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Review Article

Critical review on advancements on the fiber-reinforced composites: Role of fiber/matrix modification on the performance of the fibrous composites

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ABSTRACT

Nowadays, Fiber-reinforced Polymer Composites (FRPCs) are extensively utilized due to their remarkable properties such as high stiffness, excellent strength to weight ratio, resistance to wear, corrosion etc. Earlier, the FRPCs are prepared through synthetic fibers in order to attain high strength in conjunction with high elastic modulus. However, with the increasing economic and environmental factors regarding the accumulation of plastic waste, the development of natural and hybrid (combination of any two) fibers were started. The mechanical properties of FRPCs are largely determined by the way loads are transferred between the matrix and fibers, or by the strength of the bond between the fiber-

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Fiber-matrix interfaces
Chemical treatment
Nanoparticles
Applications

matrix interfaces. Additionally, these factors play a significant role in determining the overall performance of FRPCs. Therefore, this review discusses the recent advancements in enhancing the interaction between fiber and matrix by means of chemical treatment and the inclusion of nanoparticles. The resulting mechanical performance of the end composites and their intended applications are also presented. Few targeted application areas of FRPCs such as aerospace, automobile, mechanical and biomedical implants were discussed in detail.

1. Introduction

Due to the increasing expansion of the industrial sectors, there is a demand for materials with enhanced characteristics in terms of strength, stiffness, density, reduced cost, and increased sustainability. The composite material serves as one of the materials with such improvement in the properties. Composite materials are typically composed of a matrix phase and a reinforcement phase in form of particles or fibers [1]. FRPCs are composed of a polymer matrix and high-strength fibers, which can be either synthetic, natural, or a combination of both [2]. The FRPCs are extensively used for aerospace, submarines, automotive, structural applications etc. (Fig. 1) [3].

In the last 20 years, investigations into synthetic fiber-reinforced polymer composites (FRPCs) utilizing materials like glass, carbon, or aramid fibers have demonstrated the creation of composites with exceptional strength and stiffness [4]. Several investigations have been carried out to enhance the bond between the interface of the fiber and matrix by modifying their chemical interaction, expanding the load transfer region of fibers, and implementing both methods simultaneously [5]. Although, there has been some worry about the collection of plastic debris in the environment. This issue has therefore driven researchers worldwide to create environmentally friendly materials through cleaner production methods [6,7]. To deal with the thousands of tonnes of composite garbage produced each year several distinct FRPCs recycling procedures, such as mechanical recycling, thermal processes (pyrolysis), solvolysis, have been explored. However, these procedures are not only costly and necessitate harsh decomposition conditions, but they also damage the size, morphology, and surface structure of fibers, lowering their economic value [8].

As a result, incorporating natural fibers into the polymer matrix to develop composites has significantly improved their properties and mitigated the problem of waste accumulation [9,10]. The majority of natural fiber composites consist of plants, minerals, and animals, with jute, hemp, bamboo, pineapple, and leaf fibers being among the most commonly used natural fibers. Natural fiber composites performance is heavily influenced by the length, shape, and interfacial adherence of the fibers to the matrix. These fibers provide excellent mechanical, thermal, and acoustic insulation, as well as the most important property i.e. biodegradability [11]. In terms of FRPC research, mineral-based fibers have not been extensively examined due to the dangers of asbestos to human health, whereas plant-based fibers provide intriguing features like lower cost and biodegradability characteristics. Fibers include the following: bast, grass, reed, core, seed, and

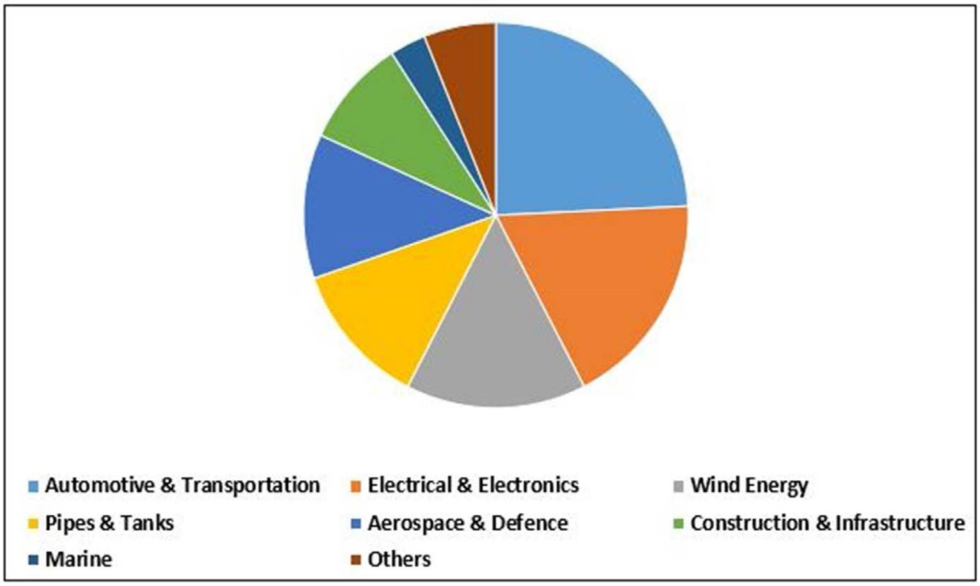

Fig. 1 – Global fiber reinforced PMCs market [3].

all other varieties, which may also include wood and roots [12,13]. Nano-additives like graphene oxide, fly ash, Al2O3, and ZnO have been utilized to enhance the durability and reinforce natural fiber composites, resulting in an increased lifespan [14,15].

Further exploration into the field of fiber reinforced composites has resulted in the development of hybrid composites, which combine natural and synthetic fibers. These hybrid composites are characterized by composite structures that incorporate more than one type of fiber [16]. FRPC composites containing hybrid fibers are capable of withstanding greater loads in multiple directions compared to those reinforced with a single fiber. Moreover, the surrounding matrix is responsible for keeping them in the right place and orientation, which acts as a better medium for transferring loads between them. In the past years, several combinations for hybrid fiber PMCs such as carbon/glass, bamboo/glass, banana/kenaf and jute/glass, etc. were studied [17,18]. The incorporation of such fibers into polymer matrix has led to the enhancement of mechanical performance due to following reasons: (1) when two fibers of the same length and different diameters are combined in a polymer matrix, it has several benefits over using only one fiber in composites. Varying fiber diameters improved the effective bonding area between fibers and the matrix, facilitating even distribution of stress and (2) when the low-elongation fiber breaks first, the high-elongation fiber is able to bear the load, which prevents matrix failure and leads to better stress transmission from the matrix to the fibers, ultimately resulting in improved mechanical properties [19].

Hence, it is crucial to comprehend and investigate various fiber types concerning their characteristics and uses in composite production. In addition, the mechanical performance of these composites can be enhanced by integrating nanoparticles or modifying their chemistry. Consequently, there is an appeal for an updated literature review on the recent advancements in fiber-reinforced composites. This article aims to outline and condense information on fiber-reinforced composite materials, encompassing their practical utilization in industry and forthcoming outlooks.

2. Classification of fiber-reinforced PMCs

FRPCs are made up of short and continuous fibers that are organized in both unidirectional and bidirectional configurations [20]. However, this review limits with the advancements in the field of continuous fibers based FRPCs. Due to stringent environmental regulations, eco-friendly composite materials are being increasingly utilized by industries and researchers these days [21]. Therefore, there are developments of a variety of fibers for composite materials, with natural and synthetic fibers being the most common. Moreover, combining these two fibers together in a polymer matrix to create a hybrid composite leads to exceptional material properties [22]. Fig. 2 represents the broad classification of FRPCs on the basics of fibers classification.

2.1. *Synthetic fiber-reinforced PMCs*

Human-made synthetic fibres are produced by chemical synthesis and are further categorised as organic, or inorganic based on their composition. Because they are substantially stiffer and stronger than polymer matrix, synthetic fibres are used as a load-bearing component in composite structures [23] [–] [26]. Therefore, the use of synthetic fibers as reinforcing elements increases rapidly to produce lightweight materials with improved strength, modulus, and stiffness [27]. The aerospace and automotive industries began using synthetic fibers during the early decades. The Table 1 below lists the typical mechanical characteristics of some common synthetic fibers.

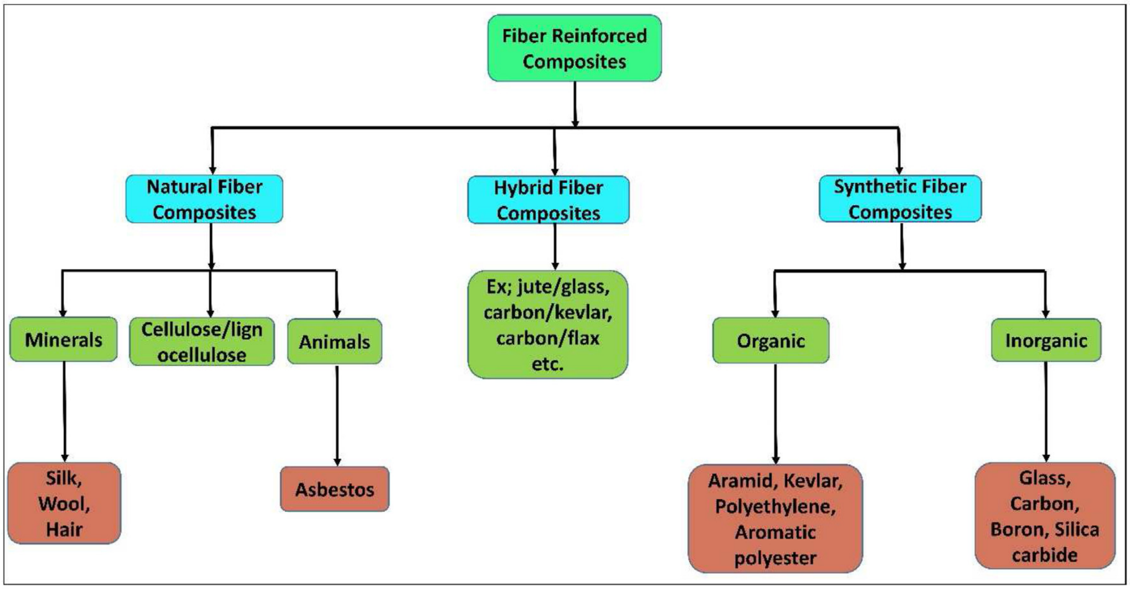

Fig. 2 – Classification of fiber based polymer matrix composites [18].

Table 1 – Typical mechanical properties of synthetic fibers [28–33].

Synthetic fibers	Tensile strength (MPa)	Young's modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)	Elongation at break (%)	Melting point (°C)	Density (gm/cc)	Fiber diameter (mm)
Carbon fiber	3500	228	5200	3.50	1.8	3652	2.267	0.005–0.010
Glass fiber	3445	85	1000	4.82	4.8	1135	2.58	0.0038–0.02
Aramid fiber	3380	67	850	3.23	3.4	500	1.44	0.01–0.02
Basalt fiber	4840	89	750.06	46.75	3.15	1500	2.7	0.01–0.02
Dyneema fiber	3400	115	1563	91	3.5	152	0.975	0.17–0.18
Vectran fiber	3210	72.4	1410	85	3.7	330	1.40	0.12–0.15

Recently researchers developed 2 materials for aerospace structures by incorporating carbon fibers (CFs) with polyether ether ketone and benzoxazine through compression molding and resin transfer molding. Material 1 and material 2 show the tensile strength of about 898.3 and 739.8 MPa respectively this was due to the low pressure inserted during the infusion of epoxy in RTM results in more uniform components and decreased ductility. The results were used for manufacturing the back section of the fuselage of a regional aircraft [34]. The carbon fiber composites are also prepared by using additive manufacturing techniques and tested for their tensile strength and interlaminar shear strength (ILSS). It was found that 0/90° oriented continuous carbon fiber composites retain about 52% and 96% tensile strength in die-punched and unnotched conditions whereas short and continuous carbon fiber composites show 25% lower ILSS in comparison with fully continuous carbon fiber composites (45%) due to increased fracture strength and toughness [35,36]. Recent attempts were made to enhance the mechanical properties of CFRP laminates used for manufacturing fuel tanks and gas cylinders by toughening them with hydroxyl-terminated polyurethane (HPTU) (Fig. 3 (a)). Due to increased interfacial adhesion between the fiber-matrix interface, HPTU treated laminates exhibit greater tensile and flexural strength in both room and cryogenic temperature environments. (Fig. 3 (b), (c)). The crack density was also lower in HPTU treated composites that leads to protecting the laminates from microcracking at elevated temperatures [37]. Grafting the fiber surface with a novel hyperbranched polymer also helped to create the high interfacial adhesion between carbon fiber and epoxy resin, which results in increased interfacial shear strength (IFSS) (78.2%), ILSS (40.9%), and impact strength (39.2%) when compared to ungrafted fiber composites [38]. Subsequently, for improved interfacial adhesion between epoxy and CF surface, researchers also grafted carbon fiber surfaces with carbon-based nanofillers like multiwall carbon nanotubes (MWCNTs), graphene nanoplatelets, and graphene oxide [39,40].

