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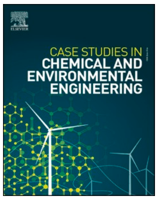

Case Report

Sustainable bamboo fiber reinforced polymeric composites for structural applications: A mini review of recent advances and future prospects

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ABSTRACT

This article reviews the present status and prospects of sustainable bamboo fiber reinforced polymeric composites (BFRCs). Because of its rapid growth, renewability, and minimal environmental effect, bamboo has emerged as a viable contender in response to the increasing demand for eco-friendly materials across a variety of sectors. Bamboo is going to be a significant lignocellulosic material. Moreover, a summary of the production procedures, mechanical qualities, and uses of bamboo fiber reinforced composites also discussed. The problems and possibilities connected with the development of BFRCs which negatively influence their performance in a variety of industrial applications also addressed further.

1. Introduction

BFRCs have emerged as a crucial type of sustainable polymeric products. In the past, carbon and glass fiber reinforced composites were more in demand [1,2], but they were not very sustainable. Consequently, scientists and manufacturers are continuously exploring more sustainable options for composites. Bamboo has now become the new breakthrough material like as so many other lignocellulosic woody or fibrous materials [3,4]. There are almost 1250 species of bamboo are found worldwide [5]. They are also widely grown in the Asian countries which could meet the increased need for lignocellulosic materials throughout the globe. The research on bamboo fiber reinforced polymeric composites as a substitute for conventional petroleum-based composites has been on the rise [6,7], driven by the growing demand for environmentally friendly materials in various industries. The use of bamboo as a reinforcement for polymeric composites is attractive since it is a renewable resource and has exceptional mechanical and physical properties, however, they are not much popular compared to other polymeric composites, namely synthetic fiber reinforced composites. Therefore, manufacturers and scientists are relentlessly trying to explore more sustainable routes of composites. Therefore, bamboo is showing the new milestone (see Fig. 12).

Improvements in mechanical characteristics, thermal stability, and durability of BFRC have been achieved via research and development during the last several years. However, the other natural fibers like kenaf, flax, ramie, hemp, jute, coir, sisal are already in practice by the sustainable manufacturers [8–14]. Natural lignocellulosic fibers are getting popularity both lighter weight, abundance in nature, biodegradability and advanced functionalities. In addition, as the life cycle of bamboo is very short and grown extensively around the world, hence it has a big potentiality. The bamboo fibers are extensively grown in some Asian countries like China, Indonesia, Myanmar, Bangladesh, Vietnam, Thailand, and so on [15]. Therefore, researchers are trying to find more advanced routes of utilizing this material, whereas development of

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Abbreviations: BFRCs, Bamboo fiber reinforced polymeric composites; PLA, Polylactic acid; PP, Polypropylene; MUF, Melamine urea formaldehyde; PE, Polyethylene; UF, Urea formaldehyde; TGA, Thermogravimetric analysis; HDPE, High density polyethylene.

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bamboo fiber reinforced biocomposite is one of them [16,17] for different structural applications (Fig. 1). These developments allow for their incorporation into a wide range of fields, including as transportation, aircraft, building, and consumer products.

An overview of the production methods, mechanical and physical qualities, and uses of sustainable bamboo fiber reinforced polymeric composites is the goal of this in-depth analysis. The possibilities and difficulties of using these materials in the future is discussed as well in this overview. This review work has broken this down like this: Initially, a quick primer on bamboo fibers useful qualities is given. After that, a discussion on how to make polymeric composites using bamboo fiber reinforcement is carried out. The tensile, flexural, and impact strengths, as well as the thermal and water resistance of the composites, are discussed next. The many industries that have found success using BFRCs have also been covered in this overview.

The limitations and potential of BFRC is discussed further, including the need for standardized testing and characterization methods, the creation of sustainable and cost-effective manufacturing processes, and the discovery of new applications and markets. To sum up, this study will present a thorough and current assessment of the developments in sustainable BFRCs, showing its promise as a practical alternative to conventional petroleum-based composites.

2. Classification of fibers

The two major groups of natural fibers are those derived from plants and those derived from animals. There are three main types of plant fibers: those extracted from the seed, the bast, and the leaves [19,20]. It is the hairs on the seeds of plants that are used to create textiles like cotton and kapok. Plants' stems or their outer skins are used to extract bast fibers like jute, flax, bamboo, and hemp. Plant leaves are the source of fibers like sisal and abaca. As bamboo fibers are extracted from the bamboo plant's stem, these fibers are classified as bast fibers. The bamboo fibers may be used for many different purposes because of their many positive qualities. The fact that bamboo can be continually replenished adds to its appeal as a green structural material.

Natural fibers (Fig. 2) provide a variety of benefits over synthetic fibers when used in polymeric composites. In comparison to synthetic fibers, natural fibers are often more affordable, lighter in weight, and better for the environment [21–24]. Natural fibers are superior to synthetics in terms of heat insulation and sound absorption. However, beside enormous benefits to using natural fibers in polymeric composites, there are also some drawbacks. It takes more time and effort to prepare natural fibers, and those fibers may have different qualities depending on the plant they came from and how they were processed. Also, natural fibers may degrade over time, particularly when wet.

A) Vegetable fibers

Vegetable fibers are derived from plant sources and include materials such as cotton, flax, jute, sisal, hemp, and bamboo [25]. They are known for their high strength, low weight, and biodegradability. They are widely used in the production of textiles, paper, and composite materials.

B) Animal fibers

Animal fibers are derived from animal sources, such as wool and silk [26,27]. They are known for their softness, warmth, and durability. They are commonly used in the production of textiles but are not

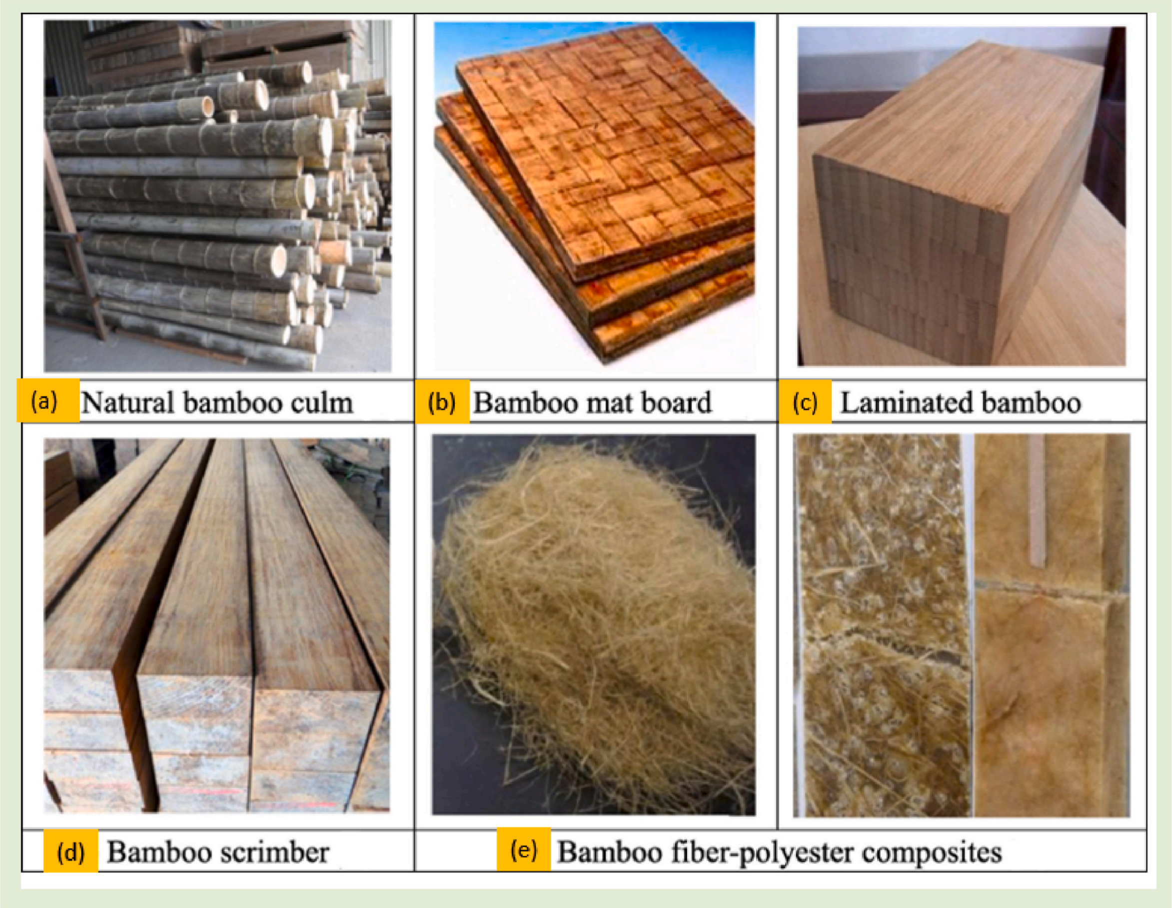


Fig. 1. Different bamboo material-based products [18]. Reprinted with the permission from Elsevier. Copyright, Elsevier 2020.

