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*Article*

# Effect of Optimized Alkaline Treatment on the Chemical, Microscopic, and Mechanical Properties of Banana Fibers for Sustainable Composite Applications

**Abbas Mohammed Atiyah [1], Hind Mohammed Atiyah [2], Zeina Mohammed Ali [3], Mohammed Mishari Krir [4]**

1. Department of Medical Physics, College of Applied Medical Sciences, Al-Shatrah University, Al-Shatrah city, Iraq
2. Department of Medical Laboratory Sciences, College of Applied Medical Sciences, Al-Shatrah University, Al-Shatrah City, Iraq
3. Department of Medical Physics, College of Applied Medical Sciences, Al-Shatrah University, Al-Shatrah city, Iraq
4. Directorate of Education of Babylon, Al-Musayyib Education Department

* Correspondence: abbasmohammed@shu.edu.iq, Zeina.ma@shu.edu.iq

**Abstract:** In this study, for the first time, attempts to research banana fibers (Musa sapientum), as a new sustainability composite reinforcement material have been taken, which their composition and morphology were affected by chemical treatment with NaOH solution. NaOH treatment on banana fiber: structure and mechanical performance Within the context of this research, the effect of NaOH treatment on the structural integrity of polymeric composites is presented by highlighting differences in both chemical (Figure 2a) and physical properties (quasi-static tensile behaviors) between abaca fibers treated with different concentrations[57]. In this work, two treatment concentrations were implemented (5 wt% and 10 wt%) under controlled circumstances. Scanning electron microscopy (SEM) characterized surface morphology, while Fourier transform infrared spectroscopy (FTIR) analyzed chemical modifications. The mechanical performances of the tensile testing were presented: The Tensile strength and Young's modulus were significantly higher in 5 wt% NaOH, and so less amount of other materials removed from raw jackfruit seeds caused increasing solid surface roughness improving fiber matrix interfacial interaction In comparison, 10 wt% NaOH treatment causes a deterioration in structure and mechanical properties Thus, the results demonstrate that careful optimization of alkaline treatment conditions is essential for improving natural fibers performances and promoting them as fillers of eco-friendly composite materials.

**Keywords:** Banana fibers, alkaline treatment, sodium hydroxide (NaOH), SEM, FTIR, mechanical properties, sustainable composites

Graphical Abstract A scheme showing the influence of alkaline treatment (NaOH) on pulp surface structure and mechanical properties of banana fibers is presented, demonstrating how excessive treatment can render fibers unsuitable for composite reinforcements with optimum reinforcing efficiency at 5 wt% NaOH

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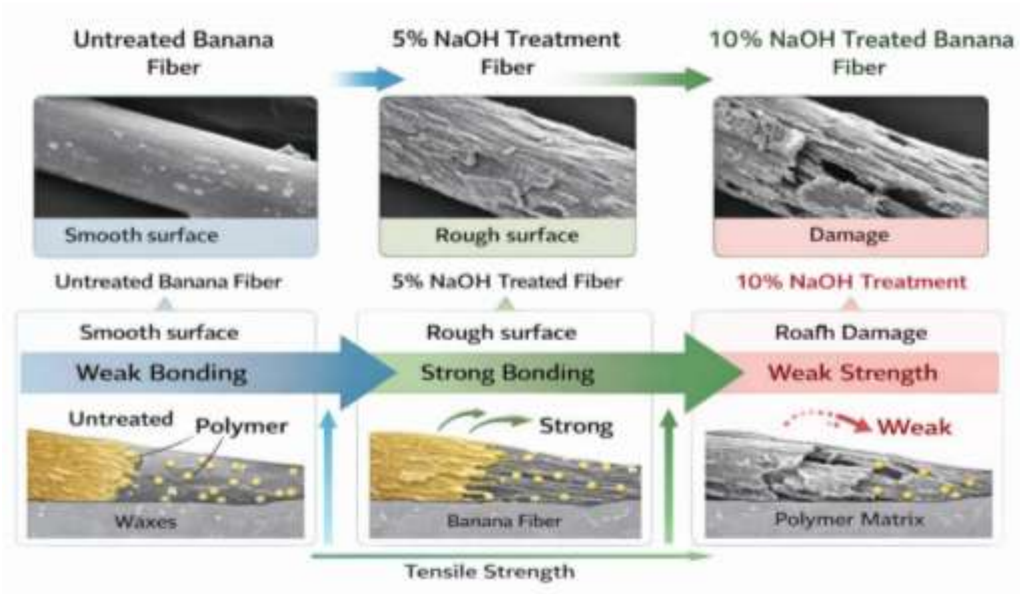



