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Tensile Test Analysis with Directional Variation of Composite Fibers Combining Sisal Fiber and Polyester Matrix Coconut Fiber as Materials on Aircraft

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ABSTRACT

The increasing demand for sustainable and lightweight materials in the aviation industry has driven interest in natural fiber–reinforced composites as alternatives to conventional synthetic fibers. This study explores the mechanical performance, particularly tensile strength, of hybrid composites made from sisal and coconut fibers embedded in a polyester matrix, focusing on the influence of fiber orientation. Unlike previous studies that primarily investigated single natural fibers, this work evaluates a hybrid configuration with three orientations (0°, 45°, and 90°). Composites were fabricated using the hand lay-up technique and tested according to ASTM D3039 standards with a Universal Testing Machine (UTM). Results show that fiber orientation substantially influences tensile properties, with the 90° arrangement achieving the highest modulus of elasticity (2.312 GPa), followed by 0° (1.742 GPa) and 45° (1.245 GPa). These findings confirm the crucial role of fiber alignment in stress transfer and demonstrate that sisal–coconut composites can deliver competitive mechanical performance. The study contributes novel insights into hybrid natural fiber composites and suggests their potential use as sustainable alternatives for non-primary structural applications in lightweight aircraft.

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INTRODUCTION

The pursuit of lightweight, high-strength, and sustainable materials has intensified in the aerospace sector over the past two decades, driven by the need to enhance aircraft efficiency while minimizing environmental impact. Traditional structural materials such as aluminum alloys, titanium, and synthetic fiber–reinforced composites (e.g., carbon and glass fibers) have long dominated the industry due to their superior mechanical performance and durability (Baker & Scott, 2011; Prasad & Narayan, 2020). However, their high production costs, energy-intensive processing, and end-of-life recycling challenges limit their long-term sustainability (Sharma et al., 2020). These constraints have stimulated growing interest in natural fiber composites, which offer mechanical competitiveness alongside advantages in availability, cost-effectiveness, and environmental performance.

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Natural fibers including jute, hemp, flax, sisal, and coconut coir are abundant in tropical regions and possess diverse mechanical properties suitable for composite reinforcement (Ahmed et al., 2018; Patel et al., 2021). Sisal (Agave sisalana) fibers exhibit relatively high tensile strength, low density, and strong adhesion to polymer matrices, making them attractive for structural reinforcement (Ali et al., 2020). Coconut coir (Cocos nucifera), a widely available agricultural by-product, provides excellent elasticity, seawater resistance, and thermal stability, though its tensile strength is lower compared to sisal or flax (Neto et al., 2015; Huda, 2018). When combined, sisal contributes rigidity and strength, while coir offers toughness and flexibility, suggesting that hybridization could yield composites with balanced performance.

To date, natural fiber composites have been extensively studied in the automotive, marine, and construction industries (Satyanarayana et al., 2021; Khalid et al., 2022). In aerospace applications, however, most studies emphasize carbon/natural fiber hybrids or advanced resins reinforced with single natural fibers (Faruk et al., 2019; Pickering et al., 2020). Research specifically addressing sisal–coconut hybrid composites remains scarce, particularly regarding their mechanical behavior under tensile loading with varying fiber orientations. Existing works often evaluate either sisal–polyester or coir–polyester systems individually, leaving a gap in understanding their combined reinforcement potential (Das et al., 2021; Mehta & Singh, 2022).

This gap is significant because fiber orientation critically influences stress transfer and overall composite performance, yet its role in hybrid natural fiber systems has not been systematically quantified. Furthermore, few studies benchmark natural fiber composites against aerospace testing standards such as ASTM D3039 or Federal Aviation Regulations (FAR) Part 25. Addressing this knowledge deficit is essential to assess the feasibility of deploying natural fiber composites in secondary or non-critical aircraft structures—such as interior panels, fairings, and unmanned aerial vehicle (UAV) components—where sustainability and cost reduction are prioritized over maximum load-bearing capacity.

Accordingly, the present study investigates the tensile properties of sisal–coconut fiber composites reinforced with polyester resin, with a specific focus on three fiber orientations (0°, 45°, and 90°). By examining modulus of elasticity, tensile strength, strain response, and failure mechanisms, this research provides a systematic evaluation of fiber orientation effects and benchmarks the findings against aviation material standards. The novelty of this work lies in its targeted assessment of a sisal–coconut hybrid composite for aerospace-relevant applications, contributing new insights into the potential of sustainable natural fiber reinforcements in lightweight aircraft design.

METHOD

This study employed an experimental quantitative approach with laboratory-based tensile testing to investigate the effect of fiber orientation on the mechanical properties of hybrid natural fiber composites. The composites were fabricated using sisal (Agave sisalana) and coconut coir (Cocos nucifera) fibers as reinforcements in a polyester resin matrix. Fiber orientation (0°, 45°, and 90°) served as the independent variable, while tensile strength and modulus of elasticity were measured as dependent variables. All procedures adhered to ASTM D3039/D3039M-17 standards for polymer composite tensile testing.

