Enhancing Banana Fibre Properties for Waste Stabilization and Possible Industrial Applications through Chemical Modification

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Abstract

Natural fibres have emerged as sustainable alternatives to synthetic fibres because of their biodegradability, renewability, low density, and reduced environmental impact. Among these, banana fibres (*Musa sapientum*), obtained from agricultural waste, offer significant potential as reinforcement materials in composite applications. This study investigated the chemical extraction and structural modification of banana fibres to enhance their sorption and mechanical properties through sequential retting, scouring, bleaching, and mercerization treatments. The effects of bleaching time, temperature, and hydrogen peroxide concentration on fibre performance were systematically evaluated to establish optimum processing conditions. Moisture imbibition increased considerably following chemical treatment, indicating improved fibre surface activity and hydrophilicity. The highest moisture absorption capacity of 58.5% was obtained at a bleaching temperature of 100°C after 40 min of treatment. Fibres bleached with 5% and 10% hydrogen peroxide (H_2O_2) exhibited high equilibrium moisture absorption, while mercerized fibres processed under the same conditions recorded substantially higher equilibrium moisture contents of 80% and 90%, respectively. Mechanical evaluation further revealed that fibres bleached with 2% H_2O_2 and subsequently mercerized with 22% sodium hydroxide (NaOH) exhibited superior load–elongation characteristics compared with fibres treated using higher hydrogen peroxide concentrations (10% and 15% H_2O_2), indicating that excessive oxidant concentrations may adversely affect fibre integrity. Based on the experimental results, an effective bleaching condition of 2–5% H_2O_2 at 100°C for 40 min was established for achieving an optimal balance between sorption and mechanical performance. Overall, the study demonstrates that controlled chemical modification is an effective strategy for enhancing the functional properties of banana fibres, thereby promoting their utilization as sustainable reinforcement materials in polymer composites and other environmentally friendly engineering and industrial applications.

Keywords:
Banana fibres;
Chemical modification;
Mercerization;
Bleaching;
Natural fibre composites.

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1.0 INTRODUCTION

Concerns about global economic and environmental safety are greatly influencing research efforts to create new materials for varying industrial applications (Mutasim et al, 2018). A significant amount of these is derived from natural renewable resources to limit unwanted degradation endangering the environment. Natural fibres, are gaining acceptance for their renewability, low density, and relatively low cost. However, their large-scale cultivation is largely hinged on agricultural inputs, hence their preferred source is agricultural wastes such as the pseudo-stems of banana plants (Maryam et al, 2025). Their full biodegradability is key to eco-friendly composite applications (Kenned et al, 2020; Mavinkere et al, 2022).

Many researchers have further highlighted the potential of banana fibres in diverse applications (Pilien et al, 2022., Bekraoui, et al, 2022., Badanayak et al, 2023). Plant fibres are also being developed for the purpose of pollution control as modified fibres can selectively absorb oil from water (Akatwijuka , 2024). They are also reported to have great potentials to remove heavy metal ions such as$Cu^{2+}, Cr^{3+} and Zn^{2+}$from industrial effluents due to their ion exchange capabilities (Akatwijuka ,2024). The same report also indicated their possible conversion to activated carbon source for use as filters in the removal of colour from water.

Another most important characteristics of polymeric fibres that determine their performance is the strength (Jordan et al, 2017).

Among the many mechanical properties of fibres, tensile properties are probably the most frequently considered, evaluated and used industrially. This is because they are important indicators of the materials behaviour under load in tension (Jordan et al, 2017). Measurement of this property provides data on tensile yield strength, tensile strength at break, tensile modulus and elongation at yield and break. These properties are function of molecular structure and inter molecular organization (Bakri et al, 2017).

However, prominent limitations as the presence of weak components such as waxes and pectin in natural fiber cell walls coat the reactive functional groups hence inhibiting interaction with the matrix affecting product quality. This study aims to enhance the performance of Banana Fibre chemical modification, specifically its tensile strength and water absorption for possible industrial applications.