The interfacial bonding of various polymer matrices (epoxy resin, casting resin, orthocryl resin, and polyester resin) with carbon fiber-based blade runner's artificial leg were tested and found that orthocryl resin-based carbon fiber composites shows increased tensile and bending strength of 483.93 MPa and 494.17 MPa respectively [41]. Additionally, Brazilian industries under the ABNT-NBR15708:2011 recommendations for manufacturing stairs and decking in Brazil, Kolding footbridge in Denmark, eye-catcher building in Switzerland, and ETAR Vila Moura in Portugal also pioneered the development of glass fiber-reinforced polymer (GFRP) composites for structural applications [42]. Glass fiber is also utilized to make polylactic acid (PLA) foams with different fiber contents. It has been discovered that at a fiber content of 20 wt%, tensile and flexural strength are increased by two times, while impact toughness is increased by around three times [43]. GFRPs have been used in the construction sector, but their application has been constrained by weak ILSS and fracture toughness. The introduction of carbon-based nanofillers on GF surfaces has improved their performance. GFRP composite panels by grafting GF surface with varying (0–0.5) wt.% of MWCNTs were fabricated through solution dip-coating process (Fig. 4 (a)). The GFRPs have superior ILSS and fracture toughness with 0.3 wt% MWCNTs by cause of uniform dispersion of MWCNTs on the surface of fibers (Fig. 4 (b), (c)) [44]. Similarly, graphene oxide particles were employed to treat GF surfaces, the addition of multiple functional groups increased the ILSS, flexural, and tensile strength of the GFRP composites by 28%, 22%, and 19%, respectively [45].

Researchers revealed that reinforcing GFRP laminates with 10 wt% micronized rubber nano-fillers gave them outstanding mechanical characteristics at a cheap cost, with tensile, flexural, and compression strengths of 191.54, 238.85, and 20.31 MPa, respectively [46]. Concurrently, the use of Aramid fibers (AFs) was initiated as reinforcements for advanced composite materials, such as sports equipment, automotive rubber hoses, and aircraft structural materials due to their high strength, high modulus, low density, excellent tenacity, and stable heat resistance [47,48]. However, the application was limited due to the smoothness and lack of active group which reduces the bonding between fiber and matrix [49,50]. As a result, the AF surface must be modified to increase fiber surface activity and improve composite interface adhesion [51–53]. So, researchers used an easy and fast dip-coating approach to graft aramid nanofibers on macro-aramid fiber surfaces, resulting in enhanced IFSS (70.27%) and short beam shear strength (25.6%) (Fig. 5) [54]. Similarly, researchers also attempts to enhance the bonding through the addition of carbon-based nanofillers (graphene oxide) and 0.3 wt% graphene oxide resulted in increased bending strength, bending modulus, ILSS, and mode I fracture toughness by 67%, 85%, 29%, and 59% respectively [55]. Subsequently, a non-destructive modification method was used to graft aramid fiber surface through co-polymeric reaction and resulting in preserved fibers mechanical performance and increased IFSS (28.8%) and flexural strength (23.8%) [56].

The surface bonding of epoxy and fiber are improved simultaneously by modifying with Al_2O_3 nanoparticles in

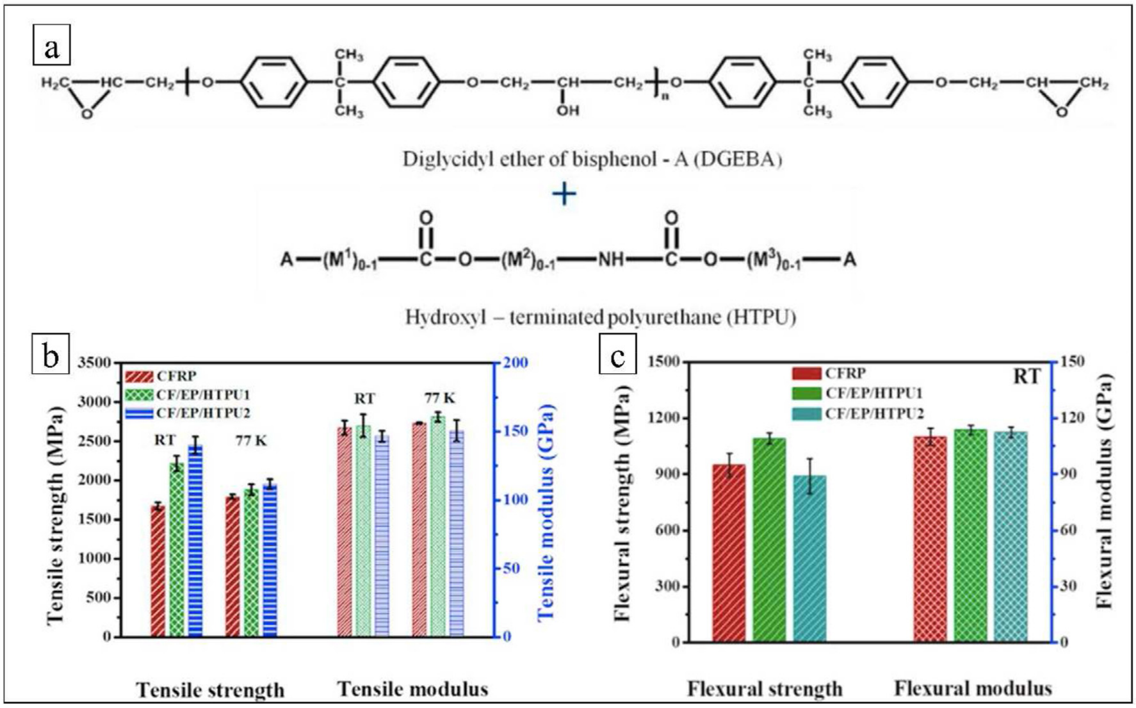

Fig. 3 – (a) Schematic of DGEBA matrix with HPTU; (b) Tensile strength; (c) Flexural strength of the composite laminates [37].

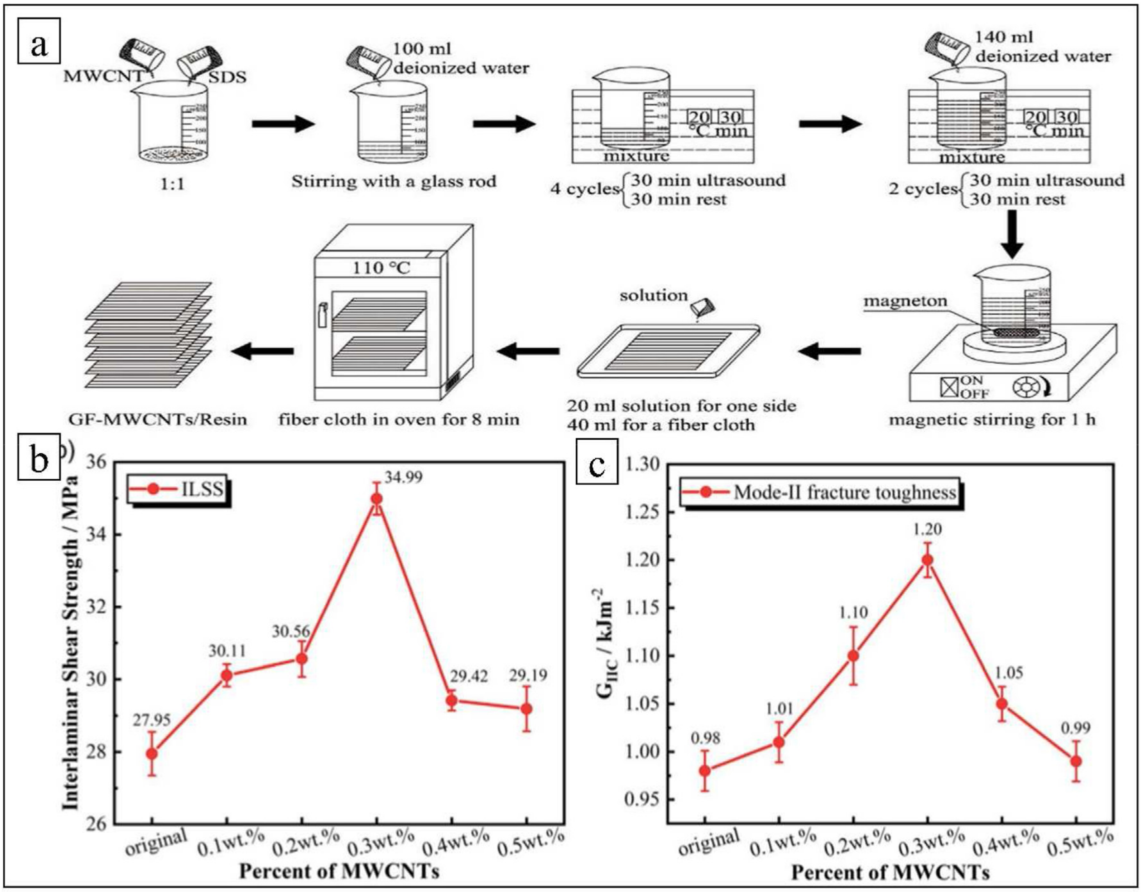

Fig. 4 – (a) Process flow diagram for solution dispersion and solution dip-coating; (b) ILSS; (c) Mode II fracture toughness of GFRP composite panels [44].

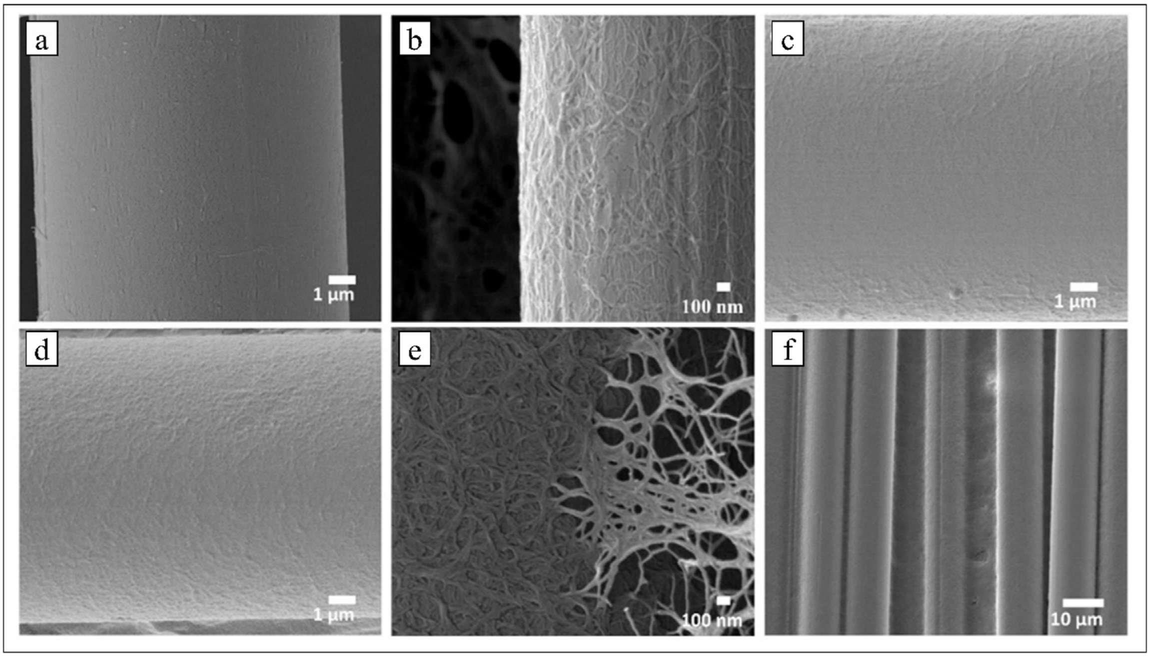

Fig. 5 – Scanning electron microscopy images for pristine aramid fibers and aramid nanofibers treated aramid fibers surface. (a) Pristine aramid fiber, (b) 1 min treated aramid fiber, (c) 2 min treated aramid fiber, (d) 3 min treated aramid fiber, (e) creation of a web structure between neighbouring fibers and the agglomeration of aramid nanofibers along the fiber surface, (f) aramid unidirectional tape covered with aramid nanofibers [54].

