Effect of Interfacial Bonding Characteristics on Physical, Mechanical and Fire Performance of Bamboo Fibre Reinforced Composites

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Abstract This chapter reviewed the influence of interfacial bonding characteristics of bamboo fiber on the composites' mechanical, physical, thermal, and fire performance. Because of their complete biodegradability and renewability, being economical, non-toxic, non-abrasive and environmentally friendly, having high aspect ratio, socio-economical advantage and strong mechanical performances, bamboo fibers are considered promising reinforcements for polymer composites. As an alternative to petroleum-based or synthetic materials, bamboo also has the potential to be used in biopolymer composites, which can be utilized as construction, building, architectural and other advanced materials. However, strong and substantial interfacial bonding of the bamboo fibers with the polymer matrix is required to create high-end load bearing composites. Therefore, it is critical to achieve a good fiber-matrix interaction, resulting in lesser voids and better adhesion and mechanical properties. Thus, most bamboo fibers are treated, hybridized, laminated, and coupled using chemical agents to enhance the fiber-matrix bonding, which in turn enhances the performance. The detailed understanding of the aspects of fiber-matrix interaction and their respective influences on the various properties of the bamboo composites are given in this chapter, along with the superiority of the bamboo fibers in being used as the polymer reinforcement.

Keywords Interfacial bonding · Bamboo fiber reinforced composites · Physical performance · Mechanical performance · Thermal performance · Fire performance · Bamboo · Composite

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1 Introduction of Bamboo

Among perennial grasses, bamboo is one of the fastest growing and strongest ones. However, it should be noted that bamboo grows much slower than grass. Bamboo is widespread across the globe and is a member of the family *Poaceae* and subfamily *Bambusoideae* [1, 2]. More than 120 genera and around 1700 species of bamboo are mostly found in North, Central, and South America, Africa, and Asia [3]. Since antiquity, bamboo has been widely used in South America and several Asian countries as a sustainable substitute for wood, being frequently used even in buildings. Table 1 shows the coverage of bamboo in the world. Wood can take up to 20 years to grow, whereas bamboo grows to maturity in only about three years, with tensile strengths comparable to mild steel. The fastest-growing bamboo species grow vertically about two inches in an hour, while there are some specific species (Moso bamboo) that can reach heights of 60 feet within just three months [4]. Bamboo has an astonishing rate of development, causing no harm to the ecological equilibrium due to extensive removal and cultivation. Bamboo products have seen a steady and significant increase in demand for various applications. Scarcity of wood in many countries across the world has helped in this increased demand for bamboo, which is proven to be a great alternative to wood, especially due to its growth rate and mechanical properties (Fig. 1).

Generally, the use of bamboo as building materials, ornamental accents, and panels, as well as its production, distribution, and commerce, negatively influence the environment and the global economy. Although bamboo is technically grass, it is sometimes referred to as the “poor man’s lumber” [7]. The Forest Resource Assessment by FAO in 2015 recognized bamboo as being an intricate part of the forest [8]. Bamboo may also be utilized successfully for carbon sequestration. Therefore, their products may be the best substitute for the growing concern about global warming and the ongoing destruction of tropical forests [9]. Planting bamboo could help faster transfer to a circular economy by offering a practical, bio-based substitute for materials that are not renewable and have a high carbon footprint [10]. Thus, bamboo is often considered a tree or plant for productive forests.

Planting productive forests with foreign tree varieties is an engrained venture in southwest Europe and the Mediterranean [11]. Plantations offer a chance to diversify

Table 1 Countries and regions with bamboo coverage [5]

Countries	Bamboo regions	Percentage
Thailand, Sri Lanka, Philippines, Malaysia, Korea, Japan, Indonesia, India, China, Cambodia, Burma, Bangladesh	Asia–Pacific Region	65
Some European Countries, Venezuela, Nicaragua, Mexico, Honduras, Guatemala, Columbia, Costa Rica, Brazil	America Region (Latin America, South America, and North America), European Region	28
Eastern Sudan and Mozambique	African Region	7

Fig. 1 Bamboo (*Gigantochloa scortechinii*) strips from Malaysia [6]

financial portfolios even though they require a sizable investment, a lot of labor, and substantial capital to establish productive plantations [11]. From this angle, bamboo farming has been more popular and has a growing demand recently in Europe. Species like *P. pubescens*, used for landscaping and producing wood, fibers, shoots, and biochemical components, among other things, are particularly prized for their various uses [12]. In addition, Europe has also benefited economically and environmentally from growing bamboo. Bamboo plantations have a few special characteristics, such as the fact that they need less upkeep and are more ecologically friendly than other crops since they don't use pesticides. Furthermore, while most wood species require 10 to 50 years to attain maturity in the climate of Europe, bamboo plants need just 5–7 years [13].

Additionally, maintaining bamboo requires little work and less money, with the primary requirements being weeding during the first two years, adding organic fertilizer, and watering. Bamboo offers a potential financial investment in Europe's energy crop. Bamboo may flourish on damaged and marginal soils because of its extensive rhizome and fibrous root systems, dense leaves, and green mulch, stabilizing the soil, reducing erosion, and retaining water [14]. Contradictions are common in studies on bamboo's potential for the environment. Although some researchers assert that one of the critical reasons behind growing cultivation of bamboo across the world is due to it being a more environmentally friendly substitute to current forestry practices, it is important to evaluate its eco-friendly impacts when cultivated for profitable reasons [15]. Bamboo spreads primarily via the growth of rhizomes. As a result, the location of the plantings must be considered in the neighborhood. For instance, preventing bamboo from expanding into ecologically sensitive areas would be important. In addition, production sites need long-term management measures to lessen the number of abandoned bamboo plots that might be a source of invasive bamboo species [16].

China, Africa, India, South and Central America, and other places where bamboo is a native plant have received most of the attention in economic studies of bamboo plantations [5]. Bamboo's economic advantages are frequently considered as are its ecological advantages, thus connecting both the defensive and offensive roles [17, 18]. Examples include the "twofold potential" of using bamboo, (1) creating wood and shoots, and (2) storing carbon, resulting to carbon credits. The latter feature might also improve farmers' financial situation [19–21]. However, according to [22] and [23], bamboo is more sustainable compared to conventional crops. Its Net Economic Benefit (NEB) is lower than the common crops, especially in the initial years after its release. A bamboo intercropping system is the greatest tactic for small-scale farmers in Ghana, according to [24], because it can boost system efficiency, diversify sources of income, and uphold environmental sustainability.

