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Review

Physical, Mechanical, and Thermal Properties of Natural Fiber-Reinforced Epoxy Composites for Construction and Automotive Applications

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Featured Application: Due to its environmental acceptability, technological feasibility, and economic viability, natural fiber-reinforced epoxy composite exhibits many potential engineering applications.

Abstract: Industrialization and population growth have significantly increased the demand for lightweight, high-strength materials for construction and automotive applications, ultimately increasing the demand for eco-friendly materials. Due to its environmental acceptability, technological feasibility, and economic viability, natural fiber-reinforced composite exhibits many potential engineering applications. However, the production and recycling of natural fibers are expensive. Researchers are now comparing natural fiber-reinforced composites with synthetic composites to determine the best materials, especially for construction and automotive engineering applications. This review paper focuses on natural fiber reinforced epoxy composites' physical, mechanical, and thermal characteristics. These properties are critical for the effective design and use of composite materials such as construction and automotive applications. This review begins with a background of epoxy and natural fibers. The physical and chemical treatment for natural fiber composites to improve their properties is also briefly discussed, along with the critical factors affecting the physical, mechanical, and thermal properties of natural fiber-reinforced composites. Finally, concluding remarks and suggestions for future works are given.

Keywords: natural fiber; composites; thermal properties; physico-mechanical properties; construction; automotive; eco-friendly

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1. Introduction

The demand for low-energy consumption processes and low environmental impact have furthered the development of natural fiber-reinforced composites (NFRCs) in various industries. Natural fibers exhibit numerous benefits compared to synthetic fibers, such as biodegradability, lightweight, cheap, low density, acoustic insulation, and improved life-cycle performance characteristics [1–5]. The selection of materials and design plays an important role in engineering design. The materials should possess excellent physical, thermal, and mechanical properties to make better products and fulfil customer demand. The emergence of new technologies, population growth, industrialization, and housing shortages has led to the growth of construction and automotive industries worldwide [6]. There is a need for alternative building materials due to the unsustainability of modern construction materials. Using natural resources to create biodegradable composite materials is one such step toward protecting the environment. Composites manufactured from natural fibers as reinforcements are an alternative in this direction [1].

Matrix material is required in fabricating NFRCs to bind natural fibers and fillers to form a structure [7]. Epoxy has been widely used as a matrix material in NFRCs due to its excellent abrasion properties, good electrical insulating quality, resistance to moisture and chemical attacks, high mechanical strength, and appreciable resilience [8–10]. Epoxy can be cured without using a curing agent or heating at room temperature without pressure [11]. Prileschajew [8] was the first to discover epoxy resins in 1909. However, the first commercial production of epoxy resin began in the late 1940s. Epoxy adhesives became commercially available in the early 1950s, and continuous innovations have been made in various applications. In 1953, the Shell Chemical Corporation initiated field tests to evaluate epoxy systems as surfacing materials on highways [8,12]. Additionally, in 1953, the first application of epoxy seal coating as test patches in industrial plants was made. Later, in 1957, epoxy polymer concrete was used as the first wearing course to repair pop-outs and spalled areas on the surfaces of bridge decks in California [8]. Nowadays, epoxy resins are used as a polymer with natural fiber reinforcements in countless construction applications and automobile sectors, such as thin-layer non-skid surfacing for roads and bridges, aerospace industries, and housing [8,9,12].

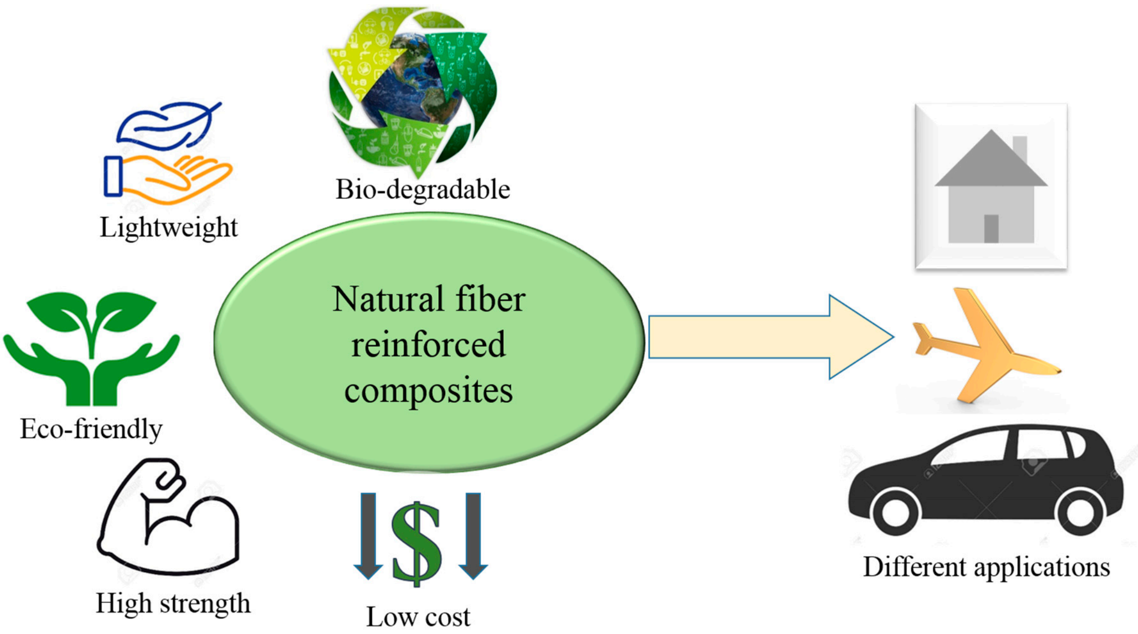
Several researchers are working on toughening/strengthening agents to enhance the properties of epoxy resin in structural and automotive applications [13–15]. Incorporating nano-silica, thermoplastic components, inorganics, carbon fibers, graphene, clay, and carbon nanotubes improves the toughness of epoxy resin [16]. The common physical and mechanical properties of epoxy resin are shown in Table 1 [17–20]. The epoxy matrix is composed of resin and hardener, which are usually mixed in a ratio of 10:1. The epoxy resin has a wide range of applications including uses for coatings, aerospace industries, composites, the bio-medical field, and electronics material. Figure 1a shows the properties of NFRCs and their applications. Figure 1b shows various steps involved during NFRCs fabrication.

Table 1. Physical and mechanical properties of epoxy resins **[17–20]**.

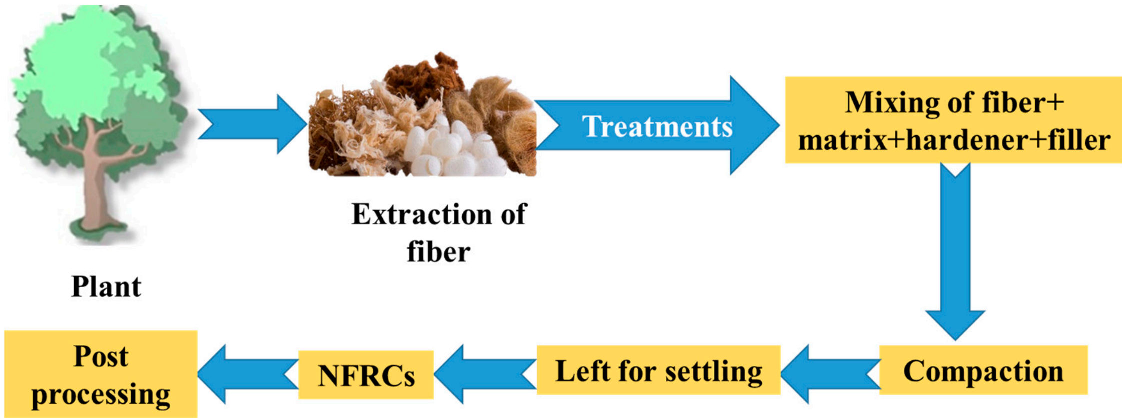
Appearance	Colourless to Pale Yellow Liquid
Flexural strength (MPa)	40–67
Specific gravity (kg/m^3)	1120–1210
Viscosity at 25 °C (kg/m s)	0.25–0.75
Heat distortion temperature (°C)	50
Solid content (%)	84
Modulus of elasticity (MPa)	3100 to 3800
Tensile strength (MPa)	90 to 120
Max percentage elongation (%)	4
Impact strength (kg/m^2)	9
Glass transition temperatures	150 to 220 °C

Few reviews are available on construction materials with synthetic and natural fiber. Still, no review covers the physical, mechanical, and thermal properties of the NFRCs used in different applications such as automotive and construction. This review paper focuses on natural fiber-reinforced epoxy composites' physical, mechanical, and thermal characteristics. Moreover, the various chemical and physical treatments and their effects on the physical, mechanical, and thermal behaviour of the NFRCs are presented. These properties are critical for the effective design and use of composite materials in construction and automotive construction applications. This review has been divided into the following sections:

(1) Epoxy-based composites based on reinforcement;
(2) Physical and mechanical properties of natural fibers;
(3) Physical properties of the natural fiber-reinforced epoxy composites;
(4) Mechanical properties of the natural fiber-reinforced epoxy composites;
(5) Thermal behaviour of the natural fibers reinforced epoxy composites;
(6) Physico-chemical treatment of the natural fibers;
(7) Applications of natural fiber-reinforced epoxy-based composites;
(8) Summary and future perspectives.



