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RESEARCH ARTICLE

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Experimental investigation of mechanical properties of jute/hemp fibers reinforced hybrid polyester composites

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Abstract

One of the primary drawbacks associated with natural fiber reinforced composites is their relatively poor mechanical properties. One potential approach to overcome this challenge is to augment the fiber loading, thereby improving the interfacial characteristics and hybridization. In this study, hybrid polyester composite structures reinforced with jute/hemp fibers were fabricated via the hand layup process, with fiber loadings varying between 30%, 50%, and 70% by volume. Fibers were subjected to alkali solutions (NaOH) containing 3% and 5% alkali in advance of the composites' formation. The impact, flexural, and tensile characteristics of hybrid jute/hemp reinforced polyester composites were investigated via laboratory studies. The composite materials that underwent testing with a 50 vol% fiber loading and 3% NaOH exhibited the maximum tensile strength (26.6 MPa), tensile modulus (733.56 MPa), flexural strength (62.7 MPa), and flexural modulus (3.04 GPa).

Highlights

- Hybrid polyester composite structures reinforced with jute/hemp fibers were fabricated.
- Hand layup method used with various fiber loadings (30%, 50%, and 70% by volume).
- Highest mechanical properties were obtained for 3% NaOH treatment and 50% fiber loading.

KEYWORDS

hybrid composites, impact strength, jute/hemp hybrid composites, mechanical properties, polymer composites, structural composites

1 | INTRODUCTION

Fiber-reinforced polymer composites (FRPs) achieved widespread usage in the transportation, construction, and sports equipment sectors on account of their superior strength to weight ratio and supplemental multifunctional characteristics.[1–5] Diverse forms of fibers (both natural and man-made) are used in FRPs including chopped short fibers, long fibers, knitted fabrics, woven fabrics, braids, and nonwovens.[6,7] Customarily used synthetic based fibers like glass, aramid, carbon, and so forth are costly and detrimental to the environment. In light of growing

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environmental consciousness, the fabrication, processing, and use of synthetic fiber based composites—are now regarded unfavorably, although their many advantages.[8] Recently, natural fibers have acquired notable consideration as a viable alternative to synthetic fibers purposes.[9,10] This is primarily due to their widespread availability and biodegradability.

Bast fibers, which belong to a diverse range of natural fiber classes, are now the subject of considerable scholarly investigation owing to their accessibility, affordability, exceptional chemical and physical characteristics, and biodegradable nature.[7,11–13] Plant-derived bast fiber is a lignocellulosic material, with cellulose serving as its essential constituent and imparting the fiber with intrinsic strength and stability.[14] The structural constituent impacts the physical and mechanical characteristics of such fibers. Fibers with a smaller microfibril angle and a higher cellulose content are prioritize for usage as reinforcement while fabricating the bast fiber reinforced polymer composites (BFRPs).[15] Jute, which has a smaller microfibril angle (~8.0°) and a greater cellulose content,[16] is composed of the following: 61%–71% cellulose, 14% hemicellulose, 12% lignin, 0.2% pectin, 0.5% wax, and 10% water. Due to its remarkable attributes including low density, moderate moisture regain, elevated stiffness and specific strength, good electrical and thermal insulation, biodegradability, low cost, and commercial availability, jute is widely regarded as the preferred bast fiber for use as a reinforcement material.[16–22] Conversely, there is a growing trend of using hemp fibers into composite materials as reinforcing agents, often in place of glass fibers due to their better strength and stiffness.[23,24] Hemp is composed of the following components: cellulose comprises 68%, hemicellulose 15%, lignin 10%, and oil and wax 0.8%.[25,26] In spite of their many benefits, bast fibers do possess a few disadvantages including lower impact strength, lower durability, and poor fiber-matrix adhesion.[27] One notable limitation of bast fiber-reinforced composites is that they exhibit suboptimal mechanical characteristics.[28] Through hybridization, increasing fiber loading, and changing the interfacial characteristics between the fiber and matrix, the weak mechanical properties could be improved.[6]

Fiber aspect ratio, fiber orientation, and fiber-to-matrix-adhesion are a few of the variables that influence the mechanical properties of fiber-reinforced composites. The enhancement of mechanical properties has been documented by multiple researchers as a result of increasing fiber loading beyond a certain threshold. The impact of optimal fiber loading on mechanical properties, including hardness, tensile strength, and flexural strength, was examined in polypropylene composites containing sugarcane bagasse fibers via the hot-pressing method. An increase in fiber content of up to 30% was found to substantially enhance the mechanical properties.[29] In their study, Karthick et al. (2018) investigated the mechanical properties of banana/glass fiber reinforced epoxy composites, specifically focusing on their tensile, flexural, and impact strengths. Different fabricated composites differ in terms of fiber length and fiber content. The findings revealed that the properties exhibited an upward trend as the fiber length and content increased by 10 mm and 15%, respectively.[30] A banana fiber reinforced polyester composite material with different fiber contents, such as 5, 10, 15, 17, and 20%, was developed by Dhakal and Keerthi (2017). The composite material's thickness was adjusted between 5 and 3 mm. Tensile, flexural, and impact strength tests were performed on the composite material. According to the test results, the composite with a thickness of 5 mm exhibited its maximum values for tensile, flexural, and impact strength when its fiber content was 20%.[31]

Synthetic fiber composites are more competitive than those composed of a single kind of bast fiber. Hybrid fiber reinforced polymer composites may circumvent this constraint by incorporating more fibers into a single kind of bast fiber.[32] An arithmetic mean is computed for the mechanical characteristics of individual components of hybrid composites. By correcting for the deficiencies of each kind of fiber, the reinforcing materials used in hybrid composites[33–36] enhance their respective strengths. Diversifying the fiber-loading ratio and subjecting the rubber matrix to chemical treatment, Hybrid composites reinforced with banana/jute/banana fiber which was fabricated by hand-lay-up technique exhibited superior tensile strength (54.6 MPa) and flexural strength (91.665 MPa) in contrast to its constituent banana fiber composites, according to an investigation by Venkateshwaran and Elayaperumal (2012).[37] In contrast to other composites, the jute/banana/jute reinforced polymer composite was shown the highest impact strength 106.67 J/m.[37] Tensile tests were conducted on epoxy hybrid composites reinforced with jute fiber and empty fruit bunches of oil palm. When oil palm empty fruit bunch/jute fibers were combined with oil palm empty fruit bunch fiber alone, a notable improvement in tensile strength and modulus was noted. When compared to pure oil palm bare fruit bunch composites, hybrid composites were found to have excellent interfacial strength.[38] Alavudeen et al. (2015) looked into the mechanical characteristics of polyester composites reinforced with woven banana/kenaf fibers. The composites benefited from the fibers' hybridization. The hybrid composites exhibited greater tensile, flexural, and impact strengths in comparison to the single banana or kenf fiber composites.[39]

