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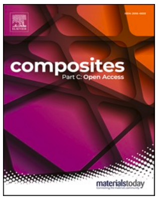

Turning waste plant fibers into advanced plant fiber reinforced polymer composites: A comprehensive review

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ABSTRACT

Plant fibers are increasingly used in fabricating polymer composite components useful in the automotive, construction, and aerospace industries. This surge in the usage of plant fibers in different industries is owing to the improved understanding of the toxicity of synthetic fibers. It is essential to point out that "*Humans need earth, not earth needs humans*" therefore policymakers and researchers are working on replacing traditional materials with green materials. Plant fibers are green materials with many advantages over synthetic materials, such as easy processing, reduction of CO_2 emissions, biodegradable, recyclable, good thermomechanical properties, and better compatibility with human health. Therefore, plant fibers are extensively used as a modifier for polymers. The drawbacks of plant fibers are the presence of OH groups in their basic structure and the presence of amorphous components. Both these drawbacks can be reduced by chemically treating the fibers. Further coupling agents can be used to increase the compatibility between the fiber and polymer. It is reported that incorporating fibers (non-continuous or continuous), and fiber mats as a reinforcement for polymers improve the mechanical, thermal resistance, thermal conductivity, and surface properties. Accelerated aging studies also reported favourable results for the use of plant fiber-based composites for long-term outdoor applications. However, plant fibers have lower strength and are hydrophilic compared to synthetic fibers, more research is required to overcome fully these drawbacks. This review examines and discusses the fundamentals of plant fiber, its processing, drawbacks, recent research trends, composites properties, prospects, and potential applications.

List of Abbreviations

BOZ	benzoxazine
CE	cyanate ester
CS	compressive strength
EB	elongation at break
FR	fire retardants
FS	flexural strength
IM	injection molding
IS	impact strength
PFRPC	plant fiber reinforced polymer composites
TS	tensile strength
PP	Polypropylene
WR	wear resistance
HDPE	high-density polyethylene
PLA	poly(lactic) acid
PHB	polyhydroxybutyrate
PF	phenol formaldehyde

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SFRC	synthetic fiber-reinforced composites
SEM	scanning electron micrographs

Introduction

Archaeological evidence confirmed that Flax was one of the oldest fibers used by humans. The earliest record of flax fibers is 30,000 years old from the Republic of Georgia [1]. The archeologist also found 9000 years old flax twines, fishing nets, flax seeds, etc., during the excavation in Switzerland [2]. The Egyptians used textiles based on flax even before 5000 BCE, and later Egyptians started constructing huts using bamboo shoots/mud walls in 1500 BCE [3,4]. These reports suggest that primitive man explored plant fibers even before metals or pottery making. Primitive men used fibers for making ropes for hunting, fishing, climbing, carrying, and clothing. The migration of humans from Africa to Europe and then to Asia caused humans to face harsh environmental conditions such as temperature change, rain, wind, etc. This caused them to explore plant fibers as clothing materials. Later cotton and hemp were discovered, and with the invention of the spindle and whorl and other techniques of hand spinning the usage of plant fibers for clothing became popular [5]. The traditional circular hut called Bhunga in Kutch, Gujarat, India is an engineering wonder with good temperature insulation, soundproofing, and fire resistance. Bhunga is made of bamboo sticks tied with grass ropes and mud mixed with cow dung and can withstand earthquakes as well as storms. Some of the Bhungas in Kutch are more than 200 years old. The government is encouraged to construct more Bhungas, which are cheap and environmentally friendly.

However, with the invention of synthetic fibers (nylon, acrylic, polyester, rayon), the use of natural fibers diminished because manmade fibers are durable, long-lasting, and have good thermal and mechanical properties. Later, the polymer composite industry boomed with the invention of fibers like carbon, glass, Kevlar, and boron fiber [5–10]. These synthetic fibers have high strength, lightweight, low cost, hydrophobic, and have good compatibility with polymers. Compared to metals, polymer composites with synthetic fibers have good stiffness, corrosion resistance, and enhanced fatigue properties. Therefore, they can be used for various applications such as automotive, aerospace, wind blades, ballistic, sports equipment, and construction and building [11]. Traditionally, glass and carbon fibers are used to manufacture polymer composites. However, synthetic fibers are non-biodegradable, toxic to the environment, and not recyclable; there are problems with their disposal, and generate large quantities of CO_2.

After use, synthetic fiber-reinforced composites (SFRC) have to landfill since there is no appropriate way to discard them, which is one of the biggest problems of mankind. Most of the traditional synthetic fibers will remain on earth for thousands of years. Also, millions of tons of polymer composites based on synthetic fibers are manufactured and used in the composite industry every year, and after use, they have to be landfilled. Reports revealed that less than 10% of plastic is recycled [12]. That means most of the polymer components after use may end up in landfills, and landfilled polymer composite accumulates is increasing daily.

On the other hand, the use of SFRC is growing due to their improved properties and lightweight. If we compare the amount and type of fibers used in composite manufacturing, the bulk of the fibers used are synthetic. Policymakers, industries, and common people are aware of these issues, and governments around the globe encourage green concept innovations. The recent Paris climate agreement also targets zero CO_2 emission by 2050. One way to achieve this target is by using plant fibers to make composites. Therefore, in recent years there has been a surge in the use of plant fibers instead of synthetic fibers in all possible applications [13–14]. This has led scientists and industries to use plant fibers in composite research and industry. But more stress on composites manufacturing using plant fibers and biodegradable materials is required for better environmental sustainability.

Using plant fibers in combination with plastics are a green alternative to metals. According to Emergen Research, the biocomposite market is forecasted to grow from 24.40 billion USD in 2021 to 90.89 billion USD in 2030 [15]. In polymer composites, plastic is the load-carrying material and it transfers the stress to the reinforcement. The reinforcement provides strength and rigidity to the composites. The advantages of plant fibers are sustainable, waste materials, require little energy for production, have low damage to processing equipment, are easily available most times, and prevent global warming [16–19]. In fact, the disposal of fibers after harvesting is a concern in the agricultural sector. There were reports from across the globe that farmers are forced to burn the plant fibers left after harvesting (crop residue), especially in Asian countries, causing the emission of greenhouse gasses, loss of nutrients in the soil, and soil properties [20–21].

However, certain factors limit the application of plant residue in the polymer composite industry; performance-wise, plant fiber-based composites are inferior to SFRC. Plant fibers are hydrophilic, but many of the polymer used are hydrophobic, therefore, the compatibility, or bonding between the polymer and fiber is a concern. The other factor, such as the internal structure of the fiber, changes in fiber diameter, fiber defects, fiber length, microfibrillar angle, strength, crystallinity, modulus, spiral angle, parts from which the fibers are isolated, extraction method, storge conditions, etc., influence the properties of the polymer composites [22–23]. For example, the properties of the bast and leaf fibers are different [24]. Also, plant fiber-reinforced polymer composites (PFRPC) exhibited the absorption of water/moisture from the atmosphere during their functioning. Therefore, more efforts are required to sort out these problems [25–32]. The other factor that influences the composite industry is the fluctuation of the price of natural fibers and supply. Consequently, the composite industries prefer traditional carbon fiber, glass fiber, and aramid fiber to manufacture composites. But most countries are agricultural, and the poor awareness about the importance of natural fibers and limited knowledge should be addressed appropriately to improve the supply of natural fibers and to overcome the reluctance in using plant fibers in advanced composites [33].

It is essential to add that there is tremendous growth in the use of composites in Asian countries like India, Japan, Thailand, Malaysia, and China which cause interest in many composite manufacturing companies to invest in these countries. However, the production of plant fibers is still poor, and a continuous supply of plant fibers is essential for the composites industries. The drawbacks such as dispersion of plant fibers, the mechanical difference between the fibers of the same type, lack of a standard method for the collection of the fibers, lack of standard processing methods, lack of standard post-processing approaches, moisture absorption, and inferior strength, etc., should be properly addressed. The merits and demerits of plant fibers [13,34–40] are given in Table 1. Most of the draw back mentioned in the table can be overcome by using a physical or chemical modification of the fibers.

As stated above, there is an increase in the use of plant fiber-reinforced polymer composites (PFRPC), for making composite components. Many articles, reviews, and books have been published in the area of plant fibers and their composites [3,4,8,11,19,25]. Most of these articles are focused on a basic introduction to cellulosic fibers, their method of extraction, properties, fabrication of polymer composites, and performance. *In this review, we aim to give the readers an insight into the history, problems, possibilities, and applications of plant fibers in composite parts.*

Classification of plant fibers

Based on the plant source, fibers can be classified as primary fibers and secondary fibers. Primary fibers are from plants cultivated primarily for fibers such as flax, hemp, and jute. The secondary fibers are from plants cultivated for fruits such as pineapple, banana, and coir [37]. Besides, secondary fibers are usually discarded as waste. However, utilizing these fibers can reduce waste disposal problems.