(**a**)



(**b**)

Figure 1. (**a**) NFRCs characteristics in construction and automotive applications. (**b**) Steps involved in NFRCs fabrication.

2. Epoxy-Based Composites

2.1. Epoxy-Based Composites Reinforced with Recycled Aggregates

Because of their environmental benefits, natural fibers are increasingly being used in various engineering applications such as automotive, infrastructure, aerospace, and packaging. Compared to glass fiber and carbon fiber composites, less research has been carried out on their reuse and recycling. Alamri and Low [21] used different fiber loadings of 19, 28, 40, and 46 wt.% to make recycled cellulose fiber (RCF)-reinforced epoxy composites. The results revealed that flexural strength, flexural modulus, fracture toughness, and impact strength increased when the fiber content rose. With 46 wt.% fiber, the maximum mechanical characteristics were obtained. Water absorption influence on the mechanical and physical characteristics of RCF/epoxy composites has also been studied. The maximum water absorption and diffusion coefficient increased as the fiber content increased. As moisture absorption increased, the flexural strength, flexural modulus, and fracture toughness decreased. However, with water absorption, the impact strength was observed to rise somewhat [21,22]. Using paper sheets made from recycled cardboard boxes, Soya oil-based resin and cellulose fibers were successfully used to manufacture the composite structures. Epoxy composites made from recycled aggregate generally have two-fold benefits: first, wastage is reduced; second, a high-strength composite can be obtained from these wastes.

2.2. Epoxy-Based Composites Reinforced with Natural Fibers

Bio-composites made from epoxy polymer and natural fibers have a great scope of research for engineering applications such as structural applications. Researchers have continued working with natural fiber and epoxy polymer-based bio-composites over the last decade. The problem with natural fibers is that they cannot be used as reinforcement material due to lignin hydrophobicity [23] and some impurities. However, the alkali-treated fibers can be used as the alkali treatment of fiber removes such impurities [24]. Therefore, the researchers focused on alkali-treated natural fibers to control synthetic fibers, and non-biodegradable waste, to produce epoxy-based bio-composites. Natural fiber composites possess environmental benefits as they are biodegradable. Natural fibers have many advantages: high strength, light weight, water resistance, corrosion resistance, high durability, electrical resistance, fire resistance, good thermal and acoustic insulating properties, and chemical resistance. As natural fiber composites are environmentally friendly, they regain attention over the synthetic fiber. The first used natural fiber composite was straw-reinforced clay for bricks and pottery [18,25,26]. NFRCs are either a combination of natural fiber and synthetic resin or natural fibers and bio-resin. Bio-resins refer to resin biodegradability; bio-resins and synthetic resins are in the form of thermoplastic or thermoset resin. Thermoset resin is the most used resin for the structural applications of natural fiber composites. NFRCs are used in aerospace industries [27,28] and automobile industries [29]. These composites have also been used in biomedical applications such as tissue and bone repair [30].

Common natural fibers are hemp, jute, nettle, coir, agave, sugar palm (Gomuti), sisal, flax, ramie, and cotton. These fiber composites are gaining importance due to their strength, corrosion resistance, biodegradability, and many more advantages in engineering applications such as automobile, aerospace, structural components, and construction. However, some disadvantages are associated with NFRCs, such as moisture absorption and processing temperature. Due to their unique features, such as low density and a cellular structure, natural fibers provide great acoustic and thermal insulation [31]. However, some of these disadvantages can be improved with fiber treatments before composite fabrication. The fiber orientation and length improve the natural fiber composites' mechanical and physical properties [7,32]. NFRCs are composites whose mechanical efficiency is determined by the fiber–matrix interface and the stress transfer function, which transfers stress from the matrix to the fiber. Many investigators in several research papers have reported this [26,33–42].

3. Physical and Mechanical Properties of the Natural Fibers

The physical and mechanical properties of common natural fibers' reinforcement are represented in Table 2.

Table 2. Physical and mechanical characteristics of natural fibers.

Natural Fiber	Physical Appearance and Texture	Density (g/cm^3)	Diameter (μm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Ref.
Jute	Light brown, fine	1.3–1.45	25–200	393–773	13–26.5	1.5–1.8	[43,44]
Sisal	White, coarse-stiff	1.45	50–200	468–640	9.4–22	3–6	[43,44]
Hemp	White to light brown, silky-fine	1.48	26.5	514	24.8	1.5–4	[45–47]

Table 2. *Cont.*

Natural Fiber	Physical Appearance and Texture	Density (g/cm^3)	Diameter (µm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Ref.
Coir	White to brown, coarse	1.15	100–450	131–175	4–6	4–6	[43,48]
Sugar palm	Brown to black, coarse-stiff	1.29	50–800	190.29	3.69	–	[49]
Sugarcane bagasse	-	0.33	67–312	222	27.1	–	[50]
Nettle	-	0.72	15.5–24.3	1594	59–115	–	[18,51]
Saw dust	Generally light yellow to brown (varies from trees to trees), particles	2.05 (SG) 0.31–0.32	75–600	16–24	0.2×10^{-3}–0.36×10^{-3}	–	[52–54]
Wood chips	Generally light yellow to brown (varies from trees to trees)	0.28–0.32	3000–16000	–	0.25×10^{-3}–0.33×10^{-3}	–	[54]
Softwood	-	1.5	–	1000	0.04	4.4	[55]
Flax Agatha	-	1.50–1.53	14.4–15.6	962–1800	46–96	–	[47]
Ramie	-	1.51	34	400–968	60–128	3.6–3.8	[43,47]
Okra	-	–	61–93	184–557.3	8.9–11.8	4–8	[56]
Agave	-	1.20	126–344	–	–	7.07	[56]
Banana	-	1.35	50–250	600	17.85	3.36	[56]
Sea grass	-	1.50	5	453–692	3.1–3.7	13–26.3	[56]
Kenaf		1.3	–	233	40–53	1.8	[50,57,58]
Cotton	White, creamy white, yellowish white, fine	1.51–1.6	2–7	287–597	5.5–12.6	3–10	[43,59]
Luffa	-	0.82	25–60	385	12.2	–	[50]
Banana	-	1.35	70–210	198.9–780.3	6.6–25.6	–	[60–62]
Rice husk	Fine, grey	2.30–2.36	45 Particle size	–	–	–	[63]
Coconut coir	-	1.15	100–450	500	2.5	3.36	[55]
Napier	-	0.36	–	73	5.68	1.4	[64]
Bamboo	White yellow	0.51–0.72	21–26	225	17.2	3	[65,66]
Abaca	-	0.83	1.5	900	12–13.8	3–12	[55]
Flax ariane	-	1.53	12–23.6	853–1825	43–73	1.2–3.2	[44,47]
Date	-	0.99	–	309	11.32	2.73	[56]
Palmyrah	-	1.09	8	180–215	4.4–6.1	–	[49]
Pineapple leaf	-	1.07–1.50	20–80	413–1627	34.5–82.5	1.6	[50]
Henequen	-	1.4	–	430–580	–	–	[24]
Ramie	-	1.50	50	220–938	44–128	2–3.8	[56]

4. Physical Properties of the Natural Fibers Reinforced Epoxy Composites

Apart from fiber, the matrix material also plays an important role in the physical properties of the NFRCs. The process of manufacturing also affects the properties of the NFRCs. The physical properties of some natural fiber-reinforced epoxy composites are shown in Table 3.

Table 3. Physical properties of natural fiber-reinforced epoxy composites.

