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Mechanical Characterization of Kevlar 49 and Pina Fiber Hybrid Composites

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Abstract

The pursuit of sustainable yet high-performance materials has accelerated research into hybrid composites that combine synthetic and natural fibers. This study investigates the fabrication and characterization of a Kevlar 49/Pina fiber hybrid composite using epoxy resin as the matrix. Kevlar 49, known for its exceptional tensile strength and energy absorption, was employed as the face sheet material, while Pina fiber, a biodegradable reinforcement extracted from pineapple leaves, was incorporated as the core layer. The composite laminates were fabricated using the wet hand lay-up technique and evaluated for tensile, impact, flexural, hardness, and interlaminar shear properties following ASTM standards. The results demonstrated a tensile strength of 65.08 MPa with an average Young's modulus of 3900 MPa, along with moderate ductility (~3.3% elongation). Impact resistance reached an average of 21.2 kJ/mm², indicating effective energy dissipation through synergistic Kevlar fibrillation and Pina fiber pull-out mechanisms. Interlaminar shear strength averaged 125 MPa, confirming good interfacial bonding facilitated by alkali treatment of Pina fibers. Flexural strength at room temperature was 130 MPa but decreased with rising temperature, reflecting the thermal sensitivity of the epoxy matrix. Micro-Vickers hardness tests showed a mean value of 31.27 HV, highlighting moderate surface durability. Scanning Electron Microscopy further validated strong matrix adhesion, limited fiber pull-out, and crack deflection mechanisms contributing to toughness. The study establishes that Kevlar 49/Pina fiber hybrid composites offer a promising balance between performance and sustainability. Their combination of high impact resistance, moderate strength, and environmental benefits makes them suitable for protective gear applications, where energy absorption and structural integrity are critical.

Keywords: Hybrid composites; Kevlar 49; Pineapple fiber; Mechanical properties; Hand lay-up technique

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INTRODUCTION

In recent years, the development of hybrid composites has gained significant attention in materials science and engineering due to their enhanced mechanical properties and potential applications [1–5]. Among various combinations, the integration of high-performance synthetic fibers with natural fibers presents an innovative approach to achieving optimal material characteristics while maintaining environmental sustainability [6,7]. This research focuses on the fabrication and testing of a hybrid composite combining Kevlar 49, a well-established synthetic fiber, with Pina fiber, a sustainable natural fiber derived from pineapple leaves. Kevlar 49, developed by DuPont, has established itself as a remarkable synthetic fiber with exceptional tensile strength-to-weight ratio, making it five times stronger than steel in this aspect. Its applications range from protective equipment to aerospace components, owing to its superior mechanical properties [8,9]. However, despite its outstanding tensile strength, Kevlar 49 exhibits limitations in compressive strength, creating an opportunity for improvement through hybridization with complementary materials. Pina fiber, extracted from pineapple leaves, represents a promising natural fiber alternative that offers several advantages, including biodegradability, low density, and good mechanical properties [10,11]. The average fracture strength of pineapple leaf fiber, combined with its low linear density, makes it an attractive choice for reinforcement in composite materials. Furthermore, the utilization of Pina fiber addresses growing environmental concerns while potentially reducing overall material costs [12,13]. The concept of hybrid composites, where two or more different types of fibers are combined in a single matrix, has emerged as an effective strategy to overcome the limitations of individual fibers while capitalizing on their respective strengths [14]. The matrix material plays a crucial role in such composites, serving as a medium for stress transfer and providing environmental protection to the reinforcing fibers. In this study, epoxy resin (LY-556) with hardener (HY-951) was selected as the matrix material due to its excellent adhesion properties, dimensional stability, and resistance to environmental degradation [15,16]. The fabrication of hybrid composites presents various challenges, including optimal fiber orientation, proper adhesion between different fiber types, and uniform distribution of load throughout the structure [17,18]. The wet hand lay-up technique, despite being one of the simplest methods, offers adequate control over fiber placement and resin distribution, making it suitable for this research. This method allows for the strategic placement of Kevlar 49 layers on the outer surfaces to maximize impact resistance, while the Pina fiber layer in between enhances the overall mechanical properties of the composite [19]. The investigation of mechanical properties in such hybrid composites is essential to understand their behavior under various loading conditions and to determine their suitability for specific applications [20,21]. The comprehensive testing approach adopted in this study includes tensile testing, fracture analysis through Izod impact testing, interlaminar shear strength evaluation, and hardness testing using micro-Vickers equipment [22,23]. These tests provide crucial data about the material's performance under different stress conditions and its potential failure modes [24]. This research aims to contribute to the growing body of knowledge in hybrid composite materials by exploring the synergistic effects of combining Kevlar 49 with Pina fiber [25,26]. The study's findings could have significant implications for industries seeking materials that balance high performance with environmental sustainability [27,28]. Additionally, this work addresses the current trend toward developing materials that meet both engineering requirements and environmental considerations, potentially opening new avenues for applications in automotive, aerospace, and protective equipment industries [29,30]. The systematic investigation of this hybrid composite's fabrication process and mechanical properties will provide valuable insights into the potential of combining synthetic and natural fibers for enhanced material performance, while also addressing the growing demand for sustainable engineering materials [31,32].

MATERIALS AND METHODS

The experimental work utilized Kevlar 49 and pineapple fiber (Pina fiber) as the primary reinforcement materials. Kevlar 49, a para-aramid synthetic fiber known for its high tensile strength-to-weight ratio (3000–3620 MPa), was selected for the face sheets. Pina fiber, extracted from pineapple leaves, was chosen as the core material due to its biodegradability and good mechanical properties (tensile strength of 170 MPa). The matrix system consisted of Araldite LY-556 epoxy resin and Aradur HY-951 hardener mixed in a 100:10–12 ratio by weight. The composite was fabricated using the wet hand lay-up technique. Two layers of Kevlar 49 were placed on either side of a single layer of Pina fiber to form a sandwich structure. The fibers were oriented unidirectionally and bonded with epoxy resin. The laminate was cured at room temperature for 24–48 hours. Test specimens were prepared according to ASTM standards: ASTM D3878 for tensile and Izod impact tests, ASTM D2344 for interlaminar shear strength, and ASTM E384 for hardness testing. Tensile testing was performed on a Universal Testing Machine at a crosshead speed of 5 mm/min and ambient conditions (23°C, 50% humidity). The Izod impact test measured fracture strength, while the interlaminar shear strength test evaluated the delamination resistance. Micro-Vickers hardness testing was conducted with a 0.05 kg load (490 mN). Characterization techniques included stress-strain analysis for determining Young's modulus, yield strength, ultimate tensile strength, and fracture strength. The material's bending behaviour was evaluated through three-point flexural testing, while surface hardness was measured using the Vickers hardness test method with a diamond pyramid indenter. Figure 1 depicts preparation of pine apple fiber (a) harvesting pineapple leaves, (b) fiber extraction, (c) washing and cleaning, (d) drying the fibers. Table 1 shows the properties of kevlar 49 and pina fiber.

