technology Sdn. Bhd., Johor, Malaysia.

Sodium hydroxide pellets (NaOH, ≤99.0% purity, R&M Chemicals, supplied by Ever Gainful Enterprise Sdn. Bhd., Selangor, Malaysia) and acetic acid obtained from Evergreen Engineering Sdn. Bhd., Selangor, Malaysia were used as chemical reagents for fiber treatment. All chemicals were used as received without further purification. Glacial acetic acid (CH_3COOH, ≥99.8% purity, Analytical Reagent grade, R&M Chemicals, Malaysia) was used for the neutralization process. All chemicals were used as received without further purification.

Preparation of the Fibers

The fibers from OPEFB and banana were selected as the primary reinforcing materials for composite fabrication in this study, owing to their availability, biodegradability, and potential as sustainable reinforcement agents for bio-based wall insulation applications. The fibers were initially purified by immersion in clean tap water for 24 h, followed by thorough washing and rinsing with hot water to remove surface impurities and reduce residual organic matter. After cleaning, the fibers were sun-dried for two weeks, then oven-dried at 100 °C for 5 h to remove excess moisture. The dried fibers were subsequently cut to lengths of 1 to 2 cm to facilitate effective surface treatment. The prepared fibers were stored in zip-locked plastic bags prior to further processing.

Alkaline Treatment

This study involved treating dried raw OPEFB and banana fibers with three distinct concentrations of aqueous NaOH of 3, 6, and 9 wt% each for 60 min while agitated at a room temperature of 28 °C. In general, this alkali treatment effectively removed substantial quantities of hemicellulose and surface impurities from the fiber. Treated fibers were subsequently rinsed with running water, followed by pH neutralisation using acetic acid (CH_3COOH) to remove any residual alkali deposits on the fibers' surface. Lastly, the treated fibers were dried at 25 °C for 48 h, followed by 24 h of oven drying at 60 °C to remove any residual moisture. The desiccated fibers were preserved in a desiccator within a sealed plastic bag to prevent moisture contamination from the air before chemical and

thermo-mechanical analyses. The selected NaOH concentration range was based on commonly reported values in the literature (2 to 10 wt%) for effective lignocellulosic fiber modification, while treatment time and temperature were fixed to ensure consistent processing conditions and to isolate the effect of alkali concentration.

FT-IR Analysis

Fourier-transform infrared spectroscopy (FTIR) was performed to identify changes in chemical composition, particularly the removal of hemicellulose and lignin components of untreated and NaOH-treated OPEFB and banana fibers. The analysis was performed using a Thermo Scientific Nicolet 6700 device equipped with attenuated total reflectance (ATR) functionality. The FTIR spectra were obtained over the range 4000 to 400 cm^{-1}, utilising suitable resolution settings to identify functional group alterations resulting from the surface treatment process.

Scanning Electron Microscope

Scanning electron microscopy (SEM) was used to examine surface morphology and structural changes induced by alkali treatment. Surface roughness and impurity removal are indicators of potential improvements in interfacial bonding. The cross-sectional and surface morphologies of OPEFB and banana fibers were observed and evaluated using a Hitachi S-3400N SEM instrument (Kyoto, Japan). The acceleration voltage was 15 kV, and the surfaces of the OPEFB and banana fibers were pre-coated with a thin gold layer. All 50 mm in length specimens were observed at various magnifications.

Thermogravimetric Analysis

Thermogravimetric analysis (TGA) was conducted to evaluate thermal stability, which is relevant for insulation materials exposed to temperature variations. The thermal properties regarding the stability of untreated and NaOH-treated OPEFB and banana fibers were assessed using a Mettler Toledo TGA/DSC analyser (Schwerzenbach, Switzerland). Approximately 10.60 mg of each fiber sample was placed in an alumina crucible and exposed to pyrolysis in an inert nitrogen environment with a fixed flow rate of 30 m/min at a temperature range of 30 to 500 °C, and a heating rate of 20 °C/min. TGA is a method used to quantify mass loss as a function of temperature, facilitating the evaluation of the thermal degradation characteristics and the stability of natural fibers under controlled atmospheric conditions.

Tensile Testing

Tensile testing was conducted to evaluate the effect of alkali treatment on fiber stiffness and load-bearing capacity. This analysis provides insight into structural stability, which is critical for screening preliminary insulation materials. Both untreated and NaOH-treated OPEFB and banana fibers were evaluated for tensile strength. A single fiber tensile test was performed using an Instron 3365 Dual Column Tabletop Universal Testing Machine (UTM) in accordance with ASTM D3379. Each fiber filament was mounted and glued to a custom paper holder frame with a 20 mm gauge length. After securing the ends of the paper frame in the UTM grips, the sides of the frame were carefully cut to expose the fiber for testing. Each fiber used had an approximate total length of ±70 mm. The test was performed with a maximum load capacity of 5 kN and a crosshead speed of 1 mm/min. The tensile strength of the fibers was calculated using Eq. 1:

$$T = \frac{F}{A} \quad (1)$$

where T represents tensile strength in MPa, F is the maximum force in Newtons, and A is the average cross-sectional area of the fiber in square meters. The average tensile strength was determined from five replicates (n = 5) for each treatment condition.