Composites	Density (g/cm^3)	Porosity/Volume of Void Fraction	Water Absorption % (Till Steady State)	Ref.
Jute/epoxy (25/75)	1.08	7.50	-	[31]
Jute/epoxy (35/65)	1.276	1.09	10	[67]
Bagasse/epoxy (3/97), 5 mm fiber length	1.14	1.02	7.12	[26]
Bagasse/epoxy (3/97), 10 mm fiber length	1.13	1.94	8.11	[26]
Bagasse/epoxy (3/97), 15 mm fiber length	1.12	2.62	16	[26]
Hemp/epoxy (9/91)	1.275	3.40	0.7	[18]
Hemp/epoxy (25/75)	1.10	6.12	-	[31]
Nettle/epoxy (9/91)	1.283	5.17	1	[18]
Hemp + nettle/epoxy (18/82)	1.35	2.46	1.2	[18]
Prosopis juliflora/epoxy (20/80)	1.14	-	-	[68]
Abutilon indicum/epoxy (20/80)	1.12	-	-	[68]
Tapsi/epoxy (20/80)	1.31	-	-	[68]
Coir/epoxy (30/70)	1.28	-	0.09	[69]
Banana/epoxy(30/70)	1.10	-	0.1	[69]
Sisal/epoxy (30/70)	1.16	-	0.05	[69]
Flax/epoxy (25/75)	1.07	8.09	-	[31]
Jute + hemp/epoxy (25/75)	1.09	6.89	-	[31]
Flax + hemp/epoxy (25/75)	1.08	7.52	-	[31]
Jute + hemp + flax/epoxy (25/75)	1.10	6.30	-	[31]
(Kevlar + Jute)/epoxy ((20 + 20)/60 0° fiber orientation	1.23	4.27	-	[70]
(Kevlar + Jute)/epoxy ((20 + 20)/60 30° fiber orientation	1.22	5.20	-	[70]
(Kevlar + Jute)/epoxy ((20 + 20)/60 45° fiber orientation	1.20	6.75	-	[70]
(Kevlar + Jute)/epoxy ((20 + 20)/60 60° fiber orientation	1.20	6.75	-	[70]
Agave raw fiber	1.20	-	7.69	[71]
Agave fiber with 5% NaOH	1.30	-	8.74	[71]
Agave fiber with 10% NaOH	13.2	-	8.64	[71]

4.1. Wear Behaviour

The sliding wear resistance of the NFRCs shows its ability to resist fiber breakage, polymer degradation, thinning, and separation. The wear characteristics of NFRCs also depend upon the fiber orientation and interfacial adhesion between the reinforced fibers [72–74]. The wear properties of the epoxy matrix can be significantly improved by incorporating different natural fibers because fiber addition increases mechanical strength [68,75]. The wear characteristics of the NFRCs improve with the fiber loadings; however, the higher fiber loading reduces the wear characteristics as the formations of voids occur during the fabrications of the composites. Composites of a high degree of wear resistance and coefficient of static friction (CoF) can be used as the bearing materials in automobiles or other applications.

Shivamurthy et al. [76] investigated the wear behaviour of the banana fibers (short length) and $Al(OH)_3$ particulate (filler) composites in an epoxy matrix. The findings indicated that combining fiber and filler in an epoxy matrix has a synergistic effect that improves the wear resistance of the composites. Similar observations have also been seen by Prasad et al. [77]. Mylsamy and Rajendran [78] investigated the wear behaviour of NFRCs of agave fiber of different lengths (3, 5, and 7 mm). They found that with an increase in the wt.% of the filler in the composite, the maximum CoF increased, leading to better friction properties of the composites. Ridzuan et al. [79] observed that the Napier fiber-based epoxy composite CoF was higher than the hemp and pineapple fiber-based epoxy composite at each wt.% of filler due to the lower penetration depth in Napier fiber-based epoxy composites. The effect of nanoclay (1, 3, and 5 wt.%) on the mechanical behaviour of sisal fiber-reinforced epoxy composites was investigated by Mohan and Kanny [80]. They observed that the composites' wear properties marginally decreased due to the increased water adsorption upon reinforcing. The wear characteristics of the NFRCs depend upon factors such as fiber orientation, loading, aspect ratio, and interfacial adhesion. Adding fibers up to a certain limit increase the wear characteristics of NFRCs. The addition of filler can also improve the wear performance. Moreover, the penetration depth of the fibers also affects the wear behaviour of the NFRCs.

4.2. Porosity

Porosity or voids are critical parameters in NFRCs that affect mechanical and physical properties. Porosity occurs due to the presence of air during processing and restricted wettability of fibers, lumens, and other hollow structures within fibers/fiber bundles (which may close during high-pressure processing). The porosity of the NFRCs also depends on the fiber type, fiber orientations, and fiber length [81,82]. With increased fiber loading, the porosity of the NFRCs rises due to an increase in density or fiber matrix compatibilization [33]. The porosity in the NFRCs can be reduced during the fabrication with the proper precautions and high pressure.

Oladele et al. [83] reported that treated fiber-reinforced composites exhibited less porosity than the untreated fiber reinforcement due to proper binding between fiber and matrix resulting from higher roughness of the treated fiber surface. Gieparda et al. [84] found that a 1% silane modification of flax fiber significantly reduced the porosity of the composite. Ramakrishnan et al. [85] reported that the addition of banana (fiber) and ash (filler) in the composites of sisal/pineapple and epoxy reduced the porosity of the composite. Laraba et al. [86] investigated the performance of the jute and alfa fiber epoxy composites for construction applications and concluded that the hybrid composites of these fibers could be effective for a non-structural component in building materials.

The porosity in the NFRCs affects the mechanical properties; therefore, it should be taken care of during the fabrication of NFRCs. Although porosity can be eliminated, it can be minimized with fiber loading, fiber treatment, and precautionary measures during the fabrication.

4.3. Water Adsorption

A comparative study between treated and untreated banana/epoxy composites was performed by Venkateshwaran et al. [87]. The natural fibers with high water adsorption decreased the composites' mechanical properties. Water absorption is more likely to increase with the increase in cellulose content because, with cellulose content, the number of free hydroxyl groups also increases [88]. The water absorption of treated banana/epoxy composites at 1% NaOH concentration exhibited improved properties and reduced hydrophilicity. Prasad et al. [89] reported that an increase in fiber content increased the water adsorption of NFRCs attributed to water penetration between the fiber and matrix gap, lumen, and shell wall. Water adsorption resistance increased with the hydrophobic matrix (epoxy) attributed to the lumen space being occupied by the matrix material [90]. Moreover, water adsorption of the NFRCs was reduced with alkali treatment. However, higher concentrations of alkalization increased the water adsorption of the NFRCs.

The physical properties of the NFRCs increase with fiber loading, fiber treatments, and filler addition. Higher porosity leads to a deterioration in the physical properties of the NFRCs significantly. Water adsorption is also critical in NFRCs and can be decreased with the proper fiber treatment and use of hydrophobic matrix material.

5. Mechanical Properties of the Natural Fibers Reinforced Epoxy Composites

Table 4 includes the mechanical characteristics of the epoxy bases' natural fiber composites and the effect of fiber loadings, orientation, lengths, and treatments. The chemical treatments of the fibers decrease the moisture content and other impurities that restrict the adhesion between fibers and matrix, which leads to improved mechanical strength. The plasma treatment of the fibers also improves mechanical characteristics. Still, longer plasma treatments of the fibers reduce the mechanical characteristics as the degradation of the fibers occurs due to the longer time of plasma treatment. The fiber treatments and optimum fiber loadings show the optimum properties of the NFRCs that lead the NFRCs to different constructional applications such as automobiles, aerospace industries, and housing applications.

Table 4. Natural fiber–epoxy composites—mechanical behaviours [91].