Figure 1. Preparation of Pine Apple Fiber (a) Harvesting Pineapple Leaves, (b) Fiber Extraction, (c) Washing and Cleaning, (d) Drying the Fibers

Table 1. Properties of Kevlar 49 and Pina Fiber

Property	Kevlar 49	Pina Fiber
Density (g/cm³)	1.44	1.526
Tensile Strength (MPa)	3000–3620	170
Young's Modulus (GPa)	112	6.21
Elongation at Break (%)	2.4	3
Thermal Conductivity (W/m-K)	0.0400	0.045

Materials Selection and Specifications

The primary reinforcement materials selected for this experimental investigation are Kevlar 49 and Pina fiber, combined with an epoxy resin system. Kevlar 49, a para-aramid synthetic fiber, was chosen for its exceptional tensile strength-to-weight ratio, thermal stability, and resistance to impact. It exhibits a tensile strength in the range of 3000–3620 MPa, a Young's modulus of 112 GPa, density of 1.44 g/cm^3, and an elongation at break of approximately 2.4%. Due to its high stiffness and energy absorption capacity, Kevlar 49 was used as the outer face sheets of the hybrid laminate to maximize strength and impact resistance. Pina fiber, derived from pineapple leaves, was selected as the natural reinforcement component for its biodegradability, low density, and moderate mechanical performance. With a tensile strength of about 170 MPa, a Young's modulus of 6.21 GPa, density of 1.526 g/cm^3, and an elongation at break of nearly 3%, Pina fiber serves as the core layer of the hybrid composite. The use of Pina fiber not only reduces the overall cost and weight of the composite but also promotes sustainability by utilizing an agricultural waste product. Kevlar 49 was employed in its commercial woven mat (plain weave) form, widely available for composite applications. The woven mat offers a balance between in-plane strength and interlaminar stability, making it suitable as outer face sheets for the hybrid laminate. During fabrication, the Kevlar 49 mat layers were aligned in a unidirectional orientation to maximize tensile and impact resistance. Pina fibers, extracted from pineapple leaves, were prepared in short fiber bundles that underwent 5% NaOH alkali treatment to remove impurities and enhance fiber-matrix adhesion. After treatment, the fibers were sun-dried and manually aligned in a unidirectional arrangement to serve as the core reinforcement layer. The use of Pina fibers in aligned short form not only improved stress transfer across the matrix but also ensured reproducibility in hybridization with Kevlar 49. This careful selection of fiber form and orientation ensured that the hybrid laminate effectively combined the high strength and stiffness of Kevlar 49 with the sustainability and toughness of Pina fibers.

The matrix system employed was Araldite LY-556 epoxy resin with Aradur HY-951 hardener, mixed in the ratio of 100:10–12 parts by weight as per manufacturer recommendations. The epoxy resin possesses a viscosity of 10,000–12,000 mPa·s at 25°C and a density of 1.15–1.20 g/cm^3, while the hardener exhibits a viscosity of 10–20 mPa·s at 25°C with a density between 0.91–0.99 g/cm^3. This resin system was selected due to its excellent adhesion, dimensional stability, low shrinkage during curing, and strong compatibility with both synthetic and natural fibers. To ensure proper impregnation of fibers and uniform wet-out, the resin-hardener mixture was prepared immediately prior to fabrication. The gel time of the mixed system ranged from 120–180 minutes at 25°C and about 30 minutes at 40°C, providing sufficient working time during the hand lay-up process. All materials were stored in a controlled environment of 23°C and 50% relative humidity to prevent moisture absorption and surface contamination prior to composite fabrication. The hybrid design, consisting of Kevlar 49 as outer layers and Pina fiber as the core, was selected to exploit the high tensile strength of Kevlar and the sustainability and toughness of Pina fiber, thus achieving a balance between mechanical performance and eco-friendliness. Figure 2 depicts experimental setup and failure observation of composite samples (a) flexural test machine, (b) universal testing machine, (c) delamination.

(a) (b) (b)

Figure 2. Experimental Setup and Failure Observation of Composite Samples (a) Flexural test machine, (b) Universal Testing Machine (UTM), (c) Delamination

Sample Preparation

The composite samples were prepared using the wet hand lay-up technique, which is simple yet effective for polymer matrix composites. First, a release gel was sprayed on the mold surface to prevent adhesion of the polymer to the mold. Thin plastic sheets were placed at the top and bottom of the mold plate to achieve a good surface finish. The fibers were arranged in a specific orientation: two layers of Kevlar 49 were placed on either side of a single layer of pina fiber to form a sandwich structure. This arrangement was designed to maximize impact absorption capabilities while maintaining good compressive properties. To ensure reproducibility, specific processing parameters were carefully maintained during composite fabrication. The resin-to-hardener ratio was fixed at 100:10 by weight, as per the manufacturer's recommendation. After mixing, the resin-hardener system provided a working gel time of approximately 150 minutes at room temperature. The laminates were cured under controlled environmental conditions of 25 ± 2°C and 50 ± 5% relative humidity. During curing, a flat metal plate with an applied load was used to exert a uniform pressure of approximately 0.5 MPa, ensuring proper compaction and minimizing void formation. The curing duration was maintained at 48 hours to achieve

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full polymerization of the epoxy system. These defined parameters allowed consistent fiber impregnation and reproducible mechanical properties across all fabricated specimens. The Kevlar 49 was used in its commercial mat form, while the pina fiber underwent a surface treatment process where it was soaked in 5% NaOH solution for 3–4 hours, then sun-dried for 4–5 hours to remove impurities and enhance fiber-matrix bonding. This mixture was then carefully applied to each layer of fiber using a brush, ensuring uniform distribution. After placing each layer, a roller was used with mild pressure to remove trapped air and excess resin. After stacking all the required layers, the top mold plate was positioned, and pressure was applied. The cured composite plates were removed from the mold and cut into standard test specimens according to ASTM specifications for mechanical testing: ASTM D3878 for tensile and fracture tests, ASTM D2344 for interlaminar shear strength, and ASTM E384 for hardness testing.

The fiber volume fraction of the hybrid laminate was determined based on the mass of fibers incorporated, their respective densities, and the overall composite volume. The Kevlar 49 layers accounted for approximately 32 vol.%, while the Pina fiber core contributed about 18 vol.%. The remaining fraction (50 vol.%) consisted of the epoxy matrix. This ratio reflects the designed configuration with Kevlar 49 as the face sheets and Pina fiber as the core, ensuring a balance between strength, toughness, and sustainability.

