Natural Fiber Composites

Subjects: Engineering, Manufacturing

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Recent advancements in natural fiber composites have minimized the usage of man-made fibers, especially in the field of structural applications such as aircraft stiffeners and rotor blades. However, large variations in the strength and modulus of natural fiber degrade the properties of the composites and lower the safety level of the structures under dynamic load. Without compromising the safety of the composite structure, it is significant to enrich the strength and modulus of natural fiber reinforcement for real-time applications.

natural fiber composite woven natural fiber orientation

1. Introduction

This century has already perceived notable achievements in green technology, especially in the domain of materials science, with the evolution of high-performance materials made from natural resources for various structural, manufacturing, bio-medical, aerospace, and automotive applications [1][2]. Due to their natural abundance, ease of processing, design flexibility, and feasibility of manufacturing complex shapes, natural fiber composites are good alternatives to conventional materials. They are also light in weight and hazardless to the environment [3][4]. The main problem with natural fibers is the variation of properties and characteristics, such as strength and modulus [5]. The cellulose composition of the cell wall, environmental circumstances during growth, geographical considerations, microfibrillar angle, and other factors all influence the fiber’s strength [6]. The structure of the natural fiber is shown in **Figure 1**. Properties of natural fiber composites depend on several parameters, such as processing technique, fiber strength, interfacial bonding between fiber and matrix, type of reinforcement, weaving pattern, and fiber orientation [7].

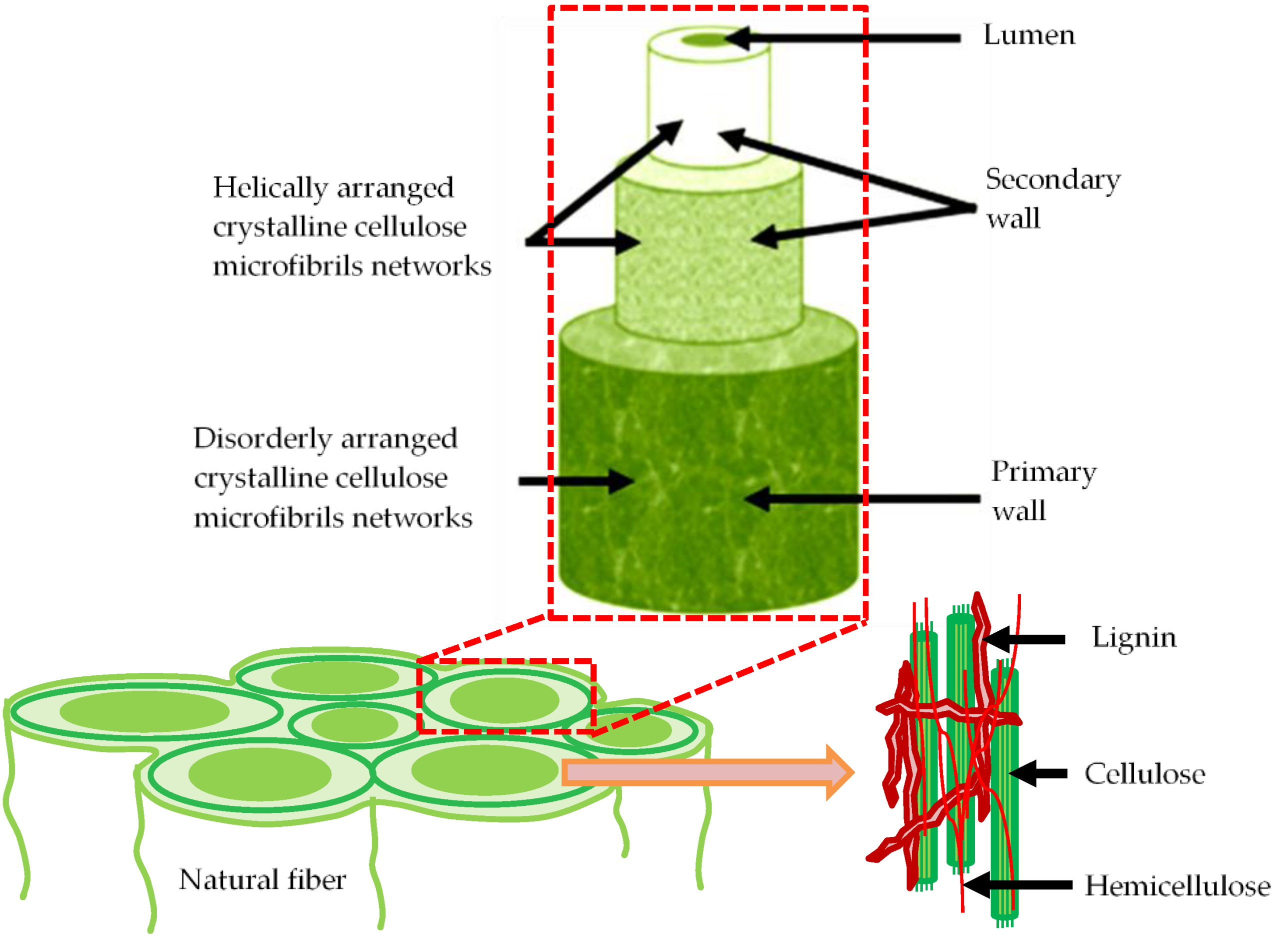
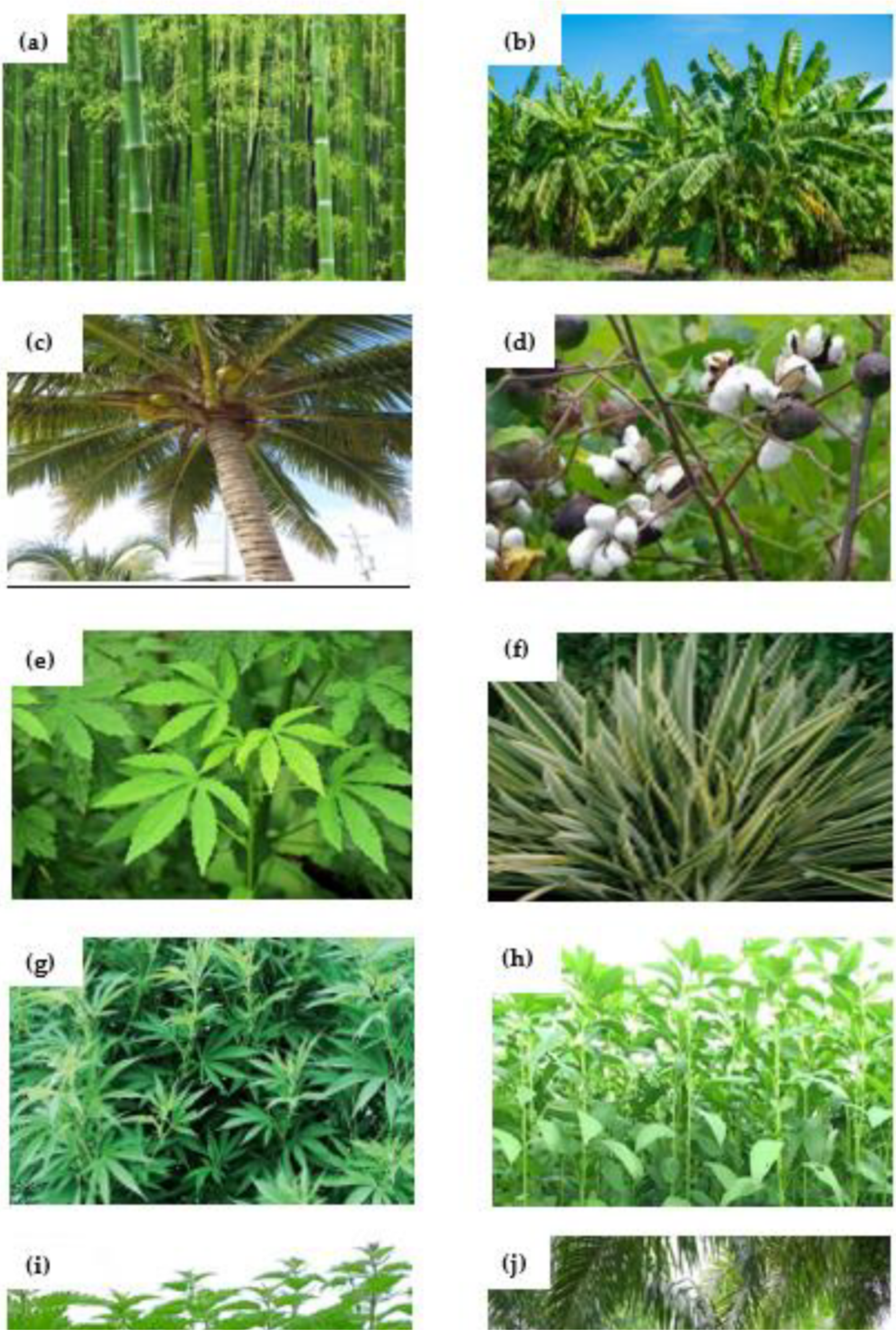


