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Bamboo Fiber Composites

Processing, Properties and Applications

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Editors are honored to dedicate this book to their parents

Preface

Natural fibers for producing biocomposites are an emerging area in polymer science. The rise in ecological anxieties has forced scientists and researchers from all over the world to find new ecological materials. Therefore, it is necessary to expand knowledge about the properties of bamboo fiber composites to expanding the range of their application. This book presents an extensive survey on recent improvements in the research and development of bamboo fibers that are used to make biocomposites in various applications, because of its outstanding features like lightweight, low cost, environmentally friendly and sustainablility. The unique feature of this book is it presents a unified knowledge of bamboo composites on the basis of synthesis, characterization, properties and applications. This book also focusses on the recent advances in bamboo fibers and its composites from renewable resources and introduces potential applications of these materials. This book gives a sound knowledge on bamboo composites to the readers with numerous example illustrations, methods and results for graduate students, researchers and industrialists. Readers will have a quick reference by exploring the research literature on the subject with commercial value-added research applications of bamboo composites.

The objective of the book is to summarize many of the recent developments in the area of bamboo composites. As the title indicates, the book will emphasize new challenges for the synthesis characterization and properties of bamboo composites. Our book covers the void for the need of one stop reference book for the researchers. Leading researchers from industry, academy, government and private research institutions across the globe will contribute to this book. Academics, researchers, scientists, engineers and students in the field of natural fiber composites will benefit from this book which is highly application-oriented. Moreover, it will provide a cutting-edge research from around the globe on this field. Current status, trends, future directions, opportunities, etc., will be discussed in detail, making it friendly for beginners and young researchers.

We are thankful to all authors who contributed chapters in this edited book and made our imaginary thought into reality. Lastly, we are thankful to Springer team for continuous support at every stage to make it possible to publish on time.

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About the Editors

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Bamboo Fiber Reinforced Composites

M. Ramesh, L. RajeshKumar, and V. Bhuvaneshwari

Abstract Natural fiber composites exhibit various advantages like biodegradability after the life of components, minimal or no emission of greenhouse gases and less pollution. Apart from the domestic and small scale industrial application of these composites, are also employed in military, automobile and aerospace applications owing to their maintenance of sustainable environment, design flexibility and continuous improvement in facing several challenges. Bamboo is one of the well-known and wide spread plants all around the globe. It is characterized by multifaceted merits such as high stiffness and fiber strength, ease of processing, sustainable use of fibers, eco-friendliness and rapid plant growing cycle. Bamboo fiber reinforced composites are considered to possess enhanced environmental friendliness than any other synthetic fiber reinforced composites such as glass fiber reinforced composites and they render less impact over the environment, same performance for the similar fiber content and allowing reduced use of toxic base polymers. This chapter deals with a comprehensive view of individual bamboo fiber reinforced composites as well as hybridization of bamboo fibers with other fibers. This may pave way for the researchers working on bamboo fibers to reach newer heights in terms of properties and applications.

Keywords Bamboo fibers · Bamboo composites · Processing · Properties · Hybridization

1 Introduction

Utilization of petroleum based products and fibers have become very hard due to various constraints like very high oil rates, environmental effects of synthetic fibers,

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problem of disposal, and depleting fossil fuels. Hence applications that were occupied by synthetic fibers could no longer sustain and so the industrialists have turned towards the usage of natural fibers which are environmental friendly materials and could be largely considered as potential substitutes for synthetic fibers. Amongst all natural fibres, bamboo is considered to be essential due to its significant features like naturally available, biodegradable, grows rapidly, absorbs carbon dioxide from the environment and available widely. Increased tensile and flexural strength and modulus in a bamboo fiber is achieved owing to uniform spread of cellulose within lignin matrix longitudinally, so it could be factored as a composite material. To improve the interfacial bonding, the bamboo has to be treated with hydrophobic and nonpolar eco-friendly material since it is hydrophilic and polar inherently. Being highly competitive alternate to the wood, bamboo has been adopted and accepted by many researchers by conducting fast and increased number of experiments. Through the experiments it is evident that bamboo can replace wood in a much better way [1].

Bamboo has diaphragm till the end of its length and amongst the diaphragms, internodes are available. Diaphragms are used to support the stem. Hollow gap between the internodes, which extends until next node, are named as lacuna. This lacuna is encompassed by a non-uniform length of culm wall starting from internodes. Sometimes internodes without lacuna is known as solid bamboo which is rare are known as male bamboo. The gap and size between the internodes is reduced by incrementing the length of the bamboo due to the narrowing nature of culm wall from bottom to the top [2]. Internal design of bamboo is curved and thinly with narrow shape in macro level view. In case of micro view, it has a thread or a filament that is strengthened by cellular parenchymatic tissue making up the softer parts of leaves which is behaving as a matrix. Major elements constituted in bamboo are hemicellulose, cellulose, lignin, ash and some other derivative elements accompanied by silicon dioxide [3]. The major and significant properties of bamboo is designed and determined by these compositions which yield good and improved toughness, strength and ductility with less density. Figure 1 shows the bamboo plant, a small circular ring from the plant, its macro view and the scanning electron microscopic (SEM) images.

Outer layer of single bamboo filament is covered with several layer which is in the shape of concentric circle which share the same centre. Those several layers are encountered with heavy cell wall with some lumen, some pits and lesser micro fibril angle which indicates overall anisotropic properties of the fibers. The diameter and length of the single bamboo fiber is 10–30 μm and 1–4 mm respectively [4]. It is highly desirable to improve the mechanical behaviour of the single layer bamboo, which is widely used to reinforce the composites. Figure 2 shows the SEM image of single bamboo fiber along its cross section and in longitudinal direction.

Various researchers indicated the different values of tensile strength of various forms of bamboo fibers used and the following cases were used to analyse the tensile behaviour of the bamboo in several forms: chemical isolation, bundle fiber examination, examination of puny bamboo strip and mechanical separation of vascular bundles. Comparatively chemical isolation process enhanced the tensile behaviour of the bamboo than mechanical separation technique. In mechanical separation tensile

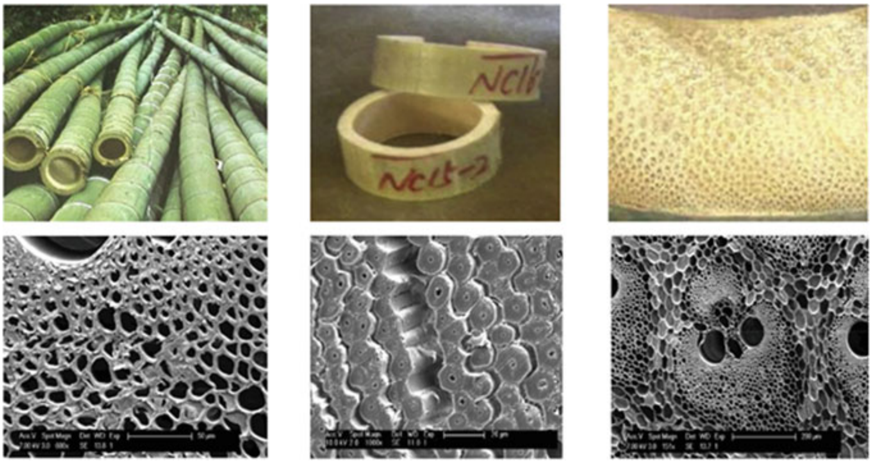

Fig. 1 Bamboo plant and its cross-sectional microscopic images [2]

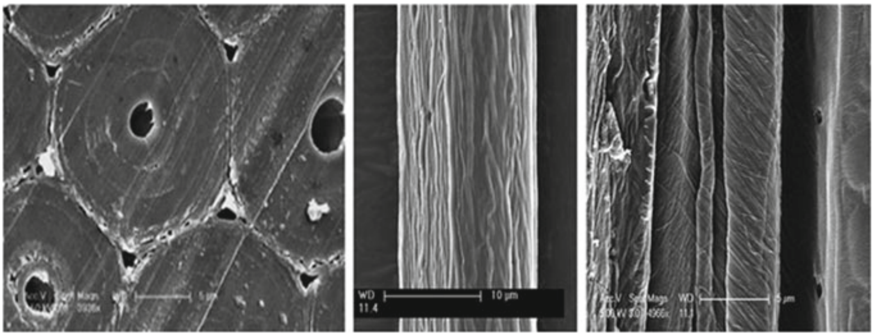

Fig. 2 SEM image of single bamboo fiber [2]

behaviour of bamboo strips is reduced by increasing the bundle size of the bamboo fibers. This could be due to poor interfacial bond created between fiber and its centre lamella and the impairment of fiber during its extraction and surface treatment [5]. So to retain fiber properties, it is has to be prevented from breaking during its preparatory stages. Table 1 shows physical, mechanical and various other general properties of single bamboo fiber.

2 Bamboo Fiber Composites

Prospective applications of bamboo fiber reinforced composites increase day by day and its inspiring properties such as biodegradability, cost and availability has

Table 1 Properties of bamboo fiber

S. No	Property	Unit	Value	Sources
Mechanical properties				
1.	Elastic modulus	GPa	27–40	[6]
2.	Elongation	%	2.89	[2]
3.	Tensile strength	MPa	1504–2036	[2]
4.	Tensile modulus	GPa	25.24–28.46	[2]
5.	Hardness	HV	23.45	[5]
General properties				
6.	Specific gravity	No unit	0.4–0.8	[5]
7.	Moisture absorption	%	13	[5]
8.	Linear density	g/cm^3	1.44	[5]
9.	Failure strain	%	1.2–1.9	[6]
Thermal properties				
10.	Transition temperature	°C	426.11	[3]
11.	Thermal degradation	%	52.35	[3]
12.	Fiber enthalpy (at 65 °C)	J/g	8.94	[3]
13.	Activation energy	J/K	23.22	[3]

opened avenues for bamboo fiber composites in the areas like pharmaceuticals, furniture, biomedical, construction, cosmetics, automotive and electronics. Upon clearly understanding the properties of bamboo fibers, manufacturing of bamboo fiber reinforced composites by using various techniques has to be dealt with. Before proceeding to manufacture the composites, the bamboo fibers were treated with various solutions, either acidic or alkaline, expecting the properties of the composites to improve. Surface treatment using various alkaline solutions like sodium hydroxide, benzoyl chloride, potassium permanganate and so on are the mostly used treatments. Generally, alkaline treatments are employed over the natural fibers which facilitate to remove the cellulose and hemicellulose contents over the fiber surface making it uneven and aiding the natural fiber to have better interfacial bonding with the encompassing matrix.

In general, the bamboo fibers are treated with alkaline solution of various concentrations, for enhancing its chemical interaction and tensile characteristics, followed by coating of bamboo fibers with many thermosets like polyurethane, polyethylene and semi-interpenetrating polymer network polymers like polystyrene. Few researchers inferred that when the bamboo fibers were treated with 10% NaOH, fiber-matrix interaction was better and the fiber surface was not deteriorated while 20% alkaline treatment declined the strength of bamboo fiber composites [7]. Few attempts were also made to reinforce the alkali treated bamboo fibers in bio-based starch resins. From the experiments, those authors inferred that bamboo fibers acted as fillers instead of playing the role of reinforcements due to their small aspect ratio in the order of 20.

Bamboo fiber reinforced polyester and epoxy composites were prepared by using treated bamboo fiber by compression moulding and hand layup techniques. Both of them used alkaline treatment for making the fibers devoid of hemicellulose and lignin content by which the fiber-matrix interface of the composites were strengthened [8, 9]. Huang and Young [10] manufactured bamboo fiber reinforced epoxy composites by means of resin transfer moulding process where they used quasi-unidirectionally arranged fiber orientation. The fibers were treated with 0.1 N of alkaline NaOH solution. Alkaline treatment rendered better properties of bamboo fiber composites including tensile, impact and interface shear stress. Khan et al. [11] attempted the preparation of bamboo fiber reinforced epoxy composites by means of compression moulding method. They treated the bamboo fibers with 6% alkaline NaOH solution while the percentage of alkaline solution was determined by the single fiber fragmentation test. 6% NaOH removes the surface cellular contents better than its other counterparts such as 2 and 10% NaOH and due to the presence of minimal wax content over the surface, the properties of the composites were enhanced. Lequan et al. [12] fabricated unidirectional bamboo and coir fibers reinforced polypropylene composites by means of compression moulding method. Initially a prepreg of unidirectionally aligned bamboo fibers were prepared to make it as a sandwich between the polypropylene faces. Nabinejad et al. [13] manufactured unidirectional bamboo fiber reinforced polyester composites through vacuum assisted resin transfer moulding method. Bamboo fibers were treated with 3, 5 and 7% of NaOH in this case and the optimum percentage of treating agent based on the test results were evaluated. Choudhury et al. [14] prepared 0°/+45°/+90°/–45° ply bamboo fiber reinforced PLA green composites by adopting compression moulding method. Here the machinability study was carried out on the untreated bamboo fiber reinforced composites. Wang et al. [15] determined the effects of fiber surface treatment on tensile and bonding behaviour of unidirectional bamboo fiber reinforced epoxy composites. Various percentages of alkali such as 1, 4 and 7% of NaOH was applied to the bamboo fibers and the composites were manufactured by hot pressing moulding technique.

Xie et al. [16] prepared bamboo fiber bundle reinforced phenol–formaldehyde composites through hot pressing technique. Behaviour of bamboo bundles and its influence over the mechanical and physical properties of the composites were evaluated. Yu et al. [17] manufactured the bamboo laminated sheets reinforced phenol–formaldehyde composites through compression moulding method. Mechanical properties of these composites were evaluated. In both of the above cases, fiber surface treatment was not carried over instead of which the fiber bundles and mats were soaked in the resin itself for a specific period of time which was considered as treatment. Anatomical properties of the bundles and mats determined the enormity of properties of bamboo composites [18, 19].

Few authors tried to prepare hybrid composites with either treated or untreated bamboo fibers and evaluated the required properties. Untreated kenaf and bamboo fibers reinforced hybrid epoxy composites prepared through hand-layup method for evaluating the hybridization effects upon the thermal and thermo-oxidative stabilities [18]. The thermo- mechanical and dynamic mechanical properties of woven bamboo and kenaf fiber mats reinforced epoxy composites prepared by hand-layup method where the bamboo and kenaf mats were kept untreated [20]. Fei et al. [21] used the same untreated bamboo and kenaf mats reinforced hybrid epoxy composites to assess the weathering behaviour and the effects of soil burial upon the colour and bio-degradability of the composites. In all the above cases, treatment of the bamboo fibers was absent and the authors indicated that treatment of fibers might had given still better results.

Liew et al. [22] prepared bamboo and jute fibers reinforced low density polyethylene composites by hot press method and evaluated thermo-mechanical properties of the composites. The dewaxed and delignified bamboo and jute fibers were treated with 6% NaOH before the preparation of composites. Kumar et al. [23] investigated the mechanical properties of treated bamboo fiber and hollow glass microsphere polypropylene composites fabricated by injection moulding method. 6% NaOH solution was used for the treatment of bamboo fibers and the hollow glass microspheres were treated using silane compounds. Gogoi et al. [24] assessed the mechanical properties and crystallinity of bamboo fiber reinforced hollow glass microspheres filled polypropylene composites after treating the short bamboo fibers by using 6% of alkali NaOH pellets. Kannan et al. [25] evaluated the mechanical properties of alkali-treated short bamboo fibers and glass fibers reinforced polypropylene composites manufactured by hot pressing technique. For treating the bamboo fibers 7% NaOH solution was used. Figure 3 shows the scanning electron microscopic images of treated and untreated bamboo fibers.

Among all these methods, mercerization is one of the most suitable low-cost treatments for natural fibers by which the non-cellulosic substances will be extracted, rendering increased wetting ability of fiber [18, 20]. The main objective of alkali-treatment is to produce fibers with improved wetting and spreading characteristics and the consequent changes in the dimension, fine structure, morphology, and mechanical properties. From the studies it could be inferred that for treating bamboo fibers alkaline treatment was most commonly used and specifically 6% or 7% NaOH solution was often used for the fiber surface treatment. Commonly bamboo fiber reinforced composites were prepared by using polyester, epoxy and polypropylene as matrix materials [26].

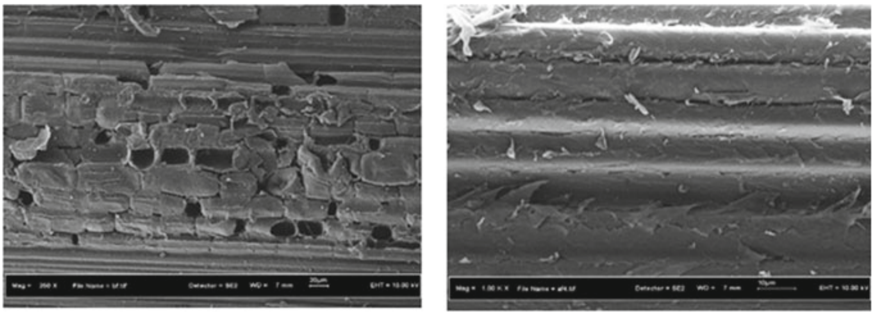

Fig. 3 SEM images of untreated and treated bamboo fibers [25]

3 Properties of Bamboo Fiber Composites

3.1 Mechanical Properties

Mechanical characteristics of bamboo fiber reinforced polymer composites depend upon the following factors: (i) fiber modulus and strength, (ii) chemical stability, stiffness and strength of the matrix material, (iii) extent of interfacial bonding between bamboo fiber and its matrix at the time of transfer of stress from one to the other. If the interfacial compatibility exists between matrix and bamboo fibers, then even low volume fraction of bamboo could be sufficient to perform the reinforcement role in the bamboo fiber reinforced composites. Interfacial bond, in turn, depends on the type of chemical treatment used and the resulting structure of bamboo fiber after such chemical treatment [27]. During alkaline treatment of bamboo fibers, NaOH reacts with the cellulose present in the fiber forming a product of sodium cellulosate which remains stable. Meanwhile, Na^{+} ions in the alkali solution replace the hydrogen ion of the hydroxyl group in cellulose. During further treatment process, when the fibers were washed with dilute sulphuric acid and then by distilled water, once again the hydrogen ion regains its position from sodium ion in sodium cellulosate present within the fiber cellulose resulting in actual fiber structure [28]. Though the resulting structure has cellulose II structure while initially the fiber may possess cellulose I structure, this factor is believed to play a significant role in enhancing the properties of bamboo fiber reinforced composites. Figure 4 illustrates alkali-treated bamboo cellulose fibers.

Tensile, flexural and impact behaviour of bamboo fiber reinforced composites were analyzed by various researchers by varying the volume fraction of bamboo fibers or the chemical treatment of fibers [30]. Inferences were made from the results obtained and the composites were characterized by SEM in most of the cases. The tensile, flexural, compressive and shear strength of the bamboo bundle reinforced phenol formaldehyde resin were done by varying the density (800, 1000 and

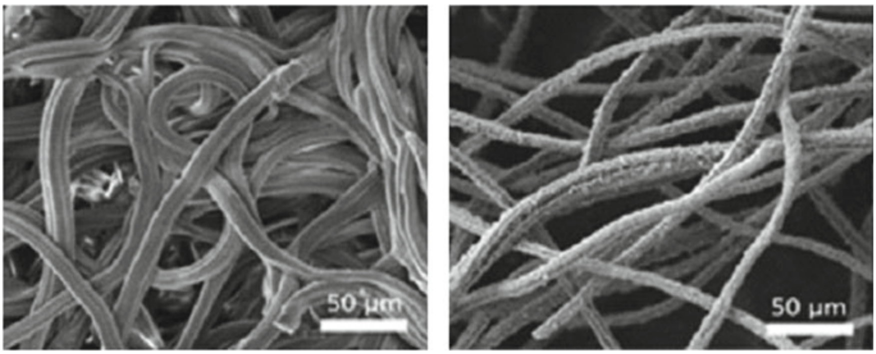

Fig. 4 SEM micrographs of alkali treated bamboo fiber [29]

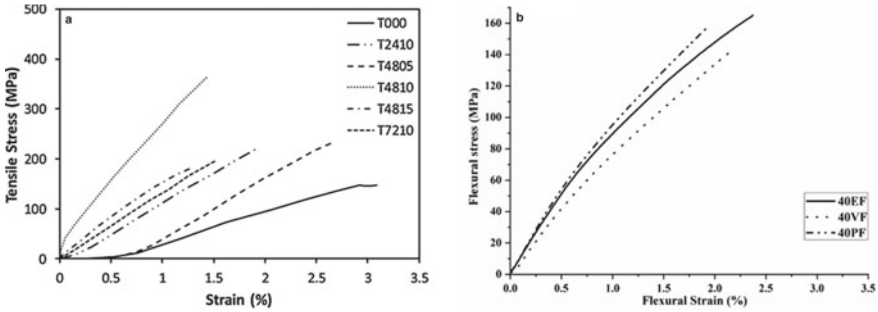

Fig. 5 Tensile and flexural stress–strain curve of bamboo fiber composites [26]

1200 kg/m^3) of the fiber for preparing the composites. From the results it could be seen that the composites containing maximum density bamboo fiber exhibited better mechanical properties due to the collapse of parenchyma which contains thick lumen structures. This results in solid state composite materials after since they are fabricated by hot pressing method [31]. The flexural behaviour of outdoor bamboo fiber reinforced epoxy composites by preparing the composites with four different densities were evaluated. It is inferred that due to the variability in permeability of resin with various regions of the outdoor bamboo fiber, majority of the failure zones had fallen at fiber matrix interface. Hence they concluded that when a composite of much higher density was used for bending applications, internal stresses developed would also be more within the composite [32]. Figure 5 shows the tensile and flexural stress–strain graph of bamboo fiber reinforced composites.

The tensile, compressive and short beam strength of the bamboo fiber bundle reinforced phenol formaldehyde composites with a fiber density of 1.03 g/cm^3. When compared with bamboo fiber bundles, composites prepared by using the fiber bundles possessed better mechanical properties due to the densification of fiber within the matrix and the thickening of ground tissue. Enhancement of mechanical properties was also attributed to the increase of bamboo fibers per unit volume in bamboo fiber reinforced composites [33]. The tensile and flexural strengths of alkali-treated bamboo fiber reinforced epoxy and polyester composites separately with varying treatment duration and fiber volume fraction was investigated. Results indicated that composites containing higher volume fraction of high density bamboo fibers and composites prepared from fibers that were alkali-treated for a long duration exhibited better properties than its counterparts. When the bamboo fibers were treated for longer durations, the interfibrillar zone of the fibers decreases facilitating a better removal of impurities leading to a fibrillary arrangement parallel to the direction of load application. This aspect improves the mechanical properties of the bamboo fiber reinforced composites. These behaviours stayed independent of the matrix material used for composite preparation [34].