Contrary to the hydrophobic behavior of polymer matrices, bast fibers possess hydrophilic properties. In BFRPs, this mismatch of properties upshots inadequate interfacial bondage among the fibers and polymer matrix.[40]

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At present, researchers are using several physical and chemical fiber modification techniques to enhance the interfacial adhesion properties between polymer matrices and bast fibers.[5,41] Among other methods, alkalization is the most often used chemical alteration process. By alkalizing fibers with a strong base like sodium hydroxide (NaOH), contaminants like lignin, hemicellulose, pectin, oil, and waxes may be eliminated.[42,43] The enhanced surface roughness of bast fibers treated with NaOH strengthens the mechanical fiber-matrix interaction. Additionally, the increased roughness facilitates a more extensive interface between the matrix and the fibers.[44,45] Furthermore, NaOH is capable of altering the surface chemistry of bast fibers by forming hydroxyl and carboxylic acid functional groups. These groups can react with matrix's functional group to form robust interfacial bonds.[6,46–48]

Jacob et al. (2004) assessed the mechanical characteristics of an oil-palm and sisal fibers reinforced matrix. Transverse fiber hybrid composites proclaimed inferior mechanical characteristics compared to longitudinal fiber composites. For 1 h, the fibers were treated with NaOH solutions of varying concentrations. It was demonstrated that the tensile strength of treated composites increased in comparison to untreated composites. 4% NaOH composites exhibited the greatest tensile strength.[49] The consequences of alkali-treated coir fiber-reinforced epoxy based composites were assessed in the investigation of Yan et al. (2016) where the flexural strength of composite was incremented 16.7% after the alkali treatment.[50] In 2015, Fiore et al. studied that, the flexural strength of kenaf fiber/epoxy composites was found elevated after alkali treatment contrasted to the pure epoxy resin-based composite materials.[51] The mechanical properties of sisal/carbon fiber reinforced hybrid composites were investigated experimentally, and it was discovered that fibers treated with 18% NaOH significantly enhanced the properties of the fiber composites.[52] An examination of the impact of surface modification on the thermo-mechanical properties of bamboo fibers revealed that a 1-h treatment with 4% NaOH resulted in a 10% increase in fracture strength relative to untreated fibers.[53]

The mechanical characteristics of hybrid composites were amplified by the use of a stacking sequence, as stated by many researches.[54] The impact energy was found to be enhanced by the carbon fiber/Kevlar hybrid composite, which consisted of Kevlar fibers sandwiching the carbon fibers. The mechanical properties of hybrid materials as a result of stacking. The hybrid composite was produced by hand layup utilizing a treated kenaf mat and woven kenaf and Kevlar fabrics stacked in a variety of sequences. The mechanical characteristics of hybrid composite including Kevlar as its outermost layer were shown to be relatively better compared to other distinct hybrid composite materials.[55] Among the many types of natural fibers, jute and hemp fibers are relatively promising. For instance, research has shown that jute fibers stretch more effectively than hemp fibers, despite the latter being more resilient and brittle. Consequently, the brittleness and mechanical strength of the composite are enhanced when hemp and jute fibers are combined in a hybrid laminate.[56]

The mechanical properties of jute/hemp fiber reinforced hybrid composites composed of epoxy resin and polylactic acid have been the subject of investigation and documentation by a number of researchers. Short jute, hemp fibers, and polyester resin are used in this study to fabricate the composite structures. Prior to the fabrication of the composites, the fibers underwent treatment with an alkali (NaOH) solution. To ensure fiber alignment within the composite structures, a carding process was implemented. To the author's best knowledge (available from literature), this combination has not been studied yet. The primary objective of this experimental study is to investigate the effects of alkali treatments and fiber loading on the tensile, flexural, and impact properties of composite structures. FESEM (field emission scanning electron microscopy) was employed to examine the fracture morphologies of the test specimens.

2 | MATERIALS AND METHODS

2.1 | Materials

A local manufacturer in Adana, Turkey, supplied the hemp fiber. Jute fibers were provided by Erkaplan Yarn Carpet Textile Food Industry and Trade Limited in Gaziantep, Turkey (Erkaplan Ğplik Halı Tekstil Gıda San ve Tic. Ltd. Şti.). Local chemical retailer Yontar Group in Adana, Turkey, supplied the resin (unsaturated polyester) and hardener (di-methyl ethyl ketone peroxide). The polyester-based resin had a density of 1.3 gm/cm^3 and a viscosity of 1700 cps.

2.2 | Fiber treatment

Each hemp and jute fiber were separated into two portions. Each portion was subjected to a one-hour treatment at room temperature with 3% NaOH and 5% NaOH, respectively. A constant mass ratio of 30:1 was maintained between fiber and solution. The treated fiber underwent multiple washes using distilled water prior to being dried at room temperature. In Figure 1, the untreated and treated fibers are illustrated. The average length and diameter of the hemp fibers utilized were 10 mm and 16 microns,

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respectively. In contrast, the jute fibers possessed length and diameter measurements of 2 mm and 12 μm, respectively.

2.3 | Fiber preparation

Both untreated and treated fibers underwent processing in a tiny carding machine. This operation aimed to align and straighten the fibers along their axis, increase the volume of fiber per unit weight, and ultimately transform the fiber into a rope-like structure. The densities of jute and hemp fiber were lowered to 0.5 and 0.6 gm/cm^3, respectively, after the carding procedure. Decreasing the density of jute and hemp fibers that help create lightweight composites, is a novelty of the research. Prior to the addition of resin, rope-like fibers were trimmed to the mold's 18 cm length and put in the longitudinal direction across the mold. A schematic representation of the processing of jute and hemp fibers prior to composite production is visualized in Figure 2.

