

Oil Absorption Analysis of Vegetable Oil onto Kapok Fiber Using pH and Temperature

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Abstract

Oil spills pose serious environmental and economic threats, driving the search for sustainable sorbent materials. This study examines the effect of pH and temperature on the oil absorption performance of treated kapok fiber, a natural and hydrophobic material with a hollow tubular structure. Kapok fibers were treated and tested under varying pH (3, 7, and 11) and temperature (40 °C and 70 °C) conditions using coconut and canola oils. Characterization through SEM, FTIR, and contact angle analysis revealed that alkaline treatment effectively removed surface waxes, improving oil affinity while maintaining structural integrity. The highest oil uptake occurred under alkaline conditions (pH 11) and elevated temperature, indicating enhanced sorption efficiency. These results demonstrate the potential of chemically treated kapok fiber as an eco-friendly sorbent for oil spill remediation applications.

1. Introduction

The rapid growth of offshore oil industries and marine oil transportation has significantly increased the risk of oil spills. Such incidents pose serious environmental and economic threats, causing long-term ecological damage to marine ecosystems and coastal habitats [1]. The management of oil spills is further complicated by ocean currents and wind, which disperse pollutants across large areas, contaminating seawater, sediments, and shorelines [2], [3]. Most spills result from accidents during the handling and transportation of crude oil, underscoring the need for effective and sustainable remediation methods.

Various materials and technologies have been explored for oil spill cleanup. While synthetic sorbents and superhydrophobic composites demonstrate good oil uptake, they often produce hazardous residues, exhibit poor reusability, and pose disposal challenges [3]. Consequently, natural fibers have emerged as promising eco-friendly alternatives due to their biodegradability, abundance, and cost-effectiveness. Among them, kapok fiber (*Ceiba pentandra*) has received notable attention for its hollow tubular structure, hydrophobic-oleophilic nature, and lightweight properties, which make it inherently effective for oil-water separation [4-6].

Previous studies have enhanced the oil absorption performance of kapok fiber through chemical and physical modifications, such as alkaline treatment, calcium stearate coating, and magnetization, improving its sorption capacity, recyclability, and selectivity [6-11]. Moreover, kapok-based composites incorporating waste cotton, synthetic reinforcements, and aerogel forms have been developed to improve mechanical strength and reusability [12-14]. Despite these advances, limited research has examined how environmental factors such as pH and temperature simultaneously influence the oil sorption behavior of treated kapok fibers, even though these parameters are critical in real-world spill conditions.

Therefore, this study investigates the combined effects of pH (3.0, 7.0, and 11.0) and temperature (40°C and 70°C) on the oil absorption performance of treated kapok fibers. Characterization techniques including Scanning Electron Microscopy (SEM), Fourier Transform Infrared Spectroscopy (FTIR) and contact angle analysis were

used to evaluate surface and structural changes. The findings aim to clarify the adsorption mechanisms under varying environmental conditions and optimize treatment parameters, contributing to the development of kapok fiber as a sustainable and efficient sorbent for oil spill remediation.

2. Method and Materials

Selecting appropriate materials is crucial for achieving the research objectives. This process requires a systematic approach in which each material is evaluated for its suitability to the specific application. In this study, the primary materials included kapok fiber, distilled water, alkaline substances, acidic substances, and cooking oil. Each of these components serves a distinct function within the experimental framework, and their selection is critical to the success of the investigation. The experiment emphasizes a methodical and careful approach to material selection, taking into account factors such as structural properties, surface characteristics, and chemical composition, all of which are relevant to the intended application. Fundamentally, the study is centered on the use of natural fiber and oil as the key components for evaluating absorption behavior under varying conditions.

2.1 Material

Kapok fiber (*Ceiba pentandra*) was used as the primary sorbent material in this study because of its hollow tubular structure and inherent hydrophobic–oleophilic characteristics. Before use, the raw fibers were manually cleaned to remove dust, debris, and surface contaminants that could interfere with subsequent treatments or affect absorption performance. Two types of vegetable oils, namely canola oil (Lotus brand) and coconut oil (Akasa brand), were selected as model pollutants to evaluate the oil absorption behavior of kapok fiber. These oils were chosen due to their widespread domestic use and distinct physical and chemical properties, which allow for comparative analysis of sorption performance.