Latha et al. [35] analyzed the strength of hollow glass microsphere (HGM) filled bamboo epoxy hybrid composites were and stated that the presence of HGM filler in half the proportion of high strength natural fiber rendered better mechanical properties like tensile, flexural and impact strength. Yet, due to the presence of spherical HGM which is brittle in nature, the failure mode of hybrid composites were also brittle. The mechanical properties like tensile and impact characteristics of short bamboo fibers reinforced HGM filled polypropylene composites were tested by varying the filler content between 5 and 20% by weight. It is observed that the tensile strength of the hybrid composite was higher for the composites with 5% HGM and the values decreased thereafter. They also visualized that the addition of synthetic filler decreased the mechanical property in spite of the presence of high strength bamboo fiber [36].

The tensile strength of kenaf and bamboo fiber reinforced epoxy composites are determined and found that the hybridization of bamboo with kenaf fibers improved the tensile properties of hybrid composites. It is noted that the strength values were lesser than individual bamboo composites which could be attributed to the lower strength values of the kenaf fibers. The strength improvement observed in the composites could directly be attributed to the usage of bamboo fibers whose strength is higher than kenaf fibers. It is also observed that bamboo fibers possessed high elongation at break than kenaf fibers which is the reason for their higher strength [37]. Earlier researchers coined that when a fiber with less elongation was hybridized with a fiber with high elongation, then strain required by the load to penetrate the fibers was enhanced and this could be due to the role of fibers with high elongation to act as crack resistors at the micro-level [19, 38]. The mechanical properties of bamboo and glass fiber reinforced polypropylene composites were investigated by varying the fiber volume fraction. Results indicated that the tensile, flexural and impact strength was high for the composites containing glass and bamboo fibers in equal proportion of 30% by volume of reinforcement in total [39]. Above studies indicate that reinforcement of high strength bamboo fiber in high volume fraction results in enhanced mechanical properties of bamboo composites and the same effect would result in hybridization also.

3.2 Thermal and Thermo-Mechanical Properties

The thermal degradation and thermal oxidation stability of bamboo and kenaf reinforced polyester and epoxy hybrid composites were investigated. Results indicated that bamboo composites exhibited better thermal stability than kenaf fiber reinforced composites. This could be attributed to the higher lignin and cellulose present in the bamboo fibers than in kenaf fibers. When such bamboo fibers with appreciable thermal properties was hybridized with any other natural fibers like kenaf, the resulting thermal stability of hybrid composites would also be better. Composites containing higher volume fraction of bamboo in the hybrids may also possess better thermal stability in case of hybrid composites [40]. The thermo-mechanical properties of alkali treated jute and bamboo cellulose reinforced hybrid low density polyethylene composites were assessed. Results indicated that hybrid composites containing jute and bamboo fibers in equal proportions exhibited better stability while the activation energy is also high for the hybrid composites. Due to the presence of surface roughness and pores on the treated fiber surfaces and its better matrix adhesion ability, treated fiber hybrid composites exhibited higher activation energy when compared with other composites [41].

The thermo-mechanical behaviour of bamboo and kenaf mat reinforced epoxy composites were assessed through thermogravimetric analysis. Results revealed that the coefficient of thermal expansion (CTE) was higher for the bamboo fiber reinforced composites due to its better dimensional stability. Hybridization effect of kenaf fibers reduced the overall CTE, though the kenaf mat is aligned in orientation. For the composites containing 50:50 kenaf and bamboo fibers exhibited low CTE and so less expansion [32, 42]. The thermal behaviour of bamboo kenaf based epoxy hybrid composites were assessed by weathering the samples and through soil burial. It was observed that the cellulose present in fibers, which has high thermal stability than hemicellulose, decomposed by means of depolymerisation due to the presence of larger crystalline chain of elements. This was predominant in kenaf fibers which had lower cellulose content [33, 43]. Figure 6 depicts the cole–cole plot for bamboo and kenaf reinforced epoxy composites representing the loss and storage modulus after thermal degradation.

As far as the hybrid composites were concerned, after weathering the thermal decomposition behaviour was reversed between them. Higher decomposition was noted for kenaf followed by hybrid composites while bamboo composites were thermally stable. Increase of various degradation temperatures like initial, mean and final temperatures were noticed when the content of bamboo fibers increased in hybrid composites [44, 45]. Soil burial of composites revealed that these composites displayed better thermal stability at higher temperatures than kenaf fiber reinforced composites and hybrid composites owing to the presence of less amount of hemicellulose in bamboo fibers. Moisture absorption of fibers from the soil increases when

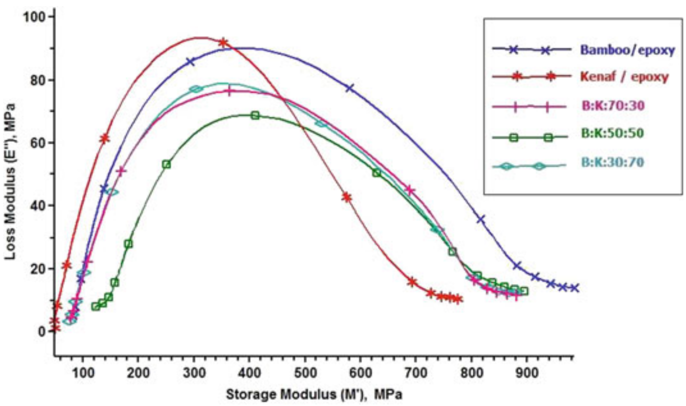

Fig. 6 Cole–Cole plot of bamboo kenaf reinforced epoxy hybrid composites [32]

the content of hemicellulose increases and hence the biodegradation also increases consequently decreasing the thermal stability [46, 47]. Alongside when the surface of the bamboo fibers were treated chemically to tailor the composites as per requirements, mechanical characteristics such as stiffness, hardness, surface reactivity and strength of the composites are enhanced [48, 49].

4 Conclusion

Since bamboo is a natural fiber, its environmental conservativeness is unquestionable and incomparable with other plants. Due to this reason, bamboo stands tall among other fibers in developing engineering and research applications along with various processing techniques for the bamboo fibers. Production of bamboo fiber composites and other bamboo based engineering materials and products in large scale is highly important in constructing many green structures purely based on bamboo composites. This in turn requires the aid of automation so that those large scale products are produced with ease. Bamboo fibers can also be employed in many non-technical applications like interior panels, mobile cases, shell based materials and storage containers when a heterotype fiber structure of bamboo fibers is made to evolve by processing methods like filament-wound processing, weave forming and vacuum molding. If the bamboo fibers are hybridized with any other natural fiber, the coupled property enhancements may render wide range of applications apart from the aforementioned ones. By using such bamboo fiber reinforced polymer composites, an eco-friendly atmosphere can be created and thus hazardous effects can be reduced.

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Bamboo: A Potential Natural Material for Bio-composites

Divakaran Divya, Suyambulingam Indran, and Kurki Nagaraja Bharath

Abstract The exploration and utilization of natural eco-friendly materials with high performance, biodegradability and renewability is a need of the hour, in the aspect of diminishing the detrimental effects of synthetic materials and thereby to pledge a sustainable tomorrow. The application of bamboo-based materials expanded largely worldwide due to its significant properties over conventional materials as biodegradable, recyclable, sustainable, luxurious, and environmentally friendly benefits that maintains the ecological standards. This chapter principally deals with the bamboo geographical distribution, bamboo production, anatomy, bamboo clum properties, bamboo fiber extraction techniques, fiber characterization and the adorability of bamboo fiber as a potential natural reinforcement material for bio-composites and its application in various sectors.

Keywords Natural fiber · Bamboo culm · Bamboo fiber · Bamboo reinforced composite · Fiber characterization

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1 Introduction

Bamboo is an evergreen perennial plant with two major parts as a woody culm and an underground rhizome. The plant belongs to the subfamily Bambusoideae of the family Poaceae [1, 2]. It is considered as grass with hollow and woody stem since even the large bamboo trees are often different from other woody trees in the aspect of lacking vascular cambium and apical meristem cells. Though bamboo is considered as a monocotyledonous plant that does not possess secondary growth in contrast to other woody dicotyledonous plants that possess secondary growth [3]. Bamboo is the fastest growing plant that probably grows up to 1 m per day and can grow over a height of 100 feet (30 m). The ecological features of bamboo are no replanting, no fertilizer, no pesticides, or skilled person needed to maintain its growth. Therefore, this plant is recognized as one of the most sustainable resources in the world.

The culm is the straight and hollow woody material found above the ground level, which holds stem, leaves, flowers, fruits, seeds, and branches. The stem is differentiated into alternate nodes and internodes with cylindrical forms, where the cells of the internodes are axially oriented to form hollow cavities inside the stem. In the nodes, cells are horizontally framed by a partition called the diaphragm, which is present between two adjacent internodes. This diaphragm serves as a transportation channel for water and nutrients inside the stem. The wall thickness and diameter of the culm increases from top to bottom while the internode length increases from bottom to middle and then reduces up to the top [2, 4]. The leaves of the bamboo are composed of a blade with a sheath and ligule.

The underground portion of bamboo is referred as rhizome. The function of the rhizome is to uptake and transfer of water and nutrients to support plant growth, along with developing new culms at rhizome nodes. Based on the branching pattern, the rhizome is categorized into two types pachymorph and leptomorph. The short, thick, curved rhizome clumps which bear apical buds and culms in tropical regions are regarded as pachymorph/sympodial rhizome or clumping bamboo. Whereas, leptomorph rhizome extends for a long distance in the soil and bear buds and roots from the specific nodes and internodes. These are distributed in temperate regions, are also known as a monopodial rhizome or running rhizome. The habitat seems like a scattered state when compared to the aggregate/clumsy nature of pachymorph rhizome [1, 5].

Bamboo is a potential eco-friendly material that possesses many applications in diverse fields. The promising features are availability, sustainability, high productivity, inexpensiveness, easy growing, quick maturity, non-hazardous nature, and good strength. Hence, bamboo has been successfully using in the construction, crafts, energy, and paper industries for the past few decades. Currently, the bamboo fibers are getting more attention from researchers due to its potentiality in making bamboo-based bio-composite products [6, 7]. Although, the ecological, environmental, industrial, and social benefits of bamboo, in comparison with other materials as plastic or concrete or steel or glass, make it a value-added natural material to support the green revolution.

2 Diversity of Bamboo Species

Bamboo plants are abundant in both tropical and subtropical/temperate areas of various continents in the world. In the subfamily Bambusoideae, around 100 genera of bamboo were identified around the world in which 1400 species are reported [2, 8, 9]. The worldwide geographical distribution and growth characteristics of various bamboo species are described in Fig. 1.

2.1 Geographical Distribution of Bamboo

Bamboo species have a wide geographical distribution over most of the continents, except Europe. The main significance of bamboo is its wide distribution and diversity due to adaptation over different climates, even from low altitude (sea level) to high altitude (hilltop/mountains). Generally, bamboo is habituated in both tropical and subtropical regions of 46° North to 47° South latitude [2, 8, 10]. Around the world, approximately 36 million ha (Hectare) of bamboo vegetation reported, of which major portion belongs to Asia, Africa, and Latin America [11].

Among these, 65% (24 million ha) are assorted to Asia, where 900 species are reported that contribute 80% species of the world. India and China are the major producers of Asia, having the bamboo resource of 11.4 million ha, 5.4 million ha, respectively. In India, approximately 145 species are reported in which *Bambusa bambos*, *B. blumeana*, *D. asper*, *D. giganteus*, *D. Strictus*, *P. heterocycla* and *P. bambusoides* possess high economic impact in Asia [12, 13].

Latin America pursues the second position by carrying 10 million hectares bamboo resources that contribute 28% of the world's production. The running bamboos are prominently found among the 270 species identified, where a significant species reported with large culm is *Guadua* spp. [2, 14]. The smallest bamboo resources have found in Africa in contrast to Asia and Latin America. Around

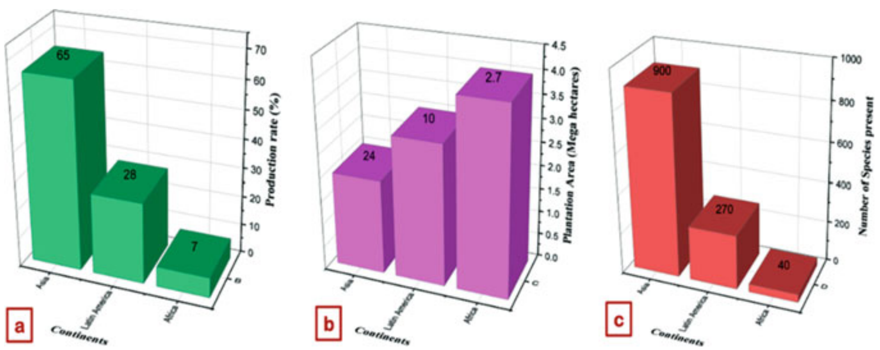

Fig. 1 Bamboo production from various continents with species and area distribution

2.7 million ha of plantations are stated that contributed up to 7% of total plantations of the world. There were 40 bamboo species identified in which *Arundinaria alpine*, *B. vulgaris,* and *Oxytenanthera abyssinica* are prominent [2]. Many countries are actively involved in the commercial cultivation of this plant, whereas China is the leading producer worldwide. Moreover, the countries of other continents are also contributing their role in cultivating bamboo for viable purposes [15].

2.2 Growth Diversity of Bamboo Species

The distribution and diversity of distinct species of bamboo are primarily dependent on the climatic condition and nutritional behavior of species. Most of the species prefer warm and humid conditions in both temperate and tropical zones. They are likely to grow on sandy loam to loamy clay soils with an average mean temperature of 20–30 °C per year. A species of India named *Dendrocalamus strictus* was found to survive in dry conditions [12]. In China, 60% of bamboo plantations are located at Fujian, Jianxi, Hunan, and Zhejiang. As well, the two species *Phyllostachys pubescens* and *Pseudosasa amabilis* are prominently cultivated in China for commercial applications. The indigenous *Chusquea* spp. are chiefly reported from Chile [11]. Although, two species of bamboo are mostly present in Africa are Savannah bamboo (*O. abyssinica*) and *Yushania alpina.*

The species of these genera are categorized under several tribes as per geographical distribution such as *Bambuseae* (woody tropical bamboo), *Arundinarieae* (temperate woody bamboos), *Olyreae* (herbaceous bamboos), *Bambusinea*, *Melocanninae*, *Guaduinae* and *Chusqueinae* [5, 12]. The famous Bamboo tribes and their distribution in various countries are tabulated in Table 1. The *Arundinareae, Bambusinea, Bambuseae,* and *Melocanninae* are the significant tribes existing in Asia. *Bambuseae,*

Table 1 Distribution of important bamboo tribes in different continents

Continents	Tribes	Country distribution
Asia	*Arundinarieae*	China
	Bambuseae	South Asia, China
	Bambusinea	South Asia, Indonesia, Myanmar, China, India, Thailand, Malaysia, Bangladesh, Japan, Nepal, Laos, Vietnam, Philippines
	Melocanninae	Myanmar, China, India, Thailand, Bangladesh, Sri Lanka
South America	*Bambuseae*	Mexico-Argentina, Colombia, Ecuador
	Guaduinae	South America
	Chusqueinae	South America
Africa	*Olyreae*	East Africa
	Bambusinea	East Africa, Ethiopia

Chusqueinae, and *Guaduinae* are the projecting tribes of South America, while *Olyreae* and *Bambusinea* are the prime tribes distributed in Africa.

Depend upon the habitat growing nature, and bamboos are also differentiated into running (monopodial) and clumping bamboos (sympodial), as described earlier. The species habituated in the temperate region are usually runners, for instance, *Phyllostachys* and *Pluoblastus*, while those located in the tropical zone are often clumpers, e.g., *Bambusa* [9]. There were few methods frequently employed for the primary production of bamboo, which are selective harvesting, post-harvest treatment, and bamboo propagation (seed propagation, vegetable propagation, cloning). Moreover, many countries are trying to increase the year-wise production of bamboo in account to improve cultivation to compete for the global market.

3 Bamboo Culm: Nature and Properties

All the plant parts extant over the soil level belongs to the bamboo culm. Generally, culm is composed of parenchyma (50%), fibers (40%), and conducting cells (10%). Bamboo culm encompasses specific properties compared to other woody plants, even as bamboo is a heterogeneous, anisotropic, lignocellulosic plant. The specificity in their anatomy and physicochemical properties shows its potentiality of using bamboo materials for various choices. The stiffness and lightweight nature of the bamboo-based materials mainly depend upon the density and chemical components present in the culm. Furthermore, the age of the culm determines the density and strength of the material, where older culm possesses more strength and stiffness. Likewise, there were notable differences reported in the cell wall components (cellulose, hemicellulose, lignin) of young and older culm, which is higher in matured stem especially form nodes to internodes [1, 16].

3.1 Anatomy of Bamboo Culm

The anatomy of the culm revealed that the outer layer of epidermal cells is shielded with a wax layer, and the inner surface is made up of sclerenchyma cells. The vascular bundles are sited from outer to the inner portion of the culm. The phloem and metaxylem vessels are extant towards the middle portion, are also embedded in parenchyma cells, which are capped with sclerenchyma sheath. The fibers are mainly distributed in the outer wall, followed by parenchyma cells, and conducting cells are frequently present towards the inner part. The fibers are comprised of sclerenchyma cells with thick walls and long, tapered ends. Fiber content is higher in the bottom and decreases from bottom to top with the increase of parenchyma cells.

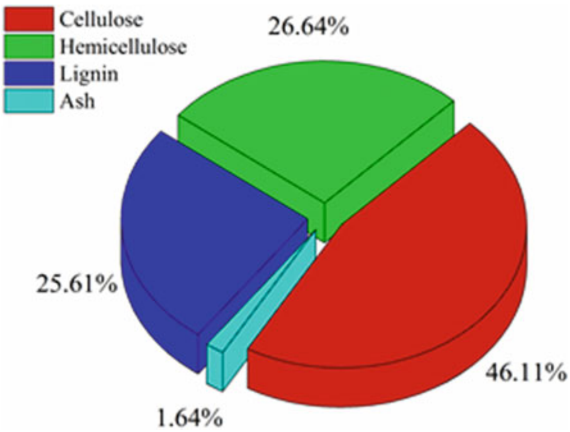

Fig. 2 Chemical constituents of bamboo culm

3.2 Chemical Constituents of Bamboo Culm

The major components of the bamboo culm are cellulose, hemicellulose, and lignin that contributes 90% of the whole material while the other 10% comprised of resins, tannins, waxes, and inorganic salts. The composition of hollo celluloses, lignin and ash vary from 51.8–79.9%, 21.4–28.5%, and 1.3–2.0% with respect to diversity in species [2]. However, in general, the bamboo culm partakes an average cellulose content of around 45%, lignin of 25%, hemicelluloses of 26%, and ash content of 1.6%, and it is represented in Fig. 2 [6, 12].

An allomorph type I_β crystalline cellulose domain is the characteristic feature of bamboo culm [17, 18]. The hemicelluloses units such as arabinoxylans/pentosan and β-glucan is present in the primary and secondary cell wall of the plant [19, 20]. The guaiacyl, syringyl, and hydroxyphenyl propane units are part of lignin residue present in the bamboo culms that increases with the age of the cell wall [21, 22]. Besides, bamboo is quite like hardwood species with the distinction of high ash content that is comprised of inorganic minerals silica, calcium, and potassium. The drawbacks of bamboo materials are associated with these constituents as high ash content leads to high wear of tools, high starch, fat, protein, and saccharide content encourage microbial degradation and low durability/biodeterioration due to high moisture and wax content.

3.3 Physical and Mechanical Properties of Bamboo Culm

The culm properties also determine the suitability of bamboo for bio-composites artifact and lightweight applications. The density of bamboo is quite high compared to hardwood species, is ranging from 0.4 to 0.9 g/cm^3. Nevertheless, the density is strongly influenced by the position in the culm, which increases from bottom to top as well as the inner part to the outer part of the culm. Interestingly, the dimensional shrinkage (radial and tangential) of the plant is less than that of other woody species, which is another characteristic that provides better dimensional stability preferred for bio-composite materials. The mechanical properties of the culm are allied with the microstructures, density, and moisture content enclosed with it. The significant characteristics such as good modulus, compression strength, and low shear strength than woody materials, which assists easy strip and strand preparation. In addition to that, bamboo species possess good modulus of rupture (52.4–122 MPa), modulus of elasticity (1700–6300 MPa), shear strength parallel to grain (4.0–13.7 MPa) and compression strength parallel to grain (24.0–69.0 MPa) [23–25].

4 Extraction, Characterization, and Properties of Bamboo Fibers

The strands associated with the vascular bundle of bamboo culm that embedded in the parenchyma cells are referred to as fibers. These fibers are composed of thick-walled, long sclerenchyma cells with tapered ends [26]. The fiber cells are arranged in a bundle that provides mechanical support to the bamboo culm. The fibers are present close to the outer surface (compactly) and the inner surface (sparingly) with uniform strength while different volumes [27, 28]. The fiber volume increases from bottom to top as proportional to density, which is higher in the outer wall of the culm [2]. There are specialized multilayered structures with different fibrils present in the longitudinal orientation in the fiber cell walls [29]. These layers exhibit in a poly lamellate structure with alternating broad and narrow lamellae, where high lignin content observed in broad lamellae. The fibers of bamboo are two to three times longer than hardwood fiber and appear like softwood tracheids. The length and width of the fiber are slightly varying from species to species with respect to the age of the plant. An earlier report showed that the bamboo species are characteristic with fiber length ranges from 1.04 to 2.88 mm, and diameter ranges from 1.0 to 24 μm [2]. The chemical composition of bamboo fiber possesses an impact on its physical, mechanical, and thermal properties. The proximate chemical components are cellulose (73.83%), hemicellulose (12.49%), lignin (10.15%), pectin (6.37%) and moisture (3.16%), is demonstrated in the Fig. 3. Bamboo fiber production is around 40,000 tons/year, which is increasing every year in a competitive manner all over the world. Although, the acceptability of bamboo fiber-based materials elevated in the field's construction, furniture, and instruments. Conversely, its eco-friendliness is attracted many scientists to process it for making goods with high environmental quality and sustainability. The other unique properties of bamboo fiber-based materials are anti-UV radiation, antibacterial, breathable, better moisture transmission, softer, easy drying, medical elements, etc. [30].

