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*Review Article*

# A Review on the Parameters Affecting the Mechanical, Physical, and Thermal Properties of Natural/Synthetic Fibre Hybrid Reinforced Polymer Composites

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The global drive towards a circular economy that emphasizes sustainability in production processes has increased the use of agro-based raw materials like natural fibres in applications that have long been dependent on inorganic raw materials. Natural fibres provide an eco-friendly, more sustainable, and low cost alternative to synthetic fibres that have been used for a long time in the development of composite materials. However, natural fibres are associated with high water absorption capacity due to their hydrophilic nature leading to poor compatibility with hydrophobic polymeric matrices, thus lower mechanical properties for various applications. Hybridization of natural fibres with synthetic fibres enhances the mechanical performance of natural fibres for structural and nonstructural applications such as automobile, aerospace, marine, sporting, and defense. There have been increased research interests towards natural/synthetic fibre hybrid composites in the past two decades (2001–2021) to overcome the identified limitations of natural fibres. Therefore, understanding the parameters affecting the properties and potential of using natural and synthetic fibre reinforcements to develop hybrid composites is of great interest. The review showed that using appropriate fibre orientation, fibre weight fraction and stacking sequence yields good mechanical, physical, and thermal properties that are competitive with what only synthetic fibre reinforced composites can achieve. In addition, these properties can be improved through pretreatment of natural fibres using different chemicals. This paper provides in review form the parameters affecting the mechanical, physical, and thermal properties of natural/synthetic fibre hybrid reinforced polymer composites from the year 2001 to 2021.

## 1. Introduction

Composites are defined as materials comprising of reinforcing/filler phase and matrix/continuous phase separated by the interface phase. The overall performance of composites is mainly influenced by the composition of these phases [1]. Fibres that form the reinforcing/filler phase serve as the principal load/stress-bearing elements, whereas the matrix ensures that the fibres are maintained at a desired orientation and location. That is, it gives the composite its net shape and determines its quality. Additionally, the matrix acts as a load/stress transfer medium and protects the fibres from environmental damage [3, 4]. Based on their sources, reinforcements are classified as either natural or synthetic. Further, reinforcement can be either short and continuous fibre, woven, short fibre mat, whiskers, or particle depending on their form [5].

Fibre reinforced polymer composites have recently replaced metals in various applications due to the need to reduce the weight and cost of the structure. Although the initial focus on fibre reinforced composites was on synthetic fibres, recent studies are exploring the possibility of using natural fibres as an alternative. The most common synthetic fibres used in fibre reinforced polymer composites are aramid, glass, and carbon [6]. Review literature indicates that glass fibre has low density, high ductility, low cost, and negligible water absorption. Additionally, glass fibre is highly available and has high strength and stiffness, making it the commonly used of all the synthetic fibres in reinforced polymer composites [7, 8]. However, synthetic fibres are associated with higher processing costs and non-renewability, resulting in global environmental pollution [9].

In contrast, natural fibre reinforced composites are characterized by low weight, low cost, renewability, biodegradability, and high specific mechanical properties. In addition, natural fibre reinforced composites are perceived to be carbon neutral and environmental-friendly [10–13]. Natural fibre reinforced composites are used in various nonstructural automobile applications such as door panels, internal engine covers, boot liners, oil filter liners, package trays, instrument panels, and oil air filters, amongst others [7].

Researchers are currently investigating the possibility of using natural fibre reinforced composites in structural applications such as exterior underfloor paneling and seatbacks [14]. Nonetheless, natural fibre reinforced composites are associated with limitations such as hydrophilicity, weak fibre/matrix interfacial bonding, poor thermal stability, and relatively low mechanical properties. Due to high moisture sensitivity, natural fibres tend to absorb water from the environment causing low fibre/matrix interfacial bonding, thus, low mechanical characteristics [15–17]. This has potentially retarded their usage as reinforcements in composites for both structural and nonstructural applications [18, 19].

Literature review shows that the hybridization technique can be used to reduce water absorption and improve the mechanical properties of natural fibre reinforced composites [20, 21]. Hybridization uses two or more reinforcement materials in a single matrix phase to exploit different properties of these reinforcements while retaining their individual properties in the resultant composites [22–24]. Thus, hybridization of natural fibres with synthetic fibres improves the mechanical strength of natural fibre reinforced composites [25]. There are three main configurations of blending synthetic and natural fibres in a hybrid composite: interlayer, intralayer, and intrayarn. In interlayer configuration, layers made of different fibres are placed on top of each other. In intralayer, both fibres are entangled within a single layer using techniques such as weaving. On the other hand, intrayarn configuration involves intertwisting both fibres within a single yarn [26].

In a hybrid reinforced composite system, the advantages of one fibre complement the disadvantages of the other fibre [27]. Natural/synthetic fibre hybrid reinforced composites offer multifunctionalities such as weight reduction that cannot be achieved with a single fibre and synergic effect between the reinforcements [28, 29]. Hybridization is considered a valid strategy and effective technique that can be used to tailor the mechanical behavior of reinforced polymer composites to desired strengths for specific applications [5, 30]. Pioneer research on fibre hybrid reinforced polymer composites was conducted on glass/carbon fibres in 1978 by Summerscales and Short [31]. The study highlighted the positive effects of glass/carbon hybridization and proposed a nomenclature system for diverse hybrid composites.

## 2. Commonly Used Natural Plant Fibres in Natural/Synthetic Fibre Hybrid Reinforced Composites

The past three decades have witnessed increased usage of fibres of natural origin in composites fabrication. The fibres are extracted from the respective plant using various methods such as dew retting, water retting, mechanical extraction, chemical retting, and enzymatic retting [32]. Natural fibres such as sisal, coconut, bamboo, jute, kenaf, hemp, banana, coir, PALF, bagasse, ramie, basalt, cattail, and oil palm are gaining attention amongst material scientists globally. This is because natural fibres are cheap, readily available, eco-friendly, renewable, biodegradable, and lightweight. The fibres which act as load-bearing elements are used as reinforcements in the composite structure. Natural fibres are extracted from different parts of the plant such as the stem, leaf, and fruit. Table 1 presents global annual production rates and the average cost of these fibres.

A study on the effect of water absorption on mechanical properties of interwoven hemp/kenaf and jute/kenaf fibre hybrid reinforced epoxy composites observed enhanced mechanical and water-resistant properties of hemp, kenaf, and jute fibres as a result of hybridization [37]. Further studies by Nallusamy and Majumdar [38] reported 53.8 and 39.0% increase in tensile and impact strengths, respectively, for jute/glass fibre hybrid composites compared with pure jute fibre reinforced epoxy counterparts. Reinforcing 50% date palm fibres in epoxy matrix increased the flexural strength and modulus of the resultant composite to 32.6 MPa and 3.3 GPa compared to 26.2 MPa and 2.3 GPa, respectively, for unreinforced epoxy composites [39]. Research has shown that the volume fraction of abaca and glass fibres and stacking sequence determine the mechanical properties of abaca/glass fibre hybrid reinforced composites [40].

Jute fibre reinforced polyester composites reported a higher water absorption rate and lower mechanical properties. However, jute/carbon fibre reinforced polyester hybrid composites exhibited reduced moisture absorption rate and enhanced tensile strength, tensile modulus, flexural strength, flexural modulus, and impact strength of 136.3 MPa, 3.4 GPa, 175.8 MPa, 9.4 GPa, and 47.4 kJ/m$^2$, respectively [41]. Similarly, hybridization of 20% carbon fibres and 10% sisal fibre within polypropylene matrix yielded higher tensile strength, tensile modulus, and impact strength of 64.5 MPa, 1.7 GPa, and 42.4 J/m, respectively, compared to 40.4 MPa, 0.8 GPa, and 30.4 J/m, respectively, for 30% sisal fibre reinforced polypropylene composites [42]. An investigation of thermal properties of woven kenaf/carbon fibre reinforced epoxy hybrid composites reported better thermal stability for a hybrid with higher kenaf fibre content compared with kenaf fibre epoxy composites [43]. Therefore, hybridization technique can eradicate the disadvantages of one single fibre, thus producing hybrid composites with desirable properties thus meeting structural property requirements for certain applications. For instance, the study has reported a reduction in material density from 1.81 g/cm$^3$ to

Table 1: Annual production of commonly used natural fibres and their sources [33–36].

| Fibre source | World production (x10 [4] MT) | Cost ($/ton) | Origin |
|---|---|---|---|
| Bamboo | 30,000 | 500 | Stem |
| Sisal | 378 | 600–700 | Stem |
| Banana | 134,000 | 890 | Stem |
| Jute | 3,450 | 400–1,500 | Stem |
| PALF | 1318 | 360–550 | Leaf |
| Hemp | 214 | 1000–2100 | Stem |
| Kenaf | 970 | 300–500 | Stem |
| Flax | 830 | 2100–4200 | Stem |
| Rice husk | 422,000 | — | Fruit/grain |
| Coir | 1200 | 200–500 | Fruit |
| Abaca | 70 | 345 | Leaf |
| Bagasse | 75,000 | 3.5–11.8 | Stem |
| Ramie | 100 | 2000 | Stem |

1.61 g/cm$^3$ and 1.48 g/cm$^3$ as a result of the addition of flax and jute fibres, respectively, in glass/epoxy system [44].

*2.1. Chemical Composition and Mechanical Characteristics of Natural Plant Fibres.* The chemical composition and mechanical characteristics of a material greatly determine the behavior of that material under conditions of applied loads. The chemical and mechanical composition of fibres is taken into account during the selection of natural fibres for various applications, for example, automobile parts and ballistic applications where high impact property is a necessity. It is important to note that the chemical composition of natural fibre affects the mechanical characteristics of natural fibres. The chemical composition of natural plant fibres also known as cellulosic fibre comprises cellulose, hemicellulose, lignin, wax, pectin, and other volatile matter. The proportion of these chemical constituents of cellulosic fibres differs from one plant to another due to variations in species, environmental conditions, maturity, and location of growth [45].

Fibres of plant origin have a crystalline structure comprising about 65–70% cellulose with a standard formula of $(C_6H_{10}O_5)_n$[45]. The presence of lignin and other noncellulosic constituents such as wax, pectin, debris, and oil affects the properties of natural plant fibres. These noncellulosic constituents hinder the bonding ability of fibre in the polymer matrix. Therefore, their removal from fibre structure before composite fabrication enhances the mechanical properties of resultant composite material. Figure 1 shows the structure of plant-based natural fibre.

In addition to chemical composition, the mechanical characteristics of natural plant fibres are influenced by growth conditions, structural strength, and type of plant fibre. Natural plant fibres are hygroscopic in nature due to the presence of a higher percentage of hydroxyl groups in their structure. Hence, plant fibres are characterized by higher moisture absorption properties. This results in weakened fibre/matrix interfacial bonding causing low mechanical properties making plant fibres undesirable for composite fabrication in their natural and unmodified state. The chemical composition and physical characteristics and mechanical properties of mostly used plant-based natural fibres are presented in Tables 2 and 3, respectively.

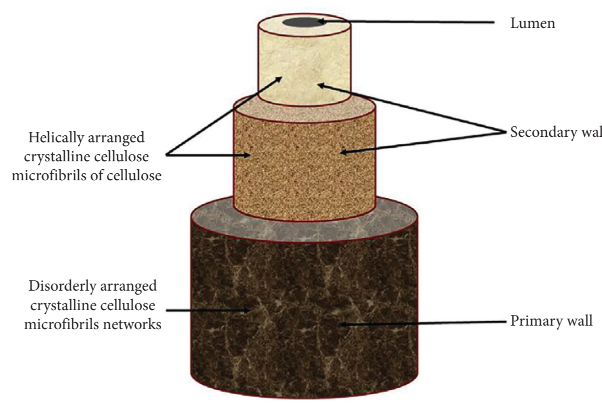


Figure 1: Structure of natural fibre [46].

*2.2. Natural/Synthetic Fibre Reinforced Polymer Hybrid Composites and Their Properties.* Several research studies on synthetic/natural fibre hybrid reinforced polymer composites with different polymer matrices such as polyethylene, polypropylene, polyester, and epoxy among others have been performed. These studies have used varying proportions of synthetic and natural fibre weight fractions, fibre lengths, fibre pretreatment techniques, and fibre orientations in the hybrid composites. Synthetic/natural fibre hybrid composites are prepared using different composite fabrication techniques such as compression molding, hand lay-up, injection molding, resin transfer molding, solution mixing, press consolidation, and extrusion machine [60]. The physical, mechanical, thermal, water absorption, and morphological properties of resultant hybrid composites have been investigated.

