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Sustainable Paper Production Using Treated Pineapple Leaf Fiber and Wastepaper Composites

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Abstract

Fibers extracted from plants offer alternatives to commercial materials to produce paper which are increasingly valuable in sustainable product development. This study investigates the potential of pineapple leaf fibers (PALF) as an alternative to synthetic fibers in composite with wastepaper for recycle paper fabrication to reduce the agricultural waste. The study focuses on the extraction and characterization by emphasizing the effects of alkaline treatment using sodium hydroxide (NaOH) on the physical and mechanical properties of the PALF. Wastepaper was then combined with treated PALF in varying ratios i.e. 1:1, 1:2, and 2:1 to create the composite paper. The properties of the synthesized PALF were evaluated in term of moisture content and tensile strength. While the morphological characteristics was evaluated using Scanning Electron Microscopy (SEM) and functional group determination by Fourier Transform Infrared Spectroscopy (FTIR). Results indicate that NaOH treatment significantly enhances the mechanical properties of PALF by improving fiber strength and reducing moisture content with the 1:2 ratio demonstrating the highest tensile strength (9234.596 Pa). Compared to the 1:1 ratio which exhibited a tensile strength of 6946.375 Pa, the 1:2 ratio resulted in a 32.9% increase in tensile strength. Similarly, when compared to the 2:1 ratio (5311.917 Pa), the 1:2 ratio showed an impressive 73.9% enhancement in tensile strength. These findings suggest that increasing the proportion of wastepaper relative to pineapple leaf fiber (PALF) enhances fiber bonding and mechanical strength, likely due to better fiber interlocking and reinforcement. With its high tensile strength and improved durability, this composite paper can be utilized in packaging materials, stationery and biodegradable wrapping papers. This study highlights the viability of PALF in the development of eco-friendly composite materials, contributing to waste reduction and promoting the use of renewable resources in material science.

1. Introduction

Pineapple scientifically known as *Ananas comosus* is an herbaceous perennial monocotyledonous plant. The plant requires an average of 200 days or 6–9 months to produce fruit and is propagated vegetatively by cuttings grown from the plant itself [1]. *Ananas comosus* is characterized by a short and thick stem (stalk) from which leaves grow in narrow, rigid, and axillary roots. Presently, Malaysia is among Asia major producers, second only to Hawaii. In 2021, Malaysia pineapple cultivation spanned 16,200 hectares and yielding approximately 525,000 metric tons of pineapples which equates to roughly 1,053,000 metric tons of pineapple biomass waste generated nationwide in that year [2]. However, this has led to the increasing industrial use of bio-composites, providing an opportunity to reduce the waste of renewable resources. Pineapple is a widely cultivated plant in regions like Malaysia which produces significant agricultural waste specifically in the form of leaves. Pineapple leaf fibers (PALF) contain high cellulose content similar to cotton, offer a promising alternative to wrapping paper [3]. PALF is extracted either mechanically or through retting but despite its potential, its industrial use is still limited. Research into its physical and chemical characteristics is essential to tap into its capabilities as a reinforcing material in composite constructions, providing a green alternative to non-renewable synthetic fibers.

The environmental impact of conventional synthetic fibers such as polyester and nylon are significant which underscore the need for sustainable alternatives like pineapple leaf fiber (PALF). Synthetic fibers release microplastics that infiltrate aquatic ecosystems, hence posing threats to marine life and potentially entering the human food chain[4]. The persistence of these materials in the environment due to their non-biodegradable nature can leads to challenges in waste management. In contrast, PALF is biodegradable fiber derived from agricultural waste and its utilization can reduce reliance on fossil fuels also mitigate pollution associated with synthetic fibers[5]. PALF is made up of numerous chemical constituents. This multicellular lignocellulosic fiber is mostly composed of lignin and polysaccharides. A fiber is made up of several tiny, thin, multicellular fibers that resemble threads. Pectin helps to firmly bind these cells together [6]. The properties of PALF can vary significantly based on the treatment applied during its extraction. One common method used to enhance the mechanical and structural properties of natural fibers is alkaline treatment, where fibers are treated with sodium hydroxide ($NaOH$). This process known as mercerization, resulting in improved fiber-matrix adhesion in composites [7]. The mercerization process using alkali treatment improves fiber crystallinity and tensile strength by swelling the cellulose structure, transforming cellulose I to cellulose II and exposing more hydroxyl groups on the fiber surface [8]. This results in improved bonding with matrix materials in composites, boosting the mechanical properties and durability of PALF when used in applications like paper and polymer composites. In contrast, untreated fibers retain these components, which may reduce fiber strength but contribute to other properties such as moisture retention [9]. The comparison between treated and untreated PALF is critical to understanding their behavior in composite materials.