Composites (wt%/wt%)	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Strength (J/m)	Impact Energy (kJ/m^2)	Hardness	Ref.
Coir/epoxy (30/70), 5 mm fiber length	3.208	25.41	-	16.0	15 HV	[92]
Coir/epoxy (30/70) 20 mm fiber length	9.15	31.28	-	16.5	12.6 HV	[92]
Coir/epoxy (30/70) 30 mm fiber length	13.05	35.42	-	17.5	16.9 HV	[92]
(Kevlar+ Jute)/epoxy (20 + 20)/60 0° fiber orientation	75	42	-	-	-	[70]
(Kevlar+ Jute)/epoxy (20 + 20)/60 30° fiber orientation	94	33	-	-	-	[70]
(Kevlar+ Jute)/epoxy (20 + 20)/60 45° fiber orientation	71	45	-	-	-	[70]
(Kevlar+ Jute)/epoxy (20 + 20)/60 60° fiber orientation	68	35	-	-	-	[70]
Sisal/epoxy (15/85)	66.74	204.3	-	-	-	[93]
Sisal/epoxy (20/85)	87.54	167.7	-	-	-	[93]
Sisal/epoxy (25/85)	74.89	235.3	-	-	-	[93]
Sisal/epoxy (30/85)	132.73	288.6	-	-	-	[93]
Sisal/epoxy (30/85), mat form	89.30	152.12	-	-	-	[93]

Table 4. *Cont.*

Composites (wt%/wt%)	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Strength (J/m)	Impact Energy (kJ/m^2)	Hardness	Ref.
Jute/epoxy (35/65)	38.00	10	-	10.2		[67]
Banana/epoxy (5/95)	26.3	46.2	-	220	54.5 HRB	[94]
Banana/epoxy (10/90)	27.2	52.5	-	2400	60.8 HRB	[94]
Banana/epoxy (15/85)	30.4	56.3	-	2700	65.4 HRB	[94]
Banana/epoxy (20/80)	29.4	54.3	-	2600	68 HRB	[94]
Coir/epoxy (30/70)			-	4 J	36 HRC	[69]
Banana/epoxy (30/70)			-	5 J	63 HRC	[69]
Sisal/epoxy (30/70)			-	4 J	54 HRC	[69]
Pine/epoxy (10/90)	53	61	-	18	-	[95]
Pine/epoxy (20/80)	50	57	-	16	-	[95]
Pine/epoxy (30/70)	39	43	-	14	-	[95]
Pine/epoxy (40/60)	36	38	-	11	-	[95]
Bagasse/epoxy (3/97), 5 mm fiber length	26.36	-	-	2.4	25 HV	[26]
Bagasse/epoxy (3/97), 10 mm fiber length	29.23	-	-	2.5	39 HV	[26]
Bagasse/epoxy (3/97), 15 mm fiber length	23.57	-	-	3.7	32 HV	[26]
Flax fabric/epoxy (26.64/73.36), 2 mm laminate thickness	35.59	-	-	-	-	[96]
Flax fabric/epoxy (21.17/78.83), 4 mm laminate thickness	29.74	-	-	-	-	[96]
Agave/epoxy (30/70), untreated, 3 mm fiber length	-	55	120	-	-	[97]
Agave/epoxy (30/70), NaOH treated, 3 mm fiber length	-	60	140	-	-	[97]
Agave/epoxy (30/70), untreated, 7 mm fiber length	-	41	100	-	-	[97]
Agave/epoxy (30/70), NaOH treated, 7 mm fiber length	-	48	115	-	-	[97]
Agave/epoxy (30/70), untreated, 10 mm fiber length	-	41.5	55	-	-	[97]
Agave/epoxy (30/70), NaOH treated, 10 mm fiber length		39	63	-	-	[97]
Areca/epoxy (50/50)	27.50	25.00	93.33	-	-	[98]
Ramie/epoxy (40/60)	86	103		-	-	[99]
Pseudo stem Banana-epoxy	45.57	73.58	92.66	-	-	[100]
Ground nuts shell/epoxy (12.5/87.5)	36.66	43.43	7.91	-	6.8 HRF	[101]
Rice husk/epoxy (12.5/87.5)	12.71	22.72	4.27	-	6.9 HRF	[101]
Coir pith-epoxy	9.00	23.00	18.67	-	-	

Table 4. *Cont.*

Composites (wt%/wt%)	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Strength (J/m)	Impact Energy (kJ/m^2)	Hardness	Ref.
Banana + sisal/epoxy (8/92), 5 mm fiber length	9.48	28.43	2.15	-	-	[102]
Banana + sisal/epoxy (12/88), 5 mm fiber length, 5 mm fiber length	16.39	26.15	2.37	-	-	[102]
Banana + sisal/epoxy (16/84), 5 mm fiber length, 5 mm fiber length	12.74	37.56	2.62	-	-	[102]
Banana + sisal/epoxy (8/92), 10 mm fiber length	8.54	22.22	5.21	-	-	[102]
Banana + sisal/epoxy (12/88), 5 mm fiber length, 10 mm fiber length	15.52	31.4	8.33	-	-	[102]
Banana + sisal/epoxy (16/84), 5 mm fiber length, 10 mm fiber length	10.3	25.56	11.56	-	-	[102]
Luffa + groundnut- epoxy (40/60)	20	53	-	1.1	-	[103]
Hemp/epoxy (9/91)	69.85	10.15	-	5.7	50.1 HV	[18]
Nettle/epoxy (9/91)	66.9	16	-	6.7	52.0 HV	[18]
Hemp + nettle/Epoxy (18/82)	71.72	14.21	-	6.2	59.1 HV	[18]
Prosopis Juliflora/epoxy (20/80)	72	254	74	-	-	[68]
Abutilon Indicum/epoxy (20/80)	67	216	92	-	-	[68]
Tapsi/epoxy (20/80)	49	225	45	-	-	[68]

5.1. Tensile Behaviour

The tensile behaviour of a material represents its ability to stretch under pulling force without failure. The natural fibers' tensile strength and modulus of elasticity increase with the cellulose content [104]. Balaji et al. [94] studied the behaviour of banana fiber-reinforced epoxy (wt.% (0–20%)) composites. The study found improvement in the mechanical properties such as tensile strength, impact strength, and flexural strength with the increase in banana fiber up to 15 wt.%, after which it decreased. Another study [76] with banana fiber-reinforced epoxy composites also found that as the banana fiber wt.% reinforcement increased, the tensile strength and hardness of the composites increased up to a certain wt.% reinforcement. Initially, the increment in the fiber and epoxy matrix adhesion leads to an increment in the tensile strength of the NFRCs as it can bear load because of increased matrix bonding by covering the complete surface area of fiber [38,105]. The decrease in the mechanical properties of the NFRC after a certain wt.% reinforcement is due to the increase in porosity caused by poor adhesive bonding between fiber and epoxy. Reddy et al. [68] presented the experimental study using different natural fibers' (Prosopis Juliflora, Abutilon Indicum, and Tapsi) reinforcement. The tensile and flexural strength of the NFRCs increased as the fiber loading increased, but after further increments (>20 wt.%) of fiber, the strengths decreased. Biswas et al. [92] showed an increment in the tensile strength of the fabricated composites as the coir fiber length increased.

Fiber orientation also plays an important role in regard to tensile strength. A study with different fiber loadings (30, 40, and 50 wt.%) and orientations (0°, 30°, 45°, and 60°)

was conducted by Maharana et al. [70]. They found that the tensile strength increased when the fiber loading was increased from 30 to 40 wt.% due to the better matrix and fiber adhesion. However, the further increment in the fiber loading (50 wt.%) lowered the tensile strength due to increased voids resulting from the improper matrix and fiber adhesion. Hossain et al. [95] investigated the effect of fiber loading in pine fiber epoxy composite. They found that the tensile strength increased up to 10 wt.% fiber loading and decreased afterwards. This was attributed to poor adhesion of fiber and matrix with the high-fiber content.

The chemical treatment of the fiber also leads to improvement in the tensile properties of the composites. Plasma treatment has improved interfacial adhesion by enhancing hydrophobicity at fiber surfaces and increasing fiber surface roughness [106]. The hardness of untreated bagasse composites and treated fibers with 10% NaOH indicated that the tensile strength of the treated composites increased, but their hardness dropped [107].

Alkali treatment, silane treatment, and isocyanate treatment have been shown to increase the tensile strength of flax/epoxy composites [108]. The 5% NaOH-treated fibers showed a higher tensile strength, attributed to a better surface smoothness and chemical interaction between matrix and fiber. However, further NaOH concentration increases decreased tensile strength as the fibers start to degrade [71]. Sakthivel and Ramesh [69] investigated the use of epoxy-based NRFCs (coir, banana, and sisal) in vehicle seat shell manufacturing applications. Boopalan et al. [109] investigated the effect of hybridization of the jute and banana fibers (100/0, 75/25, 50/50, 25/75, and 0/100 wt.%). The hybrid composite with 50/50 wt.% jute and banana fibers showed the best tensile strength due to better fibers and epoxy adhesion.

