Mechanical Performance and Energy Absorption Characteristics of Sustainable Bio-based Luffa/Woven Carbon Fabric Hybrid Epoxy Composites

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Mechanical behavior was tested for hybrid composites with natural luffa fiber and artificial woven carbon fabrics within an epoxy matrix with orientation angles of [90°], [45°], and [0/90°]. Specimens were produced with artificial and natural fibers in a four-layer configuration. Three-point bending, tensile, and low-speed impact tests were applied. In tensile tests, specimen [0/90º Carbon - Luffa - Luffa - 0/90º Carbon] exhibited the highest strength, reaching approximately 42 MPa. In three-point bending tests, specimen [0/90º Carbon - Luffa - Luffa - 0/90º Carbon] showed the highest force of approximately 120 N. In low-speed impact tests, at an impact energy of 5 J, the impactor rebounded without penetrating any of the specimens. At an impact energy of 15 J, punctures and fiber damage occurred in samples [90º Carbon - Luffa - Luffa - 90º Carbon] and [45º Carbon - Luffa - Luffa - 45º Carbon]. In contrast, sample [0/90º Carbon - Luffa - Luffa - 0/90º Carbon] reached maximum force values of approximately 6000 N at 15 J impact energy and approximately 3500 N at 5 J impact energy, exhibiting higher impact resistance without puncture. Based on these results, the woven carbon fabric orientation angle had a decisive effect on the bending, tensile, and impact behavior of hybrid composites.

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Keywords: Hybrid composite; Luffa fiber; Woven carbon fabric; Low-speed impact testing; Mechanical properties

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INTRODUCTION

Composite materials are materials formed by combining multiple different components at the macro level without dissolving into each other. The use of composite industrial equipment in technology fields, such as aviation, marine, automotive, robotics, and aerospace, makes it increasingly important that they meet the requirements for good strength, durability, thermal resistance, and stability, in addition to being of suitably low density (Bhong *et al.* 2023; Phiri *et al.* 2024; Yavuz *et al*. 2025). Fibers can be classified into two groups: artificial and natural fibers (de Azevedo *et al*. 2021; Ez-Zahraoui *et al.* 2023). The use of artificial (synthetic) fibers can have harmful effects on human health and the environment (Aldalbahi *et al.* 2021; Gonzalez *et al.* 2023). These effects include serious health problems, such as skin allergies and lung cancer (Lauerma *et al.* 2025). To reduce these negative effects, environmentally friendly materials, such as natural fibers, have begun to be preferred with increasing interest in the composite industry.

In recent years, agricultural-based natural fibers have shown great potential, offering numerous advantages, such as biodegradability, recyclability, abrasion resistance, ease of processing, low density, low cost, non-toxicity, high strength-to-weight ratio, and good acoustic properties. However, due to their cellulose content, natural fibers are intrinsically hydrophilic and have a high-water absorption capacity (Johansson *et al.* 2012; Palaniappan *et al.* 2025). This property can lead to weakening of interfacial bonds. Chemical modification processes are necessary to reduce the hydrophilic nature of natural fibers and increase surface roughness. Natural fibers, such as those obtained from squash, sisal, jute, hemp, kenaf, and flax, are comparable to synthetic fibers in terms of mechanical properties; however, they also have some disadvantages that limit their use in structural and non-structural applications. These disadvantages include excessive moisture absorption, poor wettability, low thermal stability, and susceptibility to impact damage at low speeds. Natural fibers in polymer matrices play a critical role in meeting industrial demand and support researchers' mission to address global disagreement. Although many types of natural fibers exist worldwide, only a small fraction have been used and recognized as potential reinforcing materials in polymer composite applications (Jeyapragash *et al.* 2020; Palanisamy *et al.* 2024).

In recent years, the hybridization of natural fiber composites with fibers possessing different properties has become a focal point for researchers, aiming to improve the resulting mechanical properties. This combination of artificial and natural fibers has led to the emergence of hybrid composite types, and new research is constantly being conducted. Literature shows that hybridizing natural fibers (jute, linen, cotton, kenaf, coconut, *etc.*) with artificial fibers (glass, carbon, *etc.*) both reduces costs and improves mechanical properties. The literature review focused particularly on the last five years, and some studies are given in Table 1.

Table 1. Some Studies on Hybrid Composites

Natural Fiber	Matrix	Hybrids	Tests and Analyses Conducted	Reference
Coconut	Epoxy	Fiberglass	Tensile, Bending, Water Absorption	(Bhagat *et al.* 2014)
Gongura and *Hibiscus cannabinus*	Polyester	---	Tensile, Bending	(Marichelvam *et al.* 2023)
Kenaf (KF) and sisal fibers	Epoxy	---	Tensile, Bending, Impact Resistance	(Venkatesh *et al.* 2023)
Coconut	Epoxy	Flax, Sisal, Hair Fibers	Tensile, Bending, Impact Resistance	(Boopathi *et al.* 2023)
Natural fiber (jute)	Polyester	Fiberglass	Tensile, Bending Tests	(Das *et al.* 2021)
Jute	Epoxy	Fiberglass	Tensile, Bending Tests	(de Seixas et al. 2023; Gupta et al. 2024)
Jute/Madar	Polyester	Fiberglass	Impact, Bending	(Mohanavel *et al.* 2022)
Jute, Silk, Water Hyacinth	Polyester	Fiberglass	Tensile, Bending, Impact Resistance	(Rahman *et al.* 2024)
Coconut Fiber and Sugarcane Pulp	Epoxy	Fiberglass	Tensile, Bending, Impact Resistance	(Howlader *et al.* 2025)

Luffa and woven carbon fabric were added to an epoxy matrix in specific weight ratios to produce composites. Epoxy matrices can offer significant advantages in fiber-reinforced composite production due to their ability to be processed under low shear stress. In methods such as hand lay-up, they minimize fracture and damage by preserving the structural integrity of the fibers. In contrast, extrusion-based composite production techniques generate high shear forces. This can lead to mechanical damage to natural fibers such as luffa. Therefore, the use of epoxy matrices provides a suitable system for preserving the fiber architecture and accurately determining the reinforcement effectiveness (Alsuwait *et al.* 2023). In the experiments conducted, morphological images, tensile tests, three-point bending tests, and damage surfaces were evaluated using scanning electron microscopy on these samples, and various failure mechanisms were described (Ashok *et al.* 2020; Natrayan and Kaliappan 2023). In most of the experiments conducted, the fibers were used in the form of scraps. Some of the studies on loofah sponge are also review articles, researching the past and future of this fiber (Alhijazi *et al.* 2020; da Silva *et al.* 2021). Natural composite and nanocomposite panels produced from luffa fibers and chitosan resin were studied, and their penetration resistance and compressive strength were examined. The researchers concluded that the results obtained were at an acceptable level (Goudarzi *et al.* 2022). In another study using luffa fiber, polymer composites were produced using polyester resin, marble, and natural luffa fiber particles, and their mechanical properties were then evaluated. They concluded that the luffa fiber particles contributed to stress absorption (Martínez-Barrera *et al.* 2025).

In the literature, natural fiber reinforced composites (NFRCs) have become a significant research topic in recent years due to their low density, renewability, and environmental advantages. Many studies have shown that using plant-based fibers such as flax, hemp, jute, bamboo, and sisal in composite structures can reduce costs and environmental impact. However, the lower strength and stiffness values of natural fibers compared to synthetic fibers such as glass and carbon fibers limit their use in structural applications. Therefore, most studies in the literature have focused on composite systems where natural fibers are used in hybrid form with synthetic fibers; particularly, the use of chopped plant fibers in specific ratios within resin matrices or the production of woven fibers as sheet structures and their mechanical testing has become a common approach. However, a large portion of these studies have focused on parameters such as fiber ratio, surface treatments, or matrix content, and the structural architecture of hybrid composites and the effect of naturally interconnected three-dimensional plant structures on mechanical behavior have been investigated to a limited extent. In particular, the role of plant structures with natural three-dimensional networks, such as luffa, in hybrid composites has been largely neglected. Therefore, this study aims to investigate the impact response and energy absorption behavior of hybrid composites consisting of woven carbon fiber surface layers and a natural luffa mat core. Luffa fibers differ from traditional plant fibers due to their naturally interconnected three-dimensional network structure and high porosity. Therefore, it is believed that they may have a high energy absorption capacity under impact loads and exhibit gradual deformation behavior instead of sudden brittle fracture. Luffa fibers improve load distribution within composites by maintaining their internal network structure. They are also used as reinforcement material in their natural felt form, without separating into individual fibers.