Based on the parts from which the fibers are extracted, they are

Table 1
The merits and demerits of plant fibers [13,34–40].

Merits	Demerits
Highly abundant	Lower strength compared to synthetic fibers
Low specific weight	Higher moisture absorption
Low investment	Wettability
Low cost	Swelling effect
Renewable resource (endless)	poor fire resistance and poor durability
Sustainable	Unpleasant smell due to degradation.
Biodegradable	Low thermal resistance (maximum 200 °C)
Recyclability	Restricted maximum processing temperature (maximum 200 °C)
Lower environmental impact during production	Low processing temperature limits the choice of polymer
No residues when incinerated	Poor microbial resistance
No skin irritations	Hydrophilic
Reduce CO_2 emissions	Incompatible with hydrophobic polymer matrix
Corrosion resistant	Tendency to agglomerate (distribution of fiber is not easy) due to hydrogen bonding interaction between the fibers
Acoustic insulation	Lack of a standard method for the collection of the fibers
Easy handling	Lack of standard processing methods
No safety precautions	Lack of standard post-processing approaches, moisture absorption
Non-abrasive nature	Price fluctuation
Nontoxicity	Poor supply chains
Good insulating properties (sound/thermal)	Fiber quality variation
Low wear	Composite property may vary with climatic condition and fiber type

classified as bast, leaf, fruit/seed, and stalk fibers [41]. The Fig. 1 explains the different types of plant fibers. Other than this classification, there is another type of fiber called wood fibers. Wood fibers are of two types such as softwood fibers and hardwood fibers; these are extracted from softwood and hardwood respectively [22].

The bast fibers are collected from the plant stem's outer layer (inner bark) [42,43]. They have high modulus, higher strength, and failure strain compared to leaf fibers [44]. This difference in mechanical properties of these fibers are due to their different morphology. The bast fibers are the most used fibers in the composite industry. Among the bast fibers, flax fibers are the most preferred. The flax plant grows up to 1 m, and the fibers are extracted from the stem or bast. The cross-section of the stem/bast consists of inner hollow space, then the xylem, phloem, parenchyma, and epidermis. The fiber in the phloem is bundled below the outer parenchyma and epidermis. The individual fibers can be extracted from the flax fiber using physical and chemical extraction processes [42–46] On the other hand, seed fibers like cotton are soft and are not suitable for the composite application. Other than the plant fibers, the post-agricultural waste powder such as tamarind shell powder, coconut shell powder, walnut shell powder, cashew nuts shell powder, rice husks, waste tea fibers, palm ash, okra fibers etc., are widely used in fabrication of polymer composites [16,47,48].

Extraction of plant fibers

The method of extraction of plant fibers plays an important role in their properties. Generally, natural fibers are extracted from the plants by retting, mechanical, and chemical methods [48]. Retting is of five types: (i) dew retting (field retting), (ii) water retting, (iii) enzyme retting, (iv) mechanical retting, and (v) chemical retting. In dew retting/field retting, the plants after harvesting were ground on the farm field for two-eight weeks, and thus exposed to moisture, sunlight, and microorganisms. The moisture, sunlight, and microorganisms break down the cementing materials such as pectin, wax, and oil, and separate the individual fibers. This fiber extraction method is relevant in areas with heavy dew fall and warm day temperatures. The advantages of dew retting method are (i) simple method, (ii) low cost, and (iii) more environmentally friendly, but the fiber quality is not uniform and inferior. In water retting, the fibers would be soaked in rivers, ponds, or slow streams for two weeks to remove the cementing and to separate the individual fibers. The water penetrates into the fibers and bursts the outer layers. Thus, having sites for more water to penetrate and proving sites for bacterial growth, which decay the plant fibers resulting in the separation of individual fibers. This fiber extraction method is only relevant in the areas with some water bodies [48,49]. The advantages of water retting are low cost, easy method, and higher fiber quality with better uniformity. Nevertheless, this approach is not an environmentally friendly technique also, it's a quite long process. It is essential to mention that both in water and dew retting, the microorganisms that live in streams or soil generate enzymes that help the extraction of fibers from plants [42].

In enzyme retting, enzymes isolated from bacteria and fungi such as celluloses, xylanases, laccases, pectinases, polygalacturonase, pectin methylesterase, and pectate lyase are used for the decomposition of non-

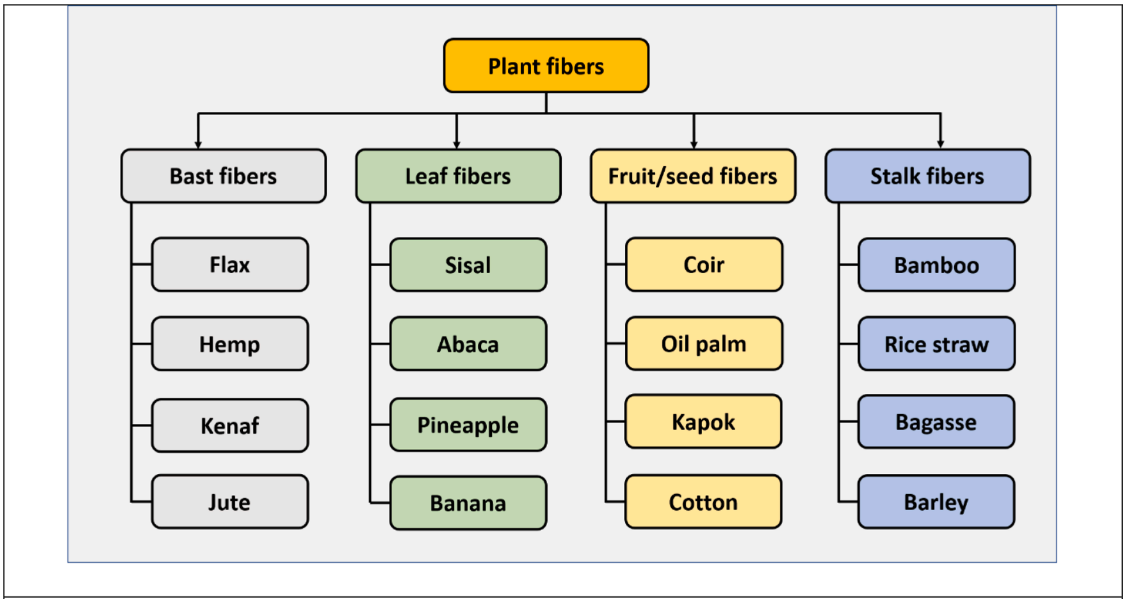

Fig. 1. Classifications of plant fibers.

cellulosic components under controlled conditions. The advantages of enzyme retting over dew and water retting are improved fiber quality, cleaner, and shorter retting time (12–24 h) [42,50,51]. In mechanical retting, individual fibers are extracted from the plant fibers by using a decorticator or hammermill. A large quantity of fiber can be extracted by this method within a short period; however, the fiber quality is poor [37,49]. Chemical retting involves the use of water-containing chemicals (NaOH). First, the tank was filled with a chemical solution. Later, the fiber was soaked in the chemical solution and boiled. The chemical reacts with plant fibers and results in the dissolution of pectin, gum, and other amorphous components from the plant. This method gives high-quality fiber in a short time (1 h), but the chemicals used are toxic to the environment, the treatment may result in color change and deterioration in strength of the fibers [42,51–53].

The plant fibers are composed of cellulose, lignin, and hemicellulose. Cellulose is the most important component in plant fibers present in the cell wall. It provides strength to the fibers. The hemicellulose surrounds the cellulose. Lignin is a natural adhesive that holds together cellulose, hemicellulose, pectin, and waxy materials. Generally, plant fibers have approximately 60–80% cellulose, 5–20% hemicellulose, and the other non-cellulosic component comprises 20% including water. The composition of the different plant fibers is given in Table 2. The properties of plant fibers are dependent on its composition and is represented in Fig. 2 [40]. From Fig. 2, the strength of the plant fiber is highest when it has maximum cellulose content.