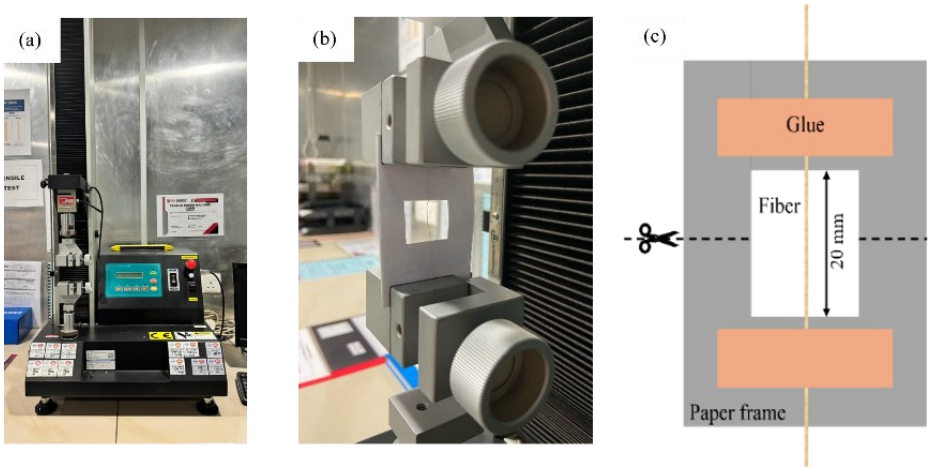

Fig. 1. (a) Instron 3365 machine; (b) fiber filament attached to machine; and (c) schematic drawing of paper frame

RESULTS AND DISCUSSION

This section evaluates the effects of alkali treatment on the chemical structure and surface characteristics of the natural fibers used in this study. Characterization techniques were applied to determine how NaOH treatment modifies the functional groups and chemical composition of the fibers. These modifications are important because removing non-cellulosic components, such as hemicellulose, lignin, and surface impurities, has the potential to improve fiber stability and structural properties, which are relevant to insulation applications.

Analysis of FT-IR

FTIR spectroscopy is a suitable method for examining alterations resulting from any chemical treatment. This technique was utilised to verify alterations in the composition of OPEFB and banana fibers following alkaline treatment by examining changes in their associated absorbance bands. Figures 2 and 3 illustrate the spectra derived from the FT-IR analysis of both untreated and treated OPEFB and banana fibers, demonstrating nearly identical patterns, with slight variations found in the treated samples. The identification of cellulose, hemicellulose, and lignin within the fiber structure was achieved using the peak response observed at designated wavelengths ranging from 400 to 4000 cm^{-1}. Major functional groups are indicated directly on the spectra for clarity. A major peak was observed at approximately 3282 cm^{-1} for OPEFB fiber, meanwhile, 3280 cm^{-1} for BF was attributed to the typical band for the –OH stretching of untreated fibers. The alkali treatment caused a shift in the band from 3282 to 3296 cm^{-1} for OPEFB fiber, and from 3280 to 3294 cm^{-1} for BF, with increased intensity relative to the untreated fiber. This alteration may be associated with reduced hydrogen bonding among cellulose hydroxyl groups, which then increases the availability of reactive hydroxyl (–OH) groups for

interfacial interaction with the matrix (Radzi *et al.* 2019). The analyses of these spectra are corroborated by the research of Siyamak *et al.* (Siyamak *et al*. 2012) that indicated a broad band in the vicinity of 3400 cm^{-1} corresponding to the stretching of the O−H bond in cellulose molecules and the water absorbed by the fiber.