The successful application of PALF in composite materials is also largely dependent on the appropriate blending ratio between the pineapple leaf fiber and other reinforcing components. Recent studies have indicated that blending PALF with other materials such as wastepaper can enhance the mechanical properties of the resulting composites [10]. Wastepaper plays a significant role as a filler that can reduce the need for synthetic fibers in composite applications. Incorporating wastepaper into composites has been shown to improve tensile strength and reduce the environmental impact by utilizing waste materials in the manufacturing process [11]. The inclusion of wastepaper in composites can also promote better biodegradability, reducing the environmental burden associated with conventional synthetic fibers[12]. Hence, the choice of mixing ratios plays a crucial role as it can affect the flexibility and overall durability of the composite. Specifically, variations in the PALF to wastepaper ratio allow for optimization of the material properties. This enabling the development of composites that meet specific performance criteria for various applications [13]. The study aims to investigate the impact of alkali treatment on the removal of lignin and hemicellulose from PALF, determine the moisture content of treated PALF, to evaluate the tensile strength of composite papers produced from wastepaper and treated PALF in various ratios (1:1, 2:1 and 1:2) while effectively applied in paper fabrication.

2. Methodology

2.1 Materials

The materials were obtained from pineapple leaf waste collected after fruit harvesting at a plantation in Pagoh, Johor, Malaysia. Utilizing this agricultural residue not only helps in waste management but also provides a sustainable source of high-cellulose fibers which are comparable to cotton and ideal for paper reinforcement [14]. Sodium hydroxide ($NaOH$) as the solvent use in mercerization was sourced from (Merck KGaA, Germany) in solid powder form. Wastepaper as a binder was collected at local printing factory. Wastepaper contains significant amounts of cellulose and hemicellulose that provide enhanced fiber adhesion, resulting in improved paper strength and flexibility [15].

2.2 Sample Preparation

2.2.1 Extraction of Pineapple Leaf Fibers (PALF)

The pineapple leaves were washed using tap water to remove the contaminants and impurities. Figure 1 showed the leaves were cut into smaller pieces for easier handling and weighted. Then, the leaves were soaked in 5% of sodium hydroxide solution for 24 hours to get rid of lignin and soften. The pineapple leaves were removed by using the hand scraping method until the fibers were seen, then slowly the fibers were extracted [16].

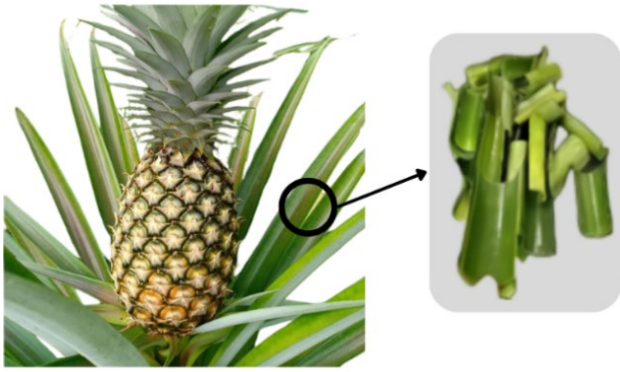


Fig. 1 *Pineapple leave was cut into smaller pieces for further extraction process*

Alkali treatment with 5% sodium hydroxide solution was used for bleaching and cleaning the surface of natural fibers to create higher-quality and stronger fibers. Excessive NaOH concentration can lead to fiber degradation, thus optimization of alkali concentration was chosen at 5%. A study found that PALF treated with 5% NaOH exhibited a 43% increase in tensile strength and a 24% improvement in Young modulus compared to untreated fibers [17]. The fibers were heated for two hours at 80°C in the sodium hydroxide solution then rinsed with distilled water to get rid of any remaining solvents and impurities [18] as shown below in Figure 2 below:

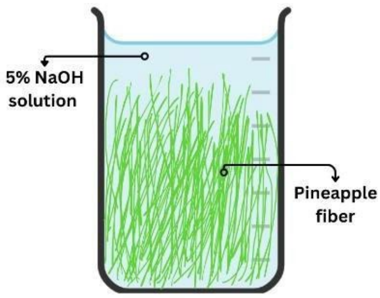
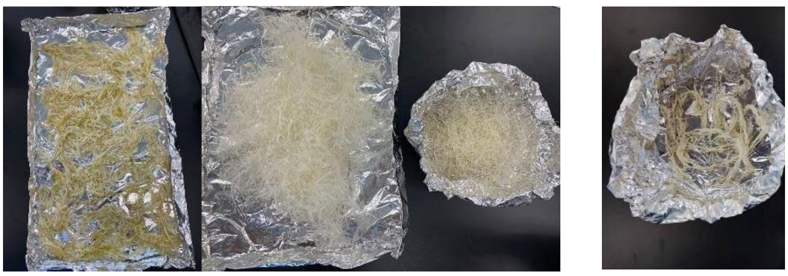


Fig. 2 *Fiber soaked in 5% sodium hydroxide solution*

2.2.2 PALF Paper Fabrication Process

The fibers dried at room temperature for about two days. Then, the fibers were weighted and dispersed into filaments as shown in Figure 3. Figure 3(a) shows the fiber extracted from pineapple leaf and soaked with NaOH. Figure 4(b) shows the fiber was directly extracted from pineapple leaf.