## 1. Introduction

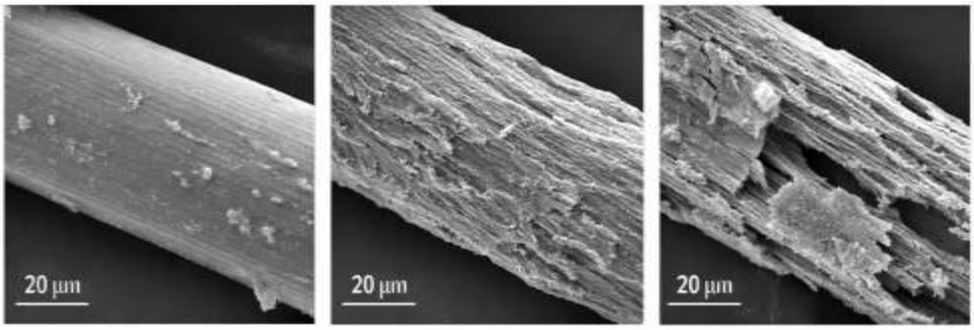
Research on low density, biodegradable and lower environmental impact compared to synthetic reinforcements has shifting attention towards natural fibers for sustainable composite applications [1]. AbstractNatural fibers have long been established as sustainable replacements for synthetic reinforcements [2]. However, the mechanical competency of neat natural fibers remains restricted when they are effectively bonded with polymer matrices due to the difficulties in obtaining good interfacial bonding, a phenomenon caused by fractions of hemicellulose, lignin and surface contaminants. In recent years, natural fibers have been considered a more sustainable alternatives for synthetic reinforcements [2], [3]. Alkaline treatment (mercerization) is one of the standard techniques to improve the properties of such type natural fibers. This process liberates non-cellulosic components, roughens the surface and results in superior fiber–matrix adhesion, which subsequently enhances mechanical properties [4]. However, excessive treatment at alkali can lead to segregation and deconstruction of cellulose fragments resulting in weakened fibre [5], [6], [7]. Recent studies have highlighted the need for fine-tuning applied methods with respect to conditions where reinforcement is integrated single-handedly with minimal damage within structure. The previous studies revealed that moderate NaOH removal increased the crystallinity and tensile strength of the fiber, and extreme concentrations were negatively impacting structural integrity [5], [8], [9].

Surface modification for enhancement of interfacial bonding and durability can also be found in literature [10], [11]. However, most previous studies have only concentrated on either chemical characterization or mechanical performance with just basic inclusion of these two factors. Thus, a complete morphological, chemical and mechanical analysis is crucial for defining optimum processing conditions of natural fibers In this perspective, the prime objective of the present work is to study effect of concentrations of sodium hydroxide (NaOH) on banana fiber. Moderate alkaline treatment (5 wt% NaOH) could reinforce the structural and mechanical characteristics of the fibers while higher concentrations result in degradation. These two components of natural fiber reinforce composites — trees and agricultural residues, are highly abundant on our planet, and with their thermal processing yield biochar which has a prominent reputation for improving soil quality. Keep Reading This Article: Enzyme-based improvement of flax fibers toward mechanical enhancements in compositesNatural fibers can be considered a sustainable substitute for synthetic reinforcements not only because of their environmental/biodegradability consciousness but also due to their decent machinal properties [2], [3], [12], paving the way toward a more ecofriendly society/development.