2 Economic and Socio-economic Aspects of Bamboo

Studies on investments in bamboo plantations in Europe are few, and a similar goes for the United States. Most researchers concentrated on the advantages and disadvantages of growing bamboo in Western Europe, especially the economic viability of using bamboo to produce biomass and the potential adaptation of bamboo as a Western European building material [25]. Even though North America, France, Italy, and other European countries have not studied the economics of bamboo, the engineering and technical elements of products created from Italian plants have been recently investigated for the past few years [9, 26, 27]. Many factors have led to bamboo's rising popularity in Italy and other places in Europe, focusing on the southern part where certain bamboo species flourish in the Mediterranean climate [28]. Two case studies from Calabria look at the viability of bamboo from a commercial and eco-friendly standpoint. Based on bibliographical research and in-person interviews, a SWOT analysis was conducted on the variables influencing farmers to plant bamboo in southern Italy.

Europe purchases 37% of bamboo goods sold globally, making it the biggest importer of bamboo products worldwide. On the other hand, Western Europe has a mixed perception of bamboo. It provides ecological knowledge and concern for the environment, on the one hand, given its natural origin and the little environmental impact of the development process. On the other hand, it is often regarded as a material of poor value [29] due to problems with numerous areas of its development (marketing, management, organization, and product development). There ae several steps in the manufacturing chain of bamboo goods (harvesting, processing, marketing, transport, plantation establishment, and management) resulting in a small market share in the west. From 2015 to 2019, the Netherlands has been the top importer with 72,020,545 €, proceeded by Spain with around 40,250,401 €. Italy is third on the list with 34,756,846 €, followed by the United Kingdom with 24,771,569 €.

France was the biggest importer of bamboo flooring between 2015 and 2019, values at 22,751,771 €. Then comes United Kingdom at 21,452,636 €, followed by Germany at 14,074,743 €, and Belgium at 10,804,083 €. The Netherlands was the top importer of bamboo panels (HS code 44,120) over the same time. Germany again comes second with a valuation of 11,524,530 €, followed by Belgium at 9,660,412 €, and France at 8,766,913 €. The EU Timber regulations (EUTR) cover all imported goods. Therefore, it is obvious that initiatives to grow bamboo in Europe has increased to satisfy this demand and reduce the environmental costs associated with shipping the product from its source countries. [29].

Every continent has a native bamboo population, except for Europe and North America, where cultivation is still in its experimental stages. However, statistics on bamboo are scarce compared to most other commodity crops since the domestic bamboo markets are still largely unorganized. In addition to other species like *P. edulis* and *P. viridiglaucescens*, certain pilot plots of *P. aureosulcata 'Spectabilis,' Phyllostachys vivax*, and *P. violascens* (syn. *P. praecox*) is situated in Belgium and Germany. These two last species are also cultivated in France with new *P. edulis* plants are emerging in Ain and Romania with around 30 hectares.

Ireland is home to plantations of *P. humilis*, *P. bissetii*, *P. mannii* (syn. P. *decora*), and *P. aurea* [30]. Even while most cultivated bamboo and its processed products are sold inside Europe, interestingly, although being a sizable importer of raw bamboo, European countries are also the world's second-largest exporter of bamboo goods, especially to Germany and France. Over 40% of the entire value of European exports went to these two nations, whereas just 8% went to China and Angola, where most of the exports were processed goods. Italy has drastically increased their bamboo import over the last three years, especially in the form of raw materials and furniture. It implies a demand for bamboo and the potential to establish a regional supply chain. The sales of veneered wood, plywood, and similar laminated bamboo wood increased significantly between 2016 and 2020, from 56,513 € to 135,848 €, as shown by ISTAT statistics [31]. Since 2014, several manufacturing consortia and cooperatives have been established, expanding the bamboo market that bears the "Made in Italy" or "Made in Europe" badge. On the other hand, there are numerous records of much older bamboo plantations, such as the 22 hectares of the bamboo plantation at Selva di Paliano in Frosinone (Rome, Lazio), the 1-hectare bamboo plantation in Lucca (Tuscany) [32], and the 0.5-hectare bamboo plantation in Syracuse (Sicily) [33]. Lucca (Tuscany bamboo plantations are currently around 70 years old, while Syracuse (Sicily bamboo plantations are around 60 years old [32, 33].

Currently, across Italy, the CBI (Consorzio Bambù Italia) has planted roughly 2,000 acres of bamboo [34]. According to [28], the primary species produced by the CBI are *Dendrocalamus brandisii,* a sympodial species that are suited to the tropical climates having pronounced dry seasons, and *Phyllostachys edulis* (Moso bamboo), part of the monopodial species that live naturally in temperate regions with cold and wet winters. The Moso bamboo is grown mostly for its shoots and a total of

148 hectares have been planted as part of plantation runs by various organizations in Italy, including Calabria (59 ha), Emilia Romagna (3 ha), Basilicata (35 ha), Marche (1 ha), Piedmont (35 ha), Friuli Venezia Giulia (2 ha), Lombardy (10 ha) and Tuscany (3 ha). They may also be found in Lake Maggiore, Lake Como, and Lake Garda in northern Italy. Between Cuneo and Trieste, there is a region with a moderate climate and comparatively heavy summer rainfall. The growing of bamboo, including species like *P. bambusoides*, *P. iridescens*, and *P. vivax*is, is extremely common in the Piedmont area. Molari et al. [27] tested the mechanical characteristics of the culms of these species. Various bamboo species have been seen becoming invasive and naturalizing in this area. There are many bamboo groves, notably those of *Phyllostachys nigra* and *P. aurea*, all over central Italy until Naples, particularly in Frosinone. Lazio, Lombardy, and Tuscany have *P. bambusoides* plantations of about 30 hectares. *P. viridiglaucescens* can further be seen in some places of Tuscany, which is an intriguing species because of its morphological traits [26]. In the United States, most of the bamboo planted is from the species of *P. nigra 'Henon.'*, *P. rubromarginata, Bambusa Balcooa, and Dendrocalamus asper.* Most of these species are grown in Florida and California, United States Bambu [35]. Bamboo farming is still in its early stages in many non-origin places throughout the world, i.e., Italy, France, United States, and there is a lack of trustworthy information on the traits and yield of the crops [36]. The demand for raw materials and related goods is not estimated either.

Despite this, a nationwide manufacturing chain is being built with several important players, including tissue culture and nursery operations, industrial growers, and specialty merchants. Although the export of raw bamboo materials decreased, this decline in export may be related to domestic bamboo use [37]. China is the top exporter to the US and the EU. The main beneficiaries of cultivating and harvesting bamboo are the farmers. The consistent source of income from growing and harvesting the bamboo has improved their ability to handle pressure if there is a loss in bamboo sales and their basic cultivation skills. An unproductive piece of ground may be turned into productive land thanks to the ecological system, which also reduces landslides and soil erosion. Bamboo growing techniques help impoverished rural farmers improve their standard of living. By interplanting bamboo with other food plants, it is possible to improve food security while simultaneously protecting the environment and damaged land. The cheapest way to cultivate bamboo is by cultivation, the most expensive ways include bamboo propagation, land, and labor. Undoubtedly, the socio-economic advantages of producing durable consumer goods via the creation of products like furniture, flooring, bamboo-based composites, fences, and other decorative items significantly impact the economic growth of many nations. Natural resource depletion and rapidly rising crude oil costs have sparked interest in using bamboo in composite technologies.

