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Weaving Architecture Effects on Mechanical and Chemical Performance of Alkali Treated Coconut Fiber Composites

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Abstract

This study examines the effect of fabric architecture and alkali treatment on the properties of coconut fiber–polyester composites as an alternative environmentally friendly material. Coconut fibers were treated with 15% NaOH for 2 hours and woven in basket weave and twill weave patterns. The composites were made using a vacuum-assisted resin infusion method with a fiber fraction of 40%, and compared with E-glass composites as a control. FTIR analysis showed a decrease in the intensity of the absorption band in the range of 1200–1300 cm^{-1}, indicating a reduction in lignin content after alkali treatment. The mechanical test results showed that the basket weave composite had higher tensile and flexural strengths, respectively, of 20.40 N/mm^2 and 78.45 N/mm^2, compared to the twill weave at 12.98 N/mm^2 and 52.31 N/mm^2. However, the highest impact resistance was obtained in the twill weave at 23.61 J/mm^2. The results of the study indicate that the weave architecture has a significant effect on the mechanical performance of the composite and has the potential to support the development of sustainable composite materials for engineering applications.

Keywords: *Coconut Fiber Composites; Alkali Treatment; Fabric Architecture; Mechanical Properties*

Abstrak

Penelitian ini mengkaji pengaruh arsitektur kain dan perlakuan alkali terhadap sifat komposit serat kelapa–poliester sebagai alternatif material ramah lingkungan. Serat kelapa diberi perlakuan NaOH 15% selama 2 jam dan dianyam dalam pola basket weave dan twill weave. Komposit dibuat menggunakan metode vacuum-assisted resin infusion dengan fraksi serat 40%, serta dibandingkan dengan komposit E-glass sebagai kontrol. Analisis FTIR menunjukkan penurunan intensitas pita serapan pada rentang 1200–1300 cm^{-1} yang mengindikasikan berkurangnya kandungan lignin setelah perlakuan alkali. Hasil pengujian mekanik menunjukkan bahwa komposit basket weave memiliki kekuatan tarik dan lentur lebih tinggi, masing-masing sebesar 20,40 N/mm^2 dan 78,45 N/mm^2, dibandingkan twill weave sebesar 12,98 N/mm^2 dan 52,31 N/mm^2. Namun, ketahanan benturan tertinggi diperoleh pada twill weave sebesar 23,61 J/mm^2. Hasil penelitian menunjukkan bahwa arsitektur anyaman berpengaruh signifikan terhadap performa mekanik komposit dan berpotensi mendukung pengembangan material komposit berkelanjutan untuk aplikasi teknik.

Kata kunci: *Komposit Serat Kelapa; Perlakuan Alkali; Arsitektur Kain; Sifat Mekanik*

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1. Introduction

Indonesia, as an archipelagic nation, is endowed with substantial natural resources, including extensive coconut (Cocos nucifera) plantations. According to the Agricultural Data and Information System Center, Indonesia's coconut production reached approximately 2.86 million tons in 2022 [1]. While the coconut fruit remains the primary commercial product, coconut husk a lignocellulosic by product is predominantly discarded as agricultural waste. However, the fibrous component of coconut husk possesses considerable potential for valorization into high-value products, particularly in response to increasing industrial demand for sustainable materials [2], [3].

Contemporary industrial sectors require materials exhibiting superior characteristics, including excellent mechanical properties, cost-effectiveness, and environmental sustainability. Traditional applications of advanced materials have predominantly focused on the transportation sector; however, recent developments have expanded their utilization to construction, architecture, and various engineering applications [4], [5]. Among advanced materials, fiber-reinforced polymer composites have exhibited exceptional mechanical performance compared to conventional materials, making them increasingly attractive for various industrial applications [6].

Composite materials are defined as engineered systems comprising two or more constituent phases with distinctly different physical and chemical properties. These constituents are combined in a heterogeneous arrangement, resulting in synergistic mechanical properties that surpass those of individual components [7]. Through systematic adjustment of constituent proportions and configurations, composites can be tailored to achieve specific strength, stiffness, and durability requirements. Fundamentally, composites consist of a continuous matrix phase and a discontinuous reinforcement phase, typically in fibrous form. The matrix functions to bind reinforcing fibers, maintain their spatial orientation, and facilitate load transfer, while also providing formability through cutting or molding processes. Conversely, reinforcing fibers serve as the primary load bearing elements, contributing significantly to the composite's mechanical integrity [8], [9].