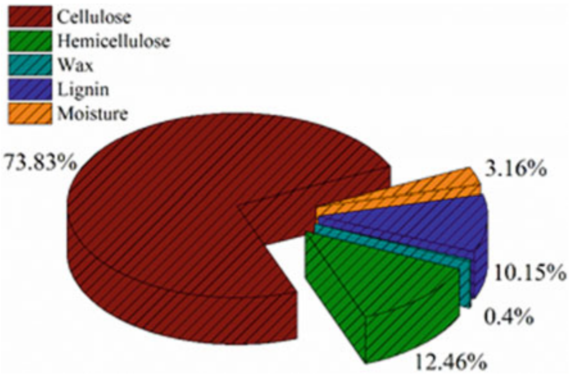

Fig. 3 Chemical composition of bamboo fiber

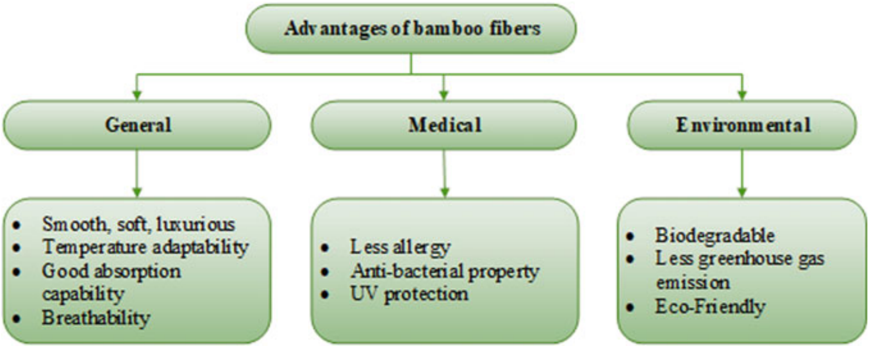

Fig. 4 Advantages of bamboo fibers

The durability or life span of the bamboo materials depends on the carbohydrate content present in it [31]. It is revealed that the carbohydrate content (glucose, fructose, and sucrose) of *Bambusa vulgaris* could be removed through the soaking technique [27]. However, these appealing characteristics such as UV-shielding, moisture-controlling, anti-bacterial, sustainability, and non-harmful properties of bamboo fiber authorize its potential to develop green bio-composites extensively for the time being [6]. The significance of bamboo fiber with respect to social, medical, and environmental aspects is depicted in Fig. 4.

4.1 Bamboo Fiber Extraction Methods

There are two kinds of fibers extracted from bamboo through a different process, are natural original bamboo fiber and bamboo pulp fiber (viscose fiber). Original bamboo fibers are directly extracted from the culm through physical and mechanical methods without any chemical mediated action. Bamboo pulp fibers are obtained through mechanical as well as chemical processing.

However, these two methods require an initial stage of the splitting of raw fiber strips from bamboo and followed by specific chemical or mechanical treatments that have to be done. In the mechanical processing, the material is initially crushed and treated with enzymes that lead to the formation of a spongy mass. Consequently, individual fibers are separated from the mesh through mechanical or manual combing. Chemical processing can be accomplished by alkali (NaOH) hydrolysis and carbon disulphide mediated multiphase bleaching. This method is used for industrial extraction of fiber due to the fact that less time requirement. Generally, fiber separation, boiling, enzyme fermentation, bleaching, acid/alkali treatment, oil soaking, and air drying are the typical methods employed for bamboo fiber extraction. Moreover, the primarily obtained fiber after the processes cutting, separation, boiling, and fermentation with enzymes are referred to as rough fiber. Along with that, further washing, bleaching, acid/alkali treatment, oil soaking, and air drying are required for obtaining fine bamboo fibers from rough fibers [13]. The extraction procedure of rough and fine bamboo fiber is summarized in Fig. 5.

The complete fiber extraction from bamboo is challenging due to the brightness of the lignin covered surface. Many researchers have been working on this aspect for many years to explore an advanced optimized extraction method to diminish the drawbacks of available techniques. Several physical, mechanical, and chemical extraction methods and their combinations are established for the past two decades. The mechanical methods such as cutting, blending, milling, crapping, sieving, combing, steam explosion, and scrapping were introduced, of which the steam explosion showed a good impact [32, 33]. Another mechanical method 'machining Center' (MC Program) designed by Hung et al. in 2019 was purely based on the cutting theory that used some measures as fiber length, shape, and diameter [34]. However, chemical methods were more efficient than physical/mechanical methods. Alkali extraction, acid neutralization, enzymatic fermentation, and oil soaking were the proximate chemical methods, of which alkali treatment was more efficient for fiber surface modification along with improving strength and interfacial interactions during composite preparation [35]. Moreover, rotting, semi-pilot scale extraction (acid and alkali), and decorticating/degumming were the combined chemical treatments specially designed for fine fiber extraction in later [36].

4.2 Characterization Methods for Bamboo Fiber

The physical, chemical, mechanical, thermal, and morphological features of the bamboo fiber can be studied to understand the basic properties and reinforcement efficiency for composite groundwork. The common methods used for the characterization of bamboo fibers are explained in detail in the following session.

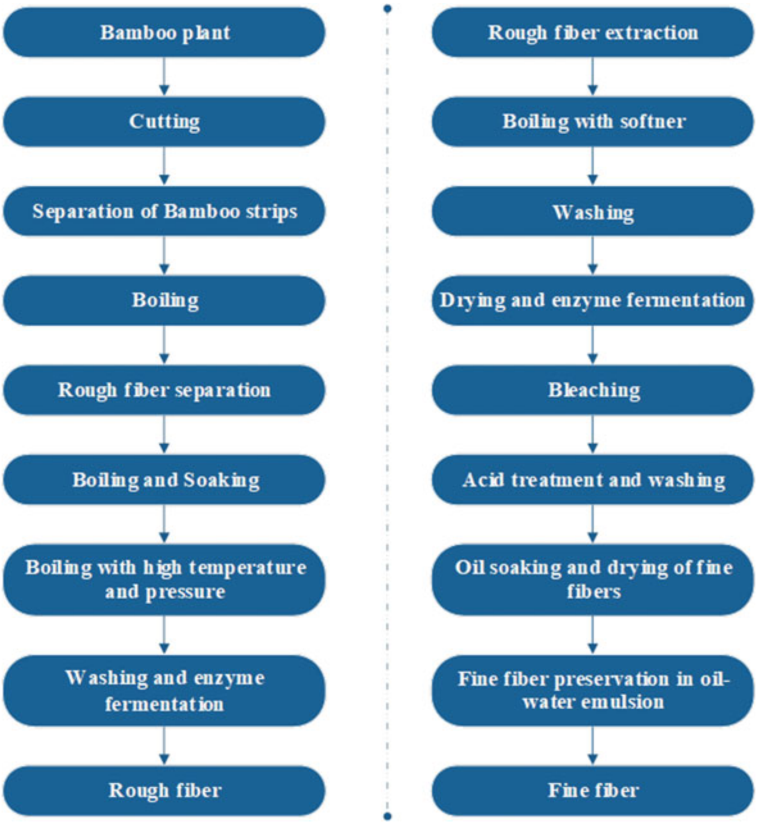

Fig. 5 Rough and fine bamboo fiber extraction method

4.3 Physical/Mechanical Characterization

The density and diameter are the two physical properties that determine the mechanical property of any fiber to a great extent. The physical properties such as the diameter and density of bamboo fiber can be analyzed through an ocular microscope, pyrometer, respectively. Fiber with low density and diameter are endorsed with good mechanical strength [37]. Likewise, the mechanical characteristics are allied with the crystallinity and tensile properties of the bamboo fiber. The crystallinity of the fiber can be tested through X-Ray diffraction analysis for the crystalline index (CI) and Crystalline Size (CS). The tensile properties as tensile strength, Young's modulus, and average tensile strain of bamboo fiber can be analyzed through a single fiber tensile test by the aid of a standard universal testing machine, where the samples with different gauge length can be experienced [38–40].

4.4 Chemical Characterization

The chemical composition of the bamboo fiber can be investigated as per the standard methods such as Kushner and Hoffer method (cellulose), TAPPI method (hemicelluloses), Klason method (lignin), Conrad method (wax) and statistical analysis (ash, moisture) [41–43]. The cellulose, hemicellulose, lignin, wax, ash, and moisture content of the fiber assists in understanding various constituents present in it along with exploring the requirement of further treatment to improve the viability of fiber. The other chemical analyses like FT-IR (Fourier transform infrared) spectroscopy, NMR (Nuclear magnetic resonance) spectroscopy, and EDX (Energy-dispersive X-ray) diffraction analysis can be employed to establish the specific functional groups, carbon and other elemental composition present in the bamboo fiber [42, 44–46].

4.5 Thermal Characterization

The sophisticated thermal characterization methods to analyze the thermal stability of fibers are TGA (thermogravimetric analysis), DSC (Differential scanning calorimetry), and DMA (Dynamic mechanical analysis). Hence, the degradation temperature of various constituents of bamboo fiber can be assigned through these methods. The thermal stability can be detected according to the degradation of crystalline cellulose. The maximum degradation temperature of the bamboo fiber can be recognized through evaluating absolute degradation temperature. Fibers partake a degradation temperature higher than that of reinforcement processing temperature have a high economic impact [39, 40, 47].

4.6 Morphological Characterization

The surface morphological features of bamboo fiber can be found by SEM (Scanning electron microscopy) and AFM (Atomic force microscopy) analysis. The SEM analysis assists in differentiating the roughness/smoothness of the surface, qualitatively. While AFM analysis quantitatively determines the average roughness and other roughness parameters of the fiber surface. The fibers contain rough surface and porous nature with less waxy inclusions showed good binding affinity towards the matrix during reinforcement [48, 49].

4.7 Properties of Bamboo Fibers

The commercialization of natural fibers primarily depends on their easy availability, high specific mechanical properties, low cost, low density, high roughness, less corrosive nature, and eco-friendliness. Even though, the interfacial interaction properties and tribology properties have to be investigated to explore the complete benefits of natural bamboo fiber for its extensive utilization in the future [4, 26, 50]. A comparative analysis of specific properties of bamboo fiber with other natural and commercial fibers are important to signify its adaptableness for reinforcement purposes and composite applications. Table 2 shows the characteristics of typical bamboo fiber in comparison with other well-established fibers. Bamboo fibers possess a low density of 910 kg/m^3 and an average diameter of 240–330 μm, which shows its adaptability for lightweight applications. Conversely, high cellulose content (73.83%), low lignin content (10.15%), high tensile strength (503 MPa), and large crystalline size are the additional significant features of bamboo fiber over other fibers listed. Good thermal stability is obligatory for using fibers for high-temperature applications. Besides that, the thermal degradation temperature is a factor that determines processing temperature for composite preparation along with retaining fiber properties. Moreover, the good thermal stability of 245 °C also revealed the suitability of natural bamboo fiber for reinforcement purposes [13].

5 Bamboo Based Composites

The cost effectiveness, less weight, high strength to weight ratio and harmless nature of bamboo fibers are the most nice-looking properties of this material which makes composite investigators to work in the direction of making bamboo fiber reinforced composites. Consequently, bamboo fiber-based composites have probable use in automotive industry, can replace the non-renewable, harmful synthetic fibers. The extensive research from all the engineering, biotechnological, textile industry, etc. are frustrating to use these bamboo fibers in healthier way in composite industry.

5.1 Preparation of Bamboo Composites

There were four different techniques employed for bamboo-fiber reinforced composite grounding. They are solution processing film, melt processing film, in-situ polymerization film, and hand lay-up or laminate method. In the old method, the extracted bamboo fibers were dispersed in a solvent followed by mixed with a polymer solution by mechanical means. The resulted solvent then vaporized at high temperatures to obtain polymer composites. The melt processing method accomplished by direct mixing of extracted fiber and melted polymer matrix was formed

Table 2 Properties of bamboo fiber in comparison with other available fibers

Fiber	Physical properties					Chemical properties						Mechanical properties			Thermal properties		Reference
	Diameter	Density	CI	CS	Microfibril angle	Cellulose	Hemi celluloses	Lignin	Moisture Content	Wax	Ash	Tensile strength	Young's modulus	Elongation at break	Thermal stability	Max. degradation temperature	
	(μm)	(Kg/m^3)	(%)	(nm)	(θ)	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)	(MPa)	(GPa)	(%)	(°C)	(°C)	
Bamboo	**240–330**	**910**	**40-58**	**11.5–18.7–**	–	**73.83**	**12.46**	**10.15**	**3.16**	**0.4**	**3.1**	**503**	**35.91**	**1.4**	**245**	**255**	[13, 51, 52]
Aerial roots of banyan tree	0.09–0.14	1234	72.47	6.28	10.88 ± 1.198	67.32	13.46	15.62	10.21	0.81	3.96	19.37 ± 7.72	1.8 ± 0.40	1.8 ± 0.40	230	358	[53]
Althaea officinalis L	156–194	1180	68	2.4	–	44.6	13.5	2.7	–	–	2.3	415.2	65.4	3.9	220	344	[54]
Arundo donax	–	1168	–	–	6.85 ± 1.23	43.2	20.5	17.2–	–	–	1.9	248	9.4	3.24	275	320	[55]
Caster fibre	0.06–0.13	1181	48.88	4.8	–	65.5	–	5.56	10.17	0.87	4.86	356.3	34.931 ± 0.45	1.02 ± 0.053	–	–	[53]
Cissus quadrangularis root	610–725	1510	56.6	7.04	5.89 ± 0.27	77.17	11.02	10.45	7.3	0.14	–	1857–5330	68–203	3.57–8.37	230	328.9	[40]
Cissus quadrangularis stem	770–870	1220	47.15	3.91	4.95 ± 0.32	82.73	7.96	11.27	6.6	0.18	–	2300–5479	56–234	3.75–11.14	270	342.1	[56]
Coccinia grandis stem	543–621	1517.5	46.09	1.91	–	63.22	–	24.42	9.14	0.32	–	424.242	26.515	16	105	320	[57]
Coccinia grandis	27.33	1243	52.17	13.38	13.25 ± 0.664	62.35	13.42	15.61	5.6	0.79	4.388	273 ± 27.74	10.17 ± 1.261	2.703 ± 0.2736	213.4	351.6	[43]
Cyperus pangorei	–	1102	41	–	–	68.5	–	17.88	9.19	0.17	3.56	196 ± 56	11.6 ± 2.6	1.69	221	324	[58]
Dichrostachys Cinerea	–	1240	57.82	–	–	72.4	13.08	16.89	9.82	0.57	3.97	873 ± 14	–	–	226	495.3	[59]
Dracaena reflexa	176.2	790	57.32	19.01	8.5 to 11.27	70.32	11.02	11.35	5.19	0.23	6.23	829.6	46.37	2.95	232.32	348.78	[60]
Ferula communis	–	–	48	1.6	–	53.3	8.5	1.4	–	–	–	475.6 ± 15.7	52.7 ± 3.7	4.2 ± 0.2	200	313.5	[54]
Furcraea foetida	12.8	778	52.6	28.36	–	68.35	11.46	12.32	5.43	0.24	6.53	623.52 ± 45	6.52 ± 1.9	10.32 ± 1.6	–	320.5	[61]
Heteropogon contortus	–	602	54.1	–	–	64.87	19.34	13.56	7.4	0.22	-	476 ± 11.6	48 ± 2.8	1.63 ± 0.06	220	337.7	[62]
Juncus effusus	3300	385	43	–	–	40.99	27.84	18.54	–	–	7.3	31 ± 8	0.7 ± 0.1	–	–	–	[63]

(continued)

Table 2 (continued)

Fiber	Physical properties					Chemical properties						Mechanical properties			Thermal properties		Reference
	Diameter	Density	CI	CS	Microfibril angle	Cellulose	Hemi celluloses	Lignin	Moisture Content	Wax	Ash	Tensile strength	Young's modulus	Elongation at break	Thermal stability	Max. degradation temperature	
	(μm)	(Kg/m^3)	(%)	(nm)	(θ)	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)	(MPa)	(GPa)	(%)	(°C)	(°C)	
Jute	26	1300	65.8	29.25	16.9	58–63	20–24	12–15	10.99	0.5	–	400–773	10–30	1.5–1.8	–	–	[64]
Passiflora foetida	101 ± 40	1328	0.6736	4.23	7.46–12.18	77.9	12.63	10.47	9.54	0.35	0.94	248–942	11–48	1.38-4.67	320	383	[65]
Pineapple leave fibre	20–80	1440	58.6	–	14	81.27	12.31	3.46	11.8	3.2–4.2	0.9–4.3	413–1627	34.5–82.5	0.8-1	–	–	[66]
Prosopis juliflora bark	20	580	46	15	10.64 ± 0.45	61.65	16.14	17.11	9.48	0.61	5.2	558 ± 13.4	–	1.77 ± 0.04	217	331.1	[67]
Red banana peduncle	150–250	990	62.1	12.1	12.64 ± 0.45	72.9	11.01	15.99	9.36	0.32	2.79	440 ± 13.4	12.41 ± 5	1.57 ± 0.04	120	353	[68]
Ricinus communis plant	60–130	1180	48.88	4.8		65.5		5.56	10.17	0.87	4.89	356 ± 23.87	34.931 ± 0.45	1.02 ± 0.053	225	326	[69]
Root of Ficus religiosa tree	25.62	1246	42.92	5.18	–	55.58	13.86	10.13	9.33	0.72	4.86	433.32 ± 44	5.42 ± 2.6	8.74 ± 1.8	325	400	[39]
Saharan Aloevera	80.61	1325.1	56.5	5.72	11.1	60.2	14.2	13.7	7.6	1.5	–	805.5	42.29	2.39	225	350	[70]
Sansevieria cylindrica	6–30	915	60	86	–	79.7	10.13	3.8	6.08	0.09	–	673.12 ± 51	6.72 ± 1.9	10.04 ± 1.5	–	–	[71]
Sansevieria ehrenbergii	20–250	887	52.27	–	–	80	11.25	7.8	10.55	0.45	0.6	50–585	1.5–7.67	2.8–21.7	223.85	333.02	[72]
Sida cordifolia	–	1330	56.92	18	–	69.52	17.63	18.02	8.51	0.42	2.62	703 ± 23	42.84 ± 2	2.89 ± 0.24	–	338.2	[73]
Sida rhombifolia	–	1320.7	56.6	2.75	7.3	75.09	15.43	7.48	12.02	0.49	4.07	673 ± 14	–	–	250	433.3	[74]
Tamarindus Indica L	564–789	1020–1270	55	5.73	–	72.84	11	15.38	6.35	0.2	0.51	1137–1360	11.23–20.72	6.56– 10.12	238	351.4	[47]
Thespesia populnea	87–256	1412	48.17	3.576	13.94 ± 1.21	70.2	12.64	16.34	10.83	0.76	1.8	557.82 ± 56.29	20.57 ± 4.46	2.80 ± 0.56	245.4	323.76	[75]

(continued)

Table 2 (continued)

Fiber	Physical properties					Chemical properties						Mechanical properties			Thermal properties		Reference
	Diameter	Density	CI	CS	Microfibril angle	Cellulose	Hemi celluloses	Lignin	Moisture Content	Wax	Ash	Tensile strength	Young's modulus	Elongation at break	Thermal stability	Max. degradation temperature	
	(µm)	(Kg/m^3)	(%)	(nm)	(θ)	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)	(MPa)	(GPa)	(%)	(°C)	(°C)	
Tridax procumbens	233.1 ± 9.9	1.16 ± 0.12	34.46	25.04	13.4 ± 0.64	32	6.8	3	11.2	0.71		25.75	0.94 ± 0.09	2.77 ± 0.27	195	250–350	[76]

through processing with extruder, injector, mold, and roller by applying pressure. The third method is related to in-situ graft copolymerization, is one of the surface modification technique with chemicals such as methyl methacrylate, polyethylene glycol (PEG), methyl ether methacrylate, methacrylamide, etc. [77, 78]. Therefore, in-situ polymerization of bamboo fiber and polymer increases interfacial adhesion, and hence it is considered as an efficient method to obtain a competent composite. The normal method is a hand-lay-up technique, where the fibers are cut into the desired length and placed over a mold, and compounding can be done by hot pressing by applying pressure [15, 56].

5.2 Eco-composites from Bamboo

The composites with good environmental quality and ecological significances are termed as eco-composites. These can be manufactured by natural fibers or natural polymers or polymer matrices. The acceptance of eco-composites increasing day by day due to the sustainability and environmentally friendly concerns of synthetic fibers. Although, many eco-bamboo fiber composites are introduced over the past few decades by reinforcing various polymer matrices. The polymers as polyester, epoxy, phenolic resin, polypropylene, and polyvinyl chloride/polystyrene-based bamboo fiber-reinforced composites are introduced successfully in various disciplines [13]. The search for apposite polymer matrix to overcome the brittle nature of the bamboo fiber has been continuing with the aim to improve the properties of fiber-polymer reinforced composites. Few investigators worked on polyester matrices and developed composite material with bamboo fiber that possesses high strength, light-weight, and low fracture behavior [79–81]. Likewise, another study reported that NaOH treated bamboo fiber-polyester composites showed extensive tensile, flexural strength, and reduced water uptake property [78].

The epoxy-bamboo fiber composite had shown excellent wear resistance and improved frictional performance. Although the alkali and silane derivatives treated fiber with epoxy polymer also resulted in less water absorption and improved fiber-matrix adhesion [82]. Improved wettability, interfacial bonding, mechanical and thermal properties were obtained by using phenolic (novalac) resin in bamboo fiber composites [35]. The novalac-bamboo fiber showed enhanced interfacial adhesion and thermal stability when the fiber treated with alkali before composite fabrication [83]. Another interesting matrix intends for composite fabrication with bamboo fiber was polypropylene. Bamboo fiber strips-polypropylene composites provided excellent flexural property in the extent to replace synthetic glass fiber [13]. Moreover, matrix anhydride mediated modification of polypropylene matrix for composite fabrication also provided good mechanical properties instead of bamboo fiber modification [84]. The interface adhesion of the fiber could be increased while using polyvinyl chloride (PVC) as the matrix along with coupling agents, which enhanced the morphological and mechanical properties of the composites as reported by Nystrom et al. in 2007 [85]. On the other hand, polystyrene and polyurethanes coated alkali-treated fiber exhibited good interfacial bonding that also resulted in high tensile strength and chemical resistance [86].