Experimental Setup

The hybrid composite was fabricated using the wet hand lay-up technique, which is a simple yet effective method requiring minimal infrastructure. Prior to fabrication, the Pina fibers were treated with 5% NaOH solution for 3–4 hours to remove impurities and enhance the fiber-matrix bonding, followed by drying under sunlight for 4–5 hours. A release gel was first sprayed on the mold surface to prevent adhesion, followed by placement of thin plastic sheets at the top and bottom to achieve good surface finish. The composite was arranged in a specific sequence with two layers of Kevlar 49 on either side (as face sheets) and one layer of Pina fiber in the middle, all oriented unidirectionally to optimize impact absorption and compressive properties. The epoxy-hardener mixture was uniformly spread using a brush, with a roller applied with mild pressure after each layer to remove trapped air and excess polymer. After stacking the required layers, the top mold plate was positioned, and pressure was applied. All tests were conducted under controlled environmental conditions (23°C, 50% humidity) using calibrated equipment including a Universal Testing Machine for tensile and flexural tests, an Izod impact tester, and a Micro Vickers hardness tester. Table 2 shows the Testing Standards and Methods.

Table 2. Testing Standards and Methods

Test Type	Standard Used	Parameters Measured
Tensile Test	ASTM D3039	Strength modulus
Impact Resistance	ASTM D256	Energy absorption
Flexural Test	ASTM D790	Flexural Strength, modulus
Interlaminar Shear Strength	ASTM D2344	Shear strength, delamination
Hardness Test (Micro Vikers)	ASTM E384	Surface hardness (HV)

Testing Procedures

The fabricated Kevlar 49-Pina fiber hybrid composite specimens were subjected to various mechanical tests following standard testing procedures. Tensile testing was performed according to ASTM D3039 standard using a Universal Testing Machine at a crosshead speed of 5 mm/min under controlled environmental conditions (23°C, 50% humidity). Three specimens were tested to ensure repeatability, with results analysed for maximum load, elongation at break, tensile stress, and Young's modulus. Fracture strength was evaluated using the Izod impact test following ASTM D256 standard. Rectangular specimens of dimensions 63 mm × 8.5 mm × 4.8 mm were tested using an impactometer, with impact strength calculated in kJ/mm^2. Interlaminar shear strength testing was conducted according to ASTM D2344 standard to assess the delamination resistance of the composite. The maximum force, stress, strain, and elastic properties were recorded for three samples to ensure consistent results. Hardness evaluation was performed using a micro-Vickers hardness tester following ASTM E384 standard. A load of 0.05 kg (490 mN) was applied, and three indentations were made at different locations to obtain an average hardness value in HV. Additionally, flexural testing was carried out using a three-point bending setup to determine the bending strength of the composite. The test was performed on a universal testing machine with simply supported ends, and the flexural strength was calculated using the formula: F.S = 3lp/2bd, where p is the applied load in Newtons, l is the specimen length, b is the width, and d is the thickness in millimeters. Figure 3 shows the thermal degradation profile (temperature vs. mass loss from tga analysis).

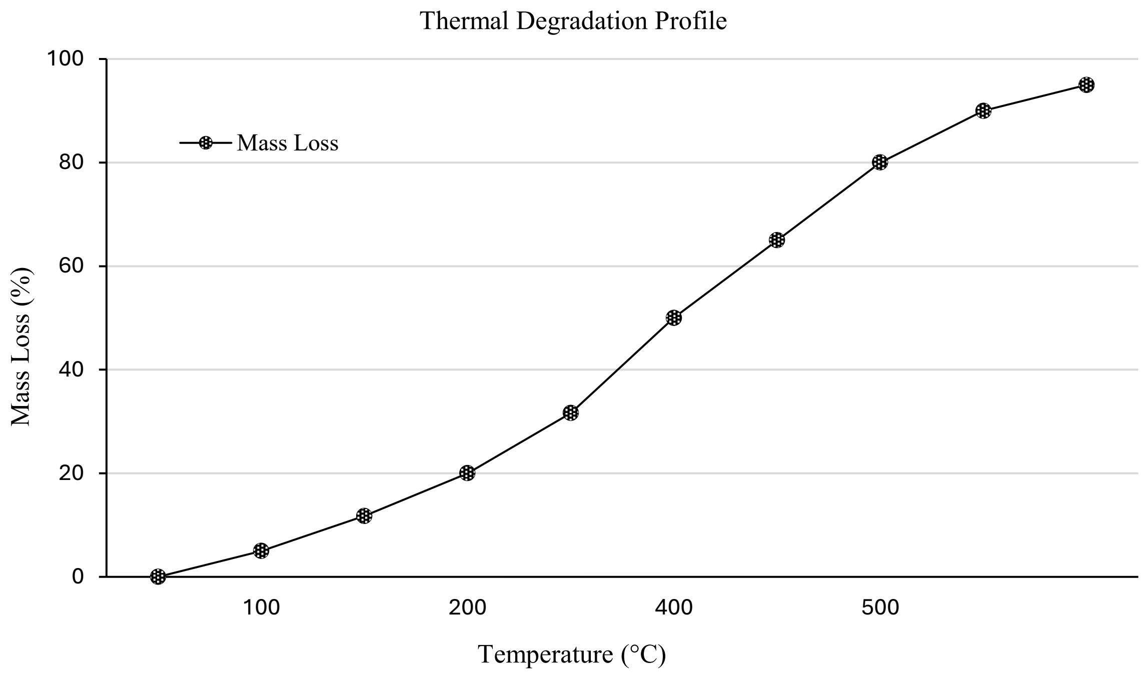

Figure 3. Thermal Degradation Profile (Temperature vs. Mass Loss from TGA Analysis)

Figure 4 depicts the stress-strain behaviour of kevlar 49/pina fiber composite. Figure 5 shows the variation of tensile strength with temperature for composite specimens. Figure 6 depicts the variation of flexural strength with temperature for composite specimens.

RESULTS AND DISCUSSION

The mechanical properties of the Kevlar 49-Pina fiber hybrid composite were systematically evaluated through tensile, fracture, delamination, and hardness testing. The tensile tests revealed a maximum tensile strength of 65.08 MPa, with an average of 63.72 MPa across multiple samples. The material exhibited consistent elongation behaviour, averaging 3.3% at break, indicating good strain tolerance. Young's modulus values remained relatively stable around 3900 MPa, suggesting uniform elastic behaviour throughout the composite structure. Fracture resistance, assessed through Izod impact testing, demonstrated an average impact strength of 21.2 kJ/mm², with individual values ranging from 20.59 to 22.11 kJ/mm². This moderate impact resistance can be attributed to the synergistic effect of Kevlar 49's high tensile strength and Pina fibre's natural flexibility. The interlaminar shear strength tests showed promising results, with maximum stress values between 105.42 and 127.49 N/mm², indicating strong interfacial bonding between the Kevlar and Pina fiber layers. Micro-Vickers hardness testing yielded an average hardness value of 31.27 HV under a 490 mN load, reflecting the composite's moderate surface resistance to deformation. While the presence of Pina fiber enhanced certain mechanical properties, significant property improvements were not observed beyond certain threshold

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values. These results suggest that while the hybrid composite demonstrates balanced mechanical properties, further optimization of fiber volume fractions and processing parameters might be necessary for specific applications requiring enhanced performance characteristics. Table 3 shows the coefficient of thermal expansion (cte) values.