Reinforcing fibers employed in composite fabrication are categorized into synthetic and natural fibers. Synthetic fibers, particularly glass fibers, have been extensively utilized in composite manufacturing due to their high strength to weight ratio and consistent properties. Nevertheless, glass fiber composites present significant limitations, including elevated production costs, non-biodegradability, and environmental concerns associated with their disposal [10], [11]. In contrast, natural fibers derived from renewable plant sources offer compelling advantages, including abundant availability, low cost, biodegradability, reduced processing energy, and lower carbon footprint. Natural fibers encompass a wide range of lignocellulosic materials obtained from various botanical sources, including leaf fibers (sisal, pineapple), bast fibers (flax, hemp, jute), seed fibers (cotton, kapok), and fruit fibers (coconut, oil palm) [12], [13].

Coconut fiber, also known as coir, represents a promising natural reinforcement material for composite applications. The increasing interest in coir fiber composites stems from multiple factors: widespread availability in tropical regions, economic viability, and biodegradability, which collectively address environmental sustainability concerns associated with conventional synthetic fiber composites [14]. Chemically, coconut fiber comprises cellulose contents (32-43%), lignin (40-45%), hemicellulose (0.15-0.25%), along with minor constituents including pectin, extractives, and inorganic compounds. This unique composition imparts distinctive properties to coir fibers, including high toughness, resistance to microbial degradation, low thermal conductivity, and excellent resilience [15], [16]. Furthermore, the high lignin content confers natural resistance to fungal attack and moisture absorption, making coir fiber particularly suitable for applications in humid environments [17].

Despite the promising attributes of coconut fiber, optimization of coir-reinforced composites requires systematic investigation of various processing parameters. Fiber treatment methods, including alkaline treatment with sodium hydroxide (NaOH), have been demonstrated to enhance fiber-matrix interfacial adhesion by removing surface impurities, modifying surface topography, and improving mechanical interlocking [18], [19]. Additionally, the weaving architecture of fiber reinforcements significantly influences the mechanical performance of composites. Different weaving patterns, such as plain (basket) weave and twill weave, exhibit distinct characteristics in terms of drapability, structural stability, and load distribution mechanisms, consequently affecting the resulting composite properties [20].

Given Indonesia's substantial coconut production and the imperative for sustainable material development, the utilization of coconut fiber as a composite reinforcement presents both economic and environmental benefits. However, comprehensive characterization of the relationships between fiber weaving patterns and resulting composite properties remains limited in the existing literature. Therefore, this study aims to investigate the effect of weaving pattern variations (basket weave and twill weave) on the chemical and mechanical properties of coconut fiber-reinforced polyester composites. Coconut fibers were subjected to alkaline treatment using 15% NaOH solution for 2 hours to optimize fiber-matrix compatibility. The mechanical performance of coir fiber composites was evaluated through tensile, flexural, and impact testing, with comparative analysis against conventional glass fiber composites. Additionally, Fourier Transform Infrared (FTIR) spectroscopy was used to identify the chemical structure and functional groups of treated coconut fibers, providing insights into fiber modification mechanisms and their correlation with mechanical properties.

This comprehensive investigation provide to increase of knowledge on sustainable composite materials and provides valuable insights for the potential industrial application of coconut fiber as an alternative to synthetic reinforcements, particularly in the relation of circular economy and sustainable manufacturing practices.

2. Method

This experimental study was performed at the Materials Engineering Laboratory, State Polytechnic of Madiun (Campus 2), Indonesia. The investigation utilized a comparative experimental approach to systematically assess the effect of fiber reinforcement structure on the obtained composite characteristics. The research included three different reinforcement arrangements: (1) basket weave coconut fiber, (2) twill weave coconut fiber, and (3) plain weave fiberglass as a reference standard. Each arrangement was exposed to identical manufacturing processes and characterization methods to ensure validity of comparative evaluation.

2.1 Materials Preparation

Coconut fibers (Cocos nucifera L.) were sourced locally from Madiun, East Java, Indonesia. The fibers were cleaned, dried, and subjected to alkali treatment using 15% sodium hydroxide (NaOH) solution for 2 hours to remove hemicellulose, lignin, and surface impurities, thereby improving fiber matrix adhesion. This treatment process was carried out following the procedure described, after treatment, the fibers were rinsed with distilled water until neutral pH and oven dried at 80 °C for 6 hours.

2.2 Composite Fabrication

Two types of reinforcement structures were prepared: basket weave and twill weave patterns of coconut fibers, with an additional fiberglass-reinforced control composite for comparison. The fiber volume fraction was maintained at approximately 40%, while the matrix occupied the remaining 60%. Each composite type was produced in triplicate (n = 3) to ensure statistical reliability.