2.4 | Composite fabrication

The hand lay-up procedure was applied in the development of the composite structures. Figure 3 illustrates the sequential process flow involved in the development of jute/hemp fiber reinforced hybrid polyester composites. The first 1% hardener was combined with the polyester resin in a jar and agitated until a paste coat formed. The time required for paste formation was 5 min. Precautions were made to prevent the development of bubbles. Mold-releasing paper was applied to the mold's underside (18 cm × 18 cm × 4 cm steel mold). Gradually, a minute quantity of resin paste was daubed onto the paper. The matrix layer, which was covered by jute fibers, was then coated with a layer of jute fibers, and the matrix was reapplied gradually onto the fiber surface. Following this, a hemp fiber layer was applied to the matrix layer. Consequently, the wet composite was rolled using a steel hand roller to improvise the contact among the fiber and the matrix, allow a uniform distribution of the resin, eliminate any trapped air between the fiber and resin,

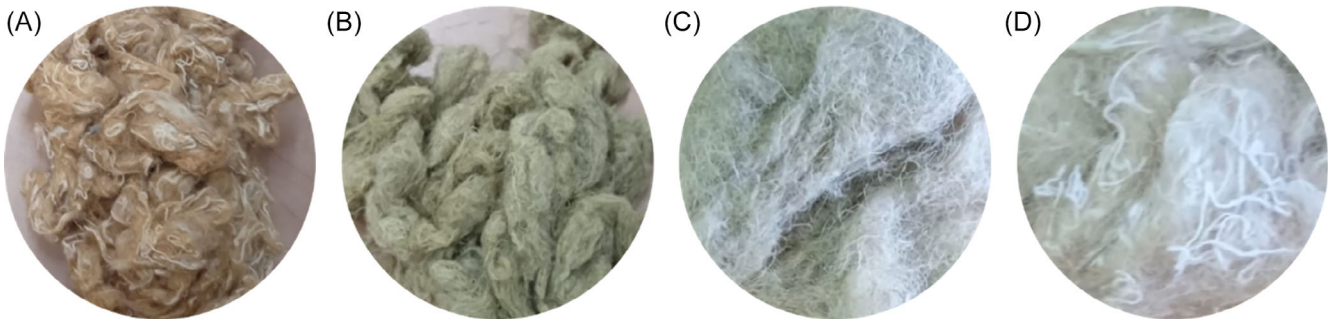


FIGURE 1 Pictorial view of fibers before and after treatment: (A) untreated jute fiber, (B) treated jute fiber, (C) untreated hemp fiber, and (D) treated hemp fiber.

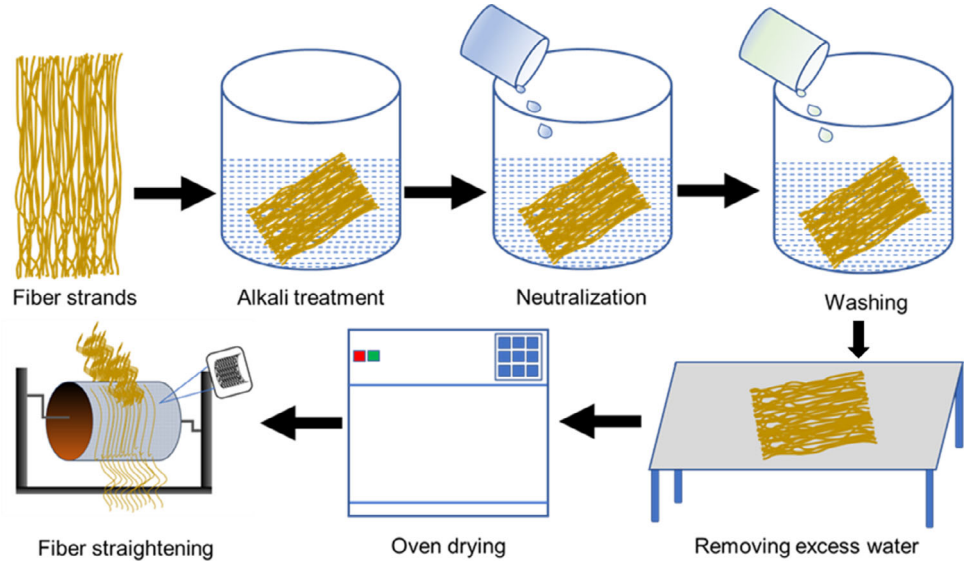


FIGURE 2 Schematic view of processing jute and hemp fibers prior to composite fabrication.

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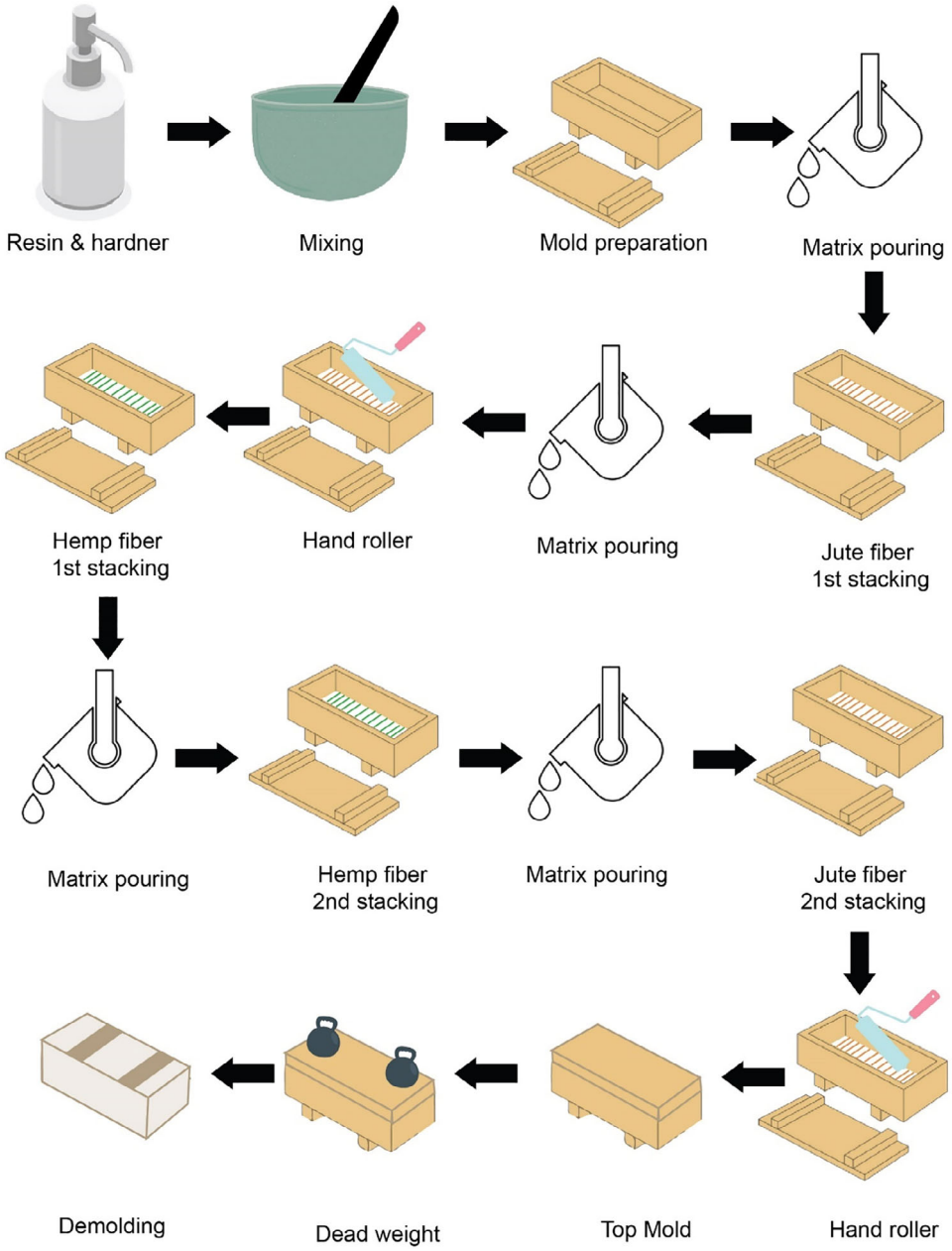