5.2. Impact Strength/Toughness

The impact energy of the materials is the resistance against the high-speed stress or material's toughness. The composite's ability to store energy during plastic deformation is improved as additional fibers are added because more energy will be required to break fiber bundles [18]. A comparative study between treated and untreated banana/epoxy composites was performed by Venkateshwaran et al. [87]. The impact strength of treated banana/epoxy composites increased at 1% NaOH concentration. Punyamurthy et al. [110] studied the effect of fiber loading (10, 20, 30, 40, 50, and 60 wt.%.) and surface modification techniques such as alkali (6%), acrylic acid (1%), permanganate treatment (0.5%), and benzene-diazonium chloride on the impact strength of the abaca-reinforced epoxy composite. The benzene-diazonium chloride-treated fiber epoxy composites showed better impact characteristics. The untreated fiber composites showed poor impact characteristics, irrespective of fiber loading. The chemical treatment improved the fiber–matrix adhesion by removing non-cellulosic components and adding hydroxyl (-OH) groups. The 40 wt.% of fiber loading showed better distribution in the matrix composite, low fractures, and better load transfer from fiber to the matrix. However, beyond 40 wt.% fiber loading, the impact strength decreased due to poor bonding and less load transfer from the matrix to fibers (Figure 2). The effect of alkali and silanized woven sisal fibers on the mechanical properties of natural rubber/epoxy composites was investigated by Srisuwana et al. [111]. They observed that grafted depolymerized natural rubber with 1 wt.% methyl methacrylate/glycidyl methacrylate had a 163% greater impact stregth value than epoxy resin. Olaitan et al. [101] performed a comparative study between groundnut shell and rice husk epoxy composites with different fiber loadings. The groundnut shell-reinforced epoxy composites showed superior mechanical characteristics compared to the rice husk-reinforced epoxy composites. Low-velocity impact behaviour of hemp–basalt/epoxy-reinforced composites was studied by Kumar et al. [112]. The results indicated better impact behaviour of hybrid composites than hemp and basalt-reinforced composites. The impact strength of NFRCs can be improved by proper chemical and physical treatments [113]. The fracture progresses along with the fiber–matrix interface in composites with poor interfacial bonding, causing debonding and substantially improving the composites' energy absorption capabilities. The good adhesion between the fiber and the matrix is responsible for better fracture resistance under impact loading [114]. Fiber loading can also improve the energy absorption capability of the fibers.

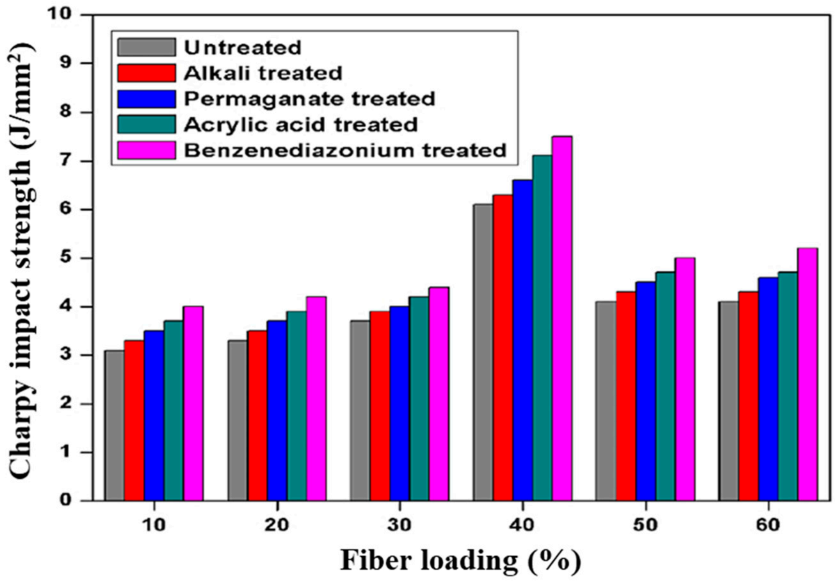


Figure 2. Effect of the fiber loading (10–60 wt.%) and chemical treatment on impact strengths of abaca-reinforced epoxy composite [110]. Reprinted with permission. Copyright 2014 MNFR.

5.3. Flexural Behaviour

The flexural strength of a material is its ability to withstand maximum tensile stress during bending without failure, or it can withstand bending forces perpendicular to its longitudinal axis. For the components subjected to bending, the flexural test is more appropriate, such as the beam in housing. The flexural modulus and strength of the composites can be increased with fiber loading and epoxy due to the fibers' higher flexural strength and modulus. Natural fibers such as bast and leaf fibers have the best effectiveness among the lignocellulosic reinforcements. Kenaf and bast fiber-reinforced epoxy composites have greater strength than kenaf core fiber composites [104]. The effect of fiber length on flexural strength was investigated by Biswas et al. [92]. They reported that with an increase in fiber length, flexural strength increases. Maharana et al. [70] studied the effect of fiber loading and orientation. They found that as the fiber content increased, flexural strength increased. Whereas, when the fiber orientation increased from 0° to 30°, the flexural strength decreased, but with a further increase (45°) in fiber orientation, the flexural strength increased. The 45° orientation was found to be optimum for all fiber loading. Hossain et al. [44] studied the effect of pine fiber loading and found that as the fiber loading increased beyond 10 wt.%, the flexural strength decreased due to the high cellulose content and the poor epoxy and pine fiber adherence. Xu et al. [35] investigated the ramie fiber-reinforced epoxy composite fabricated using vacuum-assisted resin infusion moulding. They established that hot compaction significantly improves the mechanical strength of the composites with the same fiber content. Jawaid et al. [115] indicated that the hybridization on the bilayer of oil palm empty fruit bunches and jute fiber-reinforced epoxy resin increased the tensile and flexural characteristics of the hybrid composites. Potluri et al. [116] investigated okra/kenaf and okra/banana-reinforced epoxy hybrid composites. Compared to okra fiber composites, the inter-lamina hybrid composites improved the composite's strength.

Kumar et al. [117] investigated the effect of fiber loading in wood dust-reinforced epoxy composites on the tensile and flexural strength of composites. The composites with 10 wt.% fiber loading exhibited better mechanical characteristics (161% increase in tensile strength and a 200% increase in flexural strength). In another study using the

Taguchi technique, Kumar et al. [118] found that the speed of the test affects load and tensile strength, while flexural characteristics are mostly influenced by fiber loading. This was because, during tensile testing, the load is applied along the length; hence, the fibers have less time to be oriented at a higher speed. While in the case of flexural testing, the load is applied along the thickness role [118]. Zhang et al. [41] studied the mechanical behaviour of bamboo fiber-reinforced epoxy composites concerning fiber content and length. They established that the composites' fracture toughness and flexural/bending modulus increased monotonically with fiber length and content.

The hemp fiber has hemicelluloses, lignin, and cellulosic constituents, which need to be reduced for better flexural strength. Higher flexural properties can be achieved with bleached fiber than untreated fibers due to greater interfacial adhesion in bleached fiber composites [34]. Venkateshwaran et al. [87] examined the influence of surface modification with different alkali (NaOH) treatment concentrations (0.5–20%) on the banana-reinforced epoxy composite. The NaOH treatment converted cellulose-I to cellulose-II with lattice transformation. The treatment with 1% NaOH concentration showed 52% higher tensile and 16.65% flexural strength. A further increment in the concentration of NaOH damaged the fibers and reduced the strength of the fibers. The plasma-treated fiber also improves the flexural strength of the composites. Plasma treatment improves the matrix–fiber interaction of rough surface morphology [106]. However, longer treatment with plasma decreases the flexural strength, attributed to the fiber degradation due to crosslinking caused by the formation of new inter monomeric bonds in basic fiber constituents. Hence, fiber treatments, in general, can considerably increase adhesion interaction and lead to matrix resin penetration into the fibers, blocking cell pullout. As a result, the connection between the flexural strength of composites and treatment techniques becomes more complex.

5.4. Hardness

Hardness represents the resistance of any material against scratch. Hardness becomes significant for NFRCs when used in automobile window liners, building walls, furniture, etc. The effects of thermal ageing on the scratch resistance of natural fiber-reinforced epoxy composites were studied by Ugochukwu et al. [119]. The thermal ageing of NFRCs was carried out for 7, 15, and 30 days at a temperature of 90 °C. As the thermal ageing period increased, the scratch resistance of the composites decreased. Prasad et al. [26] investigated bagasse fiber epoxy composites' physical and mechanical behaviour with four varieties of bagasse fiber and fiber lengths (5, 10, and 15 mm). They observed that hard fibers significantly increased the hardness compared to soft fibers. The effect of fiber length (10, 20, and 30 mm) of coir fiber epoxy composite was investigated by Biswas et al. [92]. They found that the hardness decreased with fiber length up to 20 mm due to the formation of voids during the fabrication of composites. It was also seen that when fiber loading increased, the hardness decreased. This might be because the tiny voids formed during composite fabrication were likely caused by inadequate wettability or bonding between matrix and fiber [120]. Balaji et al. [94] investigated the effect of treated banana fiber loading (5, 10, and 15 wt.%) on the hardness of composites. They observed that the hardness increased with the fiber loading, attributed to the hard and brittle nature of the treated banana fiber after treatment. In general, the composites with hard and brittle fiber exhibited higher hardness. Further, fiber hardness can also be improved with chemical treatment. The fiber loading and length increase the hardness up to a certain limit. After that, it declines as the further addition of fibers causes the formation of voids during the fabrication of composites.