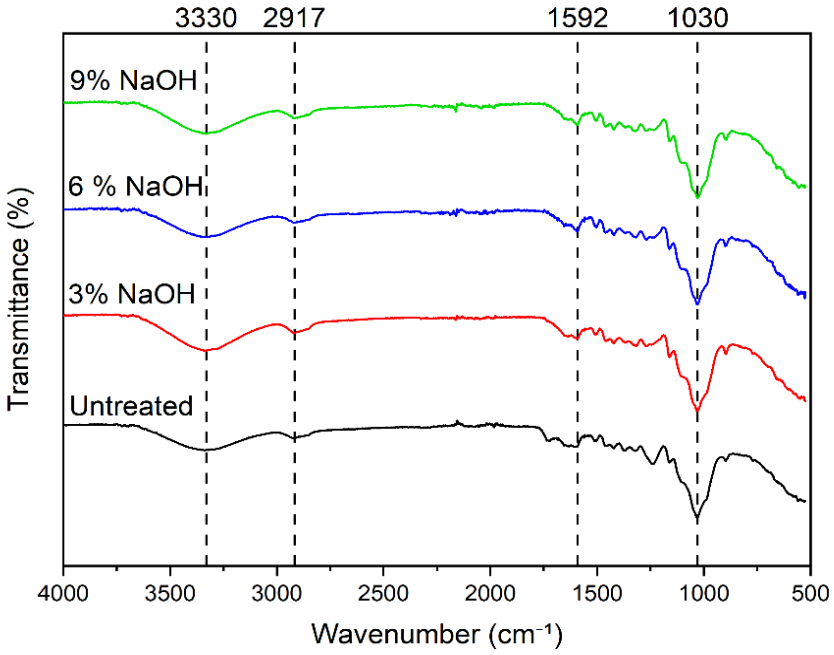

Fig. 2. FTIR spectra of OPEFB fiber

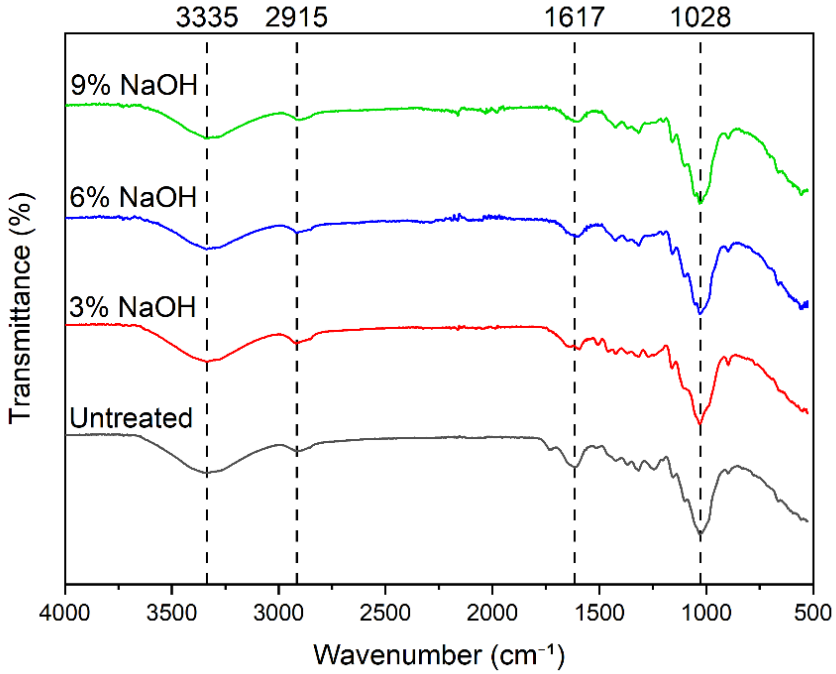

Fig. 3. FTIR spectra of banana fiber

Evident absorption bands between 2800 and 2900 cm^{-1} for all treated and untreated OPEFB and banana fibers may be associated with the alkyl C–H stretching vibrations (both symmetrical and asymmetrical) present in the cellulose and hemicellulose constituents of natural fibers (Yew *et al*. 2019). The absorbance band was slightly reduced after alkali treatment, which can be attributed to the removal of fatty acids and other aliphatic extractives containing C-H groups from the fiber surface (Chandel *et al*. 2014; Ivanovska *et al.* 2019). A slight discernible peak, about 2349 cm^{-1}, on both fibers signified the existence of wax compounds on the fiber surface (Madhu *et al*. 2019).

Simultaneously, the absorbance band at 1717 cm^{-1} was perceptible in the untreated OPEFB and banana fibers (Ishola *et al*. 2012). The carbonyl (C=O) stretching vibrations of the carboxyl and acetyl groups in hemicelluloses were related to the vibration band observed in these molecules. Nonetheless, the absence of the band in the NaOH-treated fibers with concentrations of 6 wt% and 9 wt% signified the dissolution of lignin and hemicellulose during the treatment. This finding aligns with a previous study showing that alkali treatment can eradicate hemicelluloses at specific NaOH concentrations, indicating that a 6 wt% NaOH effectively removed hemicellulose from the treated fibers.

The absorbance bands at 1242 and 1643 cm^{-1} for OPEFB fiber and at 1243 and 1645 cm^{-1} for BF were attributed to C–O and C=C stretchings of acetyl groups in lignin. Nevertheless, the bands became indistinct in the treated fiber, suggesting that alkali treatment eliminated part of the lignin (Cai *et al*. 2015). Cellulose exhibited another peak at 1028 $cm^{-1,}$ indicating C–O stretching vibration of the polysaccharide, whereas the β-glycosidic linkages between monosaccharides and C–OH bending were indicated by smaller, broader, strong peaks at 881 and 605 cm^{-1}, correspondingly. In summary, alkali treatment changed the fiber surface chemistry by partially removing lignin and hemicellulose. This process led to reduced hydrophilicity and improved surface characteristics, potentially enhancing fiber-matrix compatibility (Kathirselvam *et al.* 2019).

Scanning Electron Microscope

Scanning electron microscopy (SEM) is a broadly adopted approach for analysing the longitudinal surface of the fiber. Figures 4 and 5 show SEM micrographs of untreated and treated OPEFB and banana fiber samples at different NaOH concentrations. Observation revealed that NaOH treatment resulted in notable differences in the morphologies of treated fibers compared to untreated fibers. Figure 4a illustrates the SEM micrograph of the longitudinal untreated OPEFB fiber surface. The untreated OPEFB fiber surface exhibited wax, lignin, and other significant impurities, as evidenced by observation (Boopathi *et al*. 2012). Figure 4a illustrates and emphasises the area of silica bodies embedded on the surface of the untreated OPEFB fibers. The image shows that silica bodies were adhered to circular craters, uniformly distributed over the strands, and the surface layer contained impure material (Rosli *et al.* 2017). This finding aligns with previous research indicating that OPEFB fiber contains hemicellulose, cellulose, lignin, silica, and metal ions (Rosli *et al.* 2017). White surface patches were observed on the untreated fiber, which may have contributed to poorer interfacial bonding during composite production (Boopathi *et al*. 2012; Ganapathy *et al*. 2019). Meanwhile, Figs. 4b–d depict the presence of longitudinal surface micrographs of fibers treated with 3, 6, and 9 wt% NaOH, correspondingly. A notable change in the morphological fiber surface structure was detected following the NaOH treatment. The varying percentages of NaOH were observed

to eliminate white spots and other impurities post-treatment, as illustrated in Figs. 4b–d. The fiber surface exhibited enhanced roughness following the elimination of lignin, hemicelluloses, and wax through alkalisation (Madhu *et al*. 2019). It should be noted that these observations are based on qualitative visual examination of SEM micrographs. While surface irregularities appear more pronounced after alkali treatment, no quantitative surface roughness measurements (*e.g*., profilometry or atomic force microscopy) were conducted in this study. The morphological changes are interpreted as qualitative trends rather than quantified roughness parameters.