FIGURE 3 Step by step process flow of developing the jute/hemp fibers reinforced hybrid polyester composites.

and achieve the desired thickness. Four layers of fiber were laminated in this manner. An additional layer of mold release paper was positioned over the uppermost fiber layer inside the mold.

For consistent pressure, the upper portion of the mold weighing 10 kg was put on top, and the produced composite was left to cure at room temperature for four to 5 h. By applying pressure to the polyester and hardener combination, the surplus material was compressed. During the composites' preparation, particular attention was given to account for this loss. The hybrid polyester composites were reinforced with jute/hemp fibers at loadings of 30%, 50%, and 70%, respectively keeping the ratio of jute and hemp fiber (50:50). The mean mass of the composite plate was 350 g, while its mean thickness was 10 mm.

2.5 | Mechanical characterizations

In accordance with the methods and requirements of ASTM D638 and at a crosshead velocity of 5 mm/min, the tensile properties were assessed using the Zwick/Roell Z010 (BL-GRWO10K, Germany), a universal testing machine (UTM). The gauge length was 115 mm, and the overall length of the specimen was 160 mm. With a 100 mm gauge length and the speed of crosshead was 2 mm/min, the flexural characteristics were determined utilizing the same

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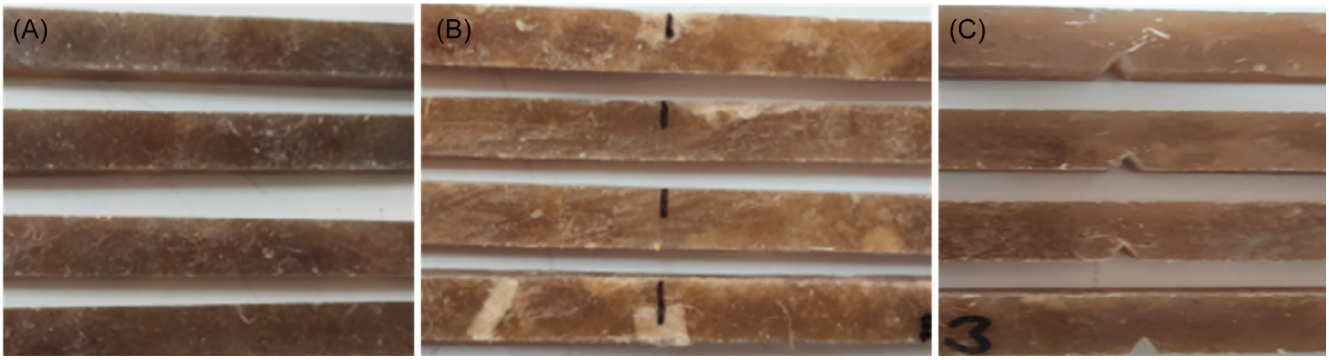


FIGURE 4 Specimen for mechanical testing. (A) Tensile test specimen (B) Flexural test specimen (C) Impact test specimen.

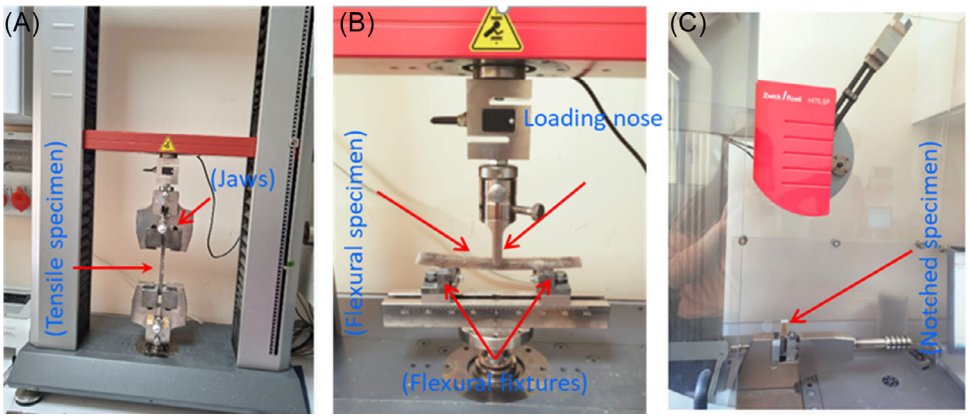


FIGURE 5 Mechanical testing: (A) Tensile properties testing (B) Flexural properties testing (C) Impact strength testing.

apparatus as specified in ASTM D790. An ASTM D256-compliant Zick/Roell (HIT5.5P, Germany), impact strength tester was used to conduct Izod impact tests on a notched specimen. A mean value of five samples was used to calculate each outcome. Figures 4 and 5 depict, respectively, test specimens and the mechanical testing being evaluated.

2.6 | Fracture characterizations

Employing Field Emission Scanning Electron Microscopy (FEI Quanta FEG 650, USA), at a voltage of 20 kV, the fractured surfaces of tensile, impact, and flexural test samples of treated and untreated composites were analyzed. Prior to FE-SEM examination, a substantial impact was seen on the image resolution due to the applying a thin layer of gold-coating on the sample to enhance electrical conductivity.