(a) (b)

Fig. 3 *Drying process in room temperature*

The wastepaper was mixed with the treated pineapple leaf fibers in the ratio of 1:1, 1:2 and 2:1. The ratios were systematically adjusted to create a range of test samples, allowing a detailed examination of the influence of fiber concentration on paper properties. Then, all the prepared mixture was blended using a blender for 15 minutes. The blended ingredients were poured onto a mesh to drain and remove any excess liquid from the material. The paper was dried in an oven (GenLab, UK) at 50°C for one hour and the tensile strength of the resulting paper was tested. Figure 4 shows the results of paper quality enhancement using pineapple leaf fibers produced with different ratios. The ratio of 1:2 produced high-quality paper which contains higher contents of fiber compared to other ratios and could have a greater tensile strength [19]. Wastepaper offers shorter fibers with better bonding capabilities but lacks the inherent strength of PALF. By blending one-part PALF with two parts wastepaper, the resulting composite benefits from the structural strength of PALF and the bonding efficiency of wastepaper fibers which leading to enhanced mechanical properties. If the fibers are evenly distributed and successfully mixed into the paper, adding more fiber may enhance the paper's strength.

(a) (b) (c)

Fig. 4 *Paper produced with different ratios of the weight of wastepaper to the weight of pineapple leaf fibers: (a) Ratio of 1:1; (b) Ratio of 1:2; (c) Ratio of 2:1*

2.3 Characterizations of Pineapple Leaf Fibers (PALF)

2.3.1 Functional Group Analysis

Through Fourier Transform Infrared Spectroscopy (FTIR) analysis, the functional groups of cellulose structure in pineapple leaf fibers with varied ratio were identified. At a resolution of 2 cm^{-1}, each sample was scanned using Agilent Cary 630 FTIR spectrometer (California, USA) with Agilent Micro Lab software throughout a spectral range spanning from 750 to 3750 cm^{-1}. FTIR analysis is used to confirm the chemical modifications in PALF after alkaline treatment by detecting changes in functional groups associated with lignin, hemicellulose and cellulose [20]. The removal of non-cellulosic components proved that the composite paper suitable for practical applications such as packaging materials, paperboard and eco-friendly wrapping solutions.

2.3.2 Morphological Analysis

In this study, pineapple leaf fibers (PALF) were subjected to microscopic analysis using a Scanning Electron Microscope (SEM) COXEM EM-30AX Plus (Daejeon, South Korea) to elucidate their surface morphology at a microscopic level. Small representative pieces of the fibers approximately 1-2 cm in length were prepared and affixed onto SEM stubs using an adhesive. The samples were mounted on aluminum stubs using carbon conductive tape and they were coated with gold prior to the examinations. SEM analysis provides detailed insights into the fiber morphology, surface structure and fiber distribution which are key factors influencing the mechanical strength and overall quality of the paper [21].

2.4 Physical Properties Analysis

2.4.1 Moisture Analysis

Determination of moisture content by calculating the weight loss of fiber after drying. 2 g of every sample was placed on an aluminum pan and heated in the oven at the temperature of 90°C for 30 minutes. The weight loss was calculated immediately after drying. The moisture content calculated in term of percentage by equation:

$$\text{Moisture Content (\%)} = \left[\frac{(W_i - W_f)}{W_i}\right] x\ 100 \quad (1)$$

Where W_i is the weight sample before drying and W_f is the weight sample after drying.

2.4.2 Tensile Strength of PALF Paper

Tensile strength was conducted on newly produced paper using an electronic luggage scale. The sample paper with ratio (1:1, 1:2 and 2:1) was cut into 3 cm x 8 cm rectangular strips. A strong stainless-steel clip is used to securely attach one end of the sample to the hook of the luggage scale. Then, the sample is tested for strength by pulling the end of the sample until it breaks. At the point of fracture, the maximum force displayed on the luggage scale was recorded. The test was repeated three times for each sample. The tensile strength of each sample was calculated using the following equation:

$$\text{Tensile Strength} = \frac{Force\ require\ to\ break\ sample\ (N)}{Cross-sectional\ area\ (m^2)} \quad (2)$$

3. Results and Discussion

3.1 Yield of Pineapple Leaf Fiber

The treated and untreated fiber yield (PALF) of has been analyzed to determine the efficiency of fiber extraction. The reading of each weight for the extraction methods and the reading of fiber yield are summarized in Table 1. The fiber yield is calculated in term of percentage based on the following equation:

$$\text{Fiber Yield (\%)} = \frac{Weight\ of\ pineapple\ leaf\ fibers\ (g)}{Weight\ of\ fresh\ pineapple\ leaves\ (g)} \quad (3)$$

Table 1 *Yield of pineapple leaf fiber*

Sample	Weight of Fresh Leaves (g)	Weight of Fiber (g)	Fiber Yield (%)
1st (Treated with NaOH)	585.55	12.84	2.19
2nd (Untreated with NaOH)	200.00	2.07	1.04

Referring to Table 1, the NaOH treatment during the fiber manufacturing process influences the increased strength of the fibers. The first sample that was treated with NaOH produced higher yield compared to the untreated one proved the first sample has an efficient extraction procedure, producing high-quality pineapple leaf fibers for various applications. The NaOH-treated PALF exhibited a fiber yield of 2.19%, which is 1.04% higher than the untreated sample. This significant increase indicates that alkaline treatment effectively removes non-cellulosic components such as lignin and hemicellulose that leads to higher fiber recovery. The treated sample also started with a higher initial mass of 585.55 g of fresh leaves compared to 200.00 g for the untreated sample, which may reflect variations in processing conditions or fiber extraction efficiency. The increase in yield due to alkali treatment aligns with previous studies that reported NaOH-treated natural fibers exhibit improved separation and fibrillation [22]. From an industrial perspective, achieving a higher fiber yield is essential for the cost-effectiveness of PALF-based composites as a lower yield would necessitate the processing of larger quantities of raw material, increasing energy and labor costs. Moreover, fiber extraction efficiency directly impacts material sustainability, making PALF a competitive alternative to synthetic fibers if optimized for large-scale production [23].

