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Structural modification of pineapple leaf fiber by Chemical and Mechanical methods

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Abstract — **Pineapple leaf fibre (PALF) emerges as a sustainable alternative to synthetic fibres, yet its inherent hydrophilicity and biocompatibility limitations necessitate surface modifications for broader applications. This study investigates the effects of chemical treatments—alkali (NaOH) and bleaching (H_2O_2)—on PALF's structural, mechanical, and crystalline properties. Fibers extracted from Ghanaian pineapple leaves underwent decortication, urea pretreatment, and variable NaOH concentrations (2M and 6M), followed by peroxide bleaching. Fourier Transform Infrared Spectroscopy (FTIR) confirmed the effective removal of lignin and hemicellulose in chemically treated samples, while X-ray Diffraction (XRD) revealed enhanced crystallinity (peaks at $2\theta \approx 22^0$ and 16^0) due to delignification. Mechanical processing retained amorphous content, underscoring the superiority of chemical methods. Alkali-treated PALF exhibited tensile strengths up to 1620 MPa, though excessive NaOH compromised fiber integrity. Bleaching improved whiteness but reduced tensile strength, highlighting trade-offs. The findings demonstrate that optimized chemical treatments (2M NaOH, 60% H_2O_2) enhance PALF's compatibility with polymer matrices, enabling applications in composites, aerospace, and biomedical fields. This work advances sustainable material science by valorizing agricultural waste while addressing critical gaps in natural fiber modification.**

Keywords— Pineapple leaf fibre, agricultural waste, chemical treatment, tensile strength.

I. INTRODUCTION

The quest for sustainable, environmentally stable, and friendly practices globally has led to the pursuit of innovative ways of using natural resources. "Sustainable development," as defined by the World Commission on Environment and Development of the United Nations, is a development that is targeted to meeting the current needs of the present generation and not in any way hindering future generations from realizing their own needs [1].

The preference of natural fibers in recent years to synthetic fibers due to unique properties like bio-renewability and eco-friendliness has sparked research into the production of these fibers to meet demands. Notwithstanding the numerous advantages of natural fibers, some other properties that have accounted for some disadvantages like biocompatibility and hydrophilic properties, can be overturned by modifying the surface properties of the fibers [2, 3]. These modifications include chemical treatment to alter the surface properties of the fibers [4]. Chemically treated fibers have been employed successfully in composite materials, notwithstanding their low densities compared to fiberglass construction and engineering fields, textiles, biomedical engineering and related fields, biopolymers, biosensors, and smart packaging. The use of natural fibers would reduce the effects of polluting our environment from waste that can be regenerated into useful products [5].

The pineapple fruit which is a delicacy for most Ghanaian families over the years was introduced into Ghana in 1548 by the Portuguese on the west coast of Africa. Pineapple farming first began in Samsam located in the Greater Accra Region [6]. Pineapple, among other products, was classified as a non-traditional export (NTE) product between the 1970s and mid-1980s. This revolutionized the cultivation of pineapple in the country [7].

There has been a decline in pineapple production in the country due to the decline in exports in recent years. This decline can lead to farmers switching to other cash crops [8], other sources of revenue can be tapped into. In the cultivation of pineapple, a typical example of such areas that can also generate a substantial amount of revenue is the conversion of the pineapple leaves into bio-friendly fibers [6].

In recent years, many people have started to focus on sustainable practices, leading to increased interest in using natural fibers instead of synthetic ones. This research examines the use of pineapple leaves as an eco-friendly option for fiber production. Pineapple fiber is a renewable, biodegradable, and locally derived material that may be able to lessen the ecological load as society struggles with the environmental effects of rapid fashion and non-biodegradable materials. The present desire for a more peaceful coexistence with nature is reflected in the resurgence of pineapple fiber as an alternative [23]. Local, cottage-scale pineapple fiber extraction and processing businesses can boost rural economies and empower communities [24].

The mechanical characteristics of pineapple fiber set it apart from other natural fibers and are one of its distinguishing

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characteristics. According to a preliminary study by Jain et al, pineapple fibers have a remarkable tensile strength that is on par with some traditional textile fibers. Their long, fine structure also increases their potential as reinforcements in composites, which opens up possibilities in the construction, automotive, and even aerospace industries. Pineapple fiber has the potential to become a game-changing resource through the interaction of these mechanical qualities and creative engineering [25]. The use of Pineapple leaves for fiber has important and wide-ranging effects on the ecosystem. Reducing waste, promoting the circular economy, and minimizing the need for new land, water, and resources are all achieved by turning agricultural byproducts into valuable resources. Furthermore, compared to its synthetic competitors, pineapple fiber's end-of-life impact is far less harmful due to its biodegradability [26].