## 2. Materials and Method

### Fiber Preparation

Banana fibers (Musa sapientum) were extracted manually from locally available banana stems. Surface-wash and oven-dry of extracted fibers was performed to obtain pure raw silk in 60 °C for 24 h The preparation procedure described was performed using methodologies commonly used in the literature recently for consistency and reproducibility [5], [13].




(a) Untreated fiber (b) 5% NaOH treated fiber (c) 10% NaOH treated fiber

Fig 1 shows the SEM micrographs of banana fibers under different treatments.

Fig. 1 Surface morphology of banana fibers Untreated fibres have a relatively smooth surface with general impurities. A major reason for the rough surface of 5 wt% NaOH is the removal of non-cellulosic elements along with chemical chains after refinement. Conversely, 10 wt% NaOH treatments cause structure damage destination and surface corrosion.

### Alkaline Treatment

The prepared fibers are divided in to three groups, group I was treated with 5 wt% of NaOH, group II and the remaining control (untreated) was subjected into 10 wt% of NaOH. The alkaline treatment was performed at room temperature (25 °C) by stirring for 4 h to allow for homogeneous exposure After the treatment, fibers were neutralized by washing with a solution of 1% acetic acid to remove any remaining alkali, followed by several distilled water washings until neutral pH. The final step was the dry fibers under controlled conditions. The above-mentioned process is similar to the earlier described alkali treatment used for modification of fiber surface properties and enhancing interfacial bonding [4], [5], [14], [15].

### Characterization Techniques

Various analytical techniques were employed to characterize the morphological, chemical and mechanical properties of both treated and untreated fibers.

Scanning Electron Microscopy (SEM)

Sector F fired Fissile-Mirarol AA*: Field emission scanning electron microscope (FESEM) forSEE: The change in surface morphology and microstructure of the fibers was analyzed by FESEM after 1 h of treatment at different conditions.

Fourier transform infrared spectroscopy (FTIR):

FTIR analysis from 4000–500 $cm^{-1}$ to identify the chemical changes and functional groups in cellulose, hemicellulose and lignin.

### Mechanical Testing:

Tensile properties were measured according to ASTM D3822 (crosshead speed: 5 mm/min)[33] including tensile strength, Young's modulus and elongation at break.

### Statistical Evaluation:

Results The experimental data were analyzed using one-way analysis of variance (ANOVA) and statistically significant difference was set at $p<0.05$ to ensure the validity of our findings.

## 3. Results and Discussion

### Chemical Mechanism

Banana fiber chemical structure alteration by an alkaline reaction of the cellulose hydroxyl groups with sodium hydroxide.

Low molecular weight alkali lignin Example:

$$Cell–OH + NaOH \rightarrow Cell–O–Na + H_2O$$

Hemicellulose removal, partial dissolution of lignin, and removal of surface impurities allow increasing cellulose micro fibrils exposure. As a result surface activity increases due to fiber crystallization and these effects have a positive impact on mechanical performance. This behavior has been widely reported in natural fiber treatment studies where cellulose exposure and consequently fiber properties are improved using alkaline treatment [16] as well as ours which report improved tensile properties upon controlled alkaline treatment [17], [18]. This behavior has been extensively discussed for natural fiber treatment [16].

### SEM Analysis

The allomorphic differences upon alkaline treatment were determined via SEM observations. Untreated fibers have relatively smooth surfaces that are covered with impurities and waxy substances preventing good interfacial adhesion Fibers treated with 5 wt% NaOH exhibit an effectively clean and a rougher surface as the amorphous components can be removed. The more active surfaces provide improved mechanical interlocking and, thereby, enhance fiber–matrix adhesion. In all cases, fibers treated with 10 wt% NaOH display descried surface erosion and structural damage which produces fiber degradation of the fiber structure The more favorable results emphasize that moderate alkaline treatment can improve fiber morphology while surplus treatment has negative effects on fiber integrity. The trends observed in this study are in the line reported on, literature [5], [19] for these type of surface modifications. A surface modification trend analogous to that observed for alkali-treated fibers has been established [4], [14].