Three distinct composite laminate configurations were manufactured to systematically investigate the influence of reinforcement architecture on material performance. The experimental matrix comprised two natural fiber-reinforced variants incorporating basket weave and twill weave coconut fiber architectures along side a conventional fiberglass-reinforced polyester composite serving shown in Figure 1 as the benchmark reference material. To ensure consistency in comparative analysis and maintain equivalent reinforcement loading across all configurations, the fiber volume fraction (Vf) was precisely controlled at approximately 40 vol%, with the polyester matrix constituting the remaining 60 vol%.

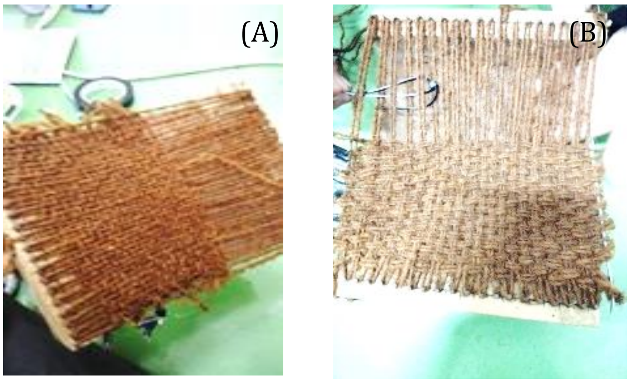

Figure 1. Twill(A) and Basket(B) weave

This fiber content was selected based on preliminary optimization studies and represents a balance between mechanical performance and processability for hand lay-up fabrication, consistent with established practices for natural fiber composites where optimal fiber loading typically ranges between 20-40 vol%.

2.3 Mechanical Testing

Mechanical characterization of the composites was performed in accordance with ASTM standards: Tensile strength was tested following ASTM D638, using a universal testing machine with a crosshead speed of 5 mm/min, as shown in Figure 2.

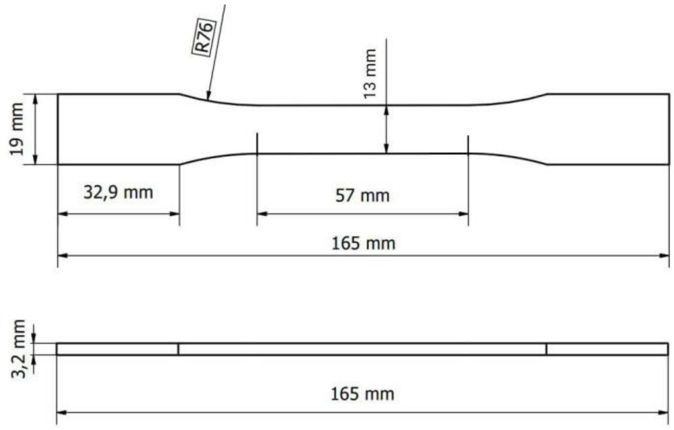

Figure 2. Tensile Test Specimens Designed Based on ASTM D638 TYPE 1.

Flexural strength test (bending test) followed ASTM D790, under a three-point bending configuration with specimen dimensions such as Figure 3.

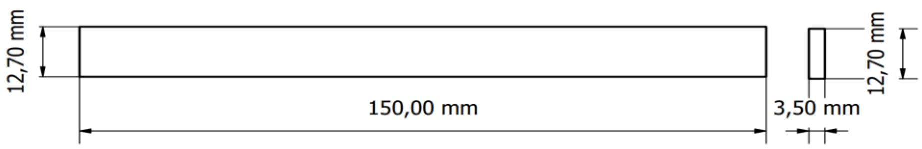

Figure 3. Dimensions of Bending Test Specimens Designed Based on ASTM D790.

Izod impact strength test was evaluated and then Impact testing is carried out in approval with specimen dimensions the ASTM D256 standard shown in Figure 4.

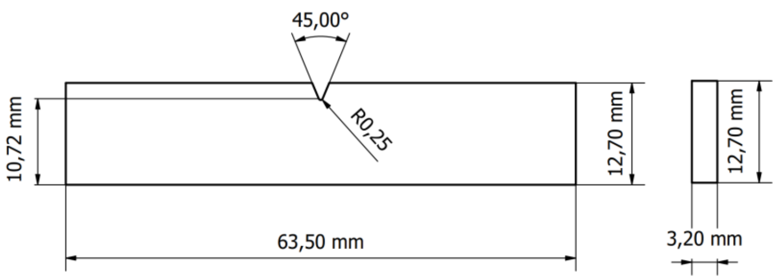

Figure 4. Dimensions of Bending Test Specimens Designed Based on ASTM D256.