Composite laminates were fabricated by hand lay-up, followed by curing at ambient temperature for 24 hours. Rectangular specimens were cut from the cured laminates using a diamond saw to dimensions of 250 mm × 25 mm × 3 mm in accordance with ASTM D3039/D3039M-17 guidelines. Each fiber orientation configuration (0°, 45°, and 90°) was prepared in five replications to ensure statistical reliability. Tensile tests were performed using a Universal Testing Machine (Instron 5982) with a maximum load capacity of 100 kN. A constant crosshead speed of 2 mm/min was applied. Load (N) and displacement (mm) were recorded automatically through Bluehill® software. Failure modes were visually inspected and classified according to ASTM failure codes, including fiber breakage, matrix cracking, delamination, and fiber pull-out.

Data Analysis

Tensile strength (σ) was determined using Equation (1):

$$\sigma = \frac{F}{A}$$

where FFF represents the maximum tensile load (N) and AAA the cross-sectional area of the specimen (mm²). Statistical analysis was conducted using one-way ANOVA to compare the effects of fiber orientation on tensile performance. Experimental results were benchmarked against reported values for aerospace-grade materials such as aluminum alloys, carbon fiber composites, and titanium alloys (Baker & Scott, 2011; Khalid et al., 2022).

Materials

The composite specimens were fabricated using a 1:1 ratio of sisal and coconut fibers as reinforcement with polyester resin as the matrix. Sisal fibers were sourced from locally cultivated *Agave sisalana* plants in East Java, Indonesia. These fibers were selected because of their favorable mechanical properties, including high tensile strength (468–640 MPa), low density, and strong interfacial adhesion potential with polymer matrices (Das et al., 2021; Neto et al., 2015).

Coconut coir fibers were collected from mature coconuts, thoroughly cleaned to remove residual lignin and dust, and subsequently dried under natural sunlight to reduce moisture content. Coir fibers are valued for their flexibility, impact resistance, and inherent hydrophobicity, making them advantageous for structural reinforcement in composite materials (Huda, 2018; Mehta & Singh, 2022). The binding matrix employed was Yukalac 157 BQTN unsaturated isophthalic polyester resin, which is commonly used in aerospace-grade composite applications due to its cost-effectiveness and reliable mechanical performance. To initiate the curing process, methyl ethyl ketone peroxide (MEKP) was used as the hardener, added at a ratio of 100:1 by weight to the resin, as per the supplier's guidelines. A catalyst content of 1% of the total resin mass was also incorporated to ensure proper cross-linking during polymerization.

The composite specimens were manufactured using the hand lay-up technique, which is one of the most widely applied methods for natural fiber–reinforced composites due to its simplicity and cost-effectiveness (Satyanarayana et al., 2018; Jawaid & Thariq, 2017). The process began with the preparation of molds, which were cleaned thoroughly and lubricated with a thin layer of wax to prevent adhesion of the composite to the mold surface. Sisal and coconut fibers were then arranged inside the mold cavity according to predetermined orientations of 0°, 45°, and 90°, ensuring consistent fiber alignment across specimens. A polyester resin was mixed with a catalyst at the recommended ratio to initiate polymerization, and the mixture was carefully dripped into the mold to fully impregnate the fibers. Manual compaction was applied using the hand lay-up method to eliminate trapped air and improve fiber–matrix bonding. The composites were left to cure under ambient conditions for 24 hours to allow complete hardening. After curing, the plates were removed from the molds and cut into standardized test specimens following ASTM D3039 guidelines for tensile testing. This process ensured that all specimens had consistent geometric and structural characteristics suitable for mechanical evaluation.

The composite manufacturing process was carried out using the hand lay-up method, which is commonly employed in fabricating natural fiber–reinforced composites due to its simplicity and effectiveness in producing high-quality laminates (Jawaid & Thariq, 2017; Satyanarayana et al., 2018). The procedure began with the preparation of molds, which were thoroughly cleaned and coated with a thin layer of wax to prevent adhesion between the composite and mold surface. Sisal and coconut fibers were then carefully arranged inside the mold according to the specified orientations of 0°, 45°, and 90°, ensuring uniform alignment and fiber distribution. A polyester resin was mixed with a catalyst at the recommended ratio to initiate the curing reaction, and the mixture was gradually poured or dripped into the mold to fully impregnate the fibers. Manual compaction was performed through hand lay-up techniques to remove trapped air bubbles and enhance the bonding between fibers and the polymer matrix. The filled molds were then left to cure under ambient room temperature conditions for approximately 24 hours, allowing the resin to harden completely and achieve structural stability. After curing, the composite laminates were removed from the molds and cut into standardized specimen dimensions in accordance with ASTM D3039 guidelines for tensile testing.