Figure 1. Structure of natural fiber.

In the last two decades, natural fiber has found extensive usage in aerospace, naval, and structural fields [8]. The main reasons behind the higher usage of natural fiber composites for weight-sensitive and structural applications such as stiffener, truss members, bio-medical, automobile interior parts, etc., by industries are the potential environmental, end-of-life discarding, and health advantages in contrast to man-made composite materials [9]. Furthermore, man-made composite materials have a high density, are expensive, and are hazardous to the environment compared to natural fiber composites [10]. As proof, natural fibers such as jute, flax, banana, hemp, and sisal have replaced synthetic fibers such as glass, carbon, Kevlar, and boron in fields that require a load-carrying capacity in the medium and low range [11]. Tarasen and Reddy [12] established the usage of natural fibers (bamboo and jute) in several areas, such as fiber-reinforced columns, special joints, packaging material, and pillars. Moreover, some natural fibers are the best sources for extracting nanocellulose fibers. These nanofibers can be added as a second reinforcement to naturally based composites. **Figure 2** depicts different natural fibers utilized in composites, and **Figure 3** displays the classification of natural fibers. Moreover, composites consist of two phases: One is the matrix phase and the other is the reinforcement phase. The reinforcement phase consists of lignocellulose, which is generally referred to as natural fiber composite. The fibers directly extracted from a living organism are called natural fibers. The fibers derived from synthetic materials are called synthetic fibers.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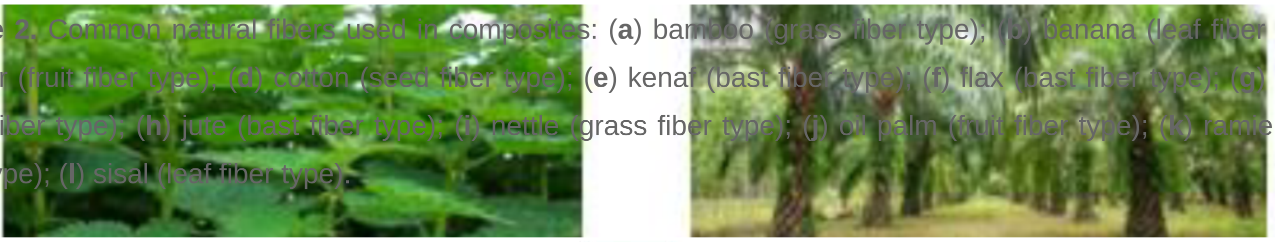

Figure 2. Common natural fibers used in composites: (**a**) bamboo (grass fiber type); (**b**) banana (leaf fiber type); (**c**) coir (fruit fiber type); (**d**) cotton (seed fiber type); (**e**) kenaf (bast fiber type); (**f**) flax (bast fiber type); (**g**) hemp (bast fiber type); (**h**) jute (bast fiber type); (**i**) nettle (grass fiber type); (**j**) oil palm (fruit fiber type); (**k**) ramie (bast fiber type); (**l**) sisal (leaf fiber type).