Strict laws requiring the design of eco-friendly consumer goods are pressuring industries to develop a method for using renewable resources, one such intriguing one being bamboo. Bamboo is one of the best resources that can be utilized as a composite reinforcement in place of glass fibers, which is sourced from depleting natural resources [38]. Researchers are searching for a more environmentally friendly way to address this environmental hazard. A new age in the composites sector has been sparked by simple access to bamboo. To avoid using wood, technical, and regulatory attempts to employ bamboo composites in the public interest are also moving quickly. Developing composites made from bamboo for household goods, transportation, and construction has given the bamboo economy a new direction while helping the average person economically and socially. In addition, promoting bamboo-based composites has opened up new job opportunities, and policies are being implemented all over the globe to increase public interest by suggesting various measures, such as exempting bamboo composites from excise taxes [39].

3 Fiber Matrix Interaction in Composites

An important role is played by the interfacial bonding between the fiber and matrix, in any composite, due to the stress being transferred through them. Thus, a good bonding at the interface is necessary to achieve ideal reinforcement and control the composites' mechanical properties. Full contact that promotes fracture propagation might also diminish strength and toughness [40]. Interfacial bonding is generally poor if hydrophilic fibers and matrices are combined, resulting in hydrophobicity and lowering the mechanical properties with unfavorable long-term effects. Due to the interfacial connection between fiber and matrix, wettability is a key prerequisite to their bonding. Fiber wetting would be a stress concentrator and might result in interfacial damage, impacting the composites' flexural and tensile strengths. Nevertheless, physical and chemical treatment may improve interfacial strength and fiber wettability. Interfacial bonding includes mechanical interlocking, electrostatic, chemical, and inter-diffusion bonding. The rough fiber surface and strong interfacial shear strength cause mechanical interlocking, which does not affect the transverse tensile strength. However, only the metallic exterior will experience electrostatic bonding [41].

In general, raw bamboo fiber and epoxy polymer have insufficient interfacial adhesion, which lowers the strength of the composite. One way of improving this is by removing the extra moisture through chemical and heat treatments, which can strengthen the interfacial bonds between the two interphases, improving the mechanical interlocking. The bonds get strengthened when reciprocating chemical groups are present in the fiber surface and matrix, causing chemical reaction and helping enhanced bonding. Therefore, it often makes sense to use a coupling agent that links the fiber and matrix to enable that chemical bonding. It is further explained by the inter-diffusion bonding between the fiber and matrix due to the interaction of the surface atoms and molecules. According to the findings of [42], chemically treating bamboo fibers for about an hour with 4 wt.% alkaline solution has detrimental effects on the fibers' tensile strength. In addition, the chemical treatment removes lignin and hemicellulose and improves the surface area's efficiency for a strong connection with the matrix. However, it is also said that a greater NaOH concentration can deteriorate the bamboo fiber characteristics if it is not properly controlled.

Chemically altering fiber is necessary to increase the amorphous nature of cellulose at the cost of its crystallinity. Hydrogen bond, available in the network structure, gets eliminated, which forms another significant anticipated change during the process. Mercerization, which is another name for alkaline treatment, is one of the many available chemical procedures that is generally utilized for strengthening both thermosets and thermoplastic composites. The fiber bundle is divided into smaller pieces during mercerization, a process known as fibrillation. As a result, reduced fiber diameter and increased aspect ratio create rough surface topography, improve adhesion at the fiber-matrix interface, and enhance mechanical characteristics [43]. In addition, the alkaline oxide will be produced due to the outer hydroxyl groups, which are generally unstable, that disintegrates and reacts with water to destroy the reactive ionized molecules. Consequently, it is anticipated that cellulosic fiber's surface roughness will be improved, and hydrophilic groups will be eliminated [44], resulting in a chemical reaction as shown in Eq. (1):

$$Bamboofiber - OH + NaOH \rightarrow Fiber - O - Na^{+} + H_2O \tag{1}$$

Many known chemical modifications have been applied to not only bamboo but also to other lignocellulosic fibers to increase the fiber matrix interaction. Some critical ones that are important and can potentially be applied to bamboo, a lignocellulosic material, are detailed in this section. Silane was applied to kenaf fibers to increase cross-linking both at the interface and the fiber surface regions, strengthening the fiber-matrix bonding [45]. Furthermore, the bi-functional groups present in the silane molecule may interact with the fiber and matrix, forming a siloxane bridge, resulting in an enhanced and powerful contact between the two while improving the mechanical performance of composite materials. In moist conditions, hydrolyzable alkoxy groups form silanols, reacting with the fibers' hydroxyl groups, as illustrated in Eq. (2) according to [46]. During the procedure, the fiber surface adsorbs the silanols chemically, creating stable covalent bonds in the cell walls. The Eq. (3) demonstrates how adding silane results in the formation of hydrocarbon chains, limiting fiber expansion. The covalent contact between the matrix and the fiber enables the cross-linked network. As for the chemical reaction, it can be represented as:

$$CH_2CHSi(OC_2H_5)_3 \rightarrow H_2O\, CH_2\, CHSi(OH)_3 + 3C_2H_5OH \tag{2}$$

$$\begin{aligned} &CH_2CHSi(OH)_3 + bamboo\ fiber - OH \rightarrow CH_2CHSi(OH)_2O \\ &- bamboo\ fiber + H_2O \end{aligned} \tag{3}$$

Using inorganic fillers in polymer matrices often results in unstable dispersion with compatibility issues, which can be limited through surface treatment of the fibers and polymer. Successful grafting of the organic monolayers onto the fibers reduces the likelihood of accumulations and enhances the dispersity simply by modifying the hydrophilic qualities to the hydrophobic ones [47]. On the other hand, the presence of silane in the fiber-matrix interphase is often considered to act as an agent or catalyst that helps in bridging or bonding, promoting adhesion between two incompatible materials. The influence on silane can be attributed to the complex chemical and physical interactions that directly affect the strength, perseverance and adhesion between the components of the composite. Therefore, coupling agents that are made from silane, with unique physical and chemical aspects will help strengthen the bonds at the interphase [48]. Heat therapy, corona, plasma ultraviolet (UV) and electron radiation are some additional forms of physical therapy.

Corona treatment is accompanied by high voltage applied to the tips of sharp electrodes that are separated at low temperatures with the help of quartz, whereas air pressure produces the plasma, which together helps increasing the surface roughness and polarity. On the other hand, plasma ultraviolet therapy is usually conducted inside a vacuum chamber, as it requires accurate composition of pressure and gas, successfully maintained with the help of a constant supply of gas. The fiber surface gains hydrophobicity through this process and increases surface roughness, including interfacial adhesion. An earlier study established that the plasma UV treatment in beneficial in effectively increasing the interlaminar shear and flexural strengths of the composites by 35 and 30%, respectively. Heat treatment, which involves heating the fiber to the fiber degradation temperature, can also change the fiber's chemical, mechanical, and physical properties [49].