3 | RESULT AND DISCUSSION

3.1 | Tensile properties

Figure 6 illustrates the tensile strengths of the hybrid polyester composite structures that were produced and reinforced with jute/hemp fibers. As seen in Figure 6A, the composite's tensile strength exhibited a progressive rise when 30% fiber was included. However, as the fiber loading reached 50%, the tensile strength achieved its maximum value and thereafter started a gradual decline. Consequently, the composite material with 50% fiber loading of demonstrated the most significant tensile properties. When the fiber loading is low, the orientation of the fibers becomes weak, impeding their ability to transfer the load to one another. Consequently, stress accumulates at specific locations within the composite, resulting in a reduction in tensile strength. Increased fiber loadings lead to a greater population of fibers, which subsequently inhibits coagulation and stress transfer. For optimal adaptation, the fiber population should be loaded at intermediate levels; furthermore, the fibers engage in active stress transfer.[49] In an evaluation conducted by Sultan Ozturk, the impact of fiber reinforcement on a phenol formaldehyde composite reinforced with kenaf fiber was examined at 6 different fiber loadings (19%, 28%, 36%, 43%, 52%, and 62% by volume). It was demonstrated that the tensile, flexural, and hardness properties of the composite increased as the volume% of fiber loading was raised to 43%, after which they decreased.[57]

Jute and hemp fibers were subjected to alkali treatment. After alkali treatment, the diameter and weight of

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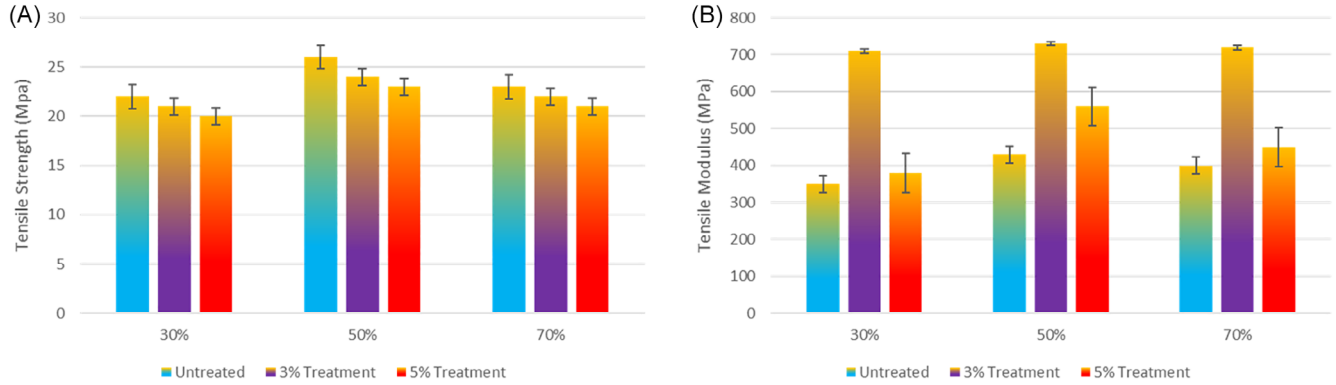


FIGURE 6 Tensile properties of the developed jute/hemp fibers reinforced hybrid polyester composite structures: (A) Tensile strength, and (B) Tensile modulus of the developed composites.

the fiber was found to decrease due to removal of the lignin. The greatest tensile strength was observed with a fiber loading of 50%. The findings indicate that jute/hemp composites treated with 3% NaOH had tensile strengths that were respectively 11.2% and 10.8% greater than those of the untreated and 5% NaOH-treated polymer composites. The amorphous regions lignin and hemicellulose are eliminated by alkali treatment, which also increases the surface roughness of the fiber and, consequently, the surface area that is in contact with the matrix. A composite's strength is diminished as a result of the fiber surface being destroyed by an excess of NaOH. On the sisal/glass hybrid composite, the impact of NaOH and Silane on its tensile properties was evaluated. As demonstrated by the SEM image, the chemical treatment eliminates the hemicellulose from the fiber, resulting in a rough surface. The rough surface enhances the adhesion between the matrix and fiber, thereby augmenting the hybrid composite's tensile strength.[58] The mechanical properties of bagasse fiber reinforced polyester composites were investigated by Vilay et al. in relation to the chemical treatment of sodium hydroxide (NaOH) and fiber loading. The researchers concluded that the treated fiber composites achieved a greater tensile value than the untreated fiber-based composites.[59] The tensile modulus of the composite constructions exhibits a progressive rise as the fiber loading rises, commencing at 30% and culminating at 50% fiber loading (Figure 6B). After a loading of 50%, however, the modulus begins to fall. This tendency is evident in all buildings, including those that were not treated, treated with 3% alkali, and treated with 5% alkali. Slight increase of tensile modulus at 50% fiber content than 30% and 70% fiber content composite. This is because at high fiber loading, composite will be able to withstand more load. Regarding the fiber-matrix interface enhancements of the HDPE-henequen fiber composite, a comparable study found no discernible impact on the modulus of elasticity.[53] The present study's reported enhancement in tensile characteristics is corroborated by prior studies. Chaudhary et al. reported that fiber hybridization improved the tensile properties of BFRPs.[60] Praveena et al. showed that the inclusion of sisal fiber in pineapple/polyester fiber reinforced composites, up to a weight of 50%, enhances the mechanical characteristics. This phenomenon can be ascribed to the hybridization effect, where both types of fibers contribute to increasing the composite's strength.[61] However, Sawpan et al. reported the stress concentration of hemp fibers reduced the tensile properties of the composite material. They found an initial decline in tensile strength at 20 wt% fiber contents, but then it increased as the fiber content increased from 20 to 50 wt%. However, at the highest fiber content of 60 wt%, there was another reduction of tensile strength.[62]

Figure 7 presents the tensile fracture morphologies of hybrid composite materials, including both untreated and treated implementations. Among the fibers and matrix is seen in the SEM micrographs in the form of an interface. It is evident from Figure 7 that untreated and treated fibers show entirely diverse surface morphologies. Tensile failure was induced by several mechanisms, including fiber delamination, stringent tensile fracture, cracked matrix, and fiber pull-out. Untreated fiber-reinforced composites were significantly prone to fiber pull-out, debonding, matrix cracking, fiber layer delamination, and so forth. This is predominantly attributable to the relatively smooth and irregular surface structure and abundance of hydrophilic elements present on the untreated fibers.[63] Conversely, as illustrated in Figure 8B, the fibers that underwent treatment demonstrate an improved affinity for the resin, leading to diminished fiber pull-out, decreased matrix cracking, and robust fiber-matrix bonding. This indicates that fiber treatment improves stress transfer between the fiber and matrix by enhancing adhesion between the fibers and the matrix, resulting in more