Figure 5 exhibits the untreated and treated surfaces of banana fiber. The SEM micrographs of alkali-treated BF (Figs. 5b-d) show a marginally smoother surface devoid of residues in comparison to untreated fibers. This discrepancy may result from the impact of alkali treatment, which is expected to remove portions of lignin, hemicelluloses, and surface wax from the fiber (Loganathan *et al.* 2020). The elimination of surface impurities on fibers is expected to enhance both mechanical interlocking and bonding reactions, which are beneficial for fiber–matrix adhesion (Mwaikambo and Ansell 2006). A previous finding indicated that the surface of alkali-treated fiber is devoid of contaminants and that the alkali solution enhances the mechanical bonding between the fiber and the matrix polymer (Hossain *et al.* 2014). After treatment with a high concentration of NaOH (9 wt%), the surface was observed to be cleaner, and the fiber's pores were more apparent. This may be linked to the elimination of fatty components from the fiber surface (Salih *et al*. 2020). Nevertheless, the mechanical properties of individual fibers may be jeopardised if there is a greater number of pores present than the level that has been stipulated (Sayanjali Jasbi *et al.* 2018).

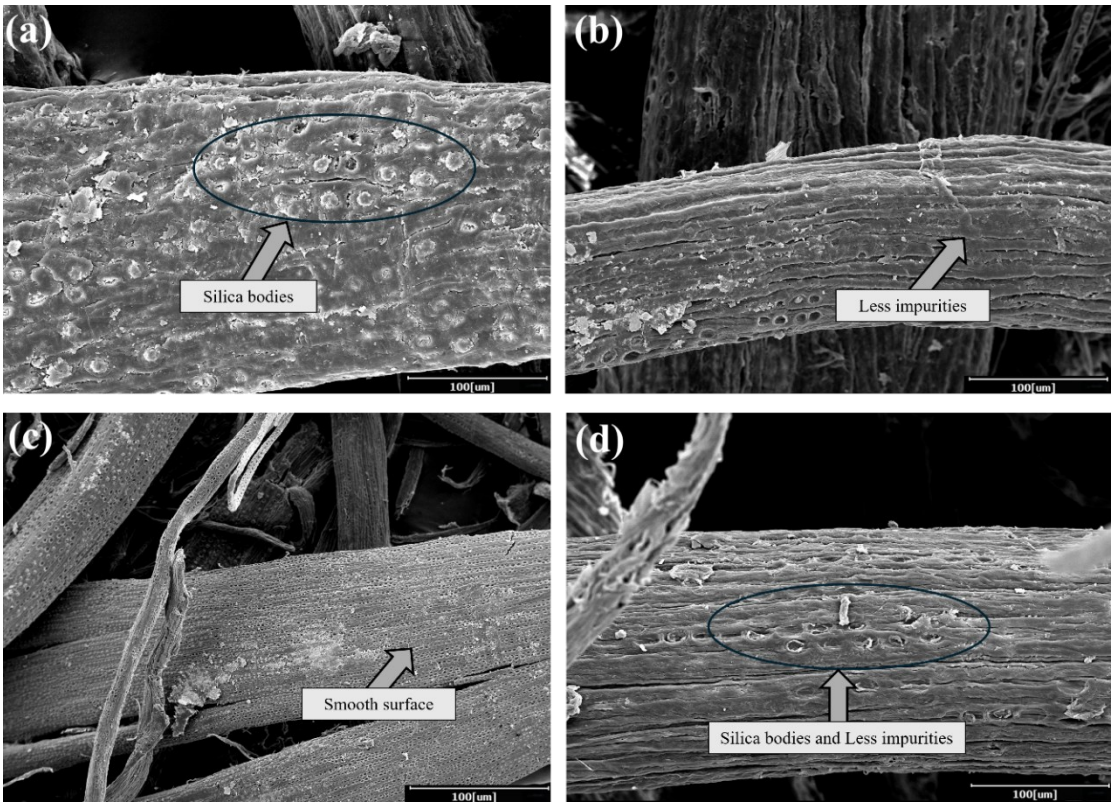

Fig. 4. SEM micrograph of alkali-treated OPEFB fibers showing surface morphology. Scale bar: 100 µm on (a) untreated, (b) 3 wt% NaOH, (c) 6 wt% NaOH, and (d) 9 wt% NaOH -treated