NaOH solution was used to separate the fibers from cellulose and lignin as well as to remove contaminants adhering to the fibers [24]. This treatment improves fiber cohesiveness and enhances their strength. Recent studies examined the effects of NaOH treatment on natural fibers including PALF and found that alkali treatment increases tensile strength by up to 30-40% due to the reduction of hemicellulose and lignin content [25]. Another study shows the effect of different NaOH concentrations (1%, 5%, 10%) on the properties of PALF. They found that a concentration of 5% NaOH provided the best balance between strength and fiber flexibility [26]. Higher concentrations of alkali are effective at removing impurities but can damage the fiber's structural integrity, resulting in brittleness. Thus, the concentration of alkali used in the method was proven the most compatible one.

On the other hand, untreated pineapple leaf fibers for second samples maintain their natural condition without going through the purifying process aided by NaOH. When untreated with NaOH, these fibers may contain more contaminants and have less optimized qualities for specific applications. Untreated fiber could be weaker and less consistent due to the presence of additional contaminants [27]. The differences between treated and untreated fibers are determined by the desired properties and intended use in a particular application or industry. The study confirmed that removing non-cellulosic components results in better bonding with matrices in composite applications. Alkali treatment can enhance the interfacial bonding with both synthetic and biodegradable polymer matrices. This led to a substantial improvement in composite tensile and flexural strength by approximately 25-30% [13]. These findings are consistent with our results that treated fibers outperform untreated ones in mechanical applications, especially where matrix-fiber interactions are crucial. Due to the greater qualities over untreated fibers, treated fibers are therefore chosen for the sample production.

3.2 Moisture Content of PALF

Table 2 shows the moisture content of PALF explained that due to its natural hydrophilic characteristics, untreated PALF has the highest moisture content with 14% when compared to treated fiber. The fiber that treated by alkaline solution showed low moisture content with 12%. Strong interfacial interaction between the matrix and the fibers may have prevented water from moving to the interface, allowing the fibers to freely attach to moisture and explain this phenomenon [28]. Current study explained that untreated fibers, such as jute and PALF exhibit higher moisture content due to the higher concentration of free hydroxyl groups and the larger amorphous regions within the fiber structure [29]. Hemicellulose is a major contributor to moisture absorption because of its amorphous and highly hydrophilic structure which contains numerous hydroxyl groups (-OH) capable of attracting water molecules. When PALF undergoes NaOH treatment, the alkaline solution breaks down hemicellulose and lignin, reducing the number of free hydroxyl groups available to bind water [30]. Another study found that alkali treatment reduces hemicellulose content in PALF by as much as 40-50%, resulting in a significant drop in the fiber's ability to absorb moisture [7]. This reduction in moisture content improves fiber dimensional stability and performance in composite applications, which is consistent with our results showing lower moisture in treated fibers. While a 2% difference may seem small, it can significantly impact paper processing, storage and usability as lower moisture absorption helps prevent microbial growth and degradation over time[31]. Thus, even minor improvements in moisture regulation due to fiber treatment can enhance the overall quality and longevity of recycled paper products.

Table 2 *The moisture content of untreated and treated PALF with 5% NaOH*

PALF sample	Moisture content (dry basis)
Untreated	14 %
Treated with 5% NaOH	12 %

3.3 Functional Group Analysis of PALF

Fourier Transform Infrared (FTIR) analysis was used to track the chemical changes within the lignocellulosic structure of the fibers. This technique enabled the identification of functional groups and chemical bonds, allowing for a detailed assessment of any alterations that occurred during processing or treatment of the fibers [10]. Figure 5 shows the comparison result of FTIR for (wastepaper: treated pineapple leaf fibers) samples in the ratio of 1:1, 1:2 and 2:1 within the wavelength range of 500 - 3750 cm^{-1}. The infrared absorption stretching in the range of 3300-3315 cm^{-1} corresponds to the hydroxyl group (—OH) of carboxylic acid and alcohol present in lignin which is in the cellulose. Transmission bands at 2887-2906 cm^{-1} is identified to the (C-H) stretching $^{-1}$ indicate water absorption by the fiber. Infrared absorption peaks at 1315-1319 cm^{-1} and 1630-1640 cm^{-1} correspond to lignin (C=C bonds) and hemicellulose (C=O bonds) respectively. These peaks decrease significantly after NaOH treatment, confirming that lignin and hemicellulose are reduced while cellulose remains intact [32]. The peak at 1011-1018 cm^{-1} represents the pyranose ring skeletal (C–O–C) or stretch of the β-1,4- glycosidic linkage between polysaccharide units in cellulose [33]. There are two prominent peaks were noted between all the samples. A peak band at 1640 cm^{-1} which presented for C=O indicate the typical structure of hemicellulose is observed in Figure 5(a). The band reduced in further spectra in Figure 5(b) and (c). The other peak in Figure 5(a) was at 1319 cm^{-1} presented for C=C stretching which known as lignin also decreased in Figure 5(c) with 1315 cm^{-1} and remain the same for (c) with 1319 cm^{-1}. Therefore, the purpose for using NaOH during scrapping and treatments results in reduced lignin and hemicellulose components while minimized the degradation of cellulose [34]. The further shift to 3300 cm^{-1} in Figure 5(c) suggests weaker hydrogen bonding after NaOH treatment, indicating more hydroxyl groups available for bonding with other materials in composites. The continued shift in the polysaccharide bands indicates that cellulose has become more exposed and perhaps slightly rearranged after the alkaline treatment [35]. Additionally, a reduction in O-H stretching intensity indicates lower moisture absorption. If the treatment successfully removes or alters hydrophilic components like hemicellulose, the fiber might absorb less water leading to a weaker O-H stretching peak [36].