different wt.% (1,2,3,4 and 5%) and it results in increased flexural and impact strength without sacrificing the tensile properties of the laminates [57]. The advancement in body armors was executed through ultra-high molecular weight polyethylene (UHMWPE) (Dyneema®) fibers manufactured through gel spinning method. Dyneema fibers are light, strong, flexible, and have a high-energy absorption capacity however, their low compression strength limits their usage in structural load applications [58]. The Dyneema SK76 fibers reinforced polymer composites are examined for their mechanical behavior and found a compromise of 83% in the tensile behavior of the laminates [59]. For body armor applications the impact behavior of Dyneema fabric reinforced with four different was tested by hitting spherical steel bullets at different speeds. It was found that laminates with flexible matrices performed substantially better in terms of perforation resistance and energy absorption, but also had more deformation and damage than rigid matrix-based composites. The major failure mode for all the laminated composites was identified as fiber failure in tension [60]. Moreover, a comparison between the impact behavior, penetration resistance, and ballistic limit of glass, carbon, and Dyneema fiber composites was also carried out through three separate test methods namely Charpy impact tests, drop-weight impact tests, and ballistic impact tests. The test results present that the Dyneema fiber-reinforced composites have high penetration resistance in comparison with CFRP and GFRP. So, the Dyneema HB26 panels with a rubber-based PUR matrix were superior for body armor applications [61]. Furthermore, attempts were made to develop high-performance liquid-crystalline polymer-based Vectran (4-hydroxybenzoic acid-2-hydroxy-6-naphthoic acid) fiber by Hoechst Celanese and Kuraray Company Ltd., Japan [62]. The establishment of Vectran fiber-based composites was started through a two-step approach by incorporating Vectran fibers in the Vectran matrix. The method resulted in increased tensile modulus (up to 161%) and a decreased elongation at break, with fiber breaking as the primary fracture mechanism [63,64]. The Vectran fiber composites also show improved translaminar fracture toughness for components subjected to compressive and buckling failure in comparison with carbon (48.26% and 95.27%) and glass (9.93% and 68.6%) fiber composites at initiation and propagation mode respectively [65]. The Vectran fiber-reinforced composites also show superior impact response in comparison with that of glass fiber reinforced composites for impact protection components [66].

The governing equation (Eq. (1)) for the relationship between damaged and undamaged material according to continuum damage mechanics in Vectran-laminated composites was suggested as [67],

$$\overline{\sigma} = \frac{\sigma}{(1-d)} \tag{1}$$

where; $\overline{\sigma}$ = stress in the damaged material,

σ = stress in the pristine undamaged material,

The material stiffness (Eq. (2)) can also be defined by extending the Eq. (1) as,

$$E = (1-d)E^0 \tag{2}$$

where; E = current stiffness,

E^0 = pristine material stiffness,

Table 2 – Typical mechanical properties of synthetic fibers reinforced polymer composites.

Composite		Processing Technique	Mechanical Properties	References
Polymer Matrix	Synthetic Fiber			
Polyether ether ketone	HTA40 Carbon	Compression molding	Tensile strength – 989.3 MPa Young's modulus – 59.7 GPa Compressive modulus – 60.4 GPa Poisson's ratio – 0.073	[34]
Benzoxazine BZ9110	HTA40 Carbon	Resin transfer molding	Tensile strength – 739.8 MPa Young's modulus – 62.9 GPa Compressive modulus – 61.7 GPa Poisson's ratio – 0.059	[34]
DGEBA epoxy resin	T800S Carbon	Hot-press molding	Tensile strength – 1600 MPa Young's modulus – 150 GPa Flexural strength – 910 MPa Flexural modulus – 100 GPa Fracture strain (%) – 1.2	[37]
E–51 epoxy resin	Boltron H30 Carbon	Hot-press molding	Interfacial shear strength – 47.2 MPa Interlaminar shear strength – 49.2 MPa Impact strength – 43.9 kJ/m^2	[38]
Polyamide PA6	T700 Carbon	Compression molding	Tensile strength – 1050 MPa Young's modulus – 50 GPa Interlaminar shear strength – 35 MPa	[68]
Epoxy resin	Carbon	Vacuum-assisted resin transfer molding	Tensile strength – 306-34 MPa Flexural strength – 446.94 MPa	[41]
Polyester resin	Carbon	Vacuum-assisted resin transfer molding	Tensile strength – 453.61 MPa Flexural strength – 294.99 MPa	[41]
Polylactic acid	ECS303A Glass	Injection molding	Tensile strength – 80 MPa Tensile modulus – 7 GPa Elongation at break – 1.5% Impact strength – 100 J/m	[43]
T411 vinyl resin	MT6401 Glass	Vacuum-assisted resin infusion	Tensile strength – 834.15 MPa Tensile modulus – 13.12 GPa Flexural strength – 343.39 MPa Flexural modulus – 19.01 GPa	[44]
Bisphenol -A epoxy resin	E-glass	Vacuum-assisted resin transfer molding	Tensile strength – 610 MPa Tensile modulus – 27.5 GPa Flexural strength – 720 MPa Flexural modulus – 17 GPa Interlaminar shear strength – 55.3 MPa	[45]
LY556 epoxy resin	E-glass	Hand layup	Tensile strength – 191.54 MPa Flexural strength – 238 MPa Compression strength – 48 MPa Hardness – 82 BHN	[46]
Epoxy resin	Aramid	Hand layup	Interfacial shear strength – 58.38 MPa	[49]
Bakelite epoxy resin	Kevlar 49 aramid	Prepreg hand layup	Flexural strength – 230 MPa Short beam shear strength – 40 MPa	[52]
Epon 862 resin	Kevlar KM2 aramid	Vacuum-assisted resin transfer molding	Interfacial shear strength – 37 MPa Interlaminar shear strength – 17 MPa Mode I fracture toughness – 0.47 kJ/m^2 Tensile strength – 556 MPa Tensile modulus – 24 GPa	[69]
Bisphenol-F epoxy resin	Kevlar 49 aramid	Compression molding	Tensile strength – 71 MPa Young's modulus – 2.54 GPa Mode I fracture toughness – 0.72 kJ/m^2	[70]
BAC170 epoxy resin	MT-9120 aramid	Autoclave	Tensile strength – 610 MPa Young's modulus – 29 GPa Bending strength – 224 MPa Bending modulus – 30 GPa Interlaminar shear strength – 33 MPa Mode I fracture toughness – 0.27 kJ/m^2	[55]
E–51 epoxy resin	Aramid III	Vacuum-assisted resin infusion	Interfacial shear strength – 36.6 MPa Flexural strength – 250.6 MPa	[56]

(*continued on next page*)

Table 2 – (*continued*)

Composite		Processing Technique	Mechanical Properties	References
Polymer Matrix	Synthetic Fiber			
L285 lamination resin	Kevlar 49 aramid	Vacuum-assisted resin infusion	Tensile strength – 495.87 MPa Tensile modulus – 27.89 GPa Flexural strength – 209.71 MPa Flexural modulus – 5.07 GPa Impact energy – 119.39 kJ/m^2 Mode I fracture toughness – 0.45 kJ/m^2	[57]
RTM6 Epoxy resin	S2 glass	Vacuum-assisted resin infusion	Tensile strength – 549 MPa Tensile modulus – 23.5 GPa Mode I fracture toughness – 1.46 kJ/m^2 Mode II fracture toughness – 1.94 kJ/m^2 Impact strength – 168 kJ/m^2	[61]
RTM6 Epoxy resin	HTA40 carbon	Vacuum-assisted resin infusion	Tensile strength – 852 MPa Tensile modulus – 64.6 GPa Mode I fracture toughness – 0.45 kJ/m^2 Mode II fracture toughness – 1.86 kJ/m^2 Impact strength – 92 kJ/m^2	[61]
RTM6 Epoxy resin	Dyneema HB26	Vacuum-assisted resin infusion	Tensile strength – 420 MPa Tensile modulus – 12.6 GPa Mode I fracture toughness – 1.29 kJ/m^2 Impact strength – 92 kJ/m^2	[61]
Epoxy resin	Vectran M	Filament winding	Tensile strength – 1209 MPa Tensile modulus – 68.8 GPa Elongation at break – 2.15%	[63]
Epoxy resin	Vectran HS	Filament winding	Tensile strength – 3427 MPa Tensile modulus – 71.9 GPa Elongation at break – 3.73%	[63]
Vectran	Vectran NT	Hot-press molding	Tensile strength – 37.7 MPa Tensile modulus – 1.31 GPa Elongation at break – 5.00%	[64]
MTM57 resin	Vectran NCF	Hand layup	Tensile strength – 1045 MPa Elongation at break – 2.58% Mode I fracture toughness – 130 kJ/m^2	[65]
MTM57 resin	S2 glass	Hand layup	Tensile strength – 603.2 MPa Tensile modulus – 28.7 GPa In-plane shear – 51.4 MPa Compressive modulus – 425.6 GPa Elongation at break – 2.8%	[66]
MTM57 resin	Vectran NCF	Hand layup	Tensile strength – 780.1 MPa Tensile modulus – 24.2 GPa In-plane shear – 29.56 MPa Compressive modulus – 84.1 GPa Elongation at break – 2.6%	[66]
Polypropylene	Carbon	Hand layup	Tensile strength – 5.3 GPa Interfacial shear strength – 10.1 MPa	[71]
Polyphenylene sulfide	Glass	Hand layup	Tensile strength – 850.6 MPa Flexural strength – 910.5 MPa ILSS – 67.4 MPa	[72]
Polyamide6/Polyphenylene sulfide	Carbon	Injection molding	Tensile strength – 70 MPa Bending strength – 125 MPa	[73]
Polysulfone	Carbon	Polymer solution impregnation method	Shear Strength – 62.9 MPa	[74]
Polysulfone	Glass	Compression molding	Flexural strength – 460 MPa Shear strength – 45 MPa	[75]
Polyethylene	Carbon	Hand layup	Hardness – 90 MPa Wear Volume – 2.7 mm^3 Friction coefficient – 0.22	[76]
UHMWPE	UKN 5000 Carbon	Thermal Pressing	Tensile strength – 819 MPa Young's modulus – 1. 54 GPa	[77]
UHMWPE	VMN-4 Carbon	Thermal Pressing	Tensile strength – 370 MPa Young's modulus – 0.75 GPa	[77]

Table 3 – Typical mechanical properties of natural fibers [82–85].

