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Review of Natural Fibre Reinforced Hybrid Composites

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Abstract

Natural fibre reinforced hybrid composites which contain one or more types of natural reinforcement are gaining increasing research interest. This paper presents a review of natural fibre reinforced hybrid composites. Both thermoplastic and thermoset composites reinforced by hybrid/synthetic fibres or hybrid/hybrid fibres are reviewed. The properties of natural fibres, the properties and processing of composites are summarised.

Keywords: Composites; Hybrid; Natural; Fibre

1 Introduction

Natural fibre reinforced composites are gaining increasing research interests, because of the light weight, low costs and abundance of raw materials, and excellent recyclability. More importantly, it provides a solution to the reuse of agricultural wastes. It is shown that natural fibre composites have a potential to replace glass in many applications [1].

A number of reviews on natural fibre reinforced biocomposites have been presented [2-10]. Ku et al. [9] reviewed the tensile properties of natural fibre reinforced composites. Malkapuram et al. [10] reviewed natural fibre reinforced polypropylene (PP) composites.

One of the main disadvantages of natural fibres as reinforcement in composites is the hydrophilic nature of nature fibres, which makes them incompatible with hydrophobic matrices. For improving the compatibility, surface modification of natural fibres is needed. George et al. [11] presented a review on interface modification and characterization of natural fibre reinforced plastic composites. Li et al. [12] reviewed chemical treatment of natural fibres for use in natural fibre reinforced composites. John et al. [13] presented a critical review of the literature on the various aspects of natural fibres and biocomposites with a particular reference to chemical modifications.

Hybrid composites are materials made by combining two or more different types of fibres in a common matrix. They offer a range of properties that cannot be obtained with a single kind of reinforcement. Hybridization of two types of short fibres having different lengths and diameters can offer some advantages over using either of the fibres alone in a single polymer matrix. Hybrid composites have attracted the attention of many researchers as a way to enhance mechanical properties of composites.

A review on hybrid composites is given by Swolfs et al. [14]. In general, the purpose of bringing two fibre types in a single composite is to maintain the advantages of both fibres and alleviate some disadvantages. For instance, replacing carbon fibres in the middle of a laminate by cheaper glass fibres can significantly reduce the cost, while the flexural properties remain almost unaffected. If a hybrid composite is loaded in the fibre direction in tension, then the more brittle fibres will fail before the more ductile fibres. The two fibre types are typically referred to as low elongation (LE) and high elongation (HE) fibres. A hybrid effect, is a deviation from the simple rule of mixtures [15, 16], is introduced to characterise the mechanical properties.

It was shown from the research on synthetic hybrid composites reinforced by glass and carbon fibres [17-24] that positive hybrid effects and improved properties were found. Inspired by synthetic fibre hybrid composites, hybrid composites reinforced by natural/synthetic fibres or natural/natural fibres are gaining increasing research interest. This paper presents a review on natural fibre reinforced hybrid composites with concentrations on the properties and processing. Both hybrid/synthetic and hybrid/hybrid fibre reinforced hybrid composites are reviewed, with the aim of showing any improvement in the properties can be achieved via hybridisation.

2 Properties of Natural Fibres

Selected properties of some natural fibres are shown in Table 1 [8, 25, 26]. It should be noted that the moduli and strengths are in the longitudinal direction. Because of the complex nature of natural fibres, these fibres often exhibit anisotropy [27-29]. For example, the transverse modulus of jute fibres was reported to be 5.5 GPa [27].

3 Properties of Hybrid Composites

3.1 Natural/Synthetic Fibre Hybrid Composites

Most research on natural and synthetic fibre hybrid composites used glass fibres with natural fibres to reinforce a matrix. Because glass fibres have better mechanical properties than natural fibres, in general, it was shown that the tensile [30-56], flexural [32, 34-36, 39-43, 45-47, 49-52, 54, 57-60], compressive [57, 61] properties, thermal stability [30, 31, 62] and water resistance [34, 35, 39, 40, 42, 49-52, 54] were improved due to the introduction of glass fibres. Various results on the impact strength including both improved [34, 35, 37, 39, 40, 45, 47-52, 54, 61, 63, 64] and deteriorated [46] impact strengths were shown. These studies are summarised in Table 2.

Table 1: Selected properties of some natural fibres [8, 25, 26]

Fibre	Density (g/cm^3)	Failure strain (%)	Tensile strength (MPa)	Stiffness/Young's modulus (GPa)
Ramie	1.5	2.0–3.8	400–938	44–128
Flax	1.5	1.2–3.2	345–1830	27–80
Hemp	1.5	1.6	550–1110	58–70
Jute	1.3–1.5	1.5–1.8	393–800	10–55
Banana	1.35	2.5	750	30
Bamboo	1.2–1.5	1.9–3.2	500–575	27–40
Sisal	1.3–1.5	2.0–2.5	507–855	9.4–28
Alfa	1.4	1.5–2.4	188–308	18–25
Cotton	1.5–1.6	3.0–10	287–800	5.5–13
Coir	1.2	15–30	131–220	4–6
Silk	1.3	15–60	100–1500	5–25
Feather	0.9	6.9	100–203	3–10
Wool	1.3	13.2–35	50–315	2.3–5

Table 2: Studies on natural/synthetic fibre hybrid composites

Authors	Fibre 1	Fibre 2	Matrix	Properties
Raghavendra Rao et al. [57]	bamboo	glass	epoxy	Flexural, compressive
Mandal et al. [60]	bamboo	glass	polyester, vinyl ester	Flexural, ILSS
Venkata Subba Reddy et al. [33]	bamboo	glass	polyester	Tensile, chemical resistance
Nayak et al. [30] Samal et al. [31]	bamboo	glass	polypropylene	Mechanical, thermal
Thwe and Liao [32, 62]	bamboo	glass	polypropylene	Tensile, flexural, fatigue
Nayak et al. [35] Samal et al. [34]	banana	glass	polypropylene	Mechanical, thermal
Pothan et al. [37]	banana	glass	polyester	Tensile, impact
Haneefa et al. [36]	banana	glass	polystyrene	Tensile, flexural
Almeida Júnior [65]	curaua	glass	polyester	Mechanical, thermal
Silva et al. [66]	curaua	glass	polyester	Tensile, flexural
Santulli et al. [67]	flax	glass	epoxy	Impact
Zhang, et al. [38]	flax	glass	phenolic	Tensile, ILSS, fracture toughness
Arbelaiz et al. [68]	flax	glass	polypropylene	Mechanical
Shahzad [63]	hemp	glass	polyester	Impact, fatigue
Panthapulakkal and Sain [39, 40]	hemp	glass	polypropylene	Tensile, flexural, impact, water absorption
Patel et al. [69]	jute	carbon	epoxy and phenolic	Tensile, flexural, water absorption, electrical

Abdullah Al et al. [41]	jute	glass	polyester	Tensile, flexural
Ahmed et al. [42, 70]	jute	glass	polyester	Tensile, flexural, ILSS, notch sensitivity
Ahmed and Vijayarangan [43]	jute	glass	polyester	Tensile, flexural, ILSS
Zamri et al. [71]	jute	glass	polyester	Flexural, compressive
Venkata Reddy et al. [44, 58]	kapok	glass	polyester	Tensile, hardness, flexural, compressive, ILSS
Davoodi et al. [46]	kenaf	glass	epoxy	Tensile, flexural, impact
Atiqah et al. [45]	kenaf	glass	polyester	Tensile, flexural, impact
Hariharan and Abdul Khalil [48]	oil palm EFB	glass	epoxy	Tensile, impact
Sreekala et al. [47]	oil palm EFB	glass	phenol formaldehyde	Tensile, flexural
Abdul Khalil et al. [49, 50]	oil palm EFB	glass	polyester, vinyl ester	Tensile, flexural
Idicula et al. [72]	PALF	glass	polyester	Thermophysical
Mishra et al. [51]	PALF	glass	polyester	Tensile, flexural, impact
Velmurugan and Manikandan [52]	palmyra	glass	rooflite	Tensile, flexural, impact, shear
Padma Priya and Rai [73]	silk	glass	epoxy	Mechanical, water absorption
Zhong et al. [74]	sisal	aramid	phenolic	Tensile, compressive, wear resistance
Noorunnisa Khanam et al. [75]	sisal	carbon	polyester	Tensile, flexural, chemical resistance
Ashok Kumar et al. [76]	sisal	glass	epoxy	Frictional coefficient, hardness, impact, chemical resistance
Amico et al. [77]	sisal	glass	polyester	
John and Naidu [53, 61, 78]	sisal	glass	polyester	Tensile, impact, compressive, chemical resistance
Mishra et al. [51]	sisal	glass	polyester	Tensile, flexural, impact
Kalaprasad et al. [55, 79]	sisal	glass	polyethylene	Tensile, thermal
Jarukumjorn and Suppakarn [54]	sisal	glass	polypropylene	Tensile, flexural, impact
Jiang et al. [64]	wood flour	glass	poly(vinyl chloride)	Flexural, impact
Valente et al. [59]	wood flour	glass	polyethylene, polypropylene	Flexural, hardness
AlMaadeed et al. [56]	wood flour	glass	polypropylene	Tensile