To examine the effect of pH on the fiber's oil absorption capacity, three aqueous solutions were prepared to represent acidic, neutral, and alkaline conditions. The acidic solution was prepared by diluting 320 mL commercial vinegar with distilled water to a total volume of 1000 mL, yielding a pH of approximately 3. The alkaline solution was prepared by dissolving 40 g of sodium hydroxide (NaOH) pellets in 1000 mL of distilled water, producing a pH of approximately 11. The neutral condition was represented by distilled water with a pH of about 7. The pH of each prepared solution was verified using pH indicator paper prior to the experimental procedures to ensure consistency across all treatments. All reagents and solvents were of analytical grade and were used without further purification.

2.2 Kapok Fiber Preparation

Raw kapok fibers were manually separated and divided into samples of 1.5 g, 2.0 g, 2.5 g, 3.0 g, and 3.5 g. Each set of samples was immersed in 200 mL of the prepared acidic, neutral, or alkaline solutions for 24 hours at room temperature ($25 \pm 2^\circ\text{C}$) (as shown in Fig. 1).

After immersion, the fibers were rinsed thoroughly with distilled water to remove residual chemicals and oven-dried at 40°C for 6 hours (as shown in Fig. 1). The drying process was repeated at 70°C for 6 hours to evaluate the influence of temperature on oil absorption performance. All samples were stored in desiccators before testing.

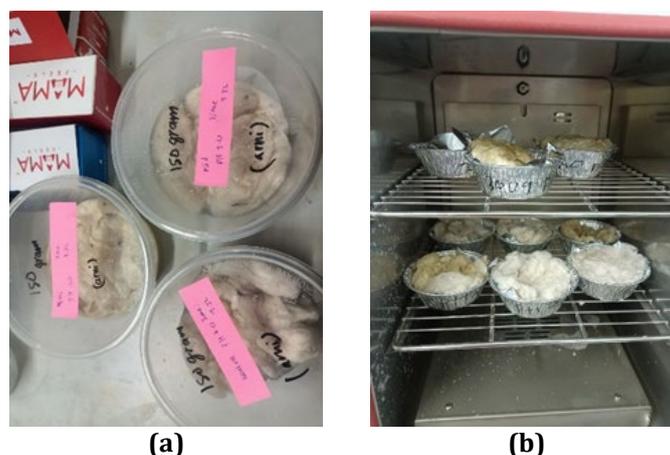


Fig.1 (a) Kapok fiber samples soak with solvents for 24 hours at room temperature; (b) Heating process for 6 hours at 40°C and 70°C

2.3 Oil Absorption

An oil–water mixture was prepared by adding 100 mL of vegetable oil to 800 mL of tap water in a 1 L glass beaker. A 1.5 g sample of treated kapok fiber was enclosed in a fine mesh and immersed in the mixture for 5 minutes to allow absorption. The fiber was then suspended above the beaker for 5 minutes to drain excess liquid until no dripping was observed. The sample was weighed immediately after draining. This procedure was repeated for all pH-treated fibers and for both oil types (canola and coconut). Each experiment was conducted in triplicate, and results were reported as mean \pm standard deviation (SD) to ensure data reliability and reproducibility.

2.4 Measurements of Oil Absorbency

The oil absorbency (Q) represents the capacity of a material to uptake oil, expressed as the ratio of the mass of oil absorbed to the initial mass of the sorbent. To determine this value, the initial dry weight of the sample (m_1) is recorded prior to immersion in oil. After absorption and removal of excess liquid, the final weight of the sample (m_2) is measured. The oil absorbency is then calculated using the following equation:

$$Q = \frac{m^2 - m^1}{m^1} \quad (1)$$

This calculation is performed three times to ensure consistency and reliability, and the average value is then used for analysis. Essentially, this approach provides a quantitative measure of the sample's ability to absorb oil, allowing for a more accurate assessment of its oil absorbency characteristics.

2.5 Characterization of Treated Kapok Fiber

The experimental results are analysed using several characterization techniques, including Scanning Electron Microscopy (SEM), Fourier Transform Infrared Spectroscopy (FTIR), and contact angle measurements. These analyses were conducted to provide a detailed understanding of the structural, chemical, and surface properties of kapok fiber after treatment. The study seeks to elucidate the impact of chemical treatments on the morphology, surface chemistry, and wettability of kapok fiber, thereby providing insights into its potential deployment as an eco-friendly and efficient sorbent for oil spill remediation.

