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REVIEW ARTICLE

An Assessment of Utilizing Natural Fibers for the Development of High-Performance Fiber Hybrid Composites for Mechanical and Fracture Toughness Properties

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Abstract

Objectives: The key objective of this present article is to understand the prominence of hybrid laminates reinforced with different types of synthetic and natural fibers on mechanical and fracture toughness properties with precise apprehension to their applications in structural, aerospace, automotive, offshore, and packaging industries, etc. Various types of hybrid composites which were manufactured by different techniques are studied to understand the significance of natural fibers to enhance the mechanical properties of hybrid composites. **Methods:** A methodical comprehensive review has been done on the various tests used for evaluating mechanical and fracture behavior of hybrid composites using Flax, Sisal, Kenaf, Jute and Banana fibers. Certainly, the abundance of Natural fibers with low cost, eco-friendly and bio-degradable characteristics have captured the attention of the researchers across the globe. **Findings:** Experimental investigations revealed that the alkaline treated natural fibers demonstrated desirable mechanical and fracture toughness properties when they were used in conjunction with synthetic fibers. Developing hybrid composites using natural and synthetic fibers will be an innovative concept, which can offer a new class of composite material for primary structural applications. **Novelty:** This review will certainly help composite research community to explore sustainable eco-friendly hybrid composites. In addition to this, there is an ample of scope to utilize the natural fibers to develop hybrid fiber composites by partial replacement of synthetic fibers in high performance FRP composites. This assessment will also give brief comprehensive report on the performance of Natural Fiber Hybrid Composites (NFHC) with respect to their mechanical properties relative to conventional FRP Hybrid composites.

Keywords: Hybrid composites; NFHC; Mechanical Properties; Fracture Properties; Bio-degradable

1 Background

A composite material is an amalgamation of two materials to attain a single structure. One out of the two materials, is a matrix phase and the other is a reinforcing phase. Both phases can be metal, ceramic or, polymer. The reinforcing phase will be typically fiber or particle phase which will be stiff and strong as compared to the other phase which is the matrix. The matrix acts as a prime load-bearing member and performs the act of transferring the load between the fibers and in some cases of complex loading, the matrix may even need to sustain loads in the direction transverse to the fiber axis. The matrix phase also helps to shield the fibers from environmental degradation, before and after processing of the composites. Composites are not only significant in terms of only structural characteristics but also in terms of thermal, electrical, tribological and environmental characteristics. As a result, composites may be thought of as a mixture of materials that differ from alloys, but in fact, the individual components retain their properties. These individual components are thus incorporated or mixed into the composite for their unique properties rather than their deficiencies in order to obtain better materials[(1)]. These composite materials possess high specific strength to weight ratio, specific stiffness to weight ratio for diverse engineering applications. Despite the fact, that an advanced composite material provides many advantages to various applications there are some serious issues like low strength and toughness that need to be looked after. Issues concerned with respect to recycling may pose a serious threat to the environment. Moreover, composite materials are relatively costlier for domestic products. To overcome these shortcomings, naturally obtained fibers have been developed in the previous few decades which focus on substituting the conventional synthetic fibers to achieve a new group of natural fiber-reinforced polymers (NFRP). Increasing awareness of ecological concern is also a major factor that forces engineering fields to create a new group of materials derived from natural resources that can be either reused or recycled. In the last few decades, many researchers and scientists have focused their attention on developing a new class of materials consisting of biodegradable fibers, synthetic fibers, and polymers to develop bio-composites and hybrid composites.

Synthetic fibers like glass, carbon, Kevlar, etc. are strong and possess high strength, high stiffness, long fatigue life, resistance to wear and corrosion. In addition to the various benefits, synthetic fibers have some drawbacks, such as high costs, high density, poor recycling, and non-biodegradable recycling. Natural fibers which are derived from plants are gaining importance as reinforcement in composite material because of their availability from natural resources, satisfactorily high specific strength, biodegradability. Also, natural fibers are cheap in terms of economics due to their abundant availability as compared to other synthetic fibers[(2)]. But some drawbacks associated with natural fibers are the utilization of raw fibers in preparing the composites, high moisture absorption, low thermal stability. The high moisture absorption characteristic of natural fiber is the major disadvantage which can be reduced significantly by the chemical treatment of fibers. Chemicals such as sodium hydroxide, isocynate, $KMnO_4$ (permanganate), peroxide, enzyme, etc., have been used in the treatment and significant changes in the mechanical and physical properties have been obtained.

Natural fibers have three main categories namely Stem, Bast or Bark (Flax, Jute, Hemp, etc.,), Leaf fibers (Banana, Sisal, Manila, etc.), Seed fibers (Cotton, Oil palm, etc.,) depending on the part of the plant from which they are obtained.