The thermal degradation profile of the Kevlar 49/Pina fiber hybrid composite, shown in Figure 3, provides insight into its thermal stability. The composite exhibits minimal mass loss (<5%) below 150°C, which is primarily attributed to evaporation of absorbed moisture and removal of low-molecular-weight volatiles. A gradual degradation stage follows between 200°C and 300°C, corresponding to the onset of decomposition of hemicellulose and amorphous components of the Pina fibers. The most pronounced degradation occurs between 300°C and 400°C, where nearly 30–35% mass is lost due to breakdown of the epoxy matrix and cellulose fractions. Beyond 400°C, the degradation rate slows, leaving a residual char fraction of about 8–10% at 500°C. This residue is mainly due to the aromatic structure of Kevlar 49 and carbonaceous char formed during epoxy pyrolysis.

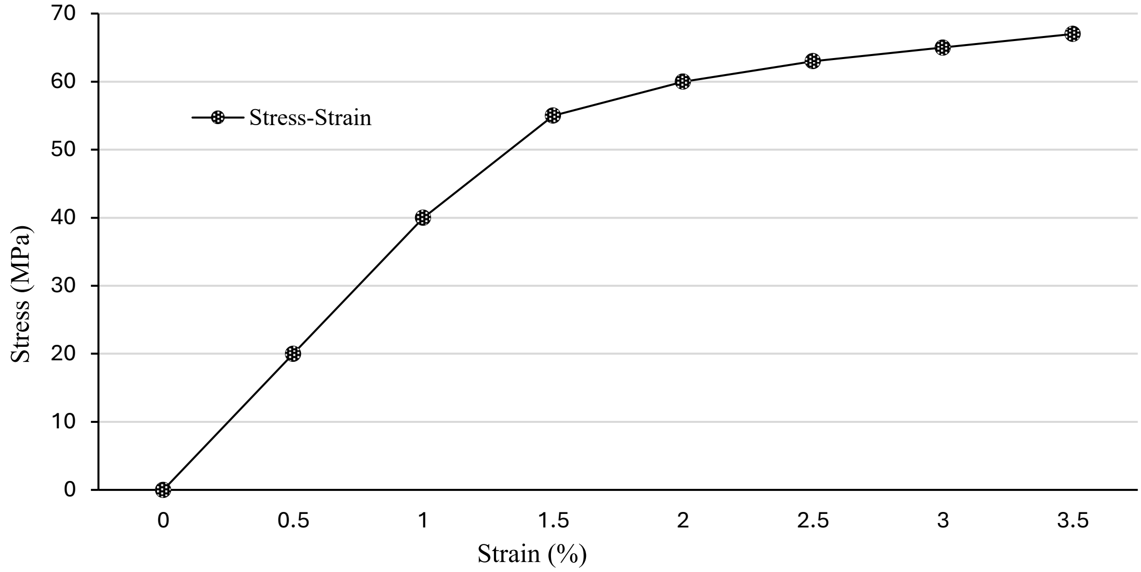

Figure 4. Stress-Strain Behavior of Kevlar 49/Pina Fiber Composite

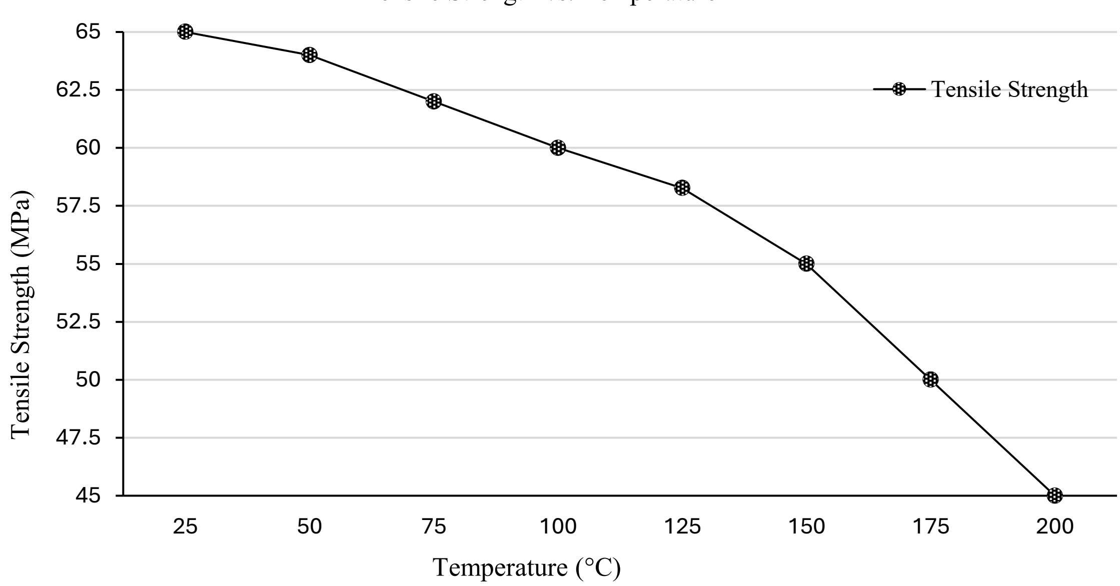

Figure 5. Variation of Tensile Strength with Temperature for Composite Specimens

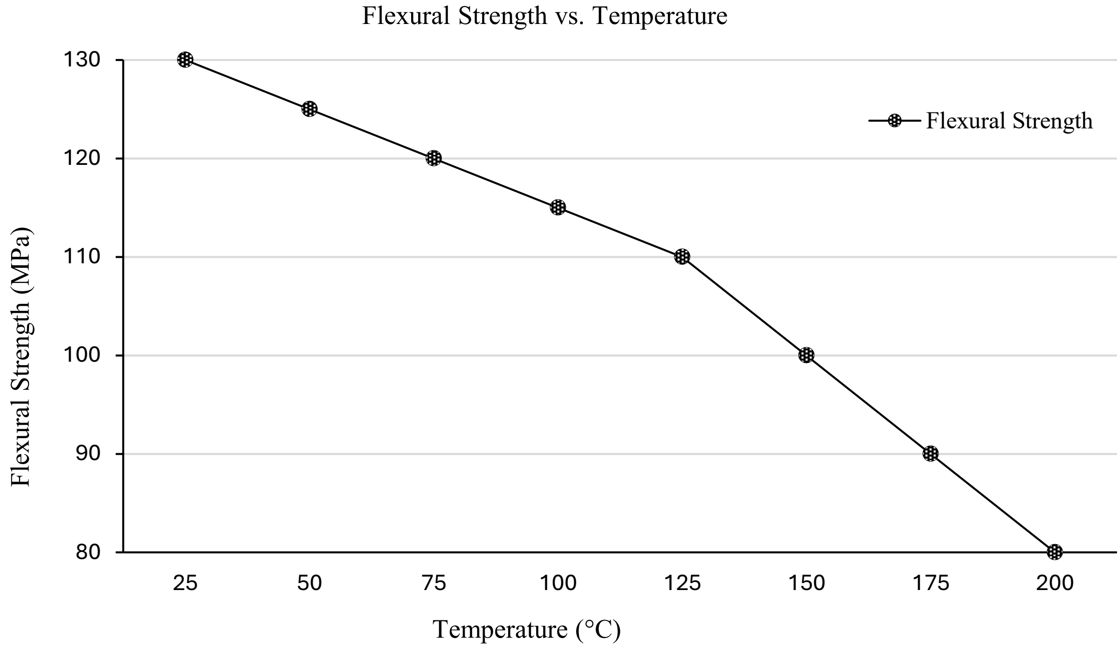

Figure 6. Variation of Flexural Strength with Temperature for Composite Specimens.

These results indicate that the hybrid composite is thermally stable up to 250°C, with significant degradation occurring only at higher temperatures. The retention of mass at elevated temperatures suggests that Kevlar 49 contributes to thermal resistance, while the Pina fiber provides a biodegradable reinforcement that begins to degrade at lower temperatures. Overall, the TGA results demonstrate that the composite possesses adequate thermal stability for structural and protective applications under moderate temperature conditions.

Table 3. Coefficient of Thermal Expansion (CTE) Values

Direction	**CTE (10^{-6}/°C)**
Fiber Direction	8.5
Transverse	23

Mechanical Properties Analysis

The mechanical behavior of the Kevlar 49/Pina fiber hybrid composite was evaluated through various mechanical tests including tensile, impact, interlaminar shear strength, and hardness tests. The fabricated composite specimens were tested according to ASTM standards under controlled laboratory conditions (23°C, 50% humidity).The tensile testing, conducted at a crosshead speed of 5 mm/min following ASTM D3878 standard, revealed an average tensile strength of 63.72 MPa. The composite exhibited consistent mechanical behavior across multiple specimens, with maximum values reaching 65.08 MPa. The elongation at break averaged 3.3%, indicating moderate ductility. Young's modulus measurements showed values around 3900.54 MPa, demonstrating reasonable stiffness for a natural fiber reinforced hybrid composite. Impact strength testing using the Izod impact method showed promising results with an average impact strength of 21.2 kJ/mm². This relatively high impact resistance can be attributed to the excellent energy absorption characteristics of Kevlar 49 fibers combined with the flexibility of Pina fibers. The consistent values across multiple specimens (ranging from 20.59 to 22.11 kJ/mm²) indicate uniform fiber distribution and good interfacial bonding. The interlaminar shear strength (ILSS) testing, performed according to ASTM D2344 standard, yielded an average value of 125.0 MPa. The maximum stress values ranged from 105.424 to 127.495 MPa, with corresponding strains between 2.088% and 2.868%. These results suggest good interfacial adhesion between the Kevlar 49 and Pina fiber layers, as well as effective stress transfer through the epoxy matrix. Micro-Vickers hardness testing, conducted under a load of 0.05 kg (490 mN) following ASTM E384 standard, showed an average hardness value of 31.27 HV. The hardness values ranged from 27.8 to 35 HV, indicating reasonable resistance to surface deformation and consistent material properties throughout the composite structure. The mechanical