In this study, three types of composite specimens were prepared based on the orientation of the reinforcing fibers within the polyester matrix. The first type, designated as Specimen A, consisted of fibers aligned at 0° relative to the applied tensile load, enabling the fibers to directly resist the external force. The second type, Specimen B, featured fibers arranged at a 45° orientation, which allowed the material to demonstrate intermediate mechanical behavior influenced by both fiber and matrix contributions. The third type, Specimen C, contained fibers positioned at a 90° orientation to the applied load, representing the least favorable alignment in terms of tensile resistance, as the matrix bore most of the load while the fibers contributed minimally. This classification of specimens was designed to evaluate the effect of fiber orientation on the tensile strength of natural fiber–reinforced composites in accordance with standard experimental practices (ASTM D3039).

Natural fiber–based composite materials consist of two main components: a matrix and a reinforcement. The matrix functions as a binder that holds the material together and provides its overall shape, while the reinforcement primarily contributes to the mechanical properties, such as strength and stiffness. Traditional reinforcements, such as carbon fibers, have been widely applied in aerospace and automotive industries due to their superior strength-to-weight ratio. However, carbon fiber is expensive to produce and is not environmentally sustainable, creating concerns for industries that are seeking greener alternatives (Baker & Scott, 2011; Jawaid & Abdul Khalil, 2015). In contrast, natural fibers such as sisal and coconut have gained attention because they are abundant, cost-effective, lightweight, and biodegradable. These characteristics make them particularly promising as reinforcements in composite materials aimed at applications where environmental impact and affordability are significant considerations (Pickering et al., 2016).

Among the many types of natural fibers, sisal and coconut fibers are notable due to their wide availability in tropical countries, including Indonesia. Sisal fiber (Agave sisalana) is obtained from the leaves of the agave plant and is categorized as a lignocellulosic fiber. Its composition typically consists of 60–70% cellulose, along with hemicellulose and lignin, which contribute to its mechanical strength and durability (Bledzki & Gassan, 1999). These properties make sisal fibers highly suitable for reinforcement in polymer composites, as they provide significant tensile strength while remaining lightweight. Coconut fiber, commonly referred to as coir, is extracted from the husk of coconuts and is characterized by its toughness and resistance to saltwater degradation. Although coconut fiber generally has lower tensile strength compared to sisal, it offers excellent energy absorption and impact resistance, making it a valuable component in composite materials (George, Bhagawan, & Thomas, 2001). When combined with a polymer matrix such as polyester, both sisal and coconut fibers can enhance the composite's mechanical performance, while offering a sustainable alternative to synthetic reinforcements

Sisal fiber is widely recognized for its favorable physical and mechanical characteristics, which make it one of the most important natural fibers in composite development. Typically, sisal fibers exhibit a color ranging from ivory white to pale yellow, depending on the extraction and drying processes. Their length can vary between 0.5 and 2 meters, offering flexibility for use in different reinforcement configurations (Mohanty, Misra, & Drzal, 2001). With a density of approximately 1.45 g/cm^3, sisal fibers are significantly lighter than conventional synthetic fibers such as glass fiber, making them particularly advantageous for applications that demand a high strength-to-weight ratio, including in aerospace and automotive components (Pickering et al., 2016).

Mechanically, sisal fibers demonstrate a tensile strength in the range of 400–700 MPa and a modulus of elasticity between 9 and 20 GPa, which allows them to provide adequate stiffness and load-bearing capability in polymer composites (Bledzki & Gassan, 1999). These properties are sufficient to improve the mechanical performance of the composite, particularly in applications where moderate strength is required without excessive weight. In addition to their mechanical properties, sisal fibers offer several practical advantages: they are strong, rigid, wear-resistant, relatively inexpensive, and biodegradable, which aligns with the increasing demand for environmentally friendly engineering materials (Jawaid & Abdul Khalil, 2015).

Despite these advantages, sisal fibers are not without limitations. One of their main drawbacks is their hydrophilic nature, which leads to a high tendency to absorb moisture. This characteristic can negatively affect the fiber–matrix interfacial bonding and reduce the overall mechanical performance of the composite, particularly under humid conditions (John & Thomas, 2008). To overcome this limitation, chemical treatments such as alkali treatment, silane coupling, or acetylation are often applied to improve fiber surface roughness and compatibility with polymer matrices, thereby enhancing the adhesion and mechanical performance of the resulting composites (Li, Tabil, & Panigrahi, 2007).

Sisal fibers are often used for the manufacture of ropes, carpets, industrial textiles, as well as introduced in engineering as a reinforcing material in polymer matrix-based composites. Due to its good mechanical properties, sisal has great potential as a substitute for synthetic fibers for lightweight structural components.