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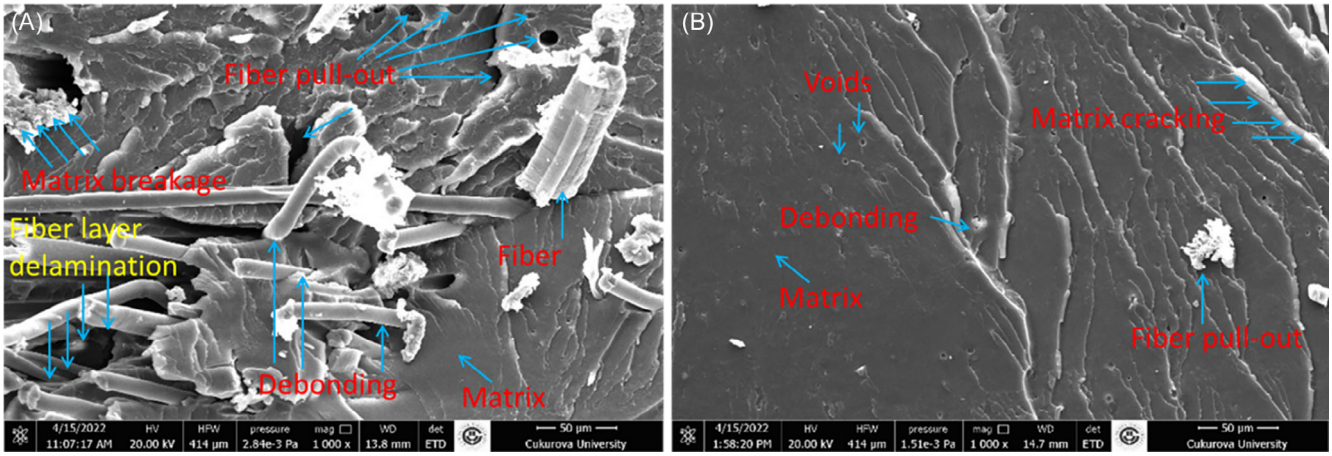


FIGURE 7 50 μm magnification SEM images of fractured surface of jute/hemp fibers reinforced hybrid polyester composite after tensile testing: (A) Untreated composite (B) Alkali-treated composite.

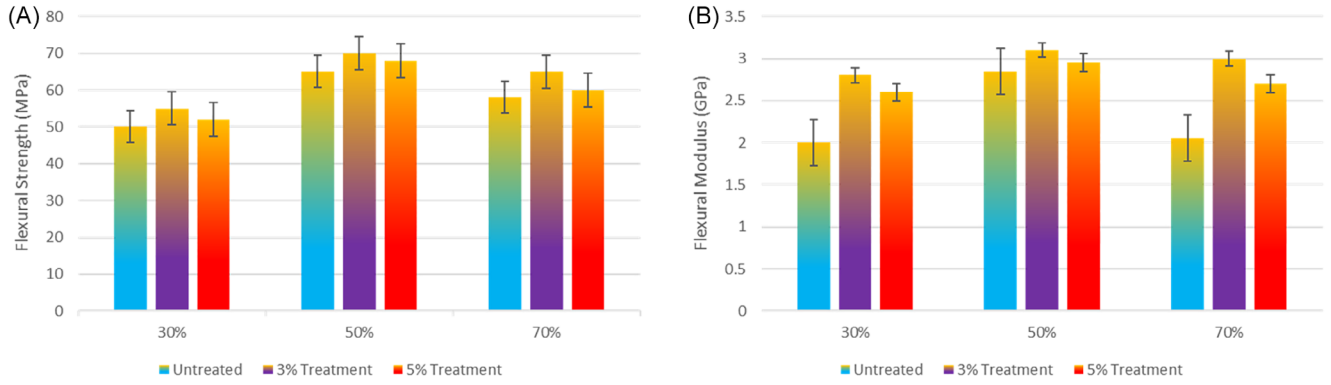


FIGURE 8 Flexural properties of the developed jute/hemp fibers reinforced hybrid polyester composite structures: (A) flexural strengths, and (B) flexural modulus of the developed composites.

uniform and intimate contact.[64] The aforementioned justifications account for the enhanced tensile properties exhibited by the treated composite.

3.2 | Flexural properties

Figures 8 and 9 illustrate the flexural characteristics of the polyester composite constructions designed using reinforced jute and hemp fibers. The utmost flexural strength was achieved at a fiber loading of 50%, as seen in Figure 8A. The flexural strength exhibited a progressive enhancement till it equivalented 50% with the increment of fiber loading amount. Nevertheless, the flexural strength exhibited a progressive decrease when the fiber loading was escalated above this threshold. At 70% fiber loading, it regressed to a level lower than that attained at 50% fiber loading. Insufficient fiber dispersion inside the resin might perhaps account for this decline in flexural strength.

The flexural strengths of untreated, 3% NaOH-treated, and 5% NaOH-treated fibers reinforced composite constructions are visualized in Figure 8. It was determined that the flexural strength was greatest at 50% fiber loading. The flexural strength of jute/hemp fiber-reinforced composites reinforced with 3% alkali was enhanced by 10.6% and 10.3%, respectively, in comparison to untreated and 5% alkali-treated composite structures. The mechanical properties of polymer composites can be enhanced by treating fibers with NaOH, an extremely alkaline solution. The surface area and receptivity of the fibers to polymer bonding are enhanced through the elimination of lignin and hemicellulose via NaOH treatment. Enhanced load transfer and adhesion ensue from the improved interaction between the treated fibers and the polymer, thereby augmenting the strength and stiffness of the composite.[65] Adhesion characteristics between fiber and resin determine the flexural strength. Better adherence and interlocking among the matrix and fiber resulted in increased flexural strength of alkali-treated fibers. The rationale for