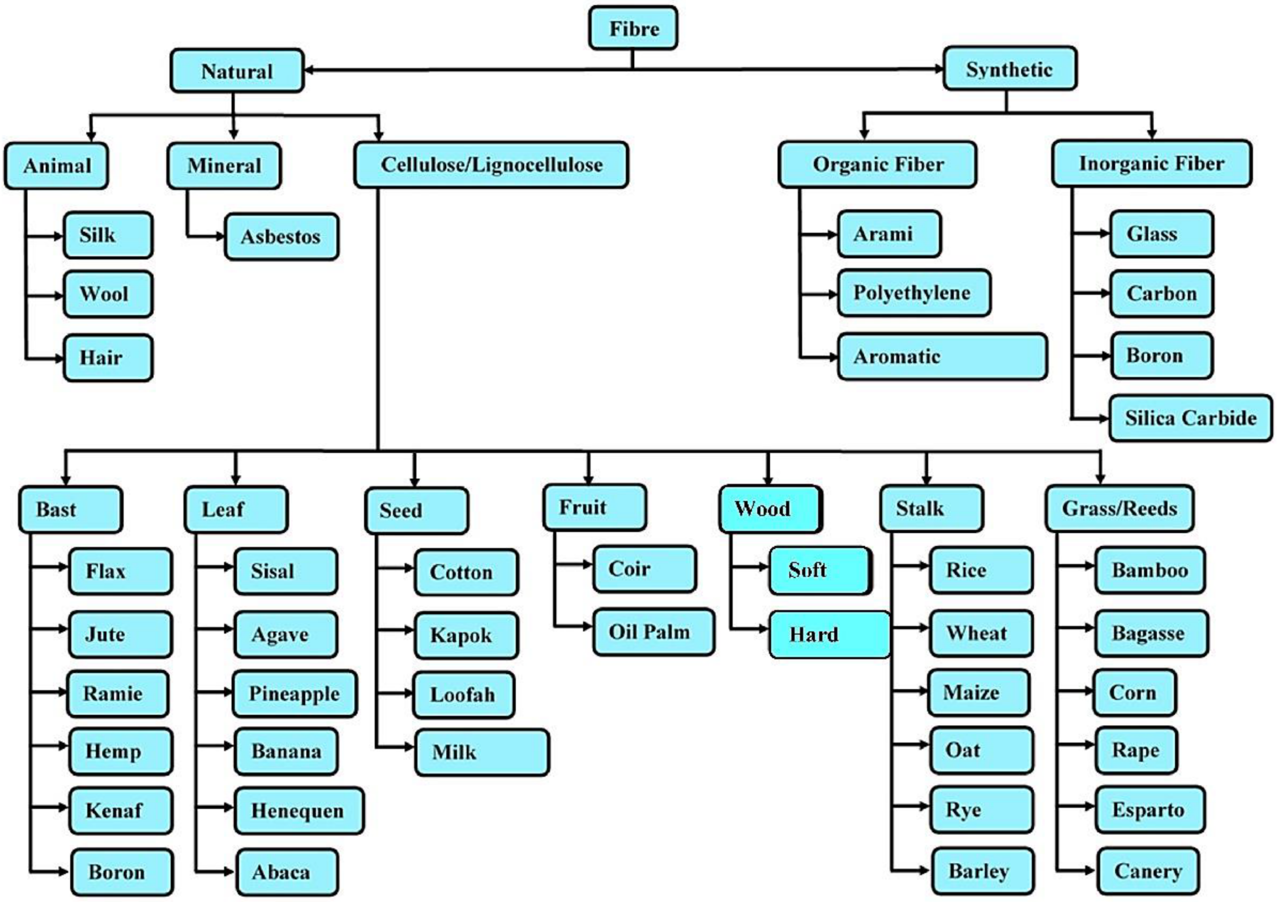

Figure 3. Classification of natural fibers.

The large variation in strength and modulus makes NFCs incompatible under dynamic load and minimizes the safety level of the component. To overcome this drawback, NFCs are reinforced with NFRs in the polymer matrix to improve the structural applications’ strength, modulus, and safety.

Most researchers have developed NFCs with random orientation and short natural fibers as reinforcements in the polymer matrix, creating non-uniform stress distribution due to fiber discontinuity, which further leads to early failure of composites. The modulus of natural fibers can be enriched by reinforcing them with natural fibers in plain, braided, and knitted arrangements. It is observed that the Young’s modulus of NFCs reinforced with NFRs in distinctive patterns in weavings such as basket, plain, stain, twill, etc. have increased promisingly. Similarly, braided NRCs enriched the Young’s modulus of jute-fiber reinforcement by 30% compared to conventional weaving [12][13]. Sapuan and Maleque [13] developed less expensive telephone stands using banana fabric (woven type) in an epoxy matrix. By substituting fiberglass with jute fiber composites, Alves et al. [14] highlighted the advantages of NFCs in the manufacture of automobile hoods.

Reinforcing the NFC with synthetic fiber enhances its mechanical properties and load-carrying capacities and can be used for different structural applications [15]. Damodaran et al. [16] applied a basic sandwich model to develop a traditional drum (Chenda) using a carbon epoxy composite and balsa core material. Comparing the acoustic performance of the traditional drum and a composite drum suggested that the high damping properties of sandwich composites could replace the wood used in the traditional drum. Based on the mechanical properties, many researchers are focusing on working on identifying fibers (plant-based) suitable for use in medium and low load applications [17][18][19][20][21][22][23][24]. The benefits of woven fabric natural composites (WFNCs) have led to an increase in their use in a variety of structural applications. When compared to randomly oriented and unidirectional NFCs, WFNCs provide higher stiffness and strength for the same amount of fibers employed. NFCs' fracture toughness is also improved by the usage of woven fabric. Riedel et al. studied the usage of WFNCs in several structural applications and concluded that using woven fabric would improve composite stiffness [25].

2. Disadvantages of Composites including Short Natural Fibers

Many researchers have investigated the mechanical, dynamic mechanical, and tribological properties of randomly oriented and short natural fibers as reinforcements in the polymer matrix. The main problem associated with short-form reinforcement in a high-density polymer matrix is that achieving uniform distribution is difficult. It affects the advantages of natural fiber composites seriously and makes them incompatible for structural applications. Almeida et al. [26] investigated the mechanical characteristics of coir fiber in a polyester matrix with a fraction of up to 80 wt% coir fiber. They found that composites with 50 wt% exhibited enhanced mechanical properties. Further addition resulted in less strength and a lower modulus of the composites due to random distribution and poor bonding between the fiber and matrix.

Another problem associated with randomly distributed short natural fibers is that the polymer matrix is agglomerates as it affects the composites properties. A similar problem was reported by Joseph et al. [27] regarding the mechanical properties of sisal/polypropylene composites. The authors concluded that fiber length, loading, and orientation affect the performance of the composites. A schematic diagram of a randomly oriented short fiber-reinforced composite is illustrated in **Figure 4**.