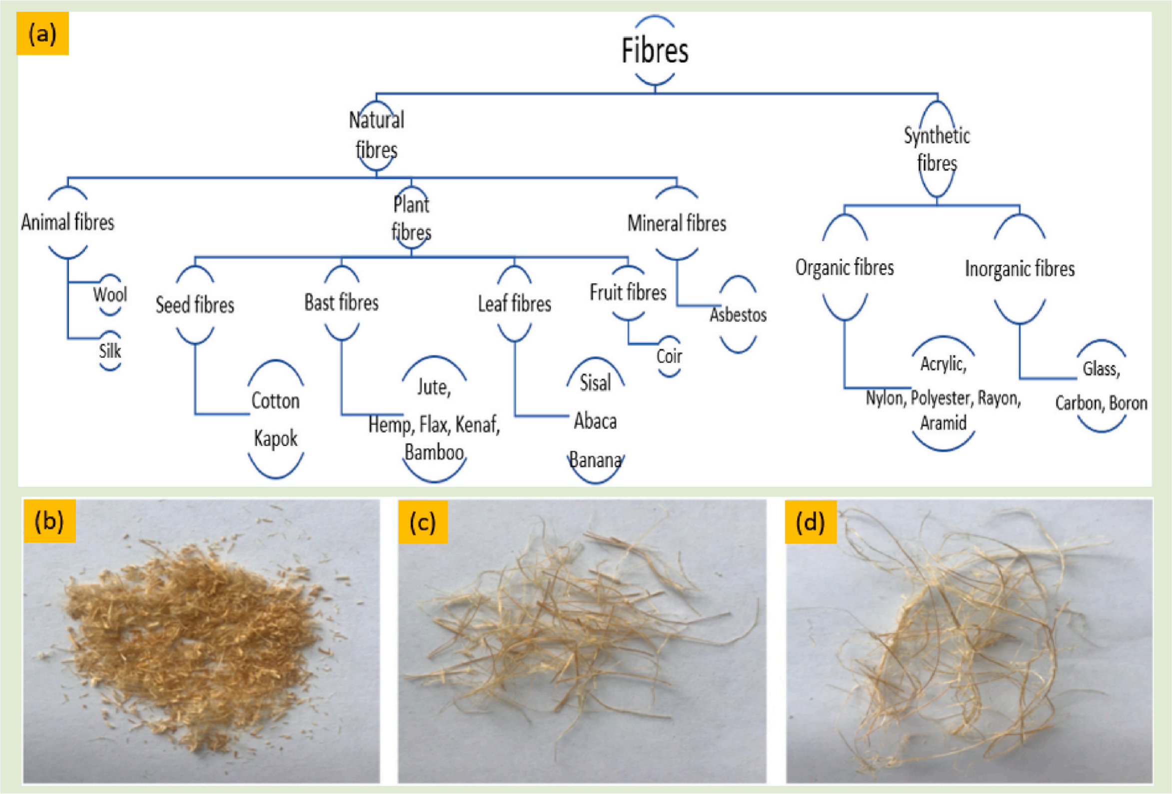


Fig. 2. (a) Classification of various natural and synthetic fibers [37]. (b) powder of bamboo, (c) bamboo fiber (short), and **(**d) bamboo fiber (long) [38]. Reprinted with the permission from Elsevier. Copyright, Elsevier 2021.

commonly used as reinforcement materials in composite materials.

C) Mineral fibers

Mineral fibers are derived from inorganic sources, such as glass, ceramic, and carbon [28,29]. They are known for their high strength and heat resistance, and are commonly used as reinforcement materials in composite materials [1,30].

D) Synthetic fibers

Synthetic fibers are man-made and include materials such as polyester, aramid, nylon, and acrylic [24,31,32]. They are known for their high strength, durability, and low cost. They are commonly used in the production of textiles and composite materials [1,33,34].

However, as this review is mainly focus on the use of bamboo fiber as a reinforcement material in polymeric composites, therefore it is mostly highlighted here. Bamboo is a sustainable and environmentally friendly material that has gained attention due to its high strength, low weight, and biodegradability. Bamboo fibers have been shown to improve the mechanical properties of polymeric composites, making them stronger and more durable. The recent advances in the use of bamboo fiber as a reinforcement material is impressive and suggest that it has significant potential for use in a wide range of applications, including construction materials, automotive components, and consumer products [35,36].

3. What is bamboo fiber?

The term “fiber” is often used to describe a long, thin, and flexible material with many applications in the manufacturing industry. Natural and synthetic fibers derived from plants, animals, and minerals are all fair game [39–42]. Bamboo fiber, one of several types of natural fiber, is produced from the cellulose of the bamboo plant. Bamboo is a rapidly reproducing plant and therefore is getting extreme attention. In recent years, bamboo fibers (Fig. 3) have gained popularity as a sustainable alternative to more conventional fibers like cotton and polyester [31,43,44] due to their robust, long-lasting, and adaptable properties.

Crushing the bamboo plant and then employing natural enzymes to break down the cellulose into a pulpy material is the method by which bamboo fiber is produced [45]. After the pulpy substance is spun into fibers, it may be utilized to create everything from clothing to paper to insulation. Because of its softness, breathability, and capacity to drain away moisture, bamboo fiber is increasingly being used in the textile and home textile industries too beside the composites. The biodegradability and natural decomposition of bamboo fiber make it a more sustainable material than many synthetic fibers, which may take hundreds of years to degrade [46,47]. Bamboo fiber is a renewable and flexible material that offers numerous advantages over conventional fibers, and it is expected to grow in popularity in the future years as consumers become more conscious of the need for eco-friendly and low-impact alternatives to conventional materials.

Bamboo fibers contain cellulose, lignin, hemicellulose, and extractives which is identical to so many other natural fibers (Fig. 4). According to Shah et al., typical bamboo fiber contain nearly 60.8% cellulose, 32.2% lignin, and 7% other components [50]. Therefore, bamboo is considered as one of the prominent cellulosic materials. The production of bamboo fiber is also shown in Fig. 3, where the process of preparing bamboo fiber starts with the careful selection of the bamboo plant. The selected plants are then boiled, cut, and the fibers are manually separated (Fig. 3). Interestingly, bamboo is a multicellular composite fibrous material. Bamboo fiber consists of significant elementary fibers which can be seen by the vascular bundles microstructure (Fig. 3 d). The SEM profiles show the surface morphology of bamboo, where the uplifted filaments are seen as packed together and could be removed by external forces as the binding is weaker [49]. The FTIR study further confirms the different chemical constituents of

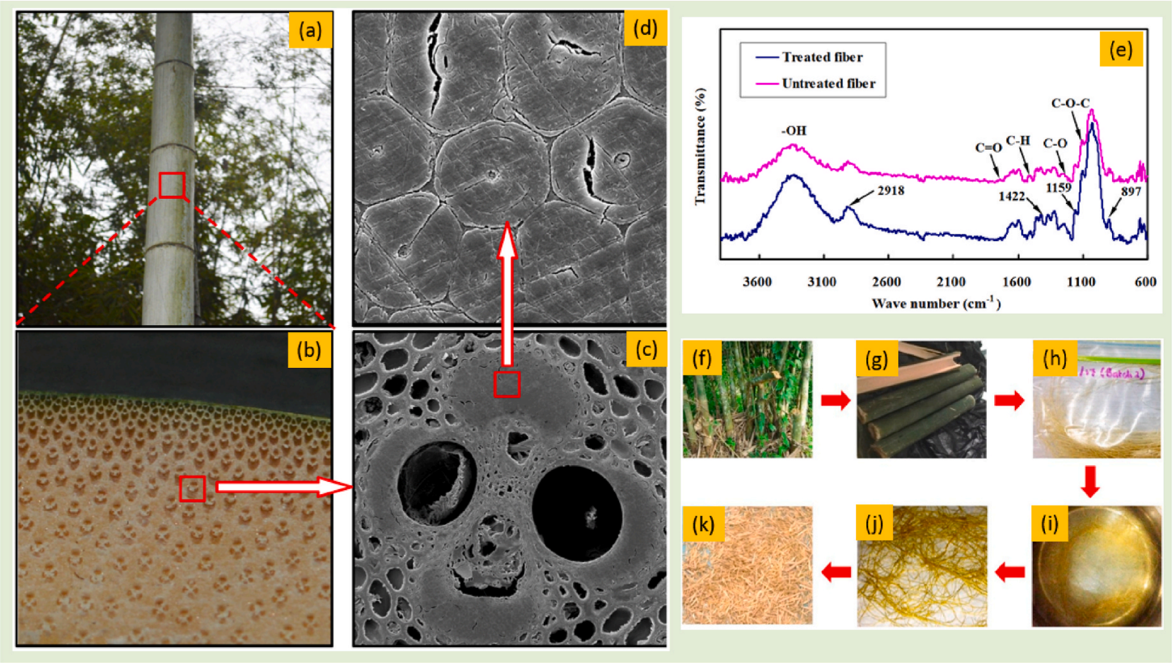


Fig. 3. (a) bamboo culm, (b) cross-section of bamboo culm, (c) vascular bundle of the bamboo fiber, (d) elementary bamboo fibers, (e) FTIR spectra of bamboo fibers, (f) selection of bamboo plant for preparing bamboo fiber, (h) cutting of bamboo plants for preparing bamboo fiber, (i) separating the bamboo fibers through manual operation, (j) boiled bamboo fibers, (k) dried bamboo fibers, (l) cutting bamboo fibers according to desired dimensions. Published under CC BY 4.0 license [48,49]. Copyright, MDPI 2015 and 2018.