Sample 1:2 in Figure 5(c) shows a significant reduction in peaks associated with hemicellulose and lignin. This means the fiber surface became cleaner, allowing for better interaction with wastepaper in the composite while leading to stronger bonding [37]. Since cellulose is the main component responsible for fiber strength, its preservation ensures that the final composite is more durable and structurally stable. Hence, it would be considered the best sample. Table 3 presents the primary

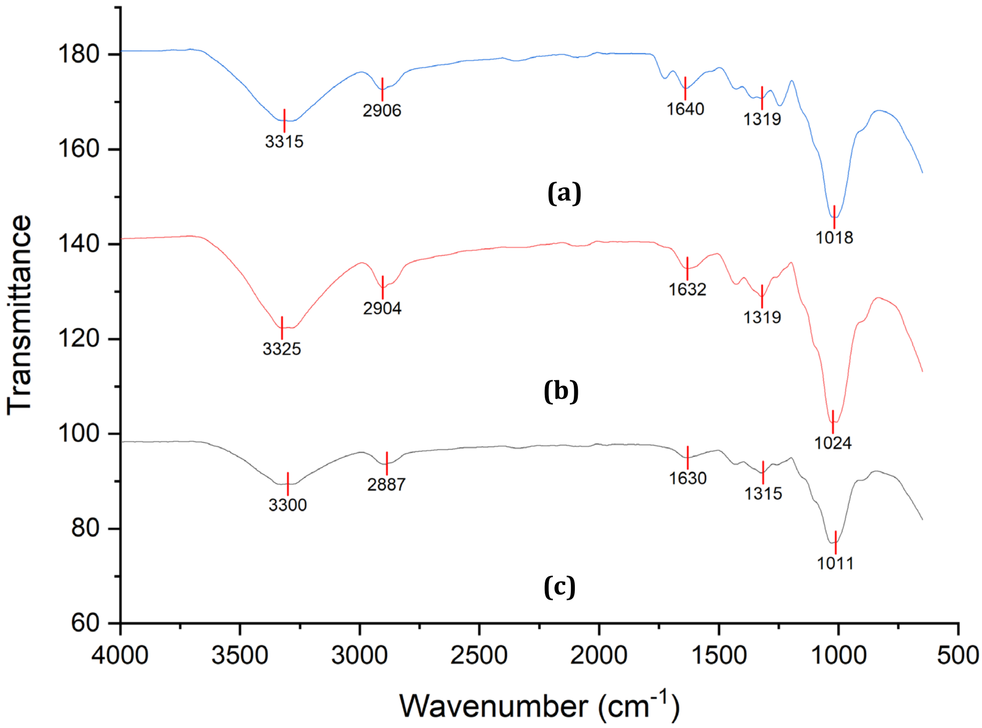


Fig. 5 *FTIR spectra of (a) Sample 1:1; (b) Sample 2:1; and (c) Sample 1:2*

Table 3 *The main spectra in the FTIR for sample 1:1, 2:1, 1:2*

Wavelength (cm^{-1})	Functional group
(a) Sample 1:1	
3315	O-H stretching vibration (carboxylic acid)
2906	C-H stretching vibration (aliphatic)
1640	C=O stretching vibration (carboxylic acid)
1319	C=C stretching vibration (alkene)
(b) Sample 2:1	
3325	O-H stretching vibration (carboxylic acid)
2904	C-H stretching vibration (aliphatic)
1632	C=O stretching vibration (carboxylic acid)
1319	C=C stretching vibration (alkene)
(c) Sample 1:2	
3300	O-H stretching vibration (carboxylic acid)
2887	C-H stretching vibration (aliphatic)
1630	C=O stretching vibration (carboxylic acid)
1315	C=C stretching vibration (alkene)