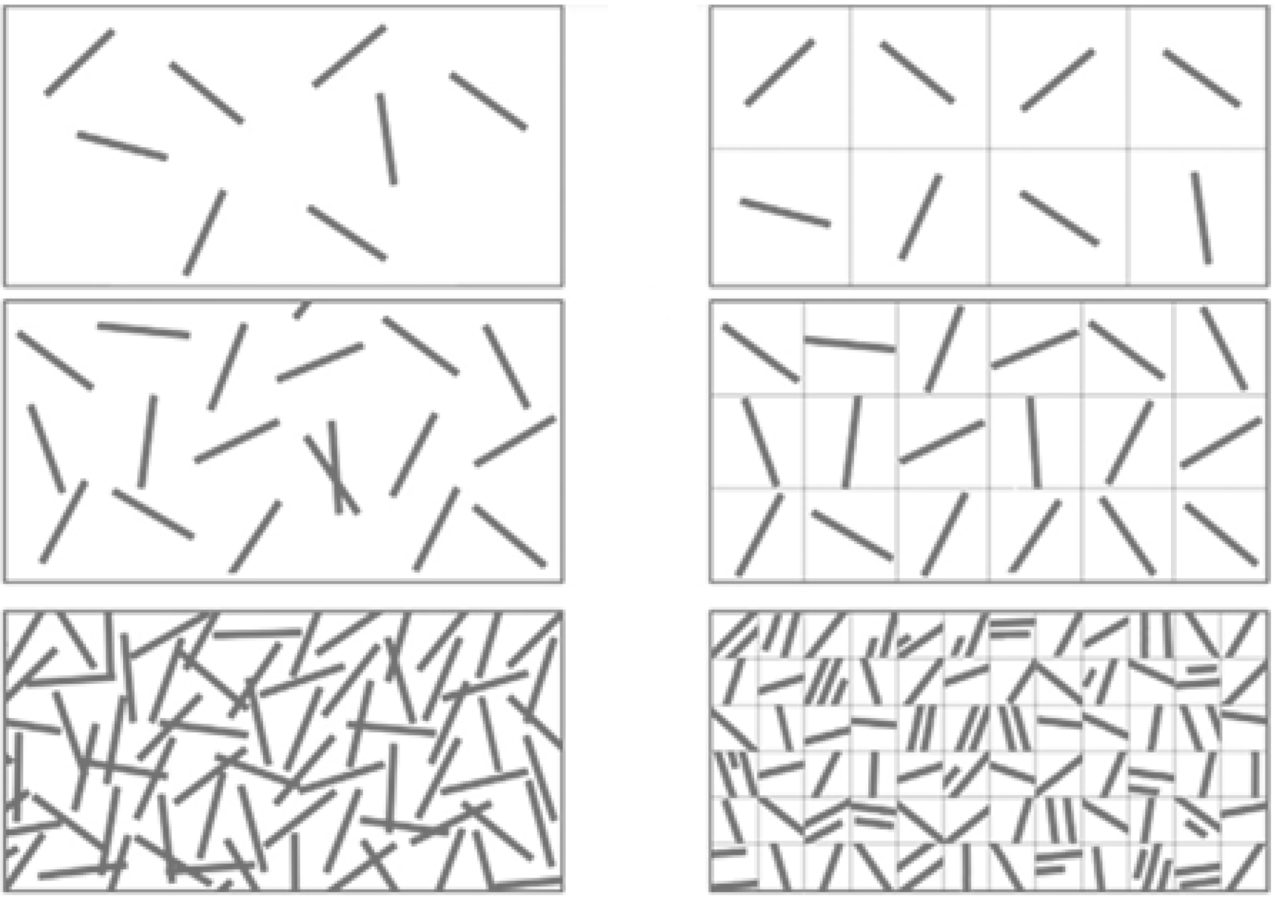

Figure 4. Schematic diagram of randomly oriented short fiber composite.

Arib et al. [28] studied the mechanical properties of pineapple leaf fiber-reinforced polypropylene composites and found that a higher volume percentage diminished the mechanical properties of the pineapple composites. Shekeil et al. [29] investigated the mechanical characteristics of kenaf fiber–thermoplastic polyurethane composites as a function of fiber weight %. They discovered that adding 30 wt% to the composites enhanced the mechanical characteristics of the composites and that adding more resulted in the composites' modulus, flexural, and tensile strength decreasing.

Researchers also found that the random distribution of NFR affects the stiffness of composites due to poor stress transfer at the interface during loading. The dynamic behavior of banana–sisal hybrid short fiber-reinforced polyester composites was investigated by Idicula et al. [30]. At 0.40 Vf, they observed a minimum peak height and maximum width for the material loss factor. It was revealed that composites with 0.40 Vf possessed higher stiffness and maximum energy. Further increasing the fiber content in the matrix reduced its stiffness due to the non-uniform fiber distribution. Similar variations were observed by Doan et al. in jute fiber/polypropylene composites [31]. Pothan et al. [32] found that 40 wt% fiber loading enhanced the storage modulus and glass transition temperature of banana fiber composite materials. They also observed that high fiber loading decreased the stiffness of the composites.

Kumar et al. [33] compared the free vibration and damping behavior of short banana and sisal fiber polyester composites. The authors found that banana fiber with a length of 4 mm and sisal fiber with a length of 3 mm at 50 wt% improved the damping and mechanical characteristics. For longer fiber length, the damping properties of composites decreased due to agglomeration. Tayeb [34] investigated the tribological properties of sugarcane fiber–polyester composites and found that the wear rate of composites decreased when fiber length varied from 1 to 5 mm. Further, increasing the length of the fiber resulted in an increased wear rate and friction coefficient of the composite material. Higher fiber length increased the amorphous nature of the composite. Shalwan and Yousif [35] investigated the mechanical and tribological behavior of polymeric composites based on natural fibers. They came to the conclusion that the properties of composite materials are impacted by fiber orientation, fiber length, and volume fraction. Yusuf et al. [36] looked into the tribological characteristics of oil-palm fiber-reinforced polyester composites and discovered that oil palm/polyester composites had better wear properties.

From the results of these reported studies, it is concluded that the properties of natural fibers with short form depend on the fiber aspect ratio, and improvements in properties are generally observed only up to a certain wt%. The main problem associated with short and randomly oriented fibers in composites is achieving uniform distribution in the polymer matrix [37]. Furthermore, it creates a poor interfacing bond between the fiber and the matrix due to a higher weight percentage, resulting in poor mechanical properties.