The classification of Natural and Synthetic Fibers are shown in Figure 1.

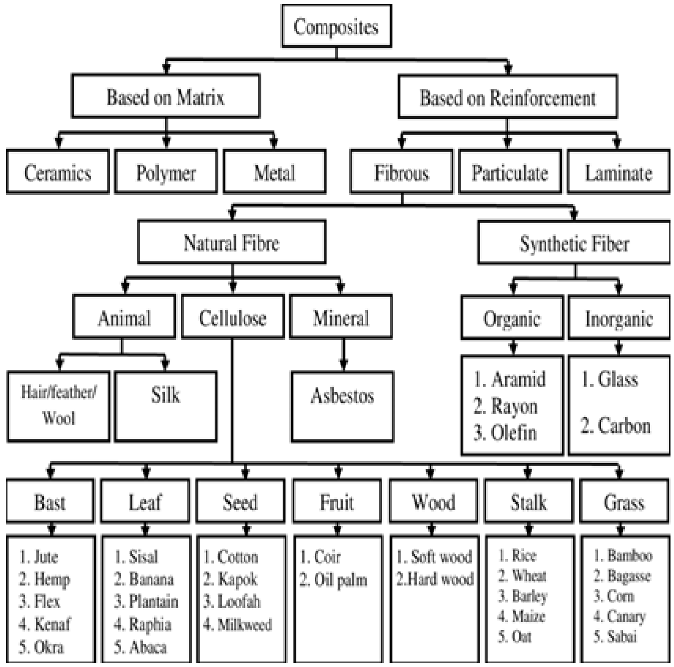

Fig 1. Classification of Natural and Synthetic Fibers (Saba et al.,[3])

In the present work, an attempt is made to evaluate the effect of using natural fibers along with synthetic fibers in terms of mechanical and fracture properties. In this regard, few of the earlier works made on the combination of natural and synthetic fiber hybrid composites are studied to draw inferences on their mechanical and fracture toughness properties. The earlier reviews made, have not focused on the mechanical and fracture properties of hybrid composites developed by combining natural and synthetic fibers. This review will offer a comprehensive insight to understand the potential utilization of natural fibers along with synthetic fibers to develop a new class of material.

2 Natural fiber composites — An overview

The awareness towards the development of polymer composite materials consisting of natural fibers is increasing very fast with respect to engineering and research fields. The characteristics of natural fibers have forced researchers to have a center of attention on the utilization of natural fibers. Major factors that are advantageous are low cost, environment-friendly, recyclability. These factors make them an eye-catching ecological alternative to Glass, Carbon and other synthetic fibers to form a hybrid composite material with desirable properties[1]. The behavior of hybrid composites relies on the content of fiber, length of the fibers, the direction of fibers, level of mixture or intermingling of fibers, fiber and matrix interface, stacking pattern of fibers, and also relies on the failure strain of single fibers. Furthermore, understanding the impact of Hybridization using various Natural fibers and synthetic fibers on mechanical and fracture behavior has been discussed under the following sections.

2.1 Flax fiber and its Hybridization with Synthetic Fibers

The Flax (Linum usitatissimum) plant shown in Figure 2 belonging to the family of Linaceae is cultivated for obtaining the fiber from which linen yarn and fabric are produced and for its nutritious seeds called linseed. It is from this seed linseed oil is obtained.

The use of NaOH treated flax fibers integrated with carbon fiber showed good improvement in strength and stiffness of the woven flax and carbon epoxy hybrid composite with less carbon volume fiber fractions. With the introduction of an 8% volume of carbon fibers, the tensile strength is improved moderately and with 14% addition of carbon fibers, the strength of the overall hybrid composite was improved significantly in comparison with non-hybrid flax epoxy composites[4]. The hybridization of carbon fiber with flax fiber yields a material possessing significantly enhanced mechanical properties. 4 ply unidirectional (UD)