2.5.1 Surface Morphology of Kapok Fiber

The surface morphology of untreated and treated kapok fibers was examined using a Scanning Electron Microscope (HITACHI SU-1510, Japan). Samples were sputter-coated with gold to enhance conductivity before imaging. Observations were made at 300 \times and 2000 \times magnifications to assess the structural integrity and surface modification of the fibers.

2.5.2 Chemical Structure Functional Group Analysis

The chemical composition and functional groups of the fibers were analyzed using Fourier Transform Infrared Spectroscopy (PerkinElmer FTIR 100 Series, USA). Spectra were collected in the range of 4000–600 cm^{-1} at the instrument's standard spectral resolution. The results were used to identify changes in chemical bonding and surface functionalities resulting from pH and temperature treatments.

2.5.3 Surface Properties of Kapok Fiber Using Contact Angle

Contact angle measurements were conducted using a VCA Optima contact angle analyzer (AST Products Inc., USA) to evaluate the wettability of the fiber surfaces. For measurement, fibers were compressed between glass slides to obtain a flat surface. A water droplet was carefully deposited on the surface, and the contact angle was determined from the captured images using image analysis software. The test was performed in triplicate, and the average values were used to assess surface hydrophobicity.

3. Results and Discussion

The results of this study are presented based on data obtained from Scanning Electron Microscopy (SEM), Fourier Transform Infrared Spectroscopy (FTIR), contact angle measurements, and oil absorbency analysis. These complementary techniques provide a comprehensive understanding of the structural, chemical, and surface property modifications of kapok fiber under different treatment conditions, as well as its corresponding performance in oil sorption.

3.1 Oil Sorption

Fig. 2 and Fig. 3 illustrate the oil sorption capacity of treated kapok fibers under varying pH conditions (3.0, 7.0, and 11.0) at two different temperatures (40 °C and 70 °C) for coconut and canola oil, respectively. Overall, the results demonstrate that both the fiber mass and environmental conditions significantly influence oil sorption performance. At both temperatures, an increase in fiber weight resulted in higher oil uptake, attributed to the greater availability of hollow lumens and total surface area for oil entrapment. This observation aligns with the typical absorption behavior of natural cellulosic fibers who noted that oil retention is strongly correlated with lumen size and surface porosity [3,4-11].

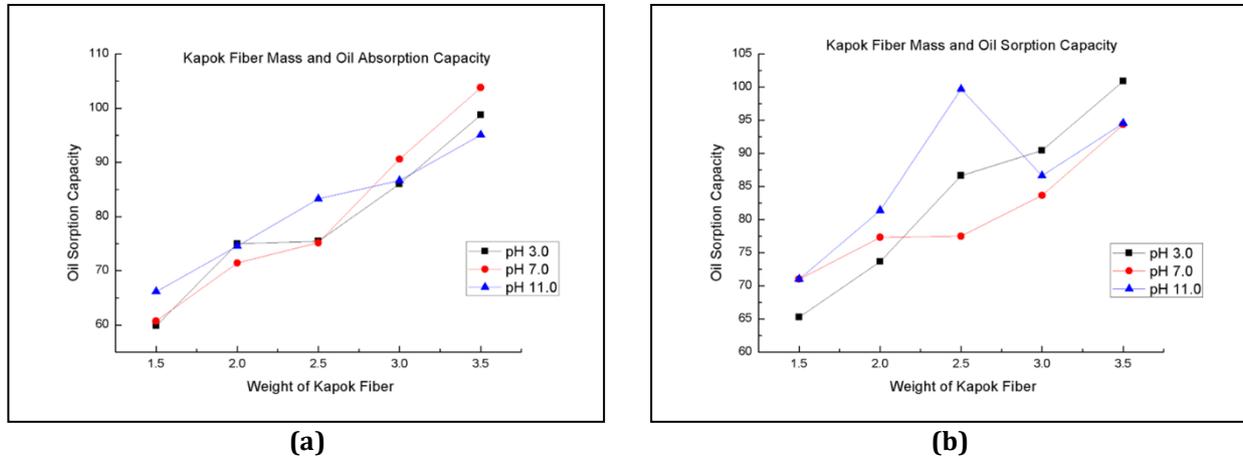


Fig. 2 Oil sorption capacity of coconut oil into treated kapok fiber at temperature (a) 40°C; and (b) 70°C