6 Application of Bamboo Fiber-Polymer Composite Structures

The bamboo fiber-polymer composites possess potential applications in various sectors, including housing, furniture, packaging, transport, etc. Treated bamboo fiber-reinforced composites own better dimensional stability, longevity, corrosion resistance, low maintenance, non-toxic and fire-retardant properties. Even though such composites are highly employed for indoor and outdoor applications by replacing other traditional or synthetic materials [13]. Based on the bamboo elements used for manufacturing, there are different kinds of biocomposites available commercially. They are categorized as.

- Bamboo strip and flattened culm sheets products
- Bamboo strand products
- Bamboo flake/particle products
- Bamboo fiber-based products

The bamboo strip-based products are made up of gluing and pressing of multi-layered bamboo strip boards. The efficiency of bamboo strips can be enhanced by subjecting culm strips to the softening process. Likewise, flattened culm sheets are established later through bamboo flattening by employing the techniques high-frequency dielectric heating and hot linseed oil immersion. There were four commercially important products are developed from bamboo strips/flattened culms as mat boards, ply bamboo, zephyr boards, and glued laminated mambo. The composites obtained from bamboo strands that glued together to form board or lumber have high economic importance for indoor and outdoor applications. These include oriented strand board, parallel strand lumber, and oriented strand lumber. The particle bio-composites are composed of thin, small, or irregular bamboo culms or from residues. Bamboo particleboard panels and particle plastic composites are examples of the particle-based process, which possess good quality and competitive characteristics comparable with bamboo fiber-based composites. Even though bamboo fiber-reinforced composites partake promising properties and appearance in comparison with other synthetic materials. The commonly available forms of bamboo-fiber products are medium density fiberboards, high-density fiberboards, and bamboo paper. Medium-density boards are formed by blending fibers with synthetic resigns through hot pressing. While high-density fiberboards are made up of wet refined bamboo fibers through hot pressing under high pressure and temperature. Usually, high-density fiberboards are often stronger and denser than medium density boards [2]. A framework of bamboo elements used for various bio-composites production is presented in Fig. 6.

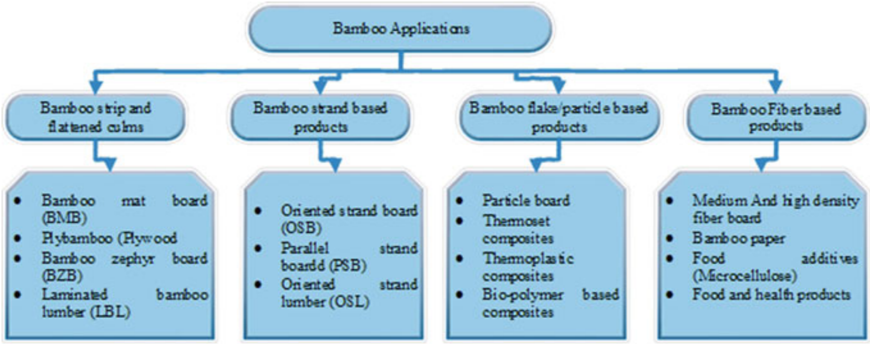

Fig. 6 Application of bamboo fiber-reinforced composites

Nowadays, bamboo composite fencing, deck tiles, railing, dustbins, outdoor furniture, decking accessories, etc. are commercially available in the market for structural applications. Their renewability, recyclability, and less polluting characteristics highly splendid to society. Moreover, the acceptance of bamboo composites in automotive industries seeks a breakthrough for its extensive uses in lightweight applications. In the automobile industry, auto-body is replaced with polymer bamboo fiber-based composited due to the features of high efficiency, light-weight, cost-effective along with defending eco-friendly government regulations. Especially, electric vehicles mainly choose fiber-based composites to increase fuel efficiency. Since the body weight can be reduced up to 70% in the course to replace traditional steel material [44].

Bamboo composites are extensively used for the fabrication in sports goods with respect to its softness, moisture permeability, thermal property, light-weight nature, and waterproof surface [4]. Water sports decks are successfully intended for sports applications. Usually, sports apparel such as surfing boards, baseballs, polo balls, etc. are produced from bamboo fiber-reinforced composites. These multilayered boards are composed of epoxy polymer and bamboo fibers with specific characteristics over bamboo glass boards. Surfing boards are light-weighted and possess waterproof surfaces commonly used for water surfing activities. There are well-known applications of bamboo composites in construction and building industries, as reported earlier [2, 3, 12, 14, 84, 87]. Bamboo bio-composites are widely used as structural interior design components in the building. Also, it can be used as concrete reinforcement for housing construction due to its low moisture rate and light-weight, eco-friendly nature in order to support the government policy of using sustainable materials.

Moreover, bamboo high-density fiberboards (BHDF) and medium density fiberboards (BMDF) were developed extensively from the fiber-polymer composites for commercial purposes [4, 12]. As well, bio-composites based flexible, thin paper sheets were prepared from bamboo cellulose finer pulp. It is also introduced thin sheets for printing, packaging, and cleaning purposes [79]. Another invention on binderless boards through hot compression of bamboo powder followed by steam explosion was applicable for indoor uses. The plastic composites produced with bamboo fiber by using polymer materials such as polypropylene, polyethylene, and polyester are of high interest in the preparation of interior car parts. Conversely, bamboo mineral composites produced by combining fibers with mineral binders are used in bamboo cement composites as construction material, which has significance over steel-reinforced concrete slabs and columns [25, 88]. Though, bamboo fiber could be substituted as lightweight construction materials that resist earthquakes to a large extent. Bamboo fiber has certain applications in food industries because of micro cellulose because of its water-binding and texturing properties. Additionally, the exploration of bamboo fibers in bakery, dairy, meat and fish products, beverages, sauces, and dressings was also experienced. Bamboo stabilizers are used as a food stabilizer, preservative of taste and flavor, along with using as a calorific additive to avoid moisture loss. However, further advancements are required to explore the potential of bamboo fiber and its composites to all sectors with the utilization of probable techniques to expand its utilization by socio-economic and environmental means [89, 90].

7 Conclusion and Future Perspective

The current environmental policy looks forward to developing eco-friendly, cost-effective natural materials from sustainable sources instead of harmful, non-biodegradable, expensive synthetic materials. Bamboo is a promising perennial plant distributed all over the world that possesses specific growth characteristics and common features required for the production of natural materials. The promising physico-chemical and mechanical properties of bamboo fiber shows the potentiality of using it in polymer composites, as an alternative to traditional materials. Certain bio-composites are developed from bamboo fibers and polymers that resulted high impact in diverse sectors. The initial adaptability of bamboo-based materials or reinforced composites points towards its extensive application in the future with advanced techniques for the fabrication of well-defined, engineered products through the green revolution.

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Fundamental Concepts of Bamboo: Classifications, Properties and Applications

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Abstract With the development up to 75 cm in a solitary day, Bamboo has enrolled its name as quickest developing plants on the planet. It's being utilized in various areas in various works and furthermore being utilized for building materials and so forth at a bigger scope. In the event that we will contrast Bamboo and steel, at that point can see that Bamboo is a lot less expensive than steel even Bamboo properties like high elastic, adaptability, light weight, sturdiness is obviously superior to the next structure materials. Right around 500 unique types of bamboo has found in our universe even in some cases inside several subspecies can check their quality. One of the heavenly bamboo "Guadia angustofolia" found in Colombia which gives a higher caliber of timber straight and solid. Two subspecies of bamboo known as 'guadua

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castilla' and 'guadua mecana' exist in nature which height comes to up to 25 m and a breadth up to 18 cm. Presently in current situation there are a significant number of businesses are looking forward as an elective choice in type of Bamboo due to having properties like reasonable, bottomless, minimal effort and great explicit quality. In this current research scarcely any audits and explores on the warm, mechanical and some different properties like high malleable, light weight, durability and so forth have been appeared. The audits incorporate how the specialists set up their investigations, the bamboo species utilized and the outcomes got.

Keywords Frames of bamboo · Green buildings · Power bamboo · Qualification tests · Bamboo power · Bamboo · Mechanical properties · Physical properties · Green building · Sustainable development · Compression test

1 Introduction

Among the grass family 'Poaceae' and the subfamily 'Bambusoideae', Bamboos are pine eternal blooming trees. The term 'bamboo' derives from the Dutch or Portuguese languages that likely appropriated it from Malay. Bamboo materialis a standard fabric built up from the pulp of the bamboo grass, the bamboo filament is subsequently built up through mashing the bamboo grass till it discrete into thin themes of filament, which is afterward revolved and washed for working into cloth. Bamboo filament is alike to the mushiness of silk. Because of its flexible effects, bamboo filaments are utilized mostly in fabric industries for making bath robes, attires and towels. Because of its hygienic creation, this is utilized for preparing sanitary napkins, bandages, nurse wears and masks. In contrast with the past, many significant industries related to aeronautics, furnishing and construction, sought for composite materials due to their overwhelming advantages such as lightweight and its durability. For example, aircraft manufacturers have increased the usage of composite materials in manufacturing aircraft. However, environmental concern is one of the downside of using composite materials. In view of most conventional composites are non-renewable and non-recyclable, pollution complication has become an issue when conventional composites are used. Natural fiber compounds have taken the contemplation of numerous industries as another substances, as their current emphasis on environmental- friendliness and sustainability.

A grass which can enlarge until 25 m within six months is known as Bamboo [1]. Every Culm appears from the earth surface at its last diameter (i.e. its girth does not enlarge throughout its existence), narrowing as it enhances in height, and extending in y-direction by cell-division "telescopically" in the middle of the intersections (i.e., the space in the middle of intersections enhances as this extends). One time completely extended, culms constantly take three to five years to grown-up to brimful power, through which they occurrence lignifications and silification. Subsequently an interval of five to six years, the culms' power starts to worsen. Internationally there are about hundred reputed "woody" herbs favorable for establishment. Clumps (Combine

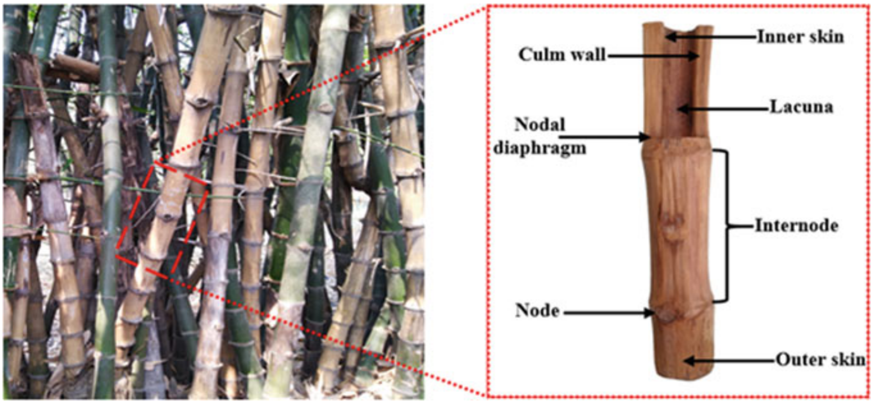

Fig. 1 General structure of a bamboo culm

of culms enlarging at a time) of the big woody herbs usually outstretch highest creation afterward around seven years and can continue systematic supplying of about 20–25% during their high-yielding lifecycle. The stem, or Culm, is fragmented through intersections, the straps at systematic gaps. The intersection evident as a shield to the inside of the Culm, that assists to avert augmenting of the partitions. The area in the middle of intersections is termed as the internodes, as represented in Fig. 1; the intermodal placing differs across the Culm and in the middle of strains. Inside the internodes, vascular bundles and cellulose fibers rush aligned to the span of the Culm [2, 3], while at the intersections they engrossment, accompanied by few of them interchanging into the nodal shield [1].

2 Historical Background of Bamboo

In its standard form, bamboo as a fabrication substance is conventionally connected accompanied by the arts of the South Pacific, South Asia, Central, South America and East Asia. In India and China, bamboo was utilized to setback effortless interruption bridges, either by preparing cables of twisting or split bamboo entire culms of adequately flexible bamboo jointly. Such kind of bridge near to Qian-Xian is mentioned in communicating dating back to 960 AD and may have nestle from far back as the third century BC, due mainly to steady preservation. Bamboo has also long been utilized as framing; the exercise has been prohibited in China for buildings above the six stories, however is motionless in steady utilization for superstructures in Hong Kong [4]. In Philippines, the nipa shed is an impartially classic e.g. of the maximum fundamental kind of housing where bamboo is utilized; the partitions are fracture and woven bamboo, and bamboo begins and poles may be utilized as its support. In Japanese architecture, bamboo is utilized essentially as a supplement oridentifying element in buildings such as fencing, fountains grates, and gutters, mostly because of the ready generous of standard timber [5]. Some regions in India, bamboo is being utilized for drying cloths indoors, both as rod elevated up close to the celling to put cloths on, and as a stick welded accompanied by acquired expert skill to hoist, spread, and to take down the cloths when dry. It is furthermore frequently utilized to construct steps i.e., aside from their standard performance, are too utilized for supporting bodies in burials in Maharashtra, the bamboo copses and jungles are known as veluvana, the title velu for bamboo is more appropriately from Sanskrit, while vana defines jungle. Moreover, bamboo is further utilized to generate bars for saffron-colored, Indian flags, which can be noticed that flying throughout India. Bamboo has created an important fragment of the raising heritage in Central and South America [1]. Vernacular creates of building such as bahareque have established that utilize bamboo in extremely churning regions. When arranged and in superior circumstances, these have been seen to execute curiously best during earthquakes [6].

3 Origin of Bamboo

Bamboos expand in the subtropical and tropical areas of Latin America, Asia and Africa, enlarging as faraway north as the southern United States or Central China and as far away south as Patagonia. They too enlarge in the regions of Northern America. The record of Chinese people transplanting and utilizing bamboo can be followed backward, 7000 years. As quick as Shang Dynasty (sixteenth-eleventh century B.C.), bamboo was earlier utilized in different feature of earliest Chinese people's day today lives. It was utilized for clothing, food, housing, musical instruments, transportation and also weapons. In the opinion of Patrick Malcolm, gold colored bamboo was the 1st of the Phyllostachys bamboo varieties to be instigated within the country United States, in 1882. In Alabama, where Bamboo was to be first utilized as rapid enlarging for barrier of wind, it was transplanted through southern tobacco countryman. A record of few repeatedly utilized systematic pieces across the globe shown in Table 1.

3.1 Suitable Structural Species

The subsequent attributes of bamboo pieces that have conventionally been utilized for fabrication are as follows:

- Enlarge regionally in prosperity
- Powerful than other regional pieces
- Huge size (50–200 mm in diameter)
- Enlarge comparatively linear or vertical
- Grown-up rapidly (3–5 years)

Table 1 Represents a record of few repeatedly utilized systematic pieces across the globe [7–9]

Scientific name (local name)	Areas found	Diameter (mm)	Solid/hollow
Guadua angustofolia Knuth	South America	120–160	Hollow
Dendrocalamusstrictus (Calcutta)	Asia	25–80	Hollow
Bambusa vulgaris	Africa, Asia, South America	80–150	Hollow
Phyllostachys edulis (Moso)	Asia	120–180	Hollow
Dendrocalamusasper (Petung)	Asia, South America	80–200	Hollow
Bambusablumeana (Spiny/Thorny Bamboo)	Asia, Asia–Pacific	60–150	Hollow
Gigantochloaapus	Asia	40–100	Hollow

- Somewhat additional impenetrable to insects and fungi (Beneath liveliness content)
- Smaller permissible to breaking.

3.2 Behavior in Earthquakes

There is a usual misinterpretation that the substance bamboo is anyhow ‘miraculously’ superior in earth tremors. As a matter of fact a discrete characteristic this holds various brittle failure manners that could influence its churning execution. Constructions of bamboo have historically executed well in earth tremors firstly due to their insubstantial creation (elevated power-to-heaviness proportion), and subordinately due to their potential to suck up vitality at relations, mainly when utilizing pins. It has been noticed afterwards earth tremors in jargon constructions such as Bahareque [10], which usually utilizes pinned relations. The workable creation of few conventional bamboo buildings may too be approvable in earth tremors, however it is not an attribute which can be effortlessly utilized in current buildings that tend to be weightier, have lesser motion liberalities and need a substantial assurance of power to earth tremors than conventional constructions. Present bamboo formations normally need elevated power gobbled relations accompanied by plaster that are regrettably comparatively hard. But, while satisfactory operation tremorous blueprint ideas are registered in coexistence accompanied by additional regionally ductile relations like pins, greater earth tremor resistance and altogether construction ductility can be attained [11].

3.3 Fire Considerations

Bamboo acts as a same path to wood in flak, which burns at a moderate and probable rate and is additionally a bad conductor of hotness; hence the bamboo in back of the blackened coating persists practically safe. However, restricted flak experiments have been performed [12], this is feasible to presume burning rates same as those for wood (e.g. 0.6 mm/min), and due to the culm partitions are so narrow this is practicable to judge that afterward blazing for just a some minutes the narrow partitions will begin to misplace power quickly. It proves that an optically displayed bamboo construction would hardly be favorable for positions where there is no flak resistivity demand like roofs and probably the partitions of single-storey constructions. It has rarely been utilized for two-storey dwellings [13], however hardly in positions where flak rules are not meticulously related or where the bamboo is sufficiently defended through e.g. cement furnish.

3.4 Specification of Bamboo

When identifying bamboo, this is supreme to confirm that it appears from a supportable origin and is gathered, obtained and optically categorized through an esteemed and experienced company. Standard norm should be incorporated in an identification shows in Fig. 2.

4 Classification of Bamboo

Bamboos have a special inspection and their excellent fruitful actions are honestly engrossing to examine. Bamboo is a segment of the accurate grassland ancestry, and builds up the huge and most fruitful organ of grassland ancestry. Over 1000 pieces and 91 genera of bamboo exist all-round the globe and they enlarge in a broad area of weather and topographical circumstances. Bamboo has the capability to enlarge in the regions, which extends from the Sub-sarahana shun of Africa, to the snowy mountain territory of the Himalayas. This has a lengthy and brief record and is one of the greatest flexible plants in the globe. The majority of the pieces are local to the equilaterals of Asia, even though some variation is local to the United States, Arundhenaria gignatia. The dimensions of bamboo pieces differ rapidly. The little variations enlarge to an elevation of 11 in., when massive wood bamboo can outstretch elevations of over 100 ft. But, few of them have been represented under the succeeding categorization sector shows in Fig. 3.

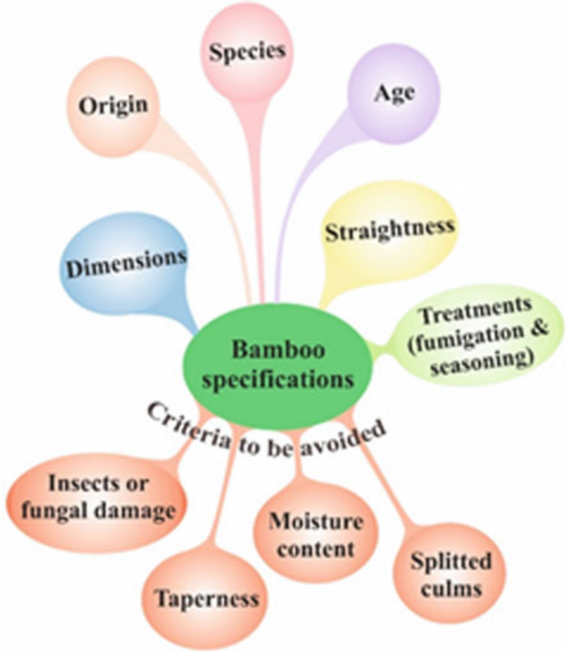

Fig. 2 Specification of bamboo

Fig. 3 Classification of bamboo [14–19]

4.1 Fargesia

Fargesia is a subfamily of blooming herbs in the grassland ancestry [20]. These bamboos are origin firstly to China, accompanied by some pieces in Vietnam and in eastern Himalayas [21]. Few pieces are cultured as decorative, accompanied by general title introducing sunshade bamboo and jet bamboo [22]. These are average to few elevation clustering bamboos, origin to alpine conifer jungles of East Asia, from China south to Vietnam and west to the eastern slopes of Himalayas. These are called in Cines as Jian Zhu, defining 'arrow bamboo'. The technological title was stated in privilege of the French promoter and layman botanist Paul Guillaume Farges (1844–1912). Fargesia are few of the globe's robust bamboos, however, they do not escalate strongly. General bamboos in the subfamily Fargesia are important nutriments for enemorous pandas, and the current blooming Fargesia nitida has had a destructing outcome on panda community. Due to Fargesia are fetching finer called for their dumpy clustering practices, they have suit economical and obtainable at most of the nurseries.

4.2 Bambuseae

The Bambuseae are the maximum various ethnic groups of bamboos in the grassland ancestry. They comprises of wooden pieces from tropical areas, incorporating few giant bamboos. Their sister category are the less herbaceous bamboos from the tropics in tribe Olyreae, while the temperate of woody bamboos are additionally hardly connected. The Bambuseae are the various tribes of bamboos in the grassland ancestry (Poaceae). They includes of woody pieces from tropical area, introducing few giant bamboos. Their sister category are the less herbaceous bamboos from the tropics in tribe Olyreae, while the temperate of woody bamboos are additionally hardly connected. The Bambuseae drop into two clades, analogous pieces from the Paleotropics (subtribes Bambusinae, Hickeliinae, Melocanninae,and Racemobambosinae and from the Neotropics [23, 24].

4.3 Guadua

Guadua is a Neotropical group of spiny, collecting bamboo in the grassland ancestry, scaling from modest to extremely huge pieces [25–27]. Sobstantially, Guadua angustofolia is famed for existence the greatest Neotropical bamboo. The group is same to Bambuseae and is occasionally covered in that group. Various animals are, to a different range, linked accompanied by stance of Guadua bamboo, for example various pieces of seedeaters, and the Amazon and Atlantic Bamboo Rats [28]. According to practical approach, Guadua is the most vital American bamboo.