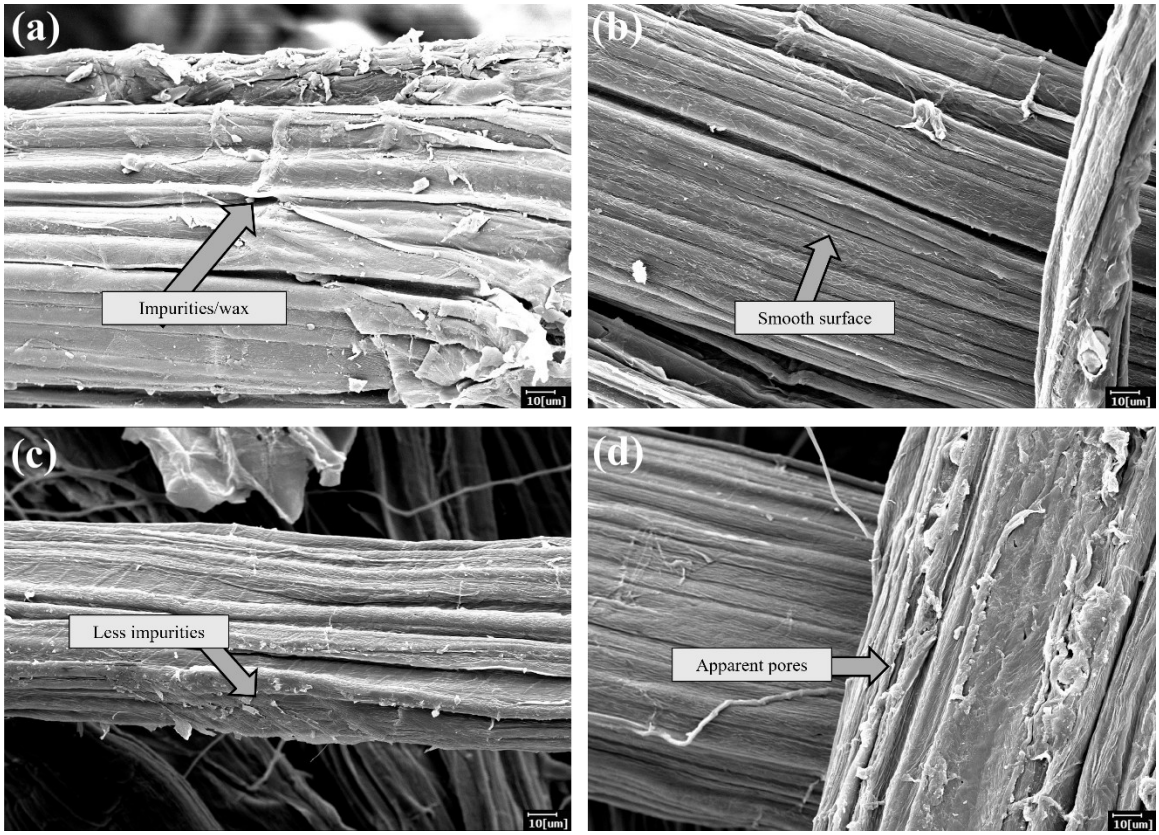

Fig. 5. SEM micrograph of alkali-treated banana fibers showing surface morphology. Scale bar: 10 μm on (a) untreated, (b) 3 wt% NaOH, (c) 6 wt% NaOH, and (d) 9 wt% NaOH-treated

Rashid *et al.* (2017) utilized SEM analysis to characterize surface morphological changes resulting from alkali treatment, including fiber surface roughness, porosity development, and structural modifications. These morphological observations directly explain the improvements in mechanical and thermal properties. SEM analysis supports the conclusion that alkali treatment modifies the external fiber morphology by reducing surface impurities and altering surface texture, thereby improving fiber-matrix interaction during subsequent composite processing. SEM observations supported these findings, showing improved interfacial bonding and reduced fiber pull-out in optimized systems, whereas excessive filler content led to structural defects (Mohammadi *et al*. 2024).

Thermogravimetric Analysis

Figures 6 and 7 present the TGA and DTG curves used to determine the stability and thermal degradation of untreated and treated OPEFB and banana fibers. These curves are displayed as the percentage sample and its derivative weight loss (%) against the temperature function. The samples underwent a degradation process in three stages, as shown. In the first stage, which occurred below 100 °C, the water molecules might have been removed by evaporation. A temperature range of 44.4 to 120 °C and a weight loss of 3.8% to 4.71% were observed during the stage, which might be due to the free water loss (Hafila *et al*. 2022; Hazrati *et al*. 2021).

The second thermal degradation, observed around 257 to 290 °C for OPEFB fiber, was associated with weight loss, mostly due to the degradation of hemicellulose and

cellulose. The outcome of this study aligns with documented hemicellulose degradation data, indicating that degradation began around 280 °C and concluded at roughly 300 °C, as shown in Fig. 6 (Yang *et al*. 2007). The initial component to decompose during thermal analysis is hemicellulose, since it consists of heterogeneous polysaccharides such as xylose, galactose, mannose, and glucose that are amorphous and readily devolatilise at low temperatures (Huzaifah *et al*. 2017; Kamaruddin *et al.* 2021). Meanwhile, previous studies on hemp fibers indicated that cellulose decomposes entirely at elevated temperatures (250 to 350 °C), whereas hemicellulose decomposes at lower temperatures (180 to 280 °C) (Kabir *et al*. 2013a). The decomposition predominantly affects cellulose, resulting in an increased whole degradation temperature of the treated fibers and enhancing their thermal stability (Zhang *et al*. 2015).

The subsequent thermal degradation was cellulose, evidenced by the distinct U-shaped peak at 331 °C in the derivative thermogravimetry (DTG) graph in Fig. 6, occurring between 331 and 350 °C. The final component is the decomposition of lignin from the fiber's surface. Lignin and other non-cellulosic chemical constituents underwent degradation, as evidenced by the distinct thermal degradation peak observed at 480 °C. The remaining substance following the full decomposition of lignin is referred to as the residual mass (Razali *et al.* 2015).

Figure 7 illustrates three stages of thermal degradation of banana fiber. Moisture was expelled during the first step at temperatures ranging from 40 to 100 °C. The second step accounts for the significant mass loss associated with the heat degradation of hemicellulose and cellulose. The last step took place at temperatures ranging from 360 to 400 °C, which correlated with lignin concentration (Kabir *et al*. 2013a). These behaviours and modifications are likely attributable to the degradation of molecular structures and connections inside cell walls during treatment. In comparison, the DTG profile curves in Fig. 7 illustrate the beginning and ultimate breakdown temperatures indicative of thermal stability. This might happen because of the differential impact of the fiber surface structure resulting from the chemicals employed in the pre-treatment process (Kabir *et al.* 2012).