3.1.1 Bamboo/Glass Hybrid Composites

Nayak et al. [30] and Samal et al. [31] studied the influence of short bamboo and glass fibres on the thermal, dynamic mechanical and rheological properties of PP composites. It was found both the stiffness and thermal stability increased with the incorporation of bamboo and glass fibres. Thwe and Liao [32] studied the mechanical properties of short bamboo fibre reinforced PP composites (BFRP) and short bamboo/glass fibre reinforced PP hybrid composite (BGRP). It was shown the moduli and strengths in both tension and flexure increased by incorporating up to 20 wt% glass fibres. The durability of bamboo fibre reinforced PP could also be enhanced by hybridization with small amount of glass fibres. Thwe and Liao [62] also studied the resistance to hygrothermal aging and the fatigue behaviour under cyclic tensile load. The results suggested that BGRP had better fatigue resistance than BFRP at all load levels tested. However, these studies did not clearly show if any hybrid effects existed.

Raghavendra Rao et al. [57] studied the flexural and compressive properties of bamboo/glass fibre reinforced epoxy hybrid composites. It was observed that both the flexural and compressive properties increased with glass fibre content. The flexural strength and modulus from their study are shown in Figure 1, from which it is seen the flexural strength and modulus of the hybrid composites are higher than those of both non-hybrid ones, which suggests the existence of positive hybrid effects. Venkata Subba Reddy et al. [33] studied the chemical resistance and tensile properties of the bamboo/glass fibre reinforced polyester hybrid composites. It was found that the hybrid composites showed better resistance to the chemicals being tested. Similar results were found for the tensile properties of the hybrid composites. Mandal et al. [60] studied the flexural and interlaminar shear properties of the bamboo/glass fibre reinforced unsaturated polyester and vinyl ester hybrid composites. It was found that 25% of glass fibres could be replaced by bamboo fibres without decreasing both the flexural and interlaminar shear strengths.

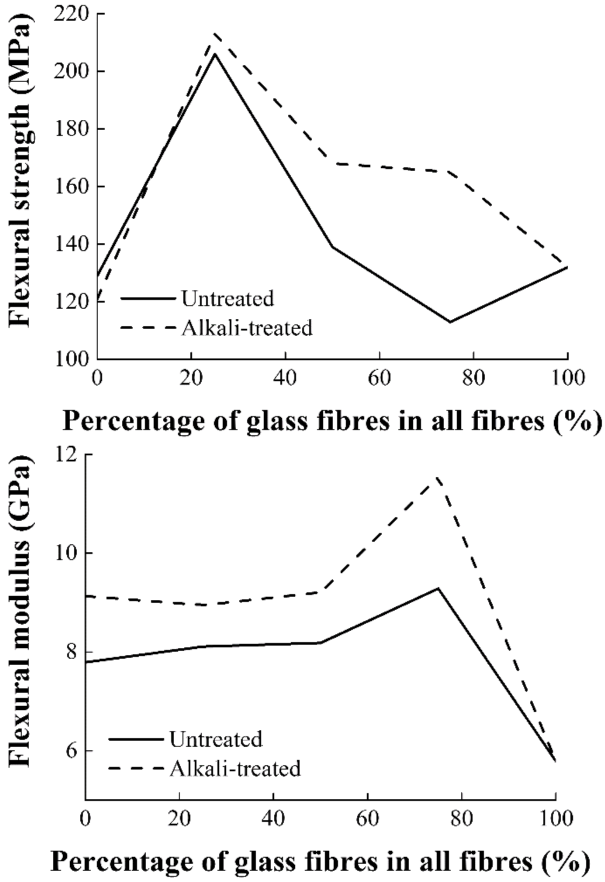

Figure 1: Flexural strength and modulus of bamboo/glass fibre reinforced epoxy composites

3.1.2 Banana/Glass Hybrid Composites

Samal et al. [34] and Nayak et al. [35] studied the influence of short banana and glass fibres on the thermal, dynamic mechanical and rheological properties of PP composites. The mechanical properties are shown in Table 3. It was found the maximum improvement in the properties was found at 30 wt% of fibre loading, with banana to glass ratio 15:15. The water absorption decreased with hybridisation. Haneefa et al. [36] studied the tensile and flexural properties of short banana/glass fibre reinforced polystyrene (PS) hybrid composites. The total fibre content was 20%. The tensile modulus and strength are shown in Figure 2, from which it is seen the tensile modulus and strength increase with the volume fraction of glass fibres and followed the RoM. However, the elongation at break decreased with increasing volume fraction of glass fibre. The flexural modulus and strength showed similar trends.

Table 3: Mechanical properties of BSGRP hybrid composites

Banana content (%)	Glass content (%)	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)	Impact strength (J/m)
30	0	45.25±0.86	985±4.1	48±1.11	1815±2.12	46±1.03
25	5	44.5±0.82	1070±2.23	51.5±0.91	1980±2.04	51±0.96
20	10	49±0.74	1155±3.53	54±0.84	2050±2.2	54.5±1.1
15	15	57±0.91	1350±5.56	58.85±0.91	2190±4.6	58±1.1
10	20	53±1.11	1210±4.85	55.5±0.88	1975±2.3	52±0.96
5	25	51±0.92	1135±3.12	52±0.79	1842±3.12	47±0.86

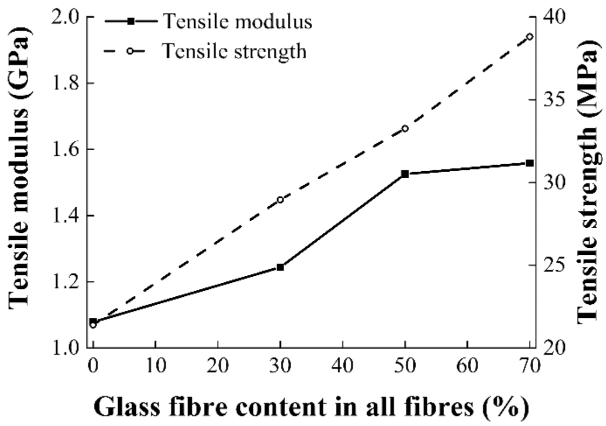

Figure 2: Tensile modulus and strength of short banana/glass fibre reinforced hybrid polystyrene composites

Pothan et al. [37] analysed the variations in the tensile and impact properties of banana fibre reinforced polyester composites caused by the addition of glass fibres. It was found that the tensile strength of banana/glass hybrid composites linearly increased with the volume fraction of glass fibres. The impact strength of the hybrid composite increased when the glass fibre volume fraction was increased up to 11%. A further increase in glass fibre volume fraction slightly decreased the impact strength.

3.1.3 Flax/Glass Hybrid Composites

Arbelaiz et al. [68] investigated the effect of fibre treatments and matrix modification on the mechanical properties of flax fibre bundle/PP composites and flax fibre bundle/glass/PP hybrid composites. Treatments using chemicals such as maleic anhydride, vinyltrimethoxy silane, maleic anhydride-PP copolymer and also fibre alkalization were carried out in order to modify the interfacial bonding between fibre bundles and polymeric matrix. The mechanical behaviours of both flax fibre bundle composites and flax fibre bundle/glass hybrid composites were studied. The results suggested that matrix modification led to better mechanical performance than fibre surface modification. Santulli et al. [67] studied the effect of partial replacement of E glass fibres with flax fibres on the falling weight impact performance of epoxy composites. The flax/epoxy laminates and hybrid E glass/flax/epoxy laminates provided a sufficient impact performance with a considerable weight reduction compared to the E glass/epoxy laminates. Santulli [80] also reviewed the impact properties of glass/plant fibre hybrid laminates. Zhang et al. [38] studied the mechanical behaviours of unidirectional flax and glass fibre reinforced phenolic hybrid composites. The tensile properties of the hybrid composites are shown in Figure 3. It is seen both the tensile modulus and strength increase with glass fibre content and follow the RoM. No hybrid effects was shown. The stacking sequence was shown to influence the tensile strength and tensile failure strain, but not the tensile modulus. The fracture toughness and interlaminar shear strength of the hybrid composites were higher than those of glass fibre reinforced composites due to the excellent hybrid performance of the hybrid interface.