In fiber-reinforced composites, impact can involve the simultaneous occurrence of energy absorption mechanisms such as fiber fracture, matrix cracks, interfacial separation, and interlayer separation. The unique structural properties of natural fibers can increase impact resistance by distributing crack propagation in a controlled manner instead of sudden fracture. The natural three-dimensional network structure of luffa fibers can prevent the concentration of stress in specific areas under impact load, allowing the load to be distributed over a wider area. Therefore, it is predicted that the luffa mat structure can increase impact tolerance and delay crack propagation in hybrid composites.

Fiber orientation and layer arrangement are parameters that affect composite performance. The novelty of this study does not lie solely in changing the fiber orientation. The unique contribution of this study is the use of luffa mat, which retains its natural structure, as a three-dimensional porous core within a layered hybrid composite system together with woven carbon fiber surface layers. Unlike traditional studies using natural fibers, luffa reinforcement is used in its whole form to preserve its intrinsic network architecture. This approach allows for the evaluation of how the bio-based cellular core interacts with different carbon fiber orientations in terms of impact response and energy absorption.

This study aimed to provide a unique contribution to the search for sustainable and high-performance materials in the literature by hybridizing luffa fiber mats with woven carbon fabric. In this study, hybrid composites were produced using an epoxy matrix reinforced with luffa and carbon fibers. Unlike the literature, layered composites were produced using luffa fiber mats as plates. For a different approach from the literature, the mechanical behavior of hybrid composites produced using woven carbon fabric orientation angles of [90°], [45°], and [0/90°] was investigated. Unidirectional [0°] woven carbon fabric was not included in the study because it exhibited a similar mechanical response to the [90°] orientation in impact tests and did not provide additional information. Instead, woven carbon fabric reinforcement was used to more realistically represent the multidirectional stress distribution under impact loads. The literature generally shows that compression, tension, and in some experiments, three-point bending tests are performed for mechanical properties. In this study, in addition to these tests, dynamic low-speed impact tests were also performed.

EXPERIMENTAL

This research aimed to determine the mechanical properties of hybrid composites produced using different orientation angles of natural fibers, namely luffa fiber and woven carbon fabric. A hybrid composite panel was obtained by placing woven carbon fabrics with different orientation angles on both the top and bottom surfaces of the luffa fibers and using epoxy resin. This hybrid panel was cured under hot pressing at high temperature. The produced materials were cut to standard sample dimensions for tensile, three-point bending, and impact tests. Impact energies of 5 and 15 J were applied to the prepared impact test specimens. In this study, the basic mechanical properties of luffa fiber hybrid composites, such as durability, elasticity, and strength, were experimentally investigated and evaluated.

Types of Woven Carbon Fabric

Woven carbon fabric is the basic component that was used to form the hybrid composite material. Resin diffuses between the layers of woven carbon fabric. The hybrid composite emerges as a single structure when the curing process is complete. In the production of the hybrid composite material, woven carbon fabric with orientations of (0º), (45º), and (0 to 90º), with a density of 300 g/m² and approximately 1.75 g/cm³, were used. The woven carbon fabric layers layers were positioned during manufacturing according to the orientation angles indicated in Fig. 1, and their positions were kept constant throughout the hand lay-up process to prevent orientation errors. Figure 1 schematically shows the different orientation configurations ([90°], [45°] and [0/90°]) of woven carbon fiber fabrics used in production. All the fibers shown in Fig. 1 belong to the woven carbon fiber fabric used as a reinforcement layer in the composite structure.

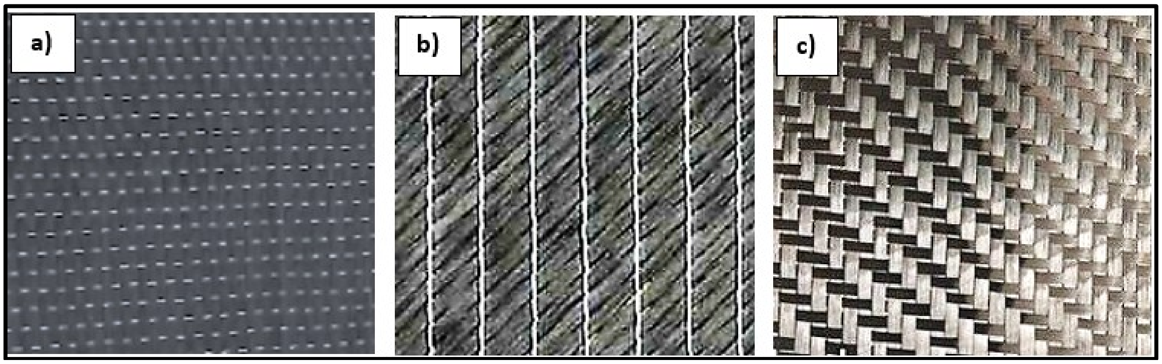

Fig. 1. Schematic representation of different orientation configurations of woven carbon fiber fabric used in composite production: (a) 0°, (b) 45° and (c) 0/90°. The figure only shows the orientation pattern of the carbon fiber reinforcement layers.

Mechanical and physical properties of woven carbon fabric in the (0°), (45°) and (0°–90°) directions are shown in Table 2 according to Dost Kimya catalog values.

Table 2. Mechanical and Physical Properties of Woven Carbon Fabrics

Property	UD Carbon Fiber (0º)	Twill Woven Carbon Fiber (0 to 90º)	Biaxial Carbon Fibre Cloth (45 º)
Areal weight	300 g/m²	300 g/m²	300 g/m²
Tensile strength	4900 MPa	3950 MPa	4120
Elastic modulus	220 GPa	238 GPa	234 GPa
Elongation at break	2.1 %	1.7 %	1.8 %
Density	1.76 g/cm³	1.76 g/cm³	1.79 g/cm³
Fiber diameter	~7 µm	~7 µm	~7 µm

Luffa Fiber

In Turkey, luffa fiber production is carried out in the Mediterranean, Aegean, and Southeastern Anatolia regions, where luffa cultivation is intensive. Antalya, Adana, İzmir, and Mersin are particularly prominent centers for luffa production and the subsequent extraction of fiber. Luffa fiber is widely used in textile and biocomposite material production due to its environmentally friendly structure, light weight, and mechanical strength. The luffa fibers used in this study, shown in Fig. 2, were produced in the Kumluca region of Antalya. The fibers were cut vertically with a utility knife to open up the woven structure and formed into sheets. To ensure homogeneity and uniform layer formation in production, the fibers were pressed under 10 bar pressure for approximately 45 min before the application of epoxy resin. The thickness of luffa pads before pressing was approximately 2 to 5 mm. This thickness decreased with the pressure applied during sample preparation. Luffa fiber layers, due to their natural structure, have an unoriented, random fiber distribution and were used as the core layer in the composite.

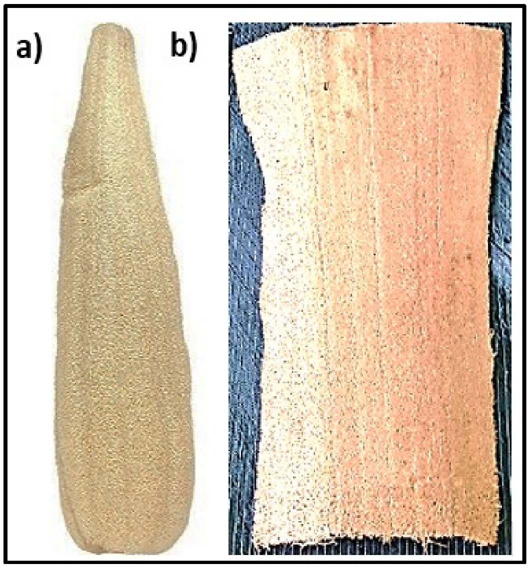

Fig. 2. Natural fiber: a) Luffa fiber in its natural state, b) Luffa fiber prepared for production

The average physical and chemical properties of luffa fiber are shown in Table 3.

Table 3. Average Chemical and Physical Properties of Luffa Fiber (Hadigheh *et al.* 2021)

Chemical Properties (%)					
Cellulose	Lignin	Hemicellulose	Ash	Solubility in Hot Water	1% NaOH Solubility
55 to 74	8 to 23	10 to 30	0.4 ± 1	3.3	16.4
Physical Characteristics					
Density (g/cm^3)	Fiber Diameter (μm)	Aspect Ratio	S_{bahis} m^2/g	Pore Diameter (mL/g)	Medium Pore Size (nm)
0.56 to 1.38	270 ± 20	340 ± 5	1 to 30	0.001 to 0.857	1.753 x 10^3

Composite Production by Hand Lay-up Method

Epoxy and hardener are chemicals that form the resin mixture and enable it to solidify. MGS H287 hardener and MGS L285 epoxy were used in the production of the layered composite material. The names of the woven carbon fabric and luffa fiber used in this study are given in Table 4.