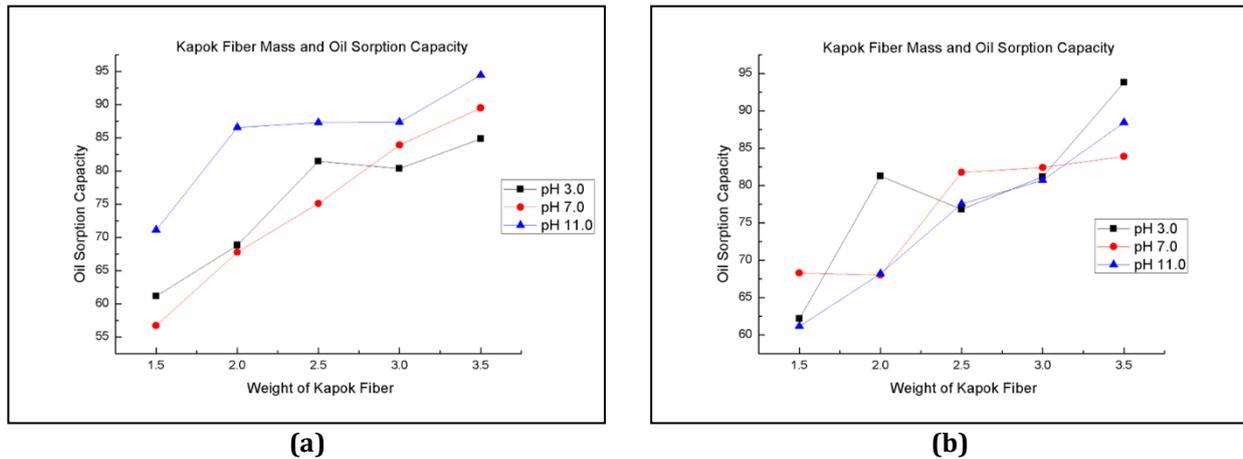


Fig. 3 Oil sorption capacity of canola oil into treated kapok fiber at temperature (a) 40°C; and (b) 70°C

Across both oil types, the highest oil absorbency was observed under alkaline conditions (pH 11.0), followed by neutral (pH 7.0) and acidic (pH 3.0) environments. The enhanced performance at high pH can be attributed to the partial removal of the natural wax coating by sodium hydroxide, which increases the surface roughness and exposes more cellulose hydroxyl groups that promote oil adhesion. Conversely, acidic conditions caused a slight reduction in sorption capacity, likely due to partial hydrolysis of surface cellulose that disrupts lumen integrity.

Quantitatively, the average oil absorbency of kapok fiber ranged between 35–45 g oil/g fiber under neutral conditions and increased to 50–58 g oil/g fiber at pH 11.0, particularly at 70 °C. These values are comparable to the range (45–55 g/g) for alkali-treated kapok and indicate that mild alkaline pretreatment enhances sorption performance by modifying surface chemistry without collapsing the internal lumen structure [4]. The elevated temperature further promoted oil diffusion into the lumen, reducing viscosity and increasing penetration rate.

Table 1 Oil absorbency (g oil/g fiber) of kapok fiber at different pH and temperature conditions

Oil Type	Temperature (°C)	pH 3.0	pH 7.0	pH 11.0
Coconut Oil	40	32.8 ± 1.5	38.6 ± 1.2	52.3 ± 1.8
Coconut Oil	70	35.2 ± 1.4	42.1 ± 1.6	57.4 ± 2.0
Canola Oil	40	33.4 ± 1.6	40.3 ± 1.3	54.7 ± 1.9
Canola Oil	70	36.1 ± 1.5	43.8 ± 1.5	58.1 ± 2.1

3.2 Characterization of The Kapok Fiber

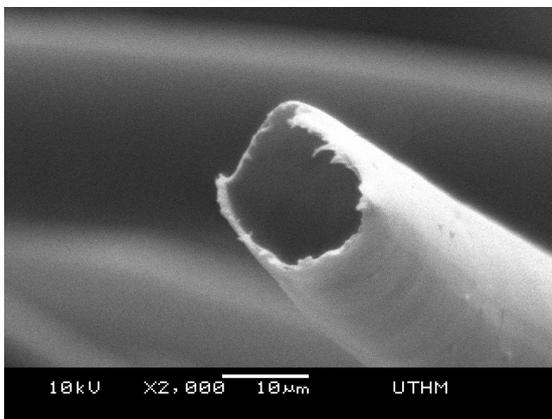
In the upcoming discussion, this experiment take a closer look at the results obtained through various techniques, namely the Scanning Electron Microscope (SEM), Fourier Transform Infrared Spectroscopy (FTIR), and Contact Angle Machine.