In mechanical extraction, fiber-extraction methods significantly impact fiber yield and type, affecting filament construction, synthetic synthesis, and characteristics [9, 10] In chemical extraction, alkali treatment is a standard substance therapy for regular strands, transforming cellulose strands from translucent to antiparallel [11]. Factors like filaments, fixation, salt type, temperature, and treatment time affect the transformation. NaOH is used for alkali degumming PALF, removing gum content, and treating filaments with 2-4% [12, 13]. Degumming is a process that removes hemicelluloses, lignin, wax, and oils from PALF fibers. It increases strength, pliable modulus, and permeability compared to untreated strands. Degumming can also be achieved by combining acids with a cleaner, and the decorticated filaments separate [12]. Degumming separation is a simple and environmentally friendly process, but poor execution can potentially harm the cellulose constituents of the fiber.

After filaments are removed from leaves, strands are connected by sticky materials, including synthetically produced gum content. This gum deterrent prevents moisture handling, so removal is essential. Degumming, using proteins, synthetic chemicals, or microbes, forces gum out, improving fiber's mechanical qualities like fineness, luster, brilliance, and moisture retention this process is called degumming PALF [14, 15].

For bleaching, the paper industry uses hydrogen peroxide (H_2O_2) as an oxidative agent to delignify lignin and remove hemicellulose [16]. This process improves PALF's whiteness but also produces oxidative radicals, particularly per hydroxyl anion (HOO–), which cause color shifts and affect the conjugated lignin structure [17]. PALF samples bleached with 60% H_2O_2 showed 8.7 and 38.7% removal rates, with H_2O_2 bleaching increasing fineness and decreasing tensile strength. Bleached PALF yielded weaker, homogeneous, and extensible yarn, while raw PALF showed high extension and low strength.

The goal of this study is to thoroughly investigate the many facets of pineapple fiber, including its chemical, mechanical characteristics, possible uses, and extraction techniques. Additionally, the research further examines the effects of treatments of PALFs on the appearance and properties. The results demonstrated that surface treatments will improve the mechanical properties of PALF.

II. MATERIALS AND METHODS

A. Materials

The apparatus used in this study included beakers, a thermometer, an oven, and a hot plate. The reagents utilized were urea, hydrogen peroxide (H_2O_2), sodium hydroxide (NaOH), and tap water.

B. Methodology

Pineapple leaves, an agricultural byproduct of pineapple cultivation, contain valuable fibers that can be extracted and processed for various applications. This study outlines the procedures for the extraction and chemical treatment of PALF to enhance its suitability for composite preparation.

The pineapple leaves were collected from local market sellers at Abinkyi in Kumasi Ghana. The leaves were manually separated from the fruit with special care to prevent damage and preserve fiber integrity. The separated leaves then underwent manual decortication, using a coconut shell to remove the waxy outer layer and expose the fibrous structure. The extracted fibers were thoroughly washed with tap water to remove surface impurities and were then sun-dried to achieve optimal moisture reduction.

The decorticated leaves were immersed in a urea solution (20 g of urea dissolved in 1000 mL of distilled water) for seven days. After the treatment period, the fibers were separated, washed, and sun-dried for 24 hours. Subsequently, the urea-treated fibers were divided into two samples, A and B. Sample A was treated with a 6M NaOH solution, while Sample B was treated with a 2M NaOH solution. Both samples were immersed in the respective NaOH solutions at 70°C for 2 hours in a water shaker bath. The treated fibers were then dried in a blast oven at 60°C and stored for further processing.

To improve fiber whiteness and purity, both Samples A and B underwent a bleaching process using 60% hydrogen peroxide (H_2O_2) for 2 hours. The bleached fibers were then dried and stored for composite preparation. Additionally, Sample AA was subjected to deep eutectic solvent (DES) processing to enhance fiber modification, while Sample BB underwent mechanical processing, including retting, scraping, and decortication, to obtain fibers without chemical modification.

Finally, all treated PALF samples (A, B, AA, and BB) were cooled to room temperature and stored in a controlled environment for composite fabrication. The processed fibers exhibited enhanced characteristics suitable for various applications.