Table 4. Composite Layer Names Used in Production

Composite Layers	Layer Unfolding	Thickness (mm)
$[CL]_1$	[90° Carbon - Luffa - Luffa - 90° Carbon]	2
$[CL]_2$	[45° Carbon - Luffa - Luffa - 45° Carbon]	2
$[CL]_3$	[0/90° Carbon - Luffa - Luffa - 0/90° Carbon]	2

Figure 3 shows the arrangement sequence of woven carbon fabric and luffa fiber used in the study during production. Woven carbon fabric with orientation angles of 90°, ± 45°, and 0°/90° were placed on the top and bottom surfaces, and two layers of luffa fiber were placed between them.

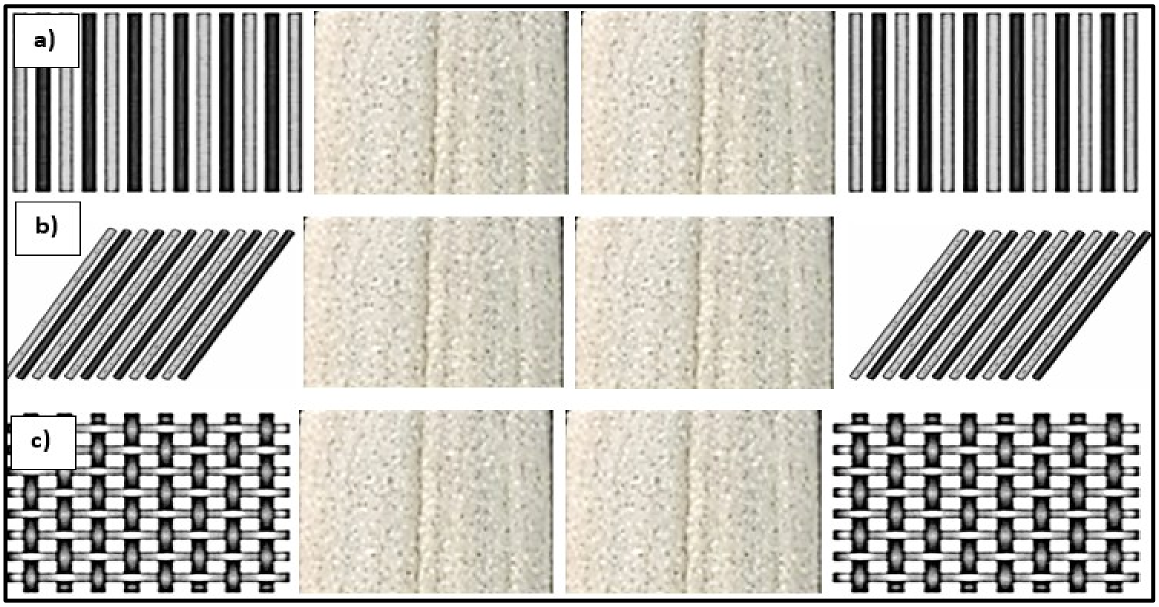

Fig. 3. Arrangement of carbon and luffa fiber hybrid composite structures: a) $[CL]_1$, b) $[CL]_2$, and c) $[CL]_3$

Production Method

In the production process of hybrid composite panels, MGS L285 epoxy resin and MGS H287 hardener were first prepared by mixing them in a 100:40 ratio by weight using a mixer for approximately 5 min. As a bottom layer, woven carbon fabric with orientation angles of 0°, ± 45°, and 0°/90° was placed, and the prepared epoxy resin was applied homogeneously using a brush and hand lay-up method. Then, two layers of natural luffa fiber were placed in the middle layer, and epoxy resin was applied using a brush. As the top layer, woven carbon fabric with the corresponding orientation angle was placed in a single layer, and epoxy resin was applied to complete the hybrid composite layers. Due to the use of the hand lay-up method, the epoxy-fiber ratio was not determined as a fixed mass ratio.

The amount of resin was controlled by applying it in such a way that it could be visually verified that all fiber layers were completely impregnated. Hybrid composite plates with dimensions of 200 mm × 300 mm were produced, consisting of three layers for each orientation angle. The prepared plates were subjected to compression and curing under a hydraulic hot press with the top and bottom plates heated to 50 °C and a pressure of 20 bar for 180 min.

The average total thickness of the composite laminates obtained after the curing processes was measured to be approximately 2 mm. The hybrid composite plates produced, with different orientation angles, were cut and sized using a band saw to the required standard sample dimensions for tensile, three-point bending, and impact tests. During the production of the samples, fiber orientations were carefully controlled, and woven carbon fabric layers were placed on the outer surfaces at the specified orientation angles, while luffa fiber layers were positioned as a randomly distributed core structure without orientation control. The test sample production process of hybrid composites consisting of a mixture of natural and artificial fibers is shown in Fig. 4.

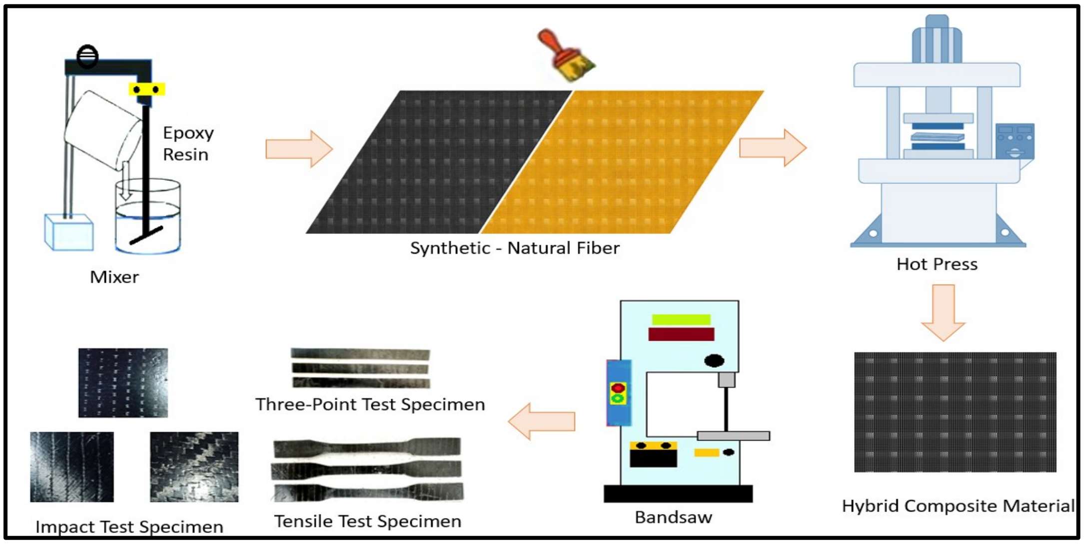

Fig. 4. Test sample production process for hybrid composite of natural and synthetic fibers

Low Speed Impact Test

Low-velocity impact tests were conducted at the Hitit University Scientific and Technical Application and Research Center (HÜBTUAM). The Instron/Ceast 9350-Fractovis Plus impact testing machine shown in Fig. 5 was used. A hemispherical, rigid impact tool with a diameter of 12.7 mm and a weight of 4.926 kg was used as the test tip. The tests were performed at room temperature (26 ± 1 ºC). The impact machine is capable of performing tests from high energies (1800 J) to low energies (2 to 3 J). Impacts were applied to the test specimens at energy levels of 5 and 15 Joules. The tests were performed according to the ASTM D3763 (2018) standard (Mulla *et al.* 2023; Şimşir *et al.* 2024).

Fig. 5. Low-speed impact testing device

Three-point Bending Test

Three-point bending tests were performed using a Shimadzu Autograph tensile testing machine with a capacity of 10 kN. The feed rate was set to 1 mm/min. Three-point bending tests were conducted on specimens with dimensions of 13 × 130 mm^2 in accordance with the ASTM D7264M (2021) standard (Kaboglu and Ferik 2022; Esleman and Önal 2023). The properties of the samples can be calculated using the test data and Eq. 1 below,

$$\sigma_f = \frac{3FL}{2bh^2} \tag{1}$$

where b is defined as the width of the specimen (mm), σ_f is the bending stress (MPa), F is the maximum applied force (N), h is the thickness of the specimen (mm), and L is the distance between the support points (mm). Figure 6 shows images of specimens with different orientation angles during testing with the testing device.