Manufacturing method of PFRPC

Based on the application point of view, the natural fibers reinforced composites can be classified into structural composites, semi-structural composites, and non-structural composites. For structural and semi-structural composites, long-aligned fibers are preferred. The discontinuous fibers are preferred for non-structural composites. This is because, for the efficient stress transfer from polymer to fiber, the fiber length should be more than the critical fiber length. And for optimum strength, the fiber length must be 8 times more than the critical fiber length. However, if the fiber length in the composite is less than the critical length then stress transfer from polymer to fiber will be non-continuous and therefore have lower strength and modulus [65–67].

The most widely used manufacturing methods are hand layup, thermoforming, compression molding (CM), resin transfer molding (RTM), vacuum-assisted resin transfer molding (VARTM), pultrusion, autoclave, hot pressing, extrusion, and injection molding (IM) [68–73]. The fabrication methods can be selected based on the type of fibers. For instance, long fibers are suitable for hand layup, filament winding and resin transfer molding. In comparison, CM and IM techniques are preferred for dis-continuous fibers. Similarly, different manufacturing techniques can be selected based on the type of applications. For example, an autoclave is preferred for aerospace; pultrusion is preferred for construction industries; RTM is preferred for transport, and hand lay-up is preferred for consumer appliances. The following section highlights different processing techniques used to fabricate the natural fiber-reinforced composites.

Table 2
The composition of the different plant fibers.

Fibers	Cellulose (%)	Lignin (%)	Hemicellulose (%)	Ref.
Stem/Bast Fibers				
Flax Fiber	75.81 ± 0.740	7.84 ± 0.791	4.03 ± 0.440	[54]
Hemp Fiber	76.12	5.65	12.28	[55]
Jute Fiber	65.44	14.35	17.61	[56]
Ramie Fiber	72.45	1.03	14.21	[57]
Kenaf Fibers	75.32	13.63	–	[58]
Coccinia Indica	64.56	12.55	14.09	[59]
Leaf fibers				
Sisal fiber	64.9	10.4	13.7	[60]
Banana fiber	68.94	18.13	–	[58]
Pineapple leaf fiber	74.44%	7.12%	13.39	[61]
Fruit fibers				
Banana peel fibers	27.07	28.51	19.71	[62]
Coir fiber	43	45	–	[63]
Grass fibers				
Bamboo fibers	41.8 ± 1.9	23.2 ± 2.7	27.2 ± 4.3	[64]
Wheat straw fibers	39.8 ± 3.1	19.8 ± 2.6	34.2 ± 2.7	[64]
Wood fibers				
Original wood fiber	46.4 ± 4.3	25.0 ± 2.2	27.1 ± 3.3	[64]

Hand layup

Hand layup is the simplest of the different fabrication methods. In this method, initially wax is applied to the open mold. Later the fibers are cut according to the mold size and then placed on the mold, and coated with resins using brushes; later rollers are used to remove the excess polymer and air entrapped inside the fiber and resin [74,75]. Photograph of the different preparation stages of hand layup process is shown in the Fig. 3. This method is most suitable for large-sized composite products. It is widely used in automotive bumpers, indoor panels, turbine blades, and boat hulls. The advantage of this method is low cost, versatility in operation, and large-sized composite products that can be fabricated. The drawbacks of hand layup are quality of the fabricated composite varies based on the operating personnel, higher production time, and lower mechanical properties [76,77].

Compression molding (CM)

CM is used for making smaller composite panels. It is a simple processing method and the composites have a better finish. The CM technique consists of a lower fixed half mold and an upper moveable mold. The fiber or fabric is cut into the mold size and embedded in the polymer melt in the mold by adjusting the temperature, then compression, cooling, and releasing the upper mold [78,79]. Complex composite parts could be fabricated by CM.

Resin transfer molding (RTM)

The RTM consists of upper and lower molds, and the fiber is cut into the shape of the mold and placed over the lower mold, later the mold cavity is closed with the upper mold. The resin is then passed into the mold cavity for impregnating the fibers, this is followed by thermal curing. Once the composite is completely cured, the upper mold is removed and the sample is demolded. The primary advantage of RTM is the smooth inner and outer surface with uniform thickness [80–82]. The advanced form of RTM is VARTM. A flexible upper mold is used with a vacuum to remove the air in the mold cavity and improve fiber-matrix bonding. The vacuum application reduces the composites' void content compared to RTM [70]. VARTM is suitable for making tanks, bridges, automotive parts, and wind turbine blades [83].

Vacuum bagging

In vacuum bagging, vacuum pressure is used to hold the fiber and matrix together. In this technique, the composite laminate is made by hand layup and then placed in an airtight bag connected to the vacuum source. The vacuum source removes the air and makes the composite laminate compact, and curing is carried out in the vacuum [84–88]. The advantages of vacuum bagging are reduced humidity, fewer voids, improved resin impregnation of fibers, squeezing out excess resin, improved properties, and large complex composite parts. Other frequently used methods for the fabrication of the composites include hot pressing, extrusion (single screw and twin screw), and IM [89–92]. The advantage of extrusion and IM technique is the production of

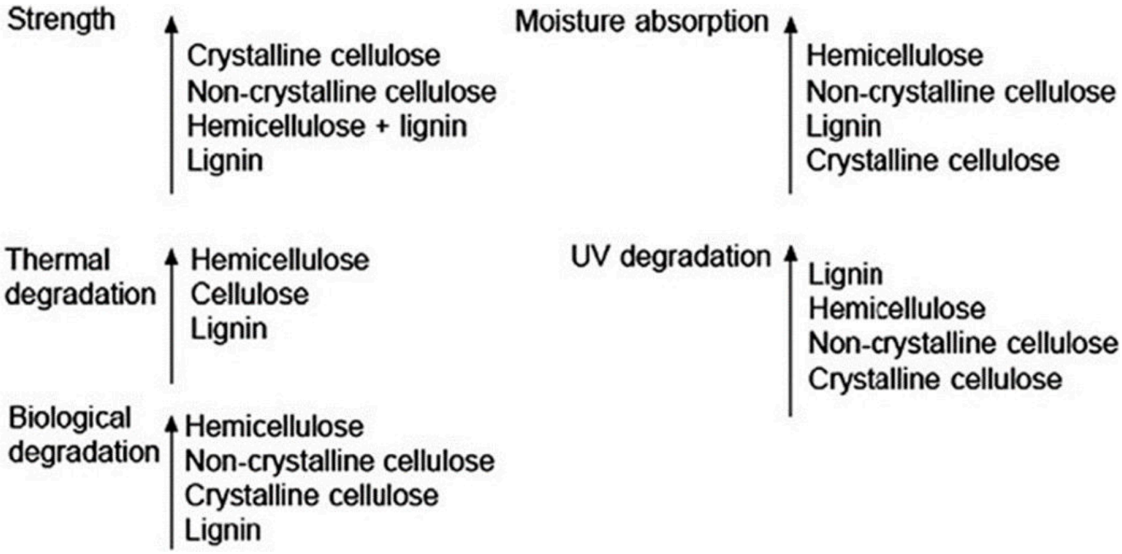

Fig. 2. Properties of plant fibers and their dependence on composition. Reprinted with permission from Ref. [40] License Number: 5,433,611,309,087.

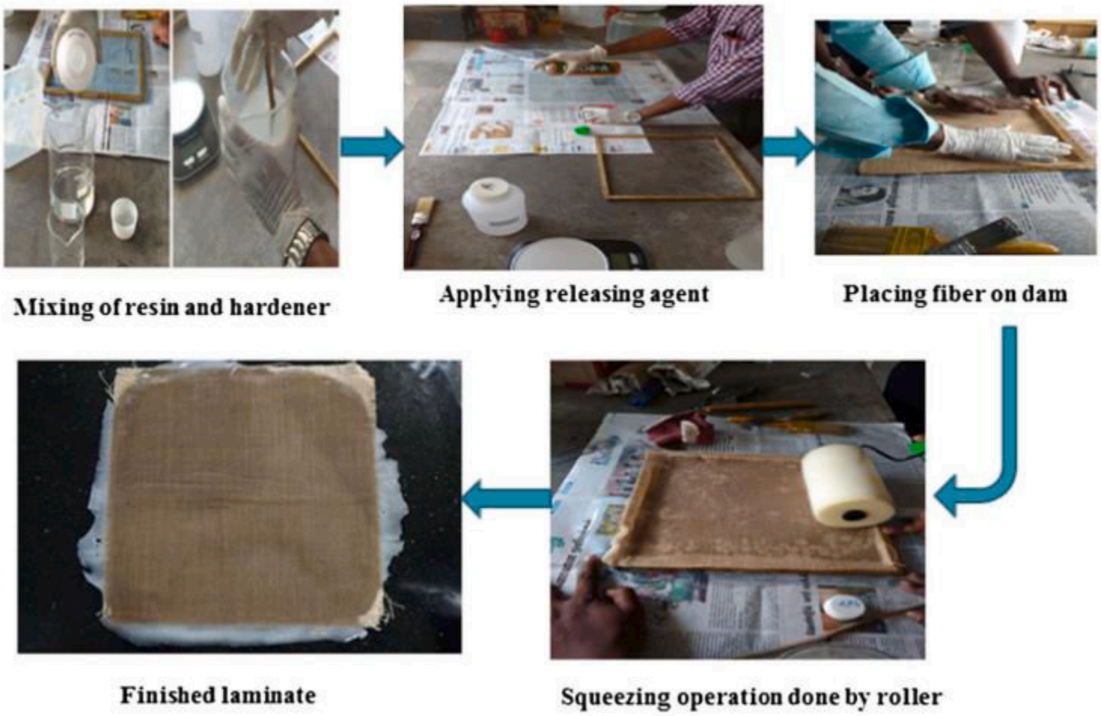

Fig. 3. Photograph of the different preparation stages of Hand layup process. Reprinted/adapted with permission from Ref. [75]. License Number: 5,433,620, 313,986.

high-quality composites with excellent finish and performance but it is an expensive method. The different manufacturing methods and important observations are given in Table 3.