Because of its standard, the group has been plenty utilized for home buildings across the inter-Andean watercourses of Colombia and in coastal Ecuador. Guadua angustofolia indigenous to Tropical America, is steadily flattering well known one time afresh as a constructing substance. Really acknowledged by Simon Bolivar for its watershed shielding and worshiped by Alexander von Humboldt for its extensive diversity of utilizations, it is being utilized in building today in South America. Scientific investigations of bamboo's mechanical attributes ("vegetable steel") have enhanced interest in its utilization. Even though bamboo culms utilized for construction can be gathered in original jungles, excess misuse guides to the exhaustion of original assets. Guadua angustofolia can be utilized in huge volume, when the administration of sustainable bamboo jungles and copses, also the development of new nurseries and farmsteads, is a primary task. Tropical bamboo can be cultivated accompanied by trimmings or by casing entire culms accompanied by ground. New herbs will germinate in the coming year. Or, Guadua can be cultivated further quickly through the chusquin technique. Culms are trim at soil level when collecting gives rise to numerous little shoots in this technique and latest herbs to enlarge across the primal herb. This technique is acceptable for huge amount jungles or farmstead collaborative. Hence bamboo is a grassland, collecting it down to the ground convinces extra latest shoots to appear, exactly similar to turf grassland. It is circumstances not called in tropical hardwood jungles. Recently quick techniques have been established by the utilization of tissue culture. Bamboo cultivated in a laboratory in the area of 1 m^2 will be enough to develop one hectare of new jungle. This herb can too be gladly conveyed in a one-half-cubic-meter box. Collecting can start 6 years succeeding transplanting, preparing bamboo a prospective origin of tropical renewable creation for industry (e.g., bio fuels). For architectural grounds, Guadua is the selected bamboo pieces. This diameter is steady for the first 15 m and after that tapers at the top. This quality has dazzled the awareness of architects, artists, designers, civil engineers, and academics. Guadua is additional constructive at separating CO_2 from the surroundings than all other tropical jungle environmentally; recent investigations in Colombia have now been correlated through the Environmental Bamboo Foundation. From the above investigations, Japan and the Netherlands have both accepted enormous plantation projects as a path of obtaining so-called "carbon credits" to balance the rate of contamination in industries.

4.4 Pseudosasa Japonica

The reed bamboo of Pseudosasa japonica [29] or metake [30] is a piece of blooming herb in the grassland ancestry Poaceae, origin to Japan and Korea. This robust bamboo generates copses up to 6 m (20 ft) height accompanied by shiny leaves up to 25 cm (9.8 in.) long [30]. The culms are commonly yellow–brown and it has palm-like leaves. The usual title, "arrow bamboo" outcomes from the Japanese Samurai, utilizing its solid and rigid canes, for their shafts [29]. This cool robust bamboo pieces (tolerant to 0 °F/−17.7 °C) enlarges completely both in shadow and brimming sunlight. Pseudosasa japonica does completely in vessels and salty air close to the ocean. Due it tends to be huge shadow tolerant than other bamboo pieces it is repeatedly utilized through planters as a copse to a tree-lined living barrier [31]. In planting in the UK this herb has obtained the Royal Horticultural Society ‘s Award of Garden Merit [30, 31].

4.5 Chusquea Culeou

Chusquea Culeou, the Chilean bamboo [32] (Spanish: Cana Coligue or Colihue) is a breed of blooming herb in the grassland ancestry Poaceae. The bamboo, origin to South America is always evergreen, dissimilar huge breeds inside the group of Chusquea, this is frost-tolerant and hence plenty propagated in temperate areas. This is origin to the Valdivian rainforests, humid temperate jungles of Chile and south-western Argentina. Chusquea Culeou is a cornerstone breeds that can manage designs of jungle energetic through upcoming reanimation of tree breeds [33–36]. Extending to 8 m (26 ft) height through 1.5 m (4.9 ft) wide, Chusquea Culeou generates a considerable cluster of plants. This has shaggy lanceolate leaves accompanied by a spine on their ending, and its bloom is a whisk of gleam brown colour. The herb too generates a caryopsis fruit. Blooming occurs after the variable times that could valid for 60 years. Afterwards flowering and delivering its nuts, then the herb plant expiry. The cane is straightforward up to 6 m (20 ft) in tall, and was utilized through the pole of their spears. They are still utilizing through the Mapuche people for a musical instrument known as trutruca. An attribute of this Chusquea is that the stalks are rigid, dissimilar from most of the bamboos. Chusquea Culeou is propagated as an attractive herb in gardens. This herb has obtained the Royal Horticultural Society’s Award of Garden Merit [32, 33, 37].

4.6 Sasa

Sasa, also called broad-leaf bamboo, is a genus of running bamboo. These species have at most one branch per node. Sasa is a group of brownie rushing bamboos maximum of which have vast, small leaves. Maximum are from Japan and are convenient in the lawn for earth shield, contrasting appearances, and as vessel herbs. They conveniently obtain no larger than 6′, have one fork at each intersection and glance finest enlargement in little shadow. Cutting down is in the springtime. Sole of the Sasa herb types, Sasa Palmata is a pine bamboo expanding to 2.5 m (8 ft) by 5 m (16 ft) at a rapid rate. It is robust to area (UK) 7. This is in leaf all year. The type is hermaphrodite (has a both male and female organ) and is fertilized through Wind. This is noticed for stunning fauna. Favorable for: light (sandy), medium (loamy) and heavy (clay) soils. Acceptable PH: acid, neutral and basic (alkaline) soils. It can grow in semi-shade (light woodland). It prefers moist soil.

5 Classification and Taxonomy of Bamboo on Construction Basis

Bamboo as a constructing substance has elevated contraction power and small mass has been sole of the maximum utilized constructing substances as assist for concrete, specifically in those positions where it is launched in prosperity. Bamboo as a constructing substance is utilized for the building of scaffolding, and structures, houses. Worthful bamboo herbs for buildings incorporate the types of the group: Guadua, Dendrocalamus and Phyllostachys, of which the family of Guadua angustofolia is origin to South America and has the greatest attributes for building jointly. Classifying bamboo has consistently been somewhat a laborious job [38], mostly for non-scientists that occur to be most of the people who required acquiring these details. It is due to the multiplex botanical titles. This proposes to clarify the creatures or people of those who would approach to utilize bamboo more regularly [39], generated a record of 'popular' bamboos, accompanied by both their botanical and familiar titles. Ten of the most familiar bamboo species are represented in Fig. 4.

Although out of all the Botanists, there have been substantial discussions on bamboo categorization and recognition over time [38]. The discussions occasionally give the outcome as change of titles or even re-categorization. Hence, it is very tough to have a universal categorization. But, the botanical titles of their geographical position, genera, and the species are utilized as clarified statistics. Additional data like botanical drawings Photos, vernacular names, descriptions etc., can also be friendly.

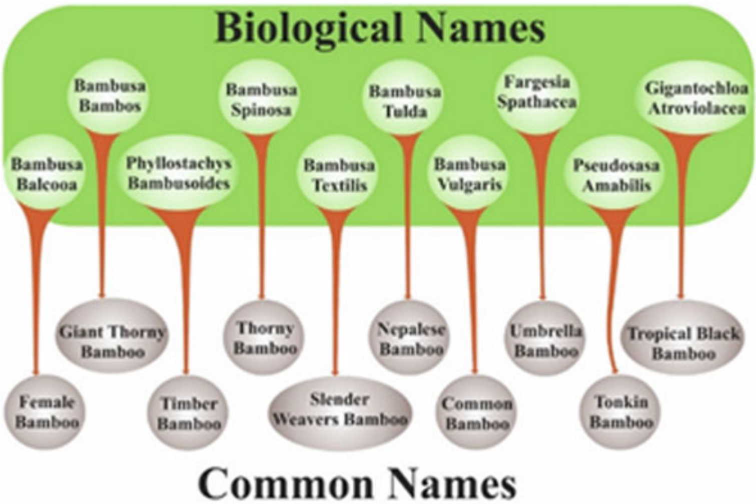

Fig. 4 Popular bamboo with biological and common name

5.1 Descriptions of Bamboo Anatomy and Structure

The analysis of bamboo reports its shape which regulates its eventual mechanical properties. Figures 5 and 6 represents the bamboo culm contains of 3-important parts:

- The stalk—fragment enlarging over the soil that may be linear orbend.
- The stalk foundation—bottom fragment of the stalk which expands into the ground.
- The stalk pedicel—the bottom fragment of the stalk, built up of additional blast segments.

The culm is constructional built of the intersections or midsections, and the segments [40]. The intersections comprise of cells cover aligned or parallel to the intersections, while the segments have lengthwise placed cells. Culms are normally hollow, namely tubes that provides the wall thickness as the dimension in the middle of the internal and the external surface of the stalk, but, few herbs accompanied by ground culms [41].

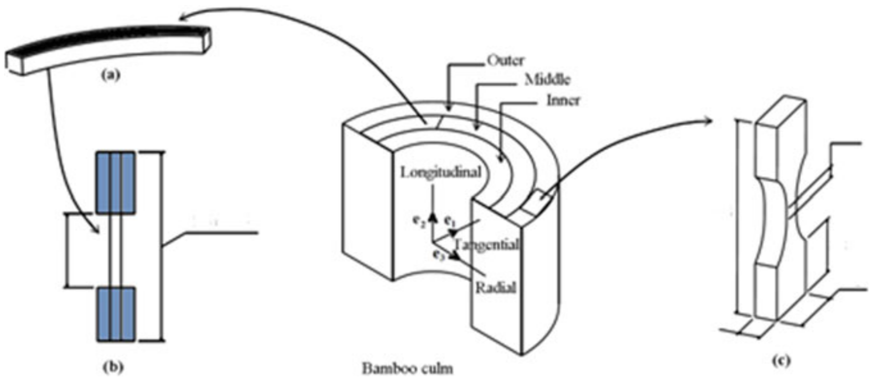

Fig. 5 Basic parts of bamboo culm

Fig. 6 Hollow and solid culm bamboo

6 Properties of Bamboo

Bamboo is repeatedly explained as extremely long lasting, but, it is mainly in accordance to the continual development of the bamboo herb and not remarkable about the long-lasting of the bamboo stalks. Real utilization, treatment, perpetuation and supervision can secure magnificent long lasting as the bamboo constructions are of more than two hundred years older, however, this is vital that the finale user is really notified to build the maximum of their bamboo outcomes. Researchers have investigated and described on the use, refining and the characteristics of these growing substance as a replacement to the enhancing reduction of wood in the jungle. The characteristics of bamboo and its coated outcomes or products verify to its power in replacement of wood. Use of bamboo has enhanced notably in the wood and wood outcome or product industries, accompanied by sufficient exchanging in most of the processing firms in the locality. In order with the establishment and utilization of bamboo-laminated wood for the reason of wood in furniture manufacture, the formation of bamboo farmsteads on degenerated lands will importantly bear manufacture and reduce the humiliation of jungle.

7 Mechanical Properties of Bamboo

The mechanical properties of bamboo rely on many components like species, culm position, and age and so on. These factors affect the fiber density of the bamboo at specific location on the bamboo. The density of the fiber will determine the strength of the bamboo. Next to these components, it is too noticed that bamboo is an orthotropic substance in natural, signification that it has dissimilar mechanical properties in the length wise, incidental and radial direction of the bamboo [42]. They showed that as the distance of the bamboo culm from the ground increases, the ultimate compressive strength also gradually increase due to the increase in fibre density. This also means that the ultimate compressive strength enhances from the internal part of the bamboo to the external fragment. According to the research collection by Janssen, dry bamboo has a better mechanical property when compared to wet bamboo [43]. Besides that, bamboo with thicker wall has better mechanical properties generally. According to Janssen, various herbs of bamboo has various mechanical properties and bamboo has the best mechanical properties when they are aged between 3 and 7 years old [43]. Young and old bamboos have lower mechanical properties [43]. According to Amada and Untao, the optimum age occurs around 2.5–4 years old [44]. Numerous tests and studies had been done by researchers on the mechanical properties of bamboo, especially on their tensile and compression properties. For example, the tensile properties of various bamboo herbs have been studied through several authors such as moso bamboo [45], and so on. However, the results obtained might differ from one study to another as different approaches are used. The species of the bamboo, specimen size and shape, presence of node and the condition of the bamboo used are different.

7.1 Tensile Properties of Bamboo

Lakkad and Pattel conducted an experiment to regulate the mechanical properties of bamboo [46]. This species of the bamboo utilized is unknown but it is mentioned that dry bamboo was used. The dimension used is 6 mm (T) × 12 mm (W) × 200 mm (L). No nodes are present in the specimens. From the experiment, the ultimate tensile strength and ultimate compressive strength of bamboo is 193 MPa and 68.4 MPa, respectively. In term of particular power, the certain tensile strength of bamboo is 214.4 km^2/s^2, which is 4 times greater to the specific tensile strength of mild steel which is 50.6 km^2/s^2. From this experiment, it has also found that the specific modulus of elasticity of bamboo is comparable to unidirectional glass reinforced plastic (GRP) but lower than the specific modulus of elastic of mild steel [47]. The particular characteristics give a perception into relative strength and stiffness on a mass basis, especially under single direction loads [47]. Li [45] has conducted tensile test and compression test on moso bamboo. The tensile and compression specimens have nodes in them. Hojo et al. [43], have conducted studies on the tensile characteristics of bamboo mat-reinforced compound. The reasons behind choosing bamboo fibre mats over natural bamboo fibbers are simpler manufacturing process, lower cost and the short length of original natural fibers. The bamboo fibre mat used has a bamboo fibber's density of 1.293 g/cm^3 and unit area weight of 907 g/m^2.

7.2 Compressive Properties of Bamboo

Compressive properties of bamboo of different species have also been studied by researchers. For e.g., the contracting properties of various bamboo herbs which have been earlier moved out through authors are Kao Jue (Bambusa pervariabilis) [48], Mao Jue (Phyllostachys pubescens) [48–50], Bambusa balcooa, Bambusa bambos, Bambusa nutans, Bambusa tulda, Dendrocalamus giganteus, Dendrocalamus strictus, Melocanna bambusoides [51] and Hawaiian Gold Timber (Bambusa vulgaris vittata) [52]. Chung and Yu [44] carried out compression tests on two bamboo species, which are Bambusa pervariabilis and Phyllostachya pubescens [48]. Bamboo culms were used as the specimens. For Bambusa pervariabilis, the average ultimate compressive strength obtained is 103 MPa while the average compressive modulus of elasticity obtained is 10.3 GPa [48]. For Phyllostachya pubescens, the average ultimate compressive strength obtained is 134 MPa while the average compressive modulus of elasticity obtained is 9.4 GPa [48]. Chung and Yu had shown that the mechanical properties of the bamboo were best to general constructional wood [48]. On the other hand, Li also conducted compression test on bamboo [49]. However, the species of the bamboo used was unknown. Li used bamboo specimens that were of different age and that were found from various positions of the stalk. Rassiah et al. [49] has conducted the Charpy impact test on refined and coated bamboo strips. The bamboo species used is the Gigantochloa scortechinii [49]. The bamboo plant was trim into plunder fibre fragments utilizing a chopper and a hand saw. Then plunders were trim into thicknesses of 1.5, 2.0, and 2.5 mm. Three regions of the bamboo plants are cut, which are inner section, middle section and outer section. The bamboo strips were then exposed to the hand lay-up operation. The laminated bamboo samples are fabricated by mixing unsaturated polyester with methyl ethyl ketone peroxide catalyst and then brushing this mixture on the bamboo strips. The Charpy impact test was carried out in accordance of ASTMD 6110 standard [49].

7.3 Fracture Toughness

The property of fracture toughness is that, which represents the quantity of stress needed to generate a crack or defect [51]. It describes how far a material can go to resist fracture at the crack. As bamboos is used in many high load structures and are exposed to wear and tear, it is essential to know its fracture properties to take the necessary precautions. Mode I and Mode II fracture properties of bamboo will be discussed here.

7.4 Mode I Fracture Properties

In Mode I fracture, the rupture surface is perpendicular to the direction of the greatest tensile loading [51, 53]. In Mode I fracture toughness, the mechanical property that will be studied is fracture toughness, KIC. Liou and Lu [51] had carried out Mode I fracture test on bamboo culms of Moso bamboo (Phyllostachys pubescence) [53]. This study has used ASTM E399 test method, which involved arc shape bend specimens.

Amada and Untao did a throughout study on the fracture properties of 2-years old Mousou bamboo (Phyllostachys edulis) [52]. First of all, they have conducted Mode I fracture test on specimens from different culm. Besides that, we can also see that the fracture toughness of bamboo increases with its height.

On the other hand, Amada and Untao also conducted Mode I fracture test on the bamboo nodes. Amada and Untao suggested that this fibre made little or no contribution to the fracture properties of the node [52]. The average fracture toughness obtained for the bamboo node is 18.4 MPa $\sqrt{m}$, which is significantly lower when compared to the bamboo culms. Amanda and Untao have also concluded that the fracture toughness of the bamboo intersection is contributed through the parenchyma cells [52].

7.5 Mode II Fracture Properties

Mode II fracture properties involve in-plane shear loading, which is the sliding of one crack face with respect to the other in its on plane [53]. The total number of samples used in their study is 43 samples and the average Mode II fracture toughness obtained is 1303.18 J/m^2, 1107.54 J/m^2 and 1216.06 J/m^2, respectively with some deviations between methods. For all three methods, the bamboo height has minimal effect on the fracture toughness of the bamboo.

7.6 Effect of Moisture on the Mechanical Properties of Bamboo

Since bamboo is constantly exposed to harsh environment, such as exposure to rain and river, the result of wetness or water contented on its mechanical properties has to be properly studied. Numerous researchers have conducted test to regulate the result of moisture on the mechanical properties and all have proven that the mechanical properties of bamboo is weaken by the presence of moisture.

7.7 Tensile and Compression Properties

Lakkad and Godbole [54] have conducted an experiment that revolves around the result of water engrossment on the mechanical properties of bamboo. Three types of specimen configurations are prepared: dry; soaking in distilled water for 144 h ("wet" samples); soaking in boiling water for 2 h ("boiled" samples). For the "wet" and boiled" bamboo samples, their weight gain are recorded from time to time to monitor water saturation level. The tensile modulus of elasticity of the specimens is dropped by 47.7% and 31.1% when immersed in distilled water for 144 h and simmered in distilled water for 2 h, respectively. On the other hand, the tensile strength of the specimens is dropped by 36.9% and 26.6% when immersed in distilled water for 144 h and simmered in distilled water for 2 h, respectively. It shows that exposing bamboo to water has drastic effects on its tensile properties. Soaking the bamboo in distilled water for long term does more damage to its mechanical properties than boiling it in distilled water in a less span of time. The bamboo fibers are not damaged by the high temperature. However, the diffusion of water within the "wet" and "boiled" bamboo samples do reduce its tensile properties. As additional water has been engrossed by the "wet" bamboo samples when compared to the "boiled" bamboo samples, their tensile properties are much reduced. In order of contraction properties, the reduction in compressive strength is more or less the same for the "wet" and "boiled" samples. The decrease in contraction power is around 50%. It is very evident that water content in bamboo can greatly decrease their tensile and compression properties. Similar study has also been conducted by Yap et al. [48] on Bambusa vulgaris vittata type bamboo and practically the same decrement of the mechanical properties was found. Dorez et al. [55] reported the result of environmental aging on the tensile properties of bamboo glass fiber strengthen polymer matrix hybrid composites. The length of the glass fiber is 3 mm and the length of the bamboo fiber is 1–6 mm, which both are randomly oriented in the resultant composite plate. Dog-bone shaped specimens accompanied by dimensions of 60 mm × 12 mm × 3 mm were produced and the tensile tests are carried out in accordance of ASTM standard D639.

7.8 Thermal Properties of Bamboo

Evaluation of thermal properties of bamboo composites and apprehension of their belongings are censorious for the design of building construction. Thermal conductivity hegemonies the rates of heat transfer by utilizing the bulk material during processing to control heating and cooling processes. Material thermal censorious plays an important role in fire safety for the long-term durability of buildings. Thermal stability of medicated and unprocessed bamboo fibers was moved out utilizing a thermo gravimetric analyzer (STA7000, Hitachi). The mass varies of bamboo fiber in the % as a basis of enhancing temperature accompanied by steady rate of warming was noticed. All specimens were kept in a pan and increase the temperature from 20 to 800 °C at a rate of heating of 10 °C/min under a nitrogen surrounding.

7.9 Scanning Electron microscopy

The superficial morphologies of unprocessed and alkali-treated bamboo fibers as well as the rupture area of the bamboo fiber strengthen polymer compounds (polyester, vinyl-ester, epoxy), were investigated through scanning electron microscope TM3030 plus Benchtop Electron Microscope Hitachi, Japan. The resemblance was executed at accelerating voltages of 5–15 kV.

7.10 Flammability of Bamboo

Jobs of bamboo are not combustible as individuals expect. Even though bamboo is original substance, the obstruction to fire is not minor to cement, iron, steel. Currently bamboo jobs are familiar because of its distinctive charmer. But, most of the individuals are too disturbance regarding the capacity of fire-prevention. Everyone believes that bamboo jobs are effortless to blaze. But, that declaration is totally incorrect! Bamboo is combustible while it's chop. On the basis of the above opinion various researchers have provided their view either through few execution tests or few differentiation accompanied by the other herbs. Nurul Zuhairah et al. [56], have introduced only method to utilize bamboo material as original fiber reinforced composites (NFRCs). The investigation was intended to find the enlarge to that of bamboo material could restore glass fiber in glass polypropylene (GPP) compounds and whether the suggested mixtures were proficient of participating, specifically in contrast to the combustibility of GPP compounds. In the field of bamboo-reinforced composites, only a very small number of researchers [57] have performed studies in flammability. However, no such investigation has been regulated on the fire performance of bamboo fabric PP composites. Most research carried out using natural fiber-glass reinforced hybrid composites has focused on physical and mechanical properties. Remarkably, flammability testing of hybrids using quantitative methods has been relatively rare as well as the prediction using Rule of Mixtures. However, no such research has been performed on flammability of bamboo-glass hybrid composites [58]. The hybrid composites, where several layers of glass in a GPP composite are replaced with bamboo fabric, may improve the flammability. Experimentation has been carried out for the thermo-physical characteristics and flammability deportment of poly (ethylene terephthalate) (PET) compound, containing bamboo charcoal (BC) stuffing. Outcomes represented that the amount of resistance reduced smartly but accompanied by small result on thermal conductivity, when PET was loaded accompanied by higher than bamboo charcoal. Thermo gravimetric analysis (TGA) disclosed that soaring bamboo charcoal loading was linked accompanied by a higher onset temperature of 50% humiliation (Td50%). However, the flammability of bamboo is under acceptable range, but it has been seen that the mixture of bamboo fabric to others, either by the method of reinforcement of composites or by using as a charcoal, gives even better result as compared to the bamboo itself. So, the central importance of bamboo fabric in flammability of these composites is the substantial contribution of bamboo fabric to the fire resistance in bamboo-glass PP composites. Nurul Zuhairah et al. [56] have mentioned in their investigation that, this was the first time for bamboo fabric used in conjunction with glass in order to increase fire resistance of the composites. So, hybridization may be useful in applications where fire resistance is important. Demand for more natural fiber materials means a reduction in glass use. A remarkable segment of the glass in GFRCs may be restored accompanied by bamboo fabric, with a positive result on fire obstruction. Hence, in near future the deduction in combustibility and the improvement in properties achieved, illustrate assurance for the mixture substances petitions.