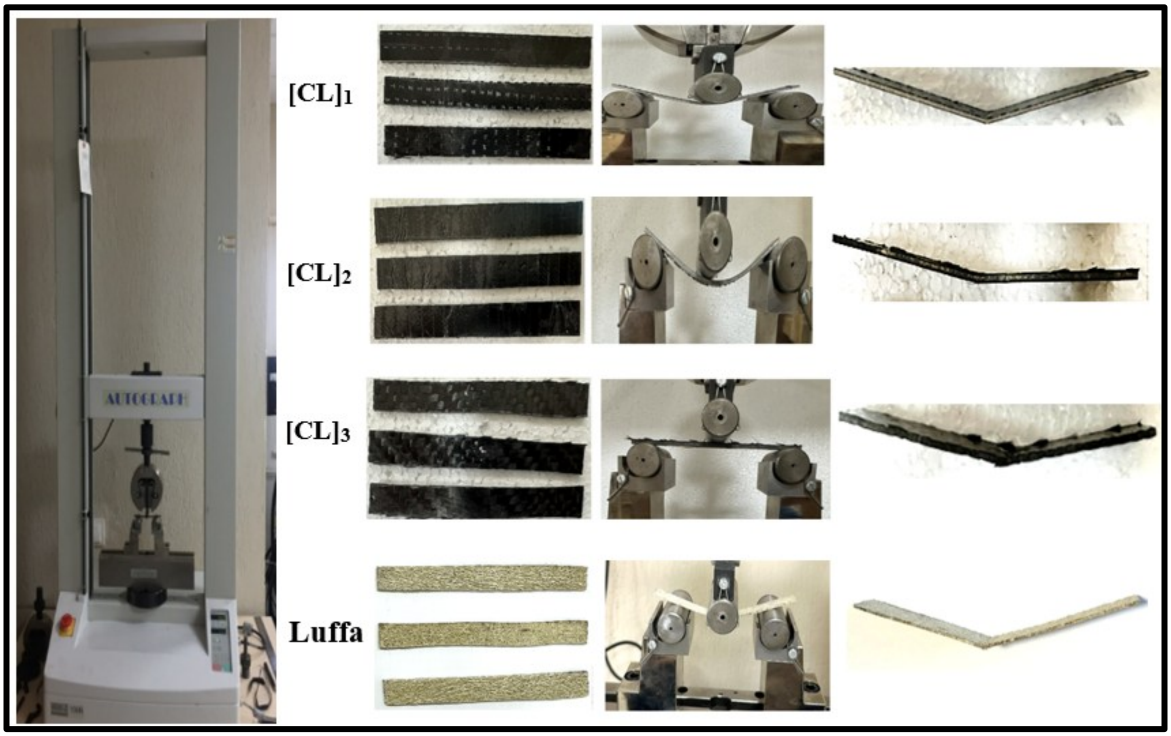

Fig. 6. Three-point bending tester

Tensile Test

Tensile tests were performed using a 10 kN capacity Shimadzu Autograph tensile testing machine shown in Fig. 6. The tests were conducted at an ambient temperature of 26 ± 1 ºC and a tensile speed of 1 mm/min. The experiments were carried out in accordance with the ASTM D3039M (2017) standard (Faidallah *et al.* 2023; Sritharan and Askari 2023). The force values obtained during the tests were substituted into Eq. (2) to calculate the stress values,

$$\sigma = \frac{F_n}{A} \tag{2}$$

where σ represents stress (MPa), A represents the standard cross-sectional area (mm^2), and F_n represents the force (N). Figure 7 shows pre- and post-test images of samples with different orientation angles, using the device used during the test.

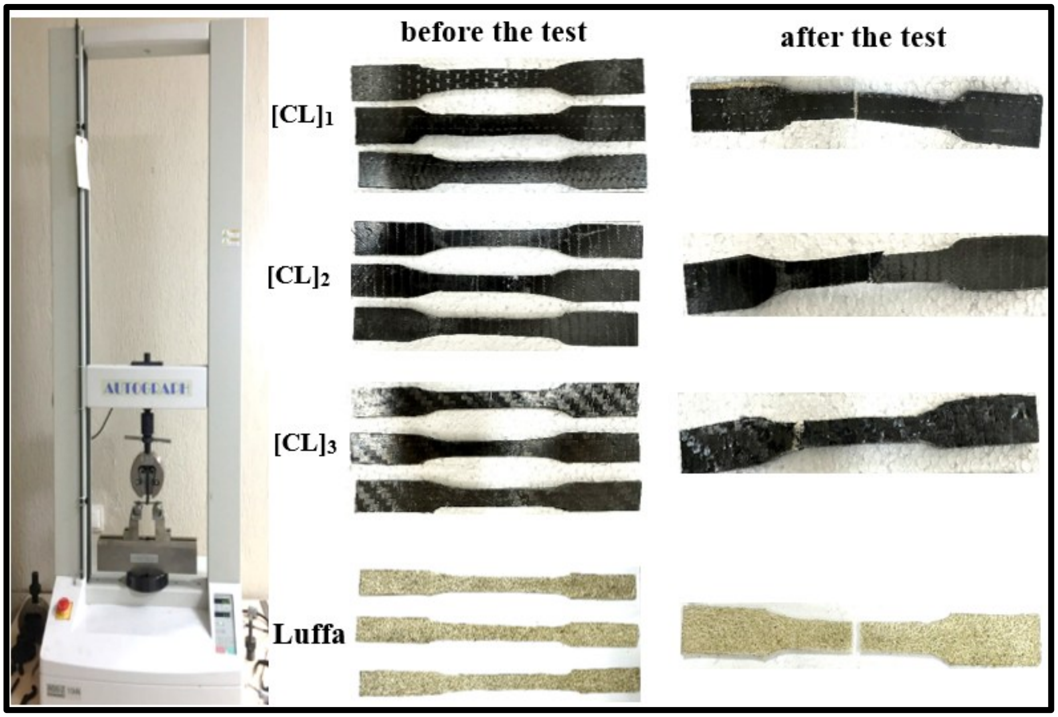

Fig. 7. Tensile test

RESULTS AND DISCUSSION

In this study, low-velocity impact, three-point bending, and tensile tests were applied. Three specimens were tested for each test, and the results were analyzed based on average values.

Three-point Bending Test Results

This study investigated the force-strain behavior of hybrid composite materials with orientation angles $[CL]_1$, $[CL]_2$, $[CL]_3$ and luffa within the scope of three-point bending testing. Figure 8 shows the corresponding force-strain curves. Three specimens from each group were tested. The average values of the tested specimens were taken to calculate the maximum force and deformation values, and graphs of these values were created.

As a result of the three-point bending tests, it was determined that specimen $[CL]_3$ exhibited the highest strength. This specimen fractured after reaching a deformation of 27 mm under a force of approximately 120 N. Specimen $[CL]_2$ fractured after reaching a deformation of 30 mm under a force of approximately 45 N. Specimen $[CL]_1$ had the lowest force value and fractured at a force of approximately 20 N and a deformation level of 18 mm. In the case of luffa, the maximum value is reached at around 9 N at approximately 30 mm deformation, after which the sample fractures. According to the results obtained, specimen $[CL]_3$ showed the highest strength value, while specimen $[CL]_2$ was found to have the highest deformation, *i.e.*, elongation capacity. In line with the three-point bending tests, it was determined that the woven carbon fabric orientation angle has a decisive effect on the mechanical properties of the composite material.

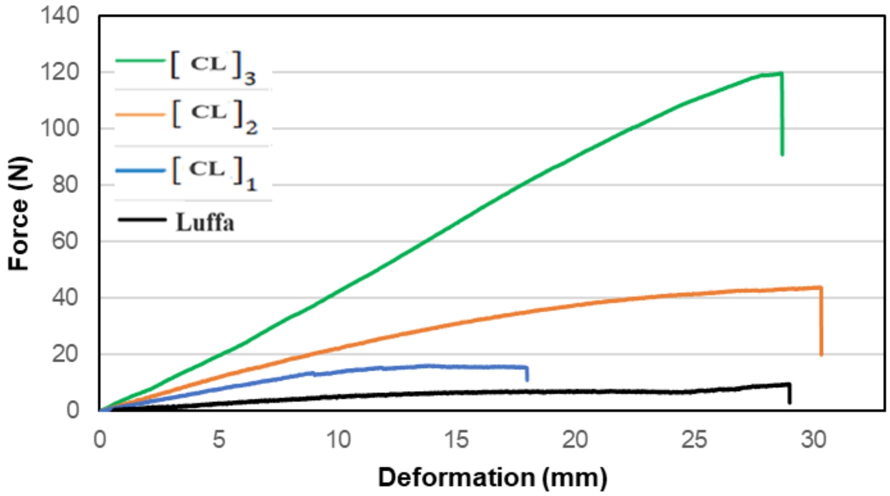

Fig. 8. Shows the three-point bending force-strain graph of the composite plates [CL]1, [CL]2, [CL]3 and Luffa

Tensile Test Results

The stress-strain behavior of hybrid composite materials with orientation angles [CL]1, [CL]2 CL]3 and Luffa was investigated within the scope of tensile testing, and Figure 9 shows the stress-strain curves obtained from the tensile test of the composite plates. Three specimens from each group were tested. The average values of the tested specimens were taken to calculate the maximum stress and elongation values, and graphs of these values were created.