Coconut fiber, commonly referred to as coir fiber, is a natural lignocellulosic fiber obtained from the mesocarp or husk of the coconut fruit. As Indonesia is one of the world's largest producers of coconuts, the country has enormous potential to utilize coconut husk waste as a raw material for environmentally friendly industries and sustainable composite development (Satyanarayana, Guimarães, & Wypych, 2007). Unlike other agricultural by-products, coconut fiber is particularly valued for its durability in harsh environments, making it suitable for applications where moisture and salinity are major concerns. Physically, coconut fibers vary in color from light brown to dark brown and typically have a fiber diameter ranging from 100 to 450 μm. Their density, approximately 1.15–1.25 g/cm³, is slightly lower than that of sisal, giving them a weight advantage in lightweight material applications (Bledzki & Gassan, 1999). Mechanically, coconut fibers exhibit a tensile strength in the range of 100–250 MPa, with a modulus of elasticity between 4 and 6 GPa. While these values are lower than those of sisal fibers, coconut fibers compensate with unique properties such as excellent elasticity, natural resistance to seawater, and stability under varying weather conditions (George, Bhagawan, & Thomas, 2001).

In addition to their mechanical properties, coconut fibers possess remarkable thermal and acoustic insulation capabilities, making them useful for specialized applications in industries that require energy absorption or soundproofing (Pickering et al., 2016). However, despite their advantages, coconut fibers also have several limitations. Their tensile strength is lower compared to sisal, and their relatively coarse surface morphology can hinder fiber–matrix adhesion in composites. As with sisal, chemical surface treatments or hybridization with other fibers are often necessary to improve bonding with polymer matrices and enhance the performance of coconut fiber–reinforced composites (Li, Tabil, & Panigrahi, 2007).

Currently, coconut fibers are widely applied in the production of mats, ropes, car seats, insulation boards, and partition panels. Within composite technology, coir serves primarily as a reinforcement material that contributes flexibility and superior energy absorption, allowing composites to withstand impact or dynamic loading conditions more effectively. These properties make coconut fiber particularly valuable in non-structural applications of the automotive and aerospace industries, where lightweight, flexible, and eco-friendly materials are increasingly in demand (Jawaid & Abdul Khalil, 2015).

Table1: Comparison of Mechanical Properties of Sisal Fiber and Coconut Fiber

Parameters	Sisal Fiber	Coconut Fiber
Tensile Strength (MPa)	400–700	100–250
Modulus of Elasticity (GPa)	9–20	4–6
Density (g/cm³)	~1.45	~1.20
Water Resistance	Keep	Excellent
Stiffness	Tall	Low
Biodegradation Resistance	Good	Good

The combination of sisal and coconut fibers within a single composite structure demonstrates the potential to produce a material that balances strength with flexibility. Sisal fibers contribute high tensile strength and rigidity, while coconut fibers provide additional flexural resistance and favorable insulating properties. This synergy creates a composite with characteristics that are particularly suitable for non-structural applications in the aerospace sector, including interior panels, secondary components, and aircraft fairings, where reduced weight and environmental sustainability are desirable.

Another critical factor in determining the mechanical performance of fiber-reinforced composites is the orientation of the fibers within the matrix. Fiber direction directly affects the way stress is distributed when a tensile load is applied. Specimens with fibers aligned at 0° to the load direction exhibit the highest tensile strength, as the fibers are positioned to carry the load efficiently and resist failure. At 45° orientation, the material undergoes a combination of shear and tensile forces, which reduces overall tensile performance but can provide enhanced resistance against complex loading conditions. In contrast, fibers oriented at 90° to the loading direction typically yield the lowest tensile strength, as they are unable to directly counteract the applied stress. However, when supported by a sufficiently strong matrix, even perpendicular fibers can contribute to improved stress distribution across the composite (ASTM, 2002).

In this study, tensile testing was performed using a Universal Testing Machine (UTM) at a constant crosshead speed of 5 mm/min. The data collected included maximum force, maximum displacement, and modes of failure, which together provided insights into the effects of fiber orientation on the tensile behavior of the sisal–coconut fiber composites. These results are essential in evaluating the feasibility of such composites for aerospace applications, particularly in components that are subjected to varied loading conditions

RESULTS AND DISCUSSION

The composite manufacturing process produced a sisal–coconut fiber composite with a relatively homogeneous structure and good solidity after the curing stage. Observations during fabrication and post-curing analysis indicated that the hand lay-up method was effective in achieving lamination between the polyester matrix and the natural fibers. The manual impregnation of resin ensured that the fibers were adequately wetted, which is critical for fiber–matrix adhesion and the overall mechanical performance of the composite. Although hand lay-up is a relatively simple and low-cost technique, it remains one of the most widely used fabrication methods for natural fiber–reinforced composites due to its practicality and ability to produce consistent results when carefully controlled (Bakar et al., 2010; Jawaid & Khalil, 2015).

Table 2: Tensile Test Results

Specimens	Modulus of Elasticity (GPa)	Max Style (N)	Displacement (mm)
A (0°)	1,742	1,982.5	8.2
B (45°)	1,245	1,323.4	10.1
C (90°)	2,312	2,678.1	5.1

Specimen C shows the best performance because the fibers are in a direction parallel to the tensile force, so they are able to withstand higher stresses. In contrast, specimen B shows the lowest value because the diagonal fiber orientation causes an uneven distribution of the load.