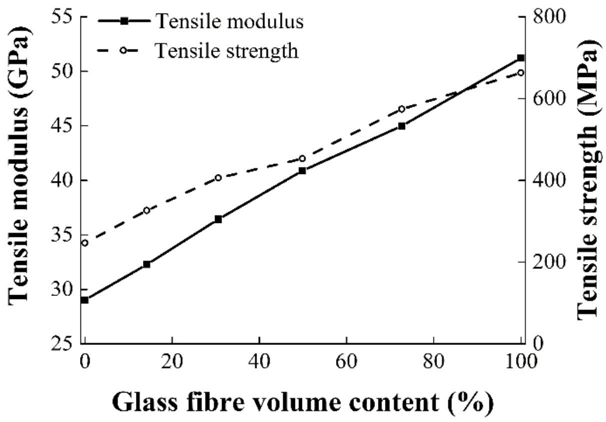

Figure 3: Tensile modulus and strength of unidirectional flax and glass fibre reinforced phenolic hybrid composites

3.1.4 Hemp/Glass Hybrid Composites

Panthapulakkal and Sain [39, 40] studied the mechanical, water absorption, and thermal properties of short hemp/glass fibre reinforced hybrid PP composites. It was found that the tensile, flexural, and impact properties of short hemp fibre composites were improved by the incorporation of glass fibres. The tensile modulus and strength are shown in Figure 4, from which it is seen both the tensile modulus and strength follow the RoM. It was also observed that water absorption tendency of the hemp fibre composites decreased by hybridization with glass fibres. Thermogravimetric studies indicated that addition of glass fibres improved the thermal stability of hemp fibre PP. All these results indicated that injection moulded short hemp/glass/PP hybrid composites resulted in enhanced performance properties and might find technical applications such as automotive interior parts. Shahzad [63] studied the effect of hybridization of hemp fibres with glass fibres on the impact and fatigue properties of the hemp/glass fibre reinforced polyester hybrid biocomposites. Replacement of about 11% of hemp fibres with glass fibres in hybrid composites increased their impact damage tolerance considerably. Hybrid hemp/glass fibre composites showed improvement in fatigue strength but no improvement in fatigue sensitivity was observed compared to hemp fibre composites.

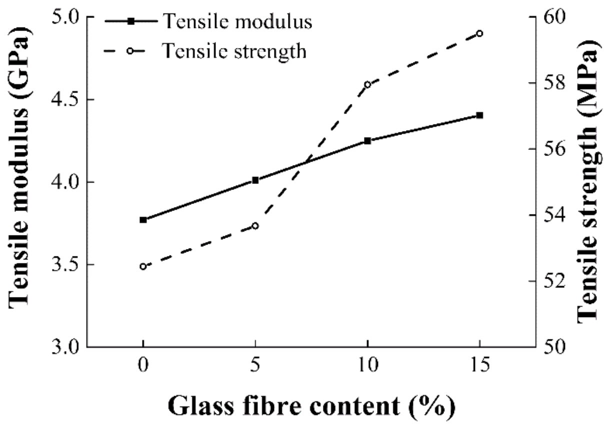

Figure 4: Tensile modulus and strength of short hemp/glass fibre reinforced hybrid PP composites

3.1.5 Jute/Glass Hybrid Composites

Abdullah Al et al. [41] prepared jute fibre (Hessian cloth) and E glass fibre (mat) reinforced unsaturated polyester (USP) composites. It was found that the mechanical properties increased when jute fibre was partially replaced by glass fibre, and the hybrid composite with a jute to glass ratio of 1:3 demonstrated improved mechanical properties over untreated jute composite. It was also shown that UV radiation treatment could further improve the properties. Ahmed et al. [42] experimentally evaluated the effect of hybridization on mechanical properties of untreated (as received) woven jute and glass fabric reinforced isothalic polyester composites. The tensile, flexural, and interlaminar shear strengths (ILSS) are shown in Figure 5, from which it is seen significant improvement in the mechanical properties were found after the inclusion of glass fibres. Addition of 16.5 wt% glass fibre, in a total fibre weight fraction of 42% enhances the tensile, flexural, and ILSS by 37%, 31.23% and 17.6% respectively. It was also shown the jute/glass hybrid composites offered better resistance to water absorption. Ahmed et al. [70] also analytically and experimentally investigated the elastic properties and notch sensitivity of untreated woven jute and jute/glass fabric reinforced polyester hybrid composites. It was shown that the jute composites had higher notch sensitivity than the jute/glass hybrid composites. In addition, Ahmed and Vijayarangan [43] studied the tensile, flexural and interlaminar shear properties of woven jute and jute/glass fabric reinforced polyester composites.

The results indicated that the properties of the jute composites could be considerably improved by incorporation of glass fibre in the two outermost plies. Zamri et al. [71] studied the water absorption of pultruded jute/glass fibre reinforced unsaturated polyester hybrid composites and their effects on the mechanical properties. The flexural and compression properties were found to decrease with an increasing percentage of water uptakes.

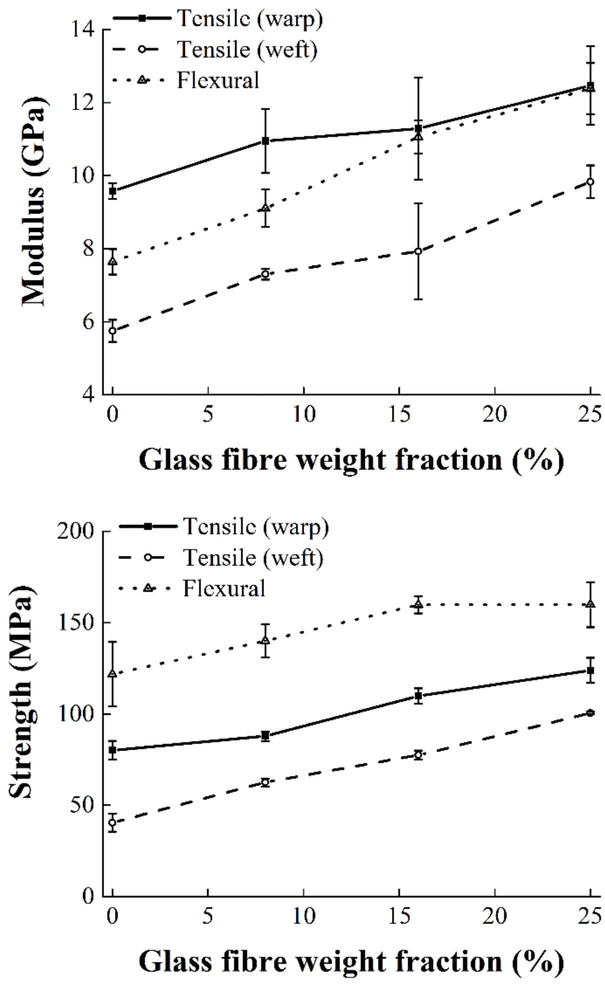

Figure 5: Moduli and strengths of untreated woven jute and glass fabric reinforced isothalic polyester composites

3.1.6 Kapok/Glass Hybrid Composites

Venkata Reddy et al. [44] investigated the tensile strength, tensile modulus and hardness of axially-oriented well-mixed kapok/glass polyester hybrid composites. It was observed that the tensile and hardness properties were enhanced with increased glass fibre content and total fibre content in the hybrid composite. Venkata Reddy et al. [58] investigated the flexural, compressive, and interlaminar shear resistance properties of kapok/glass polyester hybrid composites with and without alkali treatment of fabrics. It was observed that these properties increased with the glass fabric content in the composite. The tensile modulus and strength are shown in Figure 6, from which it is seen both the tensile modulus and strength increased with the volume content of glass fibres, and fibre treatment enhanced the tensile properties.