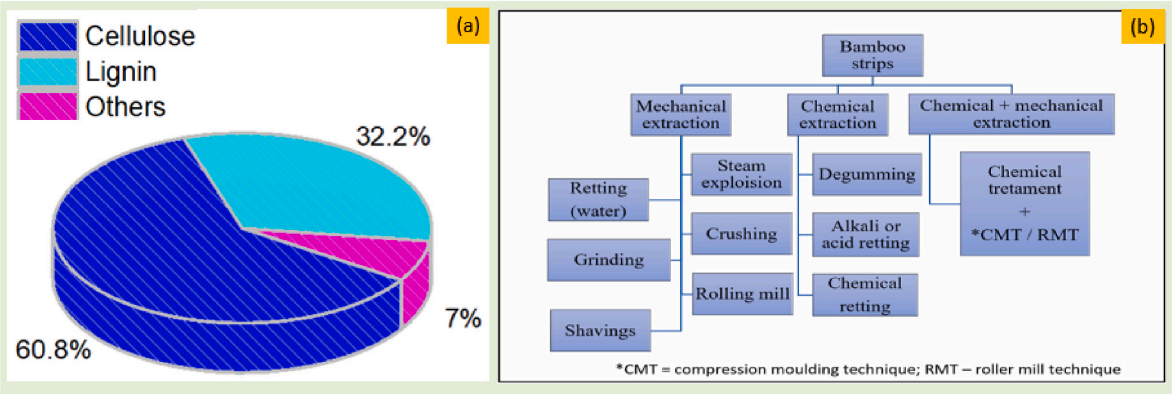


Fig. 4. (a) Chemical compositions of bamboo [50]. Copyright, NC State University, 2016 (open access). (b) extraction method of bamboo fiber [50,51]. Copyright, NC State University, 2016 (open access) and Elsevier 2022.

bamboo fibers (Fig. 3 e) through various distinct peaks like –OH group at 3200 to 3500 cm^{-1} and 2900 cm^{-1} for –CH stretching vibration [49].

Single bamboo fibers that have been chemically isolated have a tensile strength of 1770 (0.15) MPa, a tensile modulus of 26.85 (0.16) GPa, and an elongation of 2.89 (0.16)%. In comparison, mechanically separated single bamboo fibers have a tensile strength of 930 (0.19) MPa, a tensile modulus of 34.62 (0.17) GPa, and an elongation of 4.3 (0.17)% [52]. However, bundle fibers retain much less strength than single fibers. For example, chemically isolated bundle fibers have a tensile strength of 610 (0.37) MPa, a tensile modulus of 234.56 (0.35) GPa, and an elongation of 2.61 (0.32)% [52]. This trend is also observed in the case of mechanically isolated fibers, which have a tensile strength of 290 (0.71) MPa, a tensile modulus of 16.50 (0.42) GPa, and an elongation of 1.68 (0.31)% [52].

4. Extraction of bamboo fiber

Bamboo fiber can be extracted from bamboo using either mechanical or chemical or by combining both the methods [51]. A detailed extraction method is shown in Fig. 4 (b). The extraction of bamboo entails couple of steps including, harvesting bamboo, soaking, extraction, bleaching, and spinning [53,54]. In the case of harvesting, mature bamboo stalks are harvested, and the leaves and branches are removed. For soaking, the bamboo stalks are soaked in water for several hours to soften the fibers. However, the softened bamboo stalks are crushed and mechanically processed to extract the fibers during the extraction process. The extracted fibers are then bleached using hydrogen peroxide or sodium hypochlorite to remove any impurities present which is termed as bleaching. Later on, spinning is performed where the bleached fibers are spun into yarns or threads.

On the other hand, chemical method involves some steps right after the harvesting, like as, cleaning, boiling, washing, bleaching, and finally spinning [45,55]. The bamboo culms are cleaned to eliminate any dirt or debris that may have accumulated on them which is termed as cleaning. Through boiling, the bamboo culms are then cooked in a solution of water and chemicals such as sodium hydroxide or sulfuric acid. This breaks down the lignin and hemicellulose in the bamboo, enabling the fibers to be separated. The bamboo fibers are then washed to eliminate any leftover chemicals. Later, the fibers may be bleached to remove any natural color and make them whiter. Finally, the fibers are then spun into yarns, which may be used to manufacture a variety of items.

Both methods have their advantages and disadvantages. The mechanical method is environmentally friendly, but it is more labor-intensive and time-consuming [50]. The chemical method is faster and requires less labor, but it involves the use of chemicals that can be harmful to the environment if not properly disposed of.

5. Chemical treatment of bamboo materials

Bamboo is a flexible and sustainable material that has grown in favor in recent years owing to its environmental friendliness, strength, and durability. Yet, in order to make bamboo acceptable for a variety of purposes, it is often subjected to chemical treatments to improve its characteristics and extend its lifespan (Fig. 5). Like as other plant-based materials, bamboo is rich in hydrophilic groups which limit the dimensional stability and better mechanical properties. However, the chemical treatments could improve the functionality significantly. The following are some of the most typical chemical treatments for bamboo materials.

Alkaline treatment entails immersing the bamboo in a solution of sodium hydroxide or potassium hydroxide. The color, texture, and durability of the bamboo are improved by this treatment. Alkaline treatment also aids in the removal of lignin and hemicellulose, two natural components that deteriorate with time, leaving bamboo more susceptible to rot. Manalo et al. [57], investigated on the effects of elevated temperatures on the performances of bamboo fiber reinforced composites and found an improvements in their mechanical properties. They [57] treated the bamboo fibers with alkaline solutions, ranged from 4 to 8 wt% at increased temperatures, by 40, 80 and 120 °C. They [57] have further found an optimum concentration of NaOH (6%), which fibers exhibited the highest mechanical properties. In another study, Huang et al., investigated and reported on bamboo fiber reinforced epoxy composites to understand the effects of fiber diameter on the mechanical properties and found that the tensile and Youngs modulus increases (Fig. 6) with the reduction in fiber diameter [58]. The tensile strength and modulus for neat epoxy (EP) was 79 MPa and 2.5 MPa, respectively, which shown an increased trend after the reinforcement with bamboo fiber by 168.67 and 8.54 MPa, respectively. However, after the modification it shown an increase significantly by 39 and 40%, respectively [58].

Acid treatment is soaking bamboo in an acid solution, often hydrochloric acid or sulfuric acid. The fibers of the bamboo are broken down during this process, resulting in a softer, more malleable material [59]. However, in general, textiles and garments are often treated with acid [57].

Bleaching is a chemical process used to lighten the color of bamboo. While hydrogen peroxide is sometimes used, chlorine bleach is the most often used bleaching chemical for bamboo [60,61]. Bleaching is often performed to ensure that the color of bamboo goods uniform.

Fire retardant treatment This includes treating bamboo with chemicals that make it fire resistant. This treatment is often used on bamboo floors when fire safety is a concern. In this regard, Niu et al. conducted an experiment on bamboo fiber reinforced PLA composites in the presence of phosphorous-silicon aerogel [62]. This study further reported about NMR study to prove that DOPO (9,10-dihydro-9-oxa-10-phosphophenanthrene-10-oxide) and VTS (vinyl trialkoxy silane) has been grafted successfully in the composite system as seen (Fig. 7) in the resonance at 40 PPM [62]. Moreover, FTIR study further illustrate the presence of hydroxyl group and covering of SiP on bamboo fiber Fig. 7 c. Additionally, TGA curves also showed a tremendous improvement of thermal stability after incorporating phosphorous silicon aerogel (Fig. 7).

However, there are also some other treatments used for functionalizing bamboo fibers like as antifungal. Bamboo is prone to fungal assaults, which may result in degradation and degeneration. Anti-fungal treatments are used to inhibit fungal development and maintain the structural integrity of bamboo [63]. Boron chemicals, copper compounds, and boric acid are common antifungal treatments. It is vital to note that certain chemical treatments might have detrimental environmental effects, thus it is critical to choose treatments that are as

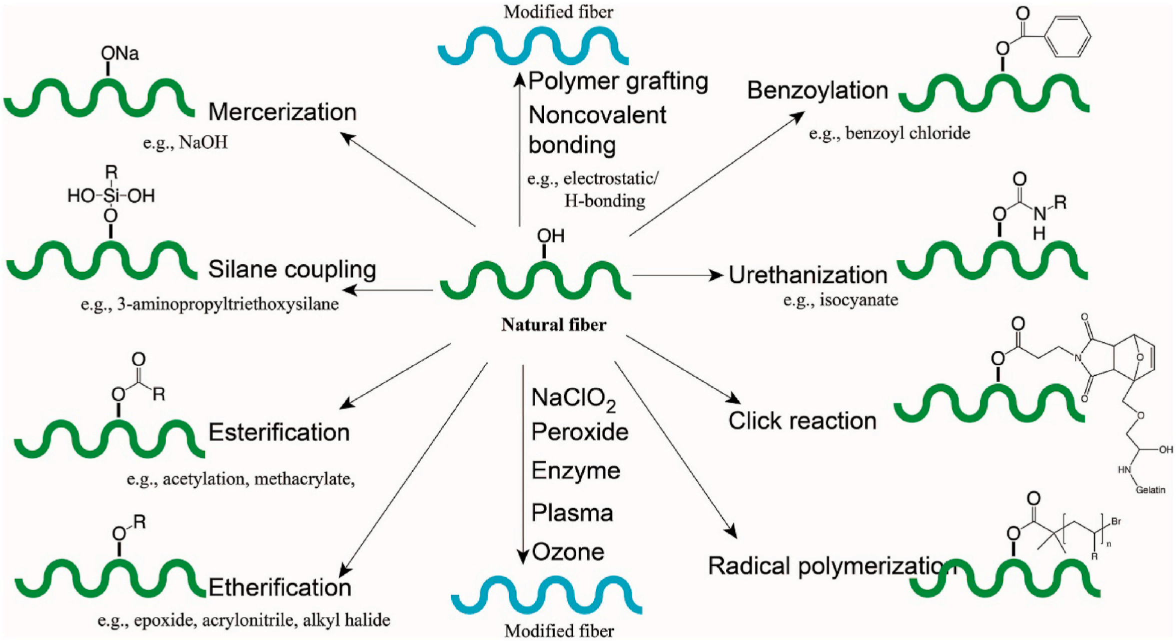


Fig. 5. Different chemical-based modification of naturally derived lignocellulosic materials [56]. Reprinted with the permission from Elsevier. Copyright, Elsevier 2020.