Fig 2. Image showing Flax plant and extracted fibers in the raw and treated form

carbon fiber and 2 cross-ply flax fiber exhibited greater improvement in tensile strength[5]. A Carbon/Flax reinforced hybrid composite material with a 20% volume fraction of flax fiber showed a large improvement in tensile strength. In addition to this, considerable weight saving was observed with reduced composite density. Similarly, a better flexural strength was noticed for 20% flax fiber volume fraction. It is also apparent that the stacking layer pattern plays a prominent role in the flexural properties of the composite[6]. Flax fiber-reinforced polymer composite structure possesses lower mechanical properties and including one layer of UD carbon fiber on extreme sides can greatly improve the mechanical properties of the composites hybridized with Flax and Carbon fiber[7]. An enhancement in tensile properties of the hybrid composites of flax and glass fiber reinforcements was noticed as the glass fiber quantity was augmented. The stacking series of fibers had a massive impact on the tensile strength of flax and glass fibers-reinforced hybrid composites. The interlaminar shear strength (ILSS) and fracture toughness of hybrid composites consisting of Flax/Glass fibers are superior when contrasted with plain glass fiber reinforced polymer composites. The twist in the yarn structure of flax fiber and rough surface flax fibers caused a significant amount of fiber bridging between flax and glass fibers that caused an enhanced interlaminar property of the composite comprising flax and glass fiber reinforcements. The fractography analysis using Scanning Electron Microscopic (SEM) images[8] gives more insight into the fiber matrix interaction during fracture under Mode-I loading of Hybrid Fiber Reinforced Polymer (HFRP) composite. From SEM images, it was clear that a large amount of torn-out glass fibers was separated from the fractured surface from the well-bonded flax fibers. Due to this nature of morphology between the interface of flax and glass fibers, the fiber bridging was observed during the actual test. Hence, an enhanced interlaminar fracture toughness in Flax-Glass HFRP composites[8]. The hybrid composites comprised of flax-glass fiber reinforcements at 0° orientation exhibited superior tensile strength as compared to that of 90° orientation. The results showed that hybrid composites showed a lower strength in contrast with the plain Glass-epoxy composites. The performance of flax and glass fiber hybrid composites reinforced with 0° and 90° fiber orientations is almost the same under flexural load which attributes that the orientation of the fiber does not alter flexural properties. The SEM photomicrographs indicate that the 0° fiber orientation composites have a lower amount of fiber pullouts and fiber breakage at fiber-matrix interaction as compared to 90° fiber orientation in Flax-Glass hybrid composite fractured specimens under tensile and flexural loading[9]. This might be one of the reasons to get higher tensile strength in 0° fiber orientation composites. Furthermore, a major enhancement in tensile strength was also noticed for acetic anhydride-treated flax fibers when examined with respect to untreated flax fibers followed by other treatments like hot water and acrylic acid treatment. Also, it was noticed that the specific flexural strength was higher for acetic anhydride-treated flax fibers in vinyl ester matrix. The ILSS of flax fiber treated with acrylic acid was augmented by 60% in comparison with untreated flax fiber and ILSS was found to be higher than compared to other treatments like hot water and acetic anhydride[10]. Symmetric hybrid composites of flax and glass fiber reinforcements were prepared by placing one layer of glass fiber into the mold. To achieve an arbitrary flax fiber mat, the essential volume of flax fibers was arranged uniformly as lumps on the glass fiber. The subsequent layer of glass fiber was placed on top of the flax fiber random mat and then a mold was closed. Unsymmetric hybrid composites were prepared in a random manner by arbitrarily arranging flax fiber under the mold and placing two layers of glass fiber on the flax fiber mat in the woven form. The acrylated epoxidized soyabean based oil was used as a matrix for both symmetric and unsymmetric hybrid composites. Lower tensile strength was observed for unsymmetric hybrid composite. Flexural strength was high when unsymmetric hybrid composites were subjected to a load with both glass fiber layers on the tension side of the midplane[11]. The tensile and flexural strength of 40% Flax fiber and 60% Glass fiber volume fraction improved as compared to other fiber volume fractions like 50% Flax fiber and 50% Glass fiber and 60% Flax fiber and 40% Glass fiber hybrid composites[12]. Fracture toughness of composites consisting of glass fibers improved by the inclusion of flax fiber in appropriate proportions to form a hybridized composite which also reduced the composite weight. Regarding the hybrid Flax-Glass fiber-reinforced composite (FGFC), a lot of torn out fibers were found during SEM examination, this was due to huge quantity of fiber interaction and intermingling of fiber as indicated exhibits a large number of fibers displaced along with torn and broken fibers resulting in fiber bridging which requires extra energy for the cracks to propagate. In addition to this, the SEM fractography also indicates some individual flax fibers extended or stretched from the yarn of the flax fibers, causing a number of fiber failures which gave a significant improvement of interlaminar toughness in FGFC, and failure of fiber bundle was also observed[13].

2.2 Sisal Fiber and its Hybridization with Synthetic Fibers

Sisal (Agave Sisalane) fiber is obtained from the leaves of sisal plants shown in Figure 3. It is a rigid fiber that is perennial and continuing succulents that can be cultivated in hot and dry areas. Sisal is an environmental-friendly fiber and recyclable.