## 3. Natural Fibres/Glass Fibre Hybrid Reinforced Polymer Composites

*3.1. Glass/Bamboo Fibre Reinforced Polymer Hybrid Composites.* Shah et al. [61] investigated the effect of varying bamboo powder concentrations on modified bamboo/glass fibre hybrid reinforced epoxy composites. The composites were fabricated using a combination of hand lay-up and compression molding techniques. The study reported a decrease in tensile strength with increasing bamboo powder

Table 2: Chemical composition and physical characteristics of common natural fibres [47–53].

| Fibre source | Physical properties | | | Chemical composition | | | | |
|---|---|---|---|---|---|---|---|---|
| | Density ($g/cm^3$) | Moisture content (%) | Diameter ($\mu$m) | Cellulose (wt.%) | Hemicellulose (wt.%) | Lignin (wt.%) | Ash | Wax |
| Bamboo | 0.6–1.1 | 11–17 | 88–125 | 26–43 | 30 | 21–31 | — | — |
| Sisal | 0.7–1.5 | 10–22 | 50–200 | 68 | 13 | 11.5 | — | 2 |
| Banana | 0.7–1.35 | 8–10 | 100–250 | 63–64 | 19 | 5 | — | — |
| Jute | 1.3–1.5 | 12.6–13.7 | 25–250 | 61–71 | 14–20 | 12–13 | — | 0.5 |
| PALF | 0.8–1.6 | 14.0 | 50.0 | 81 | — | 12.7 | — | — |
| Hemp | 1.3–1.5 | 6.2–12.0 | 25–600 | 74 | 18 | 4 | — | 2.3 |
| Kenaf | 1.1–1.2 | 9.0–12.0 | 30–40 | 53.1 | 14.3 | 8.2 | 3.5 | 0.8 |
| Flax | 1.2–1.5 | 8–12 | 12–20 | | | | | |
| Coir | 1.2–1.5 | | 150–250 | 32–43 | 0.2–0.3 | 40–45 | — | — |
| Abaca | 1.5 | 5–10 | 10–30 | 56–6 | 20–25 | 7–9 | — | 3 |
| Bagasse | 0.55–1.25 | — | — | 55.2 | 16.8 | 25.3 | — | — |

Table 3: Mechanical properties of selected natural fibres [14, 47, 48, 53–59].

| Fibre | Elongation at break (%) | Tensile strength (MPa) | Tensile modulus (GPa) | Specific tensile strength (MNm/kg) $\times 10^{-3}$ |
|---|---|---|---|---|
| Flax | 1.2–1.6 | 345–1035 | 28–80 | — |
| Basalt | 3.15 | 3150 | 89 | — |
| Bamboo | 1.3–7.0 | 140.0–800.0 | 11.0–35.9 | 1.7–2.3 |
| Sisal | 2.0–14.0 | 350.0–840.0 | 9.0–38.0 | 3.4–4.2 |
| Banana | 1.0–9.0 | 54.0–914.0 | 7.7–32.0 | 2.6 |
| Jute | 1.3–3.0 | 350–780 | 20–30 | 3.0–5.9 |
| PALF | 0.8–14.5 | 148.4 | 10.5 | 1.1–11.2 |
| Hemp | 1.0–4.0 | 300–700 | 20–70 | 3.7–7.7 |
| Kenaf | 2.7–6.9 | `150–250 | 10–20 | 2.3–5.8 |
| Coir | 15–51.4 | 95.0–593.0 | 2.8–6.0 | 1.5 |
| Abaca | 3.0–12.0 | 400.0–980.0 | 6.2–72.0 | 2.7–6.5 |
| Bagasse | 0.9–5.8 | 20.0–350.0 | 0.5–27.1 | — |
| Coconut | — | 83.0–222.0 | 12.0–32.0 | 0.38–1.10 |

loading. Additionally, the maximum tensile strength reduced from 13.0% to 1.3% as bamboo powder increased from 10 to 30 wt.%. This observation was attributed to poor interfacial bonding at higher bamboo loading. However, the flexural properties such as flexural strength, flexural modulus, and flexural strength at break increased with increasing bamboo loading. Therefore, as the bamboo loading increased from 10 to 30 wt.%, the maximum flexural strength increased from 117.3 to 131.0 MPa. The contrasting effect on tensile and flexural properties can be attributed to the inhomogeneous and anisotropic nature of the hybrid composites under investigation.

Thwe and Liao [62] investigated the effect of environmental aging on mechanical properties of bamboo reinforced polypropylene (PP) composites and bamboo/glass fibre reinforced PP hybrid composites prepared by compression molding technique. Their investigation reported an increase in tensile strength and tensile modulus by 15 and 18%, respectively, for bamboo/glass fibre hybrid composites compared to bamboo fibre reinforced counterparts. Similarly, replacing bamboo fibres with glass fibres by 10% (by mass) reported an increase of 10 and 25% in flexural modulus and flexural strength, respectively. Their results further indicated that hybridization enhances the durability of the composites. Latha et al. [63] prepared and evaluated the mechanical and tribological properties of bamboo/glass fibre reinforced epoxy composites using hand lay-up manufacturing technique. Experimental results revealed that the incorporation of glass fibre in hybrid composites significantly improved flexural and tensile properties. For instance, the study reported 111% increase in tensile strength for 50% bamboo:50% glass fibre reinforced hybrid compared to 100% bamboo fibre reinforced composites. A similar observation of increasing thermal stability, stiffness, and mechanical properties of the hybrid composites with an increase in short glass fibre content in the hybrid has been reported [64].

Gangil and Kumar [65] conducted a comparative investigation of mechanical properties of bamboo/jute-glass reinforced polyester hybrid composites fabricated by hand lay-up technique. They reported that incorporating bamboo fibres with glass fibres enhanced the impact strength, hardness, and tensile strength of the resultant hybrid composites. Their study reported hardness, tensile, flexural, and impact strengths of 35.0 $H_V$, 80.6 MPa, 53.4 MPa, and 180.0 $N/mm^2$, respectively, for bamboo/glass fibre reinforced hybrid composites compared to 20.0 $H_V$, 46.7 MPa, 39.2 MPa, and 158 $N/mm^2$, respectively, for pure bamboo fibre reinforced composites. Similarly, further studies have reported enhanced mechanical and physical properties for bamboo/glass fibre hybrid composites compared to pure bamboo fibre reinforced composites [66–70]. This is because stronger and stiffer glass fibres replaced the weaker and less stiff bamboo fibres. Additionally, the morphological analysis showed that the structure of fibre hybrid reinforced composites is compact and densified than bamboo fibre reinforced composites. Hence, higher impact, flexural, hardness, and tensile properties as compared to bamboo fibre reinforced composites.

On the contrary, Asif et al. [71] conducted a comparative study on the mechanical properties of bamboo strip reinforced composites and bamboo strip/glass fibre reinforced epoxy hybrid composites. The composite samples prepared using hand lay-up technique comprised of four layers each. To investigate the effect of adding glass fibre layers, two bamboo layers were sandwiched between two glass layers, one at the bottom and the other at the top. The study reported tensile strength and modulus of 42.8 MPa and 3.5 GPa, respectively, for hybrid samples compared to 44.1 MPa and 3.4 GPa, respectively, for pure bamboo counterparts. Therefore, the study concluded that the addition of glass fibres had no significant effect on tensile strength and tensile modulus of the resultant hybrid composites. However, the flexural strength and modulus increased from 90.0 MPa to 2.8 GPa, respectively, for pure bamboo fibre reinforced composites to 110.5 MPa and 3.4 GPa, respectively, for hybrid samples. This represents 22.9% and 15.0% increase in flexural strength and modulus due to glass fibre addition. Another study on mechanical and water absorption characteristics of bamboo/glass reinforced polyester hybrid composites reported a reduction in water absorption with an increase in glass fibre content in the hybrid composites [72]. This can be attributed to the introduction of glass fibres which are known to have poor water absorption properties.

Retnam et al. [41] analyzed the effects of fibre orientation on mechanical properties of bamboo/glass fibre reinforced polyester hybrid composites prepared by hand lay-up technique in 0°/90° and ±45° fibre orientations. The results revealed that maximum tensile, impact, and flexural strengths of 92.3 MPa, 87.0 kJ/m$^2$, and 387.7 MPa, respectively, were observed in hybrid composites with ±45° fibre orientation. In contrast, the study reported a maximum hardness value of 62.3 $H_R$ for hybrid samples with 0°/90° orientations. Salman et al. [73] reported the highest tensile and flexural properties for hybrid composites with 0°/90° fibre orientations. On the other hand, the maximum hardness property of 62.2 $H_R$ was recorded with 0°/90° fibre orientation. Similarly, Ramnath et al. [74] and Sathish et al. [75] observed maximum mechanical properties at 45° fibre orientation. In contrast, Ramesh and Sudharsan [76] suggested that 0° fibre orientation exhibited the highest impact, tensile, and flexural strength than 90° fibre orientation. Consequently, Vinayagamoorthy et al. [77] concluded that excellent mechanical properties are attained at random fibre orientation. These differences in mechanical properties reported in literature can be attributed to variations in composite fabrication and testing techniques. Table 4 summarizes reported research findings on the effect of fibre orientation on the physical and mechanical properties of synthetic/natural fibres hybrid reinforced polymer composites.

Zuhudi et al. [78] investigated the effect of hybridization on the thermal, flammability, and impact properties of bamboo/glass reinforced polypropylene hybrid composites. The study reduced the glass fibre weight fraction in glass/polypropylene composite from 60 to 30% and replaced the reduced fibre weight by adding 30% woven bamboo fibres. Bamboo/glass hybrid composites exhibited a higher Charpy impact strength of 1129 J/m compared to 530.9 J/m for bamboo fibre reinforced polypropylene composites. This represented 50% increase in Charpy impact strength as a result of glass fibre hybridization. The increase in impact strength with glass fibre incorporation can be attributed to higher energy dissipation at the glass/matrix interface required to debond the fibres from the matrix phase. Santulli [79] analyzed impact properties of glass/bamboo fibre reinforced unsaturated polyester hybrid composites with 25% total fibre content, containing 18.8 wt.% glass fibre and 6.2 wt.% bamboo fibre. The study reported a maximum impact strength of 32.0 kJ/m$^2$.

Nayak et al. [80] analyzed the effect of stacking sequence and addition of fibre layer on mechanical properties of 6% vol. NaOH treated bamboo/glass fibre reinforced epoxy hybrid composites. From experimental investigation, they found that stacking sequence has a more significant influence on the mechanical behavior of hybrid composites than the addition of fibre layers. The study showed that hybrid composites with glass fibres at the core surrounded by bamboo fibres reported maximum hardness value of 25.2 $H_V$ compared to 23.4 $H_V$ for hybrid composites with alternating glass and bamboo fibres. Table 5 summarizes fabrication techniques, matrix resin, and mechanical and physical properties of reviewed bamboo/glass fibre hybrid reinforced composites.

*3.2. Glass/Sisal Fibre Reinforced Polymer Hybrid Composites.* Aslan et al. [81] studied the mechanical behavior of sisal/carbon and sisal/glass fibre hybrid reinforced polypropylene composites. Experimental results showed that the tensile properties of sisal/carbon and sisal/glass hybrid increased with an increase in carbon and glass fibre content, respectively. However, sisal/carbon hybrid exhibited higher tensile properties than sisal/glass hybrid. Jarukumjorn and Suppakarn [82] studied the effect of glass fibre hybridization on glass/sisal fibre reinforced polypropylene hybrid composites. They concluded that adding more glass fibres into the hybrid composite slightly enhanced the tensile strength with an insignificant effect on tensile modulus. Further studies have observed enhanced tensile, compression, wear resistance, impact, and flexural properties with increasing glass fibre content in the hybrid composites [9, 83–92].

Gehlen et al. [93] investigated the tribological properties of sisal/glass reinforced polyester hybrid composites. From experimental results, sisal fibre composites exhibited the highest wear resistance followed by sisal/glass hybrid and glass fibre reinforced composites, respectively. Additionally, sisal fibre reinforced composites reported the lowest coefficient of friction due to the lubricating action of water present in hydrophilic natural sisal fibres. Similarly, Biswas

Table 4: Effect of fibre orientation on physical and mechanical properties of resultant hybrid composites.

| Hybrid composite | Fibre orientation/direction | Effects of fibre orientation | Ref. |
|---|---|---|---|
| Bamboo/glass | 0°/90° and ±45° | Hybrid composites with ±45° fibre orientation reported maximum TS, IS, and FS of 92.3 MPa, 87.0 kJ/m$^2$, and 387.7 MPa, respectively; hybrid samples with 0°/90° orientations reported optimal hardness value of 62.3 HR. | [70] |
| Kenaf/glass | 0° and 90° | Hybrid with 90° fibre orientation exhibited TS of 69.9 MPa compared to 49.3 MPa for 0°. No significant effect of fibre orientation was observed on FS and IS. | [130] |
| Sisal/glass | Longitudinal and transverse direction | Higher TS, TM, and FS in the longitudinal direction in comparison with transverse direction. | [102] |
| Glass/hemp | 0°/90° and ±45° | Hybrid with 0°/90° orientation recorded a higher tensile strength of 49.9 MPa compared to 33.2 MPa for hybrid composite with ±45° fibre orientation. However, FS of hybrid samples showed the least variation for both directions. | [155] |
| Neem/abaca/glass | Parallel, perpendicular, and 45° | Fibres arranged in 45° orientations exhibited better mechanical properties than fibres in horizontal and vertical orientations. | [176] |
| Flax/carbon | 0° and ±45° | Replacing the internal layer of CFFCCFFC with the two ±45° layers caused minimal effect on Young's modulus but reduced the UTS by 61%. | [191] |

Table 5: Mechanical and physical properties of reviewed bamboo/glass fibre hybrid reinforced composites.

| TS (MPa) | TM (GPa) | FS (MPa) | Fm (GPa) | IS (kJ/m$^2$) | Hardness | Fabrication technique | Matrix | Ref. |
|---|---|---|---|---|---|---|---|---|
| 68.6 | 16.0 | 130.1 | 86.5 | — | — | Hand lay-up | Epoxy | 62 |
| 100 | 5.7 | 166 | 6.9 | — | 25.2 $H_V$ | Hand lay-up | Epoxy | 64 |
| 92.3 | — | 387.7 | — | 87.0 | 62.3 $H_R$ | Hand lay-up | Polyester | 70 |
| 80.6 | — | 53.4 | — | 180 | 35 $H_V$ | Hand lay-up | USP | 66 |
| 42.8 | 3.5 | 110.5 | 3.3 | — | — | Hand lay-up | Epoxy | 62 |
| 180 | —- | 198 | — | — | — | Hand lay-up | Epoxy | 81 |

and Xess [94] observed that the addition of glass fibre in hybrid composite significantly reduced the wear rate in comparison to neat epoxy composite.