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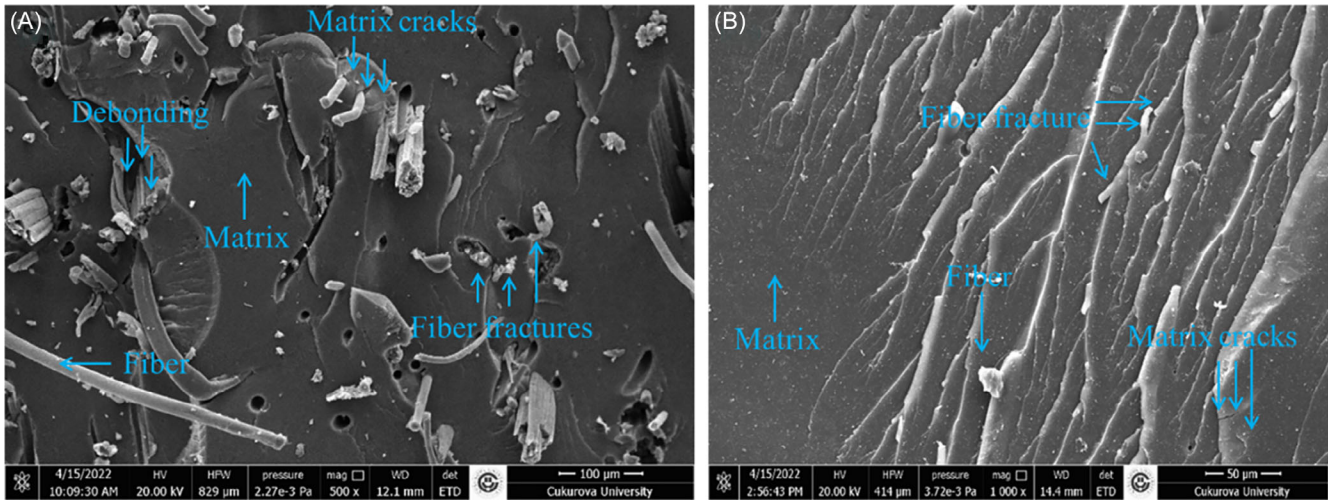


FIGURE 9 SEM images of fractured surface of jute/hemp fibers reinforced hybrid polyester composite after flexural testing: (A) Untreated composite (B) Alkali-treated composite.

this was that alkali treatment eliminated superfluous components from the fiber surface. The optimized composite structures achieved their maximum flexural modulus when treated with 3% NaOH and 50% fiber loading (as per Figure 8B). In their investigation, Shibata et al. assessed the impact of fiber loading on the flexural properties of polyester composites reinforced with abaca fiber. They discovered that the flexural modulus of every fabricated composite increases as the fiber loading increases.[59] Ahmad Mansoor et al. investigated the flexural strength and modulus of the untreated and treated epoxy composites reinforced with bamboo fiber (50% bamboo fiber with 50% epoxy composite). The results indicated that the flexural strength and flexural modulus of the treated composite were 30.7% and 26.18% greater than those of the untreated composite, respectively.[53] The mechanical properties of injection-molded short hemp and glass fiber reinforced polypropylene composites were investigated by Kumar et al. (2017). The researchers discovered that a hybrid composite consisting of 25% weight% hemp and 15% weight% glass fiber exhibited superior flexural strength, flexural modulus, and notch impact strength.[66]

On the fractured exterior of the specimen, fiber fractures, debonding, and matrix cracks are seen in Figure 9. The performance of the treated hybrid composites was clearly superior than the untreated composites, as shown by the reduced circumstance of fiber pull-out and debonding amid the fiber and matrix in the Figure 9. The bonding between fiber and matrix significantly affects the flexural strength of bast fiber reinforced polymer composites.[67] Flexural strength of bast fiber reinforced polymer composites largely rely on the interfacial adherence between the fiber and matrix, and adequate penetration of resin into the fibers, which improves the quality of the interfacial properties, and reduces fiber pull-out and debonding.[68] The previous research supports the observation of escalation of flexural strength in this study. Anbukarasi and Kalaiselvam assessed the morphological analysis of luffa fiber reinforced epoxy composites after flexural loading and observed that increases in fiber loading enhanced bonding among the fiber and matrix, resulting in reduced fiber pullout, matrix cracks, and debonding, which was the reason for the improvement of flexural strength of developed composite. Low flexural strength occurred due to low stress transfer in the composite, which caused much fiber pullout and greater debonding through fiber and matrix.[69]

3.3 | Impact properties

The impact strengths of the polyester composite structures reinforced with jute/hemp fibers are shown in Figure 10. The impact strength increased gradually as the fiber content rose and peaked at 50% fiber content, as seen in Figure 10A. However, strength decreased when more fibers were included. The impact strength was seen to be 8% less at 70% fiber level compared to 50% fiber content. The composite that underwent testing, including those treated with 3% NaOH, had the greatest impact strength. In particular, the impact strength of the composite treated with 3% NaOH was 40% more than that of the untreated composite and 10% greater than that of the composite treated with 5% NaOH (as seen in **Figure** 10B). Hemicliques, lignin, pectin, wax, and oil covering materials are all reduced in quantity through alkali treatment. The fiber surface becomes pristine as a consequence. Thus, the capacity for stress transfer between

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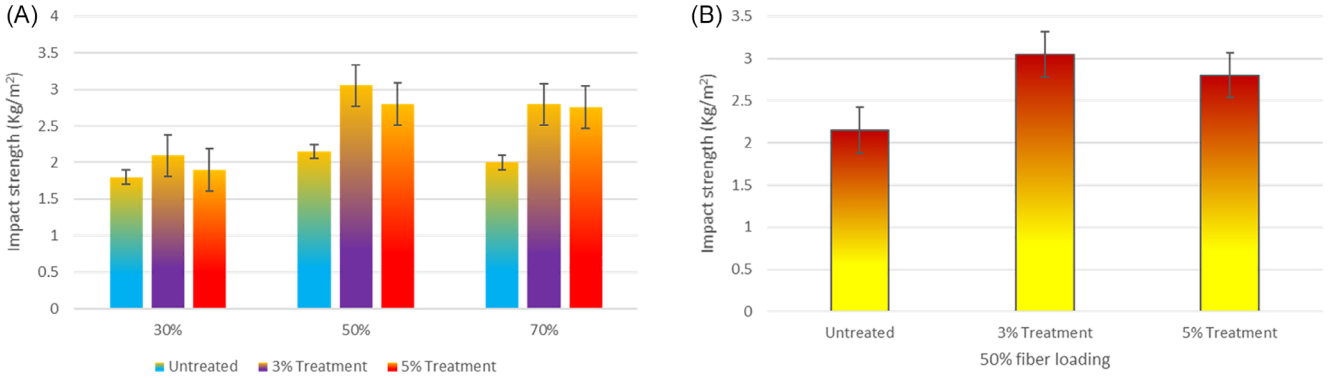


FIGURE 10 Impact strengths of the developed jute/hemp fibers reinforced hybrid polyester composite structures: (A) Effect of fiber loading, and (B) Effect of surface modification.