Properties of PFRPC

The PFRPC have many advantages over the traditional SFRC. The PFRPC are lightweight, recyclable, easily disposable, have high corrosion resistance, good fatigue resistance, and have good thermo-mechanical properties. Consequently, there is an upsurge in the studies related to PFRPC [94–96]. Many studies reported improvement in mechanical properties with incorporation of plant fibers (Table 4).

Factors affecting PFRPC

The properties of PFRPC depend on factors such as matrix type, processing conditions, the thermal stability of fiber, cellulose content, strength, modulus, hydrophilicity, aspect ratio (length and diameter), fiber content, fiber length, the orientation of fiber, fiber-matrix adhesion, and specimen conditions (dry and wet conditions). The thermal stability of plant fiber is less than 250 °C, therefore one should choose thermoplastic, and thermosetting polymers processable below 250 °C. The frequently used thermoplastics for the fabrication of plant fiber-reinforced composites are PP, polystyrene, high-density polyethylene (HDPE), and poly(lactic) acid (PLA). On the other hand, resins like

Table 3
Manufacturing methods and important observations.

Matrix	Plant fiber	Fabrication method	Important observations	Ref.
Epoxy	Jute and kenaf fibers	Hand lay-up method	Alkali-treated jute/kenaf fiber reinforced epoxy hybrid composites reported improved tensile strength (TS), flexural strength (FS), compressive strength (CS), and impact strength (IS) due to increased surface area and rough surface of the treated fibers	[75]
Epoxy	Petung bamboo fiber	Hand lay-up and hot press method	Hot press composites reported better TS compared to the hand lay-up composites	[89]
Epoxy	Flax fibers	Hand lay-up and CM	CM composite reported superior TS compared to the hand lay-up method	[79]
Polyester	Sisal fiber	RTM and CM methods.	The composites showed an optimum TS, FS, tensile modulus (TM), and flexural modulus (FM) at 30 mm fiber length and ca. 43% volume fraction. The RTM composites reported better properties compared to CM, this was due to better wettability of the fibers with polyester in RTM.	[93]
Unsaturated polyester	Banana and sisal fibers	CM and RTM	The RTM composites reported better TS, FS, storage modulus, lower void content, better fiber-matrix adhesion, and lower water absorption compared with CM composites.	[71]
Unsaturated polyester	Hemp and kenaf fibers	RTM	Improved strength.	[80]
Polyester	Hemp fiber.	RTM	Good flexural properties	[82]
Epoxy	Hemp, Kevlar, and Jute fabric	Hand lay-up followed by vacuum bagging process (to remove the air gaps and voids)	Hemp/Kevlar/epoxy composites reported better TS, but lower compression and flexural properties compared to Jute/Kevlar/epoxy composites.	[84]
Epoxy	Coir fiber + Carbon fiber	Vacuum bagging technique	The alkali-treated hybrid composites showed enhanced mechanical properties	[86]
Polypropylene (PP) (MAPP -coupling agent)	NaOH-treated kenaf fiber	Melt mixing by twin screw extrusion followed by fabrication using IM	Better TS and FS, and increased crystallinity	[72]

Table 4
Mechanical properties with incorporation of plant fibers.

Matrix	Plant fiber	Fabrication method	Properties	Ref.
Recycled HDPE	Flax fibers (randomly oriented non-woven mat)	Hand lay-up and CM technique	Increased TS, TM, and IS.	[97]
PP	Jute woven fabric mat.	Hot pressing	Increased wear resistance (WR).	[98]
PP	Hemp	Hot pressing	Improved stiffness	[99]
Urea-formaldehyde (UF) resin	Hibiscus sabdariffa fiber	CM	TS, CS, and WR increased	[100]
Epoxy	Jute fiber mat	Hand lay up	Improved TS and modulus.	[101]
Epoxy	Arctic Flax	RTM	Improved TS and stiffness	[102]
Polyester composites	Jute, banana, and intra-ply braided fabrics		Highest storage modulus, loss modulus, and natural frequency for braided yarn woven fabrics reinforced composites	[103]
Natural and Styrene-Butadiene Rubbers	Bagasse	Two roll-mill	Improved physico-mechanical properties.	[104]

epoxy, phenol-formaldehyde (PF), polyurethane, and polyesters are the frequently used thermosetting matrix [23,105,106].

The cellulose content in plant fibers had a significant influence on their properties such as good strength, stiffness, and lowest moisture absorption (Fig. 2). Therefore, the bast fibers that have the highest cellulose content are preferred for the composite industry [107,108]. The aspect ratio of fibers has an important influence on the TS of the composites. Bledzki and Juszkiewicz [109] observed improvement in the strength of the composites (PP, PLA, and poly-β-hydroxybutyrate-co-β hydroxyvalerate) with the incorporation of fibers (man-made cellulose, Abaca, and jute). The man-made cellulose-based composites gave the best TS and IS because man-made cellulose has the highest aspect ratio, therefore the stress can be efficiently transferred from the polymer to the fiber.

The fiber loading is also reported to influence the mechanical properties. Sathishkumar et al. [110] used sisal and cotton fiber woven mats for reinforcing polyester. The researchers observed improved TS, TM, FS, FM, and IS with the increasing volume fraction of the fiber mats and the optimum properties were observed at 40%. Pothen et al. [111] reinforced short banana fiber with polyester and observed maximum TS at 40% fiber loading and fiber length of 30 mm. However, the water absorption was increased with fiber loading. Fiber orientation also influences the properties of the fiber composites. Generally, short fibers are oriented randomly in the polymer composites which will deteriorate the properties of the composites. On the other hand, unidirectional composites aligned in the stress direction (applied load) give superior properties [112,113]. Lasikun et al. [114] examined the impact of fiber (Zalacca Midrib) orientation (0°, 15°, 30°, 45°, 60°,75°, and 90°) on the strength and modulus of the HDPE composites. Interestingly the composites having 0° fiber orientation (unidirectional-stress direction) showed the best IS, TS, and TM. A gradual reduction in strength and modulus was reported with increasing the fiber orientation angle and the composites having 90° fiber orientation showed the minimum values (Fig. 4). The fracture surface (scanning electron micrographs (SEM)) showed fiber slicing and fiber/matrix debonding for the composites with 90° fiber orientation which is responsible for their poor properties. Pamungkas et al. [115] also studied the impact of fiber length (from 1 mm to 9 mm), on the FS, FM, and IS of the HDPE composites, keeping the fiber volume fraction constant at 30%. The researchers observed maximum strength and modulus for the composites with 9 mm long fiber. This is because as the length of the fiber increases the load will be more evenly distributed.