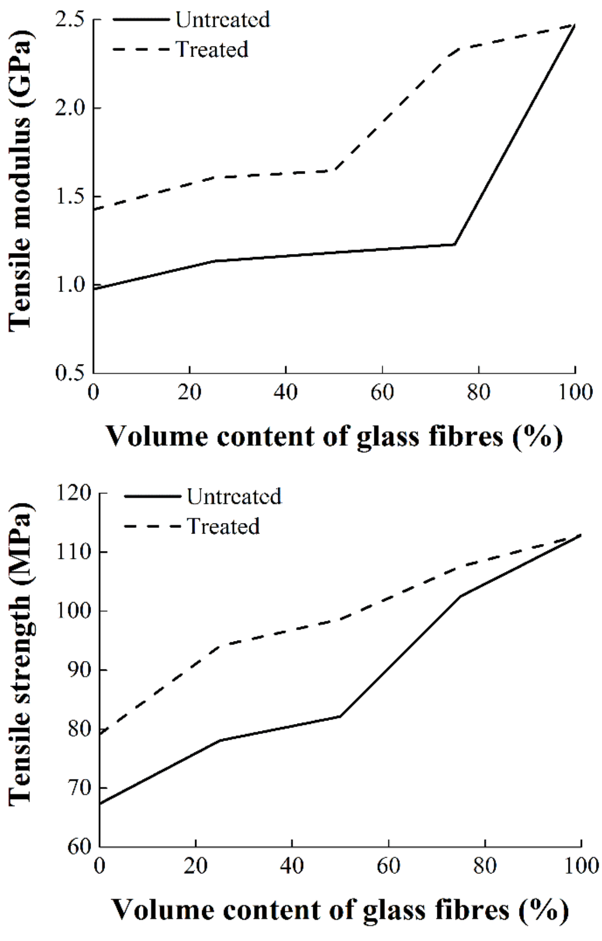

Figure 6: Tensile modulus and strength of untreated and treated kapok/glass hybrid composites

3.1.7 Kenaf/Glass Hybrid Composites

Atiqah et al. [45] developed kenaf/glass reinforced unsaturated polyester (UPE) hybrid composites for structural applications. The highest flexural, tensile and impact strength were obtained when the hybrid composite contained 15% volume fraction treated kenaf fibres and 15% volume fraction glass fibres. Davoodi et al. [46] studied hybrid kenaf/glass reinforced epoxy composites for a passenger car bumper beam. Compared to the glass mat thermoplastic, the hybrid composite showed some similar mechanical properties such as tensile strength, Young's modulus, flexural strength and flexural modulus, but lower impact strength. The results showed the potential for utilization of hybrid natural fibres in some car structural components such as bumper beams.

3.1.8 Oil Palm/Glass Hybrid Composites

Sreekala et al. [47] studied oil palm and glass fibre reinforced phenol formaldehyde hybrid composites. The tensile and flexural behaviours showed considerable enhancement by the incorporation of small volume fractions of glass fibre. On the other hand, the presence of OPEFB fibre enhanced the impact strength of the composites. Hariharan and Abdul Khalil [48] studied the tensile and impact behaviours of the oil palm fibre/glass fibre hybrid bilayer laminate composites. The tensile and impact strengths are shown in Figure 7, from which it is seen both the tensile and impact properties are improved with the addition of glass fibres. The hybrid composites which were impacted at the glass fibre layer exhibited a higher impact strength and a positive hybrid effect compared to those impacted at the oil palm fibre layer. Abdul Khalil et al. [49] evaluated the combination of oil palm and glass as the reinforcing fibres in polyester composites. The tensile and flexural strengths are shown in Figure 8, from which it is seen the hybrid composites exhibit improved properties compared to the EFB/polyester composites. Abdul Khalil et al. [50] investigated the mechanical properties of vinyl ester composites reinforced with oil palm of empty fruit bunch fibres (EFB) and glass fibres (CSM) laminated at different layer arrangements. The mechanical properties and water resistance showed improvement. While comparing the layers of orientation of hybrid composites, the composites with glass fibre at the outer layer showed higher tensile and flexural properties than others. The composites with natural fibres at the outer layer showed the highest impact properties. Overall, the hybrid composites exhibited comparable properties as compared to the glass fibre composites.

Idicula et al. [72] studied the thermophysical properties of short randomly oriented intimately mixed PALF/glass fibre reinforced hybrid polyester composites. It was shown that the incorporation of the PALF/glass fibre increased the effective thermal conductivity of the composite, and chemical treatment of the fibres further increased the thermal conductivity. Hybridisation of natural fibres with glass fibres significantly improved the heat transport ability of the composites. Mishra et al. [51] studied the mechanical properties of PALF/glass fibre reinforced polyester composites. It was found that the tensile, flexural and impact properties of PALF reinforced polyester composites were improved by incorporating small amount of glass fibres, showing positive hybrid effect. The water uptake of the hybrid composites was less than that of the unhybridized composites.

Velmurugan and Manikandan [52] studied the tensile, impact, shear and bending properties of palmyra/glass fibre reinforced rooflite hybrid composites. Two types of specimens were prepared, one by mixing the palmyra and glass fibre and the other by sandwiching palmyra fibre between the glass fibre mats. It was found the mechanical properties of the composites were improved due to the addition of glass fibre along with palmyra fibre in the matrix. The glass fibre skin-palmyra fibre core construction exhibited better mechanical properties than the dispersed construction. Addition of glass fibre with palmyra fibre in the matrix reduced the moisture absorption of the composites.

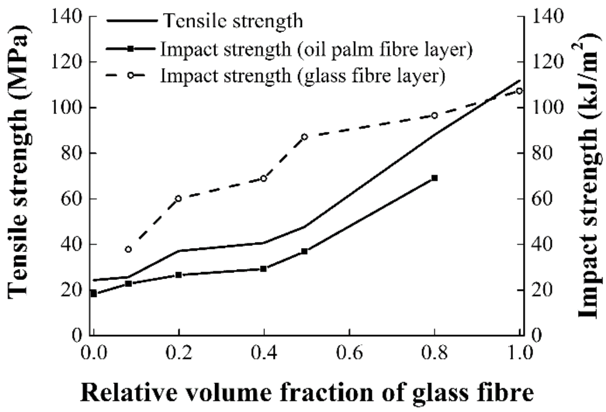

Figure 7: Tensile and impact strengths of oil palm/glass bilayer hybrid composites

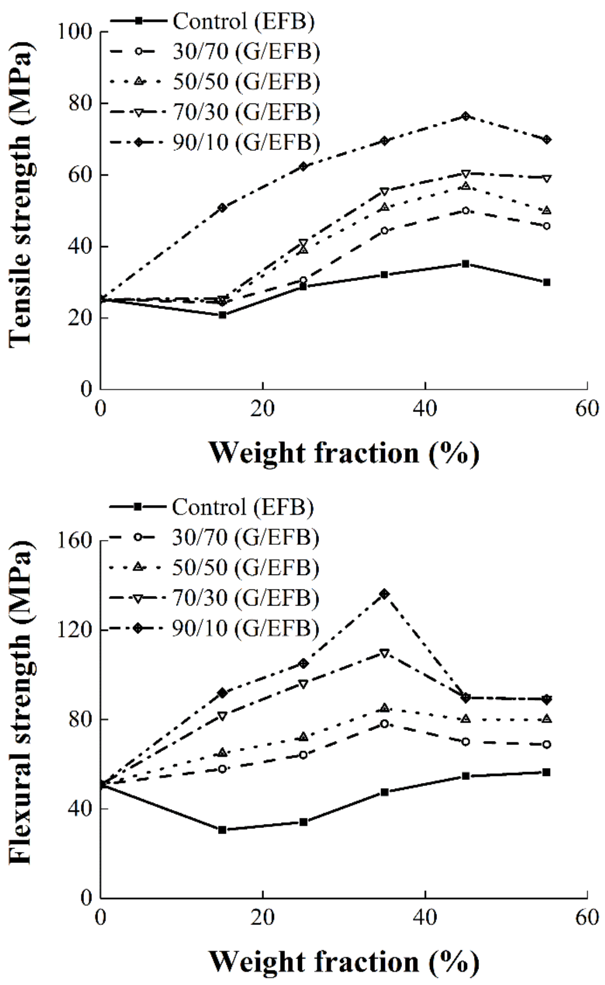

Figure 8: Tensile and flexural strengths of oil palm/glass hybrid polyester composites

3.1.9 Silk/Glass Hybrid Composites

Padma Priya and Rai [73] experimentally investigated the silk/glass fabric reinforced epoxy hybrid composites. It was shown that the addition of a relatively small amount of glass fabric to the silk fabric reinforced epoxy matrix enhanced the mechanical properties of the resulting hybrid composites. The properties increased with the weight fraction of reinforcement, and the water uptake of hybrid composites was less than that of unhybridized composites.