2. MATERIALS AND METHIODS

2.0 Preparation of Crude bark

The stem of a matured waste banana tree, obtained from a personal botanical garden was cut after the fruits were harvested. The stem was then cut into shorter logs of 25em in length and sliced into tiny pieces to facilitate drying. These were oven dried at $55°C$ overnight. This provided the bulk sample for retting and subsequent treatments.

2.1 **Chemical Treatments**

The treatment was performed according to Chalachew et al, (2025) and Temesgen (2019). However, they were modified with variations in process conditions. The procedures included retting, scouring, bleaching and mercerization.

2.1.I Retting of Crude bark

250ml of 10% ammonium oxalate solution was measured into a 400ml beaker. Sg of the dry material was inserted into the solution. The beaker and its contents were then placed on a heating mantle and heated to boiling.

After 45 minutes, the fibres were loosened from the lignin and other mucilaginous materials. The loosening or separation of the fibres was further facilitated by manual combing. The fibres were thoroughly rinsed under running water and oven dried at55℃for 20minutes. The dry reted fibres were then stored in nylon bags for further processing.

2.1.2 Scouring of Retted Fibre

A 1.0g. Sample of the retted fibre was weighed into a 250ml beaker and 150 ml of 2% NaOH was added. The mixture was then placed on a heating mantle and heated to boiling for 45minutes. During boiling, the fibres were kept under the solution by means of glass rods to prevent exposure. They were washed under running tap water and then oven dried at 55° for 20minutes.

2.1.3 Bleaching

The fibres were bleached wit H_2O_2in order to impart whiteness. 200ml of 2% H_2O_2 was measured and poured onto 0.5g of the scoured fibre. This was followed by the addition of 25ml of 5%NaOH and 0.5g each of Na_2SiO_4 and $MgSO_4$. The material was bleached at 100℃ for 40 minutes. The fibre was then washed with tap water and then dried at $55°C$ for 20mins. The procedure was repeated for 5%, 10% and 15% H_2O_2 for 50 minutes, 60 minutes at $60°C,\ 80°C\ and\ 100°C$.

2.1.4 Mercerization

For mercerization, 40ml of 22% NaOH was measured into a 150ml beaker and conditioned to 2"C in an ice bath. A 0.2g of the bleached fibre was then immersed into the solution and allowed to stay for 45 minutes. The fibres were then removed and several times washed in tap water and dried at 55° for 20 minutes.

2.1.5 Property Evaluation

Water absorption and tensile strength of the fiber were chosen as response variables because they are the ones highly affected by treatment conditions compared to other properties.

2.1.6 Determination of Moisture Imbibition

Moisture retention capacity of both crude and samples treated under identical conditions were determined. Ig of dry sample was soaked in a 100ml of distilled water, in a 250ml beaker and allowed to equilibrate for 5 minutes. It was removed and the excess water moped up with dry filter papers. The sample was then placed in the oven at$40°C$and the weight lost was monitored at 5 minutes intervals until constant weight was obtained.

2.1.7 Measurement of Tensile Strength

For the tensile test measurements using the Instron tester, the samples were prepared to give the guage length of 5em, with extra length to allow for griping by the jaws.

A cross head speed of 50mm/min and chart speed of 100mm/min suitable as test conditions were determined. The corresponding change gears and a full scale deflection of 500g were installed. Each prepared fibre specimen was inserted in the grips or jaws of the instrument and clamped in place by means of an applied compressed air. The pen and cross head functions were switched on simultaneously and the instrument response was plotted by the chart recorder. From this, the load-elongation data for each specimen was extrapolated.

3.0 Results and Discussion

3.1.1 Effects of Retting:

Retting is controlled degradation of plant stems to break down ligins, pectins and hemicelluloses holding the bundles of bast cells to allow the fibres to be separated from the stem. Ammonium oxalate was used to achieve chemical retting. Here the fibres are delignified and are loosened from the component matrix. The effect of the delignification may be attributed to the oxalic acid (from ammonium oxalate dissociation) degrading the impurities. The resulting fibres are brown, clean, strong and extensible.

On the whole, the process of retting with ammonium oxalate was seen to reduce the strength of the bundles by weakening the interstacies between the fibres within the bundles. It however provided more separation of the fibres, thus increasing fineness. These findings therefore suggest that ammonium oxalate could be an ideal retting agent.