4 Bamboo as Reinforcement in Composites

The research and production of polymer composites must now utilize natural, recyclable materials because of the rising costs of synthetic and common polymer raw materials, natural reservoirs' long-term viability, and environmental dangers [50, 51]. In the past, synthetic fibers dominated the reinforcement market, however, natural fiber reinforcement has acquired significant momentum as substitutes for artificial fiber in various applications. Using natural fibers with polymer matrices made from renewable and non-renewable (petroleum-based) resources have gained further popularity over the past ten years in an effort to compete with the widely produced synthetic counterparts [52].

To compete and gain market share in the current market that is primarily dominated by synthetic products made of petroleum or petroleum-based aspects, it is critical for the renewable and biodegradable polymer composites to have similar or enhanced performance [53]. Researchers have used softwoods and hardwoods to harvest the necessary fibers to reinforce different composites. Natural fibers have a significant economic role for several developing nations. Examples include sisal in Tanzania, jute in Bangladesh, and various West African nations' cotton [50]. Research and development on polymer composites have been conducted in nations with scarce agricultural and forestry resources. One of the agricultural products that may be used in creating polymer composites is bamboo [54]. Asia and South America are both home to a large bamboo population. Although bamboo is a naturally engineered material, several Asian nations have not fully exploited its potential. Since it takes only months for this sustainable substance to develop fully, it has become the foundation for many societies' socio-economic standing. Due to its excellent strength-to-weight ratios, bamboo has historically been used in various homes and equipment. This property results from the longitudinal orientation of the fibers. Therefore, it is possible to build composites reinforced with bamboo fibers [55, 56]. Although bamboo fibers have superior mechanical qualities naturally, they are more brittle than other natural fibers because of the additional lignin that covers them.

The applications and possible use of bamboo as the reinforcing fiber in polyer composites are immense. This can be attributed to its structural variety, mechanical attributes, fiber extraction, chemical modification, and thermal properties [57]. According to [58], bamboo has a comparatively small microfibrillar angle of 2°–10° and contains a high concentration of lignin and 60% cellulose. This distinctive quality has led to the use of bamboo fiber as reinforcement in several matrices [58]. Researchers have created several techniques to harvest bamboo fiber for composite reinforcement. Alkaline treatment can facilitate extraction and optimize bamboo fiber separation to prepare bamboo fiber-reinforced polymer composites [59, 60]. Researchers investigated the changes in bamboo fiber's fine structure brought on by exposure to various alkali solution concentrations [61]. Researchers also examined the impact of bamboo fiber mercerization on bamboo composites' mechanical and dynamic mechanical characteristics in an intriguing study [61, 62]. The primary aim is to have bamboo reinforced polymer composites that have similar or superior qualities compared to that of synthetic fibers. Twin-screw extruders have often been utilized to combine and process biodegradable polymers and bamboo fibers as reinforcements to fabricate bamboo-reinforced polymer composites. Researchers have also used orthogonal bamboo fiber strip mats to create composites with epoxy and polyester using the hand lay-up method [63, 64]. Short bamboo fiber-reinforced epoxy composites can be made using dried bamboo fibers, and the relationship between the fibers' tensile and chemical resistance qualities has been reported [65]. To produce polypropylene composites reinforced with bamboo fiber, researchers employed *Bambusa Paravariabilis*, a bamboo type widely cultivated throughout Asia [66]. Another fascinating study combined E-glass and bamboo fibers, commonly grown in Southeast Asia and widespread in Singapore, as reinforcement in hybrid composites [67]. Researchers looked at how fiber length affected the mechanical properties of polymer composites using starch resin and short bamboo fibers [68].

Using a steam explosion procedure to separate the bamboo fibers from raw bamboo trees, bamboo fiber-reinforced polymer composites' mechanical properties have also been evaluated [55]. Green composites that are biodegradable and environmentally benign have been created using bamboo fibers that are micro- or nano-sized and have a reasonable amount of strength and stiffness [69]. Bamboo and biodegradable resin are combined to create bio-based polymer composites that have also been examined for their flexural characteristics and compared with composites manufactured from kenaf [70]. The authors then calculated the flexural modulus using Cox's model, which considers the effect of fiber compression. The outcomes and experimental data were in good agreement.

The morphological and mechanical properties of the bamboo flour-filled HDPE-based composites were also examined. It is focused on the crystalline nature of the malleated elastomer modifier, combined EPR-g-MA and PE-g-MA modifier systems, and the loading rate of bamboo flour in the presence of the combined modifier [71]. In addition, researchers examined the thermal characteristics of jute/bagasse hybrid composites and found that increasing the char residue at 600 °C improved the thermal characteristics of the hybrid composites [72]. Finally, bamboo fibers, polypropylene, and polylactic acid mix composites were created, and their morphological and thermal characteristics were compared to those of plain polymers [73]. Adamu et al. [74] studied the impact of polyvinyl alcohol/acrylonitrile on bamboo nanocomposite and found out that both clay and polymer act as filler materials having a complete dispersion as shown in Fig. 2a–e.

Bamboo fibers and highly hydrophobic polymers have poor interfacial interaction because of various functionalities, notably hydroxyl groups [75]. Researchers have attempted to enhance these qualities with various interfacial treatments [76]. It has been widely researched how different matrices, including polystyrene, polyester, and epoxy resins, affect the strength of bamboo fibers. Bamboo fibers' high economic worth, specific strength, low weight, and non-hazardous nature are among these materials' most desirable characteristics, motivating researchers to concentrate on composite technology. As a result, composites made with bamboo fiber have been used in the automobile industry. They have the potential to take the place of expensive, non-renewable synthetic fibers in a variety of industries, including the home. Many nations have recently passed rules requiring 95% recyclable materials in automobiles because of an ecological hazard. The current age demands the incorporation of natural fibers into daily life, especially composites made with bamboo fiber. Using these bamboo fibers in composite materials has thus become the subject of intensive research in many fields, including engineering, biotechnology (genetic engineering), farming, and others.