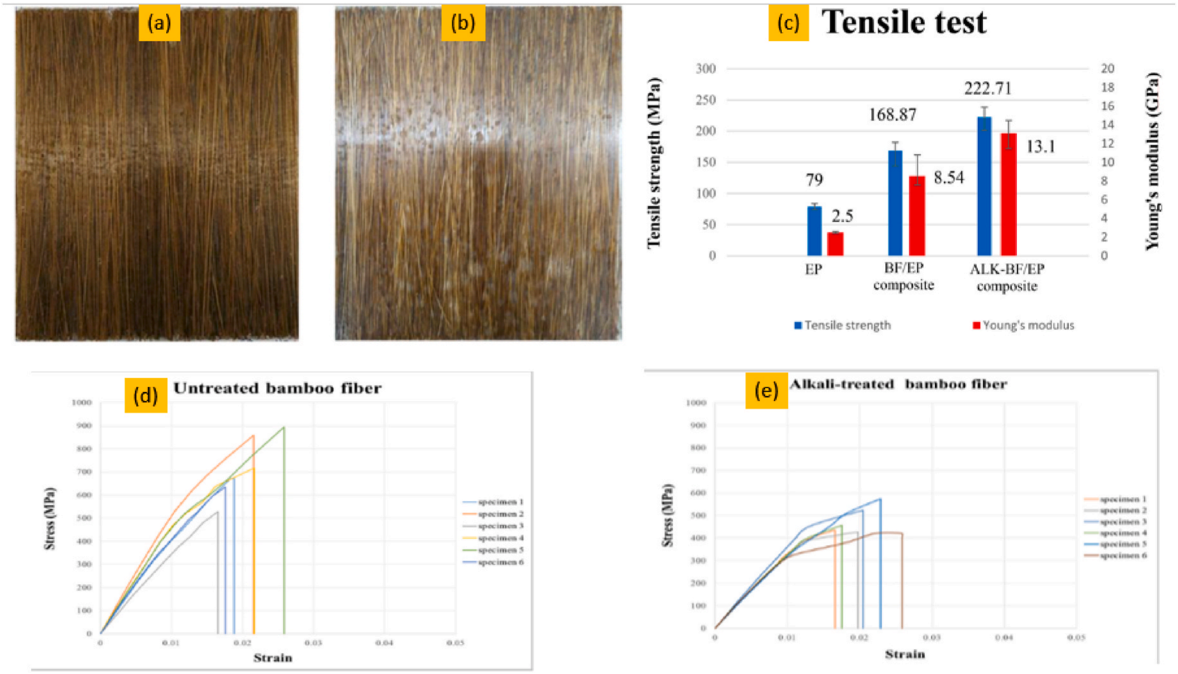


Fig. 6. Bamboo fiber reinforced epoxy composites: (a) untreated composite product, (b) treated composite product, (c) tensile properties of the products, (d) stress strain curve for untreated products, and (e) stress strain curve for treated products. Adapted with the permission from Elsevier [58]. Copyright, Elsevier 2019.

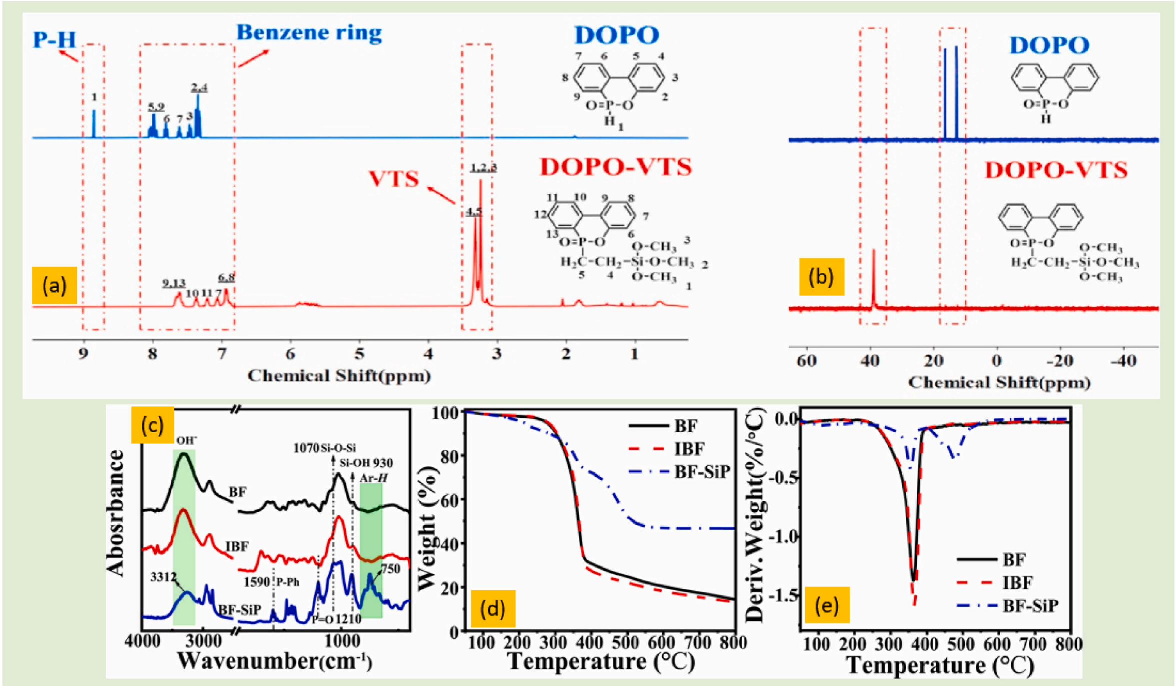


Fig. 7. DOPO-VTS study of (a) HNMR and (b) PNMR. (c) FTIR, (d) TGA, and (e) DTG analysis of BF (bamboo fiber), IBF, and BF–SiP. Adapted with the permission from Elsevier [62]. Copyright, Elsevier 2022.

environmentally friendly as possible. Also, it's crucial to follow basic safety practices while handling chemicals and to dispose of any waste in a responsible way.

6. Fabrication of bamboo fiber reinforced composites

BFRCs is a form of composite material that combines natural fibers from bamboo plants with a polymer matrix material to generate a composite with superior mechanical qualities. Many procedures are involved in the production of these composites, including the collecting and processing of bamboo fibers, the creation of polymer matrix material, and the mixing and molding of the composite material through implementing adequate technology [64]. A typical preform preparation is displayed in Fig. 8.

The following are the detailed stages in the manufacture of bamboo fiber reinforced composites:

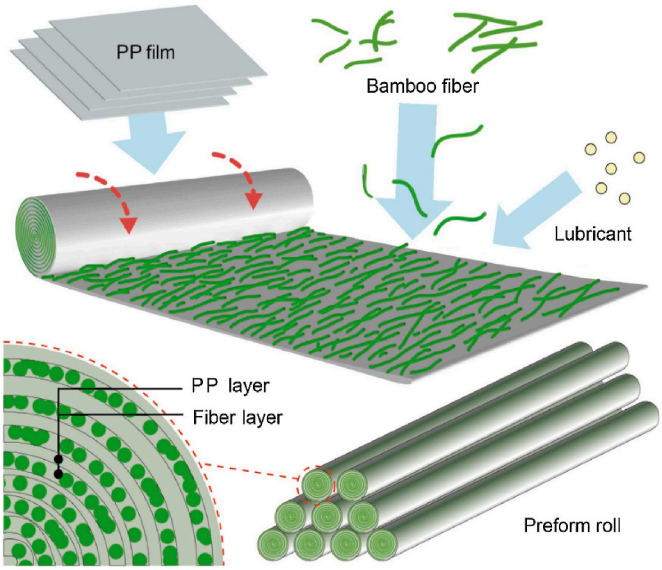


Fig. 8. A fabrication design for bamboo fiber/polypropylene preform. Adapted with the permission from Elsevier. Copyright, Elsevier 2020.

Harvesting and processing of bamboo fibers: The collection and processing of bamboo fibers is the initial stage in the manufacturing process. Bamboo stems are chopped and divided into thin strips, which are then cooked in a sodium hydroxide solution to remove lignin and other impurities [58]. The fibers that arise are then cleaned, bleached, and dried to produce a clean and homogeneous fiber.

Polymer matrix material preparation: The next stage is to prepare the polymer matrix material, which is often a thermoplastic or thermosetting polymer. To enhance its qualities and make it appropriate for processing, the polymer material is melted and blended with additives such as plasticizers, stabilizers, and colors/pigments.

Bamboo fibers and polymer matrix are then blended together utilizing different processes such as extrusion, compression molding, or injection molding [65]. The fibers are uniformly dispersed throughout the polymer matrix to guarantee that the finished composite material has acceptable mechanical characteristics.

Molding of composite material: The last stage in the production process is to shape and dimension the composite material. This may be accomplished via the use of several processes such as compression molding, injection molding, and thermoforming. The molded composite is subsequently cooled and taken from the mold, and any final touches, such as trimming or sanding, are applied [66].

Finally, the manufacturing of BFRC entails a number of phases, beginning with the harvesting and processing of bamboo fibers and progressing through the manufacture of the polymer matrix material, mixing of the fibers and matrix, and molding of the composite material. The resultant composite material has increased mechanical qualities such as greater tensile strength, flexural strength, and impact resistance, making it appropriate for construction, automotive, and consumer goods applications.