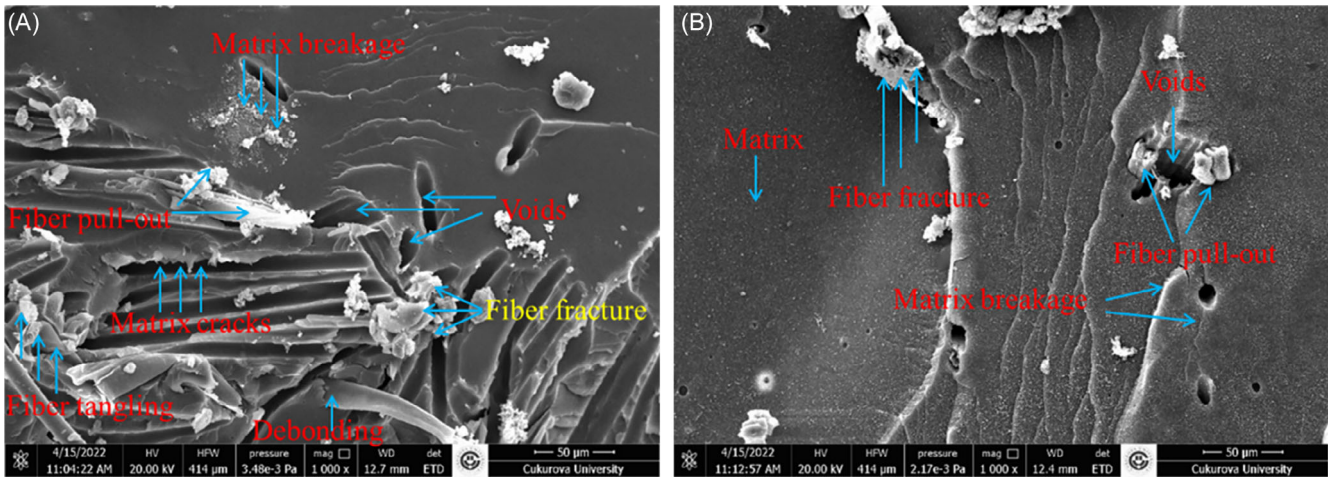


FIGURE 11 SEM images of fractured surface of jute/hemp fibers reinforced hybrid polyester composite after impact strength testing: (A) Untreated composite (B) Alkali-treated composite.

ultimate cells is enhanced as a result of the elimination of micro-voids from the fiber surface, which renders it more uniform. Furthermore, it increases the aspect ratio (length to diameter) by decreasing the diameter of the fiber. Thus, the effective fiber surface area is increased, facilitating matrix adhesion.[70] This treatment significantly enhances the thermal and mechanical properties of the composite. In the event that the concentration of alkali exceeds the optimal level, an excessive delignification of the fiber may occur, leading to its weakening or damage.[71] The effect of varying fiber contents on a composite made of arbitrarily oriented short jute and banana fiber with tensile, flexural, and impact strengths was investigated by Krishna and Gowda (2017). It was determined that 15% is the optimal fiber volume fraction for tensile and flexural strength. The impact strength of a material increases by up to 25% with the fiber content.[72] Cao et al. investigated the effect of alkali treatment on the mechanical properties of bagasse fiber reinforced polyester composites. According to the findings of that study, alkali treatment increases impact energy by 30%.[73]

As shown in Figure 11, SEM micrographs were used to assess the cracked surfaces of the treated and untreated hybrid composites subsequent to impact testing. The determining elements that impact the fracture mechanism of the created composites include fiber pull-out, debonding, matrix fractures and breakages, and fiber fracture. Treated composites demonstrated greater impact strength than untreated composites in the current investigation. It is evident from Figure 11A that debonding, fiber pullout, and matrix breakages were more severe on the cracked surfaces of the untreated composite than the treated composites, as seen in Figure 11B. The decrease in impact strength of bast fiber reinforced polymer composites is supported by previous studies. Mader et al. analyzed the adhesive properties of the fiber/matrix interface and its effect on the impact strength of a manmade cellulose/epoxy composite and stated that fiber pullout was

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the reason for the weaker interfacial shear strength that lessen the impact strength of the composite.[74] Ma et al. investigated the impact strength of glass epoxy composites and found that matrix cracking, debonding, and fiber pull-out were the reasons for lower impact strength.[75] Several researchers reported that type of fiber, and surface treatment of fibers govern the attributes of the developed composite by improving fiber-matrix adhesion and increasing the composite's impact strength.[76–78]

4 | CONCLUSION

The study findings reveal a notable increase in tensile strength, tensile modulus, flexural strength, flexural modulus, and impact strength, reaching a peak at a specific threshold of 50% fiber content. Beyond this point, however, these attributes exhibit a decline. Notably, the composite treated with 3% NaOH exhibits superior mechanical properties compared to both untreated and 5% NaOH-treated composites. The pinnacle of mechanical performance is achieved at a 50% fiber loading by volume, showcasing significant advantages over loadings at 30% and 70%. These insights stem from the experimental investigation into the mechanical properties of Jute/Hemp fibers reinforced hybrid polyester composites, contributing valuable knowledge to this field. The widespread use of natural fiber reinforced composites across various applications can be further enhanced by embracing hybridization and optimizing fiber loading, while simultaneously improving interfacial adhesion through tailored surface treatments. The composite, suitable for use as packaging material, can be further optimized by increasing the aspect ratio of fiber by volume and improving interfacial adhesion between the fiber and matrix through appropriate chemical treatment. This optimization has the potential to yield a lightweight material with a high strength-to-weight ratio, thereby creating new opportunities for the utilization of natural fiber composites in aerospace and automobile applications.

4.1 | Key conclusion points

- Mechanical properties (tensile strength, flexural strength, impact strength, tensile modulus, and flexural modulus) increased up to a threshold of 50% fiber content.
- Beyond the threshold, all mechanical attributes exhibited a steady decline.
- Alkali-treated composites demonstrated loftier mechanical characteristics than the untreated composites in mockup experiments.

AUTHOR CONTRIBUTIONS

Md. Zahidul Islam: Writing–original draft, Conceptualization, Methodology, Formal analysis, Investigation, Validation, Data curation. **Emel Ceyhun Sabir:** Conceptualization, Methodology, Project administration, Funding acquisition, Supervision, and Review & Editing; **Md. Syduzzaman**: Writing–review & editing, Formal analysis, Investigation, Validation, Data curation.

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The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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