3. Woven Natural Fiber Composite

To overcome the disadvantage of natural fiber with short and random orientation, researchers focused more on the reinforcement effect by incorporating WNFR to enhance the properties of NFCs for low and medium load applications. Because of its ease of processing, low fabrication cost, and improved characteristics, the idea of employing WNFR to produce NFCs was generally adopted. Due to stronger fiber–matrix bonding, the gap between warp and weft acts as a mechanical interlock among the polymer matrix, increasing resistance to failure under load. In addition, the chances of failure are less/delayed due to fiber pullout under dynamic loading conditions. In recent years, tremendous development in the textile sector has motivated researchers to explore the possibilities of improving natural fiber composite properties, making them suitable for many applications. Nowadays, natural fibers are used in continuous and woven forms, which further increases the inherent properties of NFCs. Several researchers analyzed the outcome of weaving patterns such as plain, twill, stain, and basket weaving patterns on the mechanical properties of NFCs. Results revealed that NFCs reinforced with NFR with varied weaving patterns exhibit improved mechanical properties. John et al. [38] and Pothan et al. [39] explained the advantages of various weaving structures such as plain, basket, twill, and satin. Out of these four patterns, plain weave gives uniform distribution, good stability, and porosity. A continuous yarn moves in the warp and weft directions in a regular 1x1 pattern in a plain weave. Plain weave has the major drawback of having a larger crimp in the warp, and the weft impacts the properties of the succeeding composite. To enhance the properties of composite materials, researchers investigated various weaving patterns and evaluated them against plain weave as a reference. Alavudeen et al. [40] tested a woven banana/kenaf polyester composite against a randomly oriented fiber composite with the same wt%. In comparison to the short fiber composite, they discovered that the woven composite had better mechanical characteristics. As a result, it has been demonstrated that continuous natural fiber improves composite performance when compared to composites made with short natural fiber with random distribution.

3.1. Mechanical Properties

The mechanical properties of natural fiber composites, such as impact, flexural, and tensile strength, are influenced by fiber percentage in the matrix, fiber strength, fiber–matrix adhesion, fiber orientation, concentration, and treatment type [41][42]. Steel, titanium, and aluminum were formerly the materials of choice for engineering, civil, aircraft, and automotive applications. WNFR composites, on the other hand, offer favorable weight characteristics and bulk strength, making them a feasible substitute for traditional materials since they have stiffness and superior strength [43][44][45]. Schematic diagrams of basic weaving patterns used in the composite field are illustrated in **Figure 5**.

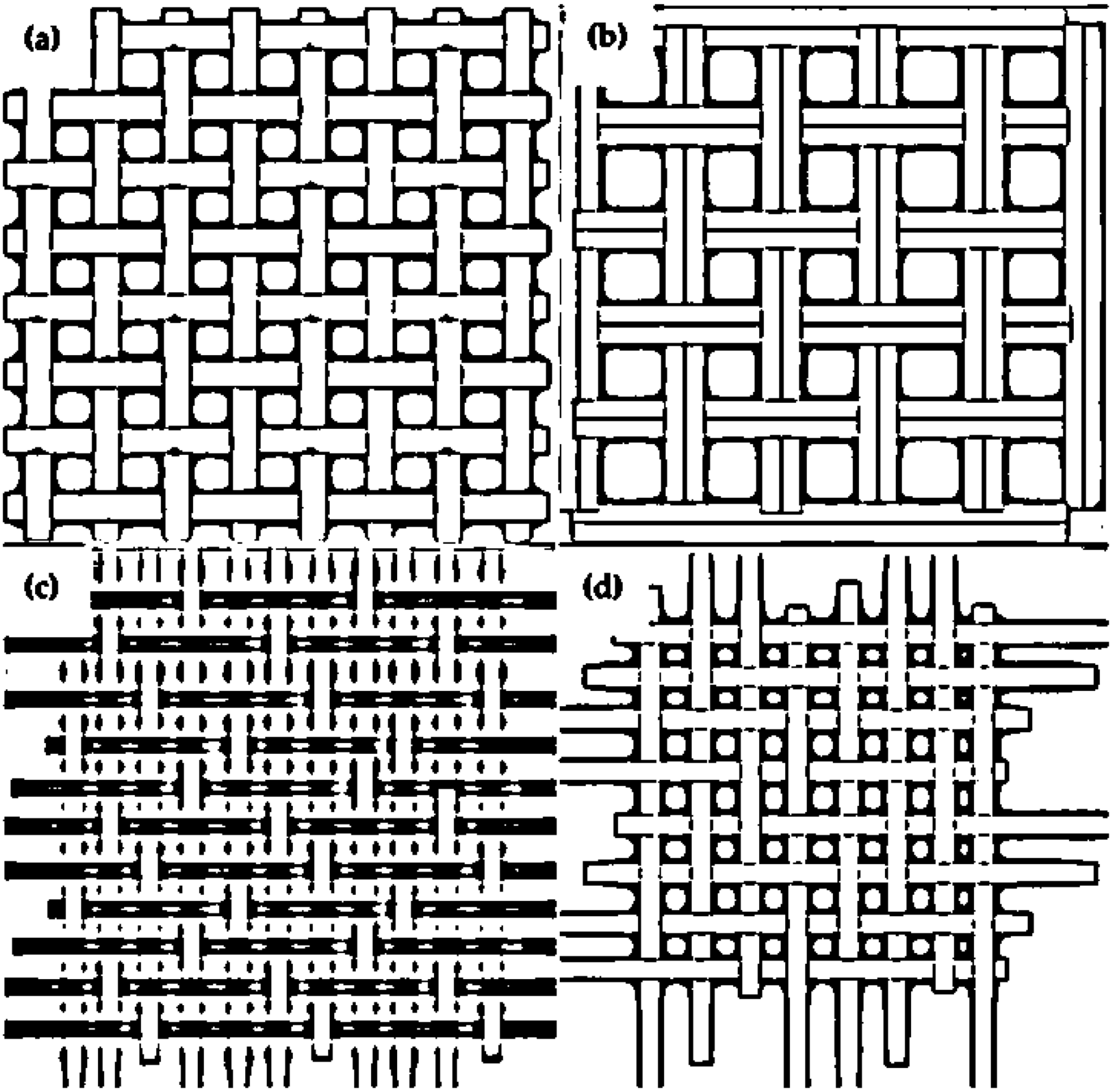

Figure 5. Schematic of various woven mats: (**a**) plain; (**b**) basket; (**c**) twill; (**d**) satin.