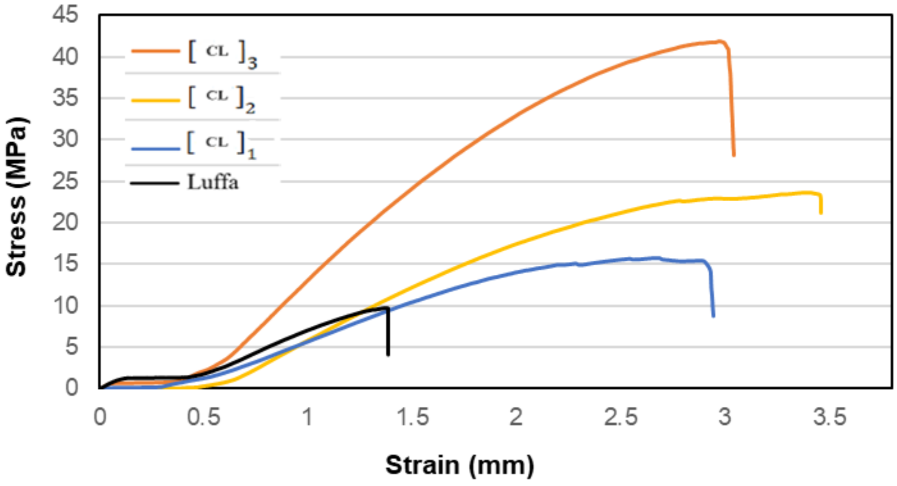

Fig. 9. Tensile test stress-strain graph of composite plates [CL]1, [CL]2, [CL]3 and Luffa

The graph in Fig. 8 compares the stress-strain curves of three different materials. Examining the graph, it can be seen that material [CL]3 exhibits the highest strength; this material fractured after showing an elongation of 3 mm under approximately 42 MPa stress. Material [CL]2 withstood an elongation of 3.4 mm under approximately 24 MPa stress before fracture. Material [CL]1 exhibits the lowest strength, reaching an elongation of 2.8 mm under approximately 15 MPa stress before fracture. A similar graph to Luffa tensile curve [CL]$_1$ was obtained, and an elongation of 1.4 mm was achieved under a stress of approximately 10 MPa. The tensile test results reveal that the materials have different tensile strength and elongation capacities. Material [CL]$_3$ has the highest strength, while [CL]$_2$ as the best elongation value. This difference between the samples indicates that the woven carbon fabric orientation used notably affects the performance of the samples under tensile stress.

Impact Test Results

In this study, the force-strain behavior of [CL]$_1$, [CL]$_2$, and [CL]$_3$ composite materials were investigated within the scope of impact tests performed under two different impact energies of 5 J and 15 J. Three specimens were tested for each orientation group at both impact energies. Using the average values obtained from the tested specimens, the maximum force and deformation values were calculated and graphs of these values were created. Damage images showing the pre-impact and post-impact conditions of the specimens under 5 J impact energy within the scope of low-speed impact tests of hybrid composite plates are presented in Fig. 10

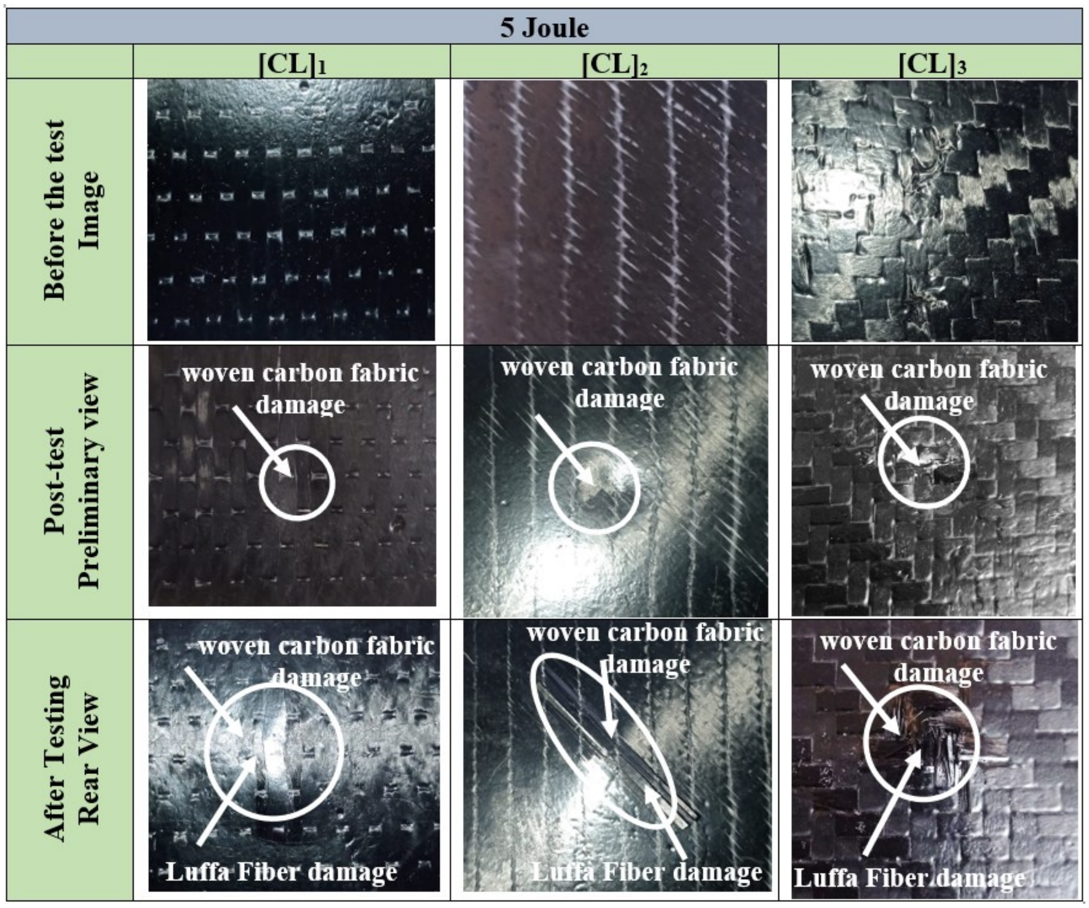

Fig. 10. [CL]$_1$, [CL]$_2$ and [CL]$_3$ images of the samples under 5 J pulse energy

When the impact test specimen images given in Fig. 10 are examined, it is seen that damage occurred in the woven carbon fabric and luffa fiber on both the top and bottom surfaces of specimen [CL]$_1$. It was determined that the impacting tip bounced off the material surface after the impact. It was observed that specimens $[CL]_2$ and $[CL]_3$ also exhibited similar impact behavior; the impacting tip bounced off the specimen without the material being punctured.