Natural fibers	Tensile strength (MPa)	Young's modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)	Elongation at break (%)	Melting point (°C)	Density (gm/cc)	Fiber diameter (mm)
Jute fiber	393–723	10–25	15–30	1.2	3.6–4.2	105–125	1.3–1.4	0.07–0.08
Flax fiber	345–1500	13–30	40–60	3–5	2.7–3.2	100–120	1.5–1.6	0.012–0.016
Hemp fiber	600–1200	5–35	60–70	3–10	0.001–0.025	150–200	1.4–1.6	0.060–0.066
Kenaf fiber	223–930	10–60	90–220	10–20	1.6–10	100–150	0.6–1.45	0.010–0.020
Bamboo fiber	100–900	20–40	100–220	12–15	1.5–2.9	70–80	1.3–1.4	0.01–0.03
Sisal fiber	450–700	3–25	70–100	1–1.5	2.2–4.2	100–210	1.3–1.5	0.20–0.28
Ramie fiber	350–750	15–55	55–110	1.1–1.6	1.6–8.9	100–190	1.4–1.5	0.022–0.034
Banana fiber	250–800	25–40	30–50	2–5	2.0–3.5	106–120	1.25–1.45	0.16–0.20
Curaua fiber	117–3000	11.5-63-7	100–300	10–35	1.0–3.9	150–300	0.57–0.92	0.10–0.14

The stiffness-damage relationship (Eq. (3)) for in-plane shear of Vectran-laminated composite was defined as,

$$G_{12} = (1 - d_3)G_{12}^0 \tag{3}$$

The typical mechanical properties of some synthetic fibers reinforced polymer composites are listed in Table 2.

2.2. Natural fiber-reinforced PMCs

Environmentalists from nongovernmental organisations and Greenpeace groups have stepped up their pressure on developing nations to safeguard natural resources with an emphasis on renewable raw materials in recent years. Thus advancement of polymer composites based on natural fibers was initiated to solve environmental problems [78,79]. The robust mechanical properties and ability to resist hydrolysis of natural fibers can be attributed to the presence of cellulose and hemicellulose within their composition. While the presence of organic or inorganic substances can be beneficial for the natural fiber's odour, color, breakdown resistance, and properties [80,81]. Typical mechanical properties of commonly used natural fibers are listed in Table 3.

A group of researchers worked together to create polymer matrix composites reinforced with natural fibers, which exhibit exceptional mechanical characteristics. Recently, an investigation was conducted on how the use of different lengths of jute fibers (root, middle, and tip) affects the tensile and flexural properties of polyester resin composites. The findings revealed that the strength variations in jute fibers significantly affect the mechanical properties of the resulting composites. The composites originating from the lower region exhibit superior tensile and flexural properties in comparison to those produced from the middle and upper regions [86].

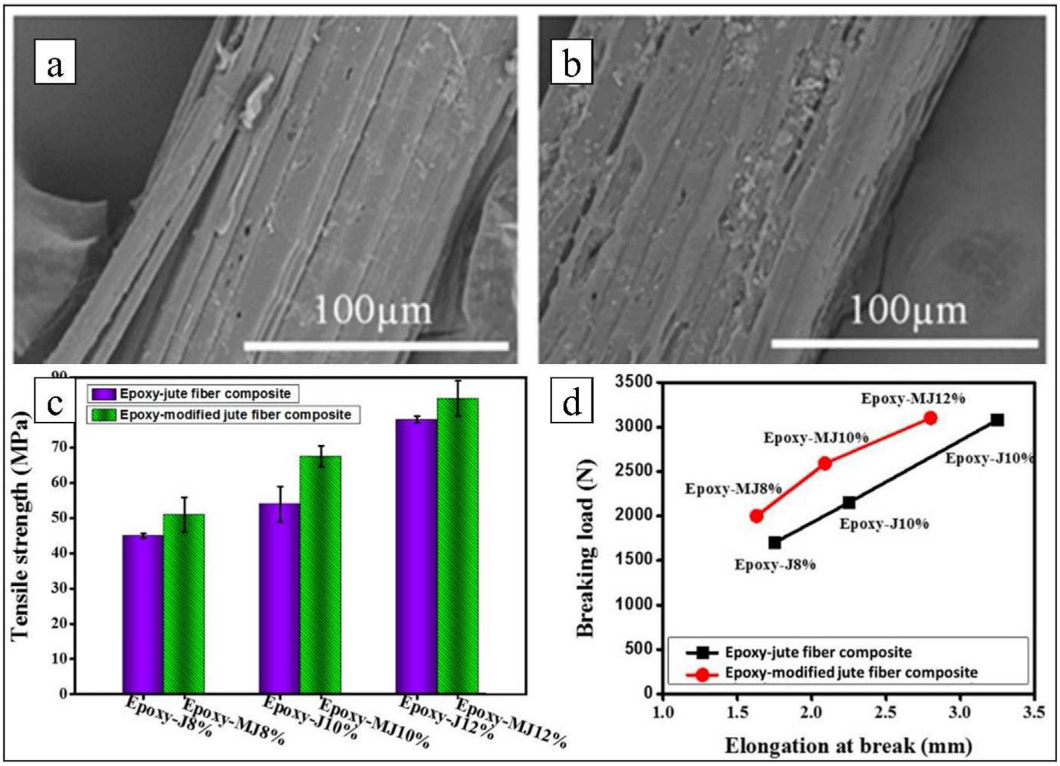

Fig. 6 – SEM images (a) Pristine jute fiber; (b) Treated jute fiber; (c) Tensile strength; (d) Elongation at break of pristine and modified jute fiber composites [88].

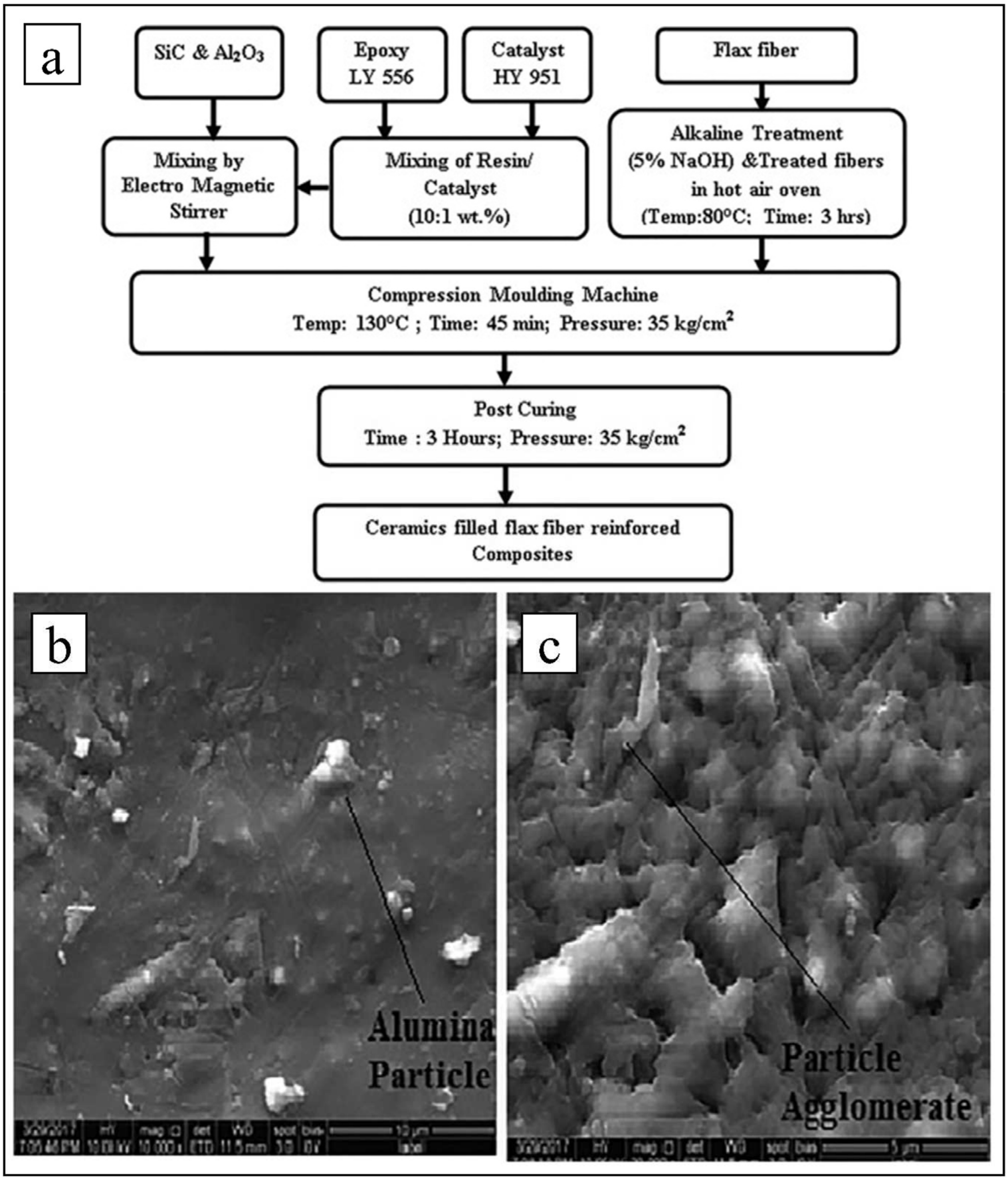

Fig. 7 – (a) Synthesis route for ceramic filled composites; SEM micrographs for (b) 10 wt% SiC content; (c) 8 wt% SiC content [92].

Later, the fiber surface was treated with 10, 20, and 30% sodium bicarbonate ($NaHCO_3$) solution for 4 h and evaluated for impact strength and dynamic mechanical behavior. It was shown that a composite treated with 10% $NaHCO_3$ has a substantial impact strength (64.57 J/m), whereas a composite treated with 20% $NaHCO_3$ has a greater storage modulus G' (2500 MPa) and loss modulus G" (471.64 MPa) and the glass transition temperature Tg (70 °C) changes significantly [87]. The jute fiber surface was also treated with a three-step scouring procedure to eliminate impurities from the fiber surface (Fig. 6 (c)), resulting in increased mechanical performance (Fig. 6 (a), (b)) [88].

Along with the treatment of the jute fiber surface, the incorporation of nano SiO_2 particles to the PLA matrix was explored to increase interface compatibility between matrix and fiber surface and sequentially enhance the mechanical characteristics and T_g of the composite laminates [89]. Certain physical characterizations need to be conducted to enhance the interfacial properties of natural fiber-reinforced composites in the meantime. Density is the most important factor for

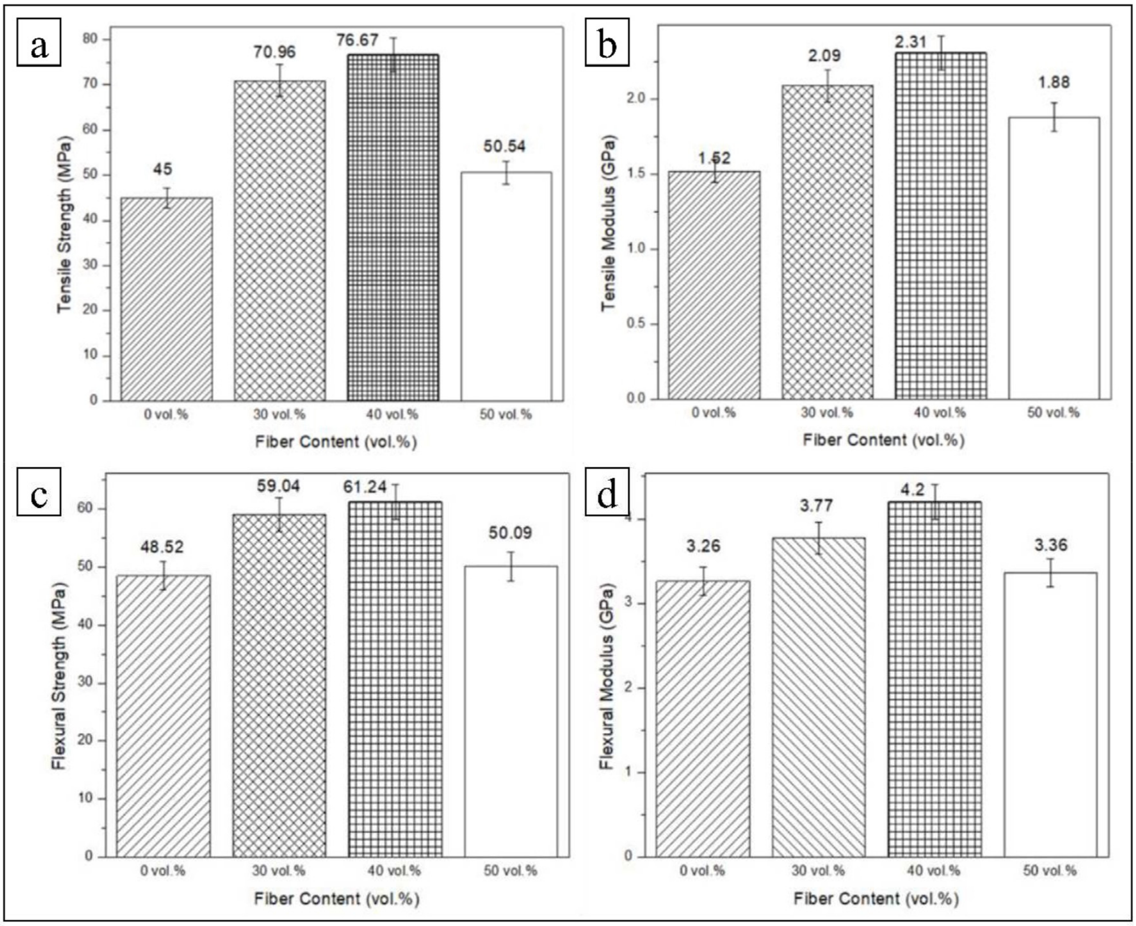

Fig. 8 – (a) Tensile strength; (b) Tensile modulus; (c) Flexural strength; (d) Flexural modulus kenaf fiber reinforced composites [96].

designing a composite because it directly influences the weight of the material. The general Eq. (4) represents the theoretical density of the composite as,

$$\rho_t = \left(\frac{1}{\frac{W_f}{\rho_m} + \frac{W_m}{\rho_f}} \right) \tag{4}$$

where; W = weight fraction,

ρ = density,

Suffix m, f, and t stand for matrix, fiber, and theoretical respectively.