Based on Table 4, soaking the fibers in alkaline solution makes it easier for certain chemical groups (like hydroxyl and carbonyl groups) on the surface of the fiber to interact with water. This is because soaking makes the fiber absorb water, opening up and exposing parts of its internal structure that were not accessible before. Then, NaOH treatment helps break down some of the non-cellulose parts of the fiber like lignin and hemicellulose which are tough substances [38]. This process makes the cellulose which is the main part of the fiber more visible and accessible. While it removes some of the unnecessary components, it leaves the basic structure of the fiber (like aliphatic chains) mostly untouched. This makes the fiber stronger and easier to bond with other materials. The chemical reactions during alkaline treatment involve the breakdown of hemicellulose and lignin which are present alongside cellulose in the fiber. As confirmed by FTIR analysis, the peaks corresponding to hemicellulose and lignin (1640-1630 cm^{-1} and 1319-1315 cm^{-1}) were significantly reduced after treatment, indicating the successful removal of components. The primary reactions can be represented in Figure 6 as follows:

Table 4 *Chemical equation for the alkaline treatment of PALF*

Compound	Reaction
Hemicellulose	$(C5H8O4)_n$ + NaOH → $(C5H8O4\text{-}Na)_n$
Lignin	Ar-COO-R + NaOH → Ar-COO^-Na^+ + R-OH
Cellulose	$(C6H10O5)_n$ + NaOH → $(C6H10O5)_n$-Na + H2O
Overall equation	Fiber (cellulose, lignin, hemicellulose) + NaOH → Mercerized cellulose + Soluble impurites (hemicellulose, lignin)

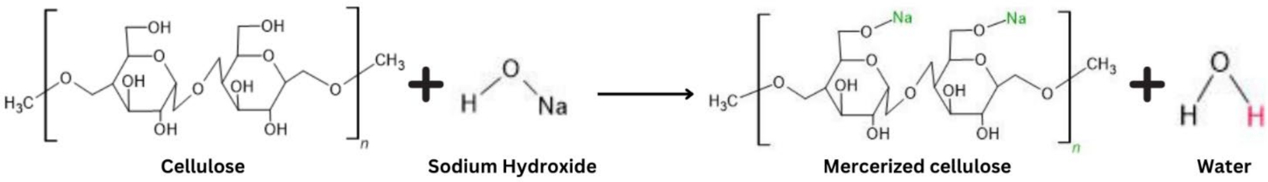
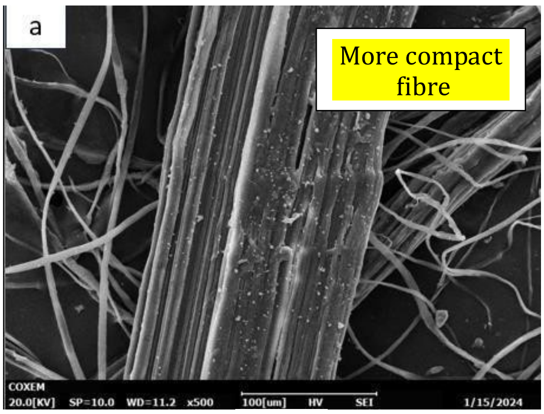


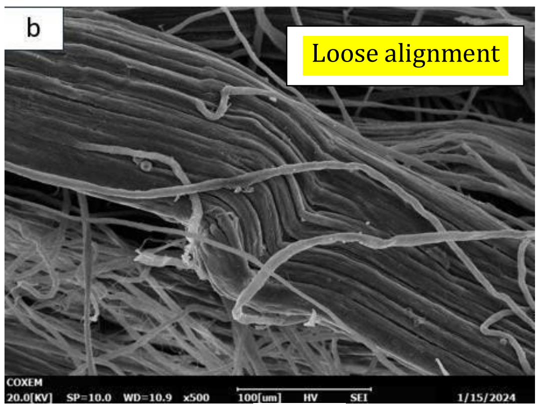
Fig. 6 *Chemical structure for the alkaline treatment of PALF*

3.4 Morphology Analysis of PALF

The morphology analysis of (wastepaper: treated pineapple leaf fibers) samples in the ratio of 1:1, 1:2 and 2:1 in Figure 7 was compared using the scanning electron microscopy (SEM). The samples were coated with gold using the rotary pumped coater, Q150R Plus before running SEM. Gold coating can increase their conductivity and produce more quality pictures [39]. Fibers with higher cellulose content typically exhibit increased tensile strength and stiffness, enhancing the overall performance of the composite material [40]. Conversely, fibers with larger diameters or higher lignin content may result in reduced mechanical properties due to increased brittleness and decreased flexibility [41]. Therefore, understanding and controlling fiber morphology are crucial for optimizing the mechanical performance of natural fiber composites. Figure 7 shows the structure of the microfibril bundle fiber in 1:1, 1:2 and 2:1.