To evaluate the feasibility of sisal–coconut fiber composites in the aviation industry, it is necessary to compare their tensile performance against the minimum strength standards commonly applied to aircraft materials. Tensile strength is one of the most important parameters in determining the suitability of materials for structural applications. Sisal fibers typically demonstrate tensile strengths in the range of 500–800 MPa, depending on the quality of the fiber and the processing methods employed. Coconut fibers, by contrast, exhibit lower tensile values, ranging from approximately 250–700 MPa, while polyester resin—the matrix used in this study—has a tensile strength in the range of only 30–60 MPa. The combination of these components, therefore, produces composites with intermediate properties that depend strongly on fiber orientation, volume fraction, and fiber–matrix adhesion.

In comparison, aircraft structural materials specified in standards such as the Federal Aviation Regulations (FAR 25) and Joint Aviation Requirements (JAR 25) typically demand much higher strength values. Aluminum alloys such as 2024 and 7075 exhibit tensile strengths of 300–500 MPa, titanium alloys range between 900 and 1200 MPa, and advanced carbon or aramid fiber composites can reach values of 600–1500 MPa depending on fiber orientation and laminate design (Baker & Scott, 2011; Peters, 2019). These figures indicate that natural fiber composites reinforced with polyester resin fall below the minimum requirements for structural applications in commercial and military aircraft.

Nevertheless, while sisal–coconut composites are not competitive with high-performance metals or synthetic composites in terms of ultimate tensile strength, they demonstrate significant potential for non-structural and secondary applications. Their strength levels are sufficient for use in light aviation contexts such as small trainer aircraft, unmanned aerial vehicles (UAVs), or drones, where weight reduction and cost efficiency are critical, and where the loads imposed on materials are significantly lower than those in large transport aircraft. Furthermore, their renewable, biodegradable nature positions them as an environmentally sustainable alternative, particularly for interior panels, fairings, and other non-load-bearing components that do not directly compromise flight safety.

In summary, while natural fiber composites reinforced with sisal and coconut fibers cannot meet the high tensile strength standards required for primary aircraft structures, they can provide valuable contributions to the aviation sector in applications where moderate mechanical performance, low cost, and sustainability are prioritized.

However, if the focus of material development is shifted toward lighter applications or lower-load aircraft, natural fiber–based composites may still hold considerable promise. Their relatively moderate tensile strength can be compensated for in applications where the mechanical demands are less stringent, such as interior panels, fairings, or secondary components in light aircraft and unmanned aerial vehicles (UAVs). In these contexts, the advantages of natural fibers—such as low density, cost-effectiveness, and biodegradability—become more significant. With further customization through fiber surface treatments, hybridization with synthetic reinforcements, or optimization of the fiber–matrix interface, sisal–coconut composites could evolve into viable, eco-friendly alternatives that contribute to reducing the environmental footprint of the aviation industry without compromising safety in appropriate applications.

Failure Mode Analysis

Figure 1: Tension Test

In materials engineering, failure analysis is a crucial step in understanding how and why a material or structure becomes damaged when subjected to a load. In the present study, failure analysis is used to elucidate the mechanisms of damage in sisal- and coconut-fiber composites with a polyester matrix, particularly under tensile loads with variations in fiber direction.

The composites under investigation possess several defining characteristics. As with most fiber-reinforced composites, they exhibit anisotropic properties, meaning that their mechanical performance strongly depends on fiber orientation. The primary weakness lies in the interface bond between the fibers and the polyester matrix. In addition, natural fibers tend to absorb moisture and undergo dimensional changes, which can accelerate degradation and reduce durability.

Several types of failure mechanisms are typically observed in natural fiber–based composites. The first is **fiber breakage**, which occurs when the applied load exceeds the maximum tensile strength of the fiber. This mode is most prevalent at a 0° orientation, where fibers are aligned parallel to the load direction and thus carry the greatest portion of the stress. In sisal–coconut composites, this type of failure is often identified by uniform fiber rupture at the peak strain point. A second mode is **delamination**, characterized by separation between layers or between the fiber and matrix components. This failure is especially common at ±45° and 90° orientations, where shear and transverse stresses act at the fiber–matrix interface. Delamination typically initiates from microdefects, voids, or regions of weak adhesion.

Another common mode is **fiber pull-out**, which occurs when the bond between fiber and matrix is insufficient to transfer load effectively. In such cases, fibers are pulled out without undergoing significant internal fracture. This mode of failure is particularly pronounced in composites containing untreated natural fibers or those lacking chemical surface modifications. Additionally, **micro-matrix cracking** may occur within the polyester resin. These small-scale cracks appear early in the loading process due to uneven stress distribution and often precede large-scale failure when combined with delamination or pull-out. Finally, **shear**

failure can develop, especially in fibers oriented at ±45°, where high shear stresses lead to diagonal cracks, matrix rupture, and extensive delamination. This severely reduces the ability of the composite to transfer load between layers.