Sanjeevi et al. [25] fabricated hybrid PF with areca fine fibers and Calotropis Gigantea fibers using the hand lay-up technique. The percentage of fiber used for the fabrication of the composites was 25, 35, and 45%. The fibers were taken in a 1:1 ratio. The mechanical test was conducted for dry and wet samples (i.e., after the water absorption test). The testing of wet composites was conducted after drying. For both dry and wet conditions, the best TS, FS, and IS were observed for composites with 35% fiber content, the values were significantly higher than neat PF. However, the researchers observed a drop in mechanical properties in wet conditions. It could be due to the diffusion of water molecules into the polymer composites through the matrix/fiber interface resulting in swelling of the fibers, followed by the de-bonding of the fibers from the matrix during the drying process. Thus, water absorption compromised the mechanical strength of the composites. The water absorption behavior of the composites was also studied by the researchers. The increase in the percentage of the hybrid fibers increased the water uptake due to the fibers' hydrophilic nature. The maximum water absorption was ca. 4.3% for 45% filler after 120 h of immersion. Nabels-Sneiders et al. [116] prepared biodegradable polymer/hemp fiber laminates for packaging applications. The researchers used hemp stalks to prepare hemp paper, later films of poly (butylene succinate-co-adipate), poly (butylene succinate), PLA, and poly (hydroxyalkanoates) were prepared, placed over hemp paper and hot pressed at three different pressures (0.5 MT, 1.5 MT, and 3 MT) to make the biodegradable composite laminates. The researchers observed good adhesion between the polyesters and cellulose because of the hydrogen bonding interaction between the ester and OH groups. The composites showed reasonably good TS, peel strength, storage modulus, and contact angle at 1.5 MT.

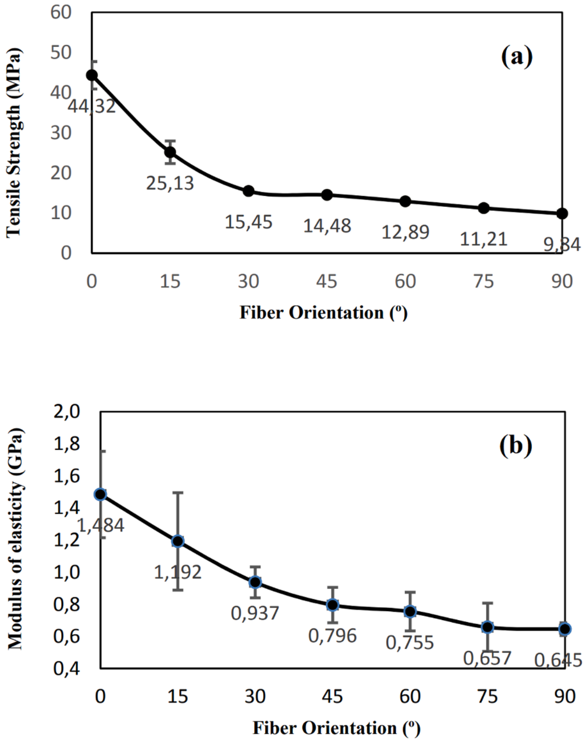

Fig. 4. Change in (a) TS and (b) TM with fiber orientation. Reprinted/adapted with permission from Ref. [114]. License Number: 5,433,621,118,970.

AL-Oqla and Sapuan [117] compared the various parameters influencing the selection of fibers such as coir, date palm, sisal, and hemp. The author compared various literatures and reported low density, low cost, maximum annual production, and highest modulus for date palm fibers among the four fibers with reasonable elongation at break (EB) and cellulose content. Therefore, the date palm fibers have reasonably good physical, chemical, mechanical, technological properties and are a good choice as fillers for making polymer composites for automotive applications.

Surface modification of plant fiber reinforced polymer composites

The interfacial layer/bonding of a few microns thickness between the plant fiber and polymer is responsible for the improvement in thermo-mechanical properties. This interfacial bonding transfer stress from the matrix to the fibers permanently [37]. Ku et al. [118] reviewed the tensile properties of different plant fiber-reinforced thermoplastic composites. It was reported that the untreated plant fiber composites showed minimum improvement or no improvement in TS compared to the pristine polymer. This review highlights the requirement for surface treatments of the plant fibers for fabricating improved composites.

Though the PFRPC showed improved young's modulus properties, some factors deteriorate the properties (TS) of the base polymer matrix, such as hydrophilicity, strength, distribution of fibers and interfacial bonding. The hydrophilicity causes the ingress of water molecules into the polymer matrix. The ingress of water molecules into the fiber matrix interface caused the swelling of the matrix which results in matrix breakage. Moreover, the water molecules present at the interface leach the soluble cellulosic components from the matrix; therefore, fiber-matrix debonding occurs and which in turn reduces the properties of the composites [26]. Also, the hydrophilicity of the fibers results in incompatibility with many polymeric matrices; this results in the ingress of more water molecules which results in the variation of composite properties. Most of the drawbacks of plant fibers can be overcome by fiber surface treatment, adding compatibilizer, and fiber hybridization [119–121]. The interfacial bonding between the fiber and polymer can be improved by surface modification of the fibers. The surface modification could remove or degrade the specific extent of hemicellulose, lignin, pectin, wax and oils from the fiber. Moreover, the fiber should be defect-free to transfer the fiber properties to the matrix. Zeng et al. [122] demonstrated that the pre-treatment of flax fibers with aqueous ammonia reduced the defects in the flax fibers; this was confirmed by electron microscopy.

Herrera-Franco and Valadez-Gonzalez [123] studied the effect of both alkali and silane treatment on the mechanical properties of continuous henequen fibers reinforced HDPE composites. The alkali treatment was used to remove the amorphous components from the plant fiber, while the silane treatment was used to improve the bonding between the fiber and polymer. The authors observed good improvement in TS, TM, FS, FM, and shear strength with treated fiber composites. The researchers performed the test in the longitudinal and transverse fiber direction. The composites with longitudinal fiber direction reported higher mechanical properties. Also, the fracture micrographs revealed a transition from interface to matrix failure with chemical treatment. Shih et al. [124] studied the effect of silane treatment on pineapple leaf, banana fiber, and recycled chopstick fiber as reinforcement for epoxy thermoset. The composition of the fiber was fixed at 20 wt%. The researchers observed good improvement in thermal stability, TS, and storage modulus for the treated fiber-incorporated epoxy composites compared to pure epoxy and untreated fiber-reinforced composites. The SEM analysis of the composites showed better adhesion between treated fiber and epoxy matrix that caused improvement in properties.

Zegaoui et al. [125] used silane coupling agent-treated hemp fibers (TNHFs) as a reinforcement in cyanate ester (CE) and benzoxazine (BOZ) blends. The researchers observed an increase in FS, FM, IS, microhardness, T_g, and thermal stability compared to CE/BOZ resin matrix and untreated fiber-modified CE/BOZ resin matrix. The improvement in properties is due to better interfacial interaction between the fiber and matrix. FS and FM of untreated and treated fiber modified CE/BOZ resin matrix at different hemp loadings is shown in Fig. 5. In another research, Zegaoui et al. [126] observed an improvement in TS, TM, FS, and TM of the CE/BOZ resin matrix with the incorporation of alkali-treated hemp fibers. Thus, it can be concluded that the surface treatment of fiber with chemical agents such as alkali and silane coupling agents improved bonding between the fiber and polymers which in turn improved the strength and stiffness of the composites.

Wang et al. [127] compared the void content and TS of untreated and scoured jute fibers reinforced epoxy composites. The researchers observed reduced void content and increased tensile properties for the epoxy composites with modified jute fiber due to the increased bonding of the fibers with the matrix. Sever and co-workers [128] studied the changes in jute fiber fabric properties with alkali, alkali + silicon, and alkali + fluorocarbon treatments, later the researchers used treated fibers for fabricating polyester composites. The X-ray photoelectron spectroscopy studies showed the presence of fluorine and silicon in fluorocarbon-treated fibers and silicon-treated fibers, respectively. The yarn TS showed a marginal decrease with chemical treatment due to the removal of lignin during the chemical treatment. On the other hand, the interfacial shear strength of the treated fibers (Yarn pull-out test results) showed higher values compared to the untreated jute fabric, with the best results for fluorocarbon-treated fibers. The water contact angle showed the highest value of 124.84 ± 17.56 and 127.54 ± 17.21 for silicon and fluorocarbon treated fibers, respectively, indicating the hydrophobicity of the treated jute fiber fabrics. Among the composites, the tensile, flexural, and interlaminar shear strength of the fluorocarbon-treated fiber fabrics reinforced polyester composites showed the highest values. The SEM micrographs showed a layer of a matrix over the fluorocarbon-treated fibers. Also, the fibers did not show any pull-out due to the good interfacial adhesion. Thus, the high fiber–matrix adhesion explains the improved mechanical properties of the composite. Zin et al. [129] studied the effect of alkali treatment of pineapple leaf fiber on the TS and adhesion between pineapple leaf fiber and epoxy matrix. Different concentrations of NaOH were used for the surface modification of the fibers. The researchers observed that 6% of the alkali treatment of the fibers for 1 h gave the maximum TS (165 MPa), approximately 18% increment compared to the untreated fibers. The thermal stability of the treated fibers was also improved when compared to the untreated fiber. The fiber and epoxy matrix bonding were studied using interfacial shear strength measurements. The value of interfacial shear strength was also reported maximum for composites treated with 6% of the alkali, representing the optimum adhesion between the fiber and epoxy matrix at 6% of the alkali-treated fibers.