In an experimental investigation, Asim et al. [46] evaluated the flexural characteristics and tensile strength of tri-layer palm oil and woven jute fiber–epoxy composites to palm oil–epoxy and woven jute–epoxy composites. Three-layer palm oil and woven jute fiber–epoxy composites had greater mechanical properties than identical composites made with other combinations. It was also discovered that the kind of fiber and its hybridization had an impact on composite characteristics. The mechanical characteristics of Cotton and Kapok fabrics as reinforcing components in a polypropylene matrix were examined by Mwaikambo et al. [47]. They discovered that adding fabric to the composite material enhanced its rigidity. Sapuan et al. [48] studied the mechanical characteristics of woven banana/epoxy composites and discovered that woven banana composites had a higher strength and modulus. The influence of a stacking arrangement on the mechanical properties of sansevieria cylindrical–coconut sheath polyester composites was investigated by Bennet et al. [49]. The maximum modulus was seen when the mat fiber was kept as an exterior layer and short-fiber mat was used as the core material.

Carmisciano et al. [50] investigated the flexural properties of a basalt woven fiber-reinforced vinyl ester composite and a glass fiber composite. Basalt woven fiber composites outperformed glass fiber composites. Venkateshwaran and Elayaperumal [51] investigated the mechanical properties of woven banana–jute–epoxy composites with various stacking sequences. They discovered that adding jute fiber as a core layer increased the flexural and tensile properties of the composite over the jute and banana composites individually. The flexural characteristics of woven pandanus and banana fabric composites with short fiber reinforcement were compared by Mariatti et al. [52]. They discovered that at the same volume %, the woven fabric composite exhibited a high modulus and strength. Finally, Khan et al. [53] investigated the mechanical characteristics of non-woven jute and plain-woven jute composites in the warp direction. They observed that in the warp direction, the woven mat composite outperformed the non-woven composite in terms of mechanical properties.

Rajesh and Pitchaimani [54] analyzed the effect of weaving patterns on mechanical properties compared with composites reinforced with randomly oriented natural fibers. Results revealed that for the same weight percentage, the woven composite improved the mechanical properties of the composites whereas randomly oriented SNFR failed relatively. Short-form reinforcement experienced higher stress concentrations as fiber discontinuity affected the bonding strength between the fibers and the matrix. It led to early failure of the composites compared to woven fabric reinforcement. The individual strength of the yarn and the amount of fiber present in the reinforcement influenced the load-carrying behavior of the composites. Similar observations were made by Alavudeen et al. [40]. They analyzed the effect of fiber strength and weaving patterns on the mechanical properties of polyester composites and compared them with randomly oriented composites. They found that irrespective of fiber strength, the weaving pattern significantly affected the strength of the composites.

Figure 5 depicts commonly used weaving patterns in the composite field, such as plain, basket, twill, and satin weaves. The main advantage associated with plain and basket weaving is the uniform orientation of the fibers in the weft and warp directions. In satin and twill weaves, the fabric will bias diagonally, which influences the load-carrying behavior of the composites. In plain and basket weaves, stress is distributed uniformly along with the warp and weft directions, which affects the mechanical properties of the composites. In twill and satin weaves, stress transfers non-uniformly and diagonally to the warp and weft directions, leading to earlier failure of the composite under loading. In the textile industry, the huckaback style is commonly used in fabrics. Due to the periodic yarn arrangement in both the warp and weft directions, the huckaback pattern enhances the fabric’s surface roughness. The gaps between subsequent strands in the warp and weft orientations are the fundamental drawback of huckaback woven composites, which causes them to break prematurely. As a result, there is a higher concentration of tension during loading. Goutianos et al. [55] studied the effects of yarn twist for woven composites. Results indicated that a higher yarn twist improved the properties of the composites, whereas a lower yarn twist exacerbated insufficient loading capacity. Pothan et al. [56] evaluated the mechanical characteristics of several types of woven sisal fiber composites and discovered that plain-woven fabric improved the composite’s properties. Shibata et al. [57] investigated the flexural strength of bamboo/kenaf fiber-reinforced composites that were unidirectional and randomly oriented. They concluded that the woven fabric, regardless of material, flexural strength, and modulus of the composite, was improved. **Table 1** shows the mechanical properties of frequently used plant fibers in the field of composites.

Table 1. Mechanical properties of plant fiber-reinforced polymeric biocomposites.

Composites	Flexural Strength (MPa)	Flexural Modulus (GPa)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Elongation at Break (%)	Author and Year	Ref.
Jute/polypropylene	77.32	4.34	56.71	1.82	–	Chandekar et al. (2020)	[58]
ramie (5-layer) /epoxy	98.73 ± 5.98	–	99.04 ± 2.85	–	–	Darshan and Suresha (2021)	[59]
Kenaf/polypropylene	45.56	2.37	24.67	2.35	–	Akhtar et al. (2016)	[60]
Sisal/epoxy	252.39 ± 12.11	11.32 ± 1.02	83.96 ± 6.94	1.58 ± 0.08	–	Gupta and Srivastava (2016)	[61]
Rice straw/LDPE	33.7	1.6	13.7	0.144	24.10	Xia et al. (2018)	[62]
Pineapple/epoxy	~100	–	80.12 ± 2.23	8.15 ± 0.23	–	Odusote and Oyewo (2016)	[63]
Rice straw/polypropylene	36.5 ± 0.5	1.28 ± 0.027	33.2 ± 0.5	1.66 ± 0.025	23.9 ± 2.9	Hidalgo-Salazar and Salinas (2019)	[64]
Reed/citric acid	12.51	2.45	–	–	0.54	Ferrandez-Garcia et al.	[65]