Fig 3. Image showing Sisal plant (left), Raw fibers after extraction process (middle), and treated fibers (right)

The appearance of Sisal fibers after 18% NaOH treatment is shown in Figure 3 on the right side. The treated fibers were used for the production of hybrid composites reinforced with Sisal/Carbon fiber. In addition, tensile and flexural test experiments were carried out on the hybrid composites prepared using treated sisal and untreated sisal fibers. In contrast with untreated hybrid composites, it was noted that for treated hybrid composites, both the tensile and flexural strength was high. This enhancement in tensile and flexural strength can be credited to rough surfaces of sisal fibers due to NaOH treatment which gives a good bond between fiber and matrix[14]. Hybrid composites consisting of reinforcements of sisal and glass fibers prepared using 18% aqueous NaOH treated sisal fibers showed superior strength with regard to tensile and flexural properties when contrasted with untreated hybrid composites. The enhancements in mechanical properties were due to proper interfacial bonding between fibers and matrix[15]. The 2% NaOH alkaline treated and trimethoxy silane treated sisal fibers in hybrid composites of sisal and glass fiber reinforcements exhibited greater tensile properties than untreated hybrid composites with unsaturated polyester resin matrix[16]. The composites with equal fiber ratios of sisal and glass fibers i.e.,50% Sisal fiber and 50% Glass fiber exhibited improved mechanical properties in comparison with a minimum percentage of sisal fiber[17]. The inclusion of glass fiber by about 0.003 volume fraction in sisal reinforced polymer composites which consists of about 0.14 volume fraction of sisal fibers increases the ultimate tensile strength for longitudinally oriented composites. Further addition of 0.003 volume fraction of glass fiber to the alkaline (NaOH) treated sisal fiber reinforced polymer composites increases the tensile and the flexural strength of the composites significantly[18]. For the hybrid composites comprising NaOH treated sisal fiber, the tensile strength increase is noted as compared to that of untreated fibers. The alkaline action of NaOH improves the roughness of the sisal fiber surface which enhances the mechanical interlocking among fiber and matrix. The fractography study clearly indicates that untreated and alkaline treated sisal fibers in the fracture surface of the composite system. Further, the alkaline treatment removes hemicellulose and lignin content from the fiber and therefore improves its bonding[19].

2.3 Kenaf Fiber and its Hybridization with Synthetic Fibers

Kenaf is a bast fiber (Hibiscus Cannabinus) and is a plant having a place with the family of Malvacae. The fibers of kenaf are obtained in the bast and core of the plant as shown in Figure 4. The bast comprises 40% of the plant. Kenaf consists of a higher amount of cellulose and possesses low density and recyclability. Kenaf possesses similar qualities as that of jute.

Generally, kenaf fibers are extracted by vertically stacking Mesta stalks which are harvested for about 155 days to 160 days of sowing for 20 days, where stalks are dried and leaves are shed. The dried stalks are sprayed with 2% urea, which has been reported to promote microbial growth and retting. Stalks are first soaked in water in which the gum that attaches the fiber to the stem is loosened for retting. The loosened fibers are then beaten to remove vegetative material and fibers are thoroughly washed with plain water and dried. After drying, the fibers were treated with optimal NaOH solution for better surface functionalities. Hybrid composite material using the modified sheet molding compound (SMC) system has good mechanical properties due to the pressure added in the process and thus a strong bond is achieved between reinforced fibers. The tensile and flexural strength of hybrid specimens consisting of Kenaf/Glass fibers are higher than that of glass mat thermoplastic (GMT). The morphological study characterizes the discrete areas among the kenaf fiber and glass fiber plies, which appears smooth, and the dispersion of

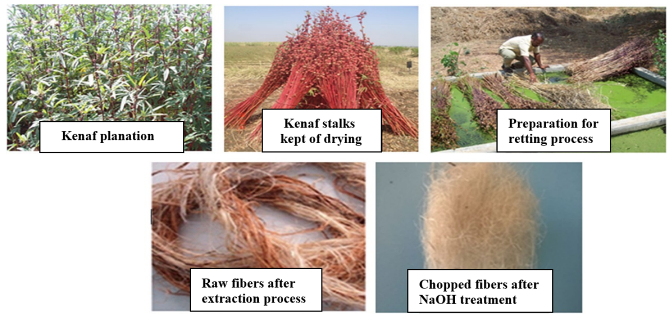

Fig 4. Kenaf (Mesta) plantation and its stages in the extraction process and appearance of fibers after NaOH treatment.

epoxy in different reinforced plies which contributes to the improved adhesion between fiber and matrix[20]. The reduction in tensile strength of Kenaf/Glass fiber reinforced hybrid composites was observed due to moisture content. This is because of the large number of hydrogen bonds between macromolecules of the polyester matrix and kenaf fiber. Reduction in tensile strength of the hybrid composites was noticed when exposed to three different aqueous solutions like distilled water, rainwater, and seawater over a specified period[21]. Mercerized treated kenaf fiber reinforced with glass fiber with unsaturated polyester resin showed higher tensile strength than untreated hybrid composites. Kenaf fibers treated with 6% NaOH diluted solution and maintaining 15:15 volume ratio of Kenaf/Glass in hybrid composites exhibited higher tensile and flexural properties. The process of mercerization of kenaf fiber is shown in Figure 5.