The residual mass for both treated and untreated OPEFB fiber and banana fibers ranged from 16% to 26%. The alkali treatment progressively eliminated non-cellulosic substances, including hemicellulose and lignin, from the raw fibers, suggesting that highly purified cellulose in natural fibers may increase their thermal stability. Table 1 indicates that the OPEFB fiber treated with 9 wt% NaOH had the highest residual content (23.8%) and demonstrated superior thermal stability. The pre-treatment method and elevated heating rates affected the mass-loss rates; however, the onset of thermal disintegration of OPEFB fiber was delayed to higher temperatures. Compared with banana fiber, the residual content was highest at 26.6%, and the degradation process occurred most rapidly over the temperature range of 257 to 360 °C. This study anticipated that treated fibers would establish a superior interface compared to non-treated fibers. The enhanced thermal stability after alkali treatment is relevant to the development of insulation panels, as fibers with enhanced thermal stability will not degrade too early and thus retain their structural integrity. The alkali treatment was also found to enhance thermal stability and char formation, as reported in the literature, which is consistent with the current trend (Rahman *et al.* 2025). Compared with conventional materials such as glass wool and mineral wool, natural fiber-based systems may not achieve optimal thermal conductivity, but they offer important advantages in renewability, biodegradability, and a lower environmental burden (Siouta *et al.* 2024).

Table 1. Thermal Decomposition Parameters (T_{on}, T_{max}, and Weight Loss) of Untreated and Treated OPEFB and Banana Fibers

Fiber	OPEFB			Banana		
	T_{on} (°C)	T_{max} (°C)	Residual (%)	T_{on} (°C)	T_{max} (°C)	Residual (%)
Untreated	257.3	331.0	16.3	280.5	330.2	26.6
3 wt% NaOH	295.0	340.3	22.8	285.3	355.6	17.3
6 wt% NaOH	288.3	350.1	22.0	287.7	352.3	19.6
9 wt% NaOH	289.0	350.7	23.8	288.3	360.1	18.0

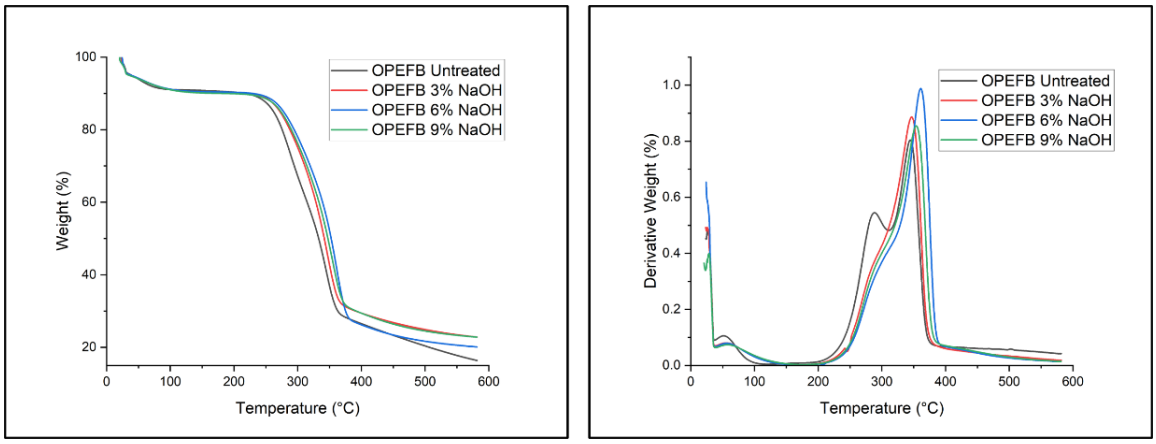

Fig. 6. Thermal degradation profiles of OPEFB fiber, showing TG and DTG curves

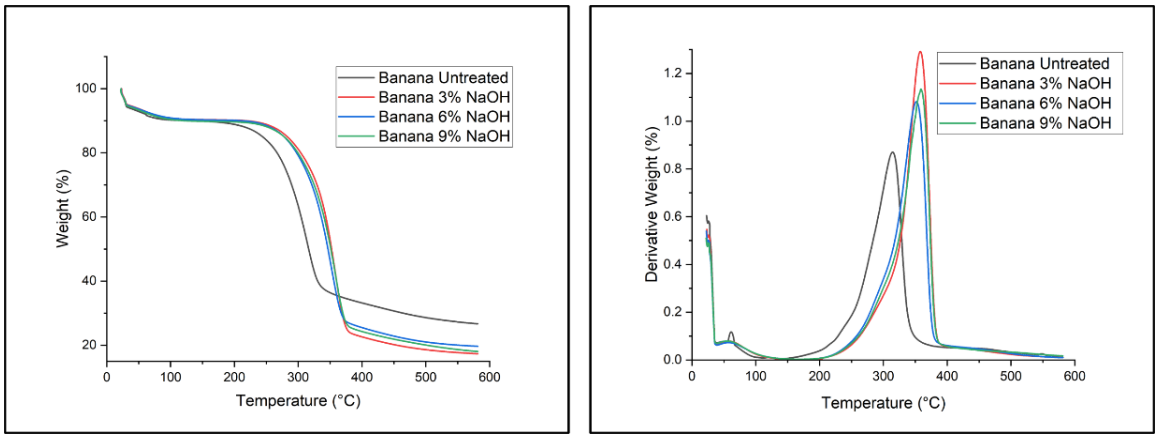

Fig. 7. Thermal degradation profiles of banana fiber, showing TG and DTG curves

Tensile Testing

A uniaxial tensile test was employed to assess the mechanical characteristics of the specimens. Figures 8 and 9 illustrate the impact of NaOH treatment at varying concentrations on the tensile strength and modulus of OPEFB and banana fibers. The results indicated a considerable enhancement in Young's modulus and tensile strength of the treated fiber, reaching the highest values of 649 and 311 MPa for OPEFB fiber. Meanwhile, 38,200 and 3060 MPa correspondingly were found for banana fiber, at a NaOH concentration of 6 wt%. This outcome indicated that treated fibers exhibited increases in tensile strength and modulus compared with untreated fibers.