4.1 Bamboo Fibers and Its Composites' Physical and Mechanical Performance

Environmental worries about the depletion of fossil fuels and the increased awareness of plastic waste led to the development of biodegradable polymers. Biodegradable polymers are mostly made from renewable, recyclable, reasonably priced natural resources that are also ecologically benign [77, 78]. By using biodegradable materials, which can be readily disposed of owing to their microbial activity and assisting in lessening the issues of plastic waste, it is possible to alleviate the environmental challenges of synthetic plastics. Researchers and developers from a variety of industries have focused their attention on biodegradable polymers to date to replace common synthetic polymers [79]. Natural fibers have been bonded with biopolymer to increase the function of the material and provide sustainability. Biocomposites

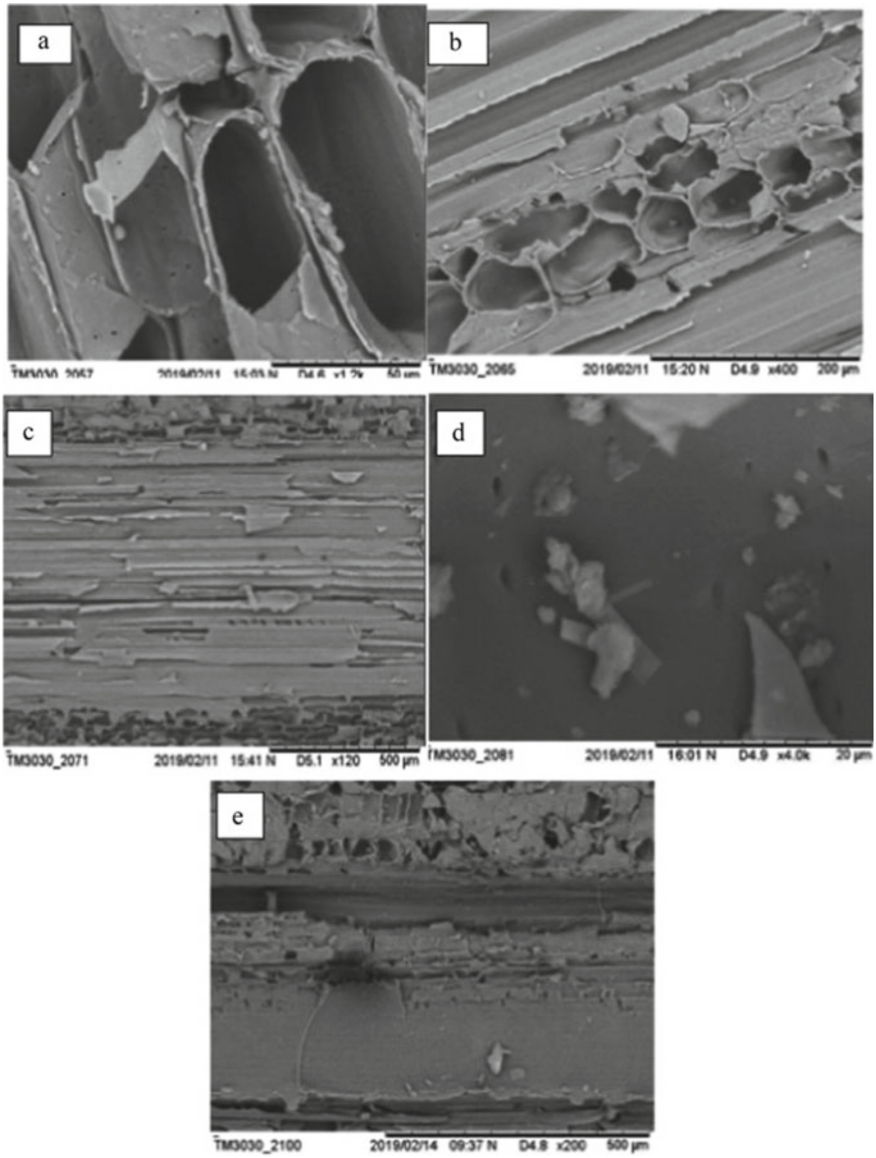

Fig. 2 SEM images show the **a** raw fiber, **b** bamboo nanocomposites 1 (BNC1), **c** BCN2, **d**, BNC3, and **e** BNC 4 [74]

are known to have high availability, full biodegradability, and economic viability [77]. Bamboo fiber is one such material that has enormous promise, particularly for polymer composites' reinforcing materials [80]. Bamboo fiber has been used progressively as reinforcement filler in biopolymers to improve mechanical performance and broaden their applications. In conclusion, using bamboo fiber as reinforcement in biodegradable polymer has outstanding potential to be extensively used in economic growth, especially in an industry in many sectors that need the application of eco-friendly products [41]. Furthermore, biodegradable polymers often reported improved mechanical performance after being reinforced with bamboo fibers, which may be related to various variables, including bamboo fiber treatment, length, and orientation.

The most well-known biopolymer is poly (lactic acid), produced from renewable agricultural raw materials and applied in various fields. Due to its remarkable mechanical qualities, high stiffness and strength, superior thermal capabilities, and biodegradability, PLA has been extensively employed to replace polymers made from fossil fuels [79]. It has been frequently mixed with inorganic fillers or natural fibers, such as wood, kenaf, flax, jute, ramie, and bamboo, to improve the properties of PLA and produce bio-based composites [81, 82]. Because of their superior physical characteristics, PLA composites with bamboo fiber reinforcements have been commonly used, particularly to improve their mechanical and thermal performances. For instance, Ochi et al. (2015) investigated the effects of adding bamboo fiber to a PLA composite on its mechanical properties. A steam explosion technique was used to extract bamboo fiber with a diameter of 100–300 m and then to make an emulsion-type PLA. Bamboo fiber content (0, 30, 50, and 70wt%) and molding temperature (120–200 °C) were adjusted to see how they affected the composites' mechanical performance, notably their flexural capabilities. The factors chosen for each sample and the composite's flexural properties were shown to have various characteristics throughout the investigation. The flexural strength plateaued between 120 and 160 °C and dramatically declined. At 160 °C, the flexural strength reached its maximum value. According to the optimal temperature, the influence of fiber content was determined, and it was discovered that the flexural strength increased linearly with increasing fiber content. Compared to the previous data, with 70 wt% bamboo fiber loading, the flexural strength was determined to have a greater value at 273 MPa. However, [78] used bamboo fiber to investigate how this reinforcement affected the PLA biocomposites' mechanical and creep resistance. With the addition of 60 wt% of bamboo fiber, the PLA composites had one of the best reported rupture and elasticity moduli. The characteristics, however, were shown to degrade when the fiber loading rose over 70% by weight.

A time-consuming approach was necessary to optimize the composites' production conditions to assess their mechanical performance. Nurul Fazita et al. [83] have used the Taguchi technique to obtain the best mechanical properties for the composites through achieving ideal production parameters by investigating the influence of the control parameters on the fiber-matrix interaction. First, the composites were created using a twin-screw extruder and a melt blending technique. They were then hot-pressed at 170 °C at a pressure of 81.58 kgf/cm^2. The Taguchi analysis shows that medium fiber sizes ranging between 150 and 250 mm, low fiber loadings of 10 wt.%, die temperature of 180 °C, and the screw speed of 200 rpm, give the maximum tensile and flexural strengths for the composites.