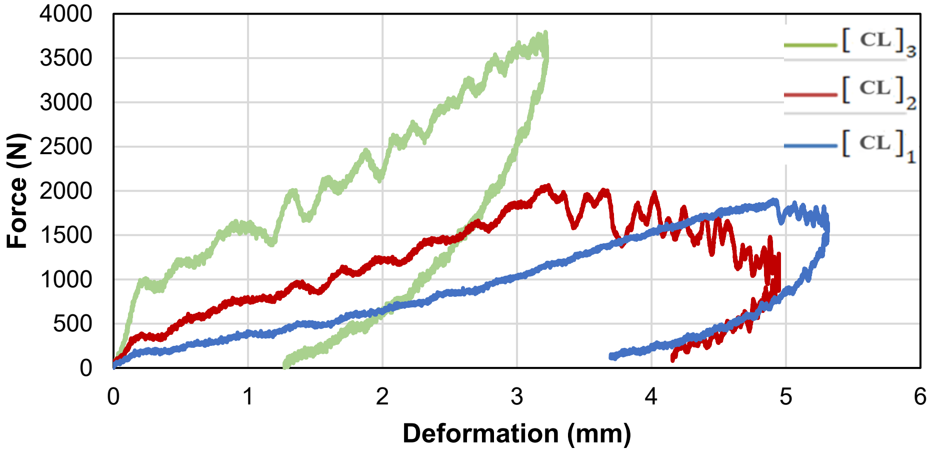

Fig. 11. Force-strain graph of $[CL]_1$, $[CL]_2$ and $[CL]_3$ hybrid composite specimens under 5 J impact energy

Figure 11 shows the force-strain graph of samples $[CL]_1$, $[CL]_2$, and $[CL]_3$, obtained from impact tests performed under 5 J impact energy of hybrid composites. Material $[CL]_3$, reached its highest maximum force value of approximately 3500 N and showed a deformation of approximately 3.5 mm. This indicates that the material exhibits high strength and provides high load-carrying capacity by effectively distributing the force during impact, but shows more brittle behavior due to limited deformation. Material $[CL]_2$, with a maximum force value of approximately 2000 N, exhibited lower strength compared to $[CL]_3$, but with a deformation capacity reaching 5 mm, it showed a more flexible and balanced response during impact. The $[CL]_1$ material, despite being the most flexible material with a maximum force of approximately 1900 N and a deformation of 5.5 mm, showed lower impact resistance and load-carrying capacity. In general, $[CL]_3$, is a suitable option for applications requiring high strength, while $[CL]_2$, stands out with its balanced strength and flexibility properties. The materials $[CL]_1$ is considered more suitable for applications where flexibility is important but high strength is not critical.

Within the scope of low-speed impact tests of hybrid composite plates, damage images showing the pre-impact and post-impact conditions of the samples under 15 J impact energy are shown in Fig. 12.

When the impact test specimen images given in Fig. 12 are examined, it is seen that in specimens $[CL]_1$ and $[CL]_2$ damage occurred in both the woven carbon fabric and luffa fiber on both the top and bottom surfaces. Fiber breaks and luffa fiber separations were detected in these two specimens, and it was observed that the impacting tip pierced the material after the impact. In contrast, in specimen $[CL]_3$, damage occurred only in the luffa fiber on both the top and bottom surfaces, and it was determined that the impacting tip exhibited a behavior of bouncing back from the material surface without piercing the specimen.

Figure 13 presents the force-strain graphs of samples $[CL]_1$, $[CL]_2$, and $[CL]_3$ obtained from impact tests of hybrid composites performed under 15 J impact energy.

Material $[CL]_3$ reached its highest maximum force value of approximately 6000 N and showed a deformation of approximately 4 mm. This result shows that the material exhibits high strength, is effective in load carrying during impact with a more brittle behavior, and the impactor bounces back. Material $[CL]_2$ exhibited lower strength with a maximum force value of approximately 2000 N, but showed a more balanced energy distribution and flexible behavior with a deformation capacity reaching 15 mm; in this sample, the impactor pierced the material. The $[CL]_1$ material showed similar deformation capacity to $[CL]_2$ with a maximum force value of approximately 1500 N, but exhibited lower force-carrying performance.

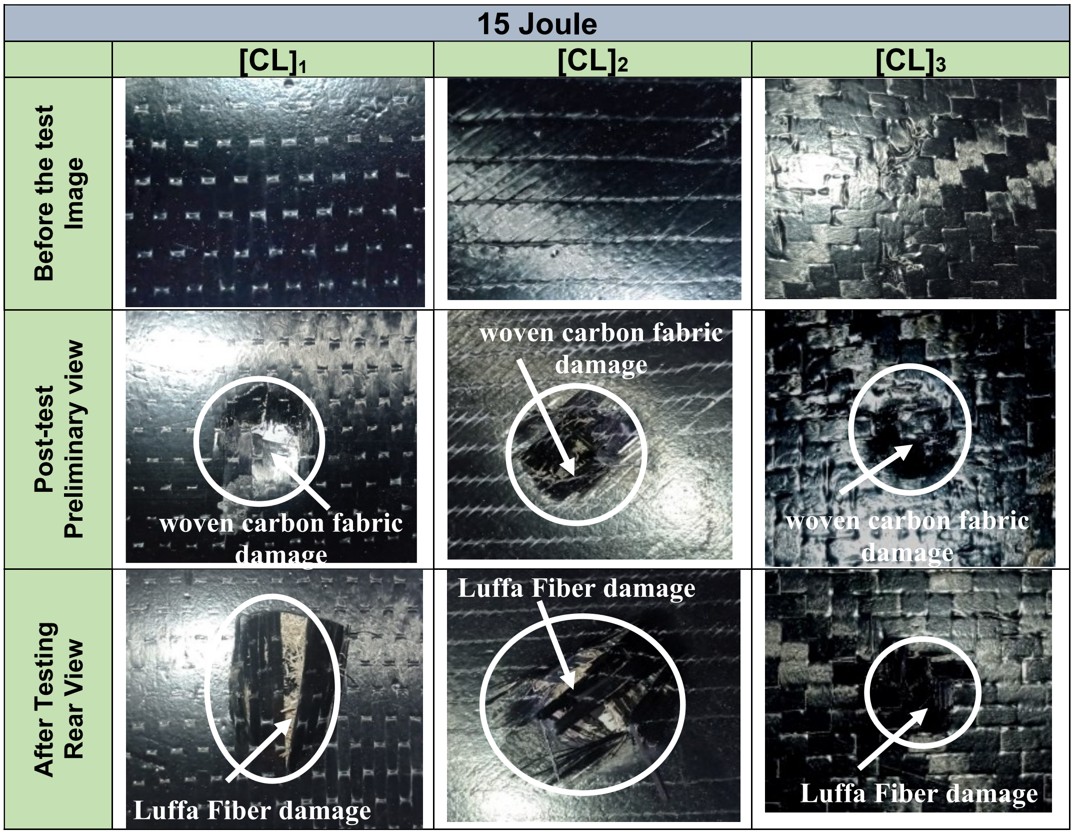

Fig. 12. Images of samples $[CL]_1$, $[CL]_2$ and $[CL]_3$ under a pulse energy of 15 J

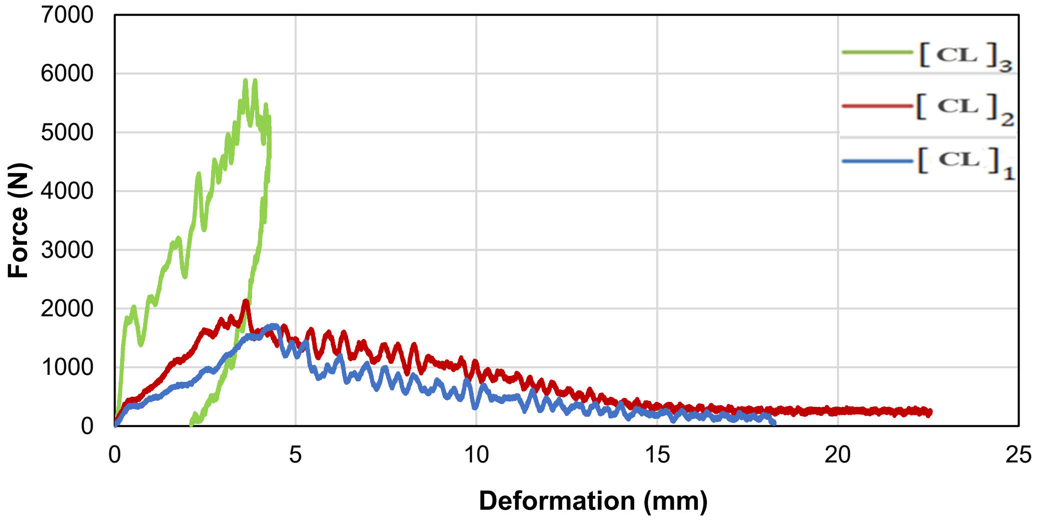

Fig. 13. Force-strain graph of [CL]$_1$, [CL]$_2$ and [CL]$_3$ hybrid composite specimens under 15 J impact energy

In general, when 4-layer composite specimens are evaluated under 5 and 15 J impact energies, [CL]$_3$ is a suitable alternative for applications requiring high strength, while [CL]$_2$ stands out with its balanced strength and flexibility properties. The [CL]$_1$ material can be considered a more suitable option for applications where flexibility is important but high strength is not critical.