3.1.2 Effects of scouring

During scouring, the fibres were treated with dilute sodium hydroxide to remove waxes and fats. Though they still looked brown, they show strong adhesion amongst themselves and they tend to form a mat when dried. This is suspected to be due to the hydrolysis of these mucilaginous materials into soluble compounds that could act like binders.

3.1.3 Effects of bleaching

At bleaching, the liquor was observed to froth excessively. This was however controlled by the addition of anti- bumping granules. The bleached fibres were white (fig 3.1c). The degree of whiteness was seen to increase bleaching ttime and concentration of bleaching agent. With increasing severity of further removal of inherent natural coloured pigments and other mucilaginous. The whitening effect is due to matters. These impurities constitute hydrophobic blockage and greatly influenccs fibre properties (Temesgen (2019)). It is therefore likely that fibre qualities such as strength, lustrous, and flexibility will increase as they are removed.

3.1.4 **Effects of Mercerization:**

The mercerized samples were stronger and more extensible. In addition, they wereglossy and lustrous. This treatment is also reportedtocause extensive broadening and widening of the amorphous regions in the fibre structure. The material is therefore expected to be more absorbed.

3.1.5 Moisture Imbibition:

The moisture sorption data measured at 78% RH and 33℃ for the crude, retted, scoured, bleached and mercerized fibres, are represented in a graphical plot as shown in figures 3.2a-d. In figure 3.2a, the absorption curve of the crude rises slightly upon uptake of water and falls within a short time. It means that the water taken up could not be retained and so was completely lost. It is therefore inferred that the water was merely adsorbed on the fibre surface. This is being expected as the crude fibre contains impurities, which constitute hydrophobic blockage. In the retted fibre, part of the impurities has been removed, so the material is able to absorb. This is evidenced in figure 3.2b. It rises above that of the crude before falling to the equilibrium value.

Figure 3.2b also depicts the sorption capabilities of the retted and scoured fibres The scoured showed higher absorption peaks and retention capabilities than the crude (Yimer, T. & Gebre, A, 2023). but lower than that of retted. This may be due to increased removal of impurities including the hydrolysis of fats and waxes. The hydrolysis products are suspected to be responsible for the cementing of the scoured fibres, thus blocking the pores in the fibre structure. This is seen to limit water permeability and hence low sorption capacity.

The peaks of the bleached material were lower than those of the retted and scoured and fastly attain equilibrium (Fig 3.2c. At mcrccrization, the fibres are said to have broader and expanding amorphous regions which is responsible for many properties such as moisture sorption. Fig 3.2d shows the sorption peaks for the mercerized fibres. The high peaks indcate greater sorption capabilities, in accordance to literature reports.

It can also be seen that the equilibrium moisture content is high and attained within short time. The fibres bleached with 10%H_2O_2at$100°C$in 40min. and mercerized gave the highest peaks and greater equilibrium value (Bekele et al, 2022). Generally, the mercerized samples are seen to have high absorption peaks, shorter desorption times and large equilibriom moisture content values. These observations suggest that the amorphous regions in the fibre structure have been greatly increased.