*Rana* et al. [91] reported an increase in tensile and impact strengths as sisal fibre weight fraction increased from 0 to 4 wt.% at constant glass fibre content. Further increase in sisal fibres beyond 4 wt.% at constant glass fibre weight fraction decreased tensile and impact strengths. Additionally, Prabu et al. [95] reported decreased tensile properties with increasing sisal fibres in sisal/glass hybrid composites. A study by da Silva et al. [93] observed that the addition of sisal fibres reduced the tensile properties of sisal/glass fibre hybrid composites compared to pure glass fibre reinforced composites. For instance, the tensile strength and modulus of sisal/glass fibre hybrid composites were 61.2 MPa and 1.3 GPa, respectively, compared to 97.3 MPa and 2.7 GPa for glass mat reinforced unsaturated polymer composites. However, incorporating sisal fibre increased the elongation at break from 3.1% for glass mat reinforced composites to 6.6% for sisal/glass fibre reinforced hybrid composites. These observations can be attributed to the water absorption property of sisal fibres, thus weakening the tensile properties.

Other research studies have reported that the addition of glass fibres enhances the hardness of the hybrid composite [84, 88]. Similarly, Amico et al. [83] reported enhanced hardness for composites with either one or two glass fibre layers. Nevertheless, no observable increment in composite hardness reported as the number of glass fibre layers was increased further. A study by Aslan et al. [81] on sisal/glass fibre reinforced hybrid composites concluded that the composite hardness reduced with a decrease in glass fibre content.

Similarly, research on the effect of fibre chemical modification and fibre length on short sisal/glass hybrid composites showed that the tensile properties of the hybrid composites increased with an increase in volumetric fractions of glass fibre in the hybrid composite. In addition, the tensile properties increased with chemical pretreatment of sisal fibres [96]. Similar studies have reported enhanced tensile, flexural, and impact properties of sisal/glass reinforced composites with chemical treatment of sisal fibres [97, 98]. For instance, Patel and Parsania [98] reported an increase in tensile strength and flexural strength by 33.7 and 37.3%, respectively, due to alkali treatment.

Further review literature shows that the orientation of fibres in the hybrid significantly influences the properties of sisal/glass composites. Ramesh et al. [99] reported that sisal/jute/glass fibre hybrid composites exhibited superior flexural strength, elongation at break, and tensile strength at 0° orientation compared to fibres oriented at 90°, as shown in Figure 2. Likewise, Palanikumar et al. [100] observed higher tensile strength, tensile modulus, and flexural strength in the longitudinal direction compared to the transverse direction for sisal/glass reinforced hybrid composites. However, Kalaprasad et al. [101] reported insignificant variations in tensile properties for longitudinally, transverse, and randomly oriented fibres in the hybrid composites.

KC et al. [102] studied the thermal and dimensional stability of sisal/glass fibre reinforced polypropylene hybrid composites. The water absorption properties decreased by 53.6% as glass fibre content increased from 10 to 20 wt.%.

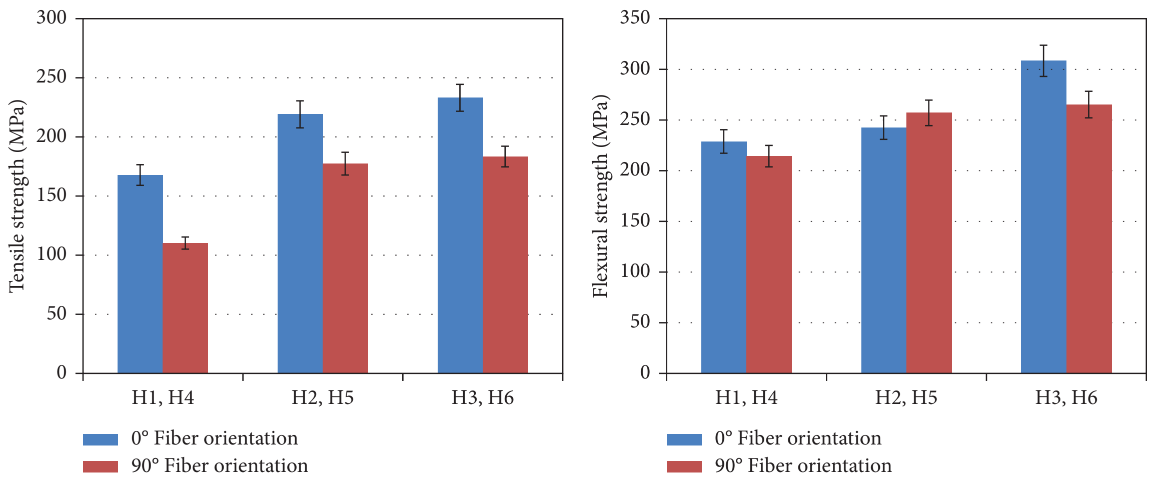


Figure 2: Effect of fibre direction on tensile and flexural strength of sisal/jute/glass fibre hybrid composite [99].

Similar research studies by Manickam Ramesh et al. [103] and Ramesh et al. [99] concluded that water absorption decreases with a corresponding increase in glass fibre content in the hybrid composites. Sisal/glass fibre hybrid composites reported a similar trend of reduced water absorption compared to sisal fibre reinforced composites [104]. Higher water saturation levels and negligible moisture uptake that characterize natural fibres and glass fibres, respectively, account for this observation. A study by da Silva et al. [93] observed that incorporating sisal fibres into glass fibre reinforced composites increased the water absorption properties of the resultant hybrid composites.

Kalaprasad et al. [105] analyzed the thermal diffusivity and thermal conductivity of sisal/glass reinforced LDPE hybrid composites. Thermal conductivity increased with the hybridization of sisal with glass fibres. Similarly, the same study reported an exponential reduction in thermal diffusivity with temperature increase. In another study, Jarukumjorn and Suppakarn [82] conducted a thermogravimetric analysis of sisal fibre hybrid composites. The highest thermal decomposition temperatures were observed with hybrid composites with 10 wt.% sisal and 20 wt.% glass with corresponding 5 and 10% weight loss, respectively. Further, thermal distortion temperature slightly increased with an increase in sisal fibres in the hybrid. Gilorkar et al. [106] observed enhanced thermal deflection and resistance for sisal/glass fibre hybrid composites compared to sisal fibre reinforced composites.

Birat et al. [86] concluded that the addition of sisal and glass fibres has no significant impact on the crystallization and melting temperatures of the hybrid composites. The study further observed enhanced thermal stability and reduced decomposition rate with the addition of glass fibres. Similarly, KC et al. [102] observed that the specific heat capacity analyzed at different temperatures remained constant with increasing glass fibre content in the hybrid composites. In addition, hybridization enhanced the thermal stability of resultant composites. In contrast, Pereira et al. [18] observed no significant effect of hybridization on the thermal stability of hybrid composites.

*3.3. Kenaf/Glass Fibre Reinforced Polymer Hybrid Composites.* Kenaf is a natural plant fibre characterized by good mechanical properties as well as low density. Therefore, replacing a portion of synthetic fibre, such as glass with kenaf, can significantly reduce the overall weight and cost of the structure besides making the structure environmentally friendly [107]. Sapiai et al. [108] studied the tensile and flexural properties of kenaf/glass fibre reinforced epoxy hybrid composites. The hybrid composites were prepared through a combination of hand lay-up and filament winding methods. The result indicated that adding high strength and stiff glass fibres increased flexural and tensile strength to 115.7 MPa and 65.3 MPa, respectively, up from 77.6 MPa to 49.5 MPa, for pure kenaf fibre reinforced epoxy composites.

Similarly, Salman et al. [73] investigated the effect of the number of kenaf layers in glass fibre reinforced hybrid composites. Kenaf layer(s) formed the core layer between three glass layers at the bottom and top of the sandwich comprising 3G/K/3G, 3G/2K/3G, and 3G/3K/3G structures. A sandwich structure with one kenaf layer between three glass layers at the top and bottom exhibited the highest tensile strength compared to other sandwich structures. Similarly, the highest tensile strength and tensile modulus of 122 MPa and 5.2 GPa, respectively, have been reported for kenaf/glass sandwich hybrid composites with 3 G/K/3G stacking sequence [109]. These studies concluded that increasing the number of kenaf layers increases the proportion of low-strength kenaf fibres thus reducing the tensile properties of the hybrid composites. Further, the addition of more kenaf fibres leads to poor interfacial bonding between the fibre and matrix [110].

Rozali et al. [111] reported the highest flexural strength and modulus for hybrid composites with kenaf fibre mat at the core surrounded by glass fibre mat. On the other hand, hybrid composites with glass fibre mat at the core surrounded with kenaf fibre mat showed a higher water absorption and swelling. EL-Wazery et al. [112] observed maximum tensile strength for hybrid composites with flax fibre at the core sandwiched with carbon fibres at the top and bottom. Studies by Fotouhi et al. [113] reported that changing the stacking sequence potentially impacts the stiffness of the inner layer, thus changing the final failure stress and strain of the composites.

Ghani et al. [114] investigated the mechanical performance of kenaf/glass fibre reinforced polyester hybrid composites in different aqueous solutions. The composites were fabricated using hand lay-up and cold press methods and immersed in seawater, distilled water, and acidic conditions for one month. From the results, the tensile strength properties of the hybrid composites declined with an increase in immersion time for all solutions. This was attributed to the formation of a weak hydrogen bond between cellulosic kenaf fibres and water molecules; thus, the samples easily failed and deformed on the application of tensile loads.

Atiqah et al. [110] studied the effect of alkali chemical pretreatment of kenaf fibre on mechanical properties of kenaf/glass fibre reinforced unsaturated polyester hybrid composites using 6% NaOH for 3 hours. The study used a constant total reinforcement weight fraction of 30% with kenaf/glass volume fractions of 0/30 (S1), 7.5/22.5 (S2), 15/15 (S3), 22.5/7.5 (S4), and 30/0 (S5). The findings showed that the hybrid with alkali-treated kenaf fibres exhibited better mechanical properties compared to untreated counterparts. For instance, treated kenaf/glass hybrid composites with 15/15 (S3) composition yielded maximum properties of 39.3 MPa, 2.4 GPa, and 140.3 J/m for tensile strength, tensile modulus, and impact strength, respectively, as shown in Figure 3.

Further, Muhammad et al. [115] studied the mechanical performance of kenaf/glass fibre reinforced epoxy hybrid composites fabricated by hot-pressing process. Silane coupling treatment of glass fibres and 6% alkali treatment of kenaf fibres followed by the addition of liquid epoxidized natural rubber (LENR) technique enhanced the mechanical performance of individual fibres. The results showed that chemical pretreatment and addition of LENR improved the impact strength, flexural strength, and flexural modulus by 40%, 13%, and 15%, respectively. In addition, the tensile properties were also enhanced. Noor et al. [116] reported higher impact strength for alkali-treated kenaf fibre reinforced polyurethane composites. Alkali pretreatment of natural fibres removes amorphous elements such as lignin, pectin, hemicellulose, hydroxyl groups, wax, and other impurities. This enhances the bonding between matrix and reinforcement phases, thus improving the mechanical properties [96, 117–124]. Nevertheless, untreated fibres reinforced composites exhibit low mechanical properties due to weak fibre/matrix interfacial bonding.

Jaafar et al. [125] investigated the effect of alkali treatment of kenaf fibres on mechanical and morphological properties of resultant kenaf/glass hybrid composites. Kenaf fibres were immersed in NaOH solution of concentration between 0% and 9% w/w. The results revealed that maximum impact strength, flexural strength, and flexural modulus of 10.6 kJ/m$^2$, 54.1 MPa, and 3.5 GPa, respectively, were reported with 3% NaOH treated composites. The morphological study further showed cracking of the fibre surface at higher NaOH concentrations. This significantly reduced fibre/matrix interaction causing poor transfer of applied load resulting, thus poor mechanical strengths. At 9% NaOH w/w, the crack became bigger with some by-product deposits on the fibre surface.

Similarly, Fiore et al. [126] investigated the effect of alkali treatment on the mechanical properties of kenaf reinforced epoxy composites. The study reported that subjecting natural fibres to high sodium hydroxide concentration damages the surface of fibres. Further, higher NaOH concentration causes fibre delignification which significantly lowers the mechanical performance of fabricated composite materials. Most studies such as by Ibrahim et al. [118]; Osman et al. [121]; and Yusuff et al. [113] have recommended an optimum NaOH concentration between 5 and 6% to produce composites with excellent mechanical properties.