Trapped air or other volatile substances may result in voids within the composite material, during the manufacturing of composites or when reinforcing fibers into the matrix. These vacancies can harm the mechanical properties of the composite. Eq. (5) represents the void content of the composites as,

$$\textit{void content}\ (\%) = \left(\frac{\rho_t - \rho_a}{\rho_t} \right) \times 100 \tag{5}$$

where; ρ_t = theoretical density,

ρ_a = actual density.

Eq. (6) represents the water absorption behavior of the composites,

$$\textit{water absorption}\ (\%) = \left(\frac{W_f - W_i}{W_i} \right) \times 100 \tag{6}$$

where; W_f = final weight of the composite after testing,

W_i = initial weight of the composite before testing [90].

Natural fiber-reinforced composites have low moisture resistance, and efforts have been made to find solutions to prevent moisture-induced composite deterioration. Jia and Fiedler explored the effectiveness of fiber pre-treatment in enhancing the mechanical properties of flax fiber-reinforced composites, which were produced using green furfuryl alcohol (FA) pre-treated flax fibers. They found that this pre-treatment method led to a significant improvement in the modulus, up to 18%, and a considerable reduction in moisture content [91]. Sathish and co-workers have demonstrated the synthesis of ceramic filled flax fiber composites (Fig. 7 (a)) with different concentrations of SiC and Al_2O_3 and discovered that a composite made with 20 wt% flax fiber, 70 wt% epoxies, 8 wt% SiC, and 2 wt% Al_2O_3 has the highest tensile strength, flexural strength, and impact strength of 44.56 MPa, 112.56 MPa, and 28.57 kJ/m^2 respectively. According to the SEM data of 10 wt% and 8 wt% SiC content, epoxy resin with an 8 wt% SiC concentration exhibits homogenous dispersion and improved interfacial bonding whereas, for 10 wt% SiC content it results

Table 4 – Typical mechanical properties of natural fibers reinforced polymer composites.

Composite		Processing Technique	Mechanical Properties	References
Polymer Matrix	Natural Fiber			
PVA217 resin	Bamboo	Press molding	Tensile strength – 330 MPa Tensile modulus – 26.3 GPa Fracture strain – 1.25%	[102]
CPRF3A resin	Bamboo	Press molding	Tensile strength – 299 MPa Tensile modulus – 29.4 GPa Fracture strain – 1.02%	[102]
Polylactic acid	Hemp	Compression molding	Tensile strength – 83 MPa Tensile modulus – 11 GPa Flexural strength – 143 MPa Flexural modulus – 7 GPa Impact strength – 9 kJ/m^2	[13]
Polylactic acid	Kenaf	Compression molding	Tensile strength – 165 MPa Tensile modulus – 17 GPa Flexural strength – 180 MPa Flexural modulus – 9 GPa Impact strength – 15 kJ/m^2	[13]
Epoxy resin	Hemp	Compression molding	Tensile strength – 82 MPa Tensile modulus – 8 GPa Flexural strength – 126 MPa Flexural modulus – 7 GPa Impact strength – 14 kJ/m^2	[13]
Unsaturated polyester	E-glass	Resin transfer molding	Tensile strength – 201 MPa Tensile modulus – 13 GPa Flexural strength – 278 MPa Flexural modulus – 11 GPa Impact strength – 107 kJ/m^2	[13]
Polyester resin	TD4 jute	Hand layup	Tensile strength – 135.6 MPa Tensile modulus – 7.42 GPa Flexural strength – 151.3 MPa Flexural modulus – 10.13 GPa	[86]
Polylactic acid	GSM 220 jute	Compression molding	Storage modulus – 2500 MPa Loss modulus – 471.64 MPa Glass transition temperature - 70 °C Impact strength – 64.57 J/m	[87]
JC-02A epoxy resin	Raw jute	Hand layup	Tensile strength – 79 MPa Elongation at break – 3.25%	[88]
Polylactic acid	Raw jute	Compression molding	Tensile strength – 11.9 MPa Tensile modulus – 0.2 GPa Bending strength – 41 MPa Bending modulus – 0.3 GPa Elongation at break – 1.2% Mode I fracture toughness – 0.55 J/cm^3 Storage modulus – 3.5 GPa Loss modulus – 12 MPa Glass transition temperature - 64 °C	[89]
L12 epoxy resin	GSM 210 jute	Hand layup & Compression molding	Tensile strength – 33 MPa Flexural strength – 46 MPa Impact strength – 3.35 J/m	[90]
Green epoxy resin	Bast Flax	Vacuum-assisted resin transfer molding	Tensile strength – 25.87 MPa Tensile modulus – 0.494 GPa	[91]
LY556 epoxy resin	Bast Flax	Compression molding	Tensile strength – 45 MPa Flexural strength – 112.5 MPa Impact strength – 29 kJ/m^2 Interlaminar shear strength – 4.2 MPa	[92]
Polypropylene	Hemp	Injection molding	Flexural strength – 59.3 MPa Flexural modulus – 4.03 GPa	[93]
High-density polyethylene	Hemp	Injection molding	Flexural strength – 41.6 MPa Flexural modulus – 2.45 GPa	[93]

Table 4 – (*continued*)

Composite		Processing Technique	Mechanical Properties	References
Polymer Matrix	Natural Fiber			
1010 polyamide	Hemp	Compression molding	Tensile strength – 58 MPa Tensile modulus – 2.9 GPa Elongation at break – 3.3% Bending strength – 98 MPa Bending modulus – 3.1 GPa	[94]
DER331 epoxy resin	Temafa kenaf	Compression molding	Tensile strength – 159.98 MPa Young's modulus – 8201.52 MPa	[95]
INF114 epoxy resin	Kenaf	Vacuum infusion	Tensile strength – 76.67 MPa Tensile modulus – 2.31 GPa Flexural strength – 61.24 MPa Flexural modulus – 4.2 GPa	[96]
Bisphenol-A epoxy resin	Bamboo	Vacuum-assisted resin transfer molding	Tensile strength – 111.54 MPa Tensile modulus – 3.90 GPa Interfacial shear strength – 24.36 MPa	[97]
LY556 epoxy resin	Bamboo	Compression molding	Tensile strength – 40.28 MPa Flexural strength – 45.23 MPa Hardness – 44.72 BHN Impact strength – 5.9 J/m^2	[98]
Bisphenol-A epoxy resin	Curaua	Hot-press molding	Tensile strength – 134.67 MPa Young's modulus – 3.08 GPa Yield stress – 35.49 MPa Elongation at break – 7.87% Mode I fracture toughness – 5.83 × 10^6 J/m^3	[99]

in agglomeration and decrease in mechanical properties Fig. 7 (b),(c) [92].

Furthermore, to enhance their mechanical properties and water absorption characteristics, hemp fiber surfaces were treated with maleic anhydride and stearic acid in the process of developing composites based on polypropylene (PP) or high-density polyethylene (HDPE) for various indoor applications. The method resulted in enhanced flexural strength of about 59.31 and 41.64 MPa and flexural modulus of 4.03 and 2.46 GPa for PP and HDPE composites respectively [93]. Likewise, the utilization of alkaline ($NaClO_2$) and epoxy resin (A-1160) solutions has resulted in the modification of the surface of hemp fibers, which were then cured with composites of plant-derived polyamide 1010 (PA1010), exhibiting enhanced strength, modulus, and specific wear rate. The reasons behind it could be attributed to alterations in the internal microstructure of the composites, which may include modifications in the interfacial contact between HF and PA1010, as well as the dispersion of fibers [94]. The use of an alkali treatment, referred to as mercerization and illustrated in Eq. (7), was found to be effective in eliminating lignin, hemicellulose, wax, and oil from the surface of the fibers. This process led to an increase in surface roughness, which resulted in a greater number of bonds being formed between the kenaf fiber and epoxy. As a result, the tensile strength was enhanced by 12.97% [95].

$$Fiber - OH - NaOH \rightarrow Fiber - O - Na + H_2O \tag{7}$$

The study also analysed the impact of various fiber loading concentrations, namely 30 vol%, 40 vol%, and 50 vol%, on the mechanical properties of kenaf fiber-reinforced composites. The results showed that the highest values of tensile strength (76.67 MPa), tensile modulus (2.31 GPa), flexural strength (61.24 MPa), and flexural modulus (4.20 GPa) were obtained at a fiber concentration of 40 vol% (Fig. 8) [96.].

The study also investigated how the interfacial adhesion of bamboo fiber reinforced composites (BF/EP) was affected by the polyacrylate-based wetting agent (BYK-358N), and the results indicated that incorporating 1% of the wetting agent led to a significant improvement in ILSS, tensile strength, and Young's modulus, with increases of 165.7%, 99.7%, and 66.7%, respectively, when compared to BF/EP composites that were not treated [97]. Nanoparticles-based bamboo fiber composites (BFC) have a wide range of applications such as door trim panels, window frames, indoor elements in housing, mirror casing, athletic products, and electronic sectors, to name a few. The addition of Al_2O_3 nanoparticles in BFC altered the tensile strength, impact strength, and hardness to about 27%. Adding nanoparticles exceeding 8% to bamboo fiber results in a considerable reduction in flexural strength due to cellulose damage [98]. Over the years, research has been conducted on numerous natural fibers, including “curaua fiber,” a Brazilian natural fiber obtained from the Ananas erectifolius plant in the Amazon. These fibers are relatively less known than other natural fibers such as jute, sisal, or hemp. However, they exhibit the highest tensile properties, making them a promising reinforcement option for engineering applications in polymer matrix composites. The tensile properties of curaua fiber-reinforced composites were improved by researchers through functionalizing the fiber or matrix with graphene oxide. They then produced four types of composites, namely CF/EM, CF/GOEM, GOCF/EM, and GOCF/GOEM. According to the findings, CF/GOEM composites exhibited higher maximum tensile strength (40%), yield stress (64%), young's modulus (60%), and toughness (28%) compared to other composites. Additionally, these composites were utilized as a substitute for synthetic glass components in a variety of applications [99]. The dynamic mechanical behavior of composites reinforced with 20 and 50 vol% curaua fibers was studied, and this analysis included both graphene oxide functionalized and non-functionalized variants. Additionally, information was gathered on the dynamic mechanical behavior of these materials. The 50GOCF/EM composites show 250% and 90% higher storage modulus (E′) and 600% and 200% higher loss modulus (E″) in comparison with CF/EM and 20GOCF/EM composites due to the addition of CF in the viscoelastic stiffness and restricting chain mobility of the epoxy matrix [100]. Furthermore, the curaua fiber-reinforced composites were also introduced to replace the kevlar fiber-reinforced multi-layered armor system by improving the ballistic performance in terms of fibrils separation, fiber pull-out, composite delamination, fiber breaking, and matrix rupture [101]. Table 4 lists the mechanical properties commonly exhibited by natural fiber reinforced polymer composites.