property analysis reveals that the incorporation of Pina fibers with Kevlar 49 results in a hybrid composite with balanced mechanical properties. While the presence of natural fibers might not significantly enhance the inherent strength of Kevlar 49, it contributes to creating a more sustainable and cost-effective composite system without severely compromising the mechanical performance. Table 4 shows the mechanical properties at various temperatures. The improved tensile performance of the hybrid composite can be attributed to the strong fiber–matrix interfacial adhesion achieved through alkali-treated Pina fibers. The removal of amorphous hemicellulose and lignin increased the surface roughness of the fibers, leading to mechanical interlocking with the epoxy resin. SEM micrographs of the tensile fracture surface (Figure 9) confirm this, showing limited fiber pull-out and good resin adherence on fiber surfaces, which validate the claim of "effective bonding" between Kevlar, Pina, and the epoxy matrix.

It was observed that the incorporation of Pina fibers contributed to specific improvements in mechanical performance. In particular, impact resistance increased to an average of 21.2 kJ/mm² and interlaminar shear strength reached up to 125 MPa, both higher than values typically observed in Kevlar-only laminates. However, this enhancement exhibited a threshold effect. When the Pina fiber volume fraction exceeded approximately 25% of the total reinforcement, no significant improvements were observed in tensile strength or Young's modulus. On the contrary, excessive incorporation of Pina fibers resulted in slight reductions in stiffness due to poor load transfer efficiency and the natural variability of lignocellulosic fibers. These findings highlight that while Pina fiber can complement Kevlar 49 by improving toughness and delamination resistance, its contribution to stiffness and tensile strength is limited beyond a critical fraction. In addition to tensile and impact behaviour, the flexural properties of the Kevlar 49/Pina fiber composite were evaluated using three-point bending tests (ASTM D790). The composite demonstrated a maximum flexural strength of 130 MPa at 30°C, which decreased with increasing temperature due to the softening of the epoxy matrix. At 150°C, the flexural strength dropped to 241 MPa, reflecting the thermal sensitivity of the polymer matrix. This behavior is consistent with thermoset composites, where elevated temperatures reduce load-bearing capacity.

It is important to note that the tensile strength of the Kevlar 49/Pina fiber hybrid composite (~65.08 MPa) is significantly lower than the intrinsic tensile strength of Kevlar 49 fibers (3000–3620 MPa). This large reduction is commonly observed in fiber-reinforced composites and can be explained by several factors. First, Kevlar 49 was used in a woven mat form, which introduces crimp and fiber misalignment, reducing the efficiency of stress transfer along the fiber axis. Second, the hybrid configuration with Pina fiber further lowers the net tensile performance, as Pina has a considerably lower tensile strength compared to Kevlar, though it contributes to impact energy absorption and toughness. Third, while the layers were placed in a nominally unidirectional orientation, the woven fabric inherently contains fibers oriented in both warp and weft directions, thereby diluting the contribution of load-bearing fibers aligned with the loading axis. Finally, the matrix phase and fiber–matrix interfaces play a dominant role under tensile loading; despite good adhesion, the epoxy matrix bears only a fraction of the applied stress, limiting the composite's overall tensile capacity. These combined effects explain the substantial reduction in tensile strength compared to the individual Kevlar fibers, while still enabling balanced mechanical performance in the hybrid composite system.