The orientation of the composites also has a significant impact on how well the composites system performs mechanically. Landes and Letcher [84] illustrated the influence of different orientations on the composites made from woven-bamboo mats reinforced PLA. In contrast to other orientations, the 0°/90° orientation had the best performance with the tensile strength and maximum elongation at 30 MPa and 30%, respectively. Further tests revealed that the change in orientations had little effect on the flexural properties, with 45°/45° and 0°/0° orientations portraying greater degrees of flexural strength than the 90°/90° and 0°/90° orientations. According to the shear test, every orientation of the composite exhibited brittle behavior. The investigation revealed that the PLA thermoplastic composites reinforced with bamboo mats had a good and acceptable result with few flaws and the substantial abilities that are very rarely seen in natural fiber reinforced thermoplastic composites. A different study by [85] observed even better tensile strength in PLA composites reinforced with bamboo fibers. Tensile strength increased by ~20% (29–35 MPa) with the addition of only about 5 wt.% of bamboo fiber.

Another study was carried out to produce a membrane film of PLA-reinforced bamboo fiber. Le Phuong et al. [86] researched membrane separation, which is currently a growing energy-efficient technology, using PLA biopolymer to create sustainable, biodegradable, nonwoven bio-based composite membrane supports with bamboo fiber and dimethyl carbonate. Bamboo fibers were bound together in the composite using PLA as a binder, resulting in a porous structure with a rough surface suitable for membrane support applications. The author found that the bio-based membrane support had a porosity of about 0.719 ± 0.132 and similar tensile strength to that of the synthetic polymer. Additionally, the composite film's mechanical stability is enhanced, swelling is reduced, and perforation is increased by up to $1068 \pm 32\ \mathrm{l\ m^{-2}\ h^{-1}\ bar^{-1}}$ in water. Furthermore, bamboo fiber's insoluble nature in most solvents also aids in enhancing the membrane supports' chemical stability. The membrane supports also showed to be durable in the long-run when it was exposed to continuous crossflow filtration for two weeks and submerged in water for more than six months. This finding demonstrated the porous properties of the bamboo-reinforced PLA composite films, which make it suitable for applications other than membrane support, such as microfiltration membranes and adsorbents.

Biodegradable polymers are often mixed with other polymers in many studies and utilized as different matrix systems in composites. The tactic of polymer mixing is thought to be particularly helpful in producing novel materials with the best possible structure and performance. This multi-component hybrid system still has a lot of promise due to its exceptional mechanical and processing capabilities. For instance, Long et al. [87] used PLA biopolymer and a synthetic polypropylene (PP), as the two different matrices, while reinforcing them with bamboo fiber to investigate the blending process. The bamboo fiber's surface had undergone various modifications, including using coupling agents like MAPP to improve the matrix and fiber compatibility. The combination of the matrices and modified bamboo fibers were used to create samples using a twin-screw extruder and 3D printing with the Fused Deposition Modeling (FDM). The investigation discovered that altering bamboo fibers to remove hemicellulose and pectin constituents and reduce their hydroxyl content improved the interfacial adhesion between PP/PLA and bamboo fiber. Furthermore, the inclusion of 5% MAPP in the BF/PP/PLA hybrid composites was found to be the ideal composition with best tensile, flexural and impact strengths that increased by 13, 11.7, and 23.5%, respectively, compared to the neat BF/PP/PLA composites. Due to their better qualities, BF/PP/PLA hybrid composites are a viable substitute for pure PLA, particularly for use in 3D printing.

Besides PLA, only a few different biodegradable polymers have been employed as the matrix for fabricating composites, especially with bamboo fibers. Poly (butylene succinate), more commonly known as PBS, forms one of those rare biodegradable and environmentally friendly polymers, which is generally produced from biowastes. It consists of 1,4 butanediol and succinic acid. Pivsa-Art and Pivsa-Art [80] researched reinforcing bamboo fiber in PBS biopolymer. They studied the effects of varying fiber matrix composition on the biocomposite's mechanical and physical properties, which can be used in indoor furniture components and in packaging as well. PBS has historically been used because of its great qualities, including good biodegradability and strong toughness owing to its low glass temperature. Alkaline-treated and untreated bamboo fiber of two distinct kinds were employed at various loadings (10, 20, and 30 wt%). This investigation discovered that alkaline treatment showed greater tensile strength than the untreated ones. When PBS is reinforced with 30 wt.% bamboo fiber, the composites' Young's modulus rises to 2575 MPa compared to only 639 MPa for pure PBS. Results for Izod impact strength also showed similar pattern, proving that alkaline treatment is beneficial in removing lignin and hemicellulose elements from the bamboo fibers and improving the surface interface between matrix and fiber. For composites to be used in industry, appropriate performance, especially mechanical qualities, is essential. Furthermore, [88] have examined PBS-based composites reinforced with nano/micro hybrid bamboo fibers, with the aim of creating useful fiber-based composites with superior strengths. The mechanical performance of the hybrid composites was observed to be greatly enhanced using hybrid nano- and micro-scale bamboo fibers. The best tensile strength and Young's modulus were reportedly achieved when a combination of carbon nanofiber (CNF)/BF, which had been thermo-compressed for 15 min, was added to PBS, increasing these properties by 240 and 700%, respectively, over neat PBS.

Another topic was the inclusion of bamboo fiber in naturally occurring materials formed from biodegradable polymers, such as starch, seaweed, etc., which was also investigated. For example, [89] used biopolymer film made from red seaweed reinforced with bamboo fiber (*Kappaphycus alvarezii*). First, red seaweed was used to extract the carrageenan, treated with a solution of 1 M NaOH. After being neutralized with HCl, the mixture is dried and processed as a biocomposite film. In contrast, the bamboo fiber was also converted into cellulose pulp before being combined with red seaweed carrageenan to produce biocomposite film. Before being cast, the seaweed solution was mixed with several loadings of bamboo pulp (0, 1, 5, 10, 15, and 20%). The analysis shows that the mechanical properties of the seaweed matrix were improved by the addition of bamboo pulp fiber, with tensile strength being 109.1 MPa, Young's modulus being 55.4 GPa, and improvement in stretchability before breakage being 22.3% in comparison to control. Furthermore, after the biopolymer was combined with bamboo fiber, improvements in water vapor permeability qualities and a high contact angle of 91° were also noted. The possibility of using biodegradable biopolymer composite films as packaging materials, particularly for the food industry, was confirmed by this discovery.

Yusof et al. [90] used bamboo fiber to strengthen the natural polymer composites made from tapioca starch and PVA to compete with the market's standard petroleum-based plastics. It has been claimed that subjecting the composites to various forms of chemical pre-treatment helps to boost their tensile and flexural strength. There in the study, treatments with permanganate and alkali were carried out. The composites were made by solution casting a mixture of starch, PVA, and bamboo fiber using glycerol as a plasticizer. The composites comprising of bamboo fibers treated with alkaline solution had higher mechanical performance in comparison to those with untreated and permanganate-treated fibers. According to the author, adding bamboo fiber improved the biocomposites' heap bearing limit and ability to withstand bending, which improved their tensile characteristics. In addition, removing undesirable ingredients from the fiber cells during the fiber treatment further improved the composite sample's mechanical characteristics. It enhanced the interlocking between the fiber and matrix. While the hybrid biocomposites' flexural characteristics also exhibited a similar pattern. The alkaline-treated sample performed the best since it was hardly breakable, indicating great flexural strength. Even though all samples had fibers of an equal length, this occurrence followed the sample's stress–strain relationship, as seen by its tensile strain behavior, determined by the bonding strength between the fiber and matrix.