III. RESULTS AND DISCUSSION

A. FTIR Analysis

Four PALF samples; chemically treated (Samples A and B), Deep Eutectic Solvent (DES) processed (Sample AA), and mechanically processed (Sample BB), were analyzed using Fourier Transform Infrared Spectroscopy (FTIR) to assess the chemical modifications induced by different treatment methods (Figure 1). Samples AA and BB were derived from

Samples A and B, respectively, before DES and mechanical processing.

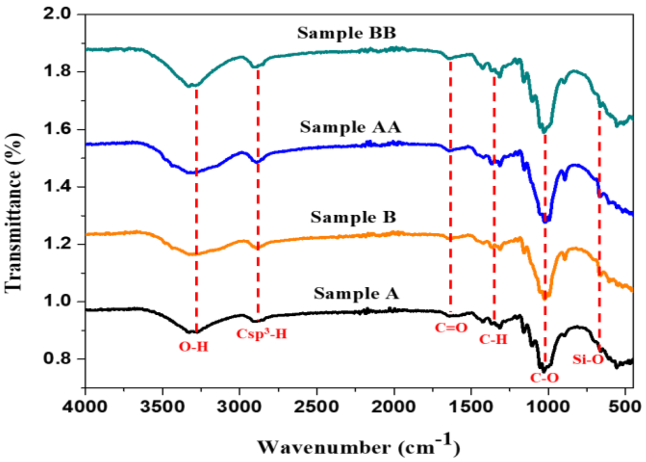

Fig. 1. FTIR spectra of Sample A and Sample B (which were treated with NaOH and H_2O_2), Sample AA (which was processed using the DES method), and Sample BB (which underwent mechanical processing).

A prominent broad absorption around 3300 cm^{-1}, attributed to O-H stretching of hydroxyl groups in cellulose and hemicellulose, was observed across all samples. This peak was sharper in chemically treated Samples A and B, indicating enhanced cellulose exposure due to the effective removal of lignin and hemicellulose [18, 19].Sample AA retained a broad O-H band, suggesting hydrogen bonding reorganization from DES interaction, while Sample BB exhibited a weaker O-H signal, consistent with limited chemical modification.

Carbonyl (C=O) stretching near 1730 cm^{-1}, associated with hemicellulose and lignin ester groups, significantly weakened in Samples A and B due to delignification and hemicellulose degradation. This peak remained more pronounced in Samples AA and BB, supporting the absence of hydrogen peroxide treatment and suggesting partial retention of hemicellulose [20].

Aromatic lignin peaks at ~1600 cm^{-1} and ~1510 cm^{-1} were notably reduced in chemically treated Samples A and B, confirming peroxide-induced delignification [21]. Conversely, Samples AA and BB displayed clear signals in these regions, indicating persistent lignin structures. The presence of these peaks in Sample AA, despite being derived from a bleached fiber, suggests that DES treatment modifies fiber chemistry differently and lacks the oxidative power of peroxide.

The cellulose backbone fingerprint region (~1250-1000 cm^{-1}), comprising C-O-C and C-OH vibrations, was evident in all samples but was most intense in Samples A and AA. This reflects higher cellulose purity, especially in AA, where DES facilitated cellulose enrichment without extensive oxidation. In contrast, Sample BB showed broader, less intense peaks, indicative of a more amorphous structure with greater non-cellulosic content.

Lastly, the region between 800 to 600 cm^{-1}, attributed to Si-O stretching and inorganic matter, diminished in Samples A and AA due to effective removal of mineral components during chemical treatments. However, this region remained prominent in Sample BB, reinforcing that mechanical processing retains more silica and other inorganic residues [22].

B. XRD Analysis

The crystallinity of pineapple leaf fiber (PALF) samples subjected to different treatment methods was investigated using X-ray Diffraction (XRD), as presented in Figure 2. The diffraction patterns of chemically treated Sample B and mechanically processed Sample BB reveal significant differences in their crystalline structures.