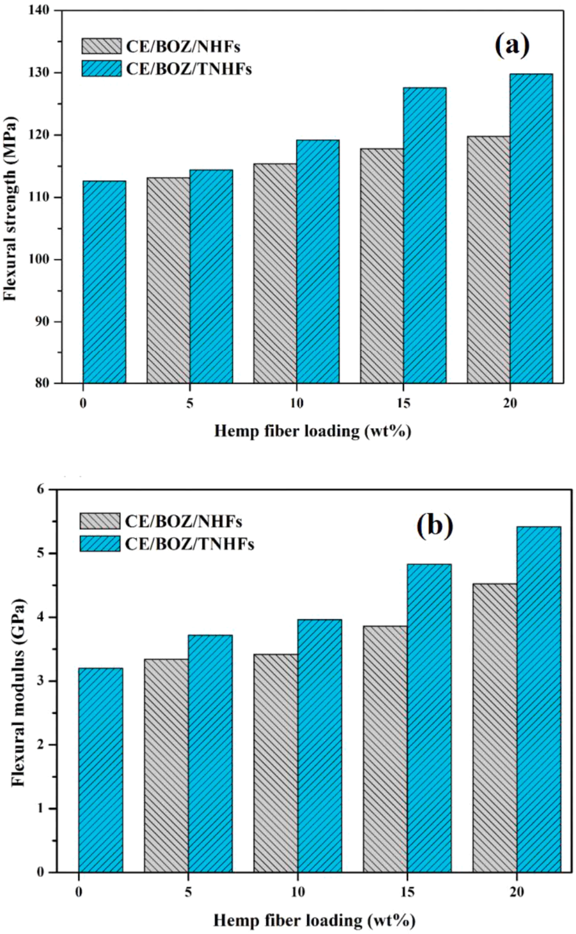

Fig. 5. FS (a) and FM (b) of untreated and treated fiber modified CE/BOZ resin matrix at different hemp loadings. Reprinted/adapted with permission from Ref. [125]. License Number 5,433,630,489,136.

Battegazzore et al. [120] fabricated multi-layered (9 layers) cotton fabrics-based PLA and polyhydroxybutyrate (PHB) composites. The coupling agent Joncryl ADR-4368 additive was applied onto the surface of the cotton for better interfacial bonding between the fiber and polymer. Neat PLA, neat PHB, and composites with and without coupling agents were studied for comparison. The results of studied properties are shown graphically in Fig. 6. The composites with coupling agent reduced the porosity from 6 to 8 and 3 to 4%, which resulted in improved FS from 101 MPa (PLA) to 107 MPa (for coupling agent modified PLA composites) and 38.5 (PHB) to 54.2 MPa (for coupling agent modified PHB composites) respectively. The other properties such as storage modulus and heat deflection temperature (HDT) were also improved for the composites with coupling agent because the coupling agent acts as a chain extender, enhancing the rigidity of the composites. The HDT in PLA composites was increased by 5 °C, but in PHB, the HDT increased by 50 °C due to the difference in the adhesion between the fiber and polymer. The IS of the PLA (15.7 KJ/m^2) and PHB (8.3 KJ/m^2) were improved considerably with the incorporation of fiber. The additive modified PLA composites showed better IS (37.7 KJ/m^2) than neat PLA (15.7 KJ/m^2) and non-modified PLA composite (28.6 KJ/m^2). The improvement in the IS was due to the fiber pull-out, indicating that the chain extender did not modify the bonding between the fiber and polymer. On the other hand, non-modified PHB composite (54.5 KJ/m^2) showed a higher IS value compared to chain extender modified PHB composites; the researchers state that the additive modified the bonding between the fiber and polymer and hence less fiber pull-out; this is also the reason for the high HDT because of the increased rigidity at a higher temperature.

In the conventional boating industry glass, carbon, and aramid fibers are traditionally used for the fabrication of components such as gratings, ducts, the hull of boats, etc. However, to reduce the environmental impact and overcome disposal-related issues, many works have recently been reported using natural fibers instead of traditional synthetic fibers. Fiore et al. [130] fabricated sodium bicarbonate treated and untreated flax and jute fiber modified epoxy composites. Vacuum infusion method

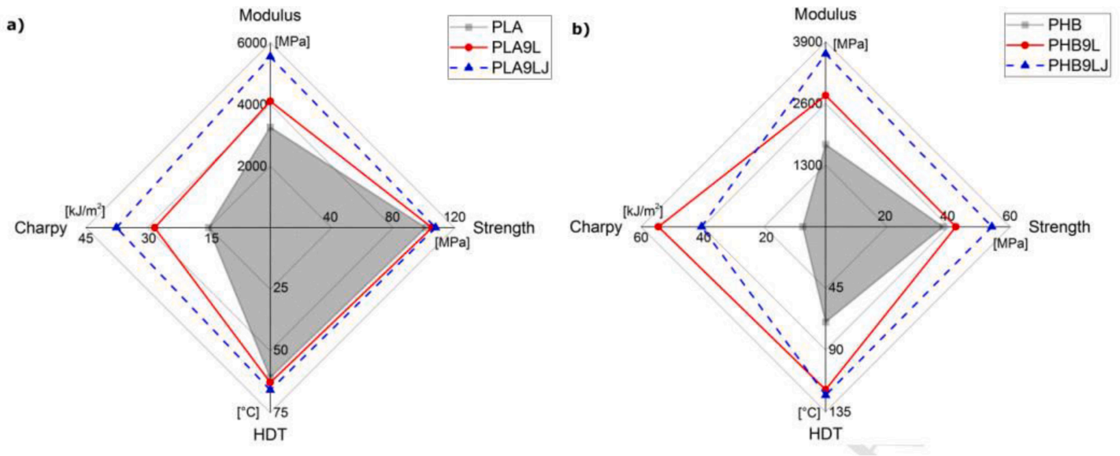

Fig. 6. The properties of the PLA composites are graphically shown. Reprinted with permission from Ref. [120]. License Number: 5,433,631,031,262.

was used to fabricate the composites. The treated and untreated composites were subjected to salt fog tests for 30 and 60 days. The treated flax composite retained the FS, even after 60 days of aging. But treated jute fiber reinforced composites showed a deteriorating effect.

Hybrid composites

Da Luz et al. [131] reviewed the application of graphene-based fillers in PFRPC. The researchers highlighted the improvements in the thermo-mechanical and ballistic performance of the graphene-based fillers modified PFRPC. Also, they reported that the graphene-based hybrid composites could support for innovative based research outcomes as well as industrial developments. Prasad and co-workers [132] fabricated mudguards for two-wheelers from reinforced epoxy hybrid composites having sisal, ramie, and pineapple mats. Five different plates with different configurations were developed using hand layup. Among the different stacking sequences, the pineapple leaf fiber/sisal fiber/-ramie fiber/sisal fiber reinforced hybrid composite exhibited the maximum TS of ~25 MPa; thus, this combination was preferred to manufacture the mudguards. Besides, the optimum drilling parameter of the composite was investigated using the Taguchi method and reported the drill diameter of 5 mm, feed rate of 50 mm/min, and speed of 3000 rpm for the efficient drilling.