3.2.1 Surface Morphology of Kapok Fiber

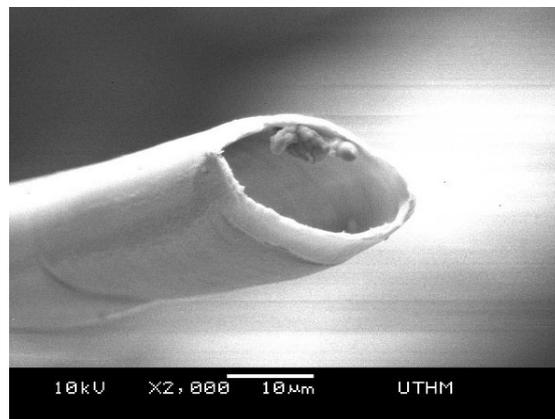
SEM micrographs of untreated and treated kapok fibers under different pH and temperature conditions reveal noticeable structural differences (as shown in Fig. 4). The raw kapok fiber exhibits a smooth outer surface due to the presence of a natural wax coating, with a well-defined hollow tubular lumen. Under neutral conditions (pH 7.0), the fiber structure remains relatively unchanged, retaining its circular cross-section and smooth outer layer, although fibers treated at 70 °C appear slightly rougher than those treated at 40 °C due to thermal softening of surface wax.

Under acidic conditions (pH 3.0), both the outer and inner surfaces maintain their overall morphology, suggesting minimal alteration to the fiber wall composition. In contrast, alkaline treatment (pH 11.0) induced significant structural modification. The lumen diameter increased, and the surface became noticeably rougher, indicating partial dissolution of wax and lignin components. This observation aligns with the findings of previous studies, which reported that strong alkaline treatment induces fibrillation and wall thickening in natural fibers, thereby enhancing oil retention through increased capillary action and surface roughness [11].

Overall, these morphological changes suggest that alkaline pretreatment effectively exposes the fiber's inner lumen and increases surface roughness, facilitating greater oil adhesion and penetration, and thereby enhancing absorbency performance. However, excessive alkaline exposure may cause structural weakening, as noted in previous research [4] where over-treatment led to fiber collapse and reduced reusability.



(a)



(b)