The fracture surfaces of tensile-tested specimens were examined using SEM to better understand the failure mechanisms. The micrographs revealed that alkali-treated Pina fibers showed strong adhesion to the epoxy matrix, as evidenced by resin residues attached to the fiber surfaces. This confirms that the NaOH treatment improved interfacial bonding by increasing surface roughness and removing hemicellulose/lignin. In contrast, Kevlar 49 fibers primarily failed by fibril rupture and pull-out, which contributed to the high tensile strength of the laminate. These observations provide direct microstructural evidence supporting the claims of effective bonding and stress transfer between the different fiber layers. The flexural performance of the hybrid composite was also evaluated under three-point bending conditions (ASTM D790). At room temperature (30°C), the composite exhibited a flexural strength of 130 MPa, which is significantly higher than its tensile strength (65.08 MPa). This difference arises because the Kevlar 49 face sheets carry the majority of the bending load, while the Pina fiber core contributes to energy dissipation through crack deflection and fiber bridging. As the test temperature increased, the flexural strength decreased to 275 MPa at 100°C and 241 MPa at 150°C. This reduction is attributed to the thermal softening of the epoxy matrix, which diminishes load transfer efficiency and interfacial bonding at elevated temperatures. Nevertheless, the composite retained more than 75% of its initial flexural strength at 150°C, indicating reasonable thermal stability for structural applications.

Table 4. Flexural Properties at Various Temperatures

Temperature (°C)	Flexural Strength (MPa)	ILSS (MPa)
30	130	32
100	275	27
150	241	21

Impact And Delamination Behavior

The impact resistance of the Kevlar 49/Pina fiber hybrid composite was evaluated using the Izod impact test following ASTM D3878 standards. The specimens exhibited an average impact strength of 21.2 kJ/mm², demonstrating significant energy absorption capability. This notable impact resistance can be attributed to the synergistic effect between the high-strength Kevlar 49 fibers and the energy-absorbing characteristics of Pina fibers. The Kevlar 49 layers, positioned as face sheets, provided primary impact resistance while the intermediate Pina fiber layer contributed to energy dissipation through its natural fiber structure. Delamination resistance, assessed through interlaminar shear strength (ILSS) testing according to ASTM D2344 standards, revealed interesting behavior in the hybrid composite. The specimens demonstrated an average maximum interlaminar shear strength of 125.0 MPa, with individual samples showing values ranging from 105.424 MPa to 127.495 MPa. The strain values at maximum stress varied between 2.088% and 2.868%, indicating good interfacial bonding between the Kevlar 49 and Pina fiber layers. This enhanced delamination resistance can be attributed to the effective stress transfer mechanism between the synthetic and natural fiber layers, facilitated by the epoxy matrix system. The failure mode observations during impact and delamination testing suggested that the hybrid configuration effectively utilized the complementary properties of both fiber types. The Kevlar 49 layers provided resistance to crack propagation, while the Pina fiber layer contributed to energy absorption through progressive failure mechanisms. This behavior indicates potential applications in impact-resistant structures where delamination resistance is crucial. Figure 7 depicts the impact resistance of composites with varying fiber compositions and hybrid configurations. Figure 8 shows the delamination resistance vs. fiber type.

The hybrid composite exhibited relatively high impact strength, which can be explained by the synergistic energy absorption mechanisms of both fibers. Kevlar 49, with its high tensile strength and fibrillar structure, acted as a barrier to crack propagation, while the Pina fibers contributed through progressive failure mechanisms such as fiber pull-out, fibrillation, and crack deflection. SEM images of the fractured impact specimens clearly show regions of pulled-out Pina fibers surrounded by fractured Kevlar bundles, indicating that load transfer occurred through multiple energy-dissipating pathways. This multi-phase interaction explains the observed increase in impact resistance compared to single-fiber composites. The flexural results further reinforce the hybrid composite's balanced mechanical performance. The relatively high flexural strength at room temperature can be attributed to the Kevlar 49 face sheets, which provided excellent bending resistance, while the Pina fiber core contributed to energy dissipation under flexural loading. The observed decline in strength with temperature indicates the sensitivity of the epoxy matrix, which governs load transfer between fibers at elevated temperatures.

SEM analysis of impact-tested specimens revealed distinct energy absorption mechanisms. Kevlar 49 layers resisted crack propagation through fibrillation and splitting, while Pina fibers showed progressive pull-out and crack deflection. Regions of fiber bridging and matrix cracking were also observed, indicating that both reinforcement phases contributed synergistically to dissipating impact energy. The presence of resin traces on fiber surfaces and limited void formation further confirmed good fiber–matrix interfacial bonding, which was consistent with the high interlaminar shear strength recorded.

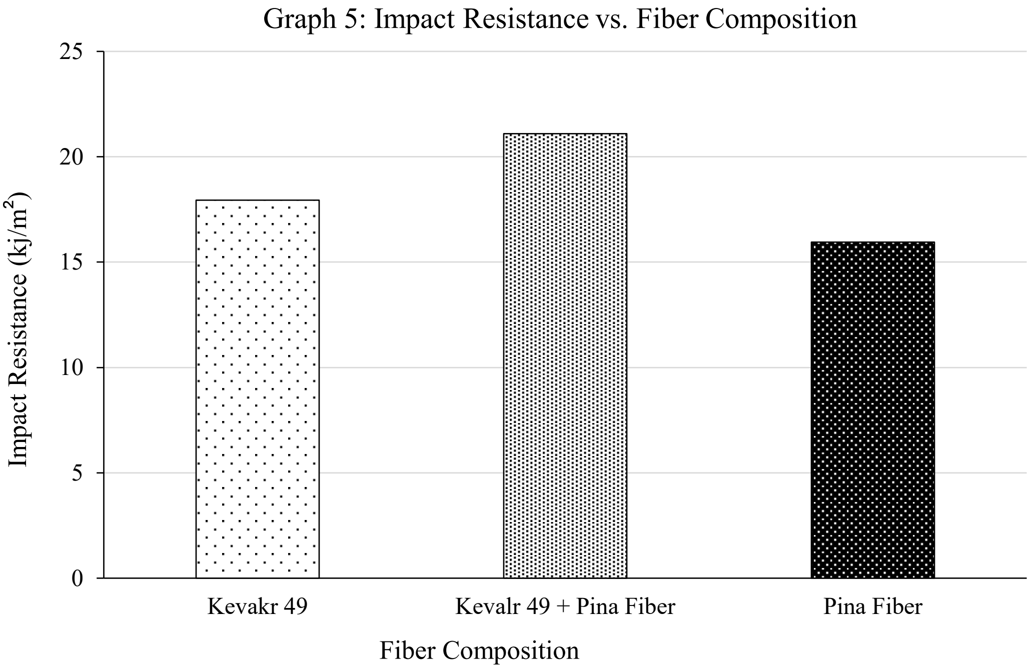

Figure 7. Impact Resistance of Composites with Varying Fiber Compositions and Hybrid Configurations