3.1.10 Sisal/Glass Hybrid Composites

Ashok Kumar et al. [76] studied the hardness, impact strength, frictional coefficient, and chemical resistance of sisal and glass fibre epoxy hybrid composites with and without alkali treatments. Amico et al. [77] studied the mechanical properties of pure sisal, pure glass, and hybrid sisal/glass polyester composites. It was shown that hybridization originated a material with general intermediate properties between pure glass and pure sisal. John and Naidu studied the variations of tensile [53], impact and compressive [61] strengths of unsaturated polyester based sisal/glass hybrid composites with fibre loading. It was observed that the tensile strength was improved with increased glass fibre content and the total fibre content in the hybrid composite [53]. The impact strength was improved with increased glass fibre content and the total fibre content in the hybrid composite. On the contrary, the compressive strength of the composite decreased with the total fibre content and also showed a lower strength than the matrix. However, a linear increase in the compressive strength was observed with increased glass fibre content in the composite [61]. In a later study, John and Naidu [78] studied the chemical resistance of the unsaturated polyester based sisal/glass hybrid composites. It was observed that the developed hybrid composites were resistant to all the tested chemicals except carbon tetrachloride. Mishra et al. [51] studied the mechanical properties of sisal/glass fibre reinforced polyester composites. It was found that the tensile, flexural and impact properties of sisal reinforced polyester composites were improved by incorporating small amount of glass fibres. The water uptake of the hybrid composites was less than that of the unhybridized composites.

Jarukumjorn and Suppakarn [54] studied the effect of glass fibre hybridization on the physical properties of sisal PP composites. It was shown that incorporating glass fibre into the sisal PP composites enhanced tensile, flexural, and impact strength without having significant effect on tensile and flexural moduli. In addition, adding glass fibre improved thermal properties and water resistance of the composites. Kalaprasad et al. [55] examined the influence of the relative composition of short sisal/glass fibres, their length and distribution on the tensile properties of short sisal/glass intimately mixed polyethylene composites (SGRP). Chemical surface modifications such as alkali, acetic anhydride, stearic acid, permanganate, maleic anhydride, silane and peroxides given to the fibres and matrix were found to be successful in improving the interfacial adhesion and compatibility between the fibre and matrix. Kalaprasad et al. [79] also evaluated the thermal conductivity and thermal diffusivity of sisal-reinforced polyethylene (SRP), glass-reinforced polyethylene (GRP) and sisal/glass hybrid fibre-reinforced polyethylene (GSRP) at cryogenic to high temperatures (120-350 K). The thermal conductivity increased with temperature and levelled off afterwards. Hybridisation of sisal with glass fibres increased the thermal conductivity of SRP. The variation of thermal diffusivity was just opposite to that of thermal conductivity. With increased temperature, an exponential decrease was obtained for thermal diffusivity.

3.1.11 Other Hybrid Composites

AlMaadeed et al. [56] developed recycled PP (RPP) based hybrid composites of date palm wood flour/glass fibre. Recycled PP properties were improved by reinforcing it by wood flour. The tensile strength and Young’s modulus of wood flour reinforced RPP increased further by adding glass fibre. Jiang et al. [64] studied the mechanical properties of wood flour/glass fibre poly(vinyl chloride) hybrid composites, and found the impact strength could be increased significantly without losing flexural properties by adding long glass fibres and over 40% of PVC. Valente et al. [59] made hybrid thermoplastic composites from wood flour and recycled glass fibres. Two thermoplastic polymers were used as matrix materials, namely low density polyethylene (LDPE) and PP. The flexural modulus and hardness were found to increase as a function of increasing wood flour and glass fibre content, whilst the flexural strength decreased as a function of increasing wood flour content, even though a positive effect of the addition of glass fibres was found.

Almeida Júnior et al. [65] carried out thermal, mechanical and dynamic mechanical analyses of intralaminate curaua/glass polyester hybrid composites. It was concluded that hybridization was successful and the hybrid composite with 30% of glass fibres replaced by curaua fibres showed similar properties compared to the pure glass fibre composite. Silva et al. [66] studied the effect of water aging on the mechanical properties of curaua/glass polyester hybrid composites. It was found that the water absorption was reduced with the incorporation of glass fibres, and both the tensile modulus and strength decreased due to water absorption.

In addition to glass fibres, natural fibres were also hybridised with carbon [69, 75, 81] and aramid [74] fibres to make hybrid composites. Patel et al. [69] investigated jute/carbon epoxy and phenolic hybrid composites. It was found that the mechanical and electrical properties were improved upon alkali treatment and acrylation of jute fibres. Noorunnisa Khanam et al. [75] studied the variation of mechanical properties such as tensile and flexural properties of randomly oriented unsaturated polyester based sisal/carbon fibre reinforced hybrid composites with different fibre weight ratios. Both the tensile and flexural properties of the sisal/carbon hybrid composites increased with the carbon fibre loading. Significant improvement in the tensile and flexural properties was observed by alkali treatment. The chemical resistance test results showed that both the untreated and alkali treated hybrid composites were resistant to all chemicals except carbon tetra chloride. Le Guen et al. [81] found the damping coefficient of flax/carbon fibre hybrid composites was 4 times higher than that of the carbon fibre composites, but the elastic modulus and strength were lower. Ashworth et al. [82]

found there was a significant increase in damping for the jute fibre reinforced composites and jute/carbon fibre reinforced hybrid composites versus the carbon fibre reinforced composites. The flexural modulus of the hybrid composites was significantly greater than the jute fibre reinforced composites and approaching the carbon fibre reinforced composites.

Zhong et al. [74] adopted surface microfibrillation of cellulose fibre for improving cellulose fibre/phenolic resin interfacial adhesion in hybrid composites composed of sisal fibre and aramid fibre. Development of microfibrils and aggregates on the fibre surface significantly increased the interfacial adhesion between the sisal fibre and resin by providing a large contact area and by inhibiting the formation of spontaneous cracks in the composites. Consequently, the compression, tensile and internal bonding strengths, and wear resistance of the hybrid composites were remarkably improved.

3.2 Natural/Natural Fibre Hybrid Composites

The studies on natural/natural fibre hybrid composites were mainly on their tensile [83-99], flexural [83, 84, 86, 88-92, 94, 95, 98-102], compressive properties [90, 91], impact strength [83, 84, 87-89, 98, 100-102], thermal stability [83, 84, 103] and water resistance [84, 86, 103]. These studies are summarised in Table 4.

Table 4: Studies on natural/natural fibre hybrid composites

Authors	Fibre 1	Fibre 2	Matrix	Properties
Srinivasan et al. [83]	banana	flax	epoxy	Mechanical, thermal
Boopalan et al. [84]	banana	jute	epoxy	Tensile, flexural, impact
Venkateshwaran et al. [85, 86]	banana	sisal	epoxy	Mechanical, water absorption
Alavudeen et al. [87]	banana	kenaf	polyester	Tensile, flexural, impact
Idicula et al. [72, 88, 89]	banana	sisal	polyester	Tensile, flexural, impact, thermophysical
Senthil Kumar et al. [99]	banana	coconut sheath	polyester	Tensile, flexural
Noorunnisa Khanam et al. [90]	coir	silk	polyester	Tensile, flexural, compressive
Adekunle et al. [100]	flax	Lyocell	AESO	Flexural, impact
Mirbagheri et al. [93]	kenaf	wood flour	polypropylene	Tensile
Tajvidi [94]	kenaf	wood flour	polypropylene	Tensile, flexural
Jawaid et al. [95, 96, 101-103]	oil palm EFB	jute	epoxy	Tensile, flexural, impact, water resistance
Paiva Júnior et al. [97]	ramie	cotton	polyester	Tensile
Ramesh et al. [104, 105]	sisal	jute	polyester	Tensile, flexural, impact
Athijayamani et al. [98]	sisal	roselle	polyester	Tensile, flexural, impact
Noorunnisa Khanam et al. [91]	sisal	silk	polyester	Tensile, flexural, compressive
Raghu et al. [106]	sisal	silk	polyester	Chemical resistance

Banana fibre has received widespread interest in the development of natural/natural fibre hybrid composites. Srinivasan et al. [83] evaluated the mechanical and thermal properties of banana/flax based natural fibre epoxy composites. The flexural strength is shown in Figure 9, from which it is seen the flexural strength of banana/flax hybrid composite (F+B+GFRP) is higher than that of either the flax fibre composite (F+GFRP) or banana fibre composite (B+GFRP). Boopalan et al. [84] studied the mechanical and thermal properties of raw jute and banana fibre reinforced epoxy hybrid composites. Jute fibre was hybridized with banana fibre to improve the mechanical properties. As shown in Table 5, the addition of banana fibre in the composites resulted in 17% increase in tensile strength, 4.3% increase in flexural strength and 35.5% increase in impact strength.