3. Results and Discussion

3.1. FTIR Analysis

Fourier Transform Infrared (FTIR) spectroscopic analysis of untreated and NaOH-treated coconut coir fibers revealed characteristic chemical modifications indicative of successful surface activation, as presented in Figure 6. The persistence of prominent absorption bands at approximately 3320 cm^{-1} (O–H stretching vibrations) and 2910 cm^{-1} (C–H stretching vibrations) confirmed the sustained presence of cellulosic components and their associated functional groups show in Table 1. [21], [22]. Conversely, marked attenuation of absorption bands within the 1200–1300 cm^{-1} region—characteristically attributed to lignin and hemicellulose moieties was observed following alkaline treatment. This reduction in lignin- and hemicellulose-associated peaks demonstrated effective elimination of non-cellulosic constituents and subsequent exposure of cellulose microfibrils at fiber surfaces [23].

These spectral transformations indicate enhanced interfacial compatibility: the treatment effectively removes amorphous non-cellulosic layers, thereby augmenting surface hydroxyl group exposure and topographical roughness, which facilitates improved wetting behavior, mechanical interlocking, and hydrogen bonding at fiber–matrix interfaces [24]. Consequently, the diminished intensity of lignin-related peaks corresponds with enhanced fiber–matrix adhesion and superior composite mechanical performance documented in contemporary investigations of natural fiber-reinforced composites.

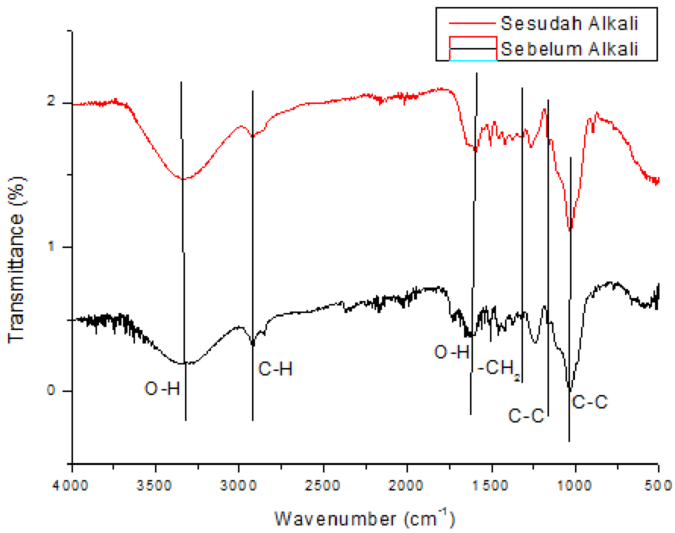

Figure 6. A FTIR Curve of Fiber Sample Before and After Alkalization

Table 1. FTIR Peaks

Band origin	Wave Number (cm^{-1})	
	Before the alkylization	**Before the alkylization**
O-H Stretch	3324,68	3336,09
C-H Stretch	2921,04	2923,89
O-H Deformasi	1615,98	1591,73
$-CH_2$ Deformasi	1316,46	1320,74
C-C Stretch	1032,63	1029,78

These spectral modifications suggest enhanced interfacial potential: the treatment reduces amorphous non-cellulosic layers, thereby increasing surface hydroxyl group exposure and roughness, which promotes improved wetting, mechanical interlocking, and hydrogen bonding at the fiber–matrix interface. Consequently, the diminished lignin-peak intensity aligns with augmented fiber–matrix adhesion and greater composite mechanical performance reported in recent studies on natural fiber composites.

3.2 Tensile Test Results

Tensile tests were carried out to evaluate the ultimate strength, strain, and modulus of elasticity of each composite. Figure 7. shows the tensile strength comparison between fiberglass, basket weave, and twill weave coconut coir composites.

The results indicated that fiberglass exhibited the highest tensile strength at 112.21 N/mm², while the basket weave composite achieved 20.40 N/mm², and the twill weave composite reached 12.98 N/mm². The higher tensile strength in the basket weave composite is attributed to its orthogonal fiber orientation (0°/90°), which distributes stress uniformly across the matrix.