### FTIR Analysis

The alkaline treatment was confirmed to have chemically modified the treatments through FTIR. Loss of the band around 1732cm$^{-1}$ associated with hemicellulose, and around 1245cm$^{-1}$ which is due to partial removal of lignin. In addition, the broad peak at 3340 cm$^{-1}$ shift corresponding to O–H stretching is indicating the change of hydrogen bond within cellulose structure along with an increase in crystallinity and better structural order of cellulose that subsequently enhance mechanistic properties of cellulose fibers. To be consistent with the results of previous studies [17], [20]. These chemical transformations facilitated the interappeared directionality of cellulose orderly and thus improved interfacial adhesion, which directly impacts mechanical performance.

Table 1. Assignment of FTIR Peaks of Banana Fibers

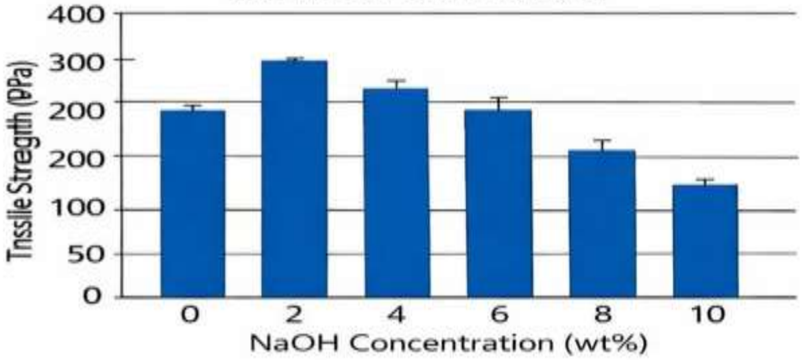
| Wavenumber (cm$^{-1}$) | Functional Group | Affected Component |
|---|---|---|
| 3340 | O–H stretching | Cellulose |
| 1732 | C=O stretching | Hemicellulose (removed after treatment) |
| 1245 | C–O stretching | Lignin (reduced) |
| 1030 | C–O–C stretching | Polysaccharides |

### Mechanical Properties

Alkaline can alter the physical properties of the banana fibres. Results depict the greater load bearing capacity of fibers with highest tensile strength and Youngs modulus at 5 wt% NaOH treated fibers. This improvement is like being credited to removal of non-cellulosic fractions, higher surface roughness and satisfactory stress transfer performance The use of low concentrations (10 wt%) NaOH in cellulose fiber treatments results from the fact that this polymer suffers structural degradation; therefore the mechanical behaviour is reduced. Chemical over-treatments resulted in damaging structure of fiber, which weakened its tensile strength and stiffness Consequently mechanical properties improvement is closely bonded to morphological

The SEM and FTIR analyses also showed chemical changes, indicating that gentle alkaline treatment was very effective. The reported tensile strength (TS) values all fall within the similar range as historic results previously reported in literature (~500–600 MP), which lends further credibility to the experimental results [14,15] Further statistical analysis (ANOVA) confirms that the differences witnessed between untreated and treated samples were strong difference ($p < 0.05$), again confirming the trends mentioned above In general, improved stress transfer is necessary for achieving better composite performance, validated by Pickering et al. [16], with the enhancement of mechanical performance being attributed to improved interfacial bonding and cellulose crystallization. Completely removal of amorphous compounds including hemicellulose and lignin leads to higher efficiency of load transfer. Excessively alkaline treatment disturbs the cellulose architecture which decreases polymer mechanical properties The efficient stress transfer is a vital factor contributing to the performance of composites [3], hence, the results were in agreement with new trends on natural fiber composites [5].