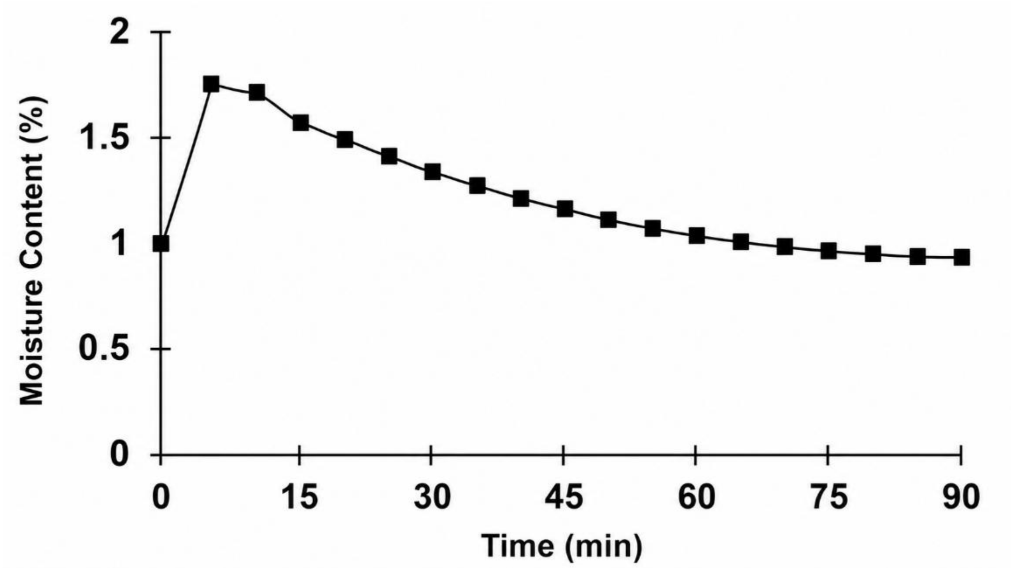

Figure 3.2a: Moisture imbibition curve for crude fibre

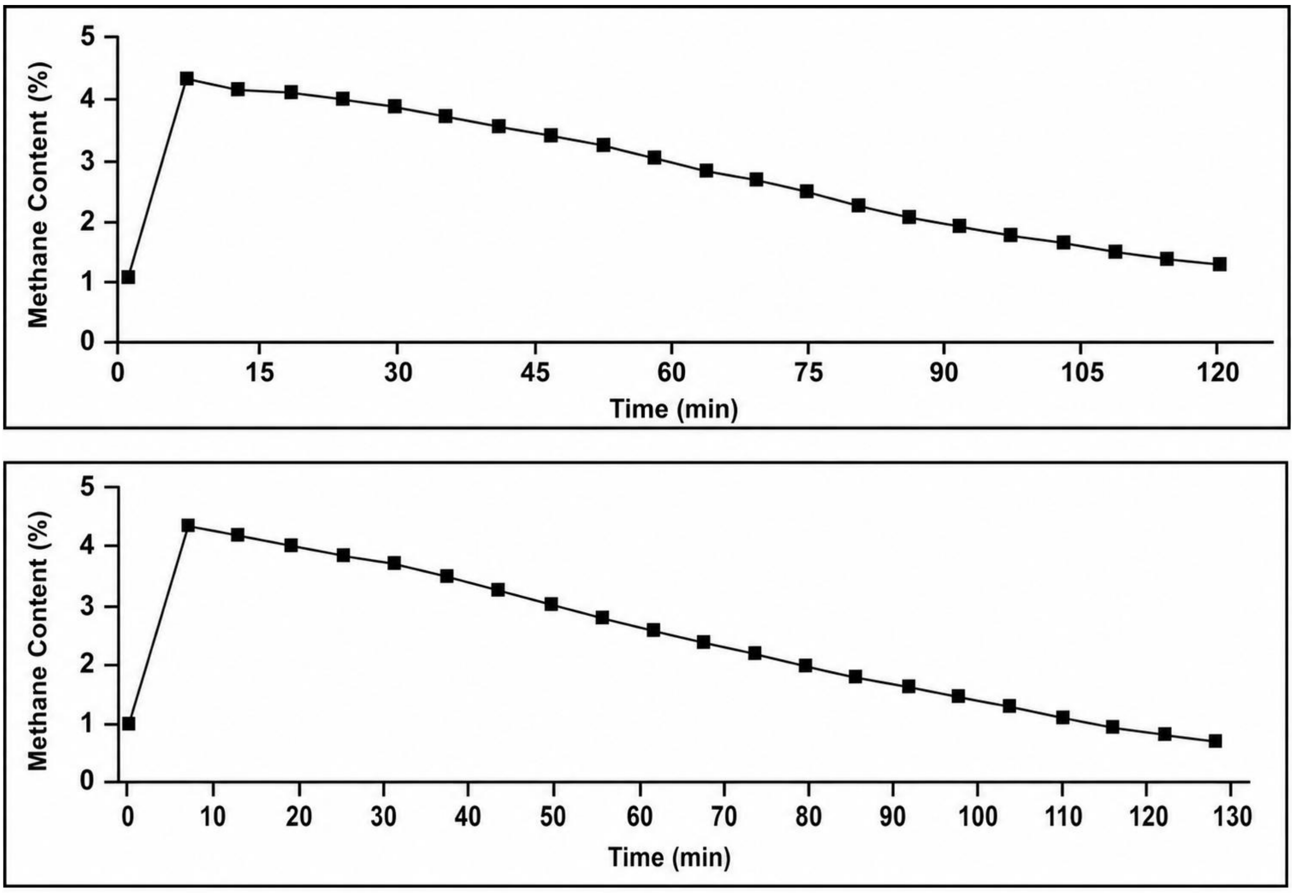

Figure 3.2b: Effects of Retting and Scouring on moisture imbibition or fibre

Key: Above: Retted fibre

Below: Scoured fibre

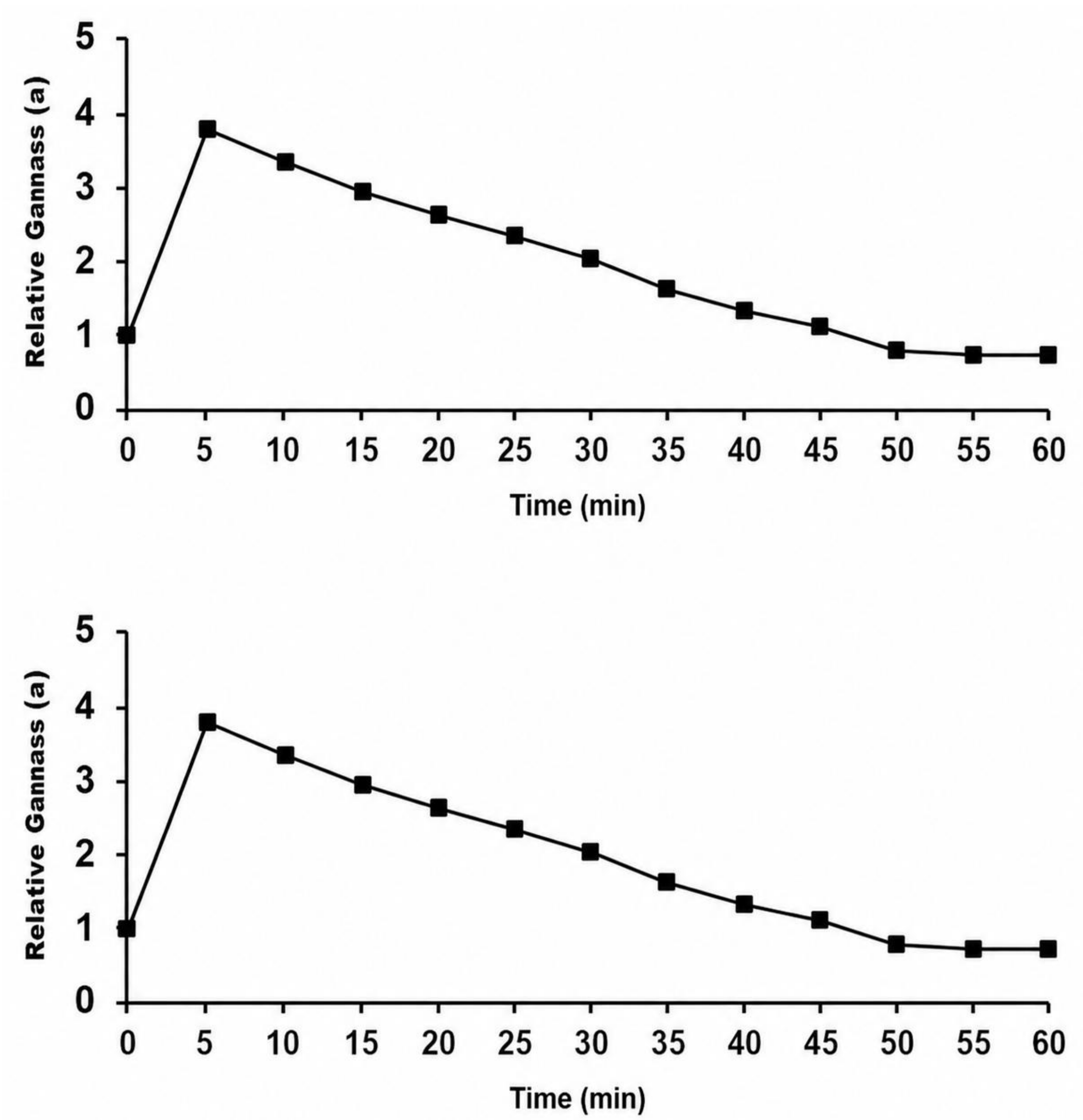

Figure 3.2c: Effects of Bleaching Temperature and Time on Moisture

Imbibition of fibres.

KEY: Above: bleached with 5% 11202 at 100^{0}C

Below: bleached with 10% 11102 100^{0}C

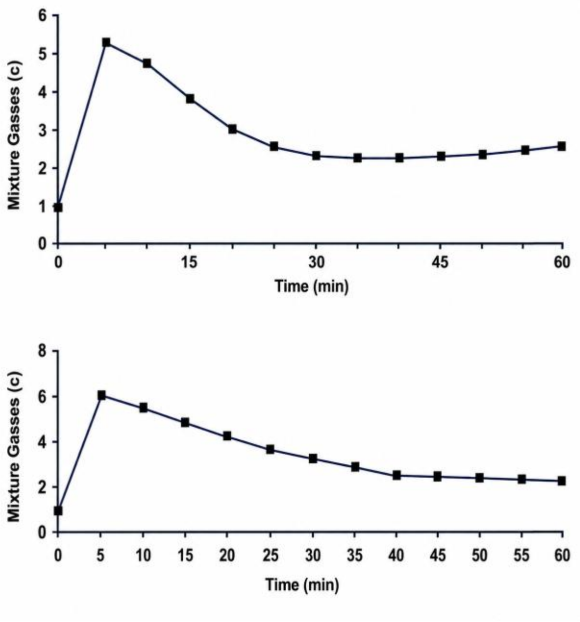

Figure 3.2d: Effects of Mercerization on Moisture Imbibition of Bleached Fibres

Key:

Above:Bleached with 5%$H_2O_2$and Mercerized

Below:Bleached with 10%$H_2O_2$and Mercerized

3.3 Mechanical Properties:

Fibres are subjected to a multitude of mechanical deformations: stretching, abrasion, bending, twisting and shearing particularly during conversion processes into fabrics. Therefore, they are required to possess sufficient strength. This is a measure of the steady force necessary to break the fibre and is given by the maximum load developed in a tensile test (Dejene, B. K, 2024).

Tensile tests conducted for the load-elongation data of the fibres treated under different conditions of time, concentration and temperature are given in tables 4.3a and 4.3b. From the data it can be observed that the influence of bleaching time was more effective at lower temperatures. Under these conditions, the fibres showed decreasing load and elongation values with increase in concentration of bleaching agent and time of bleaching. The consequence is that fibre strength also decreases. Along **the** same trend however, the mercerized samples showed higher values compared to the bleached ones, signifying greater strength and more extensibility (Dejene, B. K, 2024).

The decrease in strength suggests that the fibres are possibly degraded at higher concentrations (Ren, Z. et al, 2019). Therefore, they can be bleached and mercerized at between 2-5%concentrations of bleaching agent for a period of not more than one hour without fear of degradation.