2.3. *Hybrid fiber-reinforced PMCs*

Fiber-reinforced composites are increasing market share, but their lack of toughness has slowed their growth. In contrast to non-hybrid composites, hybrid composites provide superior mechanical balance. The primary objective of combining two types of fibers in a single composite was to retain the advantages of both fibers while minimizing their drawbacks [103]. The last review paper on hybrid fiber reinforced polymer composites was written in the year 2018, so the recent development in the area was reported in this paper [104]. Lately, the development of hybrid composite by incorporating carbon and kenaf fibers in Ly556 epoxy resin was demonstrated and the effect of stacking sequence on the mechanical and microstructural behaviour of the composite was presented. Among different stacking sequence (CKCKC, KCKCK, KKCKK, CCKCC, KKKKK and CCCCC), the CCKCC composite shows higher tensile strength in comparison with other hybrid composites due to the two skin outer layers of carbon fibers and core layer support of kenaf fibers (Fig. 9 (a)). Whereas, the flexural strength was found to be maximum in case of KKCKK hybrid composites (Fig. 9 (b)). In contradiction to this, the microstructure results shows that the skin layer of carbon fibers was protecting the core layer of kenaf fibers and the shear stress distribution will be uniform in the fiber mat (Fig. 9 (c)) [105].

The impact and flexural strength of composites combining 4/4 plies of Dyneema and glass fibers with thermoset resin were tested and compared to a 0/8 plies glass composite. Due to the 4 plies of Dyneema fibers withstanding additional stresses and dispersing the load around the edges of the composite, hybrid composite has a greater impact energy (144.4 J/cm-2) and flexural strength (225 MPa) than glass

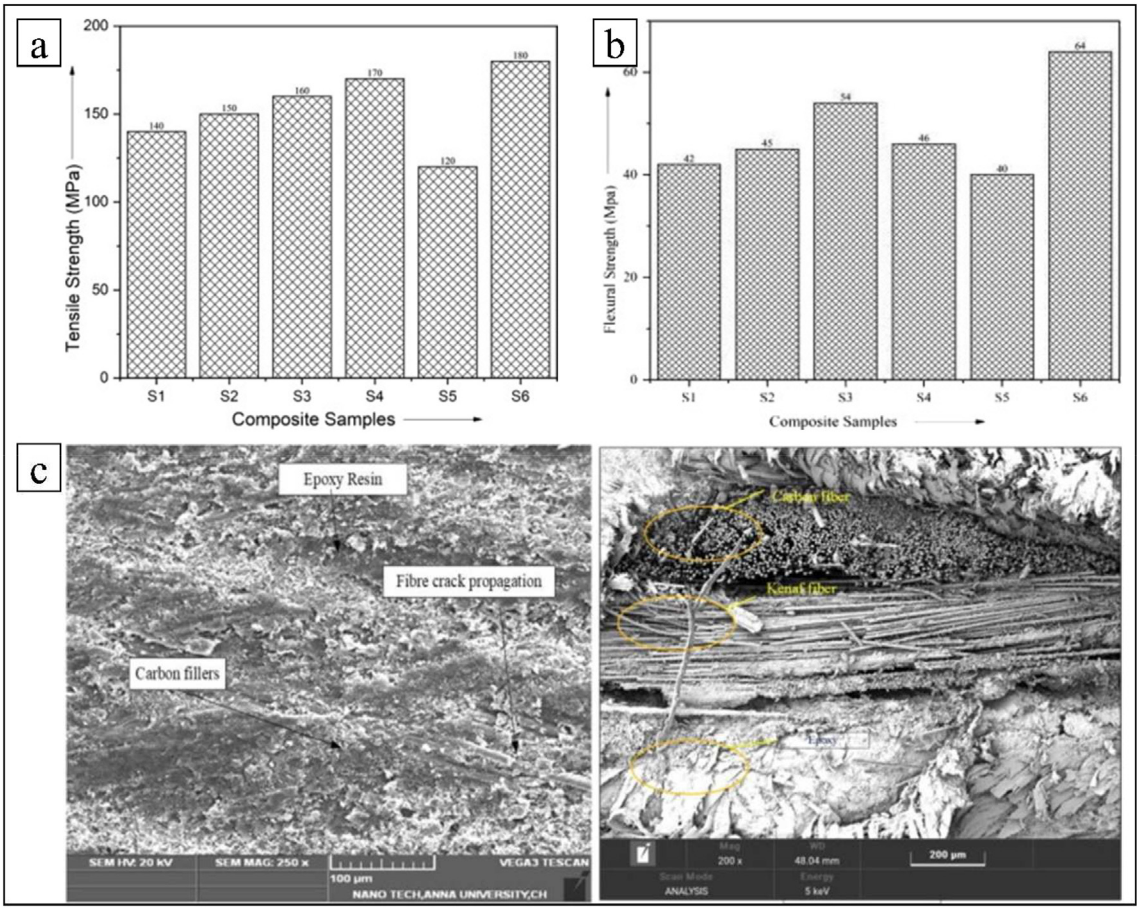

Fig. 9 – (a) Tensile strength; (b) Flexural strength; (c) SEM micrograph of hybrid (carbon/kenaf) fiber composites [105].

composite (50.50 J.cm-2, 22 MPa) [106]. Similarly, kenaf fiber/ oil palm-based composites in various concentration ratios (4:1, 1:1, and 1:4) were made, and it was discovered that the laminate prepared with oil palm (1): kenaf (4) had greater tensile strength and modulus of around 64.7 and 3640 MPa. In the case of oil palm (1): kenaf (1) concentration, greater flexural strength, and modulus of 113.14 and 7797.86 MPa were attained. The addition of kenaf fibers to an oil palm composite boosted the load-bearing capability of hybrid composites, increasing stiffness [107]. Later, to identify a suitable and cost-effective material with lower environmental impact, five consecutive samples of hybrid (carbon and flax) fibers through the hand layup method are manufactured and tested for hardness, ILSS, and weight gain and found that average hardness and ILSS of hybrid composites are 70.85 HRC and 4.49 MPa respectively. The weight gain proportion of flax fiber, carbon fiber, and hybrid fiber composite was 92%, 36.6%, and 61.9% respectively due to untreated flax fibers, voids, flaws, and irregular surface roughness as well as the presence of the −OH group in flax fiber [108]. The influence of fiber plies stacking sequence on hybrid composite mechanical performance was also investigated, and it was shown that hybrid composites had a 20% improvement in tensile strength. In comparison to the basic composite, the hybrid composite demonstrated significant strain (4.5%) and large extension (13.5 mm) in the flexural test. This hybrid composite might be used instead of glass fiber-based composite materials for medium structural applications [109]. Recently, in the area of biomedical implants researchers have attempted to construct natural fiber-based hybrid composites using various epoxy resins and discovered that a prosthetic limb comprised of glass/jute fibers and cured with vinyl ester resin had the highest tensile and flexural strength [110].

Subsequently, to enhance the mechanical performance of hybrid composites three different types of reinforcements (Vectran, carbon, and aramid) were tested and the results revealed that Vectran-carbon composite shows higher bending, impact, tensile, and interlaminar strength in comparison with Vectran-aramid and Vectran composites (Fig. 10) [111]. Table 5 represents the typical mechanical properties of hybrid fiber reinforced polymer composites.

3. Recent developments on the surface-modifications to enhance the physico-mechanical characteristics, and adhesion of fiber reinforced composites

Fiber-reinforced composites (FRCs) are a class of materials consisting of a matrix and reinforcing fibers. The physico-mechanical characteristics of FRCs are primarily evaluated by the properties of the reinforcing fibers, and their adhesion to the matrix. The surface of the fibers plays a crucial role in determining their adhesion to the matrix, and hence the overall mechanical properties of the composite. Surface modification techniques can be employed to enhance the physico-mechanical characteristics, adhesion, and compatibility properties of FRCs.

Zhang et al. supported the notion that achieving improved properties in CFRP composite laminates could be accomplished through carbon fiber functionalization [37,115]. They conducted a study where carbon fibers were coated with GO sheets, examining the mechanical performance of GO reinforced CFRP composites. Their findings revealed a notable change in the composite panel's IFSS, ILSS, and tensile properties, reinforcing the effectiveness of this approach [116].

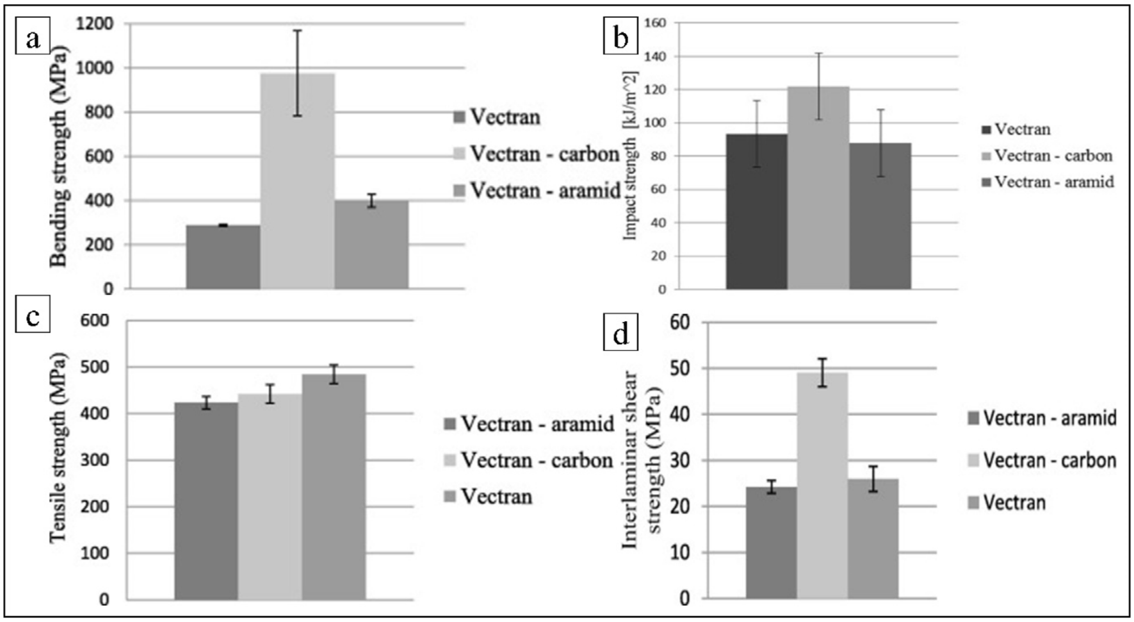

Fig. 10 – (a) Bending strength; (b) Impact strength; (c) Tensile strength; (d) Interlaminar shear strength of vectran, vectran-carbon and vectran-aramid composites [111].

Table 5 – Typical mechanical properties of hybrid fibers reinforced polymer composites.