**Figure 2: Variation of tensile strength of banana fibers with NaOH concentration**



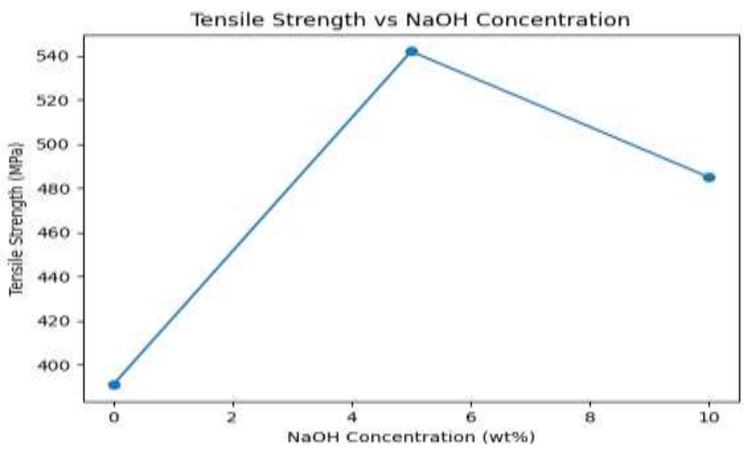




Fig. 3. Effect of NaOH Concentration on Tensile Strength

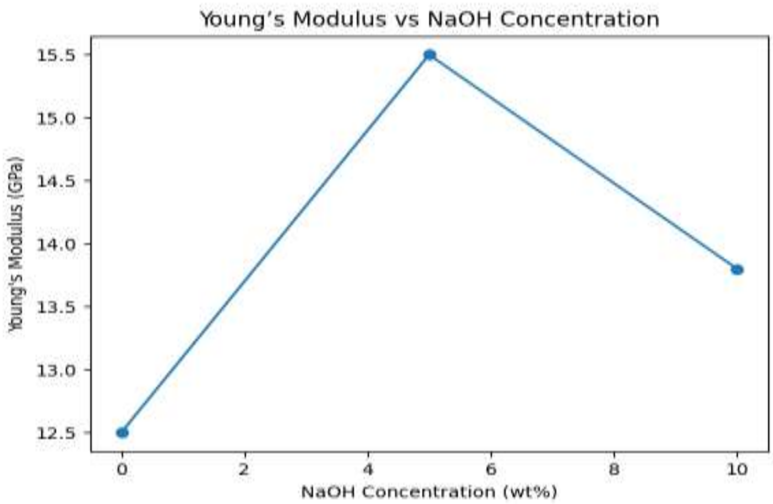



Fig. 4. Effect of NaOH Concentration on Young's Modulus

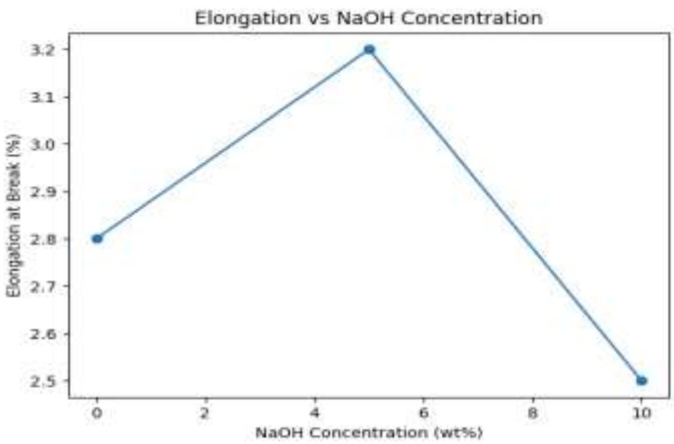



Fig. 5. Effect of NaOH Concentration on Elongation at Break

The effect of NaOH concentration on tensile strength, Youngs modulus and elongation at break are showed in figures 3–5 respectively. The performance is significantly enhanced at 5 wt% NaOH, and then gradually decreased by the concentration rising due to structural destruction.