Table 3.3a: Effects of bleaching time on fibre strength

Sample Code	treatment conditions	Average Load (KgF)	Average Elongation (mm)
BH1$_a$	2% H_2O_2 40 min bleached	0.07	1.31
BH1$_b$	" " 50 min "	0.05	1.08
BH1$_c$	" " 60min "	0.05	1.07
BH1$_d$	2% H_2O_2 40 min mercerize	d 0.27	3.80
BH1e	" " 50 min "	0.25	3.50
BH1$_f$	" " 60 min "	0.14	2.20
BH2$_a$	5% H_2O_2 40 min bleached	0.06	1.30
BH2$_b$	" " 50 min "	0.05	1.00
BH2$_c$	N " 60 min "	0.04	0.33
BH2$_d$	5% H_2O_2 40 min mercerized	0.20	2.66
BH2e	" " 50 min "	0.19	2.33
BH2$_f$	" " 60 min "	0.13	2.00
BH3$_a$	10% H_2O_2 40 min bleached	0.04	1.00
BH3$_b$	" " 50 min "	0.04	0.60
BH3$_d$	10% H_2O_2 40min mercerized	0.06	2.33
BH3$_e$	" " 50min "	0.05	2.00
BH3$_f$	" " 60min "	0.04	2.00
BH4$_a$	15% H_2O_2 40min bleached	0.03	1.00
BH4$_b$	" " 50 min "	0.02	0.50
BH4c	" " 60 min "	0.02	0.50
BH4$_d$	15% H_2O_2 40min mercerized	0.03	2.16
BH4$_e$	" " 50 min "	0.03	2.13
BH4$_f$	" " 60 min "	0.03	1.00

Table 3.3b: Effects of bleaching temperature on fibre strength

Sample Code	treatment conditions	Average Load (KgF)	Average Elongation (mm)
BH5a	2% H_2O_2 60℃C bleached	0.08	0.80
$BH5_b$	" 80^{0}C "	0.07	0.80
BH5c	" 100℃ "	0.06	0.50
$BH5_d$	2% H_2O_2 60℃C mercerized	0.20	3.00
BH5e	" 80℃ "	0.20	3.00
$BH5_F$	" 100℃ "	0.14	2.0
BH6a	5% H_2O_2 60℃C bleached	0.07	0.5
BH6b	" 80℃ "	0.05	0.3
BH6c	" 100℃ "	0.04	0.1
$BH6_d$	5% H_2O_2 60℃C Mercerized	0.19	3.20
BH6e	" 80℃ "	0.18	3.16
$BH6_f$	" 100℃ "	0.17	3.16
BH7a	10% H_2O_2 60°Cbleached	0.06	0.20
$BH7_b$	" 80℃ "	0.06	0.20
$BH7_c$	" 100℃ "	0.03	0.16
$BH7_d$	10% H_2O_2,60°℃C mercerized	0.16	2.50
$BH7_e$	" 80℃ "	0.12	1.67
$BH7_f$	" 100℃ "	0.10	1.33
$BH8_a$	15% H_2O_2,60° bleached	0.04	0.50
$BH8_b$	" 80℃ "	0.03	0.16
$BH8_c$	" 100℃ "	0.02	0.50
$BH8_d$	15% $H_2O_2$60℃ mercerize	d 0.04	2.10
$BH8_e$	" 80℃ "	0.04	1.50
$BH8_f$	" 100℃ "	0.04	1.43
Retted	10% amm.oxalate 40 min	0.04	0.00
Scoured	2% NaOH 40 min	0.04	0.00

Conclusions

The findings of this study demonstrate that chemical modification is an effective approach for improving the physical, mechanical, and sorption characteristics of banana fibres. Surface treatments involving retting, scouring, bleaching, and mercerization significantly altered the fibre structure, leading to enhanced moisture absorption and improved load–elongation behaviour. The observed improvements indicate that controlled chemical processing increases fibre surface activity and interfacial bonding potential, thereby making the fibres more suitable for engineering and environmental applications.

The results further reveal that the extent of fibre modification depends on treatment conditions, including reagent concentration, temperature, and processing time. Appropriate optimization of these parameters is therefore essential to achieving the desired balance between mechanical integrity and sorption performance. The enhanced properties obtained after bleaching and mercerization demonstrate the potential of chemically modified banana fibres to outperform untreated fibres in demanding applications.

Overall, this work confirms that chemical surface modification is a viable and sustainable strategy for upgrading agricultural waste into high-value functional materials. The improved performance of treated banana fibres makes them attractive as renewable reinforcements in polymer composites, eco-friendly building materials, filtration media, adsorption systems, packaging materials, and other environmentally sustainable applications. The study contributes to the growing body of knowledge promoting the valorization of natural fibres and supports the transition toward greener, biodegradable alternatives to synthetic materials. Future research should focus on optimizing treatment protocols, evaluating long-term durability, and investigating the performance of chemically modified banana fibres in advanced composite systems and industrial-scale applications.

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