The obtained impact test results clearly reveal the relationship between fiber orientation and structural deformation mechanisms. Limited deformation was observed in samples with high maximum force values. This indicates that these samples carried the impact load more rigidly, but exhibited more brittle fracture behavior. In contrast, samples with lower maximum force values showed higher deformation capacity. This indicates that energy is dissipated through structural deformation. In all samples, the porous network structure of the luffa layer contributes to the gradual absorption of impact energy through cellular collapse, internal friction, and interfiber contact mechanisms. This shows that in hybrid composites, impact behavior depends not only on fiber strength but also on fiber orientation and structural structure. In addition, the woven carbon fabrics on the outer surfaces act as a rigid barrier carrying the initial contact load during impact, preventing the sudden transfer of stress to the core structure. The load-carrying and crack-deflecting behavior of these outer layers changed depending on the fiber orientation. This was one of the main reasons for the differences in impact performance between the samples.

From an engineering perspective, these results suggest that the developed hybrid structures can be used in applications where energy absorption and impact resistance are critical. They can also be used as potential alternatives to fully synthetic fiber composites. While woven carbon fabrics generally provide high stiffness, they exhibit sudden fracture under impact loading. In contrast, the hybrid configurations examined in this study exhibited more gradual deformation behavior, demonstrating improved damage tolerance. Therefore, such materials can be considered promising candidates for lightweight structural components such as automotive interior panels, protective structures, and energy-absorbing elements.

The mechanical findings obtained provide fundamental data for modeling studies of similar hybrid composite systems. In future research, stress distribution, impact response, and damage propagation behavior of layered hybrid structures can be predicted using micromechanical theoretical approaches and especially numerical methods such as finite element analysis (FEA). In these models, parameters such as layer arrangement, fiber orientation, and core porosity can be defined as material inputs and simulated as mechanical performance. Therefore, the presented experimental results serve as validation data for both numerical and theoretical studies aimed at predicting the behavior of natural-synthetic hybrid composites

CONCLUSIONS

In this study, the mechanical properties of hybrid composite materials produced using natural and artificial fibers were investigated. Different woven carbon fabric orientation angles and luffa fiber reinforcement were used in the study; low-speed impact tests were applied to the samples at 5 J and 15 J impact energies, and three-point bending and tensile tests were also performed. Based on the experimental data obtained, the force-strain and stress-elongation behaviors of the samples were comprehensively evaluated.

1. The force-strain curves obtained from the low-speed impact tests showed that the woven carbon fabric orientation angle has a decisive effect on the impact behavior of hybrid composites. At both impact energies, the $[CL]_3$ sample reached the highest maximum force values, exhibited a more brittle behavior with limited deformation, and showed a high load-carrying capacity, especially at 15 J impact energy, with the rebound of the impacting tip. In contrast, although the $[CL]_2$ sample showed lower maximum force values, it exhibited a more flexible behavior with a higher deformation capacity and a more balanced distribution of impact energy. It was observed that the impact tip pierced the sample at an impact energy of 15 J. Sample $[CL]_1$ showed the lowest maximum force values at both impact energies, and despite its relatively high deformation capacity, it remained weaker in terms of impact resistance and load-carrying performance.

2. Examination of the post-impact damage images revealed that rebound behavior was dominant in all samples at low impact energy, while at high impact energy, penetration and fiber damage occurred in samples $[CL]_1$ and $[CL]_2$. In contrast, sample $[CL]_3$ exhibited higher impact resistance without penetration at both impact energies.

3. When three-point bending and tensile tests were evaluated together, it was seen that the woven carbon fabric orientation angle played a decisive role in the mechanical behavior of hybrid composites. In three-point bending tests, specimen $[CL]_3$ exhibited the highest bending strength, while specimen $[CL]_2$ showed higher deformation capacity under lower force. Specimen $[CL]_1$ had the lowest strength values in both tests. Similarly, in tensile tests, specimen $[CL]_3$ achieved the highest tensile strength, while specimen $[CL]_2$ showed the best elongation capacity. These results reveal that the woven carbon fabric orientation angle notably affects the strength and deformation behavior of hybrid composites under bending, tensile, and impact loads.

4. The composite effect of the luffa structure is evident in the fact that, in tensile and three-point bending tests, it exhibits gradual damage development over a specific deformation range instead of sudden and brittle fracture. This can be explained by

the fact that the porous and fibrous structure of the luffa distributes the load more homogeneously, thus delaying crack propagation.

5. The results obtained show that the fiber orientation angle and the number of layers affect the material performance in woven carbon fabric composites. The hybrid composites evaluated in this study can be used in non-structural applications in the automotive industry, such as bumpers, grilles, headlight frames, and trim parts. However, it appears that they can be considered as an alternative material for applications requiring impact resistance. Moreover, hybrid composites are considered to have potential applications not only in the automotive sector but also in many different industrial fields, such as defense, aerospace, construction, and sports equipment, thanks to their advantages in lightness, energy absorption, and design flexibility

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REFERENCES CITED

Aldalbahi, A., El-Naggar, M. E., El-Newehy, M. H., Rahaman, M., Hatshan, M. R., and Khattab, T. A. (2021). “Effects of technical textiles and synthetic nanofibers on environmental pollution,” *Polymers* 13(1), Article Number 155. https://doi.org/10.3390/POLYM13010155

Alsuwait, R. B., Souiyah, M., Momohjimoh I., Ganiyu, S. A., Bakare A. O. (2023). “Recent development in the processing, properties, and applications of epoxy-based natural fiber polymer biocomposites,” *Polymers* 15(1) article 145. https://doi.org/10.3390/polym15010145

Alhijazi, M., Safaei, B., Zeeshan, Q., Asmael, M., Eyvazian, A., and Qin, Z. (2020). “Recent developments in luffa natural fiber composites: Review,” *Sustainability* 12(18), Article Number 7683. https://doi.org/10.3390/SU12187683

Ashok, K. G., Kalaichelvan, K., Elango, V., Damodaran, A., Gopinath, B., and Raju, M. (2020). “Mechanical and morphological properties of luffa/carbon fiber reinforced hybrid composites,” *Materials Today: Proceedings* 33, 637–641. https://doi.org/10.1016/J.MATPR.2020.05.716

ASTM D3763 (2018). “Standard test method for high speed puncture properties of plastics using load and displacement sensors,” ASTM International, West Conshohocken, PA, USA. https://doi.org/10.1520/D3763-18

ASTM D7264M. (2021). “Standard test method for flexural properties of polymer matrix composite materials,” ASTM International, West Conshohocken, PA, USA. https://doi.org/10.1520/D7264_D7264M-21

ASTM D3039M (2017). “Standard test method for tensile properties of polymer matrix composite materials,” ASTM International, West Conshohocken, PA, USA. https://doi.org/10.1520/D3039_D3039M-17

Bhagat, V. K., Biswas, S., and Dehury, J. (2014). "Physical, mechanical, and water absorption behavior of coir/glass fiber reinforced epoxy based hybrid composites," *Polymer Composites* 35(5), 925–930. https://doi.org/10.1002/PC.22736

Bhong, M., Khan, T. K. H., Devade, K., Vijay Krishna, B., Sura, S., Eftikhaar, H. K., Pal Thethi, H., and Gupta, N. (2023). "Review of composite materials and applications," *Materials Today: Proceedings* (In Press). https://doi.org/10.1016/J.MATPR.2023.10.026

Boopathi, S., Balasubramani, V., and Sanjeev Kumar, R. (2023). "Influences of various natural fibers on the mechanical and drilling characteristics of coir-fiber-based hybrid epoxy composites," *Engineering Research Express* 5(1), Article ID 015002. https://doi.org/10.1088/2631-8695/ACB132

da Silva, R. V., Voltz, H., Filho, A. I., Xavier Milagre, M., and Carvalho Machado, C. de S. (2021). "Hybrid composites with glass fiber and natural fibers of sisal, coir, and luffa sponge," *Journal of Composite Materials* 55(5), 717–728. https://doi.org/10.1177/0021998320957725

Das, S. C., Paul, D., Grammatikos, S. A., Siddiquee, M. A. B., Papatzani, S., Koralli, P., Islam, J. M. M., Khan, M. A., Shauddin, S. M., Khan, R. A., *et al.* (2021). "Effect of stacking sequence on the performance of hybrid natural/synthetic fiber reinforced polymer composite laminates," *Composite Structures* 276, Article ID 114525. https://doi.org/10.1016/J.COMPSTRUCT.2021.114525

de Azevedo, A. R. G., Cruz, A. S. A., Marvila, M. T., de Oliveira, L. B., Monteiro, S. N., Vieira, C. M. F., Fediuk, R., Timokhin, R., Vatin, N., and Daironas, M. (2021). "Natural fibers as an alternative to synthetic fibers in reinforcement of geopolymer matrices: A comparative review," *Polymers* 13(15), Article Number 2493. https://doi.org/10.3390/POLYM13152493

de Seixas, G. B., de Queiroz, H. F. M., Neto, J. S. S., and Banea, M. D. (2023). "Effect of water on the mechanical and thermal properties of natural fibre reinforced hybrid composites," *Journal of Composite Materials* 57(11), 1941–1958. https://doi.org/10.1177/00219983231166570