6.1. Bamboo fiber reinforced thermoplastic polymeric composites

Bamboo fiber reinforced thermoplastic polymer composites are a form of composite material created by mixing bamboo fibers with a thermoplastic polymer. Bamboo fibers serve as reinforcement, increasing the composite material's strength, stiffness, and durability. The thermoplastic polymer matrix acts as a binder that keeps the bamboo fibers together and gives the composite with its shape and form. Because of its excellent strength-to-weight ratio, low density, and rapid growth rate, bamboo is an appealing material for composite manufacture. Bamboo fibers may be removed by either mechanical or chemical techniques, and the resultant fibers can be utilized to manufacture a broad variety of composite materials, including thermoplastic polymer reinforced bamboo composites.

Polypropylene (PP), polyethylene (PE), and polylactic acid (PLA) are thermoplastic polymers utilized in the production of reinforced bamboo composites [67,68]. These polymers were selected for their ease of processing and mechanical qualities. The thermoplastic polymer reinforced bamboo composites manufacturing method normally includes combining the bamboo fibers with the polymer matrix and then subjecting the combination to heat and pressure to generate the composite material. The resultant composite may be shaped and sized as desired. Some examples are shown in Table 1.

The addition of bamboo fibers to a thermoplastic polymer matrix may increase the mechanical characteristics of the composite material dramatically [85]. Bamboo fiber reinforced polypropylene composites, for example, have been discovered to have greater flexural, tensile, and impact strength than pure polypropylene [86]. Similarly, as compared to pure polyethylene, bamboo fiber reinforced polyethylene composites exhibit better tensile strength and modulus of elasticity. This is because bamboo fibers, which are derived from the bamboo plant, are known to have high tensile strength and stiffness, making them an excellent reinforcing agent for polypropylene. When bamboo fibers are added to polypropylene, they create a composite material that exhibits enhanced mechanical properties compared to the pure polymer. The mechanical properties of the composite material depend on factors such as the length, diameter, and orientation of the bamboo fibers, as well as the volume fraction and interfacial bonding between the fibers and the polymer matrix. Bamboo is a renewable resource that grows rapidly and has a minimal environmental effect when compared to other materials such as wood, making thermoplastic polymer reinforced bamboo composites an ecologically beneficial alternative. Moreover, thermoplastic polymers may be recycled, lowering the environmental effect of these composite materials even further.

Overall, thermoplastic polymer reinforced bamboo composites are a promising material for a broad variety of applications owing to its high strength, stiffness, durability, and ecologically benign nature. As research in this field progresses, these composite materials are projected to become increasingly extensively employed in sectors such as construction, automotive, and packaging.

6.2. Bamboo fiber reinforced thermosetting polymeric composites

Composites produced from bamboo fibers with a thermosetting polymer are known as thermosetting polymer reinforced bamboo composites. The great strength, stiffness, and resistance to deformation of composite materials make them a viable alternative to more conventional materials like wood and metal. Bamboo is a sustainable material that has been used for centuries due to its resilience and strength. It's great for usage in composites since it's lightweight and simple to manipulate. When mixed with a thermosetting polymer, bamboo's strong but malleable fibers produce a composite material that is both durable and lightweight [87]. Cross-linking occurs during the curing process of thermosetting polymers, making them extremely deformation- and heat-resistant. Because of their exceptional adherence to fibers and their ability to be molded into various forms, they are often utilized in the production of composite materials [2].

Thermosetting polymer reinforced bamboo composites often go through a multi-step production process. To begin, the bamboo is harvested and cleaned of its fibers. After that, a thermosetting polymer resin is applied to the fibers and cured by heat or chemicals. When the composite material has cured, it is cut and polished to the user's requirements. Several benefits over more conventional materials are realized in the final composite. This material's great moisture resistance makes it perfect for outdoor uses including decking and fencing [88]. As it is so difficult to bend or twist, it is perfect for use in beams, columns,

Table 1
Mechanical properties of thermoplastic, thermosetting, and cementitious polymeric composites.

Polymer type	Lignocellulosic material	Tensile strength (MPa)	Youngs Modulus (GPa)	Flexural strength (MPa)	Impact strength (KJ/m^2)	Reference
Thermoplastic						
PLA	Alkali treated bamboo fiber	29.39 (2.49) to 39.51 (2.61)	1.71(0.08) to 2.17 (0.15)	55.32 (1.98) to 64.25 (3.78)	6.46 (0.59) to 8.89 (1.09)	[69]
PP/PLA	Bamboo fiber	~27 to 68		~43 to 63		[70]
PLA	Bamboo fiber	~58.5 to 65.5		~81 to 96	~2.5 to 3.5	[71]
PP	Bamboo fiber	31.3 ± 0.6 to 36.2 ± 0.6	0.9 ± 0.4 to 1.1 ± 0.2	44.3 ± 1.9 to 53.0 ± 1.6		[72]
HDPE	Bamboo fiber	~25 to 35		~22.5 to 25.8		[73]
PVC	Bamboo fiber/particulate coconut shell	~26 to 68		~23 to 65		[74]
LDPE	Bamboo fiber	23.6 ± 0.5 to 45.6 ± 1.50		1.18 ± 0.05 to 1.65 ± 0.14	34.57 to 62.59	[75]
Polyester/ polystyrene	Bamboo fiber	~22 to 34	~3 to 4	55 to 75	4.5 to 21.5	[76]
Thermosetting						
Epoxy and hardener	Treated bamboo fiber	~7.81 to 18.07	–	~2.5 to 4.0	–	[66]
Polyester	bamboo fiber	~36 to 56	61 to 90		~11 to 12.8	[77]
Polyethylene	bamboo fiber	0.68 ± o.07 to 0.72 ± o.02	~19 to 85	–	–	[78]
MUF	bamboo fiber	–	–	~1.7 to 2.2		[79]
UF	bamboo fiber	–	–	~4.3 to 5.68		[80]
Silicone oil	bamboo fiber	~18.5 to 23.8	–	~20 to 29	~11.8 to 12.8	[81]
Epoxy	bamboo fiber	262 ± 75 to 363 ± 103	6.1 ± 0.1	11.2 ± 2.4		[82]
Cementitious						
Cement	bamboo fiber	~10 to 19.8		~3 to 13		[83]
Cement	bamboo fiber	–	–	0.25 to 0.32	0.6 to 6.8	[84]

and other structural components. It's also a great material for making furniture and other ornamental objects since it's lightweight and simple to work with.

Overall, bamboo composites supplemented with thermosetting polymers are a sustainable and adaptable material with several benefits over more conventional options. These materials are great for a variety of uses since they are durable, lightweight, and resistant to deformation and moisture. The extensive use of this material across sectors is projected to increase as technology develops.

6.3. Bamboo fiber reinforced cementitious composites

Cement is also another significant binder used to produce composite panels for sustainable products development [89–91]. Different wood and fibers are used for these purposes. Some of the examples are given here in Table 1 for bamboo fiber reinforced cementitious products. They also provide significant tensile, flexural, and impact strength properties (Table 1).

6.4. Bamboo fiber reinforced cementitious composites

The incorporation of nanoparticles into BFRCs has shown promising results in improving their mechanical, thermal, and barrier properties. Nanoparticles can act as reinforcements, fillers, or modifiers, depending on their properties and the desired performance of the composite material [92,93]. For example, silica nanoparticles may increase the stiffness and hardness of BFRPCs, while carbon nanotubes can boost their electrical and thermal conductivity [94].

The reasons behind the improved performance of BFRPCs with nanoparticles are mainly attributed to the high specific surface area and unique properties of nanoparticles, such as high aspect ratio, high strength, and excellent surface reactivity [94]. These properties allow nanoparticles to form strong interfacial bonding with the bamboo fibers and the polymer matrix, resulting in improved load transfer, reduced interfacial shear stress, and enhanced interfacial adhesion. Additionally, the small size of nanoparticles enables them to fill the voids and defects in the composite matrix, resulting in reduced porosity and improved mechanical properties.

7. Effects of bamboo fiber orientation on composites

The term "polymeric composite" refers to a class of materials created by fusing together two or more polymers. Natural fibers, such as bamboo fibers, are often used to strengthen composite materials. In recent years, there has been a rise in the usage of these materials due to their durability, affordability, and high quality mechanical qualities. In a polymeric composite, the mechanical characteristics are greatly affected by the orientation of the bamboo fibers [95]. The composite material exhibits isotropic behavior when bamboo fibers are randomly arranged inside a polymeric matrix [96]. As a result, the material will have uniform qualities in all directions.

Anisotropic behavior emerges, however, when bamboo fibers are oriented in a certain orientation inside the polymeric matrix. This implies the material will behave differently depending on the direction you look at it from. The composite material's anisotropic nature enables the customization of its characteristics. One property that may be enhanced by manipulating the orientation of bamboo fibers in a polymeric composite is the material's tensile strength. The tensile strength of a composite material improves when its fibers are oriented perpendicular to the applied force [97]. The reason for this is because when fibers are properly aligned, they are better able to withstand external loads.

In addition, manipulating the bamboo fibers' orientation helps increase the polymeric composite's flexural strength and stiffness. The flexural strength and stiffness of a composite material may be improved by aligning the fibers along the direction of the applied load. This is because fibers that are properly aligned will have a harder time bending. Like with any polymeric composite, the orientation of the bamboo fibers has an effect on the impact strength of the finished product. The impact strength of a composite material may be improved by aligning the fibers with the direction of the impact [98]. This is due to the increased resistance the aligned fibers will have to the impact.

Briefly, the mechanical characteristics of a polymeric composite made with bamboo fibers are significantly affected by the orientation of the bamboo fibers inside the composite. The qualities of the composite may be adjusted for various uses by manipulating the fiber orientation. For its eco-friendliness, affordability, and high quality mechanical qualities, polymeric composites reinforced with bamboo fibers are quickly rising in popularity.