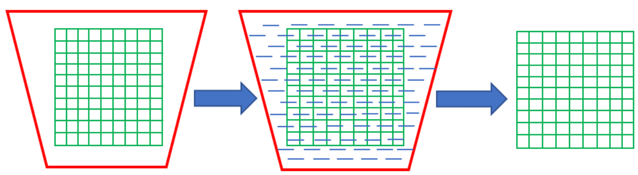

Fig 5. Mercerization process of Kenaf woven mat.

It was found that the 15:15 volume ratio of kenaf induced glass composites with NaOH treated kenaf fiber exhibited lesser matrix cracking and fiber debonding which was observed in SEM image fractures Kenaf-Glass reinforced unsaturated polyester hybrid composite. This contributes to take up higher energy ensuing higher toughness and also provides improved flexural and tensile properties of hybrid composites. It also exhibits that the encapsulation of the kenaf fiber into the matrix augments the strength of unsaturated polyester (UPE) material. In addition, the mercerization treatment offers enhanced fiber and matrix content interface bonding[22]. Short kenaf fibers were added to epoxy resin and glass fibers to form a hybrid composites and it was noticed that kenaf fibers were appropriately dispersed in epoxy resin and also very less voids were found indicating better bonding of kenaf and glass fibers in epoxy resin with a nominal amount of fiber debonding was also observed in SEM fractography studies. The inclusion of short kenaf fibers with 7.5wt% enhanced the interlaminar radial stress in comparison with plain glass-epoxy composites. Furthermore, the addition of un-treated kenaf fiber will reduce the interlaminar stresses which can be attributed to improper adhesion between the fibers[23]. Kenaf/Glass fibers reinforced hybrid composite in unsaturated polyester resin exhibited improvement in tensile strength with 10wt% of Kenaf fiber and 10wt% of Glass fiber in 80wt% resin. With the further addition of kenaf, the tensile strength decreases which is attributed to ineffective load transfer to the glass fiber due to insufficient filling of resin in the composite[24]. The hybrid composite consisting of Kenaf/Glass fiber reinforcements in unsaturated polyester (UPE) resin with 78wt% of Glass fibers and 22wt% of Kenaf fibers exhibited balanced mechanical properties. The hybrid composites showed good adhesion between Kenaf/Glass fibers with matrix[25]. With glass fibers on the outermost layers of the hybrid composites of Kenaf/Glass reinforcements exhibited equivalent tensile strength as that of non-hybrid glass fiber composites. The purpose for this is the arrangement of glass fibers on the outermost layers in the composite which is the prime load carrier under tensile loading. It was noticed that glass fiber reinforced composites had more apparent fiber pullout and fiber-matrix debonding. This is because of poor interfacial adhesion among glass fiber and matrix but the interfacial adhesion of kenaf fiber is better than glass fiber as kenaf fibers have a rough surface which is essential for proper adhesion[26]. Degradation of fracture toughness was attributed to moisture absorption in the long hybrid Kenaf/Woven Glass composite due to cracks and voids. The characteristic of water intake by the polyester matrix causes swelling and plasticization, which contributes to early failure[27].

2.4 Jute fiber and its Hybridization with Synthetic Fibers

Jute is a lengthy, soft, glossy vegetable fiber that can be spun into large and strong threads. It is obtained from plants in the genus Corchorus shown in Figure 6 which was earlier categorized with the family of Tiliaceae and of lately with Malvaceae family. *Corchorus olitorius* is the chief source of fiber. The color of Jute is similar to gold and hence it is also called a golden fiber.

Fig 6. Jute fiber plant and its fibers afterthe extraction process.

