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The influence of NaOH concentration on the mechanical properties of *Corypha gebanga* fiber-reinforced composites

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Textile composites can be manufactured utilizing both synthetic and natural fibers, such as *Corypha gebanga* fiber, being a viable option. The weaving of *Corypha gebanga* fiber with cotton thread in a plain weave configuration enables its application as a reinforcement material in textile composites involving a resin matrix. This research aims to investigate the mechanical characteristics of plain woven *Corypha gebanga* fiber textile fabric-reinforced polymer hybrid composites made from epoxy resin. This study utilized four different variations: a control group without any treatment, and three treatment groups using solutions with NaOH concentrations of 2.5%, 5%, and 7.5%. The result showed that NaOH concentrations above 2.5% seem to have a detrimental effect, as indicated by the gradual decrease in mechanical performance observed in the 5% and 7.5% NaOH-treated specimens. The decrease in tensile strength suggests that prolonged exposure to alkaline conditions leads to permanent alterations in the cellulose structure and morphology. The optimal concentration of NaOH for maximum mechanical performance enhancement is found to be 5%, which balances the removal of impurities and the avoidance of excessive fiber damage. Microscopy image analysis showed that fiber pullout occurred in all specimens tested that were cut in the direction of the warp during tensile testing. The onset of fracture was characterized by the resin breaking initially, followed by the fibers stretching and ultimately breaking.

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1. Introduction

Composites refer to materials created through the combination of two or more distinct materials, aiming to enhance the mechanical properties of the resulting materials [1–5]. Within the domain of composite science, a recent category termed textile composites have surfaced. This type of material involves the manipulation of fibers—be they natural or synthetic—into a fabric-like sheet identified as a mat [6–9]. Subsequently, this mat is integrated with resin to generate a fiber-reinforced composite, tailored to specific dimensions and criteria. In the evolution of composite materials, there has been a progression from the traditional 2-dimensional (2D) flat mats to the contemporary development of 3-dimensional woven (3D woven) mats [10, 11]. Woven materials are formed by intertwining warp threads vertically and weft threads horizontally [12, 13]. The specific arrangement of these warp and weft threads is dictated by various weave patterns such as plain weave, twill weave, and satin weave. While 2D weaving is relatively simple to manufacture and cost-effective [14], it tends to produce irregularities like notches or undulating shapes at fiber intersections. These irregularities have an impact on the structural integrity and strength of the resultant composite material [15, 16].

The fiber derived from *Corypha gebanga*, a plant species, is produced through the twisting and weaving of palm fibers obtained from the processing of palm leaves [17, 18]. In comparison to fibers fabricated from synthetic fibers, the resultant *Corypha gebanga* fiber exhibits inferior breaking strength and elongation properties [19]. Furthermore, this fiber is prone to susceptibility to damage caused by bacterial decay processes. An avenue for enhancing the mechanical properties of the *Corypha gebanga* fiber involves employing treatments such as soaking the fiber in solutions containing chitosan. Chitosan, a biopolymer derived from chitin found in crustacean exoskeletons, has garnered attention for its potential to improve the characteristics of natural fibers [20]. By subjecting the *Corypha gebanga* fiber to a soaking process with chitosan-based solutions, a positive impact on its mechanical attributes becomes apparent. The interaction between chitosan and the *Corypha gebanga* fibers leads to a potential reinforcement effect, augmenting the breaking strength and resistance to degradation caused by bacterial decay [21–23].

This treatment strategy aims to mitigate the inherent weaknesses of *Corypha gebanga* fiber by enhancing its mechanical strength. The chitosan treatment offers a viable approach to address the deficiencies observed in natural fiber-based fibers, potentially rendering the *Corypha gebanga* fiber more durable and closer in performance to fibers composed of synthetic fibers [24, 25]. Through the modification of the *Corypha gebanga* fiber's structural characteristics via chitosan treatment, this method stands as a promising means to elevate the overall mechanical quality and resilience of natural fiber-derived fibers, contributing to their practical utility and longevity in various applications. During the process of creating a composite involving the blending of *Corypha gebanga* fiber yarn and epoxy resin, the inherent mechanical weaknesses and flammability of *Corypha gebanga* fiber can potentially undermine the overall mechanical integrity of the resulting composite material [26]. To address this concern and enhance the mechanical properties of the composite, a treatment involving a solution of NaOH (Sodium Hydroxide) was developed [20].

The application of a 5% NaOH solution has been recognized for its effectiveness in strengthening the mechanical characteristics of biocomposites reinforced with sisal fiber [27]. This is attributed to the capacity of NaOH to selectively remove the amorphous regions present in sisal fibers, consequently enhancing the adhesion between the fiber constituents and the resin matrix. This enhanced adhesion is pivotal in augmenting the overall mechanical performance of the composite. Alkaline solution treatments, such as NaOH at specific concentrations, have demonstrated the potential to significantly enhance the mechanical properties of materials [28]. By utilizing NaOH treatment on *Corypha gebanga* fiber yarn prior to its incorporation into the composite, the elimination of amorphous elements within the rope's fibers may lead to improved adhesion with the epoxy resin. This, in turn, can enhance the mechanical strength and durability of the resulting composite material, mitigating the weaknesses associated with the natural fiber and potentially elevating its performance to a level closer to that of synthetic fiber-reinforced composites.

Based on previous literature reviews, this research aims to investigate the mechanical characteristics of plain woven *Corypha gebanga* fiber textile fabric-reinforced polymer hybrid composites made from epoxy resin. In this research, the following aspects are considered: Fiber sequence: The arrangement of fibers in the textile composite can affect the mechanical properties of the material. Understanding the impact of fiber sequence on the mechanical characteristics of the composites is crucial for optimizing the performance of the final product. Textile reinforcement: The use of textile reinforcement, such as woven fan palm, can improve the mechanical properties of the composites. Polymer resin: The choice of resin used in the composites plays a significant role in their mechanical characteristics. Epoxy resin is a type of polymer resin that has been used in various applications, including aerospace and automotive industries, due to its desirable properties. However, most existing research has focused on natural fibers like sisal, jute, and flax, with limited exploration of *Corypha gebanga* fibers as reinforcements in polymer composites. Furthermore, the potential of using woven textile fabrics made from *Corypha gebanga* fibers as reinforcement has not been extensively investigated.

Corypha gebanga fibers have a complex hierarchical structure. The main components of these fibers are: Cellulose: The primary structural component, forming crystalline microfibrils. Hemicellulose: Amorphous polysaccharides that act as a matrix for the cellulose microfibrils. Lignin: A complex polymer that provides rigidity and acts as a binding agent. Pectin, waxes, and other extractives: Present on the surface and between fiber cells. The fiber structure typically consists of a primary cell wall, a secondary cell wall (with S1, S2, and S3 layers), and a lumen (hollow central canal) [17].