5.5. Damping

Damping is the ability of a material to dissipate vibrational energy. Adding natural fibers to the epoxy matrix is beneficial as its damping properties increase [20]. In general, the damping characteristics of the NFRCs can be improved with natural fiber loadings [121]. As a result, NFRCs can produce lightweight materials with improved damping abilities for construction and automotive applications. Further, the chemical treatment of fibers increases the damping characteristics of composites. Azammi et al. [78] found that kenaf fiber treated with 6% NaOH showed improved tensile and structural damping properties in this connection.

Figure 3 represents the effect of fiber loading and length on the mechanical behaviour of banana fiber-reinforced epoxy composites. The mechanical properties such as tensile strength, flexural strength, hardness, and impact strength increased with fiber loading (up to 15 wt.%). However, with a further increase in fiber loading, mechanical properties decreased, with the exception of hardness, due to the hard and brittle nature of the banana fibers. The decrease in mechanical properties with fiber loading (after 15 wt.%) was due to the wetting of fibers resulting in poor stress transfer between the surfaces of fibers [94].

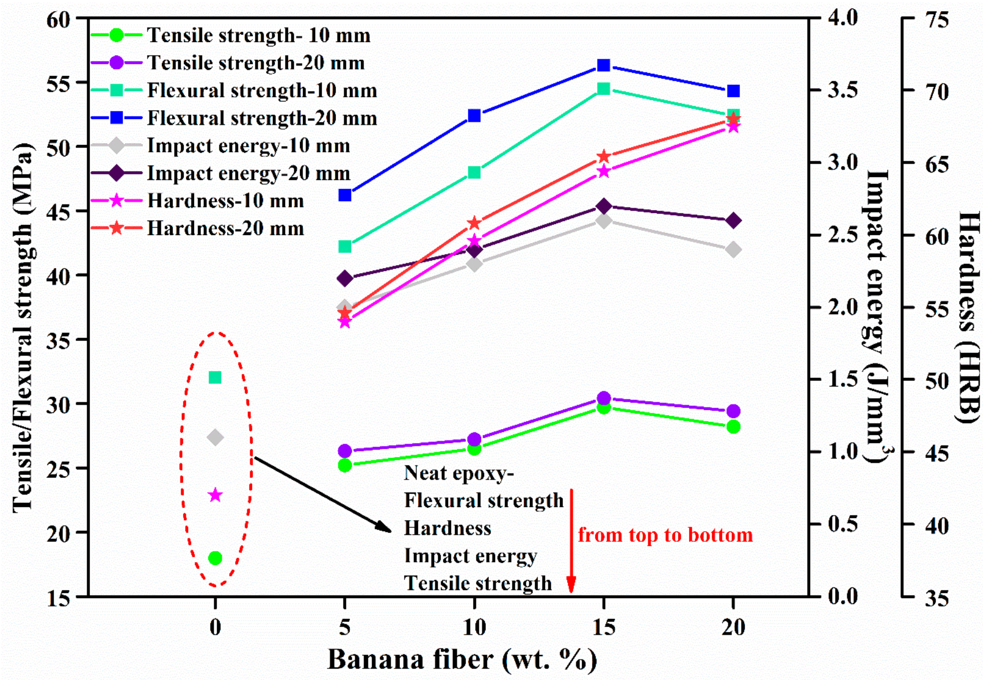


Figure 3. Effect of fiber loadings and length on the mechanical characteristics of the banana fiber-reinforced epoxy composites.

6. Thermal Behaviour of Epoxy-Based NFRCs

When NFRCs are exposed to high temperatures, they degrade due to the thermal damage of the composite components. The thermal degradation of NFRCs is mostly reflected due to the natural fiber degradation as its thermal stability is lower than epoxy [122,123]. Natural fibers have hemicellulose, cellulose, and lignin as primary components. The thermal degradation of the natural fiber is divided into four phases. The first stage involves water loss and low-molecular-weight component degradation at a temperature ranging from 50 to 150 °C for water that is not chemically bound to the fiber. The second step involves hemicellulose breakdown at temperatures ranging from 200 to 350 °C. The third stage is associated with cellulose degradation (typically between 320 and 400 °C), whereas the fourth stage is associated with lignin degradation which can occur at temperatures ranging from 100 to 900 °C [124]. Balaji et al. [125] studied the effect of bagasse fiber (20 mm) and cardanol–epoxy resin wt.% on the thermal strength of the reinforced composites. They reported higher thermal strength of the reinforced composite than pristine polymer. In a similar study, Balaji et al. [94] studied banana fiber-reinforced epoxy composites' mechanical, thermal, and morphological characteristics. They chopped the banana fibers into similar average lengths of 10 and 20 mm and prepared two sets of bio-composites by compression moulding with different wt.% of epoxy resin (0–20%). The composites' thermogravimetric analysis (TGA) showed high thermal stability up to 220 °C.

Since thermal degradation depends upon the NFRC components, the chemical treatment affects these components. In this connection, Izani et al. [126] studied the effect of fiber treatment (NaOH), boiling water, and their combination on the thermal stability of composites. Alkali-treated fibers exhibited higher thermal stability with improved tensile strength and modulus of elasticity compared to untreated fiber-reinforced composites. Zhang et al. [41] found that 6 wt.% NaOH-treated bamboo fiber-reinforced composites exhibited higher thermal stability than untreated bamboo fiber-reinforced composites. Although bamboo fiber composites disintegrated at lower temperatures than neat epoxy, the thermal stability of the bamboo fiber composites was still good. As a result, bamboo fiber composites have the potential to be used in engineering applications. Alamri et al. [127] investigated the influence of clay content on the thermal behaviour of cellulose fiber-reinforced epoxy composites. The addition of nano-clay improved the heat resistance of the composite while increasing the char residue over plain epoxy, since the coefficient of thermal expansion (CTE) of epoxy resin is significantly greater than reinforcing cellulosic fibers. Therefore, the CTE falls as the fiber concentration increases. Adding some filler also increases the thermal stability of the NFRCs [128]. Shivamurthy et al. [76] investigated the effect of adding $Al(OH)_3$ on thermal behaviour and found that composite became more fire resistant. Ramesh et al. [129] added clay as filler in kenaf fiber-reinforced composite and reported that the addition of clay increased thermal stability.

Thermal characteristics of NFRCs improve with fiber treatments with NaOH and boiling water. Furthermore, adding filler can improve the thermal properties of the NFRCs. Thermal degradation of the NFRCs also depend on fiber loadings. However, fiber loadings beyond certain limits harm the thermal characteristics of NFRCs.

7. Physico-Chemical Treatment of the Natural Fibers

The use of NFRCs is limited due to the lower mechanical strength and poor bonding with resins [130]. Hence, natural fibers require treatment depending on the type of fiber, required property, and application to provide desirable properties (interfacial bonding, wettability, roughness, and moisture absorption). Natural fiber surface modifications can be performed in physical, chemical, and physico-chemical treatments [131]. Figure 4 shows the results of treatments to natural fibers. Table 5 shows the different physical and chemical treatments used during fabricating NFRCs.

7.1. Physical Treatment of Natural Fibers

The physical approach enhances thermal properties and mechanical bonding by altering the surface and structural characteristics. Physical treatments such as corona treatment [132] and plasma treatment [106,133,134], dielectric barrier techniques, and ultraviolet treatments [135] affect the fibers' surface properties and enhance the mechanical bonding between fiber and matrix, while the chemical composition of the fibers does not become altered. The duralin process is suitable for reducing water absorption and swelling of the NFRCs [17,136]. Duralin is a heat treatment process which reduces residual shrinkage stress in NFRCs.

7.2. Chemical Treatment of Natural Fibers

Chemical treatment, on the other hand, is an attempt to change the composition of the material by adding new elements to interact with the matrix by utilizing a hydroxyl group to modify and activate the fiber structure [137]. Chemical treatment of fibers improves interfacial shear and tensile strength, modulus of elasticity, elongation at break/failure strain, fracture toughness, flexural characteristics and impact strength of composites, and thermal stability and long-term moisture resistance attributed to the reduced moisture uptake of natural fibers [138,139].