In contrast, the twill weave exhibited reduced tensile performance due to the diagonal interlacing pattern that allows minor fiber slippage and local stress concentration under axial loading. Moreover, the coconut coir fibers' inherent roughness and lower interfacial bonding compared to fiberglass limited tensile load transfer.

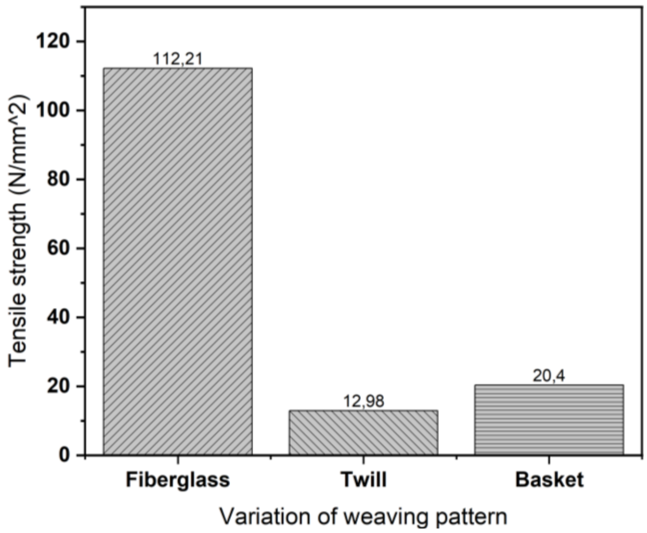

Figure 7. Tensile Strength Comparison

3.3 Bending Test Results

Bending (flexural) testing was performed according to ASTM D790 to determine each composite's ability to resist deformation under a bending load. The results shown in Figure 8 indicate that fiberglass composites achieved the highest flexural strength of 141.71 N/mm², followed by basket weave at 70.03 N/mm², and twill weave at 42.58 N/mm².

The superior flexural performance of the basket weave pattern can be attributed to its orthogonal fiber configuration, which provides enhanced structural rigidity and load-bearing capacity under bending conditions. The perpendicular interlacing of warp and weft fibers creates a more stable geometric framework that effectively resists out-of-plane deformation. Conversely, the twill weave pattern, despite its diagonal fiber arrangement facilitating better stress distribution, exhibited lower flexural strength due to reduced fiber packing density and increased structural compliance within the weave architecture.

Additionally, the natural variability of coconut coir fiber diameter and its lower stiffness compared to glass fibers contributed to the significantly reduced overall bending strength in both natural fiber composites. However, the twill weave composite demonstrated superior flexibility and greater deflection capacity before failure compared to basket weave, indicating better resilience under progressive loading conditions. This characteristic suggests potential application in components requiring moderate flexibility or energy absorption capabilities, whereas basket weave composites are more suitable for semi-structural applications demanding higher load resistance.

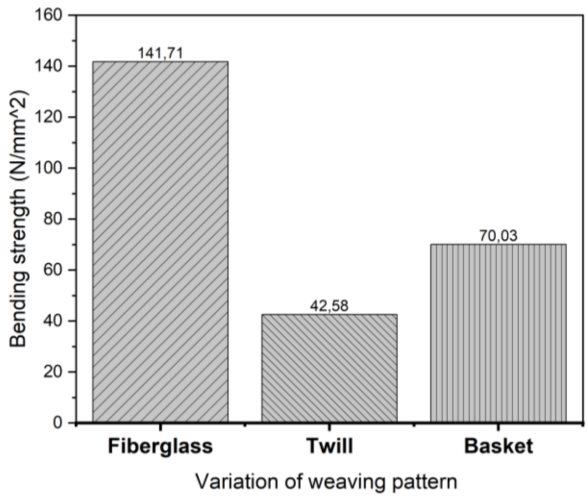

Figure 8. A Bending Strength Comparison

3.4 Impact Test Results

Impact tests were conducted using the Charpy method (ASTM D256) to determine the composite's toughness and energy absorption capability. The data showed Figure 9. that fiberglass composites had the highest impact resistance at 45.216 J/mm², followed by twill weave at 23.608 J/mm², and basket weave at 15.701 J/mm².

The superior impact resistance of the twill weave pattern compared to basket weave can be attributed to its diagonal fiber orientation, which facilitates more effective energy dissipation through multiple fiber directions. This multiaxial weave architecture enables extensive energy absorption mechanisms including fiber-matrix debonding, progressive delamination, and fiber pull-out, while simultaneously creating a tortuous crack propagation path that minimizes catastrophic failure. The diagonal configuration allows for greater structural compliance, permitting controlled deformation before ultimate failure and thereby maximizing energy dissipation capacity.