7.11 Recycling of Bamboo

Investigations have represented that of all the constructing substances which are utilized in buildings, bamboo is the less dangerous in names of misuse as it can be reprocessed and does not have discarding complications. The radicals in bamboo support to manage ground deterioration as it forms a water wall. The highest standard of manufacturing bamboo lyocell is that it's a 100% closed-loop revolution that secures all the chemicals, water, and everything else utilized to generate it is 100% reused and accommodated.

8 Applications of Bamboo

Bamboo, an eco-friendly substance, has a plenty of uses. The Bamboo plant belongs to the grassland ancestry called Poaceae in the subfamily of Bambusoideae. They are pine everlasting herbs, which primarily enlarge in the tropics. Similar to other grasses, they have parallel leaves, however for the bamboos particularly; their stalks are hollow and columnar. Bamboos are few of the quickest enlarging herbs on the planet, and are because of their single rhizome-dependent structure, few of herbs can enlarge up to 36 in. in a 24 h time. Few of the Bamboo enlarging in the exact states without any animal disruption they can extend up to 164 ft height and as high as 12–20 in. wide, this, moreover, does not implement to all bamboo herbs but to particular herbs.

8.1 Modern Uses of the Bamboo

Bamboo has been utilized in the constructing of roads and buildings in most of the regions of Orissa in India, other formations linked accompanied by convey such as bridges have been made utilizing bamboos in various locations of China also till date. Bamboo has been utilized to construct pretty home constructions which are not only powerful and muscular, however, long-lasting accompanied by the capability to resistraspy circumstances. Numerous holiday resorts close to see utilize Bamboos to include an artful connect to their developments and more than a billion people are determined to live in bamboo homes. The bamboo herb has for years supplied food for both animals and human beings and maximum Asian food productions include the utilize of the bamboo herb, bamboo wounds are eaten raw, cooked or utilized to form a stock, maximum Asian culinary shops even sell them in fried, dried, and canned versions, which are prepared to eat. In Japan, the bamboo is utilized as a food preservative because of its high antioxidant characteristics established in its dermis, which blocks the enlargement of bacteria. Bamboo is utilized to build attractive furniture that can too double up as decorative pieces in the home. Due to its brightness that is an outcome of the hollow place internally, bamboo stalks are often utilized for scaffolding throughout the construction of buildings and it is an economical, highly environment friendly manners of buildings.

8.2 Application of Bamboo Materials in Building Construction

Bamboo, as the primary architectural building in bamboo architecture, takes part in the load holding of construction structures. Bamboo has powerful adjustability in thickness and power and can build various compound adaption correspondingly based on the architectural building to convince the need of various building execution. On the other hand, the scientific demands of bamboo constructions are comparatively small and can effortlessly be united into municipal architectural buildings, for e.g., the combination of bamboo accompanied by ground soil, concrete and glue, etc., can support to enhancing the constructional power. As per the latest and current bamboo architecture, the important technique of bamboo architecture lies in the intersection position in the middle of main constructional components consisting tension and stress. The power, stiffness and solidity of intersections primarily are based on the junction power in the middle of construction elements of the building. Hence, the enhancing development of relationship construction has showed additional subscriptions to the diversification of bamboo architecture.

9 Conclusions

As, bamboo is a versatile raw material for social, economic and cultural point of view, it has been compared with steel through which it has been noticed that bamboo is much cheaper than steel even, bamboo properties like high tensile, flexibility, light weight, toughness is much better than the other building materials. In the present review work an overview of bamboo material has been studied by focusing its origin, historical background, specification, applications and different properties, like mechanical, thermal, flammability and recycling. On account of different properties of bamboo detailed study following major findings have been concluded:

- The characteristics of bamboo and its coated outcomes verify to its potential in switching wood. Use of bamboo has enhanced remarkably in the wood and wood outcome industries, accompanied by sufficient regenerating in maximum operating firms in the section.
- The mechanical properties of bamboo are weakening by the presence of moisture.
- The fracture toughness of bamboo increases with its height.
- Compression tests on two bamboo species, which are Bambusa pervariabilis and Phyllostachys pubescens. Bamboo culms were used as the specimens. For Bambusa pervariabilis, the average ultimate compressive strength has been found to 103 MPa while the average compressive modulus of elasticity obtained was 10.3 GPa.
- For Phyllostachys pubescens, the average ultimate compressive strength obtained was found to 134 MPa while the average compressive modulus of elasticity obtained was 9.4 GPa.

- It had been found that the mechanical properties of the bamboo are higher to familiar constructional wood.
- As, the bamboo fibers are not damaged by the high temperature, the diffusion of water into the “wet” and “boiled” bamboo specimens do reduce its tensile properties.
- The planes structure of unprocessed and alkali-treated bamboo fibers as well as the rupture plane of the bamboo fiber reinforced polymer compounds (epoxy, polyester, vinyl ester), were investigated by scanning electron microscope TM3030 plus Bench top Electron Microscope Hitachi, Japan. The imaging was executed at accelerating voltages of 5–15 kV.
- However, the flammability of bamboo is under acceptable range, but it has been seen that the mixture of bamboo fabric to others, either by the method of reinforcement of composites or by using as a charcoal, gives even better result as compared to the bamboo itself. So, the central importance of bamboo fabric in flammability of these composites is the substantial contribution of bamboo fabric to the fire resistance in bamboo-glass PP composites.
- Hybridization may be useful in applications where fire resistance is important. Demand for more natural fiber materials means a reduction in glass use. A notable section of the glass in GFRCs may be changed accompanied by bamboo material, with a positive result on fire obstruction.
- In near future the deduction in combustibility and the improvement in characteristics attained, illustrate assurance for the mixture substance petitions.

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Morphological and Mechanical Aspects of Bamboo Composites

Carlo Santulli

Abstract The length of bamboo culms makes the obtained fibers promising for application in composites, both for the reinforcement of oil-based matrices and of biomatrices. However, the varietal diversity of bamboo species and the mode of extraction from the plant, which can involve mechanical and chemical stages, both contribute in changing the morphology of the fibers and their performance. A number of studies exist in trying to relate the above aspects to the performance of the obtained composites, which are reviewed in this chapter. For the aforementioned reasons, the existing literature gives scattered evidence of bamboo potential in composite, despite the inherently outstanding properties of this plant. This has been explained by the difficulties in controlling mechanical and morphological properties of extracted fibers, and as the consequence of the obtained composites.

Keywords Bamboo · Composites · Species effect · Fiber morphology

1 Introduction

Bamboo is the collective definition of a group of perennial evergreens in the family Poaceae, subfamily Bambusoideae, tribe Bambuseae, which, according to Liu et al. [41], is constituted by over than 90 genera and about 200 species. It is not obvious, however, to make clear distinctions about the taxonomy of bamboo. Therefore, in other cases, much larger numbers of species have been reported: an early study by Bansal and Zoolagud [7], suggests that the known species at that time were already 1250. Quite comprehensive information on the species of bamboo available in the different parts of the world for use in materials is available in Panda [53].

With respect to other bast fibers, such as ramie or flax, bamboo fibers have a considerably thicker cell wall, which point toward higher mechanical properties [26]. The transverse section of a bamboo culm, as shown in Fig. 1, includes numerous vascular bundles embedded in the parenchymatous ground tissue [9]. As the consequence

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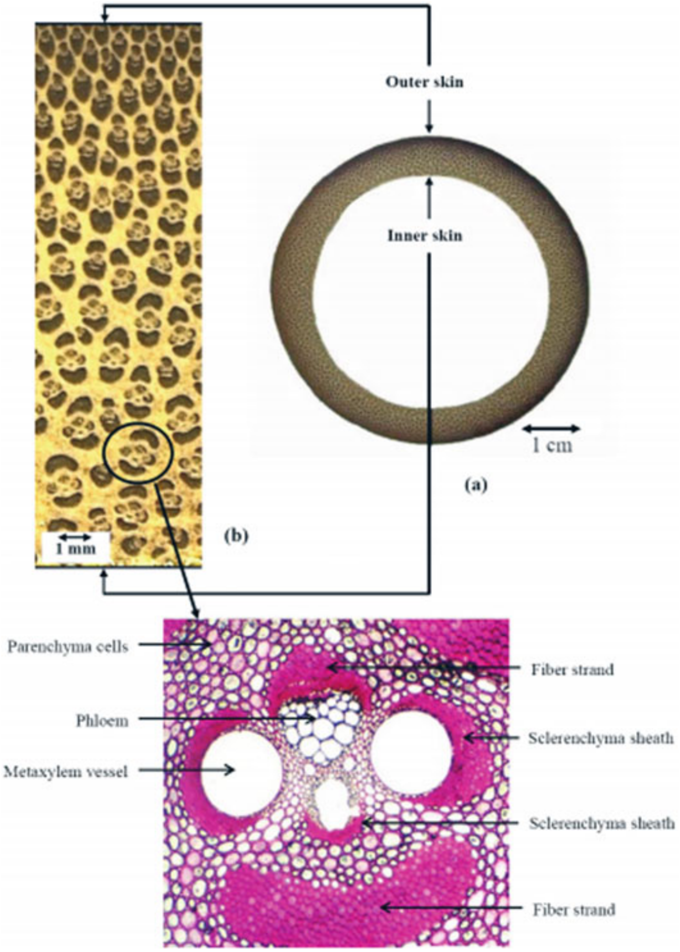

Fig. 1 The structure of a bamboo culm [9]

of this structure, the extraction process of the fibers would need to separate the large amount of parenchymal tissue from fiber strands and vascular bundles possibly causing limited damage to the fibers, despite its strong interface, which is apparent from images in Fig. 2 [79].

Bamboo has found some application in the wood sector, where it can even offer some more significant potential, due to its lower thermal conductivity, especially when coupled with a biodegradable matrix, such as poly(lactic acid) (PLA) [67]. A limitation can lie in the significant density of bamboo, which can get as high as 1.4–1.5, due to its relatively high content of lignin strongly bonded with cellulose and other components in the culms. As a matter of fact, the insoluble part, referred to as Klason lignin, was measured by Huang et al. [28], according to ASTM D1106-96,

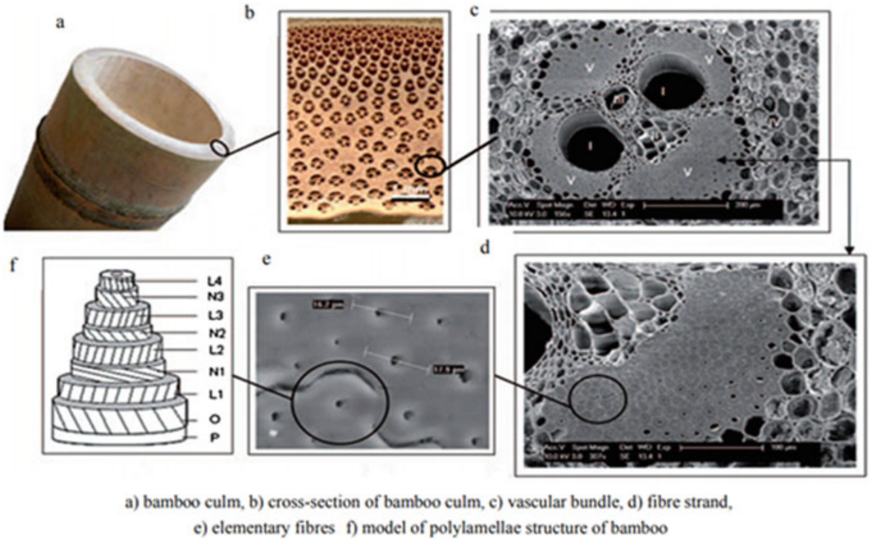

Fig. 2 Position of the fibers in the bamboo culm [79]

obtaining values between 19.67 to 28.48%). In addition, from this plant, materials with a number of geometries would be obtainable. In particular, bamboo splits and slivers, where the former are strips of the full thickness of the culm wall with some part of the green outer layer and the latter are thin, narrow sections of bamboo wood, as shown in Fig. 3, powder or charcoal. This last product has been also proposed for introduction in a polymer matrix (a polyolefin blend), mainly as an inert filler during melt compounding, with no significant influence on mechanical properties [42].

A general scheme for the treatments that allow coming from bamboo strips to fibers useful for introduction in composites is reported in Fig. 4. More details on

Fig. 3 Bamboo slivers

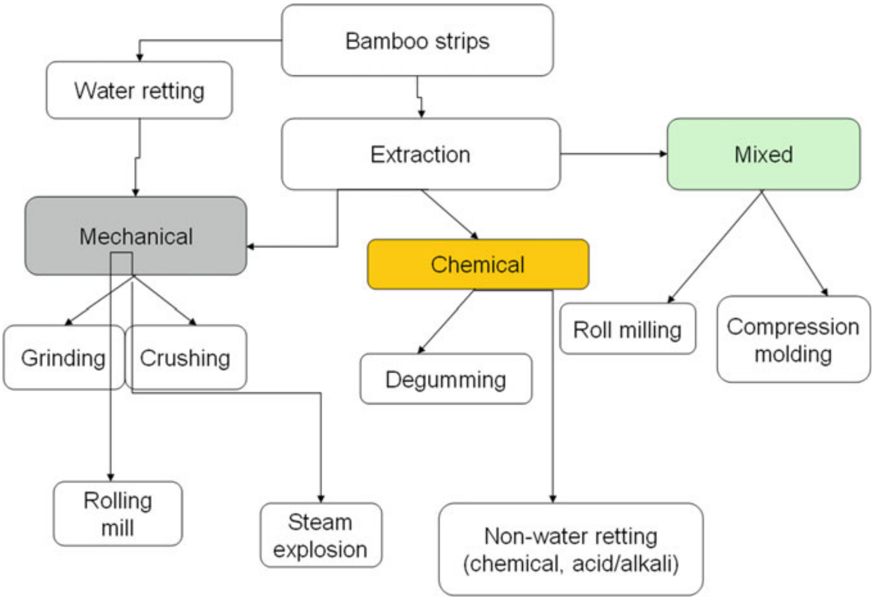

Fig. 4 Options to obtain fibers from bamboo strips

the value of the possible options for fiber extraction are offered e.g., in Zakikhani et al. [80]. Chemical extraction is usually achieved by sodium hydroxide (NaOH) at high concentration, while retting can also be acid, for example by acetylation. Another possible form coming from mechanical operations, which is also worthy for the production of paper, is bamboo pulp. The process for obtaining bamboo pulp, with not much difference with what happening with other ligno-cellulosic material, such as bagasse, involves an initial stage of shredding, followed by washing and wet depithing. This is normally completed by steam explosion, which is a low energy consumption method to obtain pulp developed in the 60s. When the need is to obtain bamboo fibers to be used in composites though, steam-exploded fibers were often reported to be rigid and not completely clean from lignin, which condensed on the surface, and therefore in need for some treatment, such as isocyanate silane, which resulted though in a reduction of tensile properties [70]. Another explored possibility for lignin elimination was a washing with dioxane solution [62], whose effects are depicted in Fig. 5. It is worth mentioning for completeness that lignin removed from bamboo fibers after steam explosion can be possibly re-used for the development of bio-based cured epoxies [59].

The morphological features of the fibers in bamboo pulp are very different. Sadiku et al. [58], reported obtaining fibers with length in the order of 2 mm and with an aspect ratio above 100, intended mainly for use into paper. This kind of product is not exactly applicable as a reinforcement of composites for its excessive hydrophilic character and limited resistance to chemical agents. Moreover, it was also noticed that for an aspect ratio lower than 20, no effective reinforcement was really obtained,

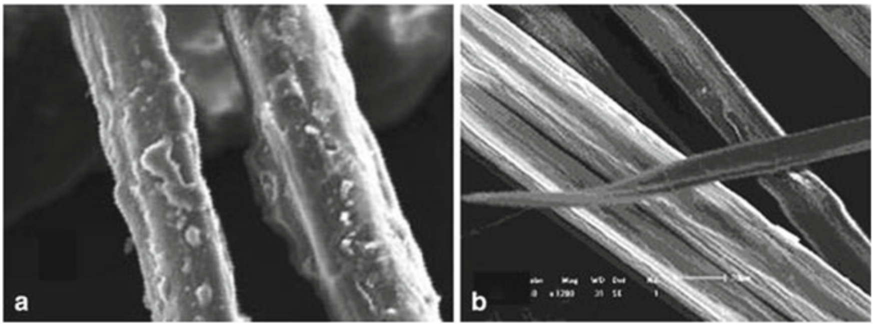

Fig. 5 **a** Steam exploded (SE) bamboo fibers. **b** SE bamboo fibers treated with dioxane/water 9:1 solution v/v [62]

at least on biodegradable matrices [66]. In other cases though [35] alkaline treatment provided fibers of few centimeters length, which are adapted as "technical fibers" for use in composites, its length being limited only by the nodes. In general though, obtaining longer and cleaner, hence fully degummed, fibers should be preferable for composites: however, in most cases mechanical stripping does not result in a sufficient separation of the single fibers to be ready for formation of a strong interface by resin impregnation.

Actually, during the last decades, bamboo fibers have often been proposed as a possible reinforcement for polymer matrices, therefore obtaining natural fiber composites. On these materials a considerable and growing interest has been revealed as a more sustainable replacement e.g., for fiberglass in some applications, such as the automotive industry [46]. To constitute an intermediate step to the aforementioned substitution, also the fabrication of bamboo/glass hybrid composites has been proposed in a number of works involving the use of polypropylene matrix [44, 48, 69, 83].

Possible application for bamboo fiber composites are in the building industry e.g., as a dissipating structure to be embedded in concrete [15], in the automotive industry for the production of components, as the prototype, which is represented in Fig. 6, or in the shipbuilding industry [65]. Beyond the use of thermosetting matrices, also bamboo fiber thermoplastic matrix composites have been proposed, in particular polypropylene [14, 45], starting already from over two decades ago, and more recently also polyethylene [25], in both cases investigating both mechanical properties and crystallization patterns. Other studies involved using poly(vinylchloride) (PVC) matrices though with limited amounts of bamboo fibers [36]. Another field of application of bamboo fiber is their combination with biopolymers based on starch, such as poly(lactic acid) (PLA) [72], synthesized from crude oil, such as polycaprolactone (PCL) [30], or by a bacterial stream, such as poly(hydroxybutirate-valerate (PHBV) [64]. The idea of these works is producing more sustainable composites through the biodegradability of their matrix.

Fig. 6 Development of a car door prototype from a bamboo fiber composite [20]

Actually, a few reviews of work performed about bamboo fiber polymer composites exist, which concentrate on different aspects; therefore, these may be considered completing each other to obtain more thorough information on this field. In particular, Shah et al. [61], offered indications about tensile properties, concentrating on a specific case, which is of paramount interest of the automotive industry, namely the reinforcement of polypropylene (PP) matrices, especially in the case they are compatibilized with maleic anhydride (MA) (therefore being referred as to MAPP). Another review, which concentrated on polypropylene/bamboo fiber composites, reports also on the possible interest of nanoclay addition for the improvement of mechanical properties [31]. Other indications in this sense are offered by Rassiah and Megat Ahmad [57], adding also some more details about the possible application as matrix of biopolymers, such as poly(hydroxybutyrate) (PHB). The review by Abdul Khalil et al. [1] set a more specific focus on biopolymers: here, the critical point of the variability of fiber properties obtained by their extraction using different methods is clearly highlighted, by comparing a number of those available in the technological practice. Among biopolymers, the particular success recently obtained by poly(lactic acid) (PLA), especially in fields, such as packaging, made it possible to propose also the introduction of bamboo fibers, also for the multiplicity of extraction processes possible, which make them adaptable also to the use in films of very low thickness. In particular, Nurul Fazita et al. [49], have dedicated a specific review to PLA/bamboo composites for packaging.

2 From Bamboo Plant to the Fabrication of Composites

The length of its culms makes bamboo one of the most promising groups of species for the extraction of fibers with high aspect ratio, hence also for composite production. In addition, the structure of bamboo plants appears quite repeatable with limited variations throughout the different species. On the other side, the properties of the culms change during aging of the plant, since with increasing age their structure undergoes cell wall thickening, as shown, concentrating on *Phyllostachys Viridiglaucescens*, by Liese and Weiner [40]. In practice, the culms are divided into segments, which are separated from each other by areas of wider section, defined to as nodes. An initial morphology evaluation would concern measurements carried out on the distance between nodes, also referred to as internodal, which became first of interest for the construction industry, where bamboo culms where proposed as the replacement for steel bars into reinforced concrete. In that case, the frequency of nodes indicated the degree of variation of culms with respect to hollow cylinder geometry with constant section [23]. Along the culms, mechanical properties also considerably change especially between nodes and internodes regions, less so between different internodes [2].

As far as use of bamboo in polymer composites is concerned, internodal distance has an influence on the maximum possible length of the fibers for use in composites, although in principle it is not necessary to exclude nodes from fiber selection, being aware of the aforementioned variation in properties with respect to internodes. More refined evaluations regard the density distribution in the internode sections, which have an effect on the internal density distribution and consequently on the different strength of the fibers. This density variation depends on the relative proportions and growing patterns between tissues from vascular bundles tissues and parenchymal ones (Huang et al. 2014). After fiber extraction, the nodal structure and tissue distribution patterns still result in some variability of their length and diameter, and therefore in widely scattered strength values: despite this, some modelling has also been attempted [73]. For the fabrication of composites, it is crucial to evaluate whether bamboo fibers would be able to compete with or even outdo other fibers as reinforcement. This could appear evident in general, due to the structure of bamboo culm,however, the extraction process may result in some damage inflicted to the fibers.

As the consequence, comparative studies with other vegetable fibers have been carried out, as it is case e.g., with sisal and Jowar [54], with Vakka, sisal and banana [56], with jute [8, 47], with jute and kenaf [27]. It is significant for example to note that bamboo composites have similar flexural properties to kenaf ones, although they are less compressible, due to the lower void content and lumen dimensions [63]. The great majority of these comparative studies is based on possible alternative use of fibers available in the same region e.g., in India or in South-East Asia. The comparison with bamboo may also be based though on a morphological similarity between the plants, such as it is the case for a study on *Arundo donax*, however both reinforcements being used rather in the form of powder, which is of limited suggestion about relating the morphologies of the two ligno-cellulosic fillers [55].