Yorseng et al. [133] used kenaf, sisal, and kenaf/sisal hybrid woven fabric (three layers) to reinforce the bioepoxy system. It was observed that incorporating kenaf, sisal, and kenaf/sisal hybrid woven fabric reduced the TS, EB, and IS of neat bioepoxy. The result indicated that incorporating natural fiber had a detrimental effect. However, the mechanical properties of accelerated aged neat bioepoxy and their composites (after accelerated aging test) showed a comparable value. Also, the accelerated aging composites showed a hydrophobic behavior. These results indicated that natural fiber fabrics could be a potential material for fabricating the composites for semi-structural application. In another research, Yorseng et al. [134] compared the properties of synthetic and bioepoxy matrix hybrid composites. The researchers used bamboo (BB), basalt (BS), and carbon fiber (CB) fabrics for making BSBBBS and CBBBCB composites. Both synthetic and bioepoxy composites showed good improvement in TS, TM and IS with the incorporation of fabrics. After the weathering studies, a significant drop in mechanical properties was observed for both neat bioepoxy and synthetic epoxy due to the chain breakage of the polymers. However, the decline in tensile and impact properties was marginal in hybrid composites due to the protecting effect of fiber fabrics. The dynamic mechanical and thermal stability of the composites before and after weathering studies showed marginal variations. All the composites were stable up to 290 °C in a nitrogen atmosphere and showed reasonably high modulus below the T_g. However, incorporating fabric increased the water absorption and the water absorption was observed to be high for bioepoxy composites than synthetic- epoxy composite. Senthilkumar et al. [135] fabricated composites based on sisal fiber mat (SSSS), hemp fiber mat (HHHH), and their hybrid mats and subjected the composites to accelerated aging for 2222 h (corresponding to approximately one year). The thermo-mechanical properties of the accelerated composites were compared with untreated samples (before accelerated weathering test). The TS and IS of the neat epoxy were improved with the incorporation of fiber mats, but the FS was reduced. Compared to untreated samples, the TS and FS of the weathered composites marginally reduced due to the degradation of the composites during weathering test, and this was witnessed from the low residue of the weathered composite from the TGA measurements. On the other hand, the weathered composites showed high IS compared to neat epoxy, even better than untreated HHHH, SSSS, and HSHS composites. The high impact values of the weathered composites were due to the weakening interface between fiber and composites during the accelerated weathering. The researchers recommended the composites for outdoor applications that require impact resistance.

Miscellaneous properties and applications of PFRPC

Damping properties of PFRPC

Damping minimises the vibrations and sounds, which is crucial in composite applications such as automobiles, aircraft, construction, sports, etc [136]. Plant fibers are known for their damping and acoustic characteristics this is due to their hierarchical structure with a high level of porosity, entanglement, and heterogeneity in the cell wall [137]. The parameters such as matrix type, fiber type, stacking, porosity, and interface influence damping. Liu et al. [138] reviewed the damping properties (loss factor/tan δ) of flax/epoxy composites. The researchers stated that the damping properties were improved with the addition of plant fibers. On the other hand, many thermoplastics reported lower damping when reinforced with plant fibers due to reduced polymer mobility in the composites [139].

Hadiji et al. [140] studied and compared the damping properties of plant fiber (nonwoven flax, hemp, kenaf) and glass fiber-reinforced PP composites by free flexural vibration test. Significantly high damping for plant fiber-reinforced PP composites was observed compared to the glass-fiber reinforced PP composites. The researchers observed that the fiber orientation has little influence on the damping properties, while the increased porosity increased the damping. Abbès et al. [137] reported improved damping properties of neat polyester by 6 −14%, 8 −25%, and 2–15% with the incorporation of one nettle layer, one nettle and glass layer, and one nettle layer sandwiched with glass layers (glass/nettle/glass layers) respectively, at frequencies ranging between 1 and 12.6 Hz, corresponding to the natural frequency of automotive. The study encourages the use of green hybrid composites for semi-structural automotive applications.

Ballistic performance of plant fiber composites

Wambua et al. [141] developed natural fiber (flax, hemp, or jute fabrics)/ polypropylene (PP) composite, PP composite with steel sheets as facing, and PP composite with steel sheets backing and facing to study the ballistic limit. The researchers found that the hybrid PP composites with backing and facing steel sheets displayed superior ballistic performance compared to polymer composites, PP composites with steel sheets as facing, and plain steel armor. The critical kinetic energy absorbed for various composites at the ballistic limit (V50) is shown in Fig. 7. The observed results indicated that the flax composites had better kinetic energy absorption compared to hemp composite, jute composite, and mild sheet alone.

The body armor system is broadly classified as two types such as soft body armor system and multilayer armor system. Naveen et al. [142] reviewed the possibility of using natural fiber instead of Kevlar and aramid fabrics for body armor applications. The review reported that natural fibers can be a potential material for ballistic applications such as bulletproof helmets, vests, and body armor systems. In a soft body armor system, hybridizing the synthetic fiber with natural fiber reported enhanced energy absorption with a minimum depth of indentation. Similarly, the natural fiber reinforced composite-based multilayer armor system had improved kinetic energy absorption and dissipation. Thus, the researchers reported that the natural fiber reinforced composites can be used to prevent the shock waves caused by the ballistic impact. Monteiro et al. [143,144] analysed the possibilities of using natural fibers in multi-layered armor systems with front ceramic followed by natural fiber reinforced polymer against high-impact energy projectiles for personal ballistic protection. The researchers observed that the natural fibers, fabrics, or non-woven mats reinforced polymer composites can capture the ceramic fragments resulting from the projectile impact. Further, it was concluded that the composites could absorb more ballistic impact energy than Kevlar with the same thickness. A photograph of the multi-layered armor systems target after the ballistic test with the second layer is shown in Fig. 8 [144].

Fire retardancy studies of plant fiber composites

Both natural fibers and polymers are susceptible to thermal decomposition and flammability. Therefore, knowledge of the susceptibility of composite materials to heat or flame is essential for its application in any advanced materials. According to federal aviation regulation, there are three flammability tests for any composite materials for aerospace applications. They are vertical burn test, heat release rate, and smoke density. On the other hand, cone calorimetry test, and room corner test was usually employed to determine the flammability in composites for construction and building applications. Based on the values of parameters such as heat release rate, limiting oxygen index, vertical and horizontal burning, and smoke generation one can evaluate the thermal decomposition and flammability of the composites. To retard the flame or thermal decomposition of the composites, many chemical agents such as magnesium hydroxide, aluminum hydroxide, ammonium sulfamate, ammonium phosphates, ammonium bromide, boric acid, nanoclay, and nanotubes have been used [145]. Bachtiar et al. [146] used bidirectional flax fabric as a reinforcement for epoxy polymer. Also, they used ammonium polyphosphate and aluminum hydroxide as fire retardants (FR) for protecting the composites from fire. Results reported that with increasing the FR content, the thermal decomposition temperature was also found to be increased. Besides, the researchers observed different mechanisms for ammonium polyphosphate and aluminum hydroxide. For instance, ammonium polyphosphate modified composite produced higher amount of char for preventing further burning, while aluminum hydroxide contained OH groups and hence produced water vapor to reduce degradation. Based on the UL-94 V tests and limited oxygen index, the best results were observed for 30% ammonium polyphosphate composites. The composites with 30% ammonium polyphosphate reported a V-0 rating and a limited oxygen index value of 30.3 (±6.9%). Further, the SEM images showed an adequate coating of FR over the flax fibers, which improved the flame retardancy of the modified composites. The researchers also studied the effect of flame retardant on the mechanical properties of the composites. The data showed a marginal drop in TS and modulus. Khalili et al. [147] studied the fire retardancy of ramie fabrics-based composites. The composites consist of three layers of ramie fabrics coated on either side with fire retardants such as expandable graphite and alumina trihydrate. The results revealed that the time to ignition was increased while other parameters such as total heat release, peak heat release rate, specific extinction area, and total smoke release were reduced. Suggesting the coating layers over the ramie fabrics could act as a fireproof for the composites.

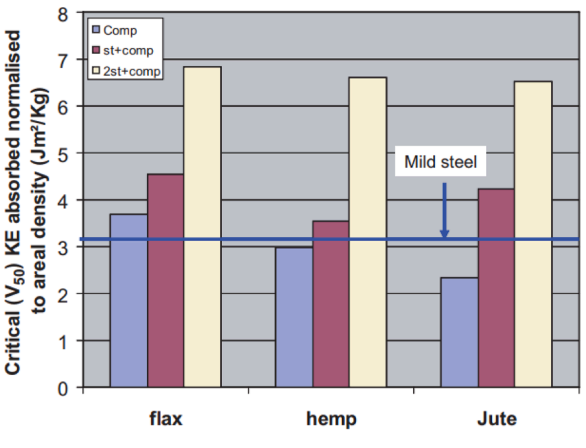

Fig. 7. Critical kinetic energy absorbed normalised to the areal densities of flax, hemp and jute composites. Reprinted with permission from Ref. [141]. License Number 5,433,631,498,182.