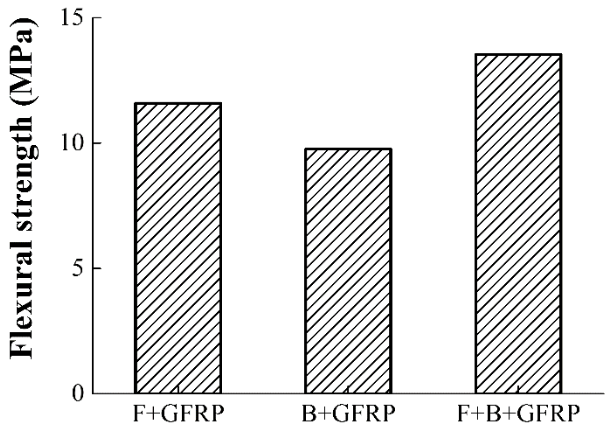

Figure 9: Flexural strength of banana/flax hybrid epoxy composites

Table 5: Mechanical properties of jute/banana fibre hybrid composites

Weight ratio of jute/banana	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)	Impact strength (kJ/m^2)
100/0	16.62	0.664	57.22	8.956	13.44
75/25	17.89	0.682	58.60	9.065	15.81
50/50	18.96	0.724	59.84	9.170	18.23
25/75	18.25	0.720	59.30	9.056	17.89
0/100	17.92	0.718	58.06	9.048	16.92

Venkateshwaran et al. studied the tensile modulus and strength [85] and the mechanical and water absorption behaviour [86] of short, randomly oriented banana/sisal fibre reinforced epoxy hybrid composites. The tensile modulus and strength are shown in Figure 10. Conversely, it was shown that addition of sisal fibre in banana/epoxy composites of up to 50% by weight resulted in increased mechanical properties and decreased moisture absorption property.

Alavudeen et al. [87] studied the mechanical properties of woven banana fibre, kenaf fibre and banana/kenaf fibre polyester hybrid composites. It was shown from Figure 11 that the tensile, flexural and impact strengths of the woven banana/kenaf fibre hybrid composite were superior to those of the individual fibres.

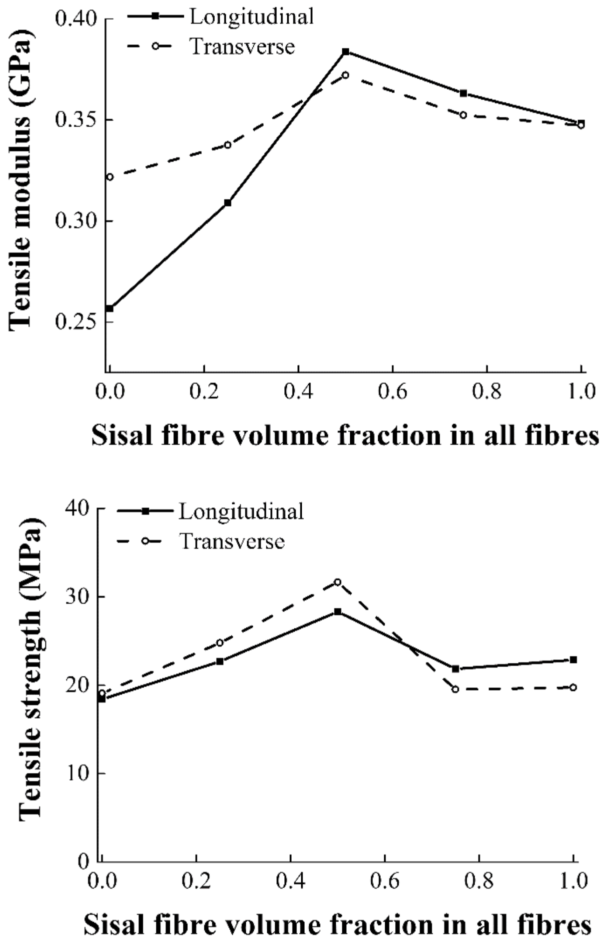

Figure 10: Tensile modulus and strength of banana/sisal hybrid epoxy composites

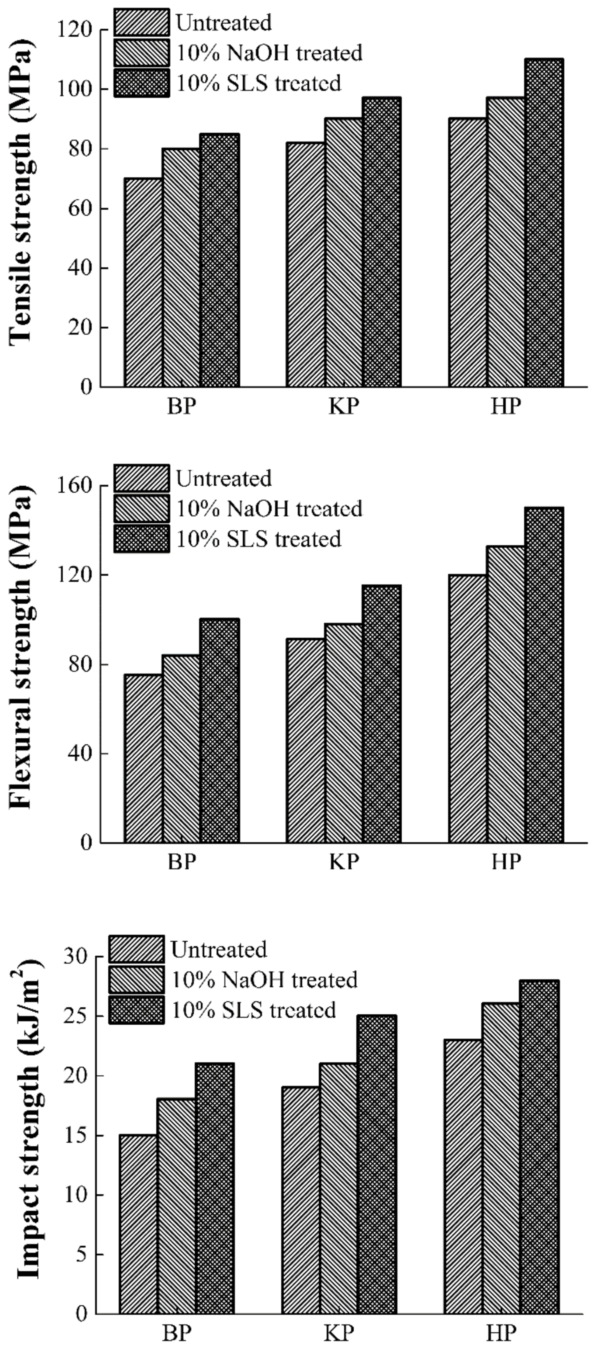

Figure 11: Tensile, flexural and impact strengths of BP (woven banana), KP (kenaf) and HP (banana/kenaf) hybrid polyester composites

Idicula et al. studied the dynamic and static mechanical properties [88, 89] and the thermophysical properties [72] of randomly oriented intimately mixed short banana/sisal fibre reinforced polyester hybrid composites. It was shown that the incorporation of the banana/sisal fibre decreased the effective thermal conductivity of the composite, and chemical treatment of the fibres increased the thermal conductivity. The tensile properties were slightly greater in the trilayer composite with banana as the skin material. The bilayer composites showed higher flexural and impact properties [89]. Senthil Kumar et al. [99] studied short banana and woven coconut sheath fibre hybrid polyester composites. It was shown that the hybrid layup with higher relative content of banana fibre yielded higher tensile and flexural strength in both conditions. Alkali treatment showed a positive effect on the evaluated properties.

Noorunnisa Khanam et al. [90] investigated coir/silk unsaturated polyester-based hybrid composites with different fibre lengths. Coir fibres were treated with NaOH and significant improvement in tensile, flexural, and compressive strengths of the coir/silk hybrid composites was observed by these treatments. Similar results were found for the sisal/silk unsaturated polyester based hybrid composites [91]. Raghu et al. [106] studied the chemical resistance of silk/sisal fibre-reinforced unsaturated polyester-based hybrid composites, and showed that the silk/sisal hybrid composites were strongly resistant to almost all chemicals except carbon tetrachloride.

Adekunle et al. [100] studied the impact and flexural properties of flax fabrics and Lyocell fibre reinforced bio-based thermoset composites. The hybrid composites were made by sandwiching plies of the carded Lyocell fibre mat in between the flax fabrics. It was shown that the flexural properties increased with the outer ply thickness but also depended on the weave architecture of the reinforcement. The hybridization with Lyocell fibre had a great impact on the water absorption properties of the composites, because water uptake reduced drastically when compared to other composites. Adekunle et al. [92] studied woven and non-woven flax fibre reinforced renewable thermoset resins derived from soybean oil. A tensile strength of about 119 MPa and Young's modulus of about 14 GPa were achieved, with flexural strength and modulus of about 201 MPa and 24 GPa, respectively. When one ply of a glass fibre mat was sandwiched in the mid-plane, the tensile strength considerably increased to 168 MPa.