Hashim et al. [117] investigated the effect of alkali treatment under different conditions on the physical characteristics of kenaf fibres. Kenaf fibres were subjected to alkali concentrations of 2, 6, and 10% w/v at different temperatures of 27, 60, and 100$^0$C and immersion duration of 30, 240, and 480 minutes. The study revealed that alkali treatment influences physical properties. In addition, fibre density and weight loss increased while fibre diameter and the cross-sectional area declined with increasing NaOH concentration. Besides alkali chemical pretreatment, propionic anhydride treatment, enzymatic treatment, silane treatment, and combination of silane and alkali treatment have been used to modify the surface of kenaf fibres [127]. Table 6 summarizes reported research findings on the effect of fibre chemical pretreatment on the physical and mechanical properties of synthetic/natural fibres hybrid reinforced polymer composites.

Davoodi et al. [7] fabricated and investigated the mechanical characteristics of kenaf/glass reinforced epoxy hybrid composites for car structural components. The mechanical properties of hybrid composites were compared with those of glass fibre reinforced composites. From their study, they found that hybrid composites exhibited higher tensile and flexural properties. The study attributed this observation to the fabrication method used that made the composite more compact. The excellent interfacial adhesion between fibres and matrix promoted the maximum transfer of tensile and flexural load, thus enhanced mechanical properties for hybrid composites compared to pure glass counterparts. Yusuff et al. [123] suggested that the mechanical properties of hybrid composites are influenced by composite fabrication techniques used, amongst other factors. However, Sapiai et al. [108] concluded that the addition of glass fibres enhances the mechanical properties of kenaf/glass hybrid composites. Sanjay et al. [25] observed that hybridization with glass fibre enhances the mechanical properties of kenaf/jute fibre reinforced epoxy composites.

Ramesh and Nijanthan [128] analyzed the flexural, impact, and tensile properties of kenaf/glass fibre reinforced epoxy hybrid composites using finite element analysis. The hybrid composites with 0° and 90° fibre orientations were prepared using hand lay-up technique. The results revealed that hybrid composites with 90° fibre orientation exhibited a

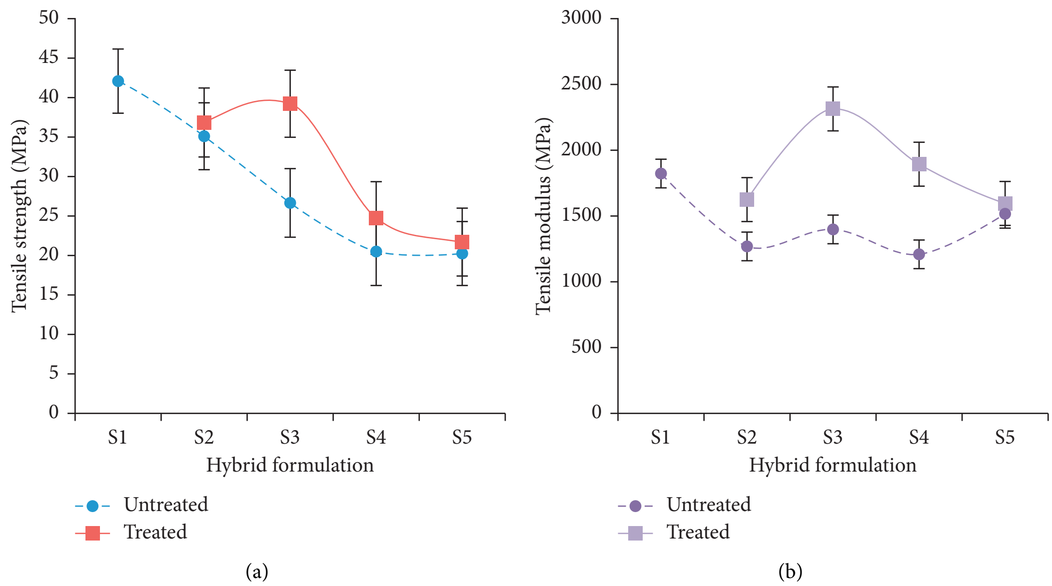


Figure 3: Effect of alkali treatment on (a) tensile strength and (b) tensile modulus of glass/kenaf fibre hybrid composites [110].

Table 6: Effect of natural fibre chemical pretreatment on physical and mechanical properties of resultant hybrid composites.

| Hybrid composite | Chemical pretreatment | Effects of pretreatment | Reference |
|---|---|---|---|
| Glass/sisal | 5% NaOH Sol. at 30 °C for 8 h | TS and FS increased from 26.4 to 35.3 MPa and from 46.7 to 64.1 MPa, respectively, on alkali treatment. | [100] |
| Kenaf/glass | 6% NaOH solution for <3 h | 15/15 v/v kenaf/glass yielded maximum properties of TS, TM, and IS of 39.3 MPa, 2.4 GPa, and 140.3 J/m, respectively; these values were close to pure glass composite | [112] |
| Glass/kenaf | Silane coupling for glass fibres and 6% alkali for kenaf fibres | Chemical pretreatment improved the IS, FS, and FM by 40%, 13%, and 15%, respectively | [117] |
| Glass/kenaf | 6% NaOH solution | Alkali treatment increased the IS by 127% in comparison with samples with untreated kenaf fibres. Treatment of kenaf fibre led to a decrease in FM of composite samples. | [118] |
| Kenaf/glass | Immersion in NaOH solution of concentration between 0% and 9% w/w | Maximum IS, FS, and FM of 10.6 kJ/m$^2$, 54.1 MPa, and 3.5 GPa, respectively, reported with 3% NaOH treated composites. The morphological study showed fibre surface cracking at higher NaOH concentrations. | [127] |
| Kenaf/glass | 2, 6, and 10% w/v NaOH solution at 27, 60, and 100°C and 30, 240, and 480 min | Alkali treatment influences physical properties. Fibre density and weight loss increased while fibre diameter and the cross-sectional area declined with increasing NaOH concentration. | [119] |
| Carbon/jute | 5% NaOH for 3 h | Treated samples showed a higher FS of 380 compared to 200 MPa for untreated hybrid composites with carbon/jute/jute/carbon configuration. | [180] |
| Sisal/carbon | 7.5 and 10 wt.% NaOH | Hybrids with 10 wt.% NaOH treated sisal fibres exhibited enhanced mechanical behavior and thermal conductivity compared to hybrids with 7.5 wt.% NaOH sisal fibres. | [181] |
| Sugar palm/glass | Benzoylation treatment | Hybrid composites with benzoyl treated sugar palm fibre recorded maximum tensile stress and strain of 31.56 MPa and 0.95%, respectively, compared to 20.4 MPa and 0.75% for untreated sugar palm/glass fibre composites. | [158] |
| Basalt/glass | 1M HCl and 1M NaOH solution for 3 days | Untreated 5G4B5G hybrid recorded TS of 269.7 MPa compared to 356.4 and 335.8 MPa for HCl and NaOH treated samples, respectively. Hence, acid treatment is better in improving TS. | [47] |

higher tensile strength of 69.9 MPa compared to 49.3 MPa for 0° fibre orientation. The higher tensile strength can be attributed to the applied load parallel to fibres at 90° fibre orientation. However, there was no significant difference in impact and flexural strengths in both 0° and 90° orientations, as shown in Figure 4.

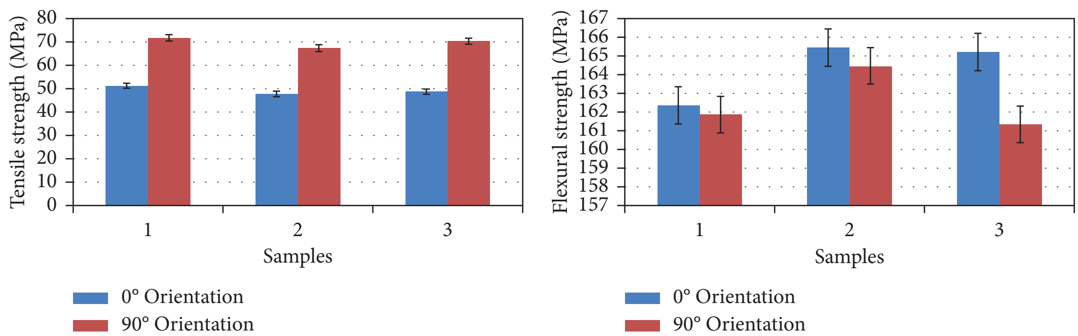


Figure 4: Effect of fibre orientation on tensile and flexural strengths of kenaf/glass fibre hybrid composites [128].

*3.4. Jute/Glass Fibre Reinforced Polymer Hybrid Composites.* Research by de Queiroz et al. [11] investigated jute/glass fibre adhesively bonded joints and the effect of interlaminar glass layers required to produce pure glass bonded joints. From the results, the failure load of jute/glass hybrid joints increased with an increase in interlaminar glass layers. Samanta et al. [70] reported a drastic increase in jute/glass hybrid composite tensile strength with glass layers. The study recorded tensile strengths of 41.4, 75.6, and 153.4 MPa for one, two, and three glass layers, respectively. Similarly, Braga and Magalhaes [129] analyzed the thermal and mechanical behavior of jute/glass reinforced epoxy hybrid composites. Their study reported an increase in flexural strength, impact energy, tensile strength, and density and a decrease in water absorption with the addition of glass fibres. However, Vijaya et al. [130] reported tensile strengths of 51.1, 68.4, and 85.9 MPa for jute/glass, banana/glass, and jute/banana/glass hybrids, respectively. Therefore, jute/glass hybrid composite exhibited the lowest tensile strength compared to other hybrid composites. In another similar study, jute/glass fibre reinforced polyester hybrid composites reported the highest impact strength of 752 J/m compared to 326 and 500 J/m for banana/glass and jute/banana/glass hybrids, respectively [131].

Sanjay and Yogesha [132] conducted a study on the effects of hybridization on jute/kenaf/glass reinforced epoxy hybrid. The composites were fabricated using vacuum bagging technique which produced composites with low void volume fraction; thus, high composite properties were recorded. The study revealed that hybridization of kenaf and jute fibres with glass fibres reported maximum tensile modulus and strength. Similarly, Ramnath et al. [133] evaluated the mechanical behavior of abaca/jute/glass fibre reinforced epoxy hybrid composites fabricated by hand lay-up technique. From the results, jute/abaca/glass composites exhibited higher tensile strength and modulus of 57 MPa and 290 MPa, respectively. On the other hand, jute/glass composites reported tensile strength and tensile modulus of 46.5 MPa and 250 MPa, respectively, compared to 44.5 MPa and 270 MPa, respectively, for abaca/glass hybrid composites.

Gujjala et al. [134] and Ramesh et al. [135] investigated the mechanical properties of jute/glass reinforced polyester hybrid composites. These studies concluded that adding glass fibres can improve the mechanical properties of hybrid composite. Das et al. [136] investigated the impact of stacking sequence on the mechanical performance of jute/glass fibre hybrid reinforced polyester composites. Maximum tensile strength, tensile modulus, flexural strength, and flexural modulus of 137.6 MPa, 4.6 GPa, 252.4 MPa, and 10.6 GPa, respectively, were reported for hybrid composites with alternating jute and glass fibre layers. In contrast, neat jute/polyester composites exhibited the lowest mechanical properties of 64.6 MPa, 3.5 GPa, 127.2 MPa, and 3.5 GPa, respectively. The study concluded that glass fibre content and stacking sequence, that is, the position of glass fibre layers in composites significantly influence the mechanical properties of the resultant hybrid composites.

Akil et al. [137] analyzed the effect of water absorption on mechanical properties of jute/glass fibre reinforced unsaturated polyester composites. The composites were immersed in water for 4076 hours at room temperature and pressure conditions. From the study, jute/glass hybrid composites exhibited superior retention of tensile and flexural properties at higher temperatures than jute fibre reinforced composites. Thus, hybridization of natural fibres with synthetic fibres can strike a balance between cost-performance and the environmental impact of composite materials. Abd El-Baky et al. [138] investigated the mechanical characteristics of cost-effective novel jute/glass fibre reinforced epoxy hybrid composites prepared by a combination of hand lay-up and compression molding techniques. The study suggested that hybridization with high-strength glass fibres to the core of the composites potentially increased the tensile properties while the flexural properties decreased. Nevertheless, Ahmed and Vijayarangan [66] reported that the incorporation of glass fibres as outer layers significantly enhances the properties of jute/glass reinforced polyester hybrid composites.

Further studies have reported increased flexural and tensile properties with glass fibre content for jute/glass fibre reinforced hybrid composites. The studies attributed this observation to the addition of high-strength glass fibres to jute fibres [10, 139]. Further review literature has reported lower tensile, impact, flexural, and interlaminar shear strengths for glass/jute reinforced hybrid composites compared to glass fibre reinforced polymer composites. However, these properties were higher than jute fibre reinforced composites [66, 140, 141].

Ouarhim et al. [29] compared the mechanical and water absorption properties of jute/glass fibre hybrid composites at two hybrid configurations: inter- and intralayer. Experimental results showed that hybrid configuration directly influenced the properties of the hybrid composites with the interlayer configuration presenting the least resistance to moisture absorption. Selver et al. [44] observed constant tensile properties with notable differences in flexural strength as the stacking sequence changed for jute/glass fibre reinforced hybrid composites. Similar studies by Sanjay et al. [25] and Sanjay and Yogesha [132] have reported a direct correlation between mechanical properties and stacking sequence for jute/kenaf/glass fibre reinforced epoxy hybrid composites.