The use of *Corypha gebanga* fibers as reinforcement in polymer composites appears to be a relatively novel aspect of this study. Most previous research on natural fiber-reinforced composites has focused on more commonly used fibers such as jute, sisal, hemp, or flax. While natural fiber-reinforced polymer composites have been extensively studied, the use of *Corypha gebanga* fibers as reinforcement is relatively unexplored. The exploration of *Corypha gebanga* fibers as an alternative natural fiber reinforcement is a unique aspect of this paper. Furthermore, most previous studies have focused on individual fibers or non-woven mats, with limited research on the potential of woven textile fabrics as reinforcement. This study aims to bridge this gap by investigating the mechanical properties of composites reinforced with woven *Corypha gebanga* fiber fabrics, exploring the effects of fiber orientation, and optimizing the alkali treatment conditions to enhance the composite performance.

2. Experimental

2.1. Materials

The raw materials used in this research include 1 mm diameter fiber extracted from the leaves of *Corypha gebanga* palm trees using a traditional hand-stripping and twisting process. A 30/2 cotton yarn spun from medium staple cotton fibers was used for the weft threads. The cotton yarn had a linear density of 59.06 tex (59.06 g/1000 m) and an average tensile strength of 294.2 cN/tex. The matrix material was an epoxy R804 J500 resin, which was manufactured by PT Justus Kimiaraya Surabaya, Indonesia, a low viscosity epoxy system commonly used for composite manufacturing with a tensile strength of 72 MPa and an elongation at break of 4.8%. The woven *Corypha gebanga* fiber can be seen in Fig. 1. The instrumentation for experimentation consists of: ESP32 microcontroller unit for test automation and data logging, BMP180 pressure transducer for vacuum monitoring, Relay modules and solid-state relays for electro-mechanical system control, 12 V 3 A DC power supply for energizing vacuum components, DC-DC buck converter to provide suitable logic voltages, Printed circuit boards for constructing circuits, Female pin headers to enable removable connections, Solenoid-actuated pneumatic valves to regulate vacuum, Bourdon tube vacuum gauge for secondary pressure measurement, Pneumatic fittings and valves machined from brass stock, Vacuum chamber equipped with a quick-seal lid to house the composite samples, Rotary vane mechanical vacuum pump for evacuating the chamber, Diaphragm-style vacuum pump for degassing the resin prior to infusion. The integration of these devices and hardware implements the vacuum-assisted resin infusion process and acquisition of relevant experimental data.

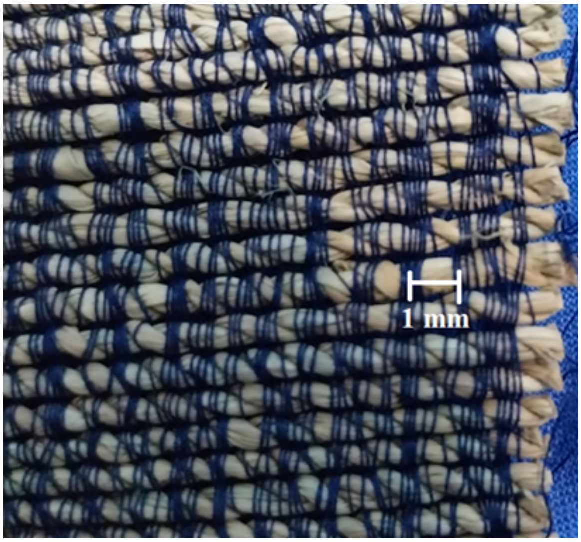


Fig. 1. Woven *Corypha gebanga* fiber

2.2. Method

The NaOH solution concentrations of 2.5%, 5%, and 7.5% were selected based on previous studies cite19,26 that reported improved fiber-matrix adhesion and mechanical properties within this range for various natural fibers. The *Corypha gebanga* fibers were woven into a plain weave fabric with a construction of 12 ends/inch and 8 picks/inch, using the cotton yarn for the weft (horizontal) direction. This construction was chosen to provide structural integrity to the fabric while maximizing the content of *Corypha gebanga* fibers. The use of cotton yarn in the weft direction is a common practice in natural fiber fabric production, as it helps to hold the reinforcing fiber bundles together and provides stability to the weave structure. However, it's important to note that the cotton yarn contributes to the mechanical properties of the composite, particularly in the weft direction The process of NaOH solution treatment, also known as alkaline treatment, involves the immersion of a material in a solution composed of water and NaOH. This treatment is predicated on the hypothesis that the elimination of weak layers, including lignin, lipids, waxes, and other impurities, which have the potential to diminish the strength of *Corypha gebanga* fiber within the composite, is facilitated by the treatment. The underlying mechanism of this process is believed to be the solubility of these weak layers in the alkaline solution, leading to their removal and subsequent improvement in the composite's overall strength and durability [29].

After being treated and printed, the composite will be tested for mechanical strength through tensile tests and bending tests. The NaOH solution reacts with the impurities in the *Corypha gebanga* fiber, such as lignin, fat, and wax, causing them to dissolve or precipitate out of the solution. This process is known as saponification, where the hydroxide ions (OH-) react with the impurities, breaking down the weak bonds that hold them together. The NaOH treatment can cause structural changes in the fibers, such as the removal of non-cellulosic components and the formation of new chemical bonds [18, 30]. This can lead to a more ordered and aligned fiber structure, which can improve the mechanical properties of the composite.

2.3. Fabricating composite molds

The *Corypha gebanga* fibers are woven with cotton thread using a plain weave. The dimensions of the webbing are 25×25 cm. The fabric was then subjected to the NaOH treatment by immersing it in the respective solution for 1 hour at room temperature. After treatment, the fabric was thoroughly rinsed with deionized water until a neutral pH was achieved, and subsequently air-dried. Printing is carried out using an Internet of Things-based vacuum infusion printing tool. The vacuum infusion process was carried out using a custom-built setup consisting of a vacuum chamber, a rotary vane vacuum pump capable of achieving a pressure of −0.9 bar, and a diaphragm pump for resin degassing. The treated fabric was placed in the vacuum chamber, and the epoxy resin was degassed and infused into the fabric under vacuum at a pressure of −0.6 bar, ensuring complete impregnation. The infused composite was cured at room temperature for 24 hours, followed by a post-cure at 80°C for 6 hours. Visual inspection is conducted to check for voids, and the mass fraction of the printed composite can be calculated in the following equation:

$$W_i = \frac{m_i}{m_{\text{tot}}} = 0.28, \tag{1}$$

where W_i is mass fraction of the printed composite material, m_i is mass of a specific component or material within the composite, and m_{tot} is total mass of the composite material. In this study, the fiber volume fraction was determined to be 30% based on the dimensions of the fiber and the amount of epoxy resin used in the composite preparation.