Mirbagheri et al. [93] investigated the tensile properties of wood flour/kenaf fibre PP hybrid composites. As shown in Table 6, the tensile modulus increased with the content of kenaf fibres. Tajvidi [94] studied a natural fibre hybrid composite containing equal proportions of kenaf fibres (KFs) and wood flour (WF) as the reinforcements and PP as the polymer matrix. The hybrid composite exhibited tensile and flexural moduli and strength values closer to those of the KF composite, which indicated a higher reinforcing efficiency of KFs compared with WF.

Table 6: Tensile modulus of kenaf/wood flour hybrid PP composites

Kenaf fibre weight content (%)	Wood flour weight content (%)	Tensile strength (MPa)	Tensile modulus (GPa)
0	40	41.54	2.671
10	30	40.26	2.771
20	20	40.51	2.891
35	10	43.33	3.008
40	0	46.03	3.229

Jawaid et al. [101] studied the flexural and impact properties of oil palm empty fruit bunches (EFB)/jute fibre reinforced epoxy hybrid composites with different stacking sequences such as EFB/jute/EFB and jute/EFB/jute. It was shown that compared to the pure EFB composite, the hybrid composite had higher flexural properties but much lower impact strength. In another study [102], it was found that the tensile properties were slightly higher for the composite having jute as skin and oil palm EFB as core material. Jawaid et al. [103] investigated the effect of jute fibre hybridization and different layering pattern on the physical properties of EFB epoxy composites. It was found that hybrid composites were more water resistant and dimensional stable compare to the pure EFB composite. This was attributed to the more hydrophilic nature of the EFB composite. Hybridization of the EFB composite with jute fibres could improve the dimensional stability and density.

Jawaid et al. [95] also studied the tensile and flexural performance of tri layer EFB/woven jute fibre reinforced epoxy hybrid composites. It was shown that the tensile and flexural properties of the pure

EFB composite were improved by hybridization with woven jute fibre mats. It was also observed that the tensile and flexural properties of the pure woven jute composite are the highest compared to all other composites, as shown in Figure 12. In a later study, Jawaid et al. [96] studied the effect of jute fibre loading on tensile and dynamic mechanical properties of bi-layer EFB/jute epoxy hybrid composites. The tensile properties of the hybrid composites were found to increase substantially with increasing jute fibres loading as compared to the EFB/epoxy composite. Addition of jute fibres increased the storage modulus while the damping factor shifted towards higher temperature region. The hybrid composite with EFB/jute ratio 1:4 showed maximum damping behaviour and highest tensile properties. The overall use of hybrid system was found to be effective in increasing tensile and dynamic mechanical properties of the EFB/epoxy composite probably due to the enhanced fibre/matrix interface bonding. In summary, it is shown from [95, 96, 101-103] that jute fibre is stronger than EFB and thus improved properties are found by replacing EFB by jute.

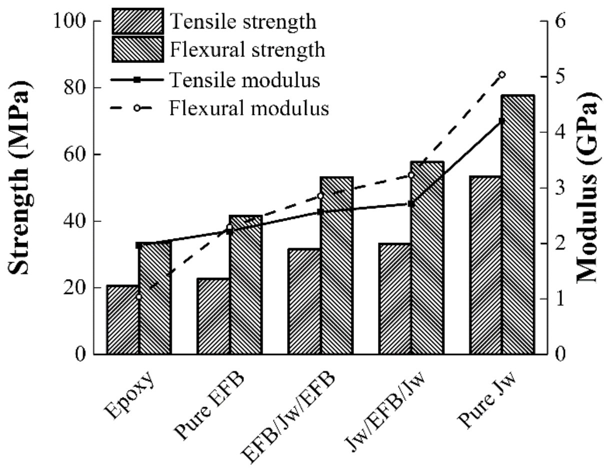

Figure 12: Moduli and strengths of EFB and woven jute reinforced hybrid epoxy composites

Paiva Júnior et al. [97] developed plain weave hybrid ramie/cotton fabric reinforced polyester composites. The results obtained showed that the main parameter governing the tensile properties of the composites was the ramie volume fraction parallel to the direction of the tensile axis.

Athijayamani et al. [98] studied the variation of mechanical properties such as tensile, flexural, and impact strengths of roselle and sisal fibre hybrid polyester composites at dry and wet conditions. It was found that exposure to moisture caused a significant drop in the mechanical properties due to the degradation of the fibre-matrix interface.

3.3 Multiple Type Hybrid Composites

A number of studies addressed the hybrid composites reinforced by more than two types of reinforcement. Petrucci et al. [107] studied various basalt, glass, flax and hemp fibre epoxy hybrid composite laminates subjected to tensile, three-point flexural and interlaminar shear strength tests. The mechanical performance of all the hybrid laminates appeared superior to pure hemp and flax fibre reinforced laminates and inferior to basalt fibre laminates. Among the hybrids, the best properties were offered by those obtained by adding glass and flax to basalt fibre reinforced laminates.

Ramesh et al. [104, 105] studied the mechanical properties such as tensile strength, flexural strength and impact strength of sisal/jute/glass fibre reinforced polyester composites. The results indicated that the incorporation of sisal/jute fibre with GFRP could improve the properties and the hybrid composite could be a substitute for GFRP.

Sain et al. [108] studied the mechanical properties of PP composites with various natural fibres such as old newsprint, kraft pulp and hemp. It was shown that the hybrid composite produced using 10 wt% of glass fibres and 30 wt% of hemp fibre showed only a marginal improvement in the mechanical properties.

Li and Sain [109] used pulp fibres, including bleached Kraft pulp (BKP) and thermomechanical pulp (TMP), hemp, flax, and wood flour for reinforcing PP. They concluded TMP was more effective in reinforcing than BKP. 40% TMP and 10% glass fibre reinforced PP had a tensile strength of 70 MPa and a specific tensile strength comparable to glass fibre reinforced PP.

3.4 Multi Scale Hybrid Composites

Okubo et al. [110] developed novel hybrid biocomposites based upon a biodegradable poly(lactic acid) (PLA) matrix reinforced with microfibrillated cellulose (MFC) and bamboo fibre bundles. Due to the relative difference in scale between microfibrillated cellulose and bamboo, a hierarchy of reinforcement was created where bamboo fibre bundles played the primary load-carrying role while cellulose served an interphase in the polymer matrix around the bamboo fibre to prevent sudden crack growth. As shown in Figure 13, it was found that by adding just 1 wt% of MFC with a high degree of dispersion an increase in fracture energy of nearly 200% was obtained.

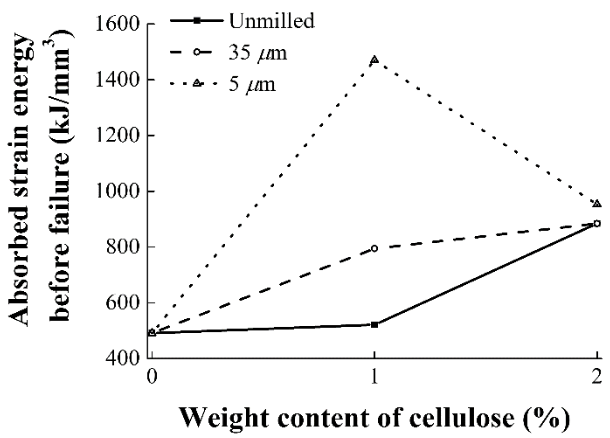

Figure 13: Axial strain energy of bamboo fibre reinforced PLA with microfibrillated cellulose at different processing conditions: unmilled, 35 μm gap calendaring and 5 μm gap calendaring

Majeed et al. [111] explained about different categories of nanoclay and natural fibre based composite with particular regard to its applications as packaging materials and also gave an overview of the most recent advances and emerging new aspects of nanotechnology for development of hybrid composites for environmentally compatible food packaging materials. Haq et al. [112] developed hybrid bio-based composites from blends of unsaturated polyester and soybean oil reinforced with nanoclay and natural fibres. It was shown that a proper stiffness/toughness balance could be obtained by controlling the amount of bio-resin and nanoclay content. Moreover, the multiphase hybrid biocomposites had multifunctional attributes, such as improved barrier and thermal properties.