(a)



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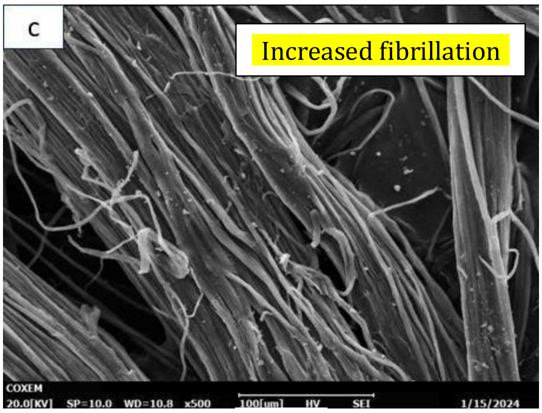

(c)

Fig. 7 *SEM image (a) Sample 1:1; (b) Sample 2:1; (c) Sample 1:2 under magnification of 500x*

In composite materials, optimal performance is often linked to uniform dispersion of reinforcing fibers and proper adhesion between the fibers and matrix. In this case, wastepaper as the matrix and treated PALF as the reinforcement. When PALF was treated with NaOH solution, it causes the defibrillation of PALF by removing the cellulose bundle [42]. In sample 1:2, where the ratio of treated PALF is higher than in other samples, the increased fiber content can improve the overall structural integrity and mechanical properties. In this study, Figure 7(a) SEM show less fiber exposure or agglomeration leading to weaker interfaces between fibers and matrix. Equal amounts of wastepaper and treated PALF could result in some fibers not being evenly dispersed or well bonded to the matrix. This could lead to weak points in the structure and reducing its performance. Figure 7(b) present more areas of the matrix without enough fiber reinforcement, creating voids or cracks. In this case, the lower fiber content relative to wastepaper may not provide enough reinforcement to the composite. A reduced fiber-to-matrix ratio typically results in weaker mechanical properties and a less interconnected fiber network. Figure 7(c) likely have a more homogenous and denser fiber distribution, contributing to the overall mechanical properties such as tensile strength, stiffness and toughness. Homogeneous fiber was indicated by the uniform alignment of fibers with minimal clustering and evenly dispersed structures throughout the observed area. If the fibers appear consistently arranged without large voids or excessive entanglement, this suggests effective fiber treatment and dispersion [43]. Additionally, denser fiber distribution can be inferred from the compact packing of fibers, where minimal gaps or air pockets are present. Here, the higher PALF content ensures that more fibers are interacting with the matrix leading to better load distribution, stronger interfacial bonding and increased mechanical strength [44]. The treated PALF can form a dense network that reinforces the wastepaper matrix, enhancing the overall properties of composite materials. Recent studies have demonstrated that increasing the fiber content in natural fiber-reinforced composites enhances mechanical properties due to better fiber-matrix interaction. For instance, composites with higher natural fiber content (PALF in particular) showed improved tensile strength and structural integrity due to enhanced fiber dispersion and bonding with the Sample 1:2 performs better [45]. This improved surface morphology is consistent with our result that the greater proportion of treated PALF ensures better mechanical reinforcement and surface morphology in the composite. Pineapple fibers (PALF) are composed of cellulose, hemicellulose, lignin, pectin, and other minor components such as waxes and fats. Figure 8 provides an overview of the microfibril bundle structure undergoes significant changes before and after alkaline treatment (NaOH treatment). Before treatment, fibers are bundled with natural polymers (lignin, pectin) that make them stiff, irregular, and contaminated with impurities. Then, after alkaline treatment it illustrates that fibers are cleaner, more cohesive and stronger with more organized cellulose structure that enhances their mechanical properties.