2.4. Preparation of composite specimens

The composite material is cut according to the ASTM D3039 [31] tensile test standards as shown in Fig. 2, this particular geometry is chosen to ensure that the test specimens are representative of the material's properties in the desired direction, and to minimize the effects of any external influences, such as edge defects or uneven stress distribution. Bending tests are conducted in accordance with the ASTM D790-03 standard that can be seen in Fig. 3 [32]. These dimensions are designed to ensure that the test specimens are representative of the material's properties in the desired direction, and to minimize the effects of any external influences, such as edge defects or uneven stress distribution. The bending tests were conducted using a Universal Testing Machine (UTM). The actual load speed during the bending test was set at 10 mm/min. This speed was chosen to ensure consistent application of load and to accurately measure the flexural properties of the composites.

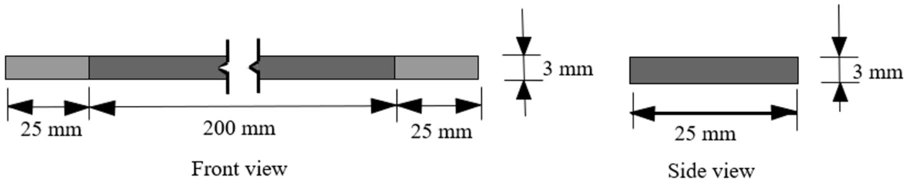


Fig. 2. ASTM D3039 standards for tensile testing

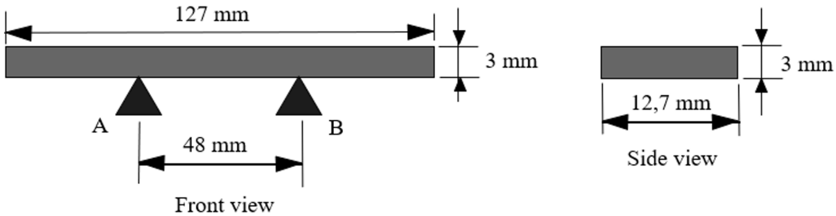


Fig. 3. ASTM D790-03 standards for bending testing

The dimensions of the tensile test specimens are 2.5×25×0.3 cm, while the bending test specimens have dimensions of 1.27×12.7×0.3 cm. The specimens are cut in two different directions: the warp direction and the weft direction. After cutting the composite according to the test standards, tensile and bending tests are conducted following the ASTM standards listed. The data obtained from the test results is recorded and processed. The equations for tensile stress, strain, and modulus of elasticity can be written in the following equations:

$$\sigma = \frac{F}{A_0}, \tag{2}$$

$$\varepsilon = \frac{\Delta l}{l_0}, \tag{3}$$

$$E = \frac{\sigma}{\varepsilon}, \tag{4}$$

where σ is stress (MPa), F is force (N), A_0 is initial cross-sectional area (mm^2), ε is strain, Δl is discrepancy in initial and final lengths (mm), E is modulus of elasticity (N/m^2) [33]. Subsequently, the bending stress, strain, and modulus of elasticity can be written in the following equations:

$$\sigma = \frac{3FL}{2bd^2}, \tag{5}$$

$$\varepsilon = \frac{6\delta d}{L^2}, \tag{6}$$

$$E_b = \frac{L^3 m}{4bd^3}, \tag{7}$$

where b is cross-sectional width (mm), L is cross-sectional length/span (mm), d is specimen thickness (mm), δ is deflection, m is the tangent slope of the deflection load curve (N/mm) and E_b is the bending elastic modulus (MPa) [27].

3. Result and Discussion

3.1. Tensile strength

A tensile test was conducted on fabric specimens to characterize the mechanical properties in different orientations and after various chemical treatments. Specimens were cut along the warp direction and along the weft direction. Tensile loading was applied until failure and the maximum stress and strain were quantified. Additionally, specimens were treated by soaking in NaOH prior to tensile testing. The results demonstrated anisotropic behavior, with higher tensile strength exhibited by specimens oriented in the warp direction compared to the weft direction. This is likely due to the differences in straightness and alignment of the fibers in each direction. Figs. 4 and 5 show the tensile stress in the warp and weft directions of woven *Corypha gebanga* fiber fabric specimens reinforced with cotton yarn in the weft direction.