8. Effects of physical/chemical properties of bamboo fiber

Bamboo is an environmentally benign and sustainable natural material that has sparked considerable interest in the production of polymeric composites. Bamboo fiber-reinforced polymeric composites are lightweight, robust, and cost-effective. Bamboo fiber qualities vary depending on species, age, and growth circumstances. Bamboo fibers' physical and chemical qualities have a considerable impact on the performance of polymeric composites. In this article, we will look at how the physical and chemical characteristics of bamboo fibers affect polymeric composites.

Bamboo fiber physical properties [99,100].

A. Fiber diameter and length: The diameter and length of bamboo fibers have an impact on the mechanical characteristics of composites. Because of enhanced fiber-matrix bonding and load transmission, longer and thinner fibers have higher mechanical characteristics.
B. Fiber content: The quantity of bamboo fiber in the composite influences its characteristics. Increased fiber content improves mechanical qualities while increasing processing difficulties and expense.
C. Fiber orientation: The orientation of the fibers in the composite influences its characteristics. A greater degree of fiber orientation enhances mechanical characteristics along the fiber path.
D. Moisture content: The mechanical characteristics of bamboo fibers are affected by their moisture content. Increased moisture content impairs fiber-matrix bonding and decreases composite mechanical characteristics.

Bamboo fiber's chemical properties [101,102].

A. Chemical composition: Bamboo fibers' chemical makeup influences their characteristics. Bamboo fibers are mostly composed of lignin, cellulose, and hemicellulose [93]. Lignin concentration influences the compatibility of bamboo fibers with polymeric matrix, while cellulose and hemicellulose content influences the mechanical qualities of the fiber.
B. Surface chemistry: The surface chemistry of bamboo fibers is critical for interfacial interaction between the fibers and the polymeric matrix. The presence of hydroxyl (-OH) groups on the surface of bamboo fibers promotes interfacial bonding and boosts surface energy.
C. Surface modification: Chemical, physical, or biological surface modification of bamboo fibers may increase their compatibility with the polymeric matrix. Chemical modification of bamboo fibers includes the addition of functional groups to the surface, while physical modification entails modifying the surface shape. The employment of microorganisms to change the surface of bamboo fibers is referred to as biological modification.
D. Finally, the physical and chemical characteristics of bamboo fibers have a considerable impact on the performance of polymeric composites [94]. The mechanical characteristics of composites are affected by fiber diameter, length, content, and orientation. Bamboo fibers' chemical composition, surface chemistry, and surface modification all have an impact on their compatibility with the polymeric matrix [103]. Thus, it is vital to consider the physical and chemical characteristics of bamboo fibers when creating polymeric composites for particular purposes.

9. Performance characteristics of bamboo fiber reinforced composites

As a reinforcing element in composites, bamboo is only one of the many ways in which its eco-friendliness, fast regeneration, and adaptability make it a valuable resource. A lot of research has gone into bamboo fiber reinforced composites (BFRC) because of its unusual qualities [15,71,104]. They include high strength and low weight as well as high stiffness and high impact resistance. Several parameters, including matrix type, fiber orientation, fiber content, and processing conditions, affect the performance characteristics of BFRCs. There is some flexibility in the kind of matrix material utilized in BFRCs; it may be either thermoplastic or thermosetting resins. Because to their superior compatibility with bamboo fibers, hardness, and recycling potential, thermoplastic matrices are the best option for BFRCs. Epoxy and polyester, two common thermosetting resins, are employed but are difficult to recycle and break apart when subjected to impact [105]. The composite's mechanical characteristics, thermal stability, and water resistance are all influenced by the matrix material used to create it.

The performance parameters of BFRCs are also heavily influenced by fiber orientation. Mechanical characteristics of a composite will vary depending on whether the fibers are oriented in a unidirectional or multidirectional pattern. Composites made with unidirectional fibers have great rigidity and strength in the fiber alignment direction but are more likely to fail in orthogonal directions. As the mechanical characteristics of an isotropic composite are the same in all directions, multidirectional fibers provide such materials. The performance parameters of BFRCs are also affected by their fiber composition. Composites with a greater fiber content are stronger and more rigid, but they may also be more brittle and less robust [106]. The ideal fiber content is context and property dependent.

The performance parameters of BFRCs are also affected by processing variables including temperature and pressure. The strength of a composite is dependent on the degree of fiber-matrix bonding [107,108], which in turn is affected by the temperature and pressure utilized during production. Performance characteristics of bamboo fiber reinforced composites are sensitive to a number of variables, such as matrix type, fiber orientation, fiber content, and processing conditions. Knowledge of these aspects may aid in the development of BFRCs with the ideal characteristics for certain uses.

9.1. *Mechanical properties*

Bamboo is a natural composite material with unique mechanical qualities that has been utilized for ages for a variety of uses. BFRCs have received a lot of interest in the area of materials science and engineering in recent years. BFRCs are composite materials composed of bamboo fibers embedded in a matrix material, which may be polymer, ceramic, or metal. This answer will concentrate on the mechanical characteristics of BFRCs.

A. Tensile strength: A material's tensile strength is its capacity to sustain pulling forces without breaking. Since bamboo fibers are robust and stiff, BFRCs have a high tensile strength. The tensile strength of BFRCs varies according to the kind and size of bamboo fibers used, the matrix material utilized, and the manufacturing technique used to create the composite [109,110]. Tensile strength of multiple bamboo fiber reinforced products are tabulated in Table 1.
B. Flexural strength: The capacity of a material to sustain bending pressures without breaking is referred to as flexural strength. Due to the peculiar microstructure of bamboo fibers, which comprises of precisely aligned microfibrils, BFRCs offer excellent flexural strength [111,112]. Bamboo fibers' microstructure helps them to withstand bending forces more efficiently, resulting in BFRCs with excellent flexural strength.
C. Compressive strength: This is a material's capacity to sustain compressive pressures without distortion or breaking. Because of the high strength and stiffness of bamboo fibers, BFRCs have excellent compressive strength. The compressive strength of BFRCs, on the other hand, may be modified by the matrix material and the manufacturing technique used to create the composite.
D. Impact resistance: The capacity of a material to absorb energy from an impact without breaking is referred to as impact resistance.

Because of the great toughness of bamboo fibers, BFRCs offer excellent impact resistance. Bamboo fibers' toughness stems from its capacity to absorb energy by generating microcracks when exposed to impact, which aids in dissipating the energy and preventing failure [113,114].

E. Fatigue resistance: The capacity of a material to tolerate repeated cyclic loads without breaking is referred to as fatigue resistance. Because of the high strength and stiffness of bamboo fibers, BFRCs offer excellent fatigue resistance. The peculiar microstructure of bamboo fibers also aids in the dissipation of energy produced by cyclic loading, resulting in BFRCs with high fatigue resistance.
F. Hardness: Hardness is a material's capacity to resist deformation or indentation [115]. Because of the strong strength and stiffness of bamboo fibers, BFRCs have a high hardness. The hardness of BFRCs may also be affected by the matrix material utilized.

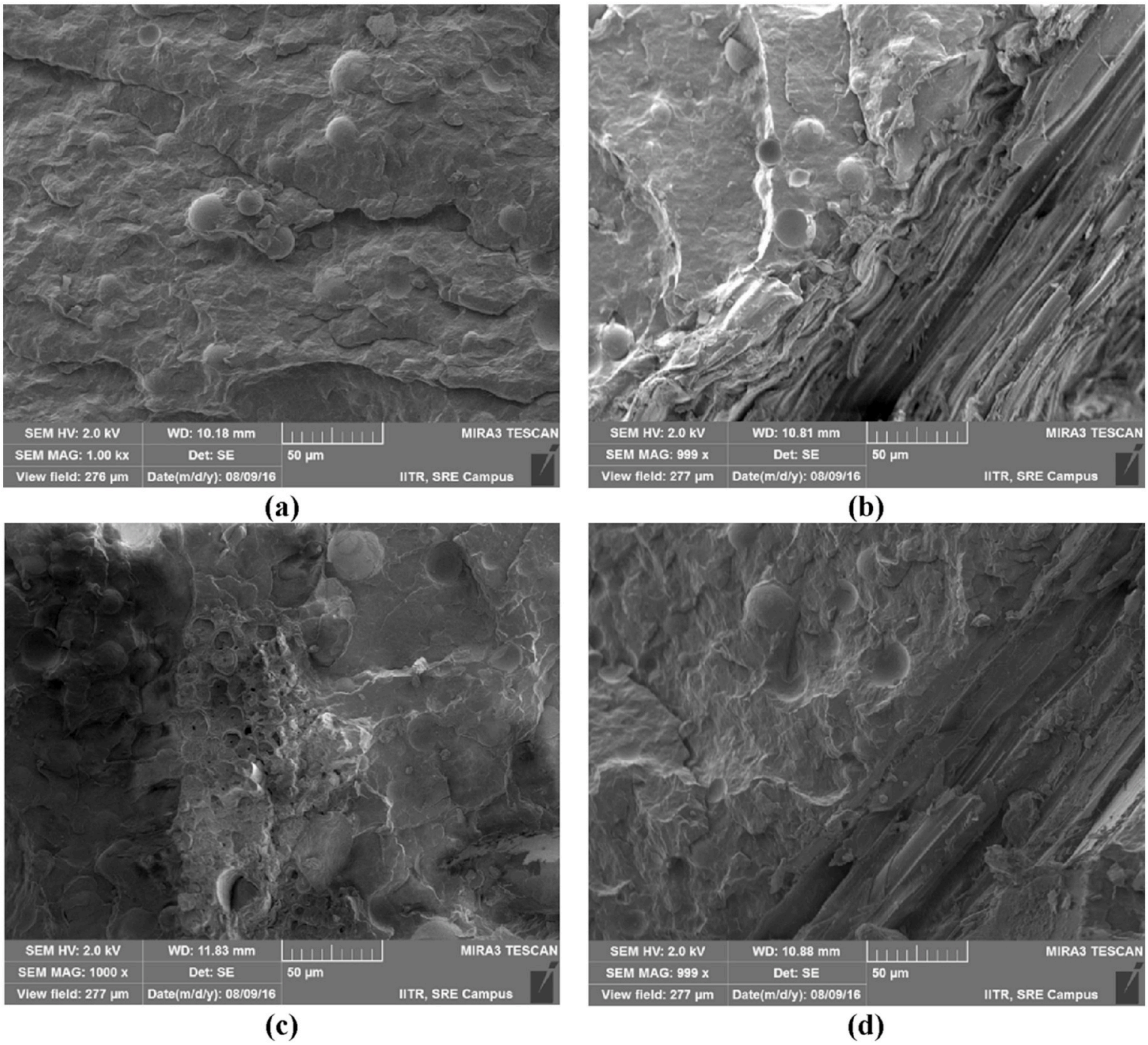
Finally, bamboo fiber reinforced composites have good mechanical qualities, making them appropriate for a broad variety of applications such as building, furniture, and automobile. The mechanical characteristics of BFRCs may be improved by choosing the right bamboo fiber type and size, matrix material, and production method.