Other comparative studies are specifically intended for use in composites where, given the very large availability of bamboo fibers, also the possible fabrication of hybrids with other ligno-cellulosic fibers has been considered. This is the case of work carried out in comparison with flax/epoxy fiber composites, where in terms of mechanical and impact properties, bamboo proved largely inferior, when applying them in the amount of 40% by weight as the reinforcement of an epoxy matrix. On the other side, a hybrid with 20% flax and 20% bamboo was able to reduce considerably this gap, due to the strict packing of flax fibers, able to improve both void content and to show better compatibility with the polymer matrix [60]. Another possibility of comparison of the performance of bamboo with other ligno-cellulosic fibers was explored again using kenaf, but comparing at the same time also bamboo fibers with bamboo charcoal: this led to the idea to produce hybrid composites with the three fillers together. Kenaf would contribute in terms of mechanical properties, bamboo charcoal would offer a higher thermal stability, while bamboo fibers would especially contribute dynamical mechanical properties, supposedly for their structural morphology [11]. The subsequent fabrication of the hybrids brought to the conclusion that 50:50 weight ratio of bamboo and kenaf fibers with a total amount of 40% by weight in epoxy resin was the optimum mixing ratio for obtaining hybrids with enhanced dimensional and dynamic mechanical properties [12]. An example of a hybrid composite with three different fibers, bamboo, coir and kenaf, indicated that an effective balance between the higher ductility of coir and the higher strength of the other fibers was also obtained, in combination with a poly(lactic acid) matrix [78].

Among other considerations, two significant factors have an influence on the morphology of bamboo fibers, therefore on the mechanical properties of the composites obtained by using these as fillers in polymer matrices: fiber extraction and the species of bamboo from which extraction takes place. In a more applicative context, one of the issues encountered in producing natural fiber composites, with respect to fiberglass, has been the much higher variability of their properties, due to the natural hierarchical structure of the fibers, originated in the case of bamboo from the bundle sheath [4]. The hierarchical cellular structure has an influence over the mechanical characteristics of the obtained fibers, in particular controlling crack propagation [24].

The previously mentioned considerations indicate that studies aimed at the production and characterization of bamboo fiber composites would need to concentrate on the effect of the morphological aspects of fiber, as resulting from their extraction and treatment, and of the variability depending on species, considering that bamboo has a particularly high number of species adapted to the production of fibers. This will have a consequence on the morphological, therefore mechanical and structural properties of the composites obtained, as discussed in the following section.

3 Fibre Extraction and Effect of Species

The main reason that requires controlling bamboo fiber extraction and morphology lies in the inherent brittleness of fibers, as received, due to them being covered in lignin [50]. This surface layer appears nonetheless having a non-uniform topography with the consequence that wetting behavior can be very variable, and has been demonstrated to be possibly reduced by autoclave treatment [22]. This occurs at the microscale, whereas the situation appears different at the nanoscale. Bamboo plant appears to be realized in nature to take the shape of highly organized multiscale structured composites, which are at the same time exceptionally tough, yet also hard and strong. Individual bamboo fibers are in fact built using a structure of cobble-like polygonal cellulose grains with diameter between 40 and 100 nm nanograins, which leads to a ductile rather than brittle behavior. Observations under the atomic force microscope that prove this particular morphology are described in Fig. 7 [82].

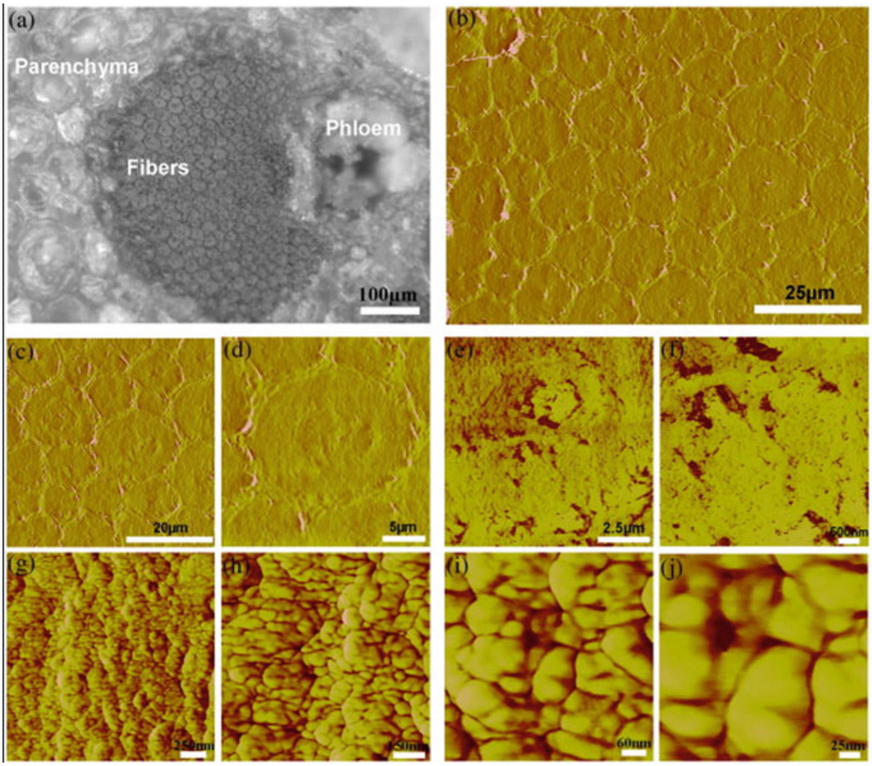

Fig. 7 Phloem fiber cap in a vascular bundle of a bamboo culm: **a** Optical micrograph of a fiber cap. **b–d** Atomic force microscopy (AFM) phase images of bamboo fibers. **e–j** AFM phase images of the nanoscale structure in the fiber cell wall [82]

Typically, the lamellar structure of the fibers presents an increasing lignin content proceeding from the lumen towards the middle lamella. In addition, the amount of lignin is higher as far as the plant becomes older [43]. The effect of this is the difficult predictability of mechanical properties of the fibers, unless these are extracted in a standardized way from fully developed plants of a young age.

The ultimate effect of species on fiber performance in composites has also been comprehensively examined in a study by Yu et al. [76], which tested a number of fibers of different species and related their section geometry with mechanical properties. For the purpose the fibers were cut at 2 m above the basal node and were either 2 or 3 years old. More specifically, the species considered were *Neosinocalamus affinis* (Rendle) Keng f. (C), *Bambusa pervariabilis* McClure (CG), *Dendrocalamopisis vario-striata* (W.T.Lin) Keng f. (DS), *Bambusa chungii* McClure (FD), Bambusa albo-lingata Chia (H), *Bambusa longispiculata* Gamble ex Brandis (HM), *Dendrocalamopisis oldhami* (Munro) Keng f (LV), *Dendrocalamus latiflorus* Munro (Ma), *Bambusa eutuldoides* var. viridi-vittata (W.T.Lin) Chia (QS), Phyllostachys heteroclada Oliver (s), and *Bambusa multiplex* cv. 'Silverstripe' (YS). It is suggested that the section geometry may considerably depart from circularity and this has some relation, though not an obvious one, with tensile performance.

To extend further the understanding of bamboo fibers' potential as the reinforcement of polymer composites, a remarkable consideration has to be done on the large variety of species that have been used for fiber extraction with intended use in composites. In particular, studies also exist with the purpose of comparing performance obtained when adding fibers obtained from different species. For example, in Bahari and Kraus [6], fibers from two Malaysian species (*Bambusa vulgaris* and *Schizostachyum brachycladum*) of bamboo are added to poly(vinyl chloride) (PVC) matrix in a particulate filler form. As indicated in Fig. 8, it is important to observe that the effect of the species of bamboo is prevalent in varying water absorption, which is of paramount significance in composites.

A significant consideration, preliminary to proceed with fiber extraction, is that the section of the culm used for the purpose would be the most suitable one. With this idea, in the study by Zakikhani et al. [81], four different bamboo species (*Dendrocalamus pendulus, Dendrocalamus asper, Gigantochloa levis, Gigantochloa scortechini)* have been compared, as regards their morphological, physical and mechanical properties. The study evidenced that, while the highest aspect ratio and Young's modulus were shown by *Dendrocalamus asper,* in contrast the highest specific strength was obtained by *Gigantochloa levis.* This comparison was aimed at evaluating the maximum fiber length to be extracted from the plant: to have fibers longer than the internode distance is only possible in case of mechanical extraction e.g., by stripping off dried bamboo culms or by other cutting procedures, which lead to bamboo slivers or bundles. All these operations enable a good separation, so that these can be able to retain their natural characteristics, as reported among others by Deshpande et al. [21], which raised a considerable concern though on the scattering of diameters and tensile strength obtained by compression molding and roller mill extraction. This method allowed in some particular cases, such as for giant bamboo (*Dendrocalamus*

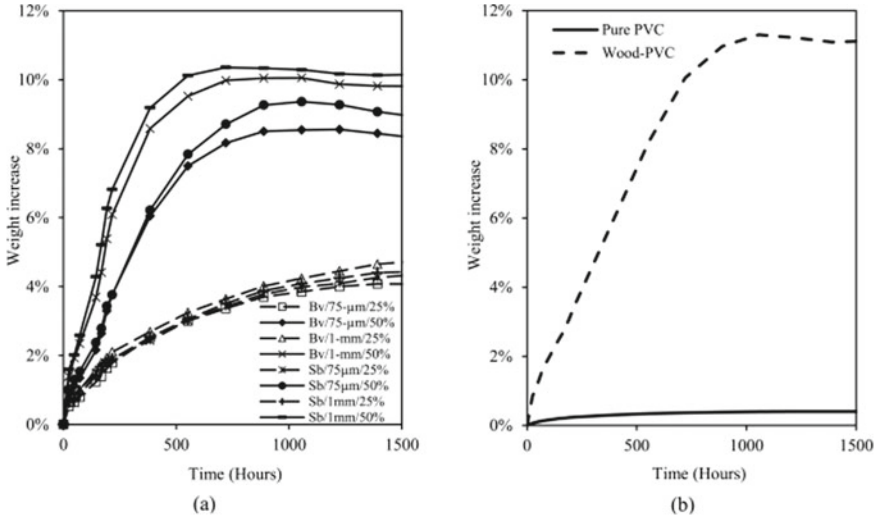

Fig. 8 Water uptake (weight increase percentage) property for all composite groups: (a) bamboo-PVC composites from different species, particle sizes and particles loading, (b) pure PVC composites and wood-PVC composites (*Note* Bv = B. vulgaris, Sb = S. brachycladum) [6]

Giganteus), obtaining fibers even more than 100 mm long, with a very variable length/diameter ratio though [51].

Other possible extraction procedures, which always follow some form of mechanical processing, normally by cutting and striping, are chemical extraction by alkali treatment using sodium hydroxide or steam explosion process. The comparison between the properties of fibers of the same bamboo species three processes which, apart from the consumption of energy and chemicals, results in disrupting the orientation of the natural bamboo fibers, therefore in a lower performance in terms of strength along the fiber direction [34]. Moreover, it is also important to notice that steam explosion can also produce the possibility of binder-less adhesion of fibers in wood-like panels as an effect of an improved isolation of phenolic hydroxyl groups of lignin [62]. Another implication of this chemical transformation is that the more effective separation of bamboo filaments obtained through steam explosion may lead to an improved flexural performance and therefore also to a tougher interface with polymer matrices, such as poly(lactic acid) (PLA) [71]. This has also been revealed effective on oil-based matrices, such as polypropylene, coupling also effectively with the traditional treatments, leading to an improved compatibility with plant fibers, such as maleic anhydride treatment [75]. The comparison among different modes of extraction has also been attempted before composites fabrication: a relevant review was provided by Zakikhani et al. [80]. In particular, bamboo fiber bundles, to be prepared for impregnation into vinylester resin, were extracted by three methods, namely steam explosion, alkali extraction, and chemical extraction, characterizing the bamboo fiber bundles for their interfacial shear strength (IFSS), improved by chemical removal of hemicellulose, and tensile properties, where all treatments proved detrimental instead [37].

4 Morphology of Extracted Bamboo Fibers and Their Properties in Composites

The objective difficulty encountered in studies on bamboo fiber reinforced composites is trying to relate morphological features of the fibers after extraction with the properties of the composites obtained. The starting point is that in natural fibers, a clear connection exists between the sectional geometry, the relevant dimension of lumen and the microfibrillar angle, therefore the winding angle by which the fibrils are turned around, and their tensile strength, as observed for example by Alves Fidelis et al. 2013. In the specific case of bamboo, the microfibrillar angle tends to be very small, in some cases as low as 2°, which results in general terms into promising tensile characteristics in fiber direction [33]. This can be very appealing for the production of bamboo fiber composites. On the other side, fibers morphology is known to be possibly modified substantially by the action of chemicals, such as it occurs for alkali treatment. In particular, the transformation from cellulose I to cellulose II, disrupting therefore the alignment of polysaccharides chains, is taking place by the effect of sodium hydroxide (NaOH) treatment, also referred to as "mercerization". Going into further detail, an increase in crystallinity has been revealed up to a concentration of NaOH equal to 15% wt. [17], which resulted in an increase into work of fracture of bamboo strips/novolac (phenol/formaldehyde) composites [18]. Another possibility to increase crystallinity is the application to bamboo fibers of heat treatment with superheated steam, which resulted up to 140 °C also into an increased stiffness of Moso bamboo fibers [77].

The change in morphology of bamboo fibers obtained using steam explosion was related to process parameters: in particular, degumming rate increased and a better separation among fibers was obtained the higher the steam explosion pressure and the longer the time this pressure was maintained. Moreover, a combination of alkali treatment and steam explosion was preferable over performing the two processes alone: as the result of combined treatment, the fibers were smoother and with smaller diameter [13].

Other than with extraction, some morphological features were observed on bamboo fibers due to the combination with specific matrices. In particular, bamboo fibers are able to contribute to the rise in crystallinity of polypropylene, also when treated with maleic anhydride (MAPP): in practice, bamboo fibers act other than reinforcement, also as nucleator of β crystallinity phase with trans-crystallinity growth [45]. On the other side, in the case of low-density linear polyethylene, despite effective mechanical/chemical extraction, leading to unbundled fibers, fiber bleaching was necessary to improve their hydrophobicity in order to obtain a sufficiently strong fiber/matrix interface [38]. However, also when using a polyethylene matrix, maleic

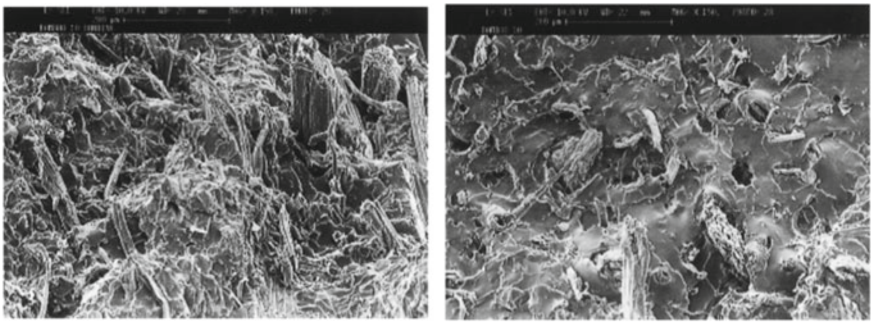

Fig. 9 Improvement of interfacial bonding between fibers in a rubber matrix bamboo composite by addition of amine-based bonding agent (micrographs 150×) [32]

anhydride treatment proved effective in increasing tensile, flexural, Izod impact properties and torque value of the composite, whereas the addition of montmorillonite (MMT) clay was more critical [25]. To further reduce the hydrophilic character of bamboo fibers in composites, particularly aiming at oil-based matrices, silane treatment was also applied to mercerized fibers, which more than halved water absorption in unsaturated polyester/bamboo composites [39].

An alternative possibility that has been also explored was the addition of bamboo fibers to a natural rubber matrix up to a 50 wt.% loading. This resulted in a considerably higher stiffness of the composite, as indicated by the subsequent increase of the Mooney viscosity, yet on the other side in a significant reduction of its tensile strength. It is worth observing though that the presence of bonding agents, namely phenol–formaldehyde and hexamethylenetetramine (HETA), solved the problem of weak interfacial bonding between fibers, as depicted in Fig. 9 [32]. This has obviously a negative influence on the sustainability of the material, although in itself a natural rubber/bamboo composite does appear already of difficult recyclability.

5 Conclusions and Future Perspective

In recent years, the use of fibrous material obtained from bamboo culms in composites has been widely explored. A number of factors can influence the success of this operation: in particular, the mode of extraction is critical: this may involve mechanical and chemical operations, would need not to damage fibers and at the same time allow obtaining sufficiently long segments, given the botanical limitations represented by the presence of nodes.

A large amount of literature exists, which concerns comparison with different fibers, with preference for the ones available in south-east Asia, such as kenaf, but more generally open also to further solutions, even to the production of hybrid composites including other ligno-cellulosic fibers together with bamboo. The polymers used include biodegradable ones, such as poly(lactic acid) and ones of more interest in the automotive and commodity industry, such as polyolefins, together with traditional thermosetting ones, such as epoxies and unsaturated polyester, which prove suitable for initial studies to propose bamboo fibers for use in this field, as a replacement for fiberglass. A difficulty appears to be also the very large number of bamboo species existing, some comparative studies on this aspect exist, yet still of limited significance. It is suggested that this will need more attention in the future to try making predictions on the possible performance of the composites to be obtained from the single bamboo species and the section and age of the plant that is used for the purpose.

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Utilization of Bamboo Fibres and Their Influence on the Mechanical and Thermal Properties of Polymer Composites

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Abstract Bamboo has been traditionally used in sports and musical equipments, household appliances, interior furnishing and decoration for many years. Other than the usefulness of bamboo in the product form, studies indicate that fibres extracted from the bamboo tree can also be used as reinforcement in composites. Bamboo fibres can be easily extracted and are available in chopped form, as long fibres and as woven mats. The bamboo fibres possess superior tensile properties and high strength to weight ratio, an important criteria for reinforcement in composite materials. This article discusses the influence of fibre parameters such as fibre orientation, fibre loading, fibre architecture, etc. on mechanical and thermal properties of the composites. Fibre treatments that has been carried out by researchers to improve the

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fibre-matrix adhesion between hydrophilic bamboo fibre and hydrophobic polymer matrix along with their mechanism and their impact in the mechanical and thermal properties has also been highlighted.

Keywords Bamboo fibre · Fibre extraction · Mechanical properties · Fibre treatment

1 Introduction

There is a mounting interest among the researchers to substitute the fibre glass and carbon fibre reinforced composites with natural fibre reinforced composites (NFRC) [1]. The foremost advantages of using the natural fibres in polymer composites are their non-abrasive nature, lower energy consumption, eco-friendly nature and abundant availability [2, 3]. Natural fibres can promote the CO_2 sequestration in the atmosphere and help in reducing the carbon foot print. In addition to these advantages, the stringent environmental regulations all around the world has also paved the way for extraction and development of new natural fibres for use in composites.

Natural fibres such as kenaf, sisal, banana, pineapple, flax, sugar palm, hemp, bamboo, jute have been extensively used as reinforcement in composites [4]. Natural fibre reinforced composites with thermoplastic and thermoset matrices have been employed in structural applications in automotive, aerospace and construction sector while it also has non-structural applications in the sports equipment, household items, etc. [5, 6]. Application of NFRC in high performance applications is still limited due to the characteristic of the natural fibres and their inferior mechanical properties. Many attempts has been made by researchers to overcome this problem as follows: (1) Modification of the fibre surface with fibre treatments, (2) Introduction of nanoparticles into the matrix, (3) hybridization with other natural fibres and synthetic fibres and (4) use of compatibilizers [2, 3, 7–9]. This review highlights recent research works on the use of bamboo fibre (BF) as reinforcement in polymer composites and the influence of fibre architecture, fibre loading and fibre treatments on the mechanical properties of composites is discussed.

1.1 Bamboo Fibres

Bamboo, a plant which belongs to the family of grasses (Poaceae), is grown for controlling soil erosion and carbon sequestration. It has many traditional applications such as musical instruments, artworks, crafted bags, tools and construction materials [10]. Other than their diversified use in applicatios, bamboo fibres can also be used as plausible reinforcement in the polymer composites. It is abundantly available in many countries and the total bamboo plantation in the world is around 22 million hectares. The global availability of bamboo fibre is over 30 million tons per year

Fig. 1 Process of making bamboo fabric mats

and over 80% of this resource is spread in Asian countries, especially in India and China [11]. Other than the use of bamboo fibre as reinforcement, recent studies show that cellulose extracted from the bamboo pulp is a bio-polymer and could be used as matrix [12, 13]. The clum of bamboo has an unique structure having many nodes along its length (shown in Fig. 1) and resembles like an unidirectional fibre consisting of cellulosic fibres surrounded in a ligneous matrix.

1.2 Extraction Methods

The clum in the bamboo plant is split into strips for the removal of the nodes as shown in Fig. 1. Extraction of fibres may be done by steam explosion or alkali extraction [14]. The steam explosion process involves heating the bamboo strips in an autoclave at around 200 °C and 0.8 MPa. The steam pressure was then suddenly reduced to atmospheric pressure to separate hemicellulose and lignin form cellulose. The process is repeated several times and the obtained fibres were washed thoroughly and dried at 100 °C overnight. The extracted bamboo fibres can be made into fibre bundles, fibre yarn and weaved into fibre mats as shown in the Fig. 1.

Similarly, in alkali extraction process, the bamboo strips were placed in a stainless steel container with 1.5 N NaOH solution. The solution was heated to at 70 °C for about 5 h and the strips were pressed in a machine. The obtained fibres were washed thoroughly and dried at 100 °C overnight in a hot air oven. For making mats the fibres were weaved and bamboo mats were obtained.

1.3 Fibre Composition and Properties

It has been reported that the structure of bamboo varies with cross section and their height. Fibre constituents such as cellulose, hemicellulose, lignin, etc. also varies from species to species. Table 1 shows the chemical composition and properties of bamboo fibres. Tensile strength and young's modulus of the bamboo fibre is between 100 MPa–600 MPa and 3 GPa–15 GPa respectively [15]. It is well documented

Table 1 Chemical composition and properties of bamboo fibres [12]

Particulars	Value
Cellulose (%)	26–43
Lignin (%)	21–31
Pentosans (%)	15–26
Ash (%)	1.7–5
Density (g/cm^3)	0.6–1.1
Tensile strength (MPa)	140–230

in the literature that mechanical properties of the bamboo fibres are influenced by their length, cross section and chemical composition.This is because fibres orient themselves along the length of the plant and it is easier to obtain long fibres of any length which are the attibutes for better mechanical properties [16].