Composites	Flexural Strength (MPa)	Flexural Modulus (GPa)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Elongation at Break (%)	Author and Year	Ref.
						(2019)	
Basalt fiber/silk fiber/epoxy	151.42	6.20	118.85	2.15	–	Georgiopoulos et al. (2016)	[66]
Sisal/cotton/polyester	270 ± 4	12.62 ± 0.41	65 ± 5	0.52 ± 0.015	12.31	Sathishkumar et al. (2017)	[67]
Hemp/sisal/epoxy	44.47 ± 2	1.892 ± 0.061	31.76 ± 0.88	1.173 ± 0.32	3.2 6 ± 0.41	Thiagamani et al. (2019)	[68]
Sisal/chitosan/epoxy	136 ± 2.8	7.023 ± 0.61	46.70 ± 3.5	3.821 ± 0.13	2.176 ±0.82	Soundhar et al. (2019)	[69]
Sisal/bagasse/epoxy	0.76	–	27.36	–	0.06	James et al. (2020)	[70]
Jute/hemp/flax/epoxy	66 ± 4	1.25 ± 0.23	60 ± 3	1.88 ± 0.21	5.8 ± 2.2	Chaudhary et al. (2018)	[71]
Banana/ramie/polypropylene	30		35 ± 2			Sai krishnan et al. (2020)	[72]
sisal/banana/coir/epoxy	48.60	3.45	26.35	1.20	–	Balaji et al. (2019)	[73]
Date palm/flax/thermoplastic starch	73.6	5	31	2.8	5.25	Ibrahim et al. (2014)	[74]
Kenaf fiber/phenolic resin	62.12	2.63	15.8	4.350	2.89	Naresh Kumar et al. (2021)	[75]
Banana/jute fiber/vinylester	70	3.26	17.98	1.89	4.5	Ravindran et al. (2021)	[76]
Red banana/ramie/vinyl ester	80	–	42	–	–	Sai krishnan et al. (2020)	[77]
Flax/jute/polypropylene	58.79 ± 1.73	1.39 ± 0.11	39.48 ± 1.61	2.85 ± 0.12	2.90 ± 0.18	Karaduman et al. (2015)	[78]
Coconut sheath/epoxy	76.80	–	58.60	–	–	Suresh Kumar et al. (2014)	[79]
Areca sheath/palm leaf sheath fiber/epoxy	51	–	46	–	0.18	Ganesh et al. (2020)	[80]
Kenaf/jute fiber	57.2	4.62	43.21	3.60	2.1	Khan et al. (2019)	[81]

Thermal and dynamic mechanical characteristics of newly developed materials are significant parameters to be examined primarily for structural applications. At higher temperatures, the interactions between molecules in

Composites	Flexural Strength (MPa)	Flexural Modulus (GPa)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Elongation at Break (%)	Author and Year	Ref.
Banana/kenaf/epoxy [83]	24	2.32	54	0.291	18.5	Sathish et al. (2017)	[82]

owers the tween the s. Rajesh weaving patterns and fiber strengths. They discovered that in the glassy zone, regardless of the weaving pattern, the composite had a small change in storage modulus. However, compared to satin, plain, huckaback, and twill woven composites, the basket-design jute composite significantly increased the storage modulus after the glassy area. At higher temperatures, the basket-design composite enhanced structural stiffness and improved resistance to free molecular movement. The basket-woven fabric's fiber yarn arrangement also reduced stress concentration and supported more weight between two consecutive yarns in the weft and warp directions. Furthermore, the list of published research work that has been conducted to demonstrate the dynamic mechanical properties is tabulated in **Table 2**.

Table 2. Some of the research work related to dynamic mechanical properties.

No.	Composites	Observations	Authors and Year	Ref.
1.	Kenaf and hemp bast fiber-reinforced polyester	The composites had a relatively higher storage modulus than other samples.	Aziz and Ansell (2004)	[84]
2.	Natural fiber-reinforced polyethylene	The developed composite had relatively better shear properties than other samples.	Franco and Valadez (2005)	[85]
3.	Coir fiber-reinforced natural rubber	Interfacial bonding influence energy dissipation was observed.	Geethamma et al. (2005)	[86]
4.	Jute fiber-reinforced green composites	The developed composites had relatively better tensile property and toughness.	Hossain et al. (2011)	[87]
5.	Doum fiber-reinforced polypropylene composites	The usage of a coupling agent in the composites improved the rheological properties.	Essabir et al. (2013)	[88]
6.	Flax- and linen-fabric-reinforced epoxy	Improved fiber/matrix adhesion reduced the damping ratio of the composite.	Yan (2012)	[89]
7.	Coconut sheath fiber epoxy	The enhanced interface bonding reduced the damping ratio of the fiber.	Kumar et al. (2014)	[90]
8.	Banana fiber-reinforced phenol formaldehyde resole	The developed composite had a better glass transition temperature and storage modulus.	Indira et al. (2014)	[91]
9.	Woven coconut sheath/polyester composite	The developed composites demonstrated better damping characteristics than the counterpart materials.	Rajini et al. (2013a)	[92]

No.	Composites	Observations	Authors and Year	Ref.
10.	Banana/polyester hybrid composites	Reducing the red-mud particle composition increased the damping properties of the composites.	Uthayakumar et al. (2014)	[93]
11.	Ensete stem fibers/polyester composites	The storage modulus of the constructed composites made from ensete fibers treated with 5.0% NaOH was 1412 MPa, i.e., it was 108% more than that of untreated ensete-fiber polyester composites.	Negawo et al. (2019)	[94]
12.	Date palm fibers/epoxy composites	The storage modulus and loss modulus were improved by including date palm fibers (DPF) in epoxy. However, 50% DPF loading showed greater performance than 40% or 60% DPF loading.	Gheith et al. (2019)	[95]
13.	Banana fiber (BF)/recycled high-density polyethylene composites (RHDPEs)	The modulus of the RHDPE matrix was significantly increased when BF was added. An increase in the storage modulus value of about 20.42% was found while adding BF to RHDPE.	Sukanya and Kothapalli (2018)	[96]
14.	Pineapple leaf fiber (PALF) hybridized with basalt-reinforced epoxy composite	Changes in fiber orientations were discovered to have a significant impact on the loss tangent and storage modulus.	Doddi et al. (2020)	[97]
15.	Luffa cylindrical/ polyester composite	The effects of fiber surface treatment (with NaOH, silane, and $Ca(OH)_2$) and fiber content on the generated vegetable fiber (luffa cylindrica) polyester composite were investigated (30%, 40%, and 50%). The $Ca(OH)_2$-treated fiber had a high peak in the damping factor (at 50%), whereas silane-treated fiber had a higher loss modulus (at 50%).	Kalusuraman et al. (2020)	[98]