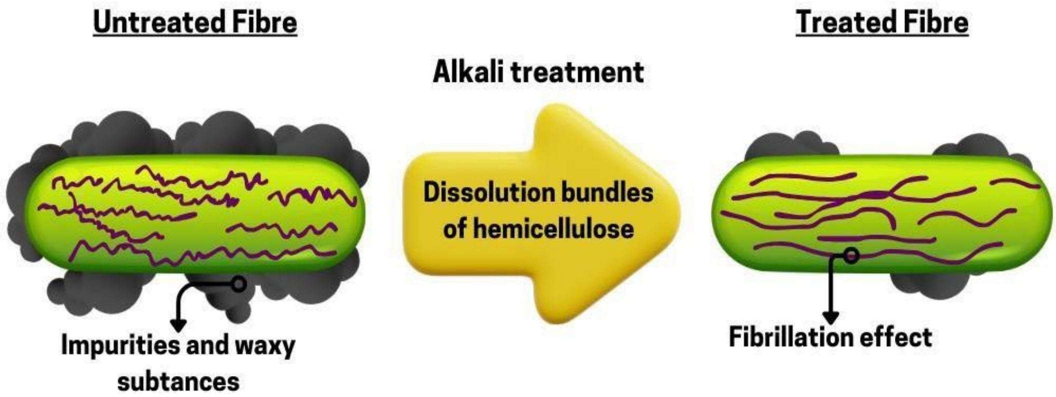

Fig. 8 *Microfibril bundle fiber structure after alkaline treatment*

3.5 Mechanical Properties of PALF Paper

Referring to Table 5, a comparison of the tensile strength among three types of samples is presented which consist of pineapple leaf fiber (PALF) mixed with wastepaper in different ratio mixtures: 1:1, 2:1, and 1:2. Figure 9 presents the result for the tensile strength of three different ratio samples. The 1:2 ratio (9234.596 Pa) exhibits the highest tensile strength due to the higher proportion of pineapple leaf fiber (PALF) which acts as a strong reinforcement. PALF, rich in cellulose that can enhances the load-bearing capacity of the composite by providing better fiber-matrix adhesion and a more uniform stress distribution. In contrast, the 2:1 ratio (5311.917 Pa) shows the lowest tensile strength likely due to the dominance of wastepaper fibers which are shorter and weaker, resulting in reduced structural integrity and fiber-matrix bonding. The 1:1 ratio (6946.375 Pa) offers an intermediate strength, balancing the contributions of both materials. Variations in tensile strength values arise from these differences in thickness. While the 1:2 ratio provides superior mechanical strength, it comes with potential trade-offs. The increased PALF content makes the composite stiffer which may reduce flexibility and limiting its use in applications requiring bending or folding. Additionally, PALF extraction and treatment involve mechanical or chemical processing, increasing production costs compared to the 2:1 ratio, which contains more readily available wastepaper. However, the 1:2 composite also offers better water resistance and durability as PALF naturally resists moisture better than wastepaper. The 1:1 ratio serve as an optimal balance between flexibility and cost, making it suitable for applications requiring moderate durability. Therefore, selecting the ideal ratio depends on the specific application requirements such as strength, flexibility or cost-efficiency is the primary concern.

Table 5 *Tensile strength with different ratios of weight of wastepaper to the weight of pineapple leaf fibers*

Ratio (W:P)	Weight Reading (kg)				Tensile Strength (Pa)
	1st	2nd	3rd	Average	
1:1	1.72	1.69	1.70	1.70	6946.375
2:1	1.34	1.29	1.26	1.30	5311.917
1:2	2.29	2.17	2.32	2.26	9234.596

In this study, the sample with a 1:2 ratio of wastepaper to PALF exhibited greater tensile strength than the other samples, attributed to its higher fiber content. Additionally, the wastepaper formulation acts as a reinforcing fiber in the new paper composite material. It was also due to the PALF and wastepaper outstanding fiber-fiber interaction. The enhanced mechanical properties of pineapple leaf fibers are connected to the high alpha-cellulose content [46]. The use of wastepaper as a reinforcement material in composites was examined. The results indicated that as the proportion of reinforcing fibers increased, the mechanical properties including tensile strength improved due to the effective load distribution across the fibers [47]. The mechanical properties of PALF composites could be enhanced by adjusting the mixing ratios of fibers which is similar to our findings [48]. This comparable study has highlighted that optimizing fiber ratios can lead to improved mechanical properties by maximizing fiber interaction which can ensured the results obtained had a certain degree of reliability.

4. Conclusion

The method to extract the fiber from pineapple leaf was studied. It was discovered that alkali treatments enhanced PALF's qualities. Remarkably, removing lignin and hemicellulose from PALF treated with a high concentration of alkali (NaOH) drives the elimination of contaminants and enhances defibrillation to improve the characteristics of the fiber. In this study, it was observed that soaking pineapple leaves in a 0.5% NaOH solution facilitated the easier extraction of fiber and the resulting ratio of (wastepaper: treated PALF) in Sample 1:2 demonstrated lower impurity levels compared to other samples. Moisture content for the treated PALF is lower with 12% than untreated PALF 14% which indicate the fiber improve its quality. Tensile strength tests on composite papers where wastepaper was combined with treated PALF in ratio 1:2 has higher tensile strength which is 9234.596 Pa compared to the other sample. The addition of PALF to the composite material led to enhanced tensile strength, highlighting its potential as a reinforcing component in composite applications. The scalability of this composite for industrial applications depends on the efficient extraction of PALF, as well as cost-effective processing techniques. However, challenges such as variability in fiber quality, high production costs, and the need for standardized processing methods must be addressed to ensure consistent product performance. Additionally, the mechanical properties of these composites such as tensile strength and flexibility may require further optimization to meet industry-specific standards. Future studies should explore on hybrid composites by incorporating other natural fibers or bio-based additives that could further improve strength, durability and water resistance to broadening the applications of PALF-based composites.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Liew Cheng Yeu, Wong Qi Hui, Adibah Rahmat, Nur Farhana Mohd Hashim, Tuan Sharatul Adawiah Tuan Zakri, Mohammad Arif Budiman Pauzan, Zalilah Murni Mat Ali @ Yunus, Saliza Asman, Nur Syabila Husna Mohd Bakti.;* ***data collection: :*** *Liew Cheng Yeu, Wong Qi Hui, Adibah Rahmat, Nur Farhana Mohd Hashim, Tuan Sharatul Adawiah Tuan Zakri;* ***analysis and interpretation of results:*** *Liew Cheng Yeu, Wong Qi Hui, Adibah Rahmat, Nur Farhana Mohd Hashim, Tuan Sharatul Adawiah Tuan Zakri, Mohammad Arif Budiman Pauzan, Zalilah Murni Mat Ali @ Yunus, Saliza Asman, Nur Syabila Husna Mohd Bakti;* ***draft manuscript preparation:*** *Liew Cheng Yeu, Wong Qi Hui, Adibah Rahmat, Nur Farhana Mohd Hashim, Tuan Sharatul Adawiah Tuan Zakri, Mohammad Arif Budiman Pauzan, Zalilah Murni Mat Ali @ Yunus, Saliza Asman, Nur Syabila Husna Mohd Bakti. All authors reviewed the results and approved the final version of the manuscript. The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.*

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