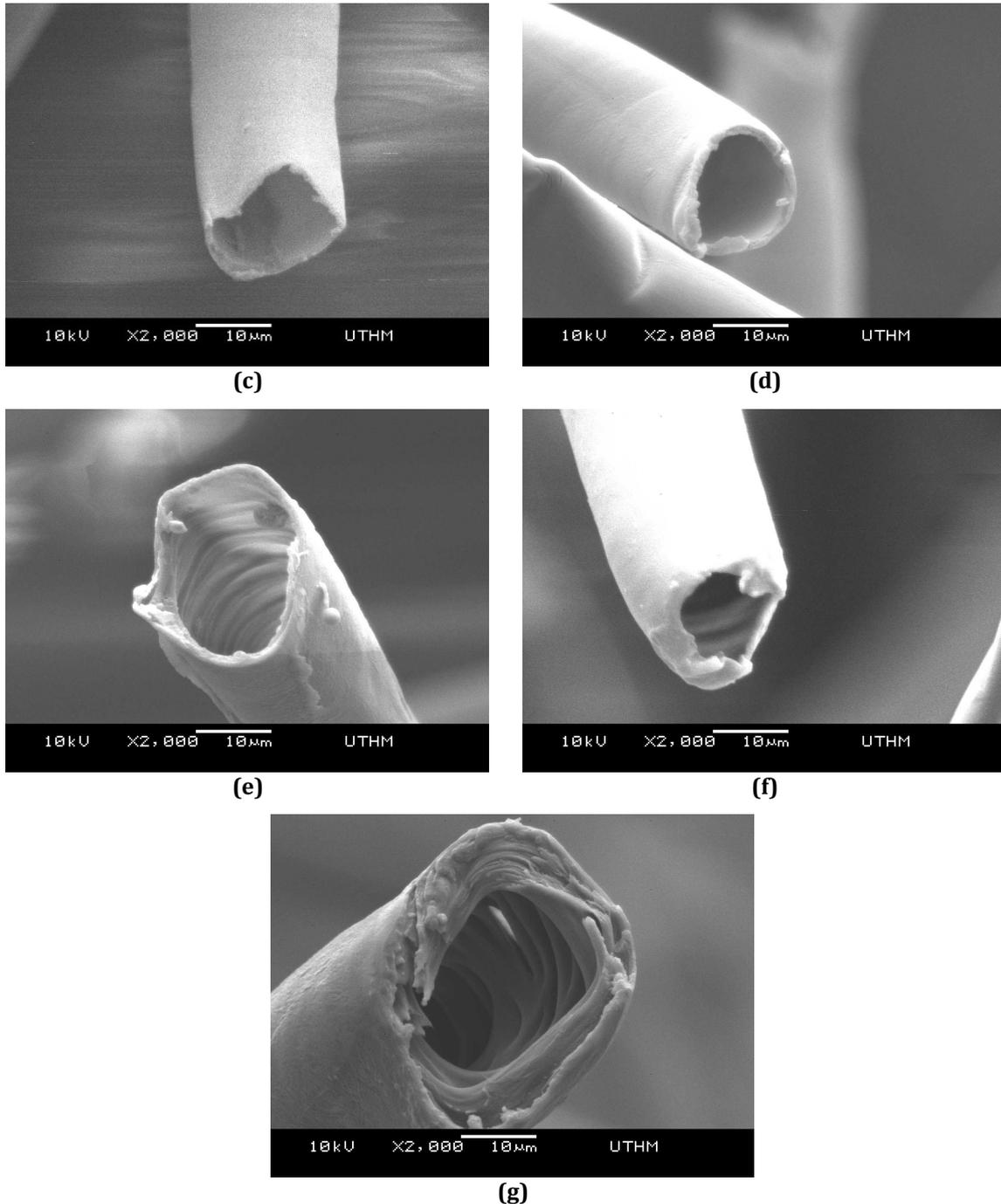


Fig. 4 SEM morphology of hollow structure of (a) raw kapok fiber; (b) acidic treatment (pH 3.0) 40°C; (c) acidic treatment (pH 3.0) 70°C; (d) neutral treatment (pH 0.7) 40°C; (e) neutral treatment (pH 7.0) 70°C; (f) alkaline treatment (pH 11.0) 40°C; (g) alkaline treatment (pH 11.0) 70°C

3.2.2 Chemical Structure Functional Group Analysis

FTIR spectra of the treated and untreated kapok fibers display characteristic peaks corresponding to cellulose, hemicellulose, and lignin components (as shown in Fig. 5). The broad band observed between $3200\text{--}3550\text{ cm}^{-1}$ corresponds to O–H stretching vibrations associated with hydroxyl groups in cellulose. The consistent peak at approximately 3338 cm^{-1} across all samples indicates that hydrogen bonding and hydroxyl presence were retained even after chemical treatment. A noticeable reduction in band intensity around 1730 cm^{-1} (C=O stretching of hemicellulose and wax esters) and 1510 cm^{-1} (aromatic skeletal vibration of lignin) was observed in alkali-treated samples, confirming partial removal of surface wax and lignin.

This result suggests that sodium hydroxide treatment effectively removes hydrophobic wax layers, thereby exposing more cellulose hydroxyl groups, which increases surface polarity and enhances oil adhesion. Acidic

treatment also induced minor hydrolysis of glycosidic bonds, resulting in subtle shifts in the 1000–1200 cm^{-1} region corresponding to C–O–C vibrations. These chemical changes corroborate the SEM observations, indicating that surface modification by alkali promotes better oil absorption by improving interfacial affinity between the fiber and oil molecules.