In a separate study, [91] investigated the possibility of combining a hybrid polymer, made by mixing starch and PVA, with nanocelluloses that are extracted from bamboo fibers. The addition of only about 6.5% nanofibrils affected the tensile strength (increase of 24%) and elongation at the break (increase of 51%) in the composites. Furthermore, the tensile properties of the small-fiber reinforced composites were substantially superior to those of the bamboo fiber reinforced starch/PVA composites, reported earlier.

4.2 Bamboo Fibers and Its Composites' Thermal and Fire Performance

Although many publications on the characterization of composites made from natural plant fibers have been thoroughly investigated, reports on the fire and thermal characterization of composites made from fibers, especially bamboo, are rare. Das et al. [92] fabricated a composite with novalic resin reinforced by bamboo fibers that were again treated with alkali. The thermogravimetric analysis helped establish superior thermal stability of the fabricated composites. The novalic resin functioned as a glue that was responsible for attaining excellent bond between the constituents, resulting in higher bonding forces and superior thermal stability. The affinity of fibers for absorbing water reduces after alkali treatment because corresponding soft metal ions occupy most of the external hydroxy groups, resulting in neutralization that causes new connections between the inherent cellulosic molecules. The creation of these bonds results in a firmly closed-packed structure of cellulose, which raises the bamboo treated with an alkali crystallinity index and increases stability [93]. This caged system supports the water of crystallization, increasing the temperature at the end. After being treated with alkali, bamboo fiber-based composites' thermal behavior, such as heat deflection temperature, was observed and claimed to have somewhat improved [94–97]. Despite a minor increase in thermal stabilities, the thermal deterioration pattern changed after fiber was added. After adding fibers, the composites' deterioration pattern changed, and their thermal stabilities somewhat improved. A significant factor that directly affects a material's thermal behavior is the fiber composition of the composite. Researchers highlighted that partial deterioration is a good cause that directly influences the thermal stability of bamboo composites in one of the comparative biodegradation studies [94]. It has been described how the structural characteristics of bamboo composites relate to different characteristics, including crystallization and interfacial morphology [98]. DSC curves were studied to evaluate the influence of the neat matrix and their alternatives. It was observed that the modified matrix had a significant influence on the DSC curves, which can be attributed to the presence of an adequate amount of b-phase form.

According to some studies, the kind of filler employed impacts the qualities of composites; for example, inorganic fillers have the potential to operate as b-nucleators and generate significant amounts of b-form, which directly impacts the thermal characteristics of the composites [99, 100]. In another investigation, bamboo fiber was considered a potential source of b-nucleators [98]. Stronger adherence between the matrix and bamboo fibers, which results in improved thermal stability, is the root of the varying degrees of thermal behavior. It tested how modified bamboo-reinforced composites with various fiber loading levels responded to heat [101]. The thermal behavior of bamboo, neat matrix and the resulting bamboo composites were compared. Increased inorganic silane concentration on the bamboo surface was found to impact maximum peak temperature directly and directly correlate with weight loss. According to the studies on the polypropylene-reinforced bamboo fiber composites' kinetics, the peak of crystallization and the starting temperatures reduced with increased cooling rate [102]. It was explained that slower cooling rates provide polymer nuclei enough time to reach an active state, which causes crystallization at higher temperatures [103]. The peak of the crystallization temperature at a specific rate of cooling had direct relation to the amount of bamboo fibers used, a finding that helped substantiate the heterogeneous "nucleation effect" of bamboo [104–106]. The studies achieved in getting lower crystallinity in the PP-BF composite, proving that a slower cooling rate was required [107–109].

The matrix melting temperature was reported to be somewhat reduced, and crystallization was enhanced when bamboo fibers were added to recycled polypropylene-based bamboo composites, indicating that the quantity of bamboo fibers directly influences the thermal characteristic of composites [102]. Other studies have also shown that recycled polypropylene crystallization rates and crystallinity percentages increased [110–112]. Bamboo fiber, when used in various loading percentages, positively affects the recycled resins' crystallization that frequently occurs at higher temperatures. The primary reason for this behavior is the nucleation effect [113, 114].

Guo et al. [115] method successfully converted natural bamboo into a composite with superior performance and having lower weight, higher tensile strength, and limited flammability. Natural bamboo is first de-lignified, woven in a superior aligned formation, and are treated before being injected with epoxy resin. The hydroxyl groups of boric acid (BA) and the cellulose backbone's diol or carboxylic groups cross-linked with each other, forming a stable and strong compound, when BA was applied in an alkaline solution. Due to the well-preserved aligned bamboo fibers, the BA-bamboo/epoxy composite showed increased tensile (by ~234%) and impact strengths (by ~177%), compared to pure epoxy. The BA-treated composite had comparable mechanical properties to the untreated ones but had substantially improved flame retardancy abilities. The treated bamboo/epoxy composite's limiting oxygen index was '26.5% larger, and cone calorimeter studies proved that the peak heat release rate (PHRR) was also ~63% lower than the original epoxy resin. Furthermore, BA resulted in greater charring of the composite, which was also proven in the thermogravimetric analysis with lesser mass loss and higher thermal stability, resulting in the substance's considerably improved fire performance. The properties of the treated composite had excellent performance to be able to be used as structural materials.

Flame-retardant bamboo-PP composites were produced by melt blending, with ammonium polyphosphate (APP) as the flame retardant and bamboo flour as the smoke suppressant and investigated by [116]. When employed as a synergist, bamboo flour can greatly improve the smoke suppression and flame retardancy performance of PP/APP composites, which was prominent in the study. It also helped improve the composites' mechanical performance, thermal degradation, and crystallization behavior. Therefore, various characterization techniques were employed, including scanning electron microscopy, cone calorimetry, thermogravimetric analysis, and limiting oxygen index, to investigate the microscopic morphology of carbon residue, flame retardancy, thermal stability, and combustion characteristics. According to experimental findings, the PP55/APP30/BF15 composite had the greatest smoke-suppression effect when APP/BF was mixed in 2:1 ratio, amounting to about 45 wt.% of the composite. It's because the residual carbon has more micropores and surface area, resulting in reduced PHRR to 308.2 kW/m^2, and increased carbon residual of 25%. In addition, the continuous carbon layer created during combustion may shield the matrix material and stop heat transmission.