Investigation of the mechanical properties of glass/jute fibre hybrid reinforced epoxy composites reported enhanced flexural, tensile, and water absorption properties compared with jute fibre reinforced epoxy counterparts. Additionally, the study observed 42.0% increase in flexural strength for treated jute/glass fibre hybrid composites in comparison to untreated jute/glass counterparts. However, the chemical treatment of jute fibres did not have a positive effect on tensile strength [144]. Further literature review by Aquino et al. [142] has reported higher water absorption for glass/jute hybrid composite than glass fibre reinforced composites. This can be attributed to the hydrophilic nature of natural fibres with high saturation levels. The absorbed water weakens the fibre/matrix interface resulting in a decrease in the mechanical properties of the hybrid composites [92, 104, 111, 112, 143].

*3.5. Flax/Glass Fibre Reinforced Polymer Composites.* Abd El-Baky et al. [144] developed flax/glass fibre reinforced epoxy hybrid composites using vacuum bagging technique. The study investigated the effect of fibre weight fraction on flexural, tensile, and impact properties. The result observed an increase in impact and flexural strength and a decrease in tensile strength with the incorporation of high-strength glass fibres. Similarly, Abd El-Baky et al. [20] reported an increase in flexural resistance and a decrease in tensile properties with the incorporation of high-strength glass fibre to the outer layer of flax/glass reinforced epoxy hybrid composites prepared using vacuum bagging technique. However, the tensile behavior of flax/glass fibre reinforced phenolic hybrid composites improved with an increase in glass fibre weight fraction [145].

Further studies by Barouni and Dhakal [146] and Cihan et al. [147] observed an increasing trend with the addition of glass fibre on damping properties and impact performance, respectively, of flax/glass hybrid composites. Hybridization of flax with glass fibre reduced the percentage of moisture uptake to 1.9%, down from 4.0% for flax fibre reinforced vinyl ester composites. Besides, flax/glass fibre hybrid composites exhibited superior load and energy capacities compared to flax/vinyl ester composites [30]. On effects of stacking sequence, Selver et al. [44] investigated the influence of stacking sequence on flexural and tensile properties of flax/glass fibre reinforced hybrid composites. Their study observed constant tensile properties with notable differences in flexural strength as the stacking sequence changed for flax/glass fibre reinforced hybrid composites. Additionally, experimental results have shown that the sequence of fibre orientation strongly influences the diffusion coefficient and saturation mass uptake of flax/glass hybrid composites [148]. Table 7 summarizes reported research findings on the effect of stacking sequence on physical and mechanical properties of synthetic/natural fibres hybrid reinforced polymer composites.

*3.6. Hemp/Glass Reinforced Polymer Hybrid Composites.* Studies by Panthapulakkal and Sain [149] reported enhanced thermal properties and water absorption resistance of hemp/glass fibre polypropylene reinforced hybrid composites. The flexural properties increased with an increase in glass fibre weight fraction to attain maximum flexural strength and modulus of 101 MPa and 5.5 GPa, respectively, at 25% hemp/15% glass. The study concluded that hemp/glass reinforced polypropylene hybrid composites are alternative and promising candidates for high strength and thermal resistance structural applications. Experimental results by Bhoopathi et al. [150] indicated better flexural, impact, and tensile strength of 2239 MPa, 5.0–5.8 J, and 35.5–38.5 MPa, respectively, for hemp/glass reinforced epoxy hybrid composites. Bhoopathi et al. [151] observed maximum tensile, impact, and flexural strengths of 61.0 MPa, 7.3 J, and 13.3 MPa, respectively, for hemp/glass hybrids.

On the effect of fibre orientations on the mechanical behavior of hemp/glass reinforced epoxy hybrid composites, Murugan et al. [152] observed higher tensile strength at $0^\circ/90^\circ$ orientation and lower flexural strength at $\pm 45^\circ$. Patel et al. [153] reported higher tensile strength and flexural strength for hemp/glass hybrid composites with inner and outer glass fibre layers, respectively. The observed hybrid properties were intermediate between properties of glass fibre reinforced and hemp fibre reinforced composites.

*3.7. Other Natural Fibre/Glass Fibre Reinforced Polymer Hybrid Composites.* Safri et al. [154] analyzed the effect of benzoylation treatment and addition of glass fibre on impact, dynamic mechanical, and postimpact behavior of sugar palm reinforced epoxy composites. From their experimental results, glass fibre addition and benzoylation treatment enhanced the impact, storage modulus, loss modulus, tan delta, and postimpact behavior of sugar palm composites. A similar study investigated the effect of benzoylation and the addition of glass fibres on mechanical, thermal, and physical characteristics of sugar palm reinforced epoxy composites. The addition of glass fibre and benzoylation treatment improved the tensile, physical, and thermal behavior of sugar palm composites. For instance, maximum tensile stress and strain of 31.6 MPa and 1.0%, respectively, were recorded for benzoyl treated 30 wt.% sugar palm/70 wt.% glass fibre hybrid composites. However, the corresponding values for untreated sugar palm fibre reinforced epoxy composites were 20.4 MPa and 0.8% [155]. Similar studies have reported enhancement of impact strength, physical, thermal, flexural, and tensile properties due to the addition of glass fibres to sugar palm composites [156–160].

Table 7: Effect of stacking sequence on physical and mechanical properties of resultant hybrid composites.

| Hybrid composite | Stacking sequences | Effects of stacking sequence | Reference |
|---|---|---|---|
| Bamboo/glass | All glass, all bamboo, GBBG, and GBGBG | Hybrid with bamboo fibres at the core surrounded by glass fibres reported maximum TS, FS, and ILSS of 180, 198, and 14.5 MPa, respectively, compared to 163, 170, and 10.2 MPa for hybrid composite with alternating bamboo and glass fibres. | [81] |
| Glass/jute/madar | GJMJG, GMJMG, GJGJG, and GMGMG | There was a direct correlation between mechanical properties and stacking sequence. The TS for GJMJG, GMJMG, GJGJG, and GMGMG was 101.9, 84.7, 100.8, and 102.4 MPa while FS was 31.7, 26.7, 55.0, and 38.3 MPa, respectively. | [82] |
| Glass/bamboo | GGGG, BBBB, BGBG, BGGB, and GBBG | GBBG hybrid reported maximum TS, TM, FS, FM, and hardness of 100 MPa, 5.7 GPa, 166 MPa, 6.9 GPa, and 25.2 $H_V$, respectively, compared to 92.8 MPa, 3.9 GPa, 142 MPa,5.7 GPa, and 23.4 $H_V$, respectively, for BGGB. | [64] |
| Kenaf/jute/glass | GJJJG, GKKKG, GJKJG, and GKJKG | GKJKG hybrid reported maximum TS, TM, FS, FM, and hardness of 129.2 MPa, 5.9 GPa, 235.5 MPa, 14.4 GPa, and 23.2 $H_V$, respectively, compared with 88.5 MPa, 5.1 GPa, 218.2 MPa, 13.6 GPa, and 22.0 for GJKJG hybrid samples. | [134] |
| Jute/banana/carbon | CJJJC, CBBBC, CJBJC, and CBJBC | The highest IS, UTS, FS, and FM of 28 J, 280 MPa, 380 MPa, and 5.488 GPa, respectively, were reported for CJJJC hybrid composites. | [180] |
| Jute/glass/carbon | JGCCGJ, CGJJGC, CCGGJJ, and JJGGCC | No effect of stacking sequence on tensile properties; however, enhanced flexural strength was observed for hybrids with carbon as outer layers, that is, CGJJGC hybrid reported optimal FS and FM compared to JGCCGJ hybrid. | [9] |
| Kenaf/aramid | KAK, AKA, and AKAK | Hybrid composites with inner kenaf fibre layer between outer Kevlar layers reported maximum tensile strength. | [201] |
| Flax/carbon | CFFC+45 ˚C+45˚FFC, CFFCCFFC, FFCCCCFF, and FCCCCCCF | The addition of flax layer to the external layers of carbon fibre laminate reduced Young's modulus by 28.1% for one layer and 45% for two layers. | [191] |
| Carbon/flax | CFFFC and FCFCF | CFFFC hybrid exhibited brittle failure in the tensile test, whereas FCFCF hybrid exhibited more significant plastic deformation. Failure strain of the CFFFC samples showed a negative hybrid effect, whereas that of the FCFCF samples improved 63.5% compared with pure carbon composites. | [192] |
| Pineapple leaf fibre/carbon | PCCP and CPPC | PCCP hybrid reported maximum TS and TM of 187.7 MPa and 5.2 GPa, respectively, at 00/900 fibre orientation. Also, superior FS and FM of 289.5 MPa and 4.8 GPa, respectively, were observed for CPPC hybrid having similar fibre orientation | [186] |
| Jute/carbon | JCCJ and CJJC | JCCJ hybrid recorded a maximum TS of 234.7 MPa while CJJC reported enhanced moisture resistance and the highest IS of 108.5 kJ/m2. | [183] |
| Basalt/glass | 5G4B5G and 2B10G2B | 5G4B5G hybrid recorded better TS and hardness of 356.4 MPa and 88.3 $H_V$ compared to 244.2 MPa and 84.1, respectively, for 2B10G2B hybrid. | [47] |

On the other hand, a study on mechanical properties of palmyra/glass fibre reinforced epoxy hybrid composites reported improved impact strength, compression strength and modulus, flexural strength and modulus, and tensile strength and modulus with the incorporation of glass fibre to palmyra reinforced epoxy composites [161]. Mishra et al. [67] investigated the effect of glass fibre on mechanical properties of pineapple leaf/glass fibre hybrid composites by varying the glass fibre content from 0 to 25% in total fibre weight fraction. Experimental results reported maximum flexural and tensile strengths at 8.6 and 12.3% glass fibre content, respectively. A similar trend of enhancement of properties of palmyra polymer composites with glass fibre incorporation has been reported in literature [162, 163].

Maisuriya et al. [164] studied tensile and flexural behavior of banana/glass reinforced polyester hybrid composites fabricated using hand lay-up technique. The study showed that the incorporation of glass fibres enhances the tensile and flexural properties of the composites. From the results, the flexural strength and modulus increased from 41.1 to 168.3 MPa and 1.3 to 5.7 GPa, respectively, as glass fibre increased from 0 to 30 wt.%. Similarly, 20% banana/20% glass fibre hybrid composites yielded maximum tensile strength and modulus of 152.3 MPa and 4.0 GPa. Also, the study reported improved mechanical behavior for banana/glass hybrid with 5% NaOH treated banana fibres compared to untreated samples. Kumar et al. [165] investigated the tribological properties of coir/banana/glass fibre reinforced unsaturated polyester hybrid composites. The findings revealed that the proportion of fibre weight fraction influences the wear properties of the composites by 96.1%. A study by Oladele et al. [166] characterized physical and wear properties of pawpaw/glass fibre reinforced epoxy hybrid composites for structural applications. Experimental results showed that the addition of glass fibres improved the wear characteristics of the hybrid composites. In addition, the curing time was gradually reduced with an increase in glass fibre content in the hybrid composites due to excellent interfacial bonding between constituents, thus achieving higher production rates. Table 8 summarizes reported

Table 8: Effect of synthetic/natural fibre composition on physical and mechanical properties of resultant hybrid composites.

| Hybrid composite | Synthetic/natural fibre composition | Effects of synthetic/natural fibre composition | Reference |
|---|---|---|---|
| Glass/sisal | 100/0, 90/10, 80/20, 70/30, 60/40 | Maximum TS and IS of 185.3 MPa and 18.4 J, respectively, was observed for 80/20 hybrid compared to 179.3 MPa and 18.1 J for 100/0 samples. | [102] |
| Sisal/glass | 0–10% sisal | Increase in TS and IS as sisal fibre weight fraction increased from 0 to 4 wt.% at constant glass fibre content, followed by properties declining as sisal fibres increased beyond 4 wt.% at constant glass fibre weight fraction. | [93] |
| Pineapple leaf fibre/Kevlar | Kevlar fibre 5–10% PALF 5–20% | Decrease in hardness and density, and increase in water absorption and porosity with an increase in pineapple leaf fibre and Kevlar fibre content. | [203] |
| Jute/glass/carbon | Jute 0–17.2% Carbon 0–8.1% Glass 0–12.4% | The mechanical properties increased substantially with increasing glass and/or carbon fibres content compared to jute/epoxy composite. | [9] |
| Sugar palm fibre/glass | SPF: *G* (v/v%) 70/30, 50/50, 30/70 | 30 wt.% sugar palm/70 wt.% glass fibre hybrid recorded maximum tensile stress and strain of 31.56 MPa and 0.95%, respectively. | [157] |
| Pineapple leaf/glass | Glass fibre content varied from 0 to 25% | Maximum FS and TS of 101.3 MPa and 92.9 were recorded at 12.9 and 8.6% glass fibre content, respectively | [68] |
| Sisal/carbon | SF: CF weight 20:10, 15:15, 10:20, and 5:25 | TS, TM, and IS of the hybrid composite increased with increasing carbon fibre weight fraction to attain maximum values of 64.5 MPa, 1.7 GPa, and 42.4 J/m, respectively, compared to 40.4 MPa, 0.8 GPa, and 30.4 J/m, respectively, for 30% sisal composites. | [41] |

research findings on the effect of synthetic/natural fibre composition on the physical and mechanical properties of synthetic/natural fibres hybrid reinforced polymer composites.