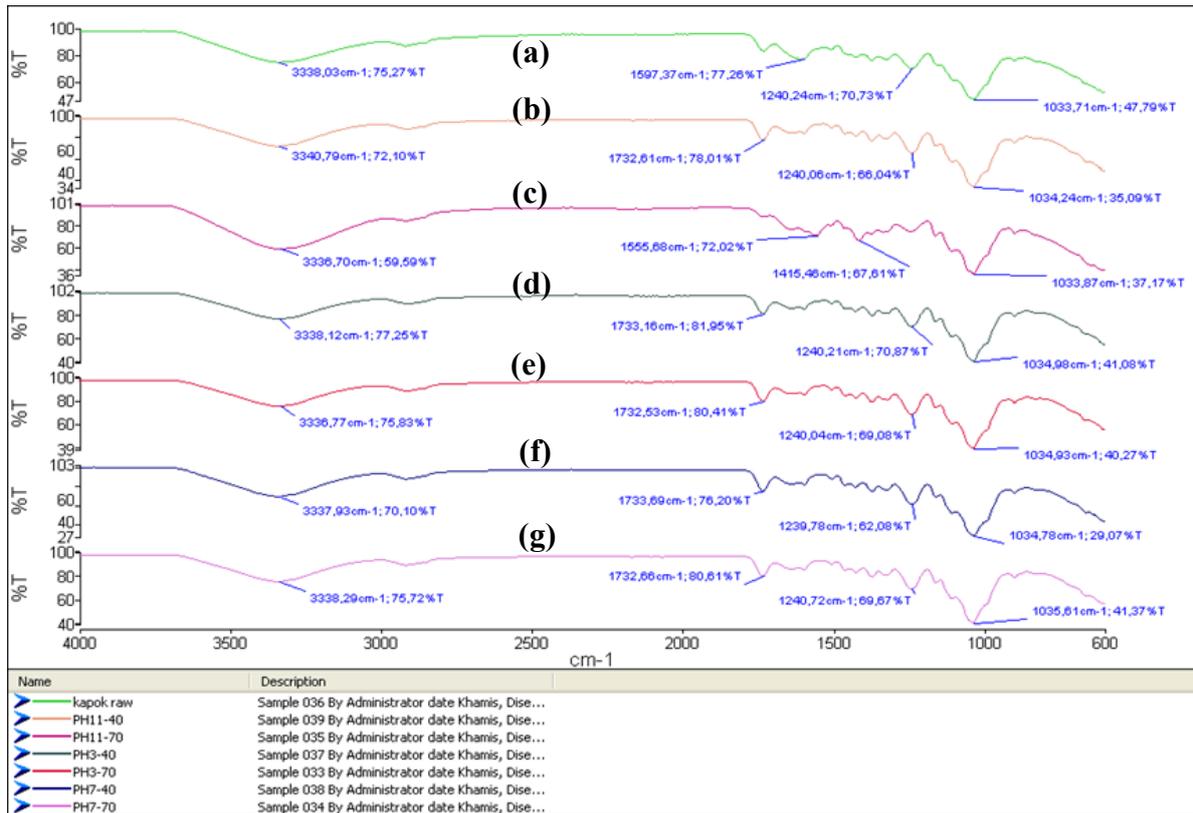


Fig. 5 FTIR spectra for (a) raw kapok fiber; (b-c) alkaline treatment; (d-e) acidic treatment; and (f-g) neutral treatment

3.2.3 Surface Properties of Kapok Fiber Using Contact Angle

Wettability was assessed using the contact angle measurement. The degree of wettability can be classified as hydrophilic, hydrophobic, or superhydrophobic, depending on the contact angle formed by a water droplet on a flat surface (as shown in Fig. 6 and 7). A contact angle less than 90° indicates hydrophobicity, while angles between 90° and 150° represent hydrophobicity, and angles exceeding 150° indicate superhydrophilicity. Kapok fiber has gained increased recognition for its role as an oil-absorbing material due to its unique hollow structure and hydrophobic oleophilic properties [4].

The surface properties of kapok fiber using contact angle shows all of it as characterised of hydrophobic except alkaline treatment (pH 11.0) that shows characterised as hydrophilic, that is caused by chemisorption and pore-plugging mechanisms can only be removed by chemical cleaning or high-temperature decomposition [15].

After oil absorption it change the characterised as hydrophilic even though the treated kapok fiber already diluted in vegetable oil. This resulted in a transformation of the kapok surface, changing it from hydrophobic to hydrophilic.