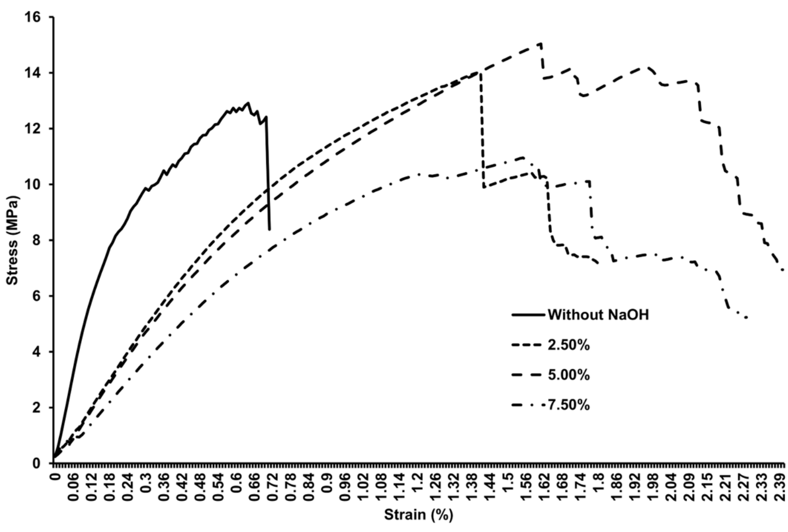


Fig. 4. Tensile stress behavior in the warp directions

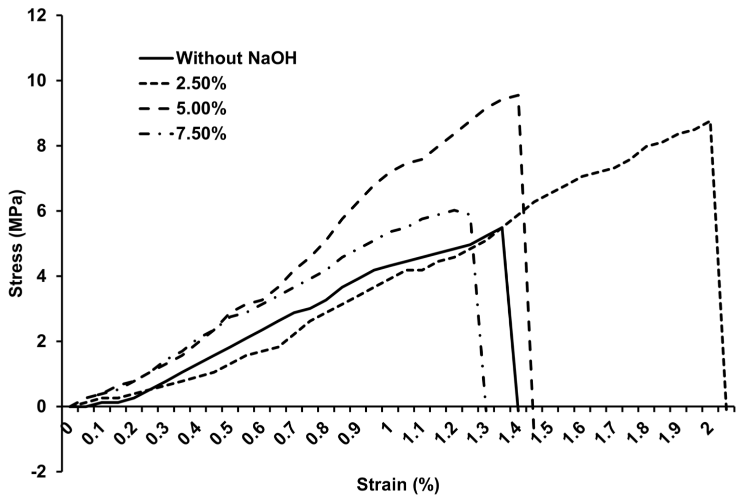


Fig. 5. Tensile stress behavior in the weft directions

From Figs. 4 and 5, it can be observed that the tensile test specimens cut along the warp direction of the *Corypha gebanga* fibers exhibit higher mechanical performance compared to specimens cut in other orientations. The maximum tensile load sustained prior to failure was measured to be 1186.86 N for the specimen treated with a 2.5% NaOH solution. Utilizing the specimen cross-sectional area in Equation 2, this maximum load corresponds with an maximum tensile strength of 15.82 MPa. This enhanced mechanical behavior can be attributed to several effects of the NaOH treatment on the native *Corypha gebanga* fibers. Alkali treatment is known to remove non-cellulosic components such as lignin, hemicellulose, and other hydrophilic extractives from natural fibers [33]. This removal of non-cellulosic materials can lead to better fiber-matrix adhesion and improved stress transfer between the fiber and the matrix. Additionally, alkali treatment can modify the fiber surface topography, increasing roughness and creating more sites for mechanical interlocking with the matrix.

However, concentrations of NaOH above 2.5% appear to have a damaging effect, as evidenced by the progressive reduction in mechanical performance for the 5% and 7.5% NaOH-treated specimens. This decline in tensile strength implies that excessive exposure to alkaline conditions may induce structural changes in the cellulose or cause fiber damage. While alkali treatment can be beneficial at lower concentrations, higher concentrations or prolonged exposure can lead to cellulose degradation, potentially through hydrolysis of glycosidic bonds or changes in the cellulose supramolecular structure [28]. It's important to note that the effects of alkali treatment on cellulose crystallinity and polymerization are complex and can vary depending on treatment conditions and fiber type. Some studies have reported increases in crystallinity index after mild alkali treatment [34], while others have observed decreases, especially at higher alkali concentrations. The degree of polymerization of cellulose is generally not increased by alkali treatment and may actually decrease due to chain scission reactions at harsh treatment conditions [22].

The alkali treatment of *Corypha gebanga* fibers can lead to complex changes in their mechanical properties. While it is well-established that NaOH treatment enhances fiber-matrix adhesion by removing amorphous components, this process can also induce structural changes that may negatively impact the fibers' integrity at higher concentrations. For instance, studies have shown that concentrations exceeding 5% can lead to cellulose degradation, resulting in a decline in tensile strength [35]. To substantiate these observations, we propose the incorporation of Near-Infrared (NIR) spectroscopy to monitor the chemical changes in the fibers post-treatment. NIR analysis has been successfully utilized in previous studies to detect alterations in functional groups and bond structures [36, 37]. Furthermore, measuring interfacial shear strength (ISS) between the treated fibers and the epoxy matrix could provide valuable insights into the efficacy of the alkali treatment in enhancing bonding performance. Additionally, examining the mechanical properties of *Corypha gebanga* fiber bundles or yarns before and after treatment will help clarify the effects of alkali treatment on fiber integrity. This could involve assessing parameters such as tensile strength and elongation, which are critical for evaluating the performance of the composites. Figs. 6 and 7 present a comparative of tensile stress under different loading conditions.

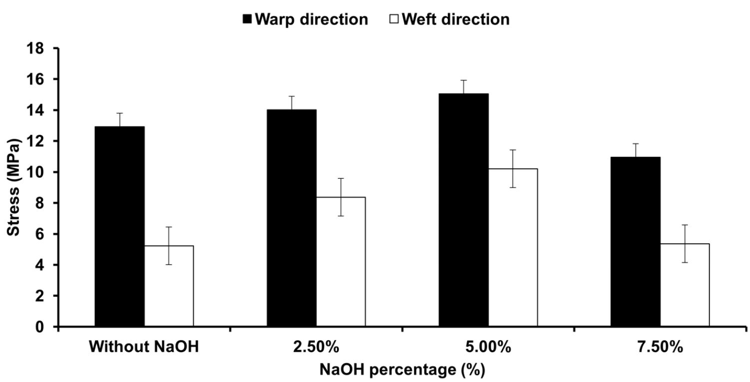


Fig. 6. Comparative of tensile stress in warp and weft directions

The surface treatment of fibers with NaOH solution can adjust the surface properties of the fibers, leading to improved adhesion and interlocking with the surrounding matrix. This treatment can remove certain components from the fiber surface, such as lignin, hemicellulose, and dirt, through a process known as chemical etching. Lignin is a complex organic polymer that provides strength and rigidity to plant cell walls. Hemicellulose, on the other hand, is a heterogeneous group of polysaccharides that play a crucial role in the formation of plant cell walls and their interactions with other cellular components. Dirt, which refers to any impu-

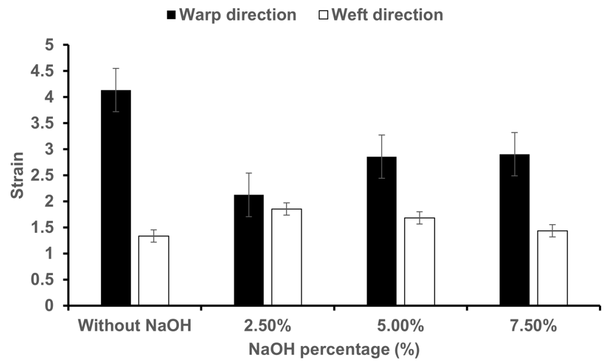


Fig. 7. Comparative of tensile strain in warp and weft directions

rities or contaminants present on the fiber surface, can also affect the adhesion properties of the fibers. When NaOH solution is applied to the fiber surface, it reacts with the lignin, hemicellulose, and dirt, causing them to break down and release from the fiber surface. This process creates a cleaner and rougher surface, which can improve the adhesion strength between the fibers and the matrix. The presence of cotton yarn in the weft direction contributes to the mechanical properties of the composite, particularly in that orientation. Based on the tensile strength of the cotton yarn (294.2 cN/tex), we estimate that it accounts for approximately 15–20% of the tensile strength in the weft direction. This contribution should be considered when interpreting the results, especially the differences observed between warp and weft orientations. Future studies could isolate the contribution of the cotton yarn by testing composites with varying ratios of *Corypha gebanga* to cotton yarn.