Mechanical Properties of Banana Fibers with Respect to Various Treatment as shown in Table (2)

| Fiber Sample | Tensile Strength (MPa) | Young's Modulus (GPa) | Elongation at Break (%) |
|---|---|---|---|
| Untreated Fibers | 391 ± 12 | 12.5 ± 1.1 | 2.8 |
| 5 wt% NaOH Treated | 542 ± 15 | 15.5 ± 0.9 | 3.2 |
| 10 wt% NaOH Treated | 485 ± 18 | 13.8 ± 1.4 | 2.5 |

Table 2 summarizes the mechanical properties of banana fibers under different treatment conditions. The correlation with mechanical results showed that fibers zelectively treated by 5 wt% NaOH produced the highest values of tensile strength and Young's modulus, confirming a relevant enhancing effect on the performance properties. The enhancement in load transfer at the fibre–matrix interface, due to higher surface roughness of the fibres, is attributed as the primary reason for this improvement. The results obtained here were in agreement with our previous studies [5], [11], [15] On the contrary the response of increasing NaOH concentration on mechanical properties showed a wholly different picture as upto10 wt% of NaOH was found to degrade the mechanical properoerties. These reductions in WHC have been attributed to structural degradation and almost complete disruption of the cellulose framework due to steam explosion pretreatment [12,13]. Similar observations are reported in the literature and attributed to the loss of strength of fiber due to extreme alkaline conditions ([6], [9], [21] Overall, these results corroborate controlled alkaline treatment is necessary for improving performance in natural fibers. Moderate treatment conditions are a sufficient balance between non-cellulosic parts removal and fiber integrity preservation, which is needed for sustainability and composite utilization [1], [22] while mechanical performance advancements mainly come from increased cellulose crystallinity, i.e. higher interfacial bonding. Although the removal of amorphous components enhances load transfer, substantial treatments destroy cellulose structure; these result in lower mechanical integrity and tensile strength (542 MPa) obtained was similar[41] to those reported in earlier studies (~500–600 MPa), confirming its efficacy [5], [16].

**Limitations**

All these results should be read with caution because there are several limitations in this study. The ongoing investigation just accounted for two NaOH focus levels and did not inspect the effect of treatment time and temperature that may assume an imperative part in fiber qualities. The fiber-scale approach might reduce the statistical significance because such small sample size and also the analysis performed at only fiber scale and not considering composite behavior. Future work will need to incorporate over a wider range of treatment parameters and other characterization methods including thermal analysis (TGA/DSC), moisture uptake, and long-term durability as well. It is also suggested to evaluate the performance of treated fibers in composite materials for better understanding.

**Discussion**

The improvements in mechanical properties show a close correlation with the interfacial bonding and improved cellulose crystallinity The removal of amorphous components like hemicellulose, lignin exposes the cellulose micro fibrils which enhance the overlap region causing the stress transfer to be more efficient. Nonetheless, strong alkalinity damages the structure of cellulose, leading to mechanical degeneration. Moderate chemical treatment enhances interfacial bonding but excessive treatment can successively degrade it [5]. These results are consistent with reported studies that indicate controlled alkali treatment remarkably improves the properties of natural fibers [3], [16].

## 4. Conclusion

The present study results show that the application of alkaline treatment is a key step to improve structural, chemical and mechanical properties of banana fibers. The 5 wt% NaOH treatment was also selected as the best condition because it eliminated hemicellulose and surface impurities while retaining cellulose. In comparison, a 10 wt% NaOH concentration leads to structural destruction and inferior mechanical performance due to the damage in cellulose network and consequently, results in better surface roughness and interfacial bonding as well as tensile properties. The relationship of the chemical modification, surface morphology and mechanical behavior highlights the efficiency of controlled alkaline treatment The mechanical properties reached seems to be reasonable and comparable with values previously reported in literature confirming the validity and credibility of results. Whether lemon or banana, these experiments indicate that treated banana fibers are a noble alternative as potential reinforcement material for green composites. The tensile strength value (542 MPa) stated here is within the range of 500–600 MPa previously reported, validating treatment

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