The occurrence and severity of these failure modes are influenced by several factors. Fiber orientation plays a central role in determining the stress distribution within the composite and the dominant mode of failure. Fiber volume fraction (Vf) is equally important, since insufficient fiber content results in poor load transfer, while excessive content can reduce bonding effectiveness with the matrix. Fiber–matrix adhesion also has a decisive influence, as weak bonding typically promotes pull-out and delamination. Moreover, porosity and manufacturing defects, such as entrapped air or uneven lamination, often act as crack initiation sites. The type of load applied—whether pure tensile, shear, or combined—further dictates the resulting crack patterns and failure progression.

From an aviation perspective, these findings underscore the critical importance of understanding and mitigating failure mechanisms in natural fiber–based composites. In aircraft applications, undetected or unexpected failure can have catastrophic consequences. Therefore, the integration of such composites requires advanced non-destructive inspection (NDI) methods to detect early-stage damage, the adoption of conservative design principles with high safety factors, and a strict limitation of these materials to non-structural components. Until further performance optimization is achieved, natural fiber composites such as sisal–coconut with polyester matrices should not be employed in primary aircraft structures where structural integrity is paramount.

To reduce the risk of premature failure and to enhance the overall performance of sisal–coconut fiber composites with a polyester matrix, several preventive strategies can be considered. One of the most effective approaches is the application of chemical treatments, such as alkalization or silanization, to the fibers prior to composite fabrication. These treatments improve surface roughness, increase chemical compatibility, and significantly enhance fiber–matrix adhesion. In addition, optimizing fiber orientation plays a crucial role in ensuring a more uniform distribution of stresses, thereby minimizing localized failures.

Manufacturing techniques also require careful refinement. The adoption of advanced processes such as vacuum bagging or resin infusion can greatly reduce porosity, eliminate voids, and improve fiber wetting. By minimizing defects introduced during fabrication, these methods help achieve a more consistent and reliable composite structure. Another viable strategy involves hybridization, where natural fibers are combined with synthetic reinforcements such as glass or carbon fibers. This approach leverages the environmental benefits of natural fibers while enhancing mechanical strength and durability, thereby making the composite more suitable for demanding applications.

Failure observations from tensile testing further highlight the relationship between fiber orientation and the dominant mode of failure. Specimens with fibers aligned at 0° (Specimen A) exhibited an LGM (Lateral Gage Middle) failure mode, characterized by fiber pull-out. This indicates that while fibers bear the primary load effectively, insufficient interfacial adhesion can lead to slippage rather than fracture. Specimens oriented at 45° (Specimen B) demonstrated an AGM2 (Angled Gage Middle) failure mode, where debonding between fibers and matrix was observed alongside fiber pull-out, reflecting the combined action of shear and tensile stresses at this orientation. Finally, specimens oriented at 90° (Specimen C) experienced a LAB (Lateral at Grip Bottom) failure mode. In this case, the failure was dominated by matrix cracking due to excessive transverse loads, which exceeded the binding capability of the polyester resin.

These results emphasize that improving adhesion, controlling porosity, and tailoring fiber orientation are essential steps in mitigating common failure modes such as pull-out, debonding, and matrix cracking. Through such preventive measures, natural fiber–based composites can achieve more reliable mechanical performance, broadening their potential applications in lightweight engineering structures.

The tensile test conducted on specimen K45 provided valuable insights into the mechanical behavior of the sisal–coconut composite under load. The specimen, with a thickness of 3.52 mm and width of 14.1 mm, was tested using a bottom support span of 120 mm. The results indicated a maximum force of 39.83 N and a maximum displacement of 10.77 mm before failure occurred. These values reflect the ability of the composite to sustain moderate tensile loading while also demonstrating a degree of flexibility, as evidenced by the relatively high displacement prior to fracture.

Although the maximum force achieved is significantly lower compared to synthetic composites such as carbon or glass fiber–reinforced polymers, the results remain encouraging when considered in the context of lightweight, non-primary aircraft applications. The balance between moderate strength and notable ductility makes this composite suitable for secondary structures, interior panels, fairings, and other components where mechanical demands are less stringent but weight reduction and environmental sustainability are important factors. This performance highlights the potential of natural fiber–based composites as an eco-friendly alternative in the aviation industry. With further optimization, such as fiber surface treatment, improved resin infusion techniques, and hybridization with synthetic fibers, the tensile properties of sisal–coconut composites could be enhanced to better align with aerospace standards for broader application.

Tensile Test Results of Sisal Fiber and Coconut Fiber Composites with Polyester Matrix

Tensile testing was carried out to evaluate the mechanical properties of composites manufactured from a combination of sisal fiber and coconut fiber with a polyester matrix. The purpose of this testing was to determine the maximum tensile strength, maximum strain, and modulus of elasticity of specimens with different fiber orientations (0°, 45°, and 90°). The test was designed to highlight how fiber alignment influences the tensile behavior of natural fiber–based composites, which is a critical factor in predicting their performance in aerospace and other engineering applications.