The increased roughness of the fiber surface can create more sites for the matrix to bond to, thereby increasing the interlocking between the fibers and the matrix. This can ultimately lead to a stronger and more durable composite material. The mechanism behind this improvement in adhesion and interlocking can be attributed to the chemical and physical changes that occur on the fiber surface during the NaOH treatment. The sodium hydroxide solution can break down the lignin and hemicellulose components, leading to the exposure of fresh fiber surfaces [21]. These fresh surfaces can then bond more effectively with the matrix, creating a stronger and more stable composite material. In addition, the NaOH solution can also remove any impurities or contaminants present on the fiber surface, such as dirt or other organic compounds, which can interfere with the adhesion process. By removing these impurities, the fiber surface becomes cleaner, and the matrix can bond more effectively with the fibers, leading to improved mechanical properties. The modulus of elasticity of tensile test is shown in Fig. 8.

The results depicted in Fig. 8 illustrate substantial discrepancies in the elastic modulus of *Corypha gebanga* fiber woven composites. Notably, the alkaline treatment of lignocellulosic fibers, such as those from *Corypha gebanga*, can lead

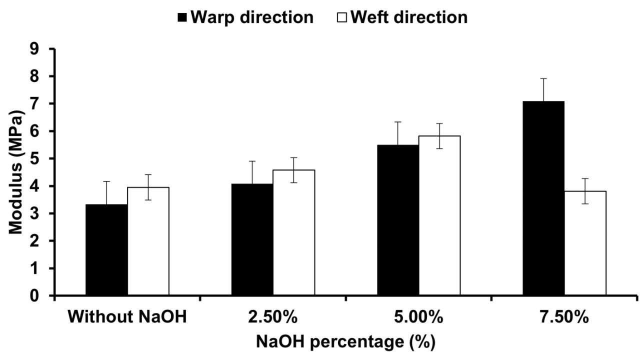


Fig. 8. Elastic modulus from tensile testing

to significant changes in fiber structure and dimensions. After NaOH treatment, notable shrinkage of the fibers was observed, which is consistent with findings reported in literature for other natural fibers. This shrinkage can be attributed to the removal of hemicellulose, lignin, and other non-cellulosic components from the fiber structure. The extent of shrinkage appeared to increase with higher NaOH concentrations. This fiber shrinkage had several implications for the composite samples that include dimensional changes, changes in fiber volume fraction, and formation of voids. These phenomena contribute to the complex relationship between NaOH concentration and mechanical properties observed in our study. The initial improvement in tensile strength at lower NaOH concentrations (up to 2.5%) can be attributed to better fiber-matrix adhesion and increased fiber volume fraction due to shrinkage. However, the decline in properties at higher concentrations (5% and 7.5%) may be partly due to excessive fiber damage and the formation of voids, which can act as stress concentrators and reduce overall composite strength.

The findings suggest that the orientation of the fibers within the composite plays a significant role in determining its mechanical properties. Specifically, the warp direction weave, characterized by fibers aligned parallel to the applied load, exhibits a higher elastic modulus than the weft direction weave, where fibers are perpendicular to the applied load. This orientation effect is consistent with previous studies on fiber-reinforced composites, wherein fibers aligned in the direction of loading have been shown to provide greater mechanical reinforcement. The influence of NaOH concentration on the elastic modulus of *Corypha gebanga* fiber woven composites is also noteworthy. An increase in NaOH concentration from 0% to 2.5% and 5% resulted in a slight enhancement in elastic modulus for both the warp and weft direction weaves. This finding suggests that the addition of NaOH, an alkali metal hydroxide, may facilitate the dispersion of fibers within the composite, leading to improved fiber-to-fiber interactions and enhanced mechanical properties [27, 34]. However, further investigation is required to fully elucidate the underlying mechanisms.

3.2. Bending strength

The bending test is a widely used experimental method in materials science to evaluate the mechanical properties of a material. It provides a means to quantify the structural integrity and elastic modulus of a specimen by applying a moment and measuring the resulting stress-strain response. In the case of woven cotton fabric, the bending test can reveal important information about its mechanical behavior under various loads. The test can measure the bending stresses present in warp and weft directions of the fabric, providing insights into its structural integrity and elastic properties. Figs. 9 and 10 show the bending stress in the warp and weft directions of woven cotton fabric specimens.

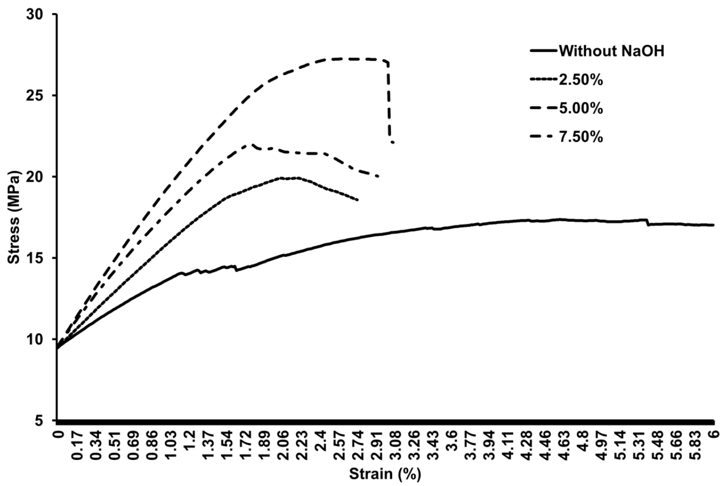


Fig. 9. Bending stress behavior in the warp directions

Fig. 9 reveal that the specimens in the warp direction exhibit the highest resistance to loads. Specifically, the maximum load that can be supported is 51.12 N with a deflection of 3.18% in specimens treated with a 5% NaOH solution. The findings of this study demonstrate that pretreatment with aqueous NaOH solutions significantly enhances the bending strength properties of natural fiber composites. The alkali treatment process removes lignins, waxes, and other hydrophobic constituents that coat the exterior surfaces of the fiber cell walls, thereby increasing the accessibility for interfibrillar bonding with the epoxy resin matrix. This enhances interfacial adhesion, allowing for more efficient load transfer and reducing crack propagation at the interface. The results show that a 5% NaOH molar concentration optimizes mechanical performance enhancements. This is attributed to the balance between cleansing fiber surfaces of impurities and avoiding excessive fiber damage or corrosion at higher alkali contents [38].