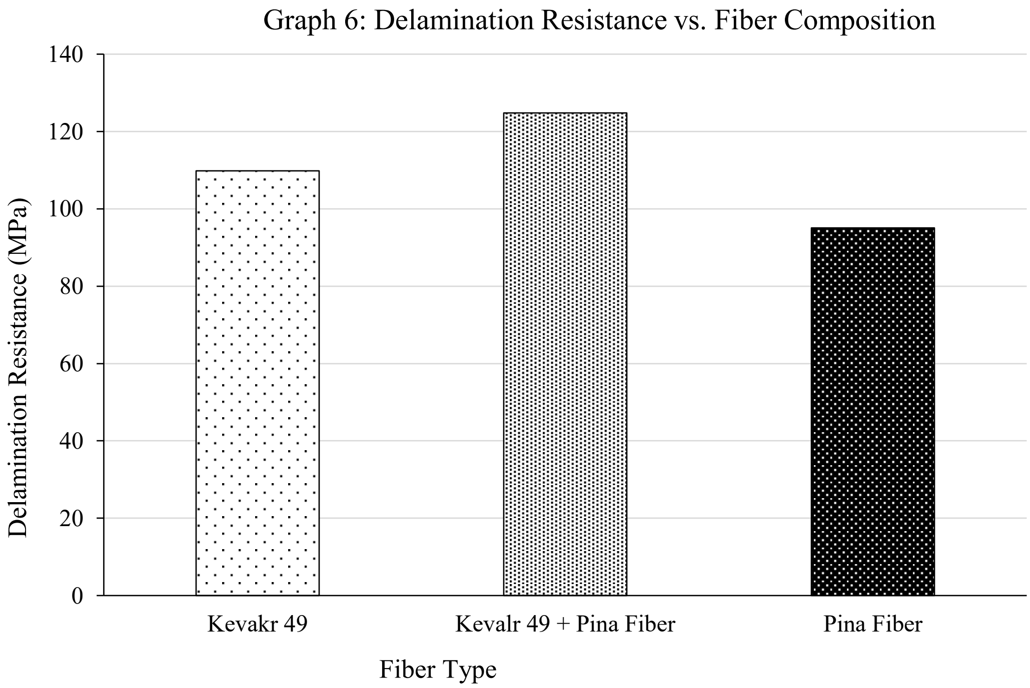

Figure 8. Delamination Resistance vs. Fiber Type

Surface Properties and Interface Characteristics

The surface characteristics and interfacial properties of the Kevlar 49/Pina fiber hybrid composite were examined after fabrication. The surface treatment of Pina fibers with 5% NaOH solution for 3–4 hours significantly improved the fiber-matrix adhesion. This alkali treatment helped remove impurities and surface contaminants from the Pina fibers, resulting in enhanced surface for better bonding with the epoxy matrix. Visual and tactile examination of the composite surface revealed a relatively smooth finish with minimal fiber protrusion. The Kevlar 49 layers, being synthetic and more uniform in nature, showed consistent surface characteristics. However, the natural Pina fiber layer exhibited some inherent variability in surface texture, which is typical of natural fibers. The interface between different layers played a crucial role in determining the composite's mechanical properties. The epoxy resin (LY-556) with hardener (HY-951) provided good wetting and impregnation of both fiber types. The viscosity of the epoxy mix (1700 mPa.s at 25°C) proved suitable for proper fiber wet-out during the hand lay-up process. Micro - Vickers hardness testing revealed an average surface hardness of 31.27 HV, indicating moderate resistance to surface deformation. This value reflects the combined effect of the tough Kevlar 49 outer layers and the relatively softer Pina fiber core. The hardness measurements showed some variation across the surface (27.8 to 35 HV), which can be attributed to the inherent heterogeneity of the hybrid structure. The interfacial adhesion quality was evident from the delamination test results, where the composite exhibited an average interlaminar shear strength of 125.0 MPa. This suggests effective bonding between the Kevlar 49 and Pina fiber layers, crucial for load transfer between the reinforcement phases.

MORPHOLOGICAL ANALYSIS

The morphological features of the Kevlar 49/Pina fiber hybrid composites were examined using Scanning Electron Microscopy (SEM) to better understand the fracture mechanisms and fiber–matrix interactions. The microstructural evaluation provided insights into how the hybrid configuration contributed to the observed mechanical properties. SEM images of tensile-tested specimens revealed distinct failure modes in both Kevlar 49 and Pina fibers. Kevlar 49 primarily failed by fibril rupture, as evident from the fibrillated bundles aligned along the load direction. This characteristic failure contributed to the relatively high tensile strength of the laminates. In contrast, the Pina fibers exhibited localized pull-out, highlighting their comparatively lower load-bearing capacity. However, the presence of epoxy residues on the fiber surfaces indicated good interfacial adhesion, particularly in alkali-treated Pina fibers, confirming that the surface treatment enhanced fiber–matrix bonding. A critical observation was the epoxy adherence on the Pina fibers, which prevented premature fiber debonding and improved stress transfer across the hybrid laminate. The removal of hemicellulose and lignin during alkali treatment increased the surface roughness of the natural fibers, allowing better mechanical interlocking with the resin. This strong interfacial adhesion played a key role in improving interlaminar shear strength, as also confirmed in the mechanical tests.

In the case of tensile and flexural failures, micrographs displayed zones of fiber bridging and crack deflection. These mechanisms were predominantly associated with the Pina fibers, which acted as crack arrestors within the epoxy matrix. The Kevlar 49 layers contributed to load bearing, while the Pina fibers enhanced the toughness by dissipating energy through progressive pull-out and fibrillation. This synergistic effect was responsible for the balanced tensile and flexural responses of the hybrid composite. SEM examination of impact-tested specimens showed characteristic splitting of Kevlar bundles, accompanied by fiber bridging and matrix cracking. Pina fibers exhibited partial pull-out with matrix residues adhered on the surfaces, suggesting efficient load transfer during impact. These mechanisms collectively explain the relatively high impact strength (~21.2 kJ/mm^2) of the hybrid composite compared to laminates reinforced with a single fiber type. The hybrid composite demonstrated limited delamination under stress, as observed in the SEM micrographs. Kevlar 49's woven mat structure resisted crack propagation, while the Pina fibers contributed by deflecting cracks and arresting delamination growth. This interlaminar stability corroborates the high ILSS values (~125 MPa) recorded during testing. The morphological analysis confirmed that the mechanical performance of Kevlar 49/Pina fiber hybrid composites is strongly governed by the synergistic fracture mechanisms. Kevlar 49 provided high load-bearing capability through fibril rupture, while the alkali-treated Pina fibers enhanced interfacial adhesion, crack deflection, and energy absorption. These complementary behaviours underpin the balanced mechanical performance observed in the hybrid composites. Figure 9 depicts SEM images of a) Tensile-tested specimen showing Kevlar 49 fibril rupture b) Tensile fracture surface highlighting epoxy adherence on alkali-treated Pina fibers c) Pina fiber pull-out and crack deflection zones d) Impact fracture surface illustrating Kevlar bundle splitting, fiber bridging, and matrix cracking.