Megahed et al. [167] investigated the specific mechanical properties of rice straw sheets/glass fibre reinforced polyester hybrid composites produced using hand lay-up technique. The results revealed that hybridization of rice straw sheets with high-strength glass fibres potentially increased the specific flexural and tensile stiffness. Further, experimental results have shown increased impact strength, erosion resistance, and tensile modulus with the increase in glass fibre content for rice-husk/glass fibre reinforced epoxy composites. Enhancement of flexural, impact, tensile, shear, water absorption, and hardness of rice straw reinforced polyester composites with the addition of glass fibres has been reported [168]. However, Rout and Satapathy [169] observed a reduction in tensile and flexural strength with glass content for rice-husk/glass fibre epoxy reinforced hybrid composites.

Shrivastava et al. [170] examined the mechanical behavior of coir/glass fibre reinforced epoxy hybrid composites fabricated by hand lay-up technique. The study concluded that fibre length and fibre weight fraction influence the mechanical properties of the hybrid composite. For instance, the tensile strength decreased with an increase in coir fibre length due to the entanglement of long fibres. However, Thwe and Liao [171] reported an increase in tensile modulus with fibre length. According to the study, longer fibres have increased transfer length, hence carry more loads than short fibres. Kaliappan et al. [172] investigated the effect of fibre orientation on the mechanical behavior of natural fibre/glass fibre hybrids at three different orientations: horizontal, vertical, and 45° orientations. From experimental results, neem and abaca fibres with 45° orientations in the respective glass fibre reinforced hybrid composite recorded higher mechanical properties.

## 4. Natural Fibre/Carbon Fibre Reinforced Hybrid Composites

Natural fibres have lower mechanical properties and higher water absorption capacity. Therefore, combining natural fibres with synthetic carbon fibre enhances the mechanical properties of resultant hybrid composites with reduced water absorption capacities. For instance, Pavikumar et al. [41] observed that jute/carbon fibre hybrid composites exhibit good fibre/matrix interfacial bonding, hence enhanced mechanical properties and reduced water absorption rate. Pinto et al. [173] investigated the effects of stacking sequence on impact, flexural, and damping behavior of hemp/carbon reinforced epoxy hybrid composites fabricated using hand lay-up and vacuum compression molding technique. The findings revealed that stacking sequence significantly influences the vibrational, impact, and flexural properties of the hybrid composites.

Similarly, Salman [174] concluded that fibre layer configurations and fibre content influenced all dynamic mechanical properties of jute/carbon hybrid composites. However, Margabandu and Subramaniam [175] reported a significant effect of stacking sequence on flexural behavior with little influence on the impact strength of jute/carbon hybrid composites. A similar effect of stacking sequence on the mechanical behavior of jute/banana/carbon has been reported in literature. Experimental results showed the highest impact strength, ultimate tensile strength, flexural strength, and modulus of 28 J, 280 MPa, 380 MPa, and 5.5 GPa, respectively, for hybrid composites with carbon/jute/jute/carbon stacking sequence. Besides, the study revealed that alkali treatment of jute fibres significantly improved the mechanical properties of the hybrid compared to untreated counterparts. The study reported flexural strength of 380 and 200 MPa for treated and untreated hybrid composites, respectively, with carbon/jute/jute/

carbon configuration that reported higher mechanical properties as illustrated in Figure 5 [176].

Jagadeesh et al. [177] investigated the mechanical and morphological properties of carbon fibre reinforced with natural areca/sisal fibre hybrid composites for railway seats, secondary structures, and panel applications. The study observed enhanced tensile strength and modulus, flexural strength, and interlaminar shear strength with the addition of carbon fibres to natural reinforcements. Further, Anuar et al. [178] investigated the dynamic mechanical characteristics of kenaf/carbon fibre and observed an increase in loss and storage modulus with the increase in carbon fibre loading in the hybrid.

A study by Sathiyamoorthy and Senthilkumar [179] observed maximum tensile strength of 234.7 MPa for hybrid composites with jute/carbon/carbon/jute configuration. Additionally, enhanced moisture resistance and the highest impact strength of 108.5 kJ/m$^2$ were observed with carbon/jute/jute/carbon configuration. However, the study reported 22% and 14% decrease in tensile and impact strengths of the hybrid, respectively, compared with pure carbon fibre reinforced composites as illustrated in Figure 6. The decrease in impact and tensile strengths can be attributed to fewer fibre pull-outs and moderate fibre/matrix interfacial bonding observed in carbon/jute/jute/carbon fibre hybrid composites. In a similar study investigating the influence of stacking sequence on mechanical and vibration properties of jute/carbon hybrid composites, the study concluded that the position of jute layers in the hybrid composite significantly affects the tensile strength and damping characteristics of the resultant composites. For instance, J/C/C/J hybrid composite exhibited superior damping properties and higher tensile strength of 234.7 MPa in comparison with 158.7 MPa for C/J/J/C hybrid [180].

A study to investigate the effect of hybridization of carbon/glass/flax/kenaf fibre hybrid epoxy composites on flexural and impact properties reported maximum flexural strength and modulus of 364.4 MPa and 24.4 GPa for carbon/flax/epoxy hybrid with $C_2F_3C_2$ stacking sequence. On the other hand, glass/flax/epoxy hybrid with $G_2F_3G_2$ demonstrated the highest impact strength of 92.9 kJ/m$^2$ [184]. Hashim et al. [181] reported maximum tensile strength and modulus of 187.7 MPa and 5.2 GPa, respectively, for hybrid composites with interior carbon layers oriented at 0°/90°. Likewise, superior flexural strength and modulus of 289.5 MPa and 4.8 GPa, respectively, were observed for hybrids with exterior carbon layers having similar fibre orientation. The scanning electron microscope (SEM) images from the study showed that stacking sequence significantly influenced hybrid composite failure mode under mechanical loading. For hybrid with carbon ply at the centre (PCCP), cracking was initiated from pineapple leaf fibre leading to primary failure resulting from carbon fibre breakage and delamination, as shown in Figure 7. On the other hand, for hybrid composite with carbon ply exterior (CPPC), cracks propagated rapidly in the carbon plies and buckled at pineapple leaf fibre layers leading to delamination in the region between the two fibres at the tension sides, as shown in Figure 8. Sezgin and Berkalp [182] reported higher impact resistance and high tensile strength whenever high-strength glass or carbon layers were placed as the outer and inner layers of the hybrid composite, respectively.

Kureemun et al. [183] investigated the effects of hybridization on mechanical properties of flax/carbon fibre reinforced epoxy hybrid composites using low carbon fibre fractions. The study showed that lamination sequences significantly influence the overall mechanical properties of the hybrid composites. A study by Ameur et al. [184] demonstrated that the ultimate tensile strength and Young's modulus of carbon/flax fibre hybrid composites increased with the number of outer carbon layers. The experimental results reported ultimate tensile strength and Young's modulus of 935 MPa and 62 GPa, respectively, for carbon/carbon/flax/flax/carbon/carbon hybrid in comparison with 522 MPa and 35 MPa for carbon/flax/flax/flax/flax/carbon hybrid. On the effect of fibre weight fraction, there was an increase in fatigue resistance and fatigue performance with carbon fibre volume fraction. However, the fatigue life and damping ratio of the composites increased with the volume fraction of flax fibre.

Similarly, a study on the effect of reinforcement of sisal and carbon fibre on the mechanical, thermal, and morphological properties of resultant hybrid composite observed an increase in mechanical properties with carbon fibre. For instance, the properties increased with carbon content to attain optimum tensile strength, tensile modulus, and impact strength of 64.5 MPa, 1.7 GPa, and 42.4 J/m, respectively, at 20 wt% carbon/10 wt.% sisal [42]. In contrast, Kumar et al. [185] observed that mechanical characteristics of carbon/flax fibre hybrid composites increased due to the high strain value of flax fibres as opposed to carbon fibres in the composite. Abd El-Baky [10] reported no effect of stacking sequence on tensile properties; however, enhanced flexural strength was observed for hybrids with carbon as outer layers. Other studies have reported the effects of stacking sequence on mechanical and physical properties of flax/carbon fibre reinforced hybrid composites [186, 187].

Dhakal and Sain [188] observed an increase in tensile strength and modulus to 517.7 MPa and 18.9 GPa, respectively, for flax/carbon hybrid between 68.1 MPa and 4.7 GPa, respectively, for flax fibre reinforced composites. Similarly, carbon/flax/flax/carbon fibre hybrid composites exhibited higher tensile strength and modulus, flexural strength and modulus, and impact strength of 128.5 MPa, 2.1 GPa, 387.7 MPa, 35.8 GPa, and 13.7 kJ/m$^2$, respectively, compared with 88.7 MPa, 1.2 GPa, 170.9 MPa, 14.2 GPa, and 27.7 kJ/m$^2$ for basalt/flax/flax/basalt fibre hybrid composites [189].

Further review literature shows that replacing one flax layer with a carbon layer in flax/carbon hybrid compositehaving six layers increases the tensile strength and modulus by 226.4 and 262.0%, respectively. Similarly, flexural strength increased from 76.4 to 160.4 MPa [190]. On the contrary, Bahrami et al. [191] observed that substituting the carbon fibre middle layer with one or two flax fibre layers does not affect the thermal stability of the resultant hybrid composites. In addition, the resultant carbon/flax fibre hybrid composite exhibited higher impact resistance and enhanced flexural and tensile properties. A study by Dhakal et al. [192] observed decreasing flexural strength and

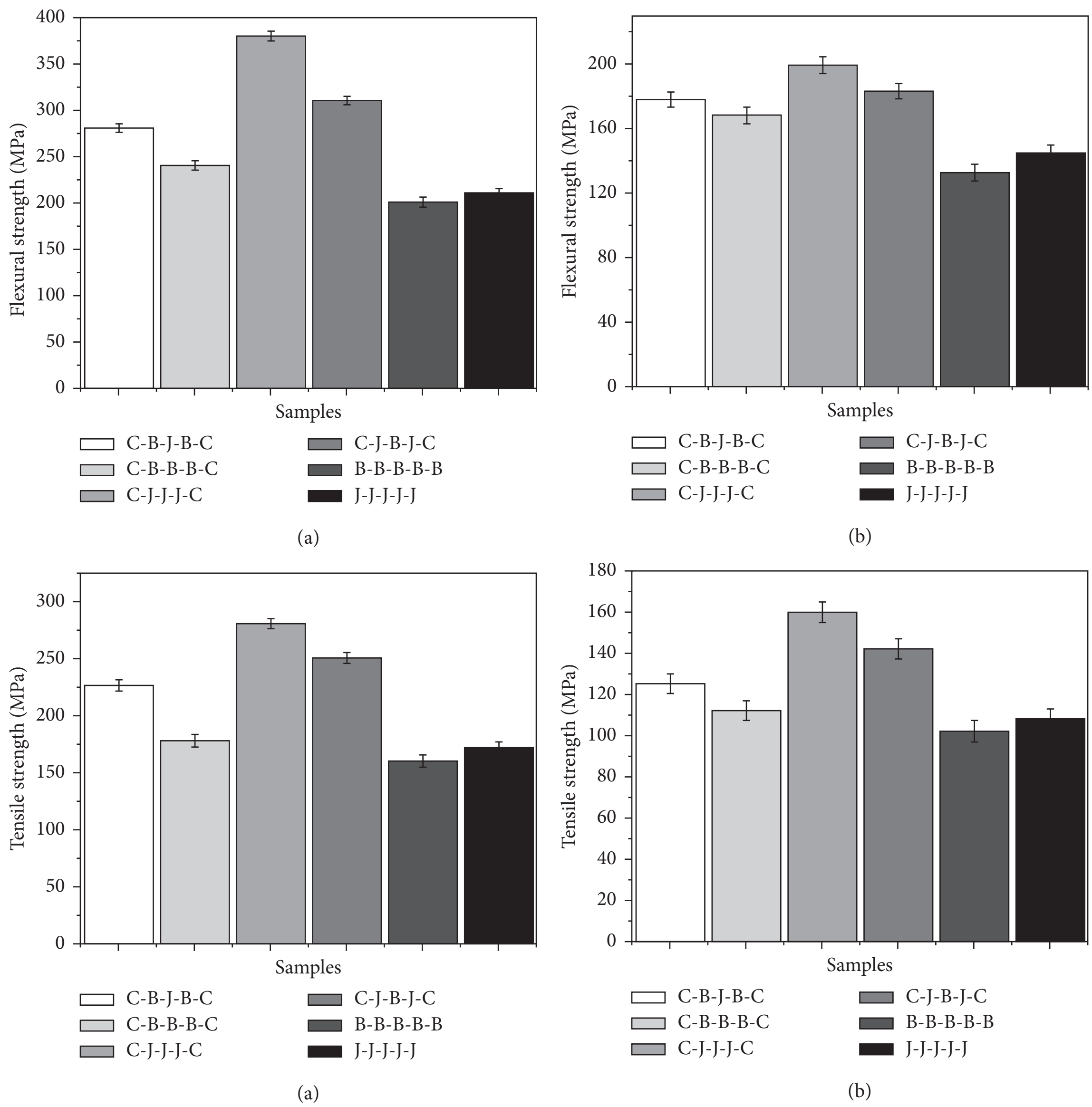


Figure 5: Flexural and tensile strength of (a) treated jute/banana/carbon fibre hybrid and (b) untreated jute/banana/carbon fibre hybrid composites [176].