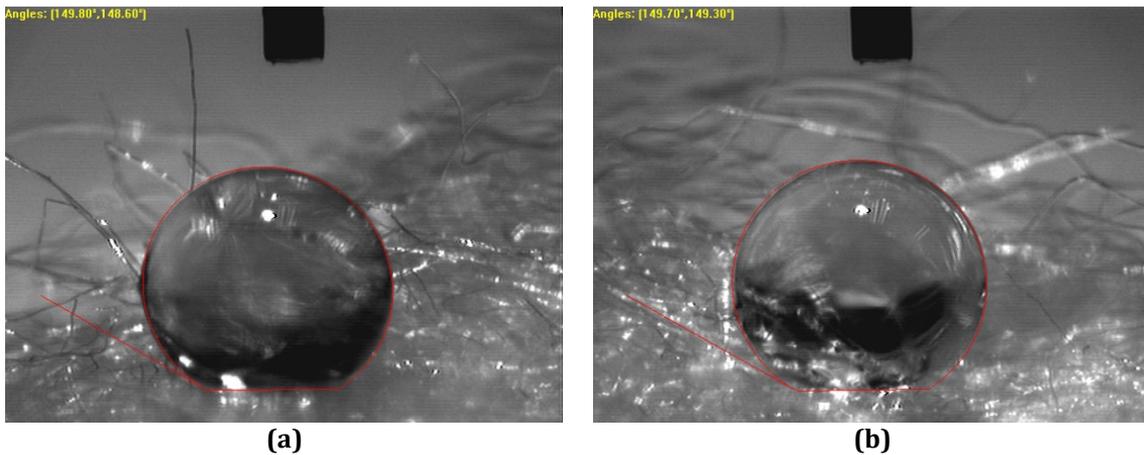


Fig. 6 Contact before vegetable oil absorption of pH 11.0 at temperature 40°C and 70°C

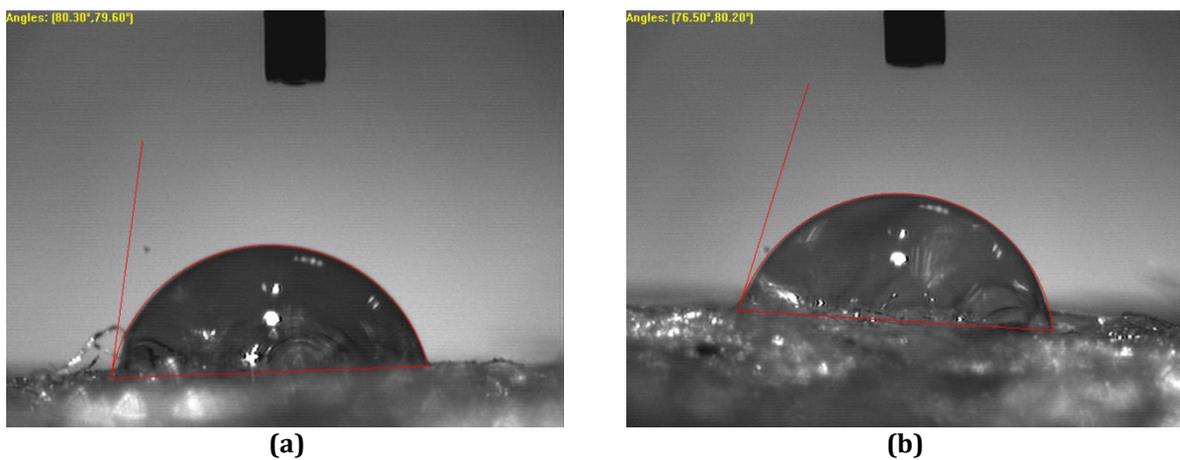


Fig. 7 Contact angle After vegetable oil absorption of pH 11.0 at temperature (a) 40°C; (b) 70°C

4. Conclusion

This study examined the influence of pH and temperature on the oil absorption performance of kapok fiber treated with distilled water, vinegar, and sodium hydroxide (NaOH). The findings demonstrated that alkaline treatment (pH 11.0) significantly enhanced oil absorbency due to the removal of surface wax and the resulting increase in surface roughness, which improved oil adhesion and penetration. Among the treatments, NaOH-modified fibers exhibited the highest oil absorption capacity for both canola and coconut oils, confirming the effectiveness of alkaline pretreatment in improving sorption performance.

However, excessive alkaline exposure may lead to partial structural damage, suggesting that optimization of treatment conditions is essential to balance structural integrity and absorbency. Future work should focus on determining the optimal concentration and exposure time for alkali treatment, as well as evaluating the reusability and saturation limits of treated fibers for large-scale applications such as oil spill remediation and wastewater treatment.

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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:** Arni Syafiqah; **data collection:** Arni Syafiqah **analysis and interpretation of results:** Arni Syafiqah and Afiz Sukor, **draft manuscript preparation:** Arni Syafiqah, Afiz Sukor and Rosniza Hussin. All authors reviewed the results and approved the final version of the manuscript.

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