Conversely, the basket weave's orthogonal (0°/90°) fiber arrangement, despite demonstrating superior performance under quasi-static flexural loading conditions, exhibits limited energy dissipation capability under high strain-rate impact conditions. The rigid geometric framework constrains deformation modes, resulting in predominantly brittle fiber fracture with minimal plastic energy absorption. Consequently, basket weave composites tend to fail more abruptly under sudden impact loads, with crack propagation following direct paths along the orthogonal fiber grid.

The substantial performance gap between natural fiber composites and fiberglass (approximately 52-66% reduction) reflects inherent differences in fiber mechanical properties, particularly elastic modulus and interfacial bonding strength. Overall, the impact results indicate that twill weave composites are more suitable for applications requiring shock absorption or impact energy dissipation, such as automotive interior panels or protective packaging components, whereas basket weave composites perform optimally under static structural loading conditions where dimensional stability and rigidity are prioritized.

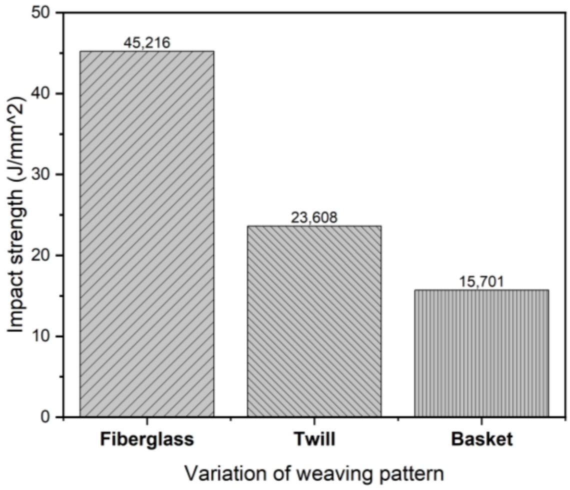

Figure 9. A Impact Strength Comparison

The experimental findings from tensile, flexural, and impact testing revealed that the mechanical actions of composite materials is predominantly governed by the weaving architecture and the quality of fiber-matrix interfacial adhesion.

The basket weave configuration demonstrated superior tensile performance attributed to its orthogonal (0°/90°) fiber alignment, which facilitates equitable stress distribution in both the warp and weft directions. This architectural arrangement minimizes stress concentration phenomena, consequently yielding enhanced ultimate tensile strength values [13]. Nevertheless, the inherent structural rigidity of this pattern adversely affects its deformation capacity and energy dissipation characteristics under flexural and impact loading conditions.

Conversely, the twill weave architecture, distinguished by its diagonal interlacement pattern, exhibited enhanced compliance that translated to improved impact resistance. The oblique fiber orientation enables more effective load redistribution through interlaminar stress transfer mechanisms, thereby mitigating catastrophic brittle fracture modes [5].

Additionally, alkaline treatment using 15% NaOH solution for 2 hours successfully modified the coconut fiber surface chemistry through selective removal of hemicellulose, lignin, and hydrophobic surface contaminants, as evidenced by FTIR spectroscopic analysis. This chemical functionalization enhanced fiber-matrix interfacial adhesion, resulting in increased mechanical performance of the composite system [25].

Although synthetic glass fiber-reinforced composites maintained superior mechanical properties across all evaluated parameters, coconut coir fiber composites particularly those employing twill weave patterns demonstrated acceptable mechanical stability coupled with significant environmental benefits, including renewable sourcing, biodegradability, and economic viability.

Consequently, the synergistic combination of weaving pattern optimization and surface chemical treatment presents a viable pathway for advancing coconut fiber-reinforced composites as sustainable engineering materials for industrial applications.

4. Conclusion

Based on the discussion of data and analysis in this research and discussion, it can be concluded that:

1. Alkali treatment using 15% NaOH for 2 hours effectively reduced lignin and hemicellulose, improving adhesion between fiber and matrix as confirmed by FTIR analysis.
2. Weaving pattern variation significantly affected mechanical performance: Basket weave showed the highest tensile strength (20.40 N/mm^2) and superior bending (70.03 N/mm^2) better twill weave
3. Fiberglass composites still showed higher strength overall (112.21 N/mm^2 tensile; 141.71 N/mm^2 bending and 45.216 J mm^2 Impact).
4. Coconut coir composites, despite their lower mechanical properties, offer strong potential for eco-friendly applications in automotive interiors, decorative panels, and semi-structural products.

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