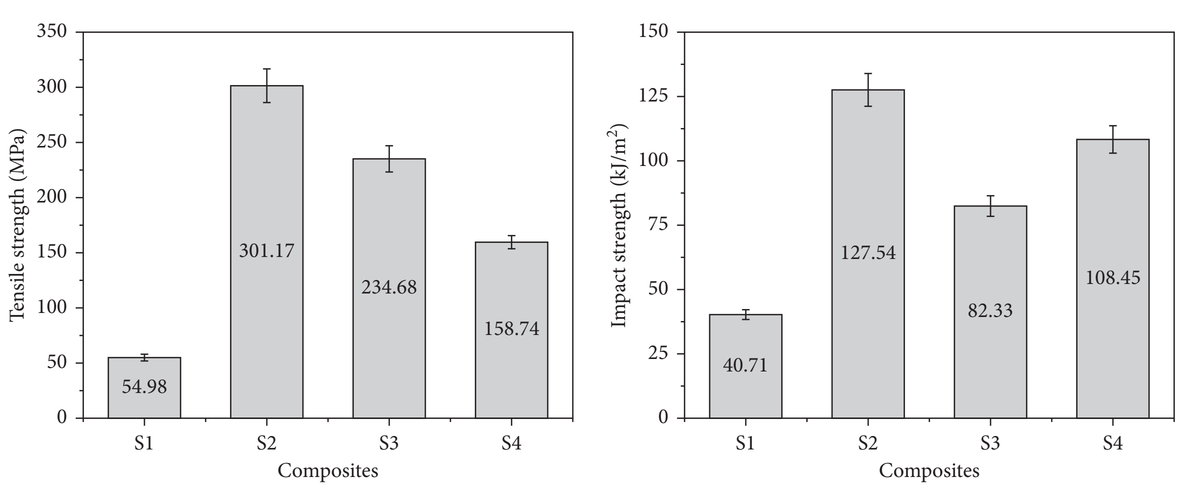


Figure 6: Tensile and impact strength of jute fibre composites (S1), pure carbon fibre composites (S2), jute/carbon/carbon/jute hybrid (S3), and carbon/jute/jute/carbon hybrid (S4) [179].

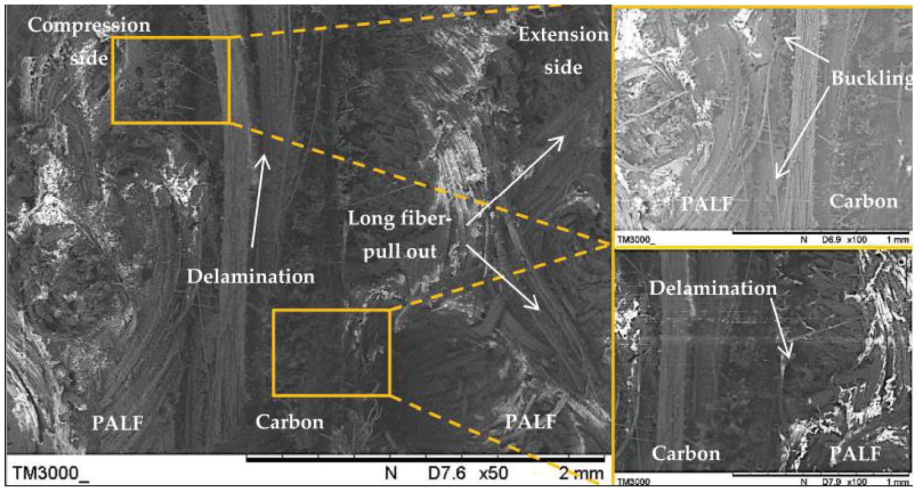


Figure 7: SEM images of the laminate with a carbon ply interior (PCCP) and ply orientation [0°, 90°] [181].

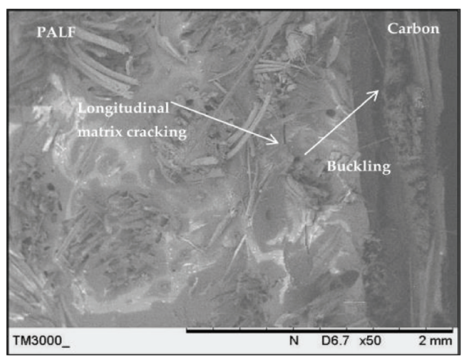


Figure 8: SEM image of the laminate with a carbon ply exterior (CPPC) and ply orientation [0°, 90°] [181].

modulus and strain to failure with increasing carbon fibre. However, it has been reported that strain to failure does not depend on carbon content [193]. Several studies have reported that the mechanical properties of natural/carbon fibre hybrid composites are significantly influenced by carbon fibre proportion. That is, hybridization of natural fibres with carbon fibres affects the mechanical properties of resultant hybrid composites [10, 178, 190, 192, 193].

## 5. Natural Fibre/Kevlar Fibre Reinforced Hybrid Composites

Singh et al. [194] studied the wear properties of bagasse/Kevlar fibre reinforced vinyl ester hybrid composites. The study investigated the influence of various factors such as fibre weight fraction, sliding distance, and velocity. The study revealed that the normal load influences the tribological properties of hybrid composites. Other similar studies have shown that matrix type, fibre type, fibre orientation, fibre weight fraction, and fibre length affect the tribological properties of hybrid composites [195]. Research on the influence of stacking sequence on the mechanical behavior of treated kenaf/Kevlar fibre reinforced epoxy hybrid composites reported maximum tensile strength for hybrid composites with inner kenaf fibre layer between outer Kevlar layers [196]. Figure 9 illustrates the schematic arrangement of kenaf and Aramid layers in hybrid composites.

Experimental investigation on hybridization of kenaf/Kevlar fibre hybrid observed enhanced mechanical properties due to kenaf and Kevlar fibre hybridization. Audibert et al. [197] investigated the mechanical behavior of flax/Kevlar reinforced epoxy hybrid composites. The study reported intermediate mechanical properties between Kevlar fibre reinforced composites and flax fibre reinforced composites. Comparative assessment of physio-mechanical behavior of pineapple/Kevlar hybrid composites has shown a decrease in hardness, ash content, and density and increase in compressibility, water absorption, and porosity with an increase in pineapple and Kevlar fibre content [198]. Further studies by Pach et al. [199] observed a positive hybridization effect with the addition of hemp fibres to Kevlar layers in polyurethane-polyurea matrix. Similarly, a positive effect on mechanical properties of natural fibre hybridized Kevlar fibre composites has been reported [200–203].

## 6. Potential Application Areas of Natural/Synthetic Fibre Hybrid Composites

Glass fibre reinforced polymer composites are the most widely used in structural applications such as in the

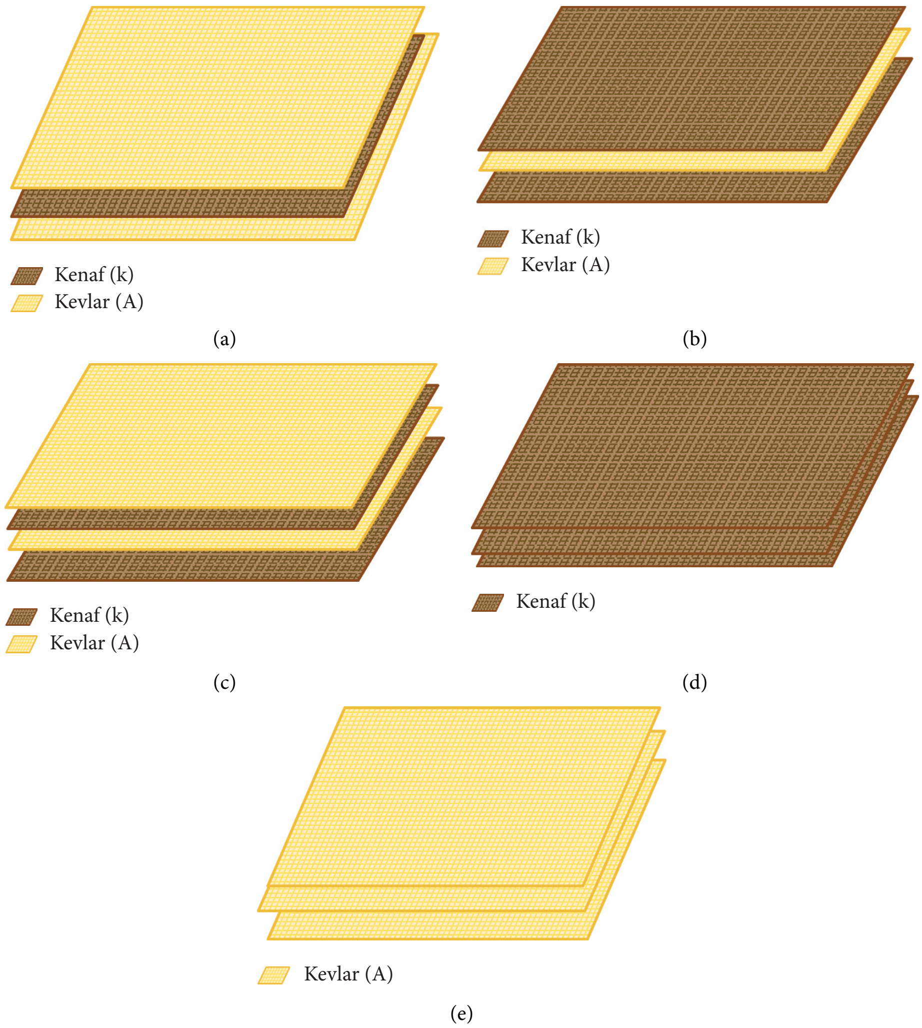


FIGURE 9: Stacking sequence for composites configuration: (a) A/*k*/A; (b) k/A/*k*; (c) A/*k*/A/*k*; (d) k/*E;* and (e) Kevlar/epoxy [196].

automobile industry. However, the global drive towards a circular economy that emphasizes sustainability in production processes has increased the use of agricultural-based raw materials like natural fibres in applications that have been dependent on inorganic oil-based raw materials for a long time. Using natural/natural fibre reinforced polymer composites in structural applications is still challenging due to some issues associated with natural fibres. The main challenges related to natural fibres limiting their structural applications include higher flammability, lower water barrier characteristics, poor fibre/matrix interfacial bonding, inconsistent raw materials, and their properties [204–206]. A review on mechanical properties of natural/natural fibre hybrid composite for bumper beam applications indicates lower impact properties compared to typical bumper beam material like conventional glass fibre composite, thus limiting their applications. Therefore, hybridization of natural and synthetic fibres provides an opportunity to partially and/or fully substitute the glass fibre content of the composite with natural fibres for various structural applications. For instance, a study on the mechanical and interfacial properties of sisal/jute/glass fibre hybrid reinforced epoxy composites concluded that composites produced from these fibres can be used as structural materials for medium load applications [99]. The general applications of natural/synthetic fibre hybrid reinforced polymer composites include aerospace, automobile, ballistic/defense, marine, and hockey equipment, as shown in Figure 10.