9.2. Morphological properties

Bamboo is a renewable and ecological material that is becoming more popular in a variety of sectors, including building, furniture, and textiles. Bamboo fibers have shown excellent mechanical qualities, including high tensile strength, stiffness, and toughness. These characteristics make bamboo fibers an appealing alternative to typical materials for composite reinforcement.

Bamboo fiber reinforced composites' morphological qualities are critical in determining their overall performance. These are the physical and structural qualities of the bamboo fibers and the composite matrix. Some of the important morphological features of bamboo fiber reinforced composites [53,116,117] are as follows.

A. Fiber length: The length of the bamboo fibers used in the composite impacts the material's overall strength and stiffness. Longer fibers provide stronger mechanical qualities, but they are more complex to produce and may need additional matrix material to entirely encapsulate the fiber.
B. Fiber orientation: The orientation of the bamboo fibers in the composite impacts the material's mechanical qualities. Depending on the



(a) (b) (c) (d)

Fig. 9. Morphological properties of bamboo fiber reinforced composites. The base matrix ratio is same for all the samples from a to d (9:1 for PP:MA grafted PP). treated hollow glass microsphere is also kept same by 10 wt%. However, short bamboo fiber contents were varied which was 0 wt% for sample a, 5 wt% for sample b, 10 wt% for sample c, and 15 wt% for sample d. Reprinted with the permission from Elsevier [118]. Copyright, Elsevier 2017.

required performance of the composite, the fibers may be aligned in a unidirectional or random orientation.

C. Fiber content: The number of bamboo fibers utilized in the composite impacts the material's overall strength, stiffness, and density. Raising the fiber content enhances the composite's mechanical qualities in general, but it may also make the material more brittle and harder to produce.

D. Matrix material: The kind of matrix material employed in the composite influences the adherence of the bamboo fibers to the matrix. A strong adhesion between the fiber and matrix is required for the composite to have excellent mechanical characteristics. In Fig. 9, a strong bonding could be seen between the matrix and bamboo reinforcement.

E. Fiber diameter: The diameter of the bamboo fibers used in the composite impacts the material's overall density and porosity. Thinner fibers tend to give a more porous material with lower density, whereas thicker fibers offer a denser material with greater stiffness.

F. Interfacial bonding: The strength of the interface between the bamboo fibers and the matrix is crucial to the composite's overall mechanical qualities. Strong interfacial bonding may increase load transmission between the fiber and matrix while also preventing delamination.

Kumar et al. [118] investigated hybrid composites created by reinforcing bamboo fiber with hollow glass microspheres in the presence of PP polymer. The researchers discovered that both fibers and polymers showed good compatibility in the matrix system, indicating that this strategy might be a potential way for manufacturing high-performance composites. In summary, the morphological features of bamboo fiber reinforced composites are critical in defining the material's overall performance. It is possible to construct composites with specific mechanical characteristics that are suited for a variety of applications by carefully adjusting the fiber length, orientation, content, matrix material, fiber diameter, and interfacial bonding.

9.3. Thermal properties

BFRCs are a form of composite material in which bamboo fibers are combined with a matrix substance, such as polymer or cement, to produce a strong and durable material. These composites outperform standard materials in various ways, including high strength, low weight, and biodegradability. Moreover, the naturally derived materials also provide better thermal stability and conductivity. Thermal characteristics are an essential element of BFRCs. A material's thermal characteristics pertain to its capacity to transmit and transport heat. This is a significant consideration in a variety of applications, including the building sector, where materials with superior thermal insulation qualities are highly appreciated [119].

Many research have explored the thermal characteristics of BFRCs, and have discovered that they provide various benefits over typical materials [120,121]. BFRCs, for example, have been discovered to have lower heat conductivity than several other materials, including steel, concrete, and wood. This means they are better at insulating against heat transfer, which may assist to minimize building heating and cooling expenses. BFRCs have also been shown to have great thermal stability, meaning that they can survive high temperatures without deteriorating or losing their qualities. This makes them excellent for use in high-temperature environments, such as the automobile sector or aerospace applications. Generally, thermal stability is investigated using TGA/DTG analysis. Therefore, a typical TGA curve of BFRC is shown in Fig. 10, illustrating a typical TGA curve of BFRC, indicating that the thermal stability of bamboo fibers in the composite increases after the loading of polymer in the system. Shah et al. [122], conducted a research

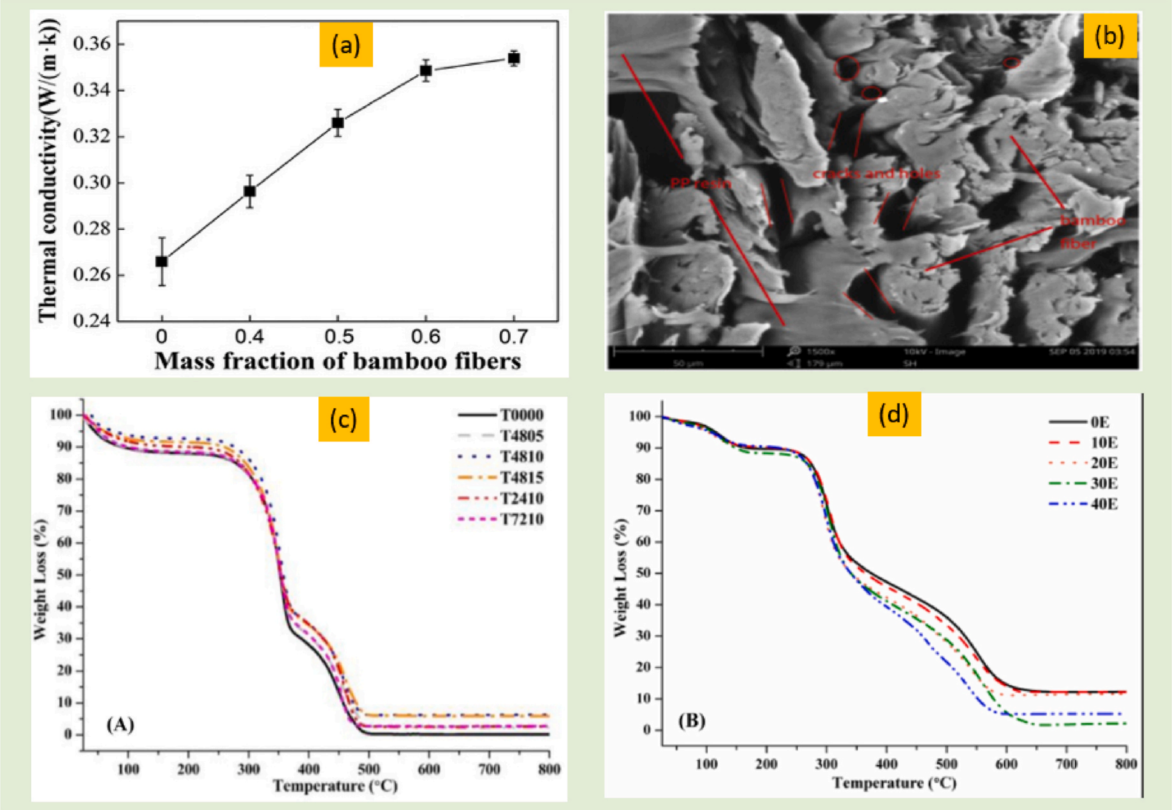


Fig. 10. Properties of bamboo fiber reinforced PP composites: (a) Thermal conductivity, (b) SEM profile [123]. Thermal stability of bamboo fiber reinforced thermosetting polymeric composites: (c) TGA analysis of different concentration of NaOH treated bamboo fibers and (d) TGA analysis of composited materials [110]. Adapted with the permission from Elsevier. Copyright, Elsevier 2020 and.