Fig. 10 shows the maximum sustainable load of 40.75 N under 5% NaOH pretreatment, corresponding to a deflection at failure of 0.9%. This corresponds to

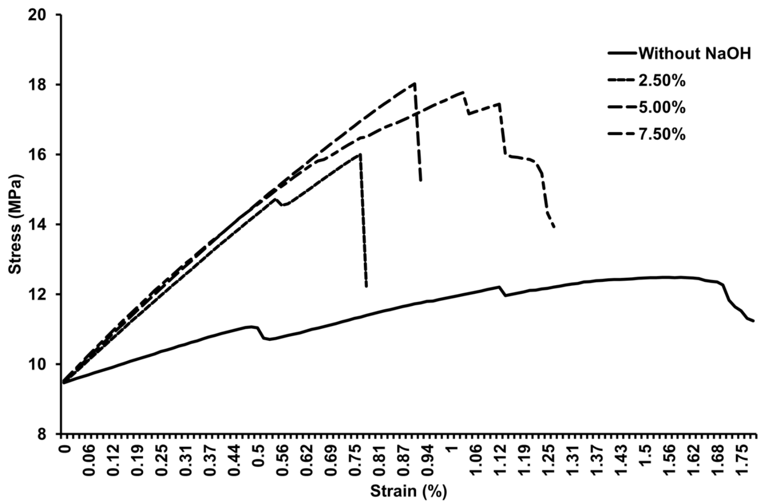


Fig. 10. Bending stress behavior in the weft directions

a maximum bending stress of 18 MPa along the principal axis. The use of NaOH solutions induces surface modifications that enhance the mechanical performance of natural fibers, as seen in other studies. The alkaline treatment removes non-cellulosic components, such as waxes, oils, and impurities, that may compromise interfacial bonding with the polymer matrix. However, excessive exposure to highly concentrated NaOH solutions can damage the cellulose molecules that comprise the load-bearing fraction of the cotton fibers. This may lead to a degradation of the cellulosic components, outweighing the benefits of surface cleaning, resulting in inferior mechanical properties. The observations indicate that NaOH concentrations exceeding 7.5% initiate degradation of the cellulosic components. Therefore, the optimal concentration of NaOH for maximum mechanical performance enhancement is found to be 5%. Figs. 11 and 12 present a comparison of bending stress and strain under different loading conditions.

The alkaline solution can be described as a chemical agent that selectively removes non-cellulosic components from the surface of natural fibers. The process of cleansing the fibers involves the dissolution of impurities, such as lignin and hemicellulose, and the removal of waxes, oils, and other surface contaminants. This results in a roughened fiber surface with exposed crystalline cellulose microfibrils, which can interact more effectively with the surrounding matrix. The improved mechanical interlocking and physical interactions between the fiber and matrix can be attributed to the increased surface roughness and the enhanced crystallinity of the cellulose microfibrils [38]. The roughened fiber surface provides a greater surface area for bonding with the matrix, while the exposed crystalline cellulose microfibrils offer improved mechanical reinforcement. As a result, the stress transfer efficiency between the fiber and matrix is improved, leading to enhanced mechanical properties of the composite material. However, it is important to note that the

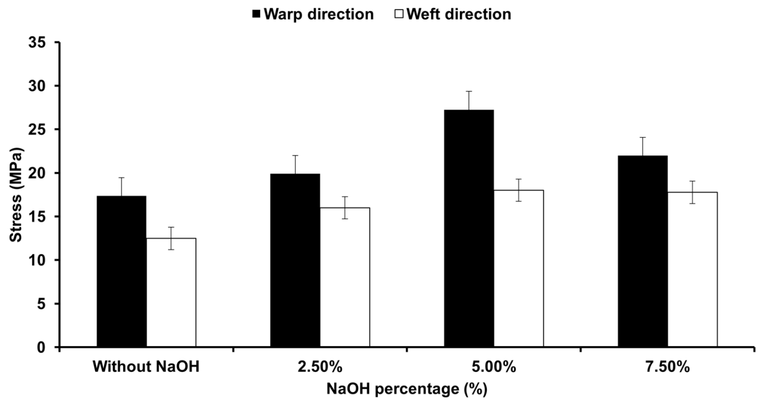


Fig. 11. Comparative of bending stress in warp and weft directions

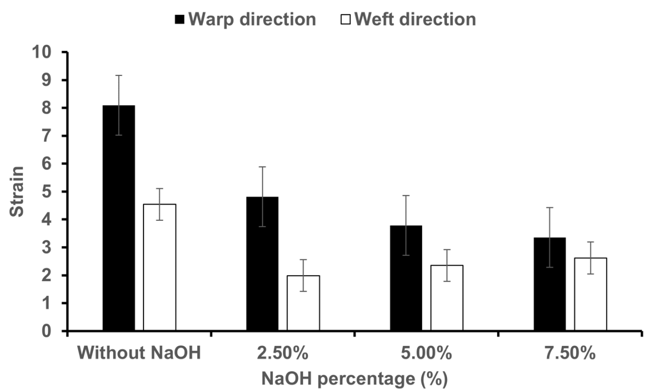


Fig. 12. Comparative of bending strain in warp and weft directions

optimization of NaOH concentration is critical to achieve the desired level of surface purification without causing excessive damage to the fibers. Excessive NaOH concentration can lead to fiber degradation, which can negatively impact the mechanical properties of the composite material. Therefore, careful control of the NaOH concentration is necessary to achieve the optimal balance between surface purification and fiber integrity.

The decline in bending attributes of natural fiber composites at higher NaOH molarities is attributed to the degradation of lignin and hemicellulose components. This degradation occurs as a result of the increased alkalinity, which exceeds the threshold required for efficient fiber surface cleansing, leading to the breakdown of unstructured, matrix-binding fractions. This breakdown causes excessive disruption and solubilization of the reinforcing constituents within the fiber cell walls, ultimately resulting in a loss of structural integrity that outweighs any potential benefits of improved matrix-fiber adhesion. To elucidate the mechanism underlying this phenomenon, detailed chemical analysis could be employed to determine the NaOH concentrations at which cellulose degradation mechanisms are activated. Such analysis would provide valuable insights into the chemical interactions between the alkaline solution and the fiber components, allowing for the optimization of the NaOH concentration to achieve efficient surface purification without compromising fiber integrity. The degradation of lignin and hemicellulose components can be attributed to the increased reactivity of the alkaline solution at higher NaOH molarities. The elevated pH environment facilitates the breakdown of these components by promoting hydrolytic and condensation reactions, leading to the formation of soluble degradation products. These products can then be removed from the fiber surface, leaving behind a clean, roughened surface that can interact more effectively with the surrounding matrix.

However, at higher NaOH molarities, the degradation of cellulose components also becomes more pronounced, leading to a decline in the structural integrity of the fiber [28]. This is attributed to the activation of cellulose degradation mechanisms, such as hydrolysis and oxidation, which can result in the cleavage of cellulose molecules and the formation of soluble degradation products. The modulus of elasticity of bending test is shown in Fig. 13.