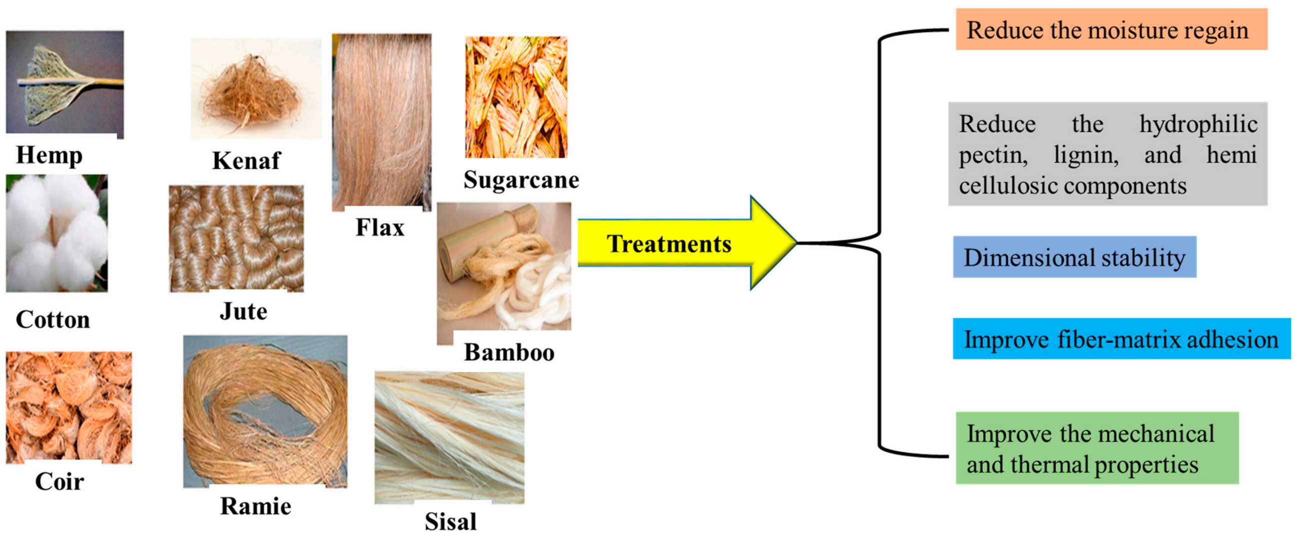


Figure 4. Results of fiber treatments [140]. Reprinted with permission. Copyright 2020 MDPI.

Several works are available based on the surface modification of the fiber surface with the chemical treatments in the literature [26,36–40]. The roughness of the fibers can be increased by alkali treatment to promote fiber–matrix adhesion. Alkali treatment eliminates components such as hemicellulose, lignin, pectin, fat, and wax from the fiber, exposing cellulose and increasing surface roughness/area, resulting in better interfacial bonding. The cellulose crystallinity increases with alkali treatment by modifying the cellulose structure as the treatment removes such materials that obstruct cellulose crystallinity. However, the harsher treatments lead the material into becoming amorphous [34]. Zhang et al. [41] investigated the interfacial adhesion between bamboo fibers and epoxy using scanning electron microscopy and reported that the interfacial bonding could be using NaOH treatment of the fibers. The presence of contaminants prevents bonding between the fibers and matrix. Typically, NaOH treatment is used to remove the wax coating and roughen the fiber surface [141]. It also results in the establishment of a strong interfacial interaction between the fiber and the matrix. The NaOH and acrylic acid-treated fibers showed improved mechanical properties. The treated fibers also showed less water absorption, leading to their construction application where higher strength is required [142].

Acetylation, despite being costly, increases the hydrophobicity and interfacial properties because the acetyl functional group (hydrophobic) is attached, after acetylation, into natural fibers [143,144]. Fiber-specific processes (mercerizing) for cellulosic fibers (cotton and bast) improve properties such as dyeing and luster due to increased specular reflection resulting from a change in fiber from flat ribbon to circular shape [145]. Chemical crosslinking treatment improves the wrinkle recovery of fibers because the amorphous cellulose molecules are restricted for movement because of crosslinking [146]. The mechanical stability of the NFRCs increases by the acetylation [144,147] and grafting treatment [18,24] of the fibers due to the increased bonding between the fiber and matrix. The grafting copolymerization of natural fibers improves hydrophobicity, stress transfer, and interfacial adhesion properties in the NFRCs [18]. Barczewski et al. [148] studied the effect of hydrogen peroxide treatment along with silanization on flax/cotton epoxy laminates and found improvement in mechanical characteristics because the treatment enhanced the adhesion between fiber and matrix. Isocyanate treatment of fiber improves mechanical properties and reduces hydrophobicity. This improvement occurs because the isocyanate functional group reacts with a hydroxyl group and forms urethane linkages, reducing hydrophobicity. Thus, fiber matrix adhesion improves, leading to better mechanical strength [149,150]. Compared to isocyanate, benzoylation treatment effectively reduces hydrophilicity. Moreover, it also improves the thermal stability of fibers. The benzoyl ($C_6H_5C{=}O$) group reduces hydrophobicity [150]. However, fibers before isocyanate and benzoylation treatment require alkali treatment to remove lignin, wax, and oil coverings. Graphene coating on jute fibers increased the shear strength (∼236%) and tensile strength (∼96%) compared to non-coated fibers due to improved mechanical interlocking between fibers and graphene [151]. Setyayunita et al. [152] studied the effect of NaCl treatment of kenaf fiber–epoxy composite and found that the mechanical properties improved significantly after NaCl treatment.

Table 5. Physical and chemical treatments of natural fibers.

Treatments	Chemical Used	Effects	Ref.
Alkali, mercerization (physical treatment)	Sodium hydroxide and potassium hydroxide	Reduces lignin content, moisture absorption ability, wax, and oil covering; improves thermal stability, tensile strength, flexural strength, and fiber–matrix adhesion	[42,139,153]
Enzyme (chemical treatment)	Hydrolases and oxidoreductases	Reduces hydrophilic pectin, lignin, and hemi cellulosic components	[154]
Acetylation (chemical treatment)	Acetic anhydride, silane toluene, and a small amount of catalyst perchloric acid	Improves dimensional stability, hydrophobicity, interfacial properties and mechanical properties	[143,144,147]
Ozone (chemical treatment)	Ozone gas	Improves surface energy and contact angle	[155]
Grafting (chemical treatment)	Acrylonitrile, methyl methacrylate, Maleic anhydride grafted polypropylene, and polystyrene	Improves UV-protective properties, hydrophobicity, and mechanical characteristics and interfacial adhesion	[18,24,156]
Isocyanate (chemical treatment)	Carbon tetrachloride and dibutyl tin dilaurate, toluene diisocyanate, isocyanate acetone	Improves mechanical properties, reduce hydrophilicity	[149,150]
Benzoylation (chemical treatment)	Benzoyl chloride	Improve hydrophobicity	[150,157]
Peroxide (chemical treatment)	Benzoyl peroxide or dicumyle peroxide	Reduces moisture absorption, improves mechanical properties.	[148]
Graphene coating	Graphene oxide	Improves mechanical and thermal properties	[151,158]
Plasma (physical treatment)	Argon cold, low frequency, and radio frequency oxygen plasma	Improves hydrophobicity and mechanical properties	[106,133]
Corona (physical treatment)	-	Improves surface energy	[132]
Sodium chlorite (chemical treatment)	-	Improves tensile strength, tensile modulus/modulus of elasticity	[152,159]
Duralin (physical treatment)	-	Reduces moisture absorption and biological degradation	[17,136,160]

8. Applications of Natural Fibers Reinforced Epoxy-Based Composites

NFRCs are used in different constructional and automotive applications. Table 6 summarizes the construction and automotive applications of different natural fibers.

Table 6. Natural fibers and their constructions and automotive applications.