Composite		Processing Technique	Mechanical Properties	References
Polymer Matrix	Fiber Combination			
LY556 epoxy resin	Glass/Carbon	Hand layup	Mode I fracture toughness – 18.36 MPa m^2 Interlaminar shear strength – 39 MPa Flexural strength – 543 MPa	[112]
Bisphenol A epoxy resin	S-glass/E-glass	Hand layup	Storage modulus – 1005 MPa Loss modulus – 1003 MPa Tan Delta – 0.3908	[113]
Bisphenol A epoxy resin	Carbon/E-glass	Hand layup	Storage modulus – 854.6 MPa Loss modulus – 1557 MPa Tan Delta – 0.4600	[113]
Bisphenol A epoxy resin	Kevlar/E-glass	Hand layup	Storage modulus – 449 MPa Loss modulus – 571.8 MPa Tan Delta – 0.4391	[113]
Epoxy resin	Carbon/Glass	Filament winding	Flexural strength – 542.94 MPa	[114]
Epoxy resin	Dyneema/Glass	Hot pressing	Impact strength – 144.4 J/cm^{-2} Flexural strength – 225 MPa	[106]
DER331 epoxy resin	Oil palm/Kenaf	Hand layup	Tensile strength – 64.7 MPa Tensile modulus – 3640 MPa Flexural strength – 113.14 MPa Flexural modulus – 7797.86 MPa	[107]
LY556 epoxy resin	Carbon/Flax	Hand layup	Interlaminar shear strength – 4.49 MPa Hardness – 70.85 HRC	[108]
LY556 epoxy resin	Jute/Basalt	Hand layup	Tensile strength – 40.978 MPa Young's modulus – 1918.013 MPa Flexural strength – 61.094 MPa Flexural modulus – 3.799 GPa	[109]
Bisphenol A epoxy resin	Glass/Jute	Hand layup	Hardness – 76 HRL Tensile strength – 72 MPa Flexural strength – 42 MPa Impact strength – 2.1 J	[110]
Vinyl ester	Glass/Jute	Hand layup	Hardness – 54 HRL Tensile strength – 69 MPa Flexural strength – 48 MPa Impact strength – 1.9 J	[110]
polyester	Glass/Jute	Hand layup	Hardness – 64 HRL Tensile strength – 60 MPa Flexural strength – 35 MPa Impact strength – 1.71 J	[110]
LH285 epoxy resin	Vectran/Aramid	Hot pressing	Bending strength – 400 MPa Impact strength – 122.08 kJ/m^2 Tensile strength – 423.49 MPa Young's modulus – 34.23 GPa Interlaminar shear strength – 25 MPa	[111]
LH285 epoxy resin	Vectran/Carbon	Hot pressing	Bending strength – 985.33 MPa Impact strength - 85 kJ/m^2 Tensile strength – 450 MPa Young's modulus – 47 GPa Interlaminar shear strength – 49 MPa	[111]

Moreover, the electrophoretic deposition method has been utilized to apply a GO coating on the surface of CF (carbon fiber) to enhance the electromagnetic interference (EMI) shielding effectiveness of CFRP composites. This technique involves depositing charged graphene particles onto the conductive carbon fibers through an electric field, leading to the formation of a thin layer on the surface. When this coated CF is incorporated into the epoxy matrix, it results in a significant 16.3% improvement in EMI effectiveness [117]. By leveraging the synergistic impact of diverse ingredients employed for functionalization, it is possible to create multifunctional composites. Researchers examined the influence of various ingredients, such as polydopamine (PDA), branched polyethyleneimine, and diamines (D400) mixed with graphene oxide, on the surface of CF (carbon fiber). They investigated several mechanical properties and discovered a noteworthy modification in the tensile strength, ILSS (interlaminar shear strength), and mode II fracture toughness of the composites compared to pristine CF and non-functionalized CF/epoxy composites [71,118]. The impact of coating GNPs (graphene nanoplatelets) on the surface of carbon fiber using a small quantity of epoxy/hardener mixture was also investigated in terms of thermal conductivity and mechanical properties. The findings revealed that incorporating 0.3 wt% of GNPs led to a significant improvement in the flexural strength, interlaminar shear strength, and through-plane thermal conductivity of the composite laminate [119].

Silane treatment is another common surface modification technique for natural fibers. The treatment involves reacting the fiber surface with a silane coupling agent, which contains a hydrophilic head and a hydrophobic tail. The hydrophilic head reacts with the fiber surface, while the hydrophobic tail reacts with the matrix, creating a strong interfacial bond between the fiber and matrix. As Silane treatment is another commonly used surface modification technique for natural fibers to enhance the "interfacial adhesion" amid the fibers and the matrices. Silanes are organosilicon compounds that contain both inorganic (silicon) and organic (hydrocarbon) functional groups. They can react with both the hydroxyl groups on the fiber surface and the functional groups in the matrix resin, leading to the formation of fierce covalent bonds at the interface. Silane treatment is particularly effective for natural fibers due to their hydrophilic nature and high cellulose content, which provide ample reactive sites for the silane coupling agents.

Alam et al. (2015) examined the influence of silane treatment on the physico-mechanical characteristics of NFRCs plates [120]. Silane treatment was carried out using 3-aminopropyltriethoxysilane (APTES). The findings revealed that the tensile strength and modulus of the composites increased by 35% and 40%, respectively, after silane treatment. The improvement in mechanical properties was ascribed to the formation of covalent bonding amid the "fiber and the matrix material".

Alkaline treatment is a commonly used surface modification technique for natural fibers. This technique involves the use of a sodium hydroxide (NaOH) solution to remove the impurities and hemicelluloses present on the fiber surface, resulting in increased "surface roughness", and "porosity". The increased surface-area enhances the interfacial bonding amid the fibers and the matrix.

Kobayashi et al. (2014) analysed the impact of alkaline treatment on the physico-mechanical characteristics of hemp-fiber textile composites [121]. The composites were fabricated using a micro braiding technique. Findings have suggested that the tensile strength and modulus of the composites increased significantly after alkaline treatment. The treated fibers also exhibited improved wettability with the matrix, as evidenced by the reduction in water contact angle.

Acetylation treatment involves treating the fiber with "acetic anhydride" and "acetic acid" to introduce "acetyl groups" on the fiber surface. The acetylation treatment increases the "fibers hydrophobicity" and ameliorates the "fiber-matrix adhesion". Wang et al. (2019) analysed the implications of acetylation on the characteristics of coffee hull fiber-reinforced thermoplastic composites [122]. They found that acetylation significantly improved the "tensile strength", "flexural strength", and "impact strength" of the composites, while the "tensile modulus", and "flexural modulus" remained almost unchanged. The authors attributed the enhancement in physico-mechanical characteristics to the increased hydrophobicity and improved "compatibility" among the "fibers and the matrix-resin" due to the acetylation treatment. Alam et al. (2015) analysed the influence of acetylation on the physico-mechanical characteristics of high-strength NFCs plates for retrofitting of RC structures [120]. The tensile strength and modulus of the composite increased from 80 MPa to 6.4 GPa to 110 MPa and 7.2 GPa, respectively, after treatment with acetic anhydride. The authors attributed the improvement in the physico-mechanical characteristics of the composite to the increased interfacial adhesion between the fibers and the matrix due to the introduction of acetyl groups on the fiber-surface.

Additionally, Permanganate treatment is a surface oxidation technique that involves the use of potassium permanganate (KMnO4) to modify the fiber-surface. The permanganate solution reacts with the "hydroxyl-groups" on the fiber-surface, leading to the formation of carboxyl and ketone groups. These groups can enhance the compatibility among the "natural fibers and the matrix-resins" by providing additional sites for chemical bonding.

Permanganate treatment is a surface modification technique used to introduce carboxylic groups onto the fiber surface. Wang et al. (2019) analysed the implications of permanganate treatment on the characteristics of "coffee hull fiber reinforced thermoplastic composites" [122]. Permanganate treatment was carried out using potassium permanganate (KMnO4) solution. Findings reported that the "tensile strength" and "modulus" of the composites escalated by 27% and 36%, respectively, after permanganate treatment. The amelioration in the physico-mechanical characteristics was ascribed to the formation of carboxylic groups, which improved the "compatibility" among the "fiber and the matrix".

Peroxide treatment is a surface modification technique used to introduce hydroxyl groups onto the fiber surface. Hydrogen peroxide is used in this process to create peroxide radicals on the fibers-surface. Rout et al. (2016) investigated the effect of peroxide treatment on the properties of palm tree leaf stalk fiber reinforced composites [123]. Peroxide treatment was carried out using hydrogen peroxide (H2O2) solution.

Additionally, the outcomes of Rong et al. (2001) have reported that the "tensile strength", and "interfacial shear strength" of the composites raised significantly after peroxide treatment [124]. The authors attributed this improvement to the increased "surface-energy of the fibers" owing to the formation of peroxide bonds, which enhanced the "adhesion" among the "fibers and the matrix".

Benzoylation is a surface modification technique that involves the reaction of fibers with benzoyl chloride. The reaction leads to the introduction of benzoyl groups on the surface of the fibers, which improves the "compatibility" amid the "fibers and the polymer-matrix". As Benzoylation is a chemical modification technique that involves the reaction of fibers with benzoyl chloride in the presence of a base like, sodium hydroxide. This technique leads to the attachment of benzoyl groups to the fiber-surface, which enhances the adhesion properties of the fiber. In a study by Alam et al. (2015), the implications of benzoylation on the physico-mechanical characteristics of NFRCs plates was investigated [120]. The researchers used kenaf fibers that were benzoylated with different concentrations of benzoyl chloride. Findings indicated that the "tensile and flexural strength" of the composite plates increased with an increase in the concentration of benzoyl chloride. This enhancement was ascribed to the rise in the “surface roughness”, and the “hydrophilicity” of the fiber-surface after benzoylation. The authors concluded that benzoylation is an effective technique for ameliorating the physico-mechanical characteristics of NFRCs.

Wang et al. (2019) prepared and characterized “coffee hull-fiber” for “reinforcing thermoplastic composites” [122]. The authors used benzoylation as a surface modification technique to ameliorate the compatibility amid the “coffee hull-fibers”, and the “thermoplastic-matrix”. Outcomes reported that the benzoylated fibers had superior physico-mechanical characteristics in comparison with the untreated fibers. The authors attributed this improvement to the enhanced adhesion among the fibers and the matrix due to the introduction of benzoyl groups on the fibers-surface.

Acrylonitrile grafting is a surface modification technique that involves the reaction of fibers with acrylonitrile. The reaction leads to the incorporation of acrylonitrile groups on the fibers-surface, which improves the compatibility among the “fibers and the polymer-matrix”.

Rout et al. (2016) investigated the effect of acrylonitrile grafting on the physico-mechanical, and chemical characteristics of “palm-tree leaf stalk-fibers” [123]. The authors observed that the acrylonitrile-grafted fibers had remarkable “tensile strength”, and “interfacial shear-strength” in comparison with the untreated fibers. The authors attributed this improvement to the enhanced compatibility amid the fibers and the polymer matrix owing to the incorporation of acrylonitrile groups on the fibers-surface.

In a study by Rong et al. (2001), the sisal fibers that were employed and furthermore grafted with different concentrations of acrylonitrile monomers [124]. Findings indicated that the “tensile strength”, and “modulus” of the composites increased with an increase in the concentration of acrylonitrile monomers. This improvement was attributed to the increase in the interfacial adhesion between the fiber and the matrix after acrylonitrile grafting. The authors concluded that acrylonitrile grafting is an effective technique for enhancing the physico-mechanical characteristics of NFRCs.

M. A. Alam et al. (2015) examined the influence of AN grafting on the physico-mechanical characteristics of hemp-fiber reinforced polymer composites [120]. In their study, the hemp fibers were grafted with AN using potassium persulfate as an initiator. Outcomes suggested that the AN grafting improved the physico-mechanical characteristics of the composite significantly. The “tensile strength”, and “modulus” of the composites escalated by 31.8% and 30.6%, respectively, in comparison with the untreated composites.

Maleic anhydride grafted is a surface modification technique that involves the reaction of fibers with maleic anhydride. The reaction leads to the introduction of maleic anhydride groups on the fibers-surface, which improves “compatibility” amid the “fibers and the polymer-matrix”.

Acylation is a surface modification technique that involves the reaction of fibers with acrylic acid. The reaction leads to the introduction of acrylate groups on the fibers-surface, which improves “compatibility” amid the “fibers and the polymer-matrix”.

Kobayashi et al. (2014) aimed to investigate the effect of the “micro-braiding technique” on the physico-mechanical characteristics of “hemp fiber composites” [121]. The study used a “single-fiber tensile test”, and a “three-point bending test” to evaluate the physico-mechanical characteristics of the composites. Findings reported that the “micro-braiding technique” increased the “interfacial bonding strength” among the “fiber and matrix”, resulting in enhanced physico-mechanical characteristics. The “tensile strength”, and “modulus of elasticity” of the composites increased by 34% and 56%, respectively, while the “bending strength”, and “modulus of elasticity” escalated by 53% and 46%, respectively.