Higher tensile strength of hybrid composite comprising jute and carbon reinforcements with vinyl ester matrix was observed than that of non-hybrid jute vinyl ester composite. The bending strength of the hybrid composite is almost equivalent to non-hybrid composites. The fractographic images of Jute vinyl ester composite (JVC) indicate the presence of the prolific amount of resin on the exterior of fiber which is pulled off from the matrix. The reason for this being improved interfacial suitability between the resin and treated fibers to a greater extent. In addition to this, SEM image also indicates that the hybrid composite with Jute-Carbon reinforcements has broken fibers but still there exists a couple of unbroken fibers and partially pulled off carbon fibers[28]. The lower tensile and flexural strength of plain jute-epoxy composites were enhanced by the amalgamation of fibers like Glass and/or Carbon into the jute-epoxy composites while making hybrid composites which resulted in reduced void content. The significant flexural strength was attained when the carbon fiber layer was placed on the outer layers of the composite during the stacking process[29]. The inclusion of glass fiber into the pure jute-epoxy composites have better mechanical properties like tensile and flexural strength significantly by stacking glass fibers on the outer layers. ILSS was noted to be significantly higher in hybrid composites made of glass fibers on the outer layers.The SEM morphology of the hybrid composites comprising of jute and glass fiber reinforcements shows two types of failure behaviors on the fracture surface of the composite in tensile loading. The first one being the stretching of glass fibers and the second is breaking or rupture with no stretching of jute fiber[30]. The incorporation of glass fibers on the outer extreme layers of hybridized composites comprising jute fibers and glass fibers improved mechanical properties like tensile strength, flexural strength, and ILSS. It also facilitates the use of natural fibers in conjunction with synthetic fibers, which decreases the weight and cost of the composite without losing strength[31]. The addition of layers of glass fiber on the outer extreme layers of the sandwiched hybrid composites improved the bending strength and reduced the tendency of the jute epoxy composites to trap water[32].

2.5 Banana fiber and its Hybridization with Synthetic Fibers

Banana fiber is a lignocellulosic natural fiber possessing lightweight characteristics. It is obtained from the pseudo stem of the banana plant (Musa Sepientum) which is shown in Figure 7. It is a bast fiber with comparatively excellent mechanical properties. Banana fiber is a gigantic perennial herb having leaf covers or sheaths that form the pseudo stem. The chemical constituents of banana fiber are cellulose, hemicellulose, and lignin.

Banana/Carbon fiber hybrid composites containing 20% Banana fibers and 80% Carbon fibers showed the highest tensile and flexural strength amongst other volume fractions of hybrid composites. As the percentage of banana fiber augmented the water absorption percentage also augmented. This is attributed to the property of banana fiber which possesses improved moisture absorption characteristics and some amount of fiber swelling which is indicated in the SEM image of Banana-Carbon hybrid

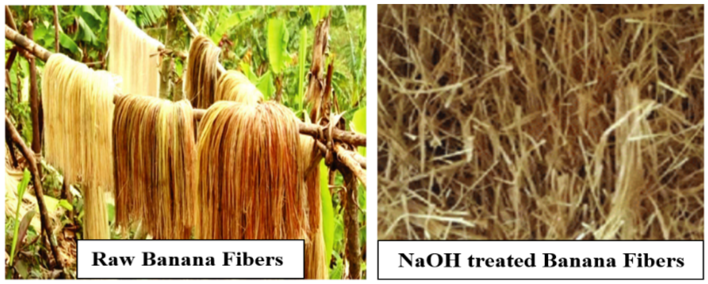

Fig 7. Physical appearance ofraw Banana fibers (left) and NaOH treated Banana fibers (right)

composites. This was the indication of moisture content still present in banana fibers which can affect the mechanical properties of the final composite[33]. Banana fiber reinforced polymer composites exhibited a marginal number of mechanical properties. However, banana and glass fiber reinforced hybrid composites showed some improvements in mechanical properties when contrasted with pure banana fiber-reinforced composites. This tendency can lead to the possible replacement of glass fiber. This further reduces the cost and weight if moderate strength is required[34]. Hybrid composites consisting of 20% Banana fibers and 80% Glass fibers exhibited higher tensile, flexural, and ILSS in comparison with other volume fraction hybrid composites which specifies the potential usage of banana fiber along with other synthetic fibers to reduce weight as well as the cost of composite material[35]. Fracture toughness tests were made on polymer composites reinforced with glass fibers (GFRP) and polymer composites reinforced with banana fiber (BFRP) with fiber volume fraction of 0.13,0.17 and 0.20 and it was found that the fracture toughness of banana fiber-reinforced composite is in close concurrence with glass fiber reinforced composite[36].

3 Results and Discussion

The influence of various selected natural fibers for their mechanical and fracture toughness properties when hybridized with synthetic fibers like Carbon and Glass fibers are shown in Table 1. It is observed that the alkaline treated natural fibers when hybridized with synthetic fibers exhibited improved mechanical and fracture properties. It is observed that the moisture absorption capacity of Hybrid composites manufactured with natural fibers can be reduced by adding synthetic fibers on the outermost layers while making composite laminates. The addition of natural fibers in controlled quantity leads to improved mechanical and fracture toughness properties which give better scope for the replacement of synthetic fibers. Further, this will ultimately lead to a reduction in the cost of manufacturing.