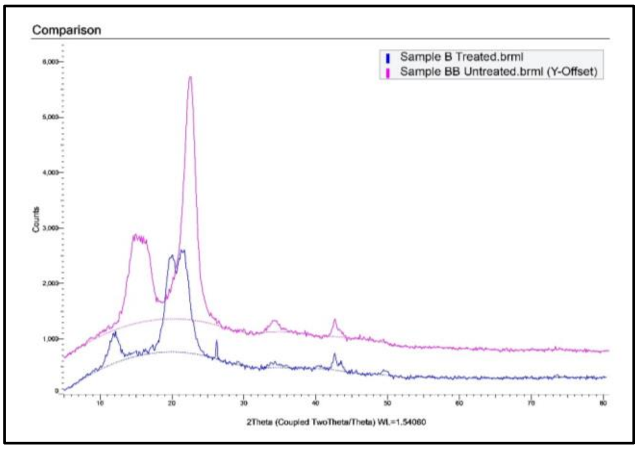

Fig. 2. X-ray diffraction (XRD) patterns of chemically treated pineapple leaf fiber (Sample B) and mechanically processed fiber (Sample BB).

Sample B, treated with a combination of alkaline and hydrogen peroxide solutions, exhibits sharper and more intense diffraction peaks, particularly around $2\theta \approx 22°$ and $2\theta \approx 16°$, which correspond to the characteristic reflections of cellulose [23]. These well-defined peaks indicate a higher degree of crystallinity, suggesting the effective removal of amorphous constituents such as lignin and hemicellulose. The increase in crystalline cellulose regions is attributed to chemical delignification, which enhances structural ordering within the fiber matrix.

In contrast, Sample BB, derived from Sample B but processed through purely mechanical means (retting, scraping, and decortication), shows broader and less intense peaks in the same regions. This indicates a lower degree of crystallinity and a higher content of amorphous material, consistent with the retention of non-cellulosic components such as lignin and hemicellulose. The diffuse nature of the peaks suggests that mechanical processing alone does not sufficiently alter the microstructure to promote cellulose crystallinity.

These observations are consistent with FTIR analysis, which also showed greater removal of non-cellulosic components in chemically treated samples. Overall, the XRD results confirm that chemical treatment significantly enhances the crystalline structure of PALF by eliminating amorphous fractions, thereby improving its suitability for high-performance composite applications.

IV. Conclusion

After being successfully extracted from pineapple leaves, the PALF was treated with 60% H_2O_2 and different alkali concentrations. FTIR images demonstrated and validated the improvement in PALF's crystalline characteristics as well as the removal of lignin and hemicellulose (amorphous phase). After being successfully extracted from pineapple leaves, PALF was treated with 60% H_2O_2 and various alkali concentrations. FTIR demonstrated and validated the improvement in PALF's crystalline characteristics as well as the removal of lignin and hemicellulose (amorphous phase). These spectroscopic results were further corroborated by the high UTS recorded for the alkali-treated PALFs, which ranged from 1090 to 1620 MPa. Although the high concentrations of NaOH improved the crystallinity and size of the PALF crystallite, it enhanced the mechanical strength and stiffness of the fiber just to a limit, after which the fiber strength and stiffness drastically decreased. It was revealed that fiber strength and stiffness are not only enhanced by increased crystallinity and crystallite size, but also by the intermediate bond between adjacent crystalline chains.

Treating PALF with NaOH and H_2O_2 can improve its properties and increase its compatibility with polypropylene (PP) matrix. By removing gum, hemicellulose, and lignin from the fiber surface and increasing its cellulose content, treating PALF with NaOH can also improve its mechanical and thermal properties, while treating PALF with H_2O_2 can bleach the fiber and make it whiter and brighter, which can improve its aesthetic appearance and decrease its water absorption. The optimal concentration, temperature, and time of the chemical treatment should be determined based on the desired properties of PALF and its applications. The article suggests that 2M NaOH and 60% H_2O_2 are suitable for PALF treatment. This work further helps to understand the processing conditions that could potentially allow the use of this material in a variety of matrixes for applications ranging from aerospace, paper industry, and biomedical applications. The FTIR analysis showed that the alkali treatment reduced the hemicellulose and lignin components of PALF, which resulted in increased cellulose content and improved compatibility with PP matrix. The FTIR spectra revealed the changes in the functional groups of PALF after the alkali treatment, such as the reduction of OH, CH, and CO groups and the increase of C=O and C-O-C groups. XRD analysis showed that the alkali treatment increased the crystallinity index of PALF, which indicated a higher degree of order and orientation of the cellulose chains. The XRD patterns also showed the changes in the crystal structure of PALF after the alkali treatment, such as the shift of the peak positions and the decrease of the peak intensities.

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