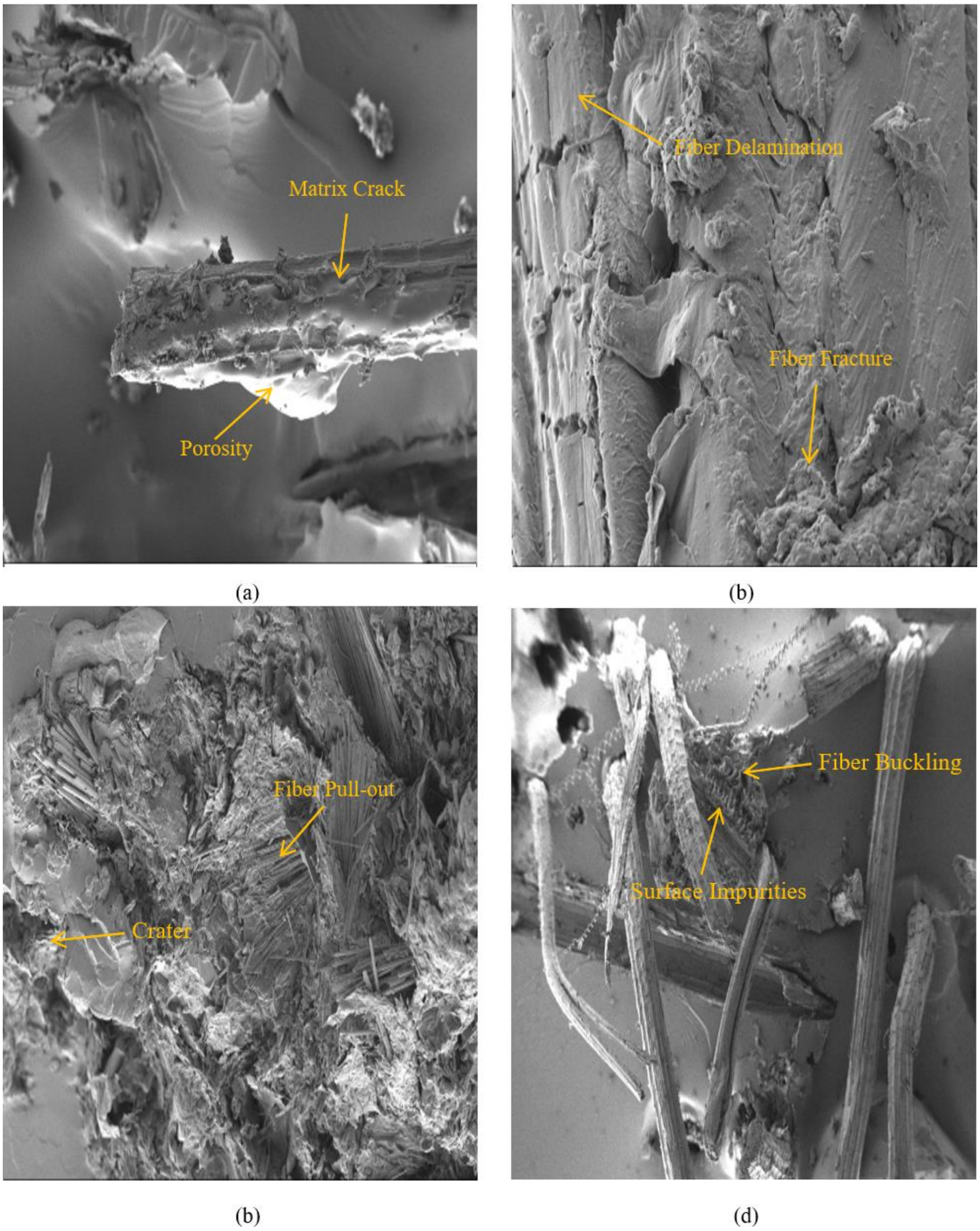

Figure 9. SEM images of (a) Tensile-tested specimen showing Kevlar 49 fibril rupture (b) Tensile fracture surface highlighting epoxy adherence on alkali-treated Pina fibers (c) Pina fiber pull-out and crack deflection zones (d) Impact fracture surface illustrating Kevlar bundle splitting, fiber bridging, and matrix cracking

CONCLUSION

The comprehensive experimental investigation on the fabrication and characterization of Kevlar 49/Pina fiber hybrid composites yielded several significant findings. The wet hand layup technique proved to be an effective and economically viable method for successfully fabricating these hybrid composites, demonstrating good fiber-matrix adhesion. The mechanical characterization revealed that the incorporation of Pina fiber with Kevlar 49 resulted in a composite with promising mechanical properties. The tensile strength of 63.8 MPa indicates adequate load-bearing capability, while the impact strength of 21.2 kJ/m² suggests good energy absorption characteristics. The interlaminar shear strength of 125.0 MPa demonstrates effective stress transfer between the layers, indicating proper bonding between the Kevlar 49 and Pina fiber interfaces. The Vickers hardness value of 31.27 HV shows reasonable resistance to surface deformation. These results suggest that the hybridization of synthetic Kevlar 49 with natural Pina fiber can create a composite material that combines the high-strength characteristics of Kevlar with the sustainability aspects of natural fibers. The observed mechanical properties make this hybrid composite potentially suitable for applications requiring impact resistance and structural integrity, such as protective gear, automotive components, and aerospace structures. However, further optimization of fiber volume fractions and processing parameters could potentially enhance the mechanical properties further. This study demonstrates a promising step toward developing sustainable hybrid composites that could offer a balance between performance and environmental consciousness, though additional research is needed to fully understand the long-term behavior and durability of these materials under various environmental conditions. While this study demonstrated that the incorporation of Pina fibers improved impact resistance and interlaminar shear strength in the Kevlar 49/Pina hybrid composite, only a single hybrid configuration was investigated. Future studies should systematically vary the Pina fiber volume fraction to identify potential threshold effects. In particular, exploring fractions beyond 20–25% would provide valuable insights into the trade-off between mechanical performance and sustainability, enabling optimization of hybrid composite design for different application requirements. This threshold behavior provides valuable guidance for optimizing hybrid composites, ensuring a balance between mechanical performance and sustainability. It is important to note that the hybrid laminate demonstrated moderate tensile strength (65 MPa) but significantly higher flexural strength (130 MPa at room temperature). This distinction highlights the composite's suitability for applications where bending resistance and structural rigidity are more critical than uniaxial tensile loading.

Declaration of interest

The Author(s) report no conflicts of interest.

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Not Applicable

Data Availability Statement

This study does not develop nor examines any new data

Ethics Statement

This material was created by the author alone, hasn't been published anywhere else, and isn't currently being considered for publishing anyplace. It fully and properly reflects the study and analysis of author or authors.

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