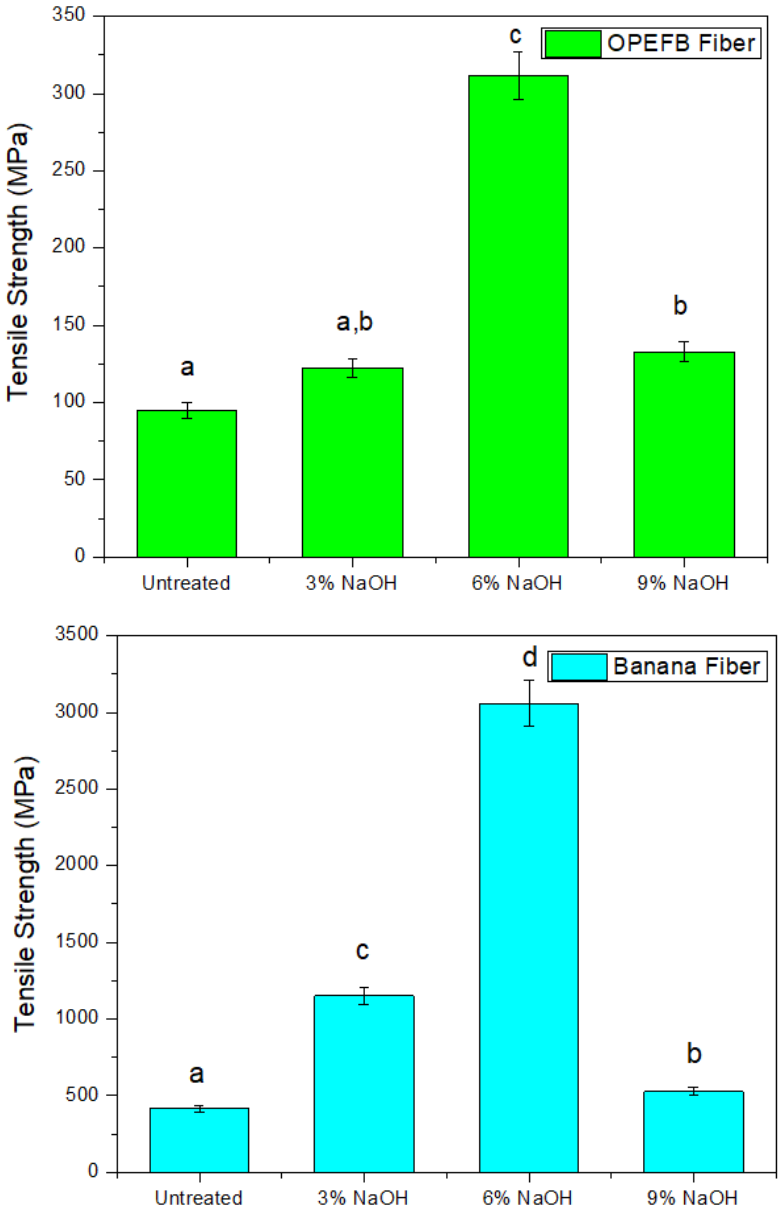

Fig. 8. Tensile strengths of OPEFB and banana fibers

In general, the improved tensile modulus and strength of the treated fiber might be attributed to a number of different considerations. This improvement may be attributed to the removal of most lignin, hemicellulose, and other undesirable components from the fibers. This removal made it easier for the fibrils to facilitate their rearrangement along the tensile deformation direction, increasing the tensile strength (Hossain *et al*. 2011). The optimal tensile strength was observed at the 6 wt% NaOH treatment, achieving a value of 311 to 3060 MPa, which represents a 228% to 637% increase than the untreated fiber. The findings corroborated our prior investigation, demonstrating that alkali treatment with a 6 wt% NaOH solution increased the fiber's tensile strength. The increase of over 600% can be attributed to the very low initial tensile strength of the untreated fibers rather than a high

absolute value of tensile strength after treatment. If the initial value is low, even a reasonable increase can lead to a large percentage increase.