Natural Fibers	Applications	Ref.
Hemp fiber	Rope, paper and packaging, furniture, electrical, banknotes, and pipes manufacturing.	[24]
Oil palm fiber	Structural insulated panels, windows, door frames, fencing, roofing, decking, and siding materials	[24]
Wood fiber	Window frames, railing systems, door shutters, decking, panels, and fencing	[24]
Flax fiber	Window frames, panels, decking, railing systems, fencing, bicycle frame, fork, seat post, snowboards, and tennis rackets	[24]
Rice husk fiber	Building panels, bricks, frame of the window, decking, and railing systems	[24]
Sisal fiber	Core in elevator steel wire cables, agricultural twine or baler twine, and freight handling	[161]
Stalk fiber	Panels in building, furniture, as bricks, constructing drains and in pipelines	[24]
Kenaf fiber	Packing material, mobile case, bags, insulating material, clothing-grade cloth, soilless potting mixes, and animal bedding	[162]
Cotton fiber	Furniture, textile composites yarn, goods, and cordage	[24]
Coir fibers	Paper weight, filling material for seat upholstery, seat cushions, cover, brush, brooms, ropes, yarns for nets, bags, mats, and padding for the mattress	[24,163]
Coconut fiber	Seat bottoms, back cushions and head, rope, mats, mattress, brush, and upholstery	[161]
Ramie fiber	Sewing thread, packaging material, fishing net, filter cloths, upholstery, canvas, and clothes	[24]
Bagasse fiber	Fencing the frame of the window, panels, decking, and railing systems	
Jute fiber	Building panels, roofing sheets, door frames, door shutters, transport, packaging, geotextiles, mobile casing, indoor elements in housing, and chipboards	[162,164–166]
Abaca fiber	Under floor body panels	[167]
Pineapple leaf	Automobile componentss, textile, and mats	[161]
Date palm	Textile for the indoor house, mats	[161]
Banana fiber	Floor protection for passenger cars	[168]
Roselle fibers	Automobile seat cover, visor in a two-wheeler, name plate, and indicator cover	[169]

8.1. Automobile Applications

NFRCs owing to their lightweight, high-strength advantages have found their application in automobile industries. The lightweight features of the NFRCs lead to better fuel economy for automobiles. In addition, emissions to the environment also reduce during the manufacturing of the NFRCs. In 1941, the first composite automobile (car) was developed, weighing 907 kg or 454 kg less than a steel car. Several investigations have been conducted in Europe to increase the use of NFRCs in the automobile sector, particularly in seatbacks, parcel shelves, boot linens, front and rear door linens, truck linens, and door-trim panels. Besides internal use in vehicles, NFRCs with synthetic polymers have been utilized outside, such as the area between the headlights and fenders of passenger buses [170–173]. In the United States, straw-based NFRCs are being explored as construction materials. Hybrid composites of basalt and hemp fibers are being investigated for various building applications [174,175]. The lightweight and high-impact characteristics of flax fiber composite lead to use in the automotive application (bonnet). The mechanical properties of Caryota fiber were found suitable for automotive components [82]. Leucas Aspera epoxy-based composite thermal and mechanical properties have been found suitable for use as brake pads [82]. Figure 5 shows different components made from NFRCs in automotive applications.

Figure 5. Automobile components made from NFRCs [176]. Reprinted with permission. Copyright 2015 SciELO Brasil.

Depending upon the component and place of application (properties of composites needed such as impact, tensile, and compressive strength), NFRCs are used as components in automobiles. The hemp and kenaf fiber composites significantly increase the Young's modulus and tensile strength [177]. Therefore, hybrid composites of hemp and kenaf can be used as components subjected to high tensile strength and lesser impact strength. Examples are furniture, boardings, or holders for grinding discs. In contrast, the composites of the cotton fibers show high-impact strength but low-impact strength [172]. These composites can be used for the component subjected to high-impact stress but low-tensile strength, e.g., the car's interior parts and safety helmets. In a few cases, components with high-tensile and impact strength are required; the composites can be manufactured by hybridizing different natural fibers, such as the bast and cotton fiber. Nachippan et al. [178] performed a comparative study between glass and hemp fiber-reinforced epoxy composites. They concluded that the hemp fiber epoxy composites could be used as the automobile component where high-impact strength and hardness are required.

Automobile industries such as BMW, Mercedes, Toyota, Daimler, Audi, and Ford have shown interest in natural fiber composites [179]. They have used NFRCs for components such as door lining and panels in car interiors. Since 1991, Daimler-Benz has strived to replace glass fiber-reinforced composites with NFRCs [180]. Interior door linings, panels, upholstery, and seatback cushions in BMW 7 series automobiles use NFRCs for sound-proofing [82]. In several Ford cars, components have been made of soya, rice, and wood composites [170]. According to Motive Industries of Calgary, an electric automobile with components made from hemp fiber at a peak speed of 90 km/h is touted as the world's most environmentally friendly car.

8.2. Construction Applications

NFRCs have been widely used for construction purposes since ancient times. Generally, husk, sawdust, or short fibers of straw mixed with clay are used to produce composites used as bricks in house construction. There are many advantages of such composites in the construction, such as low maintenance, lightweight, enough strength, rot resistance, and bio-degradability. Short sisal and jute fibers are reinforced inside a polyester matrix material used for false ceilings in workplaces and homes to make laminates [12]. Bamboo is another natural material that has been used for construction since ancient times, particularly in Asian countries [181]. The geotechnical characteristics of soil could be improved with the jute fibers, which help develop areas such as embankments, rural road constructions, river banking, and erosion control. Jute and epoxy-based NRFCs are being studied extensively in low-cost housing options, particularly in India and Bangladesh [182]. For manufacturing doorframes, jute is utilized as woven fabric reinforced inside phenolic resins [181]. Another widely used and ubiquitous building material is wood [160,183,184]. Coir fiber is mixed with cement to reduce the usage of steel rebar in beams, which helps withstand earthquakes. While using natural fiber such as coir or palm fiber in the composite reduces the density, they increase the composites' porosity. Such NFRCs could be used as natural fiber cement sheets. Bio-based insulating materials are made from hemp and straw-based composites, which have a lower environmental effect when disposed of.

In constructing sunscreens, natural fibers can replace synthetic fibers. The compressed earth blocks could be developed using banana fiber, which is affordable and stronger than ordinary blocks [185]. Woven jute fabric epoxy composites were tested with the four environmental conditions: water, vegetable oil, 5% NaOH solution, and petrol [186]. The alkali environment significantly influences the water uptake and mechanical properties of NFRCs compared to water, vegetable oil, and petrol. However, vegetable oil and petrol enhance the flexural strength of the jute fiber epoxy composite. Therefore such treated fibers can be used to construct a component that requires high flexural strength, such as structural beams [186]. NRFCs could be used to construct the roof, structural panels, and house unit beams. Abundantly available jute fibers mixed with soybean oil-based resin were used to manufacture an I-Beam using vacuum-assisted resin transfer moulding (VARTM) [187]. The resultant soybean oil and jute fiber composite was found to withstand the structural loads [187]. Further, NRFCs made from soybean oil-based resin and natural fibers such as recycled paper, flax, cellulose, pulp, and chicken feathers using VARTM technology were studied by Dweib et al. [188].

For building beams, NRFCs must have high flexural strength. Curing at room temperature of an acrylate epoxidized soybean oil resin provided a flexural modulus of 1 GPa, which increased to 2–6 GPa by 20–55 wt.% flax fiber and recycled paper reinforcement. Hybrid hemp and kenaf fiber bundles significantly increase tensile strength and the modulus of elasticity of NFRCs. However, reinforcement of these fibers to pure poly lactic acid markedly lowers the impact strength. Therefore, these composites could be used for components that require high strength (tensile strength and stiffness) and are subjected to low-impact stress. Examples are furniture, board in houses, offices, aeroplanes, and holders for grinding discs [172]. Sisal fiber in plain-woven mats was used to produce corrugated composites; the fibers were mercerized and bonded with a Cashew nut shell liquid formaldehyde resin matrix in a compression mould [189]. The fabricated composites were tested and found suitable for roofs and other construction components in tropical developing countries [189]. Further, Fabbri et al. [190] tested the hygrothermal behaviour of the coconut fiber-reinforced composites for green roof applications. They suggested coconut fiber-reinforced composites as a better material for green roofs than synthetic fiber concerning environmental impact. Figure 6 shows various building parts manufactured from different natural fibers.

Figure 6. Construction components made NFRCs [181]. Reprinted with permission. Copyright 2020 Elsevier.

9. Summary and Future Perspectives

Natural fibers available in nature can be easily made into reinforcement materials. Due to its environmental acceptability, technological feasibility, and economic viability, natural fiber-reinforced epoxy composite exhibits many potential engineering applications. Although much work has been carried out to develop these novel composites, numerous technical and economic challenges must be resolved before natural fiber-based epoxy composites can be effectively commercialized. NFRCs have been used in different construction and automotive applications as they possess good mechanical and physical characteristics. Although some drawbacks are associated with the NRFCs, such as moisture absorption, odour, and weather resistance, researchers continue the work to overcome these drawbacks.

The automobile industry, followed by the construction and consumer products industries, are the most important sectors that use NFRCs. Extensive research studies have been carried out to understand the behaviour of epoxy-based NFRCs and their properties under various processing conditions. Such studies have primarily resulted in similar findings, confirming previous results that natural fibers and epoxy complement each other. The increasing availability of biopolymers such as epoxy and environmentally friendly natural fibers compared with synthetic polymers justify further studies on developing epoxy-based NFRCs. Hence, due to their corrosion resistance, epoxy-based NFRCs, with the participation of natural fibers, are perfect for structural and automotive applications and will continue to rise in the future.

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