Chen et al. [117] examined the fire performance of designed bamboo beams when exposed to three-sided standard fire conditions. Nine tests were carried out, including two fire tests with a continuous applied load and the remaining flexural tests on the manufactured beams when exposed to the standard fire conditions. The reported parameters included the load ratio in fire tests, the duration of the fire exposure, the shaft's geometry, and the type of bamboo used to design the test conditions. Two products made from engineered bamboo frequently used in construction are bamboo scrimbers and laminated bamboo structures, which were also tested in the study. In every case, regardless of exposure to fire, the failure mechanism was flexural coupled with tensile fracture under extreme tension. Longer fire exposure times reduced engineered bamboo beams' stiffness and maximum loads, but the strain distribution along the middle span of the structures' cross-sections remained linear. As the applied load increased, the fire resistance of laminate bamboo beams decreased. After testing, each beam's charring depth was determined, and an equivalent charring rate was computed. The findings indicated that the laminated bamboo beams were charred more quickly than the denser bamboo scrimber beams. Sectional analysis and the reduced cross-section approach were employed to calculate the structures' resistance to fire and loading capacities.

5 Applications

In recent years, efforts to use bamboo as a renewable non-wood fiber have been strengthened. This renewable fiber has improved agroforestry since bamboo grows fully and matures in one and two years. Theoretical and practical research on products made of bamboo has evolved, notably in furniture, packaging, building, and transportation, since bamboo grows swiftly and is renewable. Composite materials have supplanted both interior and outdoor applications of traditional wood. When their strengths were compared, they were found to be substantially stronger (~10 times) than normal wood produced. Bamboo composite products generally have advantages over conventional composites and traditional wood due to their low maintenance, weather resistance, dimensional stability, longevity, high impact resistance, and restricted flame spread.

Today, fences, decking, deck tiles, dustbins, railings, outdoor furniture, and decking accessories are all made from bamboo composites, which usually contain up to 70% bamboo fibers and roughly 30% high-density polyethylene (HDPE), making the entire composite recyclable. These bamboo composites were designed specifically to maintain their shape and stability, be resistant to termites, have excellent stability under varying thermal conditions, and be easy to handle, transport and install. These composites made from bamboo provide enough cost and benefit to the end consumers. For structural purposes, laminated bamboo lumber (LBL) has been published in recent publications [118]. Despite the success of the LBL fabrication effort, more must be learned about how changes in strength qualities affect the LBL. The current bamboo-based composite industry has significantly influenced the development of modern economical techniques, which are less reliant on the commonly used renewable building material, wood, while being eco-friendly, producing reduced pollution, and consuming less energy. Outdoor constructions in the building industry,

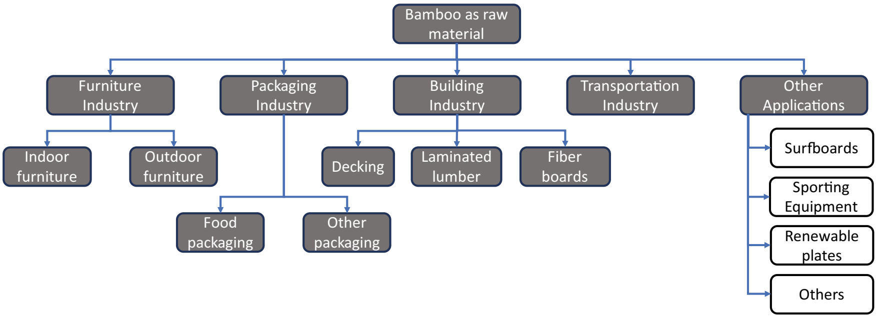

Fig. 3 The various applications of bamboo and its by-products

such as decking, form another use for bamboo composites. These decks are made of multiple layers of bamboo boards coated with epoxy matrix and a special coating over glass boards to prevent bending and preserve their shape over time. Surfboards are a general term for water-surfing composites made of bamboo. These surfboards are lightweight, have a distinctive shape, and have water-resistant surfaces. Recently, Mitsubishi Japan created a prototype using composite materials based on bamboo. They made this prototype using polyurethane resin. By employing plant-based materials, Mitsubishi could minimize the cost of manufacturing the present materials and the CO_2 emissions. Advanced composites are seldom the first choice for materials utilized in automotive applications, despite their potential advantages. Advanced composites require a significant shift in economic thinking, and the only solution is using natural plant fibers. Bamboo is a great resource to use in place of the current commonly used synthetic ones, especially with the growing raw material shortages and price spikes. The vast application field of bamboo as a raw material is illustrated in Fig. 3.

6 Conclusion and Future Perspectives

Using bamboo fibers in various products has created new opportunities for academics and businesses to develop a sustainable module for using bamboo fibers in the future. Bamboo fibers are widely employed in composite industries to help people advance their socio-economic status. Bamboo market values are strongly impacted by developing cost-efficient and environmentally friendly biocomposites made from bamboo fiber-based composites made from various matrices. Detailed research of bamboo fibers' mechanical, physical, and basic characteristics is required to build such composites. As a result, this review has attempted to compile data on the fundamental attributes of composites manufactured with bamboo fiber and their practical applications. Researchers from around the globe have conducted a broad variety of research using cutting-edge ideas to provide working and employing communities with essential assistance. Current research on composites based on bamboo fibers uses both basic and practical science. Even though other countries like India and China have made significant progress in the socioeconomic use of bamboo fiber, the ultimate goal of fully utilizing bamboo fiber is far behind its anticipated milestone, particularly in Malaysia and other countries. It would be possible to use bamboo in ways other than the typical conventional mode with the support of the industry's sustainable future for bamboo-based composites. The efficient characterization of bamboo fiber and composites made from bamboo fiber should be furthered in terms of research and testing. Even though scientists have done much work on composite materials made from bamboo, more study and innovation are still needed to address potential issues. These things will benefit urban and rural residents who depend more on composites made of synthetic materials.

A sustainable future depends on the current industrial development towards the economical and efficient production of the industrial goods and their eco-friendly production process. The market's dominance of synthetic/petroleum-based goods can be challenged by the biodegradable and renewable plant materials, only if they are high-performing, depleting petroleum usage and building a new foundation for environmentally friendly and sustainable products. Natural fibers and biocomposites made from natural resources, if can possibly be incorporated into sustainable and well-designed industrial products, have the potential to challenge the dominance of products derived from petroleum. Bamboo fiber is well-known for its renewability in terms of rapid growth and outstanding mechanical properties. Using cutting-edge technology, using bamboo fiber to create biocomposites transforms the next generation's future. A new revolution in resource conservation may be sparked by carefully crafted goods made of bamboo fibers. This quick evaluation suggests that bamboo fibers can create sophisticated, engineered products for various uses. It will be a different approach to creating biocomposites, particularly those used for common people's daily needs, such as lightweight automotive parts, sports equipment, fences, decking, and flooring. Their affordable prices, simple accessibility, and appealing designs will be the primary impetus for transitioning from a dependent present to a sustainable future.

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