3.5 Hybrid Effect

A number of studies have clearly reported the existence of hybrid effects. Raghavendra Rao et al. [57] showed the existence of positive hybrid effects for the flexural properties of bamboo/glass fibre reinforced epoxy hybrid composites. Sreekala et al. [47] reported a negative hybrid effect on the tensile strength and tensile modulus at very low and higher OPEFB fibre compositions, and a positive hybrid effect on the elongation property for oil palm and glass fibre reinforced phenol formaldehyde hybrid composites. Hariharan and Abdul Khalil [48] also reported a negative hybrid effect for the tensile strength and Young's modulus and a positive hybrid effect for the elongation at break. Mishra et al. [51] showed positive hybrid effect for the mechanical properties of PALF/glass fibre reinforced polyester composites. Ahmed et al. [70] suggested that the rule of hybrid mixture could be conveniently used for predicting the elastic properties of bidirectional [0/90] jute and glass fabric reinforced hybrid composites, which implied no hybrid effects existed. The tensile strength, tensile modulus, flexural strength, and flexural modulus showed a positive hybrid effect for the randomly oriented intimately mixed short banana/sisal fibre reinforced polyester hybrid composites [88, 89].

4 Processing

4.1 Thermoplastic Composites

Two techniques: injection moulding and compression moulding were employed to make thermoplastic composites.

4.1.1 Injection Moulding

Nayak et al. [30] and Samal et al. [31] prepared short bamboo/glass fibre PP hybrid composites using an intermeshing counter rotating twin screw extruder followed by injection moulding. Injection moulding was employed to make flax fibre bundle PP composites and flax fibre bundle/glass PP hybrid composites [68], short hemp/glass fibre reinforced hybrid PP composites [39, 40], sisal/glass PP composites [54], RPP based hybrid composites of date palm wood flour/glass fibre [56], wood flour/kenaf fibre PP hybrid composites [93, 94] and PP composites with various natural fibres such as old newsprint, kraft pulp and hemp [108].

4.1.2 Compression Moulding

Compression moulding was employed to make short bamboo fibre reinforced PP composites (BFRP) and short bamboo/glass fibre reinforced PP hybrid composite (BGRP) [32], short banana/glass fibre PP hybrid composites [34, 35], short sisal/glass intimately mixed polyethylene (PE) composites [55, 79] and wood flour/glass fibre poly(vinyl chloride) hybrid composites [64]. Valente et al. [59] made hybrid thermoplastic composites from wood flour and recycled glass fibres through a two-step process involving a kinetic mixer and a compression moulding machine. Haneefa et al. [36] prepared short banana/glass hybrid fibre reinforced PS composites by a combination of injection moulding and compression moulding.

4.2 Thermoset Composites

4.2.1 Hand Layup

Hand layup is a simple technique which has been employed to make thermoset composites. Because of its simplicity, hand layup has been widely used for making hybrid E glass/flax/epoxy composites [67], silk/glass fabric reinforced epoxy hybrid composites [73], banana/flax based natural fibre epoxy composites [83], curaua/glass polyester hybrid composites [66], jute fibre (Hessian cloth) and E glass fibre (mat) reinforced unsaturated polyester (USP) composites [41], untreated (as received) woven jute and glass fabric reinforced isothalic polyester composites [42, 43, 70], unsaturated polyester based sisal/glass hybrid composites [53, 61], woven banana fibre, kenaf fibre and banana/kenaf fibre polyester hybrid composites [87], silk/sisal fibre reinforced unsaturated polyester based hybrid composites [106], and sisal/jute/glass fibre reinforced polyester composites [104, 105].

4.2.2 Compression Moulding

Another widely employed processing method is compression moulding, which has been used for making unidirectional flax/glass fibre reinforced phenolic hybrid composites [38], intralaminate curaua/glass polyester hybrid composites [65], sisal/glass polyester hybrid composites [77], raw jute/banana fibre reinforced epoxy hybrid composites [84], short, randomly oriented banana/sisal fibre reinforced epoxy hybrid composites [85, 86], flax fabrics and Lyocell fibre reinforced bio-based thermoset composites [100], woven and non-woven flax fibre reinforced renewable thermoset resins derived from soybean oil [92], plain weave hybrid ramie/cotton fabric reinforced polyester composites [97], and roselle/sisal fibre hybrid polyester composites [98].

Compression moulding may be combined with the hand layup method. Sreekala et al. [47] adopted hand layup followed by compression moulding for making oil palm and glass fibre reinforced phenol formaldehyde hybrid composites. A combination of hand layup method, followed by compression moulding, was used in the fabrication of the hemp/glass fibre reinforced polyester hybrid biocomposites by Shahzad [63]. Noorunnisa Khanam et al. [75] prepared randomly oriented unsaturated polyester based sisal/carbon fibre reinforced hybrid composites by hand layup and compression moulding. Idicula et al. [72, 88, 89] prepared randomly oriented intimately mixed short banana/sisal fibre reinforced polyester hybrid composites by hand layup followed by compression moulding. Noorunnisa Khanam et al. prepared coir/silk [90] and sisal/silk [91] unsaturated polyester based hybrid composites by hand layup and compression moulding.

4.2.3 Casting Method

Venkata Subba Reddy et al. [33] prepared glass/bamboo fibre reinforced polyester composites by the casting method. Pothan et al. [37] prepared banana/glass fibre reinforced hybrid polyester composites by the casting method. Venkata Reddy et al. [44, 58] made the kapok/glass polyester hybrid composites by the casting method. Velmurugan and Manikandan [52] prepared the palmyra/glass fibre reinforced rooflite hybrid composites by the casting method. Raghavendra Rao [57] prepared bamboo/glass fibre reinforced epoxy hybrid composites by the casting method. Ashok Kumar et al. [76] prepared sisal and glass fibre epoxy hybrid composites by the casting method.

4.2.4 Resin Transfer Moulding

Abdul Khalil et al. made the oil palm fibre and glass fibre reinforced polyester hybrid composites [49] and vinyl ester hybrid composites [50] by resin transfer moulding (RTM). It was shown that RTM could be a suitable processing technique for natural fibre composites when high quality laminates were preferred [113]. Idicula et al. [114] compared compression moulding and RTM for making natural fibre hybrid composites and showed that resin transfer moulded composites had enhanced static and dynamic mechanical properties, compared with the compression moulded ones.

4.2.5 Other Manufacturing Methods

In addition to the aforementioned processing methods, the resin impregnation method was employed to make oil palm fibre-glass fibre hybrid bilayer laminate epoxy composites [48] and EFB/jute fibre reinforced epoxy hybrid composites[95, 96, 101-103] Petrucci et al. [107] prepared various basalt, glass, flax and hemp fibre epoxy hybrid composite laminates by the vacuum infusion process. The hot press process was used for preparing jute/carbon epoxy and phenolic hybrid composites [69], sisal/aramid fibre phenolic resin hybrid composites [74] and PALF/glass and sisal/glass fibre reinforced polyester composites [51]. Atiqah et al. [45] made kenaf/glass reinforced unsaturated polyester (UPE) hybrid composites for structural applications by SMC. Davoodi et al. [46] made hybrid kenaf/glass reinforced epoxy composites for passenger car bumper beam by a modified SMC method. Zamri et al. [71] made the jute/glass fibre reinforced unsaturated polyester hybrid composites by pultrusion.

5 Conclusions and Future Trends

Much research has been seen in the field of natural fibre reinforced hybrid composites. There have been also some applications of natural fibre hybrid composites. Tier I and II automotive suppliers were exploring hybrid glass-natural-fibre systems, as well as applications that exploited such capabilities as natural-fibre sound dampening characteristics [115]. Cicala et al. [116] applied hybrid glass/natural fibre composites to curved pipes and achieved a cost reduction of 20% and a weight saving of 23% compared to the current commercial solution.

It is seen that extensive research in the fields of natural/synthetic and natural/natural hybrid composites has been done. For natural/synthetic hybrid composites, because synthetic fibres have higher stiffness and strength than natural fibres, improved properties are found via hybridisation compared to natural fibre composites. Natural fibre composites in general show inferior properties, which has limited the application of natural fibre reinforced composites. Large variations were seen from the results in the literature, and sometimes controversial results were found. The reason might be the dominant processing technique was hand layup. Future research should focus on better understanding of the interactions between natural fibres and the matrix, improving the processing techniques, and reducing the variations of natural fibres. Because of the inherent higher variabilities, optimal and robust design should also be addressed. In addition, not many studies have addressed the cost of natural fibres [117, 118]. The cost benefits of natural fibre reinforced hybrid composites should be investigated. The functional properties e.g. barrier, thermal and electrical properties of natural fibre reinforced hybrid composites should also be studied.

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