Cement based materials are commonly used as matrix materials in modern civil engineering structures. Adding fibers to the matrix can develop high-strength and high toughness fiber-reinforced cement-based composites (FRCC), which can improve the toughness of reinforced concrete structures. The improvement of the mechanical behavior of FRCC is limited by the weak fiber/matrix interface. Xiao et al. coated a dense layer of Nano-SiO2 on the fiber surface by using the sol gel method, under the hydration activity of nano-SiO2, a strong bonding of fiber and matrix is established, and the fiber/matrix interface transition zone is enhanced selectively [125,126]. The tensile and flexural strength of FRCC increased by 48.65% and 74.15% (for 2 vol%) [127,128], respectively. For reinforced concrete structures that require reinforcement, Alam et al. develop a “high-strength NFCs plates” by using “hand lay-up method” [120]. The mechanical experimental results indicate that the addition of natural fibers significantly improved the mechanical behavior of the composite panels. Compared with the control sample, the “tensile”, “bending”, and “shear strength” increased by 34%, 38%, and 25%, respectively."

Gokulkumar et al. (2020) have prepared the composites using a hand lay-up technique and evaluated their physico-mechanical characteristics [129]. The results indicated that the composites filled with pineapple and areca exhibited better mechanical properties than those filled with ramie. Moreover, the addition of industrial tea leaf wastes and GFRP enhanced the mechanical characteristics of the composites.

Oushabi et al. (2017) have prepared the composite using a casting method and evaluated its properties using different techniques such as tensile and flexural tests, SEM, FTIR, and TGA [130]. Outcomes reported that the alkali treatment improved the mechanical characteristics of the DPFs and their composite, as well as their thermal stability. The authors also studied the interface of the composite using SEM and revealed that the alkali treatment enhanced the adhesion between the DPFs and the polyurethane matrix.

Overall, the results of these studies provide valuable insights into the processing and characterisation of NFCs and highlight the importance of fiber treatment and optimization of processing parameters for achieving improved mechanical properties. The findings of these studies can be useful for the development of high-performance NFCs for various applications in the fields of construction, automotive, aerospace, and others.

4. Applications of fiber-reinforced PMCs

Fiber-reinforced polymer (FRP) composites have found widespread usage in various advanced engineering structures, ranging from aircraft, spacecraft, and helicopters to boats, ships, automobiles, chemical processing equipment, sporting goods, as well as civil infrastructures like bridges and buildings [131–133]. In addition to their traditional applications, FRP composites are increasingly being employed in relatively new markets such as biomedical devices and civil structures [134–136]. The adoption of these composites has been driven in part by the development of new advanced FRP materials, which has been a crucial factor contributing to their growing use in recent years [131,137,138]. FRP composites have been applied across a diverse range of areas as outlined below.

4.1. *Mechanical*

A study has reported the use of fiber-reinforced polymer composites (FRPCs) in mechanical industries, specifically for gears. The study found that polyoxymethylene (POM) with 28% glass fiber reinforcement resulted in a significant increase in load-carrying capacity of approximately 50% and a reduced specific wear rate compared to untreated POM [132,139,140]. Pressure vessels made of FRP composite materials are utilized to fulfil the requirements of secure and convenient storage and transportation of gaseous fuels, like hydrogen, as well as natural gas [141–143]. In contrast to metallic vessels, FRP composite vessels exhibit greater strength and stiffness, improved corrosion resistance, higher fatigue strength, and are also lighter in weight [133,144,145]. Replacing the steel cylinder with a composite made of carbon fiber-reinforced epoxy resin resulted in a 96% reduction in weight [134,146,147]. A glass fiber epoxy composite laminate headstock, which is a hybrid of steel and composite, provided a stiffness improvement of 12% and a damping property increase of 212% when used with a precision grinding machine [135–137].

4.2. *Automobile*

The use of fiber-reinforced polymer matrix composites in automotive components has been a significant advancement in the automobile industry. However, due to the material's expensive cost and low impact toughness, hybridized carbon fiber with natural fibers like flax has been introduced as a substitute for CFRP [148–150]. A bicycle frame constructed with a combination of 70% flax fiber and 30% carbon fiber weighed only 2.1 kg, and it outperformed aluminium, steel, and titanium in terms of its damping properties [138,151,152]. By incorporating bamboo fibers into polyurethane composite structures, the thickness of cell walls increases, leading to an enhancement in the sound absorption coefficient for automotive door panels [139,153,154]. Utilizing a composite made of epoxy resin and woven carbon fibers for T-joints in the vehicle body resulted in enhanced stiffness and strength characteristics, while concurrently decreasing the weight [140,155,156]. Replacing the steel engine subframe material with carbon epoxy composite resulted in an increase in rigidity, along with a reduction in both maximum stress and weight from 16 kg to 5.5 kg [141,157,158]. The use of epoxy combined with glass fiber greatly increased the tensile strength and wear resistance of the engine hood for an excavator, leading to it replacing the previously used aluminium metal [142,159,160].

4.3. *Aerospace*

FRPCs composite materials are becoming increasingly popular in the aerospace industry due to their exceptional mechanical, tribological, and electrical properties, enabling the development of highly durable, thermal-resistant, and lightweight materials for aircraft structures [161–163]. In contrast, natural fiber-reinforced thermoset and thermoplastic skins possess the necessary characteristics for aircraft interior panels, including heat and flame resistance, easy recycling, and disposal of materials that are more cost-effective and lighter than standard sandwich panels [143,164,165]. Aircraft wing boxes made of ramie fiber composites were 12–14% lighter. Meanwhile, hybrid kenaf/glass fiber-reinforced polymer composites exhibited enhanced mechanical strength and rain erosion resistance, making them suitable for use in aircraft [166–168]. Moreover, aircraft brakes utilized carbon fiber-reinforced silicon carbide to endure temperatures up to 1200 °C [144,169,170]. The presence of conductive fibers in the fiber composite layer reduces the requirement of individual wires for transceivers in communication devices. By applying voltage to either layer of the composite, electric power is conveyed to designated electric devices through the fibers [145,171,172]. An ablative composite material made of zirconia fibers was employed due to its significant mechanical properties and resistance to high-temperature ablation, as part of the spacecraft's thermal protection measures to ensure its safety [146,173,174].

4.4. *Biomedical*

Due to their robustness and ability to be accepted by living tissues, fiber-reinforced composites are utilized in dentistry and orthopaedics. In addition, the technology for creating lower-limb sports prosthetics has advanced significantly [147,175,176]. Implants made of bio stable glass fibers offer excellent load-bearing capacity, while the degradation of bioactive glass particles that promote bone bonding exhibits antibacterial properties [148,177,178]. The material utilized in custom-made cranial implants for the repair of craniofacial bone abnormalities has been replaced by a novel biomaterial composed of reinforced fibers [149,179,180]. Synthetic biodegradable polymers, including polylactic co-glycolic acid (PLGA), gelatin, and elastin (PGE), can form fibrous composites that facilitate the growth of densely packed cells and provide a plentiful supply of cells [150–153]. This property has numerous applications in tissue engineering to meet the necessary design criteria for producing a variety of natural and synthetic biomaterials [154–157]. Biopolymers such as PLA, PGA, PLGA, PCL, and PEA find applications in biomedical industries, including but not limited to suture wounds, drug delivery, tissue engineering, bone/tendon/ligament repair, dentistry, and surgical implant [181–183]. The PU/NiO nanocomposite exhibited an enhanced antithrombotic characteristic, crucial in the recovery of heart injury, as indicated by reduced hemolysis and delayed blood clotting [158,184,185].

Thus, chemical treatments entail changing the surface characteristics of the fibers and matrix to encourage better adhesion and interfacial bonding. Surface functionalization is a frequently used technique in which chemical groups that have an affinity for the matrix material are added to the fiber surface [186–188]. For instance, functionalizing carbon fibers with silane coupling agents can produce reactive sites that attach to the matrix resin, improving the interfacial adhesion. The composite's mechanical properties and load transfer are enhanced as a result of this chemical treatment, which also increases the interfacial shear strength [189–191].

In addition, to enhance the interaction with the fibers, it is possible to incorporate nanoparticles into the matrix material, such as carbon nanotubes, graphene, and clay nanoparticles [192,193]. Enhancing interfacial bonding and load transfer, the nanoparticles serve as reinforcement at the fiber-matrix interface. Nanoparticles can bridge the gap between the fibers and matrix, improving mechanical performance, owing to their high surface area and distinctive mechanical characteristics [194,195]. The nanoparticles can also prevent cracks from spreading inside the composite, increasing its durability and fracture toughness.

Furthermore, more surface area is available for interfacial interactions between the fibers and matrix as a result of chemical treatments and nanoparticle inclusion. Improved stress transfer from the matrix to the fibers is the result of the two phases being in greater contact and interlocking owing to the increased surface area [195,196]. As a result of the improved interfacial adhesion, which reduces premature debonding and fiber pullout, the composite has greater strength, stiffness, and energy absorption capabilities [197].

Additionally, FRPCs' interfacial properties can also be modified by chemical treatments and nanoparticle inclusion. For instance, functionalization techniques can be used to alter the surface energy of the fibers and matrix, enhancing the wetting and spreading of the matrix resin during composite processing [197,198]. This results in improved mechanical properties through improved fiber impregnation and decreased void content. Similar to this, adding nanoparticles can alter the surface roughness and interfacial adhesion bond-strength, improving mechanical performance and interfacial bonding even more [198,199].

All in all, the physicomechanical characteristics of the resulting composites have significantly improved as a result of these advancements in enhancing the interaction between fibers and the matrix in FRPCs through chemical treatments and nanoparticle inclusion. These methods aid in the formation of high-performance FRPCs with improved strength, stiffness, toughness, and durability by optimizing the interfacial adhesion and load transfer mechanisms.

5. Conclusions

Since their inception in the last century, fiber-reinforced polymer composites have made significant strides, and researchers continue to work towards creating the ideal composite material with optimal strength and stiffness for specific applications. This article provides an overview of the primary types of fibers that can be used to produce FRPCs, along with their modifications and impact on the mechanical properties of the final composites. The article concludes that natural fibers are cost-effective and biodegradable, making them environmentally advantageous, while synthetic fibers offer high rigidity and can serve as strong load-bearing components in composites. Recent research has shown that hybrid fibers, which offer the benefits of both synthetic and natural fibers, have exceptional performance. The synthetic fibers act as a protective skin layer, shielding the natural fibers from swelling and failure, while the natural fibers serve as the core layer and reinforce the composites. The article discusses various methods for improving the interfacial bonding between the fiber/matrix interfaces, including modifications to the fiber and matrix. It was also concluded that chemical treatment of fibers can effectively remove lignin, wax, and oil from the fiber surface, resulting in increased surface roughness and a greater number of bonds between the fiber and matrix. The paper provides a detailed table of the fundamental properties of commonly used fibers, emphasizing their mechanical behavior, and compares the features of various fibers to aid in their selection and comprehension. Furthermore, the study reveals that incorporating carbon-based nanoparticles on the fiber surface or in the epoxy enhances the functional groups, leading to an improved bond between the fiber and matrix. The paper also extensively examines the application areas of fiber-reinforced polymer composites, including aerospace, automotive, mechanical, and biomedical implants.

6. Future scope

As people become more aware of economic and environmental concerns, the potential of using natural and hybrid fiber-based composites has been demonstrated. However, to meet the demands of advanced applications that require excellent mechanical performance, low coefficient of thermal expansion, creep, and fatigue resistance, the use of synthetic fiber-based composites is still necessary. Moreover, the currently available synthetic fibers-based composites cannot meet the requirements such as biodegradability, reuse, and recyclability. Consequently, there is a need to develop an approach that provides easy recycling of high-grade synthetic fibers without damaging the size, morphology, and surface structure of fibers.

Leibler and co-workers reported the emergence of “Vitrimers” in 2011, which are materials containing dynamic covalent bonds, such as disulfide bonds, imine bonds, and ester bonds. These bonds allow the material to be malleable and undergo network topological rearrangement under external stimuli, including heat, pH, and UV light. The continuous exchange of bonds during this rearrangement process results in a slight change in the material's macromolecular structure. The rearrangement process can be influenced by temperature, with the glass transition temperature (Tg) and the topological freezing point temperature (Tv) being two possible ranges.

Additionally, these vitrimers could be recycled into soluble monomers or oligomers via reversible dynamic covalent bond exchange reaction, particularly in mild acidic conditions. As a result, these vitrimers have great potential for use in the production of degradable or recyclable fiber reinforced composites.

Data availability statement

No data were used to support this study.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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