sites was [51] us of the composite laminate while having no influence on the glass transition temperature compared to twill and satin weaves. According to the authors, the orientation of natural fiber yarns in the warp and weft directions influenced the storage modulus of the plain-woven composite. In plain weave, a different strand arrangement in the warp and weft orientations enhances stability and minimizes porosity. The high crimp present in both the warp and weft directions is the fundamental issue with plain weave. Plain weave, however, is more rigid than satin or twill. Fangueiro and Rana [99] investigated the viscoelastic behavior of twill and plain-woven hemp fiber-reinforced polylactic acid composites. They discovered that twill weave improved the composites' viscoelastic and mechanical characteristics, as well as their loss and storage moduli. Gupta [100] discovered that plain-weave reinforcement improved the composite's dynamic mechanical characteristics more than short fibers. A dynamic mechanical investigation of oil-palm empty fruit bunch (EFB)/woven jute fiber (Jw) epoxy hybrid composites was explored by Jawaid et al. [101]. The woven jute composite's storage modulus was found to be higher than that of the hybrid composites. It revealed that the hybridization of oil-palm empty fruit bunches with woven jute fabric affects the performance of the composite under the thermal environment due to the addition of oil-palm empty fruit bunches minimizing the resistance of free molecule movement in the polymer chain. Thus, it minimizes the resistance against free molecular movement and reduces stiffness. Asim et al. [102] studied the influence of jute fiber loading on the dynamic mechanical behavior of oil-palm epoxy composites. The inclusion of jute fiber in the oil-palm–epoxy composites increased their storage modulus. It showed that adding high-strength jute fiber to the matrix prevented free molecule movement and improved the composite material's stiffness at higher temperatures. The dynamic mechanical behavior of PLA–hemp bio-composites was studied by Durante et al. [103]. They discovered that increasing the fiber ratio in the PLA matrix enhanced the composite material's glass transition temperature and storage modulus. The dynamic mechanical behavior of aliphatic–aromatic co-polyester and green composites consisting of woven flax cloth matrix was studied by Chandrasekar et al. [104]. Conferring to the results, the addition of woven fabric significantly increased the storage modulus of the green composite.

3.3. Free Vibration Behaviour

The materials used for structural applications must have superior damping properties, along with strength and stiffness. These properties are significantly influenced by the manufacturing process, type of reinforcement, and matrix. Researchers have fabricated composite laminates using a compression-molding process and compared them with a hand lay-up technique. Results revealed that composites fabricated using the compression-molding technique exhibited improved properties compared to those produced using the hand lay-up method. Kumar et al. [33] reported that the compression-molding process showed enhanced material properties and stiffness, along with energy dissipating properties. For structural applications, it is important to reduce the resonant amplitude of vibration to protect the components and structures from failure. The modal damping associated with each mode of the structure has a considerable impact on the resonant amplitude of vibration. A small exciting force can induce high amplitude vibrations at resonance due to any sizeable vibratory inertia force. In general, fiber-reinforced composites have higher damping properties than conventional materials due to viscoelastic behavior and fiber–matrix interaction.

Free vibration properties such as natural frequency and damping characteristics of fiber-reinforced composites have been analyzed by several researchers using experimental, analytical, and numerical methods. In free vibration analysis, the composite material's natural frequency and corresponding damping factor were found using the fast Fourier transfer (FFT) algorithm. It changes a time-domain signal to a frequency response signal and provides an incessant peak for the corresponding natural frequency of the composite material. Chandradass et al. [105] experimentally analyzed the outcome of nanoclay additions on free vibration characteristics of a glass fiber-reinforced composite structure. The second-phase nanoscale dispersion in the matrix and E-glass fiber greatly improved the internal damping of the hybrid composites, according to the dynamic results. Gibson [106] analyzed the modal vibration response quantities of composite materials and structures. Results revealed that impulsive excitation methods gave accurate values for the characterization of intrinsic material properties.

Recently, synthetic fibers have been replaced by natural fibers as reinforcements in the polymer matrix because of their better energy-dissipating behavior [107][108]. The development of green composites increases the usage of plant wastes, thereby reducing their carbon footprint. The free vibration behavior of woven reinforced materials improves the natural frequency of the composite material [109][110]. Rouf [111] analyzed the influence of plain, twill, and satin weaving patterns on the dynamic behavior of woven fabric composites. The author found that plain weave increased the damping properties of composites more than satin composites. Duc et al. [112] conducted a modal analysis to determine the natural frequency and damping behavior of unidirectional, laminated, and woven flax fiber (FF)/epoxy composites. They critically evaluated the factors affecting the natural frequency and damping factor of the composite material. They found that the impregnation quality, fiber/matrix adhesion, strength of the fibers, twist of the fiber yarns, and yarn crimp significantly affected the fundamental natural frequency and corresponding damping factor of the composite structure.

Similarly, the effects of structure type, type of fibers, and physical properties such as density, thickness, and manufacturing process on the stiffness of the composite laminate influence the dynamic properties [113]. Mishra and Sahu [114] carried out extensive experimental work on the free vibrational behavior of woven composites with different boundary conditions. They found that the number of layers, fiber orientation, aspect ratio, and different boundary conditions of the woven fiber composite significantly influenced their stiffness values.

According to Chandra et al. [115], fiber-reinforced composites offer better strength and stiffness, as well as a stronger damping effect, than traditional materials. Da et al. [116] measured the frequency and conducted modal damping analysis for jute/sisal hybrid polyester composites using the impulse hammer technique. They found that the average damping factor attained for the jute/sisal hybrid composite was 1.15 times higher than the composite reinforced with the jute layer alone. It was due to differences in the flexural stiffness of the jute/sisal hybrid polyester composite. Rajini et al. [117] discussed the free vibration behavior of coconut woven mat with different percentages of nanoclay added to the polyester composite. The introduction of nanoclay increased the natural frequency of the composite by up to 3 wt%, whereas further addition reduced the matrix stiffness. The damping characteristics of the composite material improved as the wt% of the nanoclay increased, owing to the efficient interaction between the fiber and matrix, which boosted the composite material’s energy dissipation. Rajesh et al. [83][118] reported similar observations for a banana–jute intra-ply hybrid composite. Results showed that the use of a basket-woven composite as reinforcement enhanced the first three fundamental natural frequencies of the composite material. Fiber orientation within the yarn plays an essential role in determining natural frequencies [119][120]. Rajesh and Pitchaimani [121] analyzed the natural frequency of woven natural fiber composites under a buckling load. Results revealed that the weaving patterns influenced the resistance against a buckling load.

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