Esleman, E. A., and Önal, G. (2023). "Three-point bending fatigue behavior of basalt-carbon-glass/epoxy hybrid composites under saltwater environment," *Fatigue & Fracture of Engineering Materials & Structures* 46(7), 2496–2509. https://doi.org/10.1111/FFE.14012

Ez-Zahraoui, S., Semlali Aouragh Hassani, F. Z., El Achaby, M., Qaiss, A. el Kacem, and Bouhfid, R. (2023). "Natural fiber reinforcements: Classification, extraction, treatment, and properties," *Multiscale Textile Preforms and Structures for Natural Fiber Composites*, Woodhead Publishing, Sawston, UK, pp. 3–29. https://doi.org/10.1016/B978-0-323-95329-0.00004-1

Faidallah, R. F., Hanon, M. M., Vashist, V., Habib, A., Szakál, Z., and Oldal, I. (2023). "Effect of different standard geometry shapes on the tensile properties of 3D-printed polymer," *Polymers* 15(14), Article Number 3029. https://doi.org/10.3390/POLYM15143029

Gonzalez, V., Lou, X., and Chi, T. (2023). "Evaluating environmental impact of natural and synthetic fibers: A life cycle assessment approach," *Sustainability Multidisciplinary Digital Publishing Institute* 15(9), Article ID 7670. https://doi.org/10.3390/SU15097670

Goudarzi, S. A., Niknejad, A., and Heidari, F. (2022). "A natural composite and nanocomposite of luffa fibers and chitosan resin under mechanical tests," *Journal of*

Composite Materials 56(15), 2367–2383. https://doi.org/10.1177/00219983221093738

Gupta, A., Shohel, S. M., Singh, M., and Singh, J. (2024). "Study on mechanical properties of natural fiber (Jute)/synthetic fiber (Glass) reinforced polymer hybrid composite by representative volume element using finite element analysis: A numerical approach and validated by experiment," *Hybrid Advances* 6, Article ID 100239. https://doi.org/10.1016/J.HYBADV.2024.100239

Hadigheh, S. A., Wei, Y., and Kashi, S. (2021). "Optimisation of CFRP composite recycling process based on energy consumption, kinetic behaviour and thermal degradation mechanism of recycled carbon fibre," *Journal of Cleaner Production* 292, Article ID 125994. https://doi.org/10.1016/J.JCLEPRO.2021.125994

Howlader, M. I., Mehedi, M. I., Alam, M. M., Mofasser, A. Z. M., Ibn Sayed, N., Alim, M. A., Assiri, M. A., and Mia, R. (2025). "Mechanical and morphological analysis of natural fiber-reinforced epoxy and polyester hybrid composites," *Results in Engineering* 26, Article ID 105010. https://doi.org/10.1016/J.RINENG.2025.105010

Jeyapragash, R., Srinivasan, V., and Sathiyamurthy, S. (2020). "Mechanical properties of natural fiber/particulate reinforced epoxy composites – A review of the literature," *Materials Today: Proceedings* 22, 1223–1227. https://doi.org/10.1016/J.MATPR.2019.12.146

Johansson, C., Bras, J., Mondragon, I., Nechita, P., Plackett, D., Šimon, P., Svetec, D. G., Virtanen, S., Baschetti, M. G., Breen, C., *et al.* (2012). "Renewable fibers and bio-based materials for packaging applications - A review of recent developments," *BioResources* 7(2), 2506–2552. https://doi.org/10.15376/BIORES.7.2.2506-2552

Kaboglu, C., and Ferik, E. (2022). "The effect carbon nanotube on three-point bending behavior of fiber reinforced composite," *Indian Journal of Engineering and Materials Sciences* 29(1), 71–79. https://doi.org/10.56042/IJEMS.V29I1.48512

Lauerma, A., Costanzo, G., and Del Giacco, S. (2025). "Effect of fibers on microbiome, health and allergy," in: *The Skin Microbiome Manual*, Springer, Cham, Switzerland, pp. 223–235. https://doi.org/10.1007/978-3-031-82689-4_12

Marichelvam, M. K., Kumar, C. L., Kandakodeeswaran, K., Thangagiri, B., Saxena, K. K., Kishore, K., Wagri, N. K., and Kumar, S. (2023). "Investigation on mechanical properties of novel natural fiber-epoxy resin hybrid composites for engineering structural applications," *Case Studies in Construction Materials* 19, Article ID e02356. https://doi.org/10.1016/J.CSCM.2023.E02356

Martínez-Barrera, G., Martínez-López, M., and Castro-López, C. (2025). "Luffa natural sponge as sustainable reinforcement for polyester polymer composites," *Journal of Composite Materials* 59(28), 3215–3232. https://doi.org/10.1177/00219983251347853

Mohanavel, V., Suresh Kumar, S., Vairamuthu, J., Ganeshan, P., and NagarajaGanesh, B. (2022). "Influence of stacking sequence and fiber content on the mechanical properties of natural and synthetic fibers reinforced penta-layered hybrid composites," *Journal of Natural Fibers* 19(13), 5258–5270. https://doi.org/10.1080/15440478.2021.1875368

Mulla, M. H., Norizan, M. N., Abdullah, C. K., Mohd Rawi, N. F., Mohamad Kassim, M. H., Abdullah, N., Faiz Norrrahim, M. N., and Manzoore Elahi, M. S. (2023). "Low velocity impact performance of natural fibre reinforced polymer composites: A review," *Functional Composites and Structures*, *IOP Publishing* 5(3), Article ID 035004. https://doi.org/10.1088/2631-6331/ACF114

Natrayan, L., and Kaliappan, S. (2023). “Mechanical assessment of carbon–luffa hybrid composites for automotive applications,” *SAE Technical Papers* 2023, Technical Paper Number 2023-01-5070. https://doi.org/10.4271/2023-01-5070

Palaniappan, M., Palanisamy, S., Louhichi, B., Ayrilmis, N., and Murugesan, T. M. (2025). “Environmentally friendly composites from agricultural residue biomass for lightweight applications in new generation structures: A review,” *BioResources* 20(4), 11189–11226. https://doi.org/10.15376/BIORES.20.4.PALANIAPPAN

Palanisamy, S., Murugesan, T. M., Palaniappan, M., Santulli, C., Ayrilmis, N., and Alavudeen, A. (2024). “Selection and processing of natural fibers and nanocellulose for biocomposite applications: A brief review,” *BioResources* 19(1), 1789–1813. https://doi.org/10.15376/BIORES.19.1.PALANISAMY

Phiri, R., Mavinkere Rangappa, S., Siengchin, S., Oladijo, O. P., and Ozbakkaloglu, T. (2024). “Advances in lightweight composite structures and manufacturing technologies: A comprehensive review,” *Heliyon* 10(21), Article ID e39661. https://doi.org/10.1016/J.HELIYON.2024.E39661

Rahman, S., Das, S. C., Saha, J., Mubarak, and Khan, A. (2024). “Fabrication and physico-mechanical characterization of short natural/synthetic fiber–reinforced hybrid composites: Effects of biodegradation and chemical aging,” *Materials. Circular Economy* 6(1), Article ID 14. https://doi.org/10.1007/S42824-024-00105-0

Sritharan, R., and Askari, D. (2023). “Improvement of the tensile properties of laminated composites reinforced with Heli-Coil forms of carbon nanotubes,” *Polymer Composites* 44(10), 7070–7083. https://doi.org/10.1002/PC.27619

Şimşir, E., Akçin Ergün, Y., and Yavuz, İ. (2024). “Investigation of Damping Properties of Natural Fiber-Reinforced Composites at Various Impact Energy Levels,” *Polymers*, 16(24), 3553. https://doi.org/10.3390/polym16243553

Venkatesh, R., Ballal, S., Krishnan, A. M., Prabagaran, S., Mohankumar, S., and Ramaraj, E. (2023). “Effect of fiber layer formation on mechanical and wear properties of natural fiber filled epoxy hybrid composites,” *Heliyon* 9(5), Article ID e15934. https://doi.org/10.1016/j.heliyon.2023.e15934

Yavuz, I., Senol, B., and Simsir, E. (2025). “Examination of energy damping behavior of fiber glass reinforced sandwich structures with extruded polystyrene core material,” *Bulletin of the Polish Academy of Sciences Technical Sciences*, e153430. https://doi.org/10.24425/bpasts.2025.153430

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