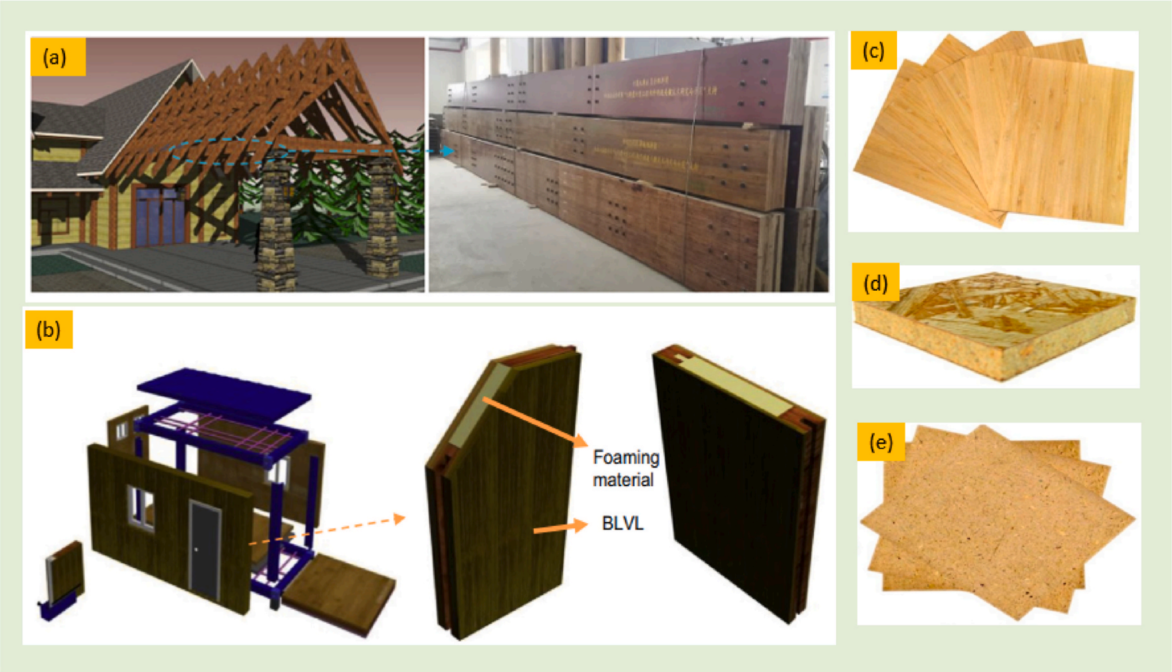


Fig. 11. Different products developed from lignocellulosic bamboo: (a) Laminated hybrid composites developed from bamboo and wood for large-span double beam [52], (b) Bamboo-based wall in a steel house [52]. Adapted with the permission from Elsevier. Copyright Elsevier. (c) Ply bamboo [131], (d) bamboo flakeboards [131], (e) bamboo MDF [131]. C, d, and e are published under open access policy of Intech Open publisher.

on the thermal conductivity of bamboo composites produced in different countries including Canada, China, and Colombia and reported that they properties also vary based on the material types and design.

The capacity of BFRCs to absorb and release moisture is another benefit. This may aid in the regulation of temperature and humidity levels in buildings, improving indoor air quality and lowering the danger of mold and mildew formation [124]. Overall, BFRCs' thermal qualities make them an appealing solution for a broad variety of applications. Because of their great strength, low weight, and biodegradability, as well as their outstanding thermal qualities, they are a sustainable and ecologically responsible solution for the building sector, as well as for usage in automotive, aerospace, and other high-performance applications.

9.4. Physical properties

Increasing interest in the growing class of bamboo fiber reinforced composites may be attributed to the material's exceptional mechanical, thermal, and environmental qualities. Because of their high moisture content, water absorption, and thickness swelling, these composites may be used in a variety of contexts [121,124]. The moisture content of a substance is the amount of water it contains relative to its dry weight. When it comes to the mechanical and physical characteristics of composites reinforced with bamboo fiber, the moisture level is a crucial physicochemical variable. Many variables, including processing conditions, ambient factors, and fiber type, may influence moisture content.

Due to the hygroscopic nature of bamboo fibers [125], composites reinforced with bamboo fibers tend to have a greater moisture content than conventional composites. This indicates that the moisture content of the composite may rise if the bamboo fibers absorb water from their surroundings. The composite's strength and stiffness may be diminished due to the presence of too much moisture.

Water Absorption: Another crucial physical feature of bamboo fiber reinforced composites is its ability to absorb water. The term refers to how much water a substance has taken in after being exposed to it for a certain length of time. Many variables, including production parameters, climatic conditions, and the kind of fiber used, might impact water absorption. It has been discovered that bamboo fiber reinforced composites absorb less water than conventional composites [126]. Due to their inherent characteristics, bamboo fibers are less likely to absorb moisture and hence maintain their shape and form in the wash. Composites designed for use in damp conditions benefit from having a low water absorption rate, since this may slow or stop the material's deterioration over time. In the case of bamboo fiber reinforced epoxy composites, Anu Gupta [127] conducted an experiment and found that the water absorption behavior of the material follows the Fickian behavior, which means that it increases with the increase in bamboo fiber content. This indicates that the water molecules are diffusing into the material through the interstitial spaces between the fibers and epoxy matrix, and the more fibers are present, the more interstitial spaces are available for water molecules to penetrate. In another study, Kushwaha et al. [128] reported that, bamboo fiber reinforced epoxy composites shown a decrease in water absorption to 24.5% from 41% after the benzoylation treatment. It means the pretreatment also can help to improve the physical properties too.

Expansion in the thickness direction after being exposed to water is measured by the thickness swelling metric. Since it might have an effect on the composite's dimensional stability, dimensional stability is an essential physical feature of bamboo fiber reinforced composites. The composite's performance may suffer if the swelling is high enough to cause warping or buckling. It has been discovered that bamboo fiber reinforced composites have less thickness swelling than conventional composites [129]. Since bamboo strands have inherent qualities that prevent them from absorbing and expanding when exposed to water, this is the case. Composites with a low thickness swelling rate are preferable for uses where dimensional stability is essential, such as building and furniture making.

Nowadays, numerical simulation is also helping the researchers to predict the performance characteristics in advance before going to composites production [108,130]. It helps to minimize the raw materials consumption and time. Moreover, energy and cost also can be minimized significantly. BFRCs have been intensively researched for

Fig. 12. Application of Bamboo fiber reinforced composites in the furniture field. Reprinted with the permission from Elsevier [135]. Copyright, Elsevier 2012.

prospective usage in a variety of structural applications. Their mechanical characteristics, however, are affected by a variety of factors such as fiber content, fiber orientation, and matrix properties. Numerical simulations might give useful insight into better understanding and optimizing the mechanical behavior of these composites and should be studied for future study.

Overall, bamboo fiber reinforced composites may be used for a variety of purposes due to its exceptional physical qualities, such as high moisture content, water absorption, and thickness swelling. There are a number of variables that may affect these qualities, including processing methods, environmental influences, and the fiber type. In order to create high-performance bamboo fiber reinforced composites that can fulfill the needs of a wide range of applications, it is crucial to have a deeper understanding of these features.

10. Economical aspects and future potential

In recent years, BFRCs made from bamboo have received a lot of interest as a possible replacement for more conventional materials including wood, steel, and plastic. The mechanical qualities of BFRCs, such as strength, stiffness, and durability, are improved by the addition of a polymer resin to bamboo fibers during production. The resulting composite material is lightweight, robust, and resistant to corrosion. The economics and possibilities of BFRCs are discussed in this article.

A Financial Perspective on BFRCs.

A. Cost-effectiveness: Bamboo is a renewable resource that can be cultivated with little inputs and hence is a cheap material for producing composites. Because that bamboo plants have a rapid development rate and may be harvested in as little as three to five years and the forests grows within 7–10 years [132], BFRCs are more cost-effective than those made from conventional materials like wood because of the cheap manufacturing costs.
B. Reduced manufacturing costs: The lightweight nature of BFRCs lowers the overall cost of production by lowering shipping and handling fees [133]. They are also cheaper to produce since they use less energy in the making.
C. Recycling: Since they can be broken down and used again, BFRCs are preferable to other building materials from an environmental standpoint. There is potential for further cost savings with the use of bamboo fibers and polymers that have been recycled. Several studies also promoting this concept as well [134].

Possibilities for BFRCs in the Future.

A. Biodegradability: Since they decompose in landfills rather of polluting the environment, BFRCs are a greener, more sustainable option. Eco-friendly materials, such as BFRCs, are becoming more in demand as people become more aware of the damage they do to the planet.
B. Increased applications: Increasingly, BFRCs are finding employment in a wide range of industries, from construction and packaging to

furniture and automobiles Fig. 11. Sports gear, airplanes, and medical gadgets are just some of the potential new uses for BFRCs that may be unlocked by further study and development. They are also becoming increasingly popular for various furniture-related applications (Fig. 12).

C. Improved properties: Research is being conducted to enhance the BFRC's mechanical qualities. Strength, stiffness, and electrical conductivity may all be improved by using nanomaterials like graphene in the composite.
D. Market demand: Rising demand from a wide range of end-use sectors is fueling expansion in the BFRCs market throughout the world. Market Research Future predicts that between 2018 and 2023, the worldwide market for bamboo fiber will expand at a compound annual growth rate of 10.3%.

Because of their low price, low production cost, and capacity to be recycled, composites reinforced with bamboo fiber have great economic promise. With their biodegradability, expanded uses, and enhanced characteristics, the future of BFRCs seems bright as well. Demand for sustainable materials like BFRCs, which might replace conventional materials as the world grows more ecologically aware, is predicted to rise.

11. Conclusion

Sustainable bamboo fiber reinforced polymeric composites have emerged as a viable material for different engineering applications, due to its superior mechanical, thermal, and environmental qualities. This paper has presented a detailed overview of current advancements in the development of bamboo fiber reinforced composites and emphasized their prospective uses in a variety of industries, including as the automotive, construction, and aerospace sectors. Challenges related with the processing and manufacture of these composites, as well as their limits and future research paths, have also been highlighted. Clearly, further study is required to maximize the characteristics of these composites and solve the difficulties connected with their processing, production, and longevity. Overall, bamboo fiber reinforced polymeric composites have the potential to provide a sustainable alternative to conventional materials and contribute to the creation of a more environmentally friendly and sustainable future. It is anticipated that these composites will find broad use in a variety of sectors as a result of technological advancements and ongoing research.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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