Tribology of plant fiber composites

Tribology is another area of interest in the manufacturing of industrial composite parts. Polymer-based natural fiber composites have many advantages over traditional metals, such as low friction, elasticity, no corrosion, and self-lubricant, and are suitable for machinery application. The commonly used method to determine the tribology was the pin-on-disk method. Many studies reported the tribology of PFRPC and showed improved resistance to friction and wear [148,149]. Rajeshkumar [150] studied the effect of fiber length and volume fraction of phoenix Sp fiber on the tribological performance of epoxy composites using a Pin-on-Disc Tribo machine. The researchers observed a reduction in the specific wear rate and the coefficient of friction with the introduction of phoenix Sp fibers, and the lowest wear rate and the coefficient of friction was observed at 40% fiber volume fraction and 20 mm fiber length. The important factor that influences tribology is the adhesion or interfacial bonding between the natural fiber and polymer. Note that the wear is caused by fiber pull-outs, debonding of the fiber from the matrix, and possible fiber breakage. Treating the fibers chemically or physically thereby reducing the OH groups, will improve the bonding between the fiber and polymer, thus reducing the chance of fiber pull-outs, fiber debonding, and fiber breakage [151] Chaudhary et al. [152] investigated the tribological behavior of jute, hemp and flax reinforced epoxy hybrid composites. The performance of WR was higher for all developed composites. Plant fibers such as areca sheath, ramie, jute, banana, kenaf, sisal, etc., have been reported for manufacturing

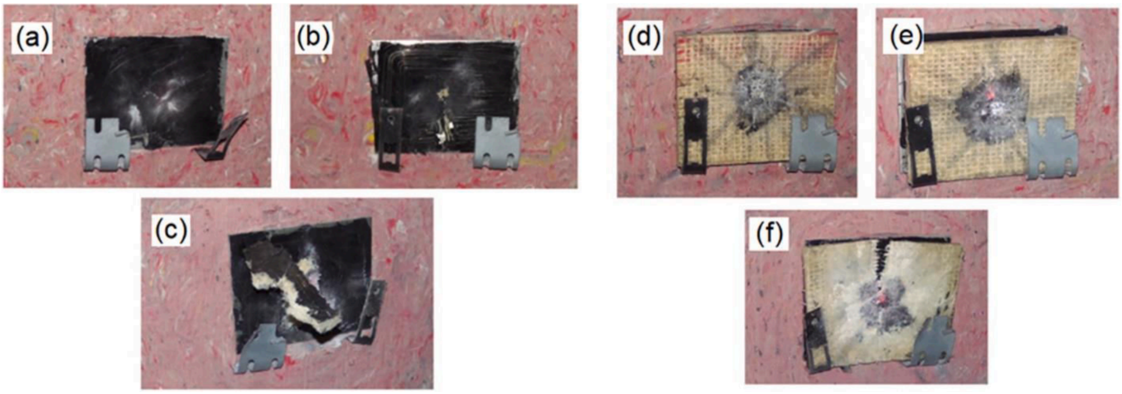

Fig. 8. Photograph of the multilayered armor systems target after the ballistic test, with second layer of (a) 10; (b) 20; (c) 30 vol.% fique aligned and (d) 10; (e) 20; and (f) 30 vol% of fique fabric polyester composites [144].

brake pads, bearing, and clutch [153,154].

Applications: current status

Up to the present time, plant fibers are primarily employed in the automotive application. Among the different fibers, flax fibers are the most widely used in the automotive industry, followed by kenaf, hemp, jute, sisal, and abaca [155]. The history of PFRPC in the automobile industry began in 1930 when Henry ford introduced a prototype car made of hemp fiber and soy resin. Later many companies such as Volvo, Daimler-Chrysler, Audi, BMW, Bosh, McLaren, Ford, Renault, and tesla make use of different fibers such as flax, sisal, banana, kenaf, hemp, abaca, and wood along with both thermoplastic and thermosetting resins for the manufacturing of interior door panels, dashboards, seat covers, boot lining, windshield, interior carpets, bumper, pillar cover panel, body panels, internal engine cover, and brake shoes. The idea of the automobile manufacturing industry is to reduce weight, reduce cost, better sustainability, recyclability, reusability, and better fuel efficacy [156–158]. BMW (Munich, Germany) and Porsche (Stuttgart, Germany) are using hemp fiber reinforced composites for the i3 electric vehicle and 718 Cayman GT4 Clubsport, respectively, to reduce the carbon footprint caused by the synthetic fibers. BMW launched a new M4 GTA that contains more plant fiber parts than any other racing car with many added advantages like reduced vibration damping, reduced greenhouse gas emission, sustainability, and safer components [159]. Recently, Lufthansa Technik and Diab's innovations developed flax fiber reinforced bio-based resin (from waste corn) composites for interior cabin components. The composites have 20% less weight and lower CO_2 emissions [160]. Faurecia [161] developed sustainable interior components for the automobile with 50% PP and 50% plant fibers. The company claimed that its products are having 50% less weight and 50% less CO_2 emission compared to 100% plastic products. Now, Faurecia is working on replacing PP with 100% recycled PP, to develop car interior products with negative CO_2 emissions. Sabic [162] developed sustainable eco-friendly composites composed of curauá fiber and polyamide (PA)−6 nylon and is used by Pematec, for the manufacturing of sun visors in automobiles. Recently, natural fibers are also used for the manufacturing of exterior components in automobiles like exterior body panels and doors [163].

Plant fibers can be a sustainable material for biodegradable packaging applications. SAS Green Gen Technologies developed environmentally friendly bottles as an alternative to glass and plastic bottles. The company used flax, wood, straw, plant residues, and bio-based resins to make bottles [164]. The plant fibers are also used in the manufacturing of perfume containers (curauá fiber and wood flour), laptop casing (hemp/PLA), bottles (cotton/PLA), food packaging (PLA/wood fiber, cassava starch/plant cellulose), etc [165]. Namvar et al. [166] review the potentiality of PFRPC in biomedical applications. For biomedical implants, the biocomposite should be biocompatible, anti-corrosive, fatigue resistant, and should have high toughness. Due to these properties, the PFRPC are used in tissue engineering, orthopedics, drug delivery, manufacturing of heart valves, etc.

ECO-COMPASS [167] is a collaborative project between European Union and China in the aviation industry. The research progress in this project proposed the use of natural fiber/recycled carbon fiber reinforced bioepoxy resin composites for interior and secondary structures in the aviation industry. Lufthansa Technik and AeroFLAX [168] together developed cabin interiors using flax fiber and biobased resins. The composites achieved good strength, flammability requirement, lightweight, and reduced carbon footprint. The other applications of natural fiber composites are infrastructure, small boats, bicycle frames, bridges, e-scooter, and travel bags. The cost and weight of composite components could be partially reduced with the replacement of traditional glass and carbon fiber composites with plant fibers. Moreover, the production of plant fiber can earn money for local farmers, especially in developing countries. One such example was Natloop Innotex LLP, Surat, Gujrat, India reached out to the farmers in Vazhakkulam, Kerala, India, for pineapple leaves for making fabrics. Thus, in a big way, traditional materials are replaced with natural fibers.

Conclusion

This review paper dealt with recent works on various aspects of PFRPC, for example, sisal, banana, hemp, jute, bamboo flax, etc. The plant fiber composites are finding applications in various fields due to their environmental benefit and property enhancement. The usage of biocomposites is forecasted to grow from 24.40 billion USD in 2021 to 90.89 billion USD in 2030. The plant fibers can be classified as bast, leaf, fruit/seed and stalk; these classifications are based on the parts from which the fibers are extracted. The type of extraction technique influences the fiber's property. Usually, the plant fibers are extracted by retting, mechanical and chemical methods. Besides, the retting is of five different types: dew retting, water retting, enzymatic retting, mechanical retting and chemical retting. The fiber's property is also influenced by its compositions such as cellulose, hemicellulose, lignin, etc. Among the compositions, cellulose could play an important role in determining the strength of composites. Most plant fiber contains 60% to 80% cellulose. For example, flax, hemp, jute, ramie, kenaf, pineapple leaf fiber, etc.

The PFRPC can be fabricated by using hand layup, CM, RTM, VARTM, pultrusion, autoclave, hot pressing, extrusion and IM techniques. The type of fabrication techniques varies depending on the type of fibers, such as long fiber, short fiber, fiber mat, etc. For instance, CM and IM techniques are preferred for short fibers. Apart from the type of fibers, the manufacturing technique can be selected based on the intended applications. Besides, the type of manufacturing technique can influence the property of composites. However, the properties of composites can be influenced by many factors: fiber surface modification, hybrid composites, varying fiber layering sequences, varying fiber loading, incorporating fillers, etc. Besides, this review paper describes various applications of PFRPC. For instance, damping, ballistic, fire retardancy, and tribology. Also, the current status of various applications of plant fibers is discussed. Though plant fiber and its composites possess many advantages, some obstacles must be overcome, such as reduced strength when subjected to outdoor applications, lesser toughness, and moisture absorption. Also, more research is required to enable the PFRPC for high load-bearing and temperature-based applications.

Declaration of Competing Interest

The authors have no conflict of interest to declare.

Data Availability

No data was used for the research described in the article.

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