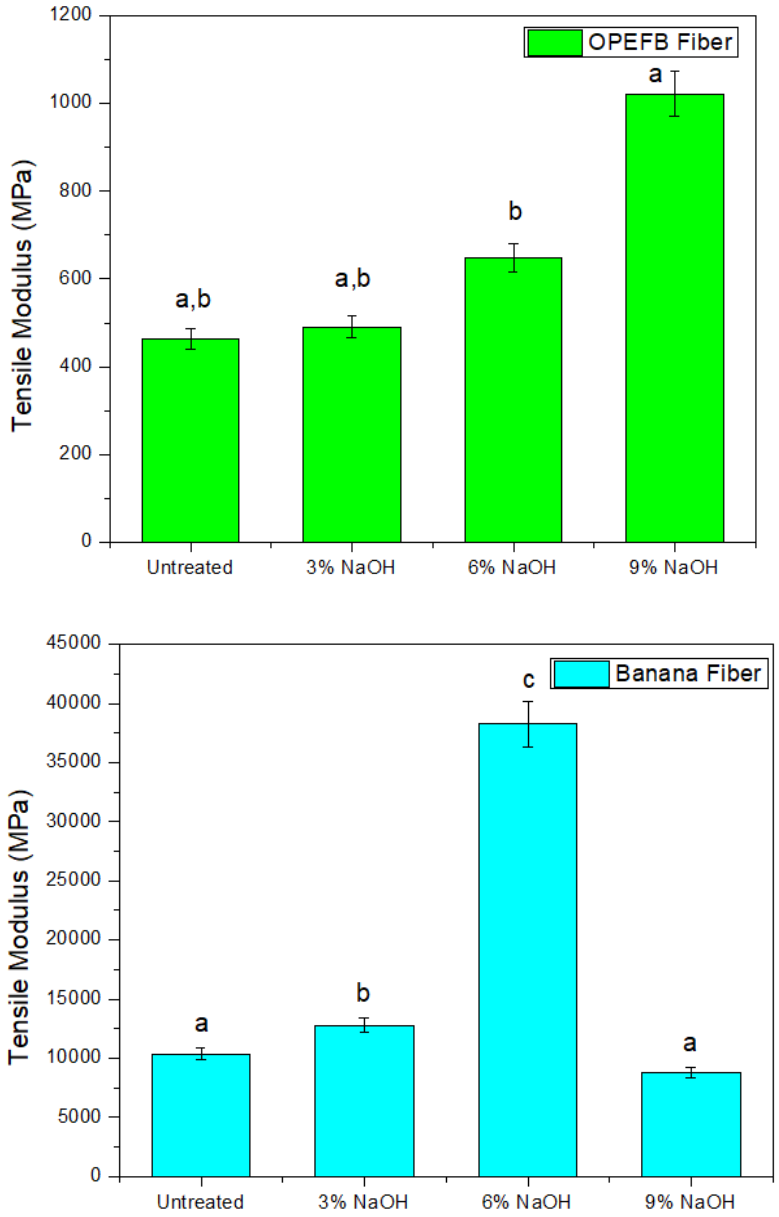

Fig. 9. Tensile modulus of OPEFB and banana fibers

Nevertheless, with a 9 wt% rise in NaOH concentration, the composites exhibited a declining trend in tensile strength, dropping to 133 and 527 MPa. This represented the lowest tensile strength among all the NaOH concentrations tested. This might be associated with the excessive alkali treatment of the fiber, which dissolves the hydrogen bonds in the cellulose and lignin structures, leading to fiber softening (Kamaruddin *et al.* 2022). The removal of non-cellulosic components may influence the fiber modulus and associated mechanical response. Due to the limited number of specimens tested, the results are interpreted descriptively to identify comparative trends rather than definitive mechanical improvement. This finding aligns with previous research studying the impact of alkali

treatment on the tensile properties of hemp fiber (Kabir *et al*. 2013b). The study establishes that mechanical properties are good predictors of fiber suitability for composite applications, which justifies the focus on tensile strength testing after alkali exposure (Augustina *et al*. 2025). In the current research, the enhanced tensile behavior after alkali treatment at a moderate concentration can be explained by the removal of hemicellulose and impurities, thereby increasing the roughness and interactions between fibers and matrices. This behavior was also reported in the tensile behavior of OPEFB and natural fibers, in which chemical treatments decreased moisture sensitivity and improved compatibility in structures (Mahardika *et al*. 2024).

The tensile test data were analyzed using one-way analysis of variance (ANOVA), and the results are presented in Table 2. The obtained p-value was less than 0.05, indicating that the differences in mean tensile strength and modulus among the OPEFB fiber and banana fiber were statistically significant.

Table 2. Summary of the Analysis of Variance (ANOVA) of OPEFB and Banana Fiber

Variables	df	Tensile strength	Tensile modulus
Mixture	3	0.00*	0.00*

Note: *Significantly different at $p<0.05$

CONCLUSIONS

The aim of this research was to conduct single-fiber characterization of oil palm empty fruit bunch (OPEFB) and banana fibers and evaluate their responses under identical treatment conditions. This preliminary investigation serves as a comparative analysis, providing valuable insights into material selection and guidance for future studies on composite development and application-level testing for building insulation systems.

1. Alkali treatment effectively removed hemicellulose and impurities present on the fibers. This modification of the fibers increased their roughness and porosity, which can be expected to enhance fiber-matrix interactions in composite materials.
2. Mechanical testing revealed a substantial improvement in tensile strength of treated fibers compared to untreated ones, with optimal results observed at 6 wt% alkali treatment, demonstrating that controlled alkali treatment is effective in enhancing the structural integrity of the fibers. This phenomenon is ascribed to the significant dissolution of hemicellulose.
3. Morphological observations exhibited increased roughness following alkali treatment, with roughness intensifying as the solution concentration rises, attributable to the removal of more hemicellulose that can enhance mechanical interlocking between the fibers and the polymer matrices of insulation panels.
4. Fourier transform infrared (FTIR) studies confirmed the removal of amorphous hemicellulose from the fibers following alkali treatment.

5. The scientific contribution of this work is based on the correlation of the NaOH treatment concentration effects with the microstructural changes in the fibers and their potential for reinforcing and thermal stability in the production of the insulation panel.
6. The comparative approach adopted in this work provides useful insights into the relative responses of OPEFB and banana fibers under identical treatment conditions, supporting informed material selection for the further development of natural fiber-based building materials. Compared with the recent studies on improving the properties of natural fibers used as insulators, the modified fibers in the present work offer competitive improvements in mechanical and thermal properties while utilizing agricultural biomass. These findings demonstrate that moderate treatment improves surface roughness and thermal stability of natural fibers by removing surface contaminants and a portion of hemicellulose/lignin, whereas excessive treatment causes damage to the natural fiber structure.

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