All specimens were prepared under controlled laboratory conditions using the hand lay-up manufacturing method. The composite panels were fabricated with a fiber volume fraction of approximately 30%, which is considered adequate for ensuring a representative distribution of fiber and matrix while maintaining structural consistency. Each specimen was cut according to ASTM standards to a length of 250 mm, width of 25 mm, and thickness of 3 mm, ensuring uniformity across all test samples. To account for variability and improve reliability, three specimens were tested for each fiber orientation (0°, 45°, and 90°).

The choice of sisal and coconut fibers reflects the balance between mechanical performance and sustainability. Sisal fiber contributes significantly to tensile strength and stiffness, while coconut fiber provides additional flexibility and energy absorption under load. When combined with polyester resin, the resulting composite specimens display anisotropic properties, meaning their tensile performance varies depending on fiber orientation relative to the applied load.

The results obtained from the materials testing laboratory demonstrate the relationship between fiber orientation and tensile strength. Specimens with fibers aligned parallel to the load direction (0°) recorded the highest tensile strength, as the fibers were optimally positioned to resist tensile forces. At 45°, the tensile strength decreased but still indicated acceptable performance due to combined shear and tensile effects. Conversely, specimens oriented at 90° exhibited the lowest tensile strength, as the fibers were perpendicular to the applied load and contributed minimally to resisting tensile stresses.

These results confirm that fiber orientation is a decisive factor in the design of natural fiber composites for practical applications. While the absolute tensile strength values remain lower than those of advanced synthetic composites, the performance achieved is promising for non-structural aircraft applications and other lightweight engineering uses, especially when sustainability and cost-effectiveness are prioritized.

Table 1: Fiber Direction Variation 0° (Parallel to Tensile Direction)

Parameters	Specimen 1	Specimen 2	Specimen 3	Average
Maximum Tensile Strength	95.6 MPa	93.2 MPa	94.7 MPa	94.5 MPa
Maximum Stretch	2,7%	2,5%	2,6%	2,6%
Modulus of Elasticity	3.52 GPa	3.48 GPa	3.50 GPa	3.50 GPa
Failure Mode	Fiber Fracture (Patah Serat)			

The results show that the orientation of the 0° fibers produces the highest tensile strength, as the fibers receive the load directly and parallel to the tensile force. The modulus of elasticity also shows a fairly good value, indicating the rigidity of the material in this direction strongly supports structural applications.

Table 2: 45° Fiber Direction Variation (Diagonal to Pull Direction)

Parameters	Specimen 1	Specimen 2	Specimen 3	Average
Maximum Tensile Strength	64.3 MPa	66.0 MPa	65.2 MPa	65.2 MPa
Maximum Stretch	3,1%	3,0%	2,9%	3,0%
Modulus of Elasticity	2.14 GPa	2.10 GPa	2.12 GPa	2.12 GPa
Failure Mode	Matrix Cracking + Delamination			

At an orientation of 45°, there is a decrease in tensile strength of about 30% compared to the direction of 0°. The tensile force acts indirectly on the fibers, so that more load is borne by the matrix and interface. There is a combination failure, namely cracking in the matrix and delamination between the fiber layers.

Table 3: 90° Fiber Direction Variation (Perpendicular to Tensile Direction)

Parameters	Specimen 1	Specimen 2	Specimen 3	Average
Maximum Tensile Strength	38.7 MPa	37.5 MPa	39.2 MPa	38.5 MPa
Maximum Stretch	2,2%	2,3%	2,1%	2,2%
Modulus of Elasticity	1.75 GPa	1.68 GPa	1.70 GPa	1.71 GPa
Failure Mode	Fiber Pull-Out + Debonding			

The 90° fiber direction indicates the lowest performance in resisting tensile forces. This can be explained by the tensile force acting perpendicular to the fiber, so that the load is transferred predominantly to the interface. The main failures observed were the pull-out of the fibers from the matrix (pull-out) and the release of the interface bonds (debonding), indicating the need for increased adhesion between the fibers and the matrix.

Summary of Test Results

Based on the tensile test results of sisal fiber composites and polyester matrix coconut fibers with variations in fiber direction (0°, 45°, and 90°), it can be concluded that fiber orientation has a very significant influence on the mechanical properties of the material, in particular tensile strength, maximum strain, and modulus of elasticity. The difference in the direction of the fibers leads to variations in the voltage distribution, the load transfer mechanism between the fiber and the matrix, and the dominant failure mode.

0° Fiber Direction – Optimal Mechanical Performance. At the 0° fiber orientation, where the fibers are arranged parallel to the direction of the tensile force, an average tensile strength of 94.5 MPa is obtained, with a maximum strain of 2.6% and an elastic modulus of 3.50 GPa. This value shows that the fiber configuration that is parallel to the tensile force is able to make maximum use of the strengthening function of sisal and coconut fibers. Fiber as the main load-bearing element is able to withstand tensile stress directly and effectively, resulting in the highest mechanical performance compared to other configurations.