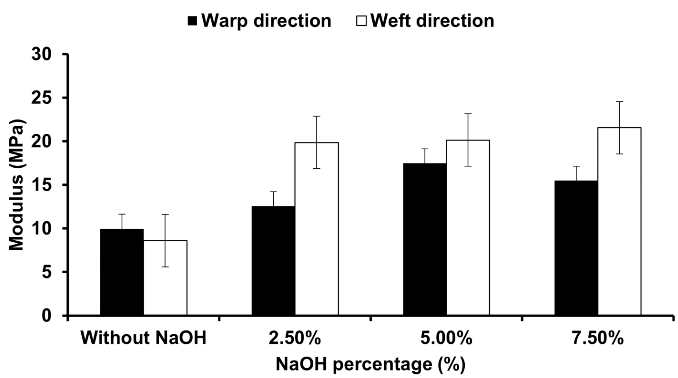


Fig. 13. Elastic modulus from bending testing

Fig. 13 shows that a maximum elastic modulus of 21.5 MPa is achieved by *Corypha gebanga* woven fabric specimens in the weft direction following a 7.5% NaOH alkaline treatment. Warp-oriented specimens that were subjected to 2.5% and 5.0% NaOH treatments exhibited an identical elastic modulus of 20 MPa. In contrast, untreated samples exhibited significantly lower modulus of elasticity values in both the warp and weft orientations. These results suggest that the bending stiffness of woven natural fiber composite materials can be improved through alkaline exposure, with a recommended NaOH concentration range of 5–7.5% for optimal reinforcement. The results demonstrate that the alkaline treatment has a significant impact on the mechanical properties of the woven natural fiber composite material. The increased elastic modulus values for the treated samples indicate that the alkaline solution effectively removed impurities and/or dissolved surface layers, leading to improved fiber-to-fiber interactions and enhanced mechanical reinforcement. The optimal NaOH concentration for maximizing the reinforcement effect was found to be between 5 and 7.5%. This concentration range was determined by analyzing the elastic modulus values for the treated samples and identifying the concentration that resulted in the highest modulus value. The results suggest that concentrations above 7.5% NaOH may not provide additional benefits in terms of mechanical reinforcement, and may potentially lead to degradation of the fibers, resulting in decreased mechanical properties [39].

3.3. Microscopy image analysis

Fractures that occur in specimens subjected to tensile testing can be visualized and analyzed using a photo microscope. This technique is employed to augment the interpretation of tensile test results. The fracture pattern is documented through photography captured at a magnification of 80x using a microscope equipped with a camera. Microscopy image analysis of the tensile test for each NaOH concentration is shown in Figs. 14 and 15.

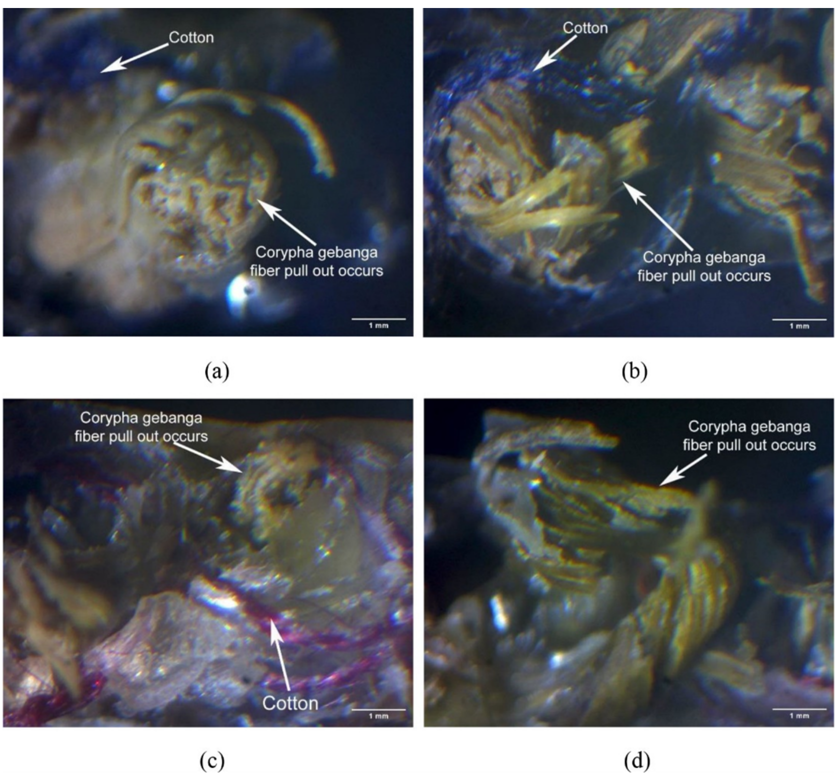
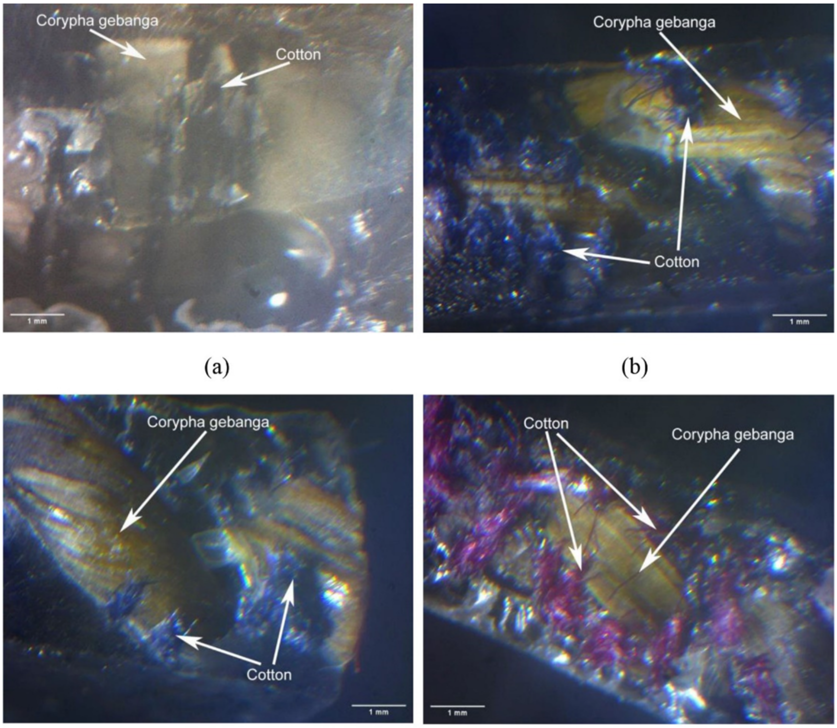


Fig. 14. (a) Tensile analysis in the warp direction at 0% NaOH concentration. (b) Tensile analysis in the warp direction at 2.5% NaOH concentration. (c) Tensile analysis in the warp direction at 5% NaOH concentration. (d) Tensile analysis in the warp direction at 7.5% NaOH concentration



(a) (b) (c) (d)