Table 1. Influenceof some selected Natural fibers in GFRP and CFRP composites for theirmechanical and fracture toughness properties

Fiber type	Details of fiber reinforcement	Results	Reference paper
Flax	The Hybrid composite was made by adding Carbon in Flax fibers for evaluating the tensile performance of the composites.	Compared to pure Flax fiber composites, with 8% of carbon fiber by volume of Flax fiber, there is a 72% improvement in tensile strength. Further, in comparison, the tensile strength was increased by 144% with respect to non-hybrid Flax composites, with an additional 6% increase in carbon volume fraction.	[4]
	The mechanical and fracture behaviors of UD Flax-Glass fiber reinforced hybrid composites were studied.	A 90% enhancement of tensile strength with respect to pure Glass epoxy composites was achieved by stacking two layers of Glass and two layers of Flax alternatively. The ILSS also increased by 60 % in contrast with plain Glass fiber composite.	[8]
	Hybrid composites consisting of 50% alkaline treated Sisal fibers with 50% Glass fibers was studied for mechanical properties	A significant increase (145%) in tensile strength was achieved for equal volume percent of Sisal and Carbon fiber.	[14]

Continued on next page

Table 1 continued

Sisal	Investigations were carried out on the hybrid composite to see the effect of alkali-treated and silane (trimethoxy silane) treated Sisal fiber with Glass fiber. Hybrid composite was tested for tensile strength with an equal volume of Sisal and Glass fibers.	Increased chemical and impact characteristics of composites with increased loading of the fibers. A substantial 53% increase was observed in the tensile properties of hybrid composites with 18% NaOH treated sisal fibers.	[15]
	Sisal fibers were treated with NaOH and trimethoxy silane (coupling agent) for making sisal–glass hybrid composites for tensile tests.	Silane treated Sisal fiber has shown good improvement (62%) in tensile strength relative to NaOH treated Sisal and Glass fiber Hybrid composite.	[16]
Kenaf	Mercerized treated Kenaf fiber reinforced with Glass fiber was utilized for manufacturing hybrid composites. The composites were examined by conducting a tensile test for mechanical properties.	Hybrid composites made with 15% Kenaf and 15% Glass by volume with 70% unsaturated polyester resin yielded 70% increase in flexural strength. But it was seen that there is no significant enhancement in other properties like impact and tensile strength as compared to untreated fibers.	[22]
	To create the hybrid composites, chopped Kenaf fibers were reinforced with glass fiber.	The addition of chopped Kenaf fibers of 7.5wt% with 42.5wt% of Glass fibers has enhanced the interlaminar radial stresses by 79% with respect to weight percent of Kenaf and Glass fibers.	[23]
Jute	The Jute and Glass hybrid fiber composite was prepared and the effects of the stacking series on the tensile, flexural, and interlaminar shear properties were tested.	By adding glass fiber on the extreme outer layers of Jute/Glass hybrid composites relative to pure Jute epoxy composites, an improvement in tensile strength of approximately 66% was noted for hybrid composites. The hybrid composite flexural strength produced by the use of one layer of glass fiber on the extreme outer layer yielded 90% of the flexural strength of the pure glass epoxy composite. The ILSS of a hybrid composite consisting of Glass fibers on the extreme outermost layer exhibited an improvement of about 12.20%.	[30]
	The hybrid composites were prepared by incorporating Glass fibers in Jute epoxy composites and examined for tensile strength, bending strength, and water resistance.	Compared to Jute epoxy composites, the tensile strength increased by 66%, and bending strength increased by 63% for the hybrid composites. The incorporation of glass fibers to the outermost layers of hybrid composites from Jute/Glass decreased the water intake tendency of the composite.	[32]
	Hybridization of Banana fibers with Carbon fiber was made to form hybrid composites. The hybrid composites were studied for tensile, flexural, impact, and water uptake properties.	Hybrid composites showed almost 96% of Tensile strength, 98% of Flexural strength, and 95% of Impact strength with respect to plain Carbon epoxy composites. Further, the water intake property was found to be very close to that of plain Carbon epoxy composites.	[33]
Banana	The amalgamated Banana-Glass fiber woven composite was fabricated using the hand layup technique and examined for tensile, flexural, and ILSS.	Banana-Glass fiber hybrid composites shown good enhancement in Tensile strength with 70%, Flexural strength 75%, and ILSS of 87% in comparison with plain Glass Polyester matrix composites.	[34]