The main failure mode in this specimen is fiber fracture, which indicates that the tensile load reaches the maximum strength limit of the fiber before the failure occurs. No significant symptoms of delamination or pull-out were found, which suggests that the bond between the fibers and the matrix is quite good at transferring the load to the maximum point.

45° Fiber Direction – Complex Load Distribution and Combination Failure. At a fiber orientation of 45°, where the fibers are arranged diagonally to the direction of the tensile force, the resulting tensile strength drops to an average of 65.2 MPa. The maximum strain increases to about 3.0%, indicating a greater deformation before the failure. The modulus of elasticity also decreased significantly to 2.12 GPa.

This decrease is due to a more complex voltage distribution mechanism. In this direction, the tensile force is not borne entirely by the fibers, but is mostly distributed through the matrix. This makes the matrix more susceptible to micro-cracking, delamination between layers, and decreased structural integrity. The failures that occur are a combination of cracking in the matrix, delamination, and separation of the fibers from the matrix locally. Although the tensile strength value decreases, this orientation still shows fairly good elasticity due to the deformation contribution of the matrix.

3. 90° Fiber Direction – Lowest Performance and Dominance of Interfacial Failure. The 90° fiber orientation, where the fibers are arranged perpendicular to the direction of the tensile force, provides the lowest tensile strength, which is an average of 38.5 MPa. The modulus of elasticity was recorded at 1.71 GPa with a maximum strain of 2.2%. This decrease in strength and rigidity can be explained by the ineffectiveness of the fibers in bearing tensile loads due to their orientation that is not aligned with the direction of the force. In this configuration, the tensile load is directly received by the matrix, while the fibers only act as fillers.

The failure that occurs is dominated by fiber pull-out and debonding at the interface between the fiber and the matrix. Pull-out shows that the fibers do not contribute optimally to withstand tensile loads due to weak bonds with the matrix. This type of failure also indicates a low efficiency of load transfer from the matrix to the fiber, which causes failure to occur early at relatively small strains. This mechanism is a major concern in the design of natural fiber-based composites, particularly in structures that have to withstand multi-directional loads.

Comparative Analysis with Aircraft Material Standards

When compared to the minimum strength standards for secondary structural materials on aircraft, as listed in the aviation engineering literature (e.g., ASTM D3039 for composite tensile tests), the minimum tensile strength required typically ranges from 150 MPa to 250 MPa depending on the type of fiber and its application. Thus, the maximum tensile strength value of 94.5 MPa obtained from an orientation of 0° is still below the minimum standard for major structural applications in aircraft. Nevertheless, these values can still be considered for secondary or interior components, such as cabin interior panels, duct covers, non-structural insulation, and other non-critical parts, especially when light weight and sustainability are primary considerations.

Practical Implications of Fiber Directional Variation

From these results, it can be concluded that: a) The 0° fiber orientation provides the best performance, making it a top choice for applications that require high tensile strength in one dominant direction; b) A 45° orientation can be used in areas that receive multi-directional loads but with special attention to the risk of delamination; c) 90° orientation should be avoided for structural applications as there is a high risk of interface failure and fiber pull-out; d) Recommendations for Improving Material Performance.

To improve the overall performance of the composite, several actions such as: Perform chemical treatment on the fibers to improve the adhesion between the faces; It uses advanced manufacturing techniques such as vacuum-assisted resin transfer molding (VARTM) to reduce void and improve compactness; Combining natural fibers with synthetic fibers (such as E-glass or carbon) as a hybrid composite to achieve a balance between strength and sustainability.

CONCLUSION

This study analyzed the tensile performance of sisal–coconut fiber composites with a polyester matrix, focusing on the effect of fiber orientation. The results indicate that these natural fiber composites have potential as environmentally friendly, low-cost alternatives for selected applications in the aviation industry. Their advantages include abundant availability, biodegradability, and acceptable mechanical performance for non-structural or light aircraft components. Fiber orientation was found to strongly influence tensile strength. Specimens aligned at 0° demonstrated the highest performance, while 45° specimens showed moderate strength with greater deformation capacity, and 90° specimens exhibited the weakest response due to interfacial failures. This confirms that proper design of fiber alignment is critical to optimizing the mechanical efficiency of natural fiber composites.

When compared with aerospace standards, the tensile strength of sisal–coconut composites remain below that of aluminum, titanium, or carbon fiber, making them unsuitable for primary load-bearing aircraft structures. However, their use in secondary and interior components—such as panels, duct covers, or insulation—remains promising, particularly where sustainability and weight reduction are prioritized. Despite their potential, limitations persist, especially in terms of tensile strength, durability, and sensitivity to environmental factors. Future improvements should focus on fiber surface treatments, hybridization with synthetic fibers, and advanced processing methods to enhance fiber–matrix bonding and reduce defects. With further development, sisal–coconut composites could evolve into viable eco-friendly alternatives that support the aviation industry's sustainability goals.

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