Fig. 15. (a) Tensile analysis in the weft direction at 0% NaOH concentration. (b) Tensile analysis in the weft direction at 2.5% NaOH concentration. (c) Tensile analysis in the weft direction at 5% NaOH concentration. (d) Tensile analysis in the weft direction at 7.5% NaOH concentration

From Figs. 14 and 15, it is apparent that fiber pullout occurred in all specimens tested that were cut in the direction of the warp during tensile testing. The onset of fracture was characterized by the resin breaking initially, followed by the fibers stretching and ultimately breaking. This sequence of events can be attributed to the fact that the fibers possess a higher strength than the matrix employed. Consequently, fiber pullout was observed in all variations of specimens cut in the direction of the warp as depicted in *Corypha gebanga*. The fiber pullout phenomenon is a well-documented occurrence in composite materials and is a direct result of the disparity in strength between the fiber and matrix materials. When the matrix material fails, the fibers are still able to withstand the applied load, leading to their partial extraction from the matrix. This phenomenon is indicative of the complex failure behavior of composite materials and serves to highlight the importance of considering both the fiber and matrix materials when evaluating the mechanical performance of composite structures [40].

The failure mechanism of specimens cut in the direction of the weft, as observed in this study, is characterized by fiber fracture occurring simultaneously with the failure of the matrix, resulting in a clean-cut appearance. This mode of failure is attributed to the fact that the strength of the fibers in the weft direction is supported by the strength of the matrix. When the load is applied in this direction, both the fibers and the matrix fail at the same time, leading to a clean break without any significant fiber pull-out or matrix deformation. This mode of failure is in contrast to the failure mechanism observed in specimens cut in the warp direction, where the fibers tend to fail before the matrix, leading to fiber pull-out and matrix deformation. The difference in failure mechanisms between the weft and warp directions is attributed to the difference in fiber orientation and the corresponding distribution of stresses within the composite material. The clean-cut appearance observed in specimens cut in the weft direction indicates a strong interfacial bond between the fibers and the matrix, which allows for efficient load transfer from the matrix to the fibers. However, the fact that fiber fracture occurs in all variations of specimens cut in the weft direction suggests that the strength of the fibers themselves may be a limiting factor in the overall mechanical performance of the composite material.

The microscopy image analysis revealed distinct failure mechanisms between specimens tested in the warp and weft directions. To better understand the implications of these differences on the overall mechanical performance of the *Corypha gebanga* fiber-reinforced composites, a detailed comparative analysis of these failure mechanisms is necessary. The failure mechanisms observed in the *Corypha gebanga* fiber-reinforced composites differ significantly between the warp and weft directions, impacting the overall mechanical performance of the material. In the warp direction, the predominant failure mechanism is fiber pullout. This process occurs in the following sequence. Initial matrix cracking: As the load increases, the epoxy resin matrix begins to crack. Load transfer to fibers: Once the matrix cracks, the load is transferred to the *Corypha gebanga* fibers. Fiber stretching: The fibers, being stronger than the matrix, begin to stretch under the applied load. This failure mechanism has several implications for the mechanical performance: Energy absorption: Fiber pullout is generally associated with higher energy absorption during failure, as the friction between the fibers and the matrix during pullout dissipates energy. Gradual failure: The pullout mechanism often results in a more gradual failure process, potentially providing warning before complete structural failure. Strength utilization: This mechanism allows for better utilization of the fiber strength, as the fibers continue to carry load even after matrix failure.

In contrast, the weft direction exhibits a different failure mechanism characterized by simultaneous fiber fracture and matrix failure. Uniform stress distribution: The load is more evenly distributed between the fibers and the matrix in the weft direction. Simultaneous failure: As the load increases, both the fibers and the matrix reach their failure point at approximately the same time. Clean fracture: This results in a clean break across the specimen, with minimal fiber pullout. The implications of this failure mechanism on mechanical performance include: Brittle failure: The simultaneous failure of fibers and matrix often results in a more brittle failure mode, with less energy absorption compared to the warp direction. Higher initial strength: The uniform stress distribution can lead to higher initial strength in the weft direction. Limited post-failure performance: Unlike in the warp direction, there is limited load-bearing capacity after the initial failure point.

4. Conclusions

The study investigated the effect of NaOH treatment on the mechanical properties of *Corypha gebanga* fibers and their woven composites. The study's findings provide valuable insights into the optimization of *Corypha gebanga* fibers and their composites for various industrial applications, and highlight the potential of these materials as sustainable alternatives to traditional materials. Higher concentrations of NaOH exceeding 2.5% seem to cause harm, as indicated by the gradual decrease in mechanical performance observed in the specimens treated with 5% and 7.5% NaOH. The decrease in tensile strength suggests that prolonged exposure to alkaline conditions leads to permanent alterations in the cellulose structure and morphology, or results in fiber damage. The study's findings indicate that pretreatment with aqueous NaOH solutions significantly enhances the bending strength properties of natural fiber composites. The optimal concentration of NaOH for maximum mechanical performance enhancement is found to be 5%, which balances the removal of impurities and the avoidance of excessive fiber damage. Exposure to highly concentrated NaOH solutions can damage cellulose molecules, leading to inferior mechanical properties. The bending stiffness of woven natural fiber composite materials can be improved through alkaline exposure, with a recommended NaOH concentration range of 5–7.5% for optimal reinforcement. Additionally, the study revealed distinct failure mechanisms in the warp and weft directions, with fiber pullout dominating in the warp direction and simultaneous fiber-matrix fracture in the weft direction. These differences contribute significantly to the anisotropic mechanical behavior of the composites, offering opportunities for tailored design in various applications.

While this study provides valuable insights into the mechanical properties of *Corypha gebanga* fiber-reinforced composites, there are several limitations that should be addressed in future research. First, the long-term durability and environmental resistance of these composites were not evaluated, which is crucial for their practical applications. Additionally, the study focused primarily on mechanical properties, and further investigation into other relevant properties, such as thermal and electrical behavior, would be beneficial. Furthermore, the research was conducted on a laboratory scale, and future studies should explore the scalability and feasibility of commercial-scale production of these composites. Exploring alternative bio-based or recycled matrix materials could also enhance the sustainability and eco-friendliness of these composites. This study highlights the potential of *Corypha gebanga* fibers as a viable reinforcement material for polymer composites, particularly in the form of woven textile fabrics. Researchers in the field of natural fiber-reinforced composites should consider exploring other underutilized natural fibers and their processing techniques to expand the range of sustainable and high-performance composite materials. Additionally, the optimization of alkali treatment conditions, as demonstrated in this study, could be applied to other natural fibers to improve their mechanical properties and compatibility with polymer matrices. Researchers should also investigate the synergistic effects of combining different natural fibers or hybridizing them with synthetic fibers to tailor the composite properties for specific applications.

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