Continued on next page

Table 1 continued

	Using hand layup procedure, Banana and Glass fiber reinforced Polyester resin composites were prepared. Both composites were tested for fracture toughness property.	The fracture toughness property of various volume fractions of composites of banana fiber was found to be about 85% higher than plain composite glass fiber.	[36]

The properties of natural fibers like density, cost, renewability, etc., are compared with synthetic fibers as shown in Table 2. The natural fibers have a greater perspective to either fully or partially substitute the synthetic fibers paving the way to reduce the weight, cost of composites. The use of natural fibers in the fabrication of composites which can be termed plant fiber-reinforced composites (PFRCs) is possible by proper adoption of processing techniques, fiber treatments, coupling agents. The PFRCs offer desirable properties and can be used in various applications like automotive, household products, sports equipment, building, and construction, etc.,[37].

Table 2. Comparison of Natural fibers and Synthetic fibers.

Property	Natural Fibers	Synthetic Fibers
Density	Low	High
Cost	Low	High
Renewability	Yes	No
Environmental Effect	No	Yes
Recyclability	Simple	Complex
Extraction/Processing	Simple	Complex
Complexity of Synthesis	Moderate	Low

The advantages, disadvantages and applications of hybrid composites comprising of synthetic fibers and natural fibers are discussed in Table 3.

Table 3. Advantages, disadvantages and applications of hybrid composites comprising of synthetic fibers and natural fibers

Hybrid Composite	Advantages	Disadvantages	Applications
Flax/Carbon	Improved mechanical properties, Light weight.	Chemical treatment is necessary for enhanced properties, Difficult to fabricate, Hydrophilic nature.	Automotive, Sports equipment, Structural, etc.
Flax/Glass	Improved tensile properties and interlaminar fracture toughness and Light weight.	Chemical treatment is necessary for enhanced properties, Difficult to fabricate, Hydrophilic nature.	Automotive, Furniture, Structural, etc.
Sisal/Carbon	Improved tensile, flexural properties, and Light weight.	Chemical treatment is necessary for enhanced properties, Difficult to fabricate, Hydrophilic nature.	Automotive, Sports equipment, Structural, etc.
Sisal/Glass	Improved tensile and flexural properties with Light weight.	Chemical treatment is necessary for enhanced properties, Difficult to fabricate, Hydrophilic nature.	Automotive, Furniture, Structural, etc.
Kenaf/Glass	Improved tensile, flexural properties and Light weight.	Chemical treatment is necessary for enhanced properties, Difficult to fabricate, Hydrophilic nature.	Automotive, Structural, etc.
Jute/Carbon	Improved tensile, flexural properties and Light weight.	Chemical treatment is necessary for enhanced properties, Proper stacking sequence has to be maintained, Hydrophilic nature.	Automotive, Structural, etc.
Jute/Glass	Improved tensile, flexural properties, interlaminar shear strength properties and Light weight.	Chemical treatment is necessary for enhanced properties, Proper stacking sequence have to be maintained, Hydrophilic nature	Automotive, Structural etc.
Banana/Carbon	Improved tensile, flexural properties and Light weight.	Chemical treatment is necessary for enhanced properties, Difficult to fabricate, Hydrophilic nature.	Automotive, Structural etc.

Continued on next page

Table 3 continued

Banana/Glass	Improved tensile, flexural properties, inter-laminar shear strength properties and Light weight.	Chemical treatment is necessary for enhanced properties, Difficult to fabricate, Hydrophilic nature.	Automotive, Structural etc.

4 Conclusions

The main focus of the article was to explore the significance of hybrid composites which is being manufactured using natural and synthetic fibers. The present assessment reveals how the physical and mechanical properties of natural fibers vary from one fiber to another. It was found that hybrid composites comprised of natural and synthetic fibers exhibited superior properties with respect to weight, specific strength, lower cost, non-abrasive, bio-degradable, and environment friendly with improved mechanical and fracture toughness properties. Based on the numerous existing works, this article demonstrates, how natural fiber-reinforced composites are utilized in various applications of engineering fields. Nevertheless, integrating natural fibers with various synthetic fibers can enhance the desired properties and can also be utilized as a substitute material for synthetic fiber for manufacturing polymer fiber composites. At the end, a detailed table is prepared which summarizes the properties, advantages, drawbacks, and applications of chosen Natural fibers and their effect on hybridization with synthetic fibers. Further, the limitation of this review is only selected natural and synthetic fiber hybrid composites were evaluated. Finally, this comprehensive review report will certainly give a reference for researchers to explore and develop a new class of hybrid composites that can meet the strength requirements in primary and secondary structural parts of various fields.

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