*6.1. Automotive.* Many countries globally have imposed restrictions for industrial use of oil-based raw materials in producing different products. One of such restrictions is the "European Guideline 2000/53/EG" imposed and executed in 2005 by the European Union (EU) Commission to ensure the usage of 85% recyclable materials in the fabrication of automobile parts [207]. Therefore, it is expected that the use of sustainable composites will continually increase in the area of automotive as replacement of aluminum and glass fibre composites with natural fibre composites could partially reduce the weight and cost of the vehicle [11]. In addition, the

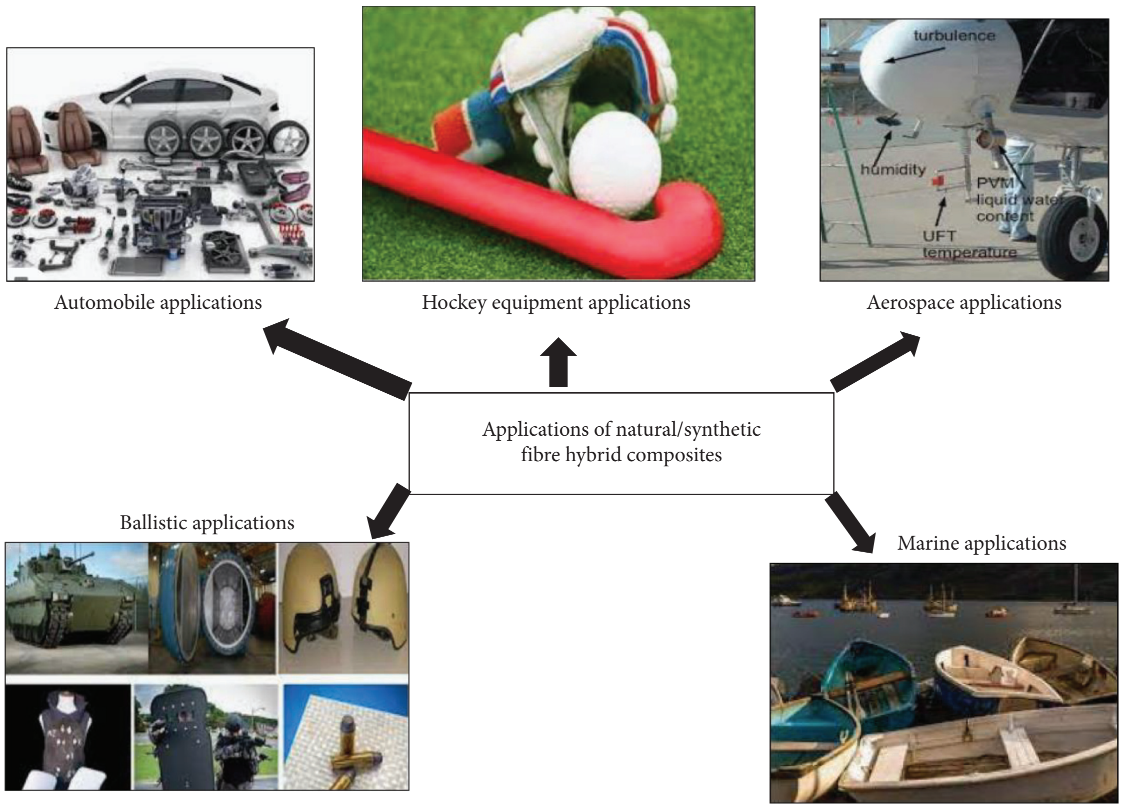


Figure 10: Application areas of natural/synthetic fibre hybrid reinforced polymer composites.

implementation of lightweight materials such as hybrid composites is one of the most likely methods to achieve fuel-efficiency demand with little impact on the environment in the automobile industry.

Kenaf/glass fibre hybrid reinforced polymer composites have been used to design and fabricate automobile lever brake [208]. A comparative study on jute/glass fibre hybrid and synthetic glass fibre composite for car bumper applications has shown that 30% jute/10% glass fibre hybrid composite had superior impact strength and hardness of 11.6 J and 65.5 $H_R$, respectively, compared to glass fibre composites. The study concluded that jute/glass fibre hybrid composites can possibly replace synthetic glass fibre composites in automobile structural applications such as bumper beam [209]. The mechanical properties of kenaf/glass fibre hybrid reinforced composites for passenger car bumper applications have been studied and compared with typical bumper beam material, glass mat thermoplastics. The study reported higher tensile strength and Young's modulus and low impact strength for the hybrid composite in comparison with glass mat thermoplastics [7]. To enhance the thermoplastic impact property of the hybrid composite to meet bumper application requirements, further studies conducted utilized CBT 160 thermoplastic toughening modifier on kenaf/glass fibre hybrid reinforced composites [210]. A roof frame for 2017 Mercedes Benz E-Class made of 70% natural fibre offering almost 50% weight reduction compared to conventional metal reinforced sunroofs has been launched [211].

*6.2. Marine Applications.* Marine structures due to their service environment are constantly subjected to rust attacks causing defects. Carbon steel is mostly used in the fabrication of most marine structures such as ship hulls. Unfortunately, carbon steel is vulnerable to corrosion in addition to variations in electromagnetic and thermal detection from long range. To overcome these challenges associated with carbon steel in marine applications, material scientists across the globe are investigating plant-based composites as a replacement for carbon steel. Besides being corrosion resistant, plant-based composites are cheaper, greener, sustainable, biodegradable, and readily available. However, plant-based composite suffers from weak compatibility between hydrophobic polymer matrices and hydrophilic natural fibres resulting in low mechanical properties. Therefore, hybridization of natural and synthetic fibres will overcome the challenges associated with natural fibres reinforced polymer composites and produce hybrid composites with better mechanical and thermal properties and superior aging resistance.

Additionally, hybridization provides a better compromise between cost, mechanical performance, and environmental impact for different applications such as marine structures [212, 213]. A research study on glass/flax fibre hybrid reinforced polymer composites reported improved flexural strength and modulus by 90% and 120%, respectively. In addition, the hybrid composites showed enhanced aging durability suitable for marine conditions, thus providing a suitable replacement for carbon steel [214]. A further study investigated the mechanical properties of woven glass/sugar palm fibre hybrid reinforced unsaturated polyester composite for small boat application [158].

*6.3. Aerospace Applications.* Natural/synthetic fibre hybrid reinforced polymer composites have shown potential applications in the aerospace industry because of their functionality, manufacturing, performance, and environmental superiority. Additionally, natural/synthetic fibre hybrid composites have a high strength-to-weight ratio, more elastic strain energy storage capacity, and high-strength ability compared to steel [215]. Similar to automotive and marine applications, hybridization of natural/synthetic fibres results in enhanced performance for various aerospace applications such as interior panel of aircrafts. Currently, glass fibre composites which are radio-frequency transparent materials are mainly used in aircraft radome. Besides radio-frequency transparency, aircraft radome should be light with high toughness and low dielectric constant. A preliminary review of different natural fibres such as kenaf, banana, bamboo, and others has shown that kenaf/glass fibre hybrid reinforced epoxy composites can replace glass fibre composites in aircraft radome applications [216].

*6.4. Defense/Ballistic Applications.* For ballistic and bulletproof applications, composites are reinforced with high-performance fibres mainly synthetic fibre because of their superior strength and modulus, high heat resistance, and excellent ability to absorb the kinetic energy of the projectile [217]. Presently, polymer composites based on aramid fibre, UHMWPE, and PBO fibres have produced acceptable results for bulletproof and ballistic applications [218]. However, these synthetic fibres are associated with higher processing costs and nonrenewability, thus disrupting the ecosystem and polluting the environment [9]. Research studies are currently ongoing to explore the possibility of replacing Kevlar fabrics with natural fibres with improved kinetic energy absorption and dissipation in ballistic applications.

A study by Alkhatib [219] observed that the addition of untreated date palm natural fibres into carbon/Kevlar fibre reinforced plastics enhanced the ballistic performance but the weight was more than the other tested hybrid plates. The study recommended the use of treated date palm fibres for massive weight reduction. Besides fibre surface treatment, the properties of natural fibres can be enhanced for ballistic applications through hybridization. Natural/synthetic fibre reinforced polymer hybrid composites have special attributes that mainly impact resistance, high specific strength and stiffness, crack resistance, and low density. These features make these hybrid composites ideal for high-velocity impact and ballistic applications [205].

In addition, treated banana/glass fibre hybrid reinforced polymer composites have reported enhanced ability to withstand higher stresses compared to pure glass fibre reinforced polymer composites [220]. Thus, the hybrid composite can be used as a replacement for glass and carbon-based field hockey equipment [221].

## 7. Summary

Natural fibre reinforced composites provide a renewable, eco-friendly, cost-effective, and sustainable alternative for synthetic fibre reinforced composites that have been associated with global pollution challenges. However, natural fibre reinforced composites suffer from low mechanical properties due to their hydrophilic nature. The low mechanical properties of natural fibre reinforced composites limit their utilization in structural and nonstructural applications. The cost-performance and environmental impact of composites can be realized by combining natural fibres and synthetic fibres in a single matrix system through a technique known as hybridization. Based on the review, the mechanical, physical, and thermal properties of natural/synthetic fibre hybrid composites are influenced by chemical pretreatment of natural fibres, stacking sequence, the orientation of fibres in the hybrid system, and fibre weight fraction of constituent fibres.

Natural plant fibres, also known as cellulosic fibre, contain noncellulosic constituents such as wax, pectin that hinders the bonding ability of these fibres in polymer matrices, necessitating their removal before composite fabrication. The review showed that properties of natural/synthetic fibre reinforced polymer composites increase with chemical modification of natural fibres through chemical pretreatment [96–98, 110, 115, 116, 125]. Chemical pretreatment removes these noncellulosic constituents, thus improving the bonding ability of natural fibres in polymer matrices. In addition, chemical pretreatment improves fibre surface roughness and wettability, thus enhancing the interfacial bonding between fibres and polymer matrices, reduces moisture absorption characteristics, and provides more strength to the resultant composites.

Secondly, the stacking sequence or arrangement of natural and synthetic fibres in the hybrid system influences the properties of the resultant natural/synthetic fibre hybrid reinforced composites. The properties are influenced by the relative position of natural and synthetic fibre layers as either inner or outer layers in the hybrid structure. Natural/synthetic fibre hybrid composites with a layer of natural fibres at the core surrounded by synthetic fibre layer(s) reported the highest tensile and flexural properties, and stiffness, and lowest water absorption properties [80, 111–113, 138]. This is because placing high-strength synthetic fibre as an outer layer increases the ability of hybrid composites to withstand mechanical loading resulting in higher mechanical behavior and lower water absorption properties compared to hybrid composites with natural fibres as outer layers. Consequently, hybrid composites with synthetic fibres as core layer surrounded by a layer of natural fibres reported higher water absorption and swelling properties [112]. This is because natural fibres being hydrophilic absorb more water from the surroundings compared to synthetic fibres that are known to have poor water absorption properties.

The effect of fibre orientation on properties of natural/synthetic fibre hybrid composites showed mixed results. For instance, hybrid composites exhibited higher tensile strength, flexural strength, and tensile modulus in the longitudinal direction compared to transverse direction [100, 128]. Consequently, fibres arranged in 45° orientations showed higher mechanical properties compared to fibres oriented in horizontal and vertical directions [172, 186]. Lastly, the physical, mechanical, and thermal properties of natural/synthetic fibre hybrid composites are influenced by weight fractions of constituent fibres. The review showed that increasing synthetic fibre weight fraction enhances the mechanical, physical, and thermal properties of the resultant natural/synthetic fibre hybrid composites [10, 67, 102, 162, 163, 168]. Further, increasing synthetic fibre weight fraction decreases the water absorption characteristics of the hybrid composites. This can be attributed to the addition of high-strength synthetic fibres with poor water absorption properties, thus increasing the ability of the resultant composites to withstand mechanical loading and exhibit reduced water absorption characteristics. The potential application areas of natural/synthetic fibre hybrid reinforced composites include aerospace, automobiles, marine, defense, and sporting industries.

## 8. Conclusion and Future Outlook

The challenge of poor interfacial adhesion between hydrophilic natural fibres and hydrophobic polymeric matrices needs to be addressed if natural fibre reinforced polymer composites are to be commercially viable. Recent research studies have attempted to address this challenge through advancements in natural fibre pretreatment and combining natural and synthetic fibres in a single matrix system through hybridization technique. Chemical pretreatment of natural fibres improves fibre surface roughness and wettability thus enhancing fibre/matrix interfacial bonding. On the other hand, through hybridization, the advantages of one fibre complement the disadvantages of the other fibre thus the properties of the resultant composites can be tailored to desired strengths for specific applications as it offers multifunctionalities such as weight reduction that cannot be achieved with a single fibre. In addition to chemical pretreatment, this review article has revealed that within the natural/synthetic fibre hybrid composite system, the properties of the resultant hybrid composites can be enhanced through appropriate stacking sequence, fibre orientation, and fibre weight fraction of each constituent reinforcement. Therefore, using these parameters, it is possible to tailor the properties of natural/synthetic fibre hybrid reinforced polymer composites to the desired structural applications.

However, with the increasing environmental concerns and awareness and demand for environmental-friendly, biodegradable, and sustainable composites in various applications, there is need for a paradigm shift from natural/synthetic to natural/natural fibres hybrid reinforced polymer composites. The challenge of poor compatibility between hydrophilic natural fibres and hydrophobic polymeric matrices can be addressed by incorporating smaller quantities of nanofiller, thus enhancing the properties of natural/natural fibres hybrid reinforced polymer composites making them commercially viable. To achieve a smart eco-conscious future, research should explore organic/natural nanofillers from agricultural wastes such as palm kernel shell, coconut shell among others as an alternative to petroleum-based inorganic nanofillers. Unlike organic nanofillers, inorganic fillers are associated with unsustainability, non-biodegradability, and high costs. Besides enhancing the properties of natural/natural fibre hybrid composites for various applications, deriving nanofillers from agro-wastes will help address the problem of improper management of these wastes leading to land and air pollution and create wealth through the trend of waste-to-wealth.

## Abbreviations

| | |
|---|---|
| MT: | Metric tons |
| Fm: | Flexural modulus |
| MPa: | Megapascals |
| IS: | Impact strength |
| GPa: | Gigapascals |
| UTS: | Ultimate tensile strength |
| PP: | Polypropylene |
| LDPE: | Low-density polyethylene |
| $H_R$: | Rockwell hardness number |
| HCl: | Hydrochloric acid |
| $H_V$: | Vicker's hardness number |
| NaOH: | Sodium hydroxide |
| TS: | Tensile strength |
| UHMWPE: | Ultra-high molecular weight polyethylene |
| TM: | Tensile modulus |
| PBO: | Polybenzobisoxazole |
| FS: | Flexural strength |
| PALF: | Pineapple leaf fibre |
| USP: | Unsaturated polyester |

## Data Availability

All the information and data are contained in the article submitted.

## Conflicts of Interest

The authors declare no potential conflicts of interest.

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