2 Fabrication of Bamboo Fibre Reinforced Composites

Bamboo finds mounting application as a substitute to wood based products such as fibre boards, particle boards and laminated lumber, veneers, and ply-bamboo. Bamboo fibres can be utilized in various forms such as splits (2 m), filaments, macrofibres (0.25 mm), microfibres (pulp, 20 μm), or nanofibres (20 nm) etc. by applying different mechanical and chemical processing steps [10]. Many researchers have attempted using bamboo as a reinforcing material in composites. Fabrication of these composites are done by different methods such as the hot press, compression moulding, hand lay up method and casting technique etc. The fabrication method is selected based on the form in which bamboo is being used. Bamboo fibre reinforced composite with thermoplastic polymers such as polypropylene, polyethylene, polyesters, polylactic acid etc. and thermoset polymers such as epoxy, polyester, etc. has been fabricated and their properties were explored. Hebel et al. [17] fabricated epoxy based composites with unidirectional bamboo fibres in the layered structure using a hot press. Compression molding technique was used to fabricate HDPE/bamboo fibre reinforced polymer composites by Han et al. [11] Bamboo fibre–reinforced epoxy composites with different orientation of bamboo fibres were prepared by Jain et al. [18]. Lu et al. [19] extracted cellulose powder particles from bamboo fibres using a high speed universal grinder, and fabricated cellulose/epoxy composites by casting method. Khan et al. [20] fabricated composites using bamboo fibre and epoxy by the conventional hand lay-up method.

2.1 Mechanical Properties

Okubo et al. [21] used bamboo fibre as a reinforcement in PLA based hybrid composites along with microfibrillated cellulose (MFC). They reported that due to the interphase between the cellulose and the PLA matrix around the bamboo fibre, abrupt crack growth was arrested. This eventually resulted in enhanced tensile performance and further the diffusion of 1 wt% of MFC in PLA matrix drastically improved the strain energy of the bamboo/PLA composite upto 200%.

The performance of composites are mostly influenced by the physical characteristics of the polymer matrix and the reinforcing fibre. Yusoff et al. [22] fabricated hybrid green composites using PLA as matrix and kenaf, bamboo, and coir fibres as reinforcements. They employed varied combinations of fibre sequences such as bamboo-coir/PLA, kenaf-coir/PLA, and kenaf-bamboo-coir/PLA with constant weight percentages of fibre to matrix and examined their mechanical performance. Their results revealed that the kenaf-bamboo-coir/PLA hybrid composites showed the highest tensile strength and modulus of 187 MPa and 7.5 GPa respectively, while the kenaf-coir/PLA hybrid composites presented the lowest tensile properties. The highest toughness was found for kenaf-bamboo-coir/PLA hybrid composites at 4.45 MJ/m^3, while the lowest was recorded for for kenaf-coir/PLA at 0.97 MJ/m^3. The bamboo-coir/PLA hybrid composites possessed 3.54 MJ/m^3. The reason for the higher toughness was due to the optimum fraction of fibre in the composites. Further, the flexural strength of kenaf-bamboo-coir/PLA and bamboo-coir/PLA hybrids was higher than that of the kenaf-coir/PLA hybrid composites which was due to the strong interaction between the fibre cell wall and the matrix. They concluded that the bamboo and kenaf fibres compensated the lower strength of coir fibre by bearing the tensile load while the coir fibre contributed in the enhanced toughness of the hybrid green composites.

Bamboo fibres with fibre diameters in the range of 178–181 μm were extracted through steam explosion method by Biswas et al. [23] Similarly they also extracted jute fibres with fibre diameters in the range of 39–66 μm through mechanical process. Composites were prepared by reinforcing bamboo and jute fibres in epoxy matrix to compare the mechanical properties of both the composites. Their results revealved that the tensile strength of the bamboo epoxy composites was 392 MPa while for the jute epoxy composites it was only 216 MPa. On the other hand there was not much difference in the tensile modulus of these fibre composites. Simlarly, they also found the flexural properties of both the fibre composites in both longitudinal and transverse fibre distribution. When the fibres were distributed longitudinaly bamboo epoxy composites exhibited 226 MPa while jute epoxy composites exhibited 158 MPa and when the fibres were transversly oreinted jute epoxy composites possessed 25.7 MPa and bamboo epoxy composites presented 11.89 MPa. The main reason for this trend is that the bamboo fibres could not take any stress as they were aligned to the parallel direction of flexural load.

Varying contents of short bamboo fibre (10, 20, 30 and 40 wt%) reinforced polypropylene composites have been fabricated using maleic anhydride polypropylene (MAPP) as the compatablizer and characterized to determine the mechanical properties. The increase in percentage of the fibre did not influence the mechanical properties. Hence, they added 20% by mass of glass fibre and formed bamboo glass fibre hybrid composites. By incorporation of glass the tensile and flexural modulus increased by 12.5 and 10% respectively. The tensile and flexural strengths increase by 7 and 25%. The decrease in tensile properties of the bamboo fibre composites were attributed to the poor adhesion between the polymer and the matrix. Further the enhancement in the properties in bamboo glass hybrid composites were attributed to the addition of stronger and stiffer glass fibre [24].

2.2 Fibre Treatments and Compatibilizer to Enhance Mechanical Properties

The main drawback in using bamboo fibre as reinforcement is their poor adhesion with many polymers. Since, the polymers are hydrophobic and the fibres are hydrophilic in nature, there exists a low interaction between the two components. Physical and chemical modifications of fibre surface can enhance the interfacial interaction between the polymer and fibre [7, 8]. So the scope of utilizing the abundantly available bamboo lies in modification of the fibre surface to achieve better performcance of the ensuing composites.

A strong interfacial adhesion between the polymer resin and fibre is required for achieving superior mechnical properties in a fibre reinforced polymer composite. Thus, strong interfacial adhesion imparts effective stress transfer and load distribution throughout the composite. Strong adhesion between the resin and the fibre can be achieved by proper wetting of the fibres by the resin and also by the chemical bonding between the fibre surface and the matrix. Hence many researchers have attempted in chemical modification of natural fibres for improving the interfacial interaction between the fibres and the resin matrix. Zhang et al. [25] investigated the effect of fibre modification by varying concentrations of NaoH (2, 6, 10 wt%) on the mechanical properties of bamboo-based composites. It was found that the 2 wt% NaOH treatment had a minor effect on the tensile properties of bamboo fibres since 2 wt% NaOH treatment could only remove small part of the surface substances, indicating that a large amount of gummy material still existed as a constraint among cellulose chains. The tensile strength of 2 wt% NaOH treatment fibres was 283 MPa when compared to the 263 MPa strength of the untreated fibre composites. On the other hand, 6 wt% NaOH treatment yielded maximum tensile strength of 368 MPa where for 10 wt% NaOH treatment the values reduced to 235 MPa. From this study they concluded that the optimal NaOH concentration was 6 wt% which yielded the highest tensile strength. The phenomenon behind the modification of fibre surface through alkali treatment and their improvement in mechanical properties is explained. Fibre constituents such as hemicellulose, lignin, pectin, wax and other surface impurities are removed due to the immersion of natural fibres in the aqueous alkali solution. Removal of fibre constituents can cause the following physical changes to natural fibre: (1) Micropores on the fibre surface leading to rough fibre surface and (2) fibrillation which splits the single fibre into fibril strands. Both the micropores and fibrillation provides better mechanical interlocking of the treated fibre with the polymer leading to better mechanical properties [5, 6, 26]. Composites with NaOH treated fibres had lees fibre pull-out and lower fibre-matrix de-bonding (which are signs of improved interfacial adhesion) was reported by from the fractured specimens observed under scanning electron microscope [27]. Fibre treatment with alkali does not always yield improvements in mechanical properties of the NFRC. For instance, Manalo et al. found that optimum mechanical properties were obtained for polyester based composite containing 6 wt% NaOH treated fibres. Strength and modulus of the composites with 8 wt% NaOH treated fibre declined. This is because high concentration of NaOH resulted in excessive removal of hemicellulose and other constituents from the fibre. This led to weakening of the fibre and makes them less effective in stress transfer between the fibre and matrix, thus leading to lower strength and modulus [28].

In a different study, alkali pre-treated bamboo fibres were subsequently dipped in aqueous silane solution containing 3 wt% of aminopropyltrimethoxysilane (AS) and tetramethoxy orthosilicate (TMOS). It is clear from their results that both AS and TMOS treatment resulted in substantial improvement in tensile, flexural and impact strength of bamboo fibre reinforced polyproylene composites. The mechanism behind the combined Alkali-silane treatment is explained as follows: Alkali treatment promoted better interlocking between fibres and matrix while silanol groups in the silane forms a covalent bond with the hydroxyl groups of the fibre leading to better compatibility between the fibre and matrix [29].

In addition to the fibre treatment, it is also possible to add compatibilizer like Maleic Anhydride (MA) in thermoplastic matrix to enhance the fibre-matrix bonding characteristic. In a recent study, recycled polypropylene/bamboo composites were examined without and without MA compatibilizer. Bamboo fibres were subjected to mercerization and acetylation on mechanical properties of it was found that the tensile and impact strength of untreated bamboo/recycled polypropylene composites was 22.4 MPa and 2.8 kJ/m^2 respectively. The chemically modified bamboo fibre/recycled polypropylene composites exhibited better tensile and impact strength when compared to the untreated composites. It could be seen that the tensile and impact strength was 29.7 MPa and 3.8 kJ/m^2 for alkali treated composites and the same for acetylated bamboo fibre composites was 31.6 MPa and 4.2 kJ/m^2. The improvement in the properties could be due to the enhanced adhesion at the interface between fibre surface and polymer after alkali and acetylation treatments. Further the incorporation of MAPP compatibilizer led to better adhesion between fibre and matrix [30].

3 Thermal Properties of Bamboo Fibre Reinforced Composites

The thermal analysis includes a group of techniques such as (i) thermogravimetric analysis (TGA) (ii) dynamic mechanical analysis (DMA) (iii) differential scanning calorimetry (DSC) and thermomechanical analysis (TMA). These techniques can be used to determine the chemical or physical characteristics of any substance since it is cooled, heated, or held at a constant temperature. These characteristics are significant for polymer characterization; additionally, these are playing a significant role in the field of foodstuffs and pharmaceuticals [5, 6, 31]. Some of the essential factors that influence the TGA, DMA, DSC, and TMA are tabulated in Table 2. Additionally, some of the critical industrial applications of these techniques are tabulated in Table 3.

Chee et al. [32] examined the DMA and TMA properties of bamboo/kenaf/epoxy matrix hybrid composites by varying the individual fibre contents (in wt%) such as 28:12, 20:20, 12:28 (bamboo/kenaf). The performance of the hybrid composites measured by comparing individual fibre reinforced composites. The results reported that the complex modulus and storage modulus of composites exhibited in the order, bamboo composite > 20:20 > 28:12 > 12:28 > kenaf composite > epoxy matrix. Furthermore, the 20:20 hybrid composites effectively transformed the loads and showed the lowest value of the coefficient of effectiveness. Regarding the dimensional stability, the 20:20 hybrid composites performed well than the rest of the counterparts. Furthermore, the bamboo/kenaf/epoxy matrix composites were subjected to accelerated weathering, and the thermal stability was compared with that of before weathered composites [33]. Interestingly, after weathered hybrid composites [i.e.,

Table 2 Influential factors of the thermal analysis techniques

TGA	DMA	DSC	TMA
Heating rate	Type of load	Furnace heating rate	Specimen preparation
Heat of reaction	Frequency	Furnace atmosphere	Stress (load)
Furnace atmosphere	Tightening torque	Recording speed	Specimen geometry
Geometry of crucible	Clamps	The geometry of sample holders	Starting temperature
Characteristics of samples	Temperature program	Location of sensors	Heating rate
	Specimen geometry	Pan type	Type of load
		Sample size	
		The solubility of evolved gases in the sample	
		Heat of reaction	
		Thermal conductivity	

Table 3 Different applications of the thermal analysis techniques

TGA	DMA	DSC	TMA
Automotive	Automobile and aerospace	Automotive	Plastics
Chemical	Chemical	Chemical	Electronics industry
Fats and oils	Fats and oils	Fats and oils	Paints
Rubber	Paints and lacquers	Paints	Textile fibres
Plastics	Rubber	Rubber	Film packings
Food industry	Plastics	Food industry	Chemicals
Pharmaceuticals	Ceramic materials	Pharmaceuticals	
	Food industry		
	Pharmaceuticals		

the mass ratio of 28:12 (bamboo/kenaf)] showed higher thermal stability in TGA; also, the complex modulus of the all the weathered composite samples were shifted to higher magnitudes. It was ascribed to the increased cross-linking reaction due to the ultraviolet radiation.

In another work, Chee et al. [34] observed the pyrolysis decomposition properties of bamboo/kenaf/epoxy matrix composites under the presence of oxygen and nitrogen gases. They reported that the decomposition temperatures were not varied by changing the working atmospheres; however, the initial decomposition temperature was shifted to the lower range, and the mass loss was observed between 450 and 600 °C. Moreover, (i) the mass ratio of 28:12 (bamboo/kenaf) hybrid composites exhibited higher thermal stability and thermo-oxidative property and (ii) the oxidation onset temperature was found to be reduced with increasing the content of natural fibres in an epoxy matrix due to the existence of hydroxyl group.

In another study, Chee et al. [34] compared the thermal stability of bamboo charcoal mat composites with the bamboo/epoxy and kenaf/epoxy matrix composites. Amongst the composites, the bamboo charcoal mat composites performed well,it was ensured by witnessing their higher temperatures from the initial and final decomposition level than the rest of the epoxy matrix composites. Nevertheless, the mechanical properties of the bamboo charcoal mat composites showed lesser than the bamboo/epoxy matrix composites. Some of the reported studies on thermal analysis techniques are tabulated in Table 4.

Another interesting study made by the researchers [44]. reported that the thermal properties of wood-plastic composites improved by incorporating bamboo charcoal as reinforcing filler, whereas the bamboo charcoal was varied in the ranges of 2, 4, and 8%. By adding 8% of bamboo charcoal, the char residue of the wood-plastic composites almost hit 13% also showed higher thermal stability. In other research work, found that increasing the content of bamboo fibril in poly- hydroxybutyrate (PHB), the thermal stability of the composites was found to be enhanced. For instance, the weight loss of pure PHB, 5 wt% of bamboo fibril/PHB, and 30 wt% of bamboo fibril/PHB were recorded as 85.26%, 80.57%, and ~60% respectively at 300 °C [45].

Table 4 Reported work on thermal characterization techniques

Reinforcement	Matrix	Characterization technique	References
Bamboo fibre	Polylactic acid	TGA	[35]
Bamboo particles modified by sodium silicate	Polyvinyl chloride	DSC	[36]
Bamboo powder	Polypropylene	TG–DTA	[37]
Bamboo fibre	High-density polyethylene	DMA	[11]
Bamboo fibre	Polypropylene/polylactic acid	TGA, DSC	[38]
Bamboo fibre was modified by sodium meta-periodate	Polypropylene	DSC	[39]
Bamboo charcoal	Ultra-high molecular weight polyethylene	DSC	[40]
Bamboo/jute	Low-density polyethylene	TGA, DSC	[41]
Bamboo fibre	Polyvinyl chloride	TGA, DSC	[42]
Bamboo fibre	Polypropylene	DSC	[43]

Ren et al. [46] compared the thermal stability of bamboo pulp fibres/high-density polyethylene (HDPE) and bamboo flour/HDPE matrix composites by analyzing the TGA thermograms. They varied the contents of bamboo pulp fibres between 5 and 50% while the bamboo flour was fixed as 50%. It was reported that the initial degradation temperature, i.e., ($T_{5\%}$) of the bamboo pulp fibre/HDPE matrix composites was found to be decreased with increasing the fibre content; however, the carbon residues showed an opposite trend. The better thermal stability of composites was ensured by comparing the initial degradation temperatures of bamboo pulp and bamboo flour reinforced composites with 50 wt% of fibre contents. The former was exhibited higher initial degradation temperature (i.e., 20.18%) than later.

In another work, Xian et al. [47] examined the thermal properties of bamboo residue fibre/polyethylene composites after introducing white mud as a secondary filler. The hybrid composites were fabricated by varying the contents of white mud from 0 to 22% and maintaining the bamboo residue fibre as 50% in all the samples. They reported that the char residue of the hybrid composites was found to be increased from 7.56 to 33.55% (until 18% addition of white mud); however, the initial degradation temperature (i.e., $T_{5\%}$, °C) was found to be decreased.

Another study illustrated that the thermal stability of bamboo fibre/polypropylene composites was observed to be enhanced by the addition of maleic anhydride grafted polypropylene (MAPP) [48]. It was ascribed to the increased molecular weight by the cross-linking reaction between the bamboo fibre and the polypropylene matrix. Furthermore, the thermal stability of these composites was found to be improved by incorporating (i) the glass fibres (15%); it was attributed to the higher thermal stability of glass fibre than the bamboo fibre. Regarding the DSC thermograms, the melting temperature of the polypropylene matrix (162 °C) was not changed by the addition of bamboo fibre, glass fibre, and MAPP. However, the degree of crystallization was found to be reduced. The degree of crystallinity of composites increased by incorporating the fibres in polypropylene. Nevertheless, the crystallinity was found to be decreased with the addition of MAPP in bamboo/polypropylene and bamboo/glass/polypropylene composites; it was attributed to the improved interfacial adhesion between the fibres and the polypropylene. Furthermore, the storage modulus of bamboo/glass fibre reinforced hybrid composites were increased by showing higher stiffness values than the pure polypropylene matrix and untreated fibre reinforced composites.

Researchers found that increasing the content of cellulose nanowhiskers (i.e., which was extracted from the bamboo pulp residue of newspaper production) from 2.5 to 10 wt% within the natural rubber, and the onset degradation temperature was shifted from 273 to 278 °C [49]. Moreover, the degradation temperature was shifted from 275 °C (natural rubber) to 350 °C (nanowhiskers/natural rubber) in the derivative thermogravimetry (DTG) curve. The improvement of degradation temperatures of these composites was ascribed to the decreased movement of the natural rubber phase in the vicinity of nanowhiskers. Yao et al. [50] reported that the effect of fibre loading on bamboo fibre/polylactide biocomposites was depended on the bamboo fibre loading. They observed that the glass transition temperature and melting temperature of the bamboo/polylactide composites were found to be increased initially and decreased with increasing the content of bamboo fibres. These observations were suggested to enhance the segmental motion of the polylactide.

The thermal stability of bamboo fibre reinforced composites were studied by (i) comparing untreated, and NaOH treated fibre composites (ii) varying the fibre loading (0–40%) and (iii) introducing three different types of the matrix such as polyester, epoxy and vinyl ester [46]. It was observed that the neat matrix (i.e., polyester, epoxy and vinyl ester) exhibited higher residues than their respective matrix- fibre reinforced composites. While considering the effect of fibre loading, 40% of fibre loaded epoxy and vinyl ester reinforced composites showed the highest residues than the rest of the fibre loaded composites. However, 40% of fibre loaded polyester matrix composites showed the lowest char residue; it was attributed to the increased interactions between the fibre and the polyester matrix. Furthermore, the thermal stability of bamboo fibre reinforced composites did not show the differences in onset degradation temperatures. Therefore, the degradation temperatures at 5 and 50% of weight losses were observed, including the different fibre loaded composites. The pure matrix samples showed higher degradation temperatures. In the case of fibre loaded composites, there was a decreasing trend noticed by increasing the fibre content; it was ascribed to the degradation of non-cellulosic substances [46].

Tang et al. [51] analyzed the thermal stability of bamboo fibre/phenolic foam composites by (i) varying their fibre lengths such as <1 and 1–3 mm and (ii) increasing the fibre loadings such as 1.5, 2.5, and 3.5%. They observed that the char residues at 600 °C were decreased with increasing their fibre loadings, which was associated with the lower thermal stability of bamboo fibre. However, there were no significant differences observed by varying the fibre lengths. In another interesting study, the effects of $CaCO_3$ treated bamboo pulp fibre/high-density polyethylene composites were studied by DMA and DSC techniques [52]. The thermal stability of these composites was analyzed by (i) varying the fibre loadings from 30 to 50 wt% and (ii) introducing three different manufacturing methods such as extrusion molding, hot press molding, and injection molding. Regarding the DMA results, the storage modulus and loss modulus of the extrusion molded composites (30% of fibre treated composites) exhibited higher than the rest of the manufacturing methods. The damping characteristics of the bamboo pulp fibre/high-density polyethylene composites were influenced by $CaCO_3$ treatment, fibre content, and fabrication technique. The crystallinity index of these composites was examined by using the DSC technique. It was observed that the $CaCO_3$ impregnated modified bamboo fibre reinforced composites showed a higher crystallinity index; it was ascribed to the increased interfacial bonding between the matrix and the $CaCO_3$. However, increasing the fibre content in hot press molded composites, the crystallinity index was found to be decreased. But it was not in the case of extrusion and injection molded composites. This observation showed the significance of varying fibre content and using different fabrication techniques [52].

Shih [53] compared the thermal stability of untreated bamboo fibre/epoxy and silane treated bamboo fibre/epoxy matrix composites. The TGA results reported that the char residues were increased from 8.9% (epoxy sample) to 13.6% due to embedding the fibres in the epoxy matrix. Regarding the DMA results, the silane treated bamboo fibre reinforced composites exhibited higher in storage modulus and loss modulus. For instance, the glass transition temperature of the pure epoxy matrix was shifted from 58 to ~75 °C due to the addition of bamboo fibres. In another work, the interfacial bonding characteristics of bamboo fibre/poly (lactic acid) was improved by using (i) NaOH treatment (ii) alkali and silane coupling agent and (iii) alkali and titanate coupling agent [54]. Furthermore, the thermal stability of these composites was subjected to TGA and DSC techniques. From the results, it was reported that the untreated bamboo fibre/poly (lactic acid) composites showed lower thermal stability than the pure poly (lactic acid) samples. However, the chemically-treated composites showed higher degradation temperatures than the pure poly (lactic acid) samples. Amongst the composites, the NaOH treated bamboo fibre reinforced composites showed the highest thermal stability than the rest of the composites. Regarding the DSC parameters, the bamboo fibre/poly (lactic acid) composites showed higher glass transition and melting temperatures than the pure poly (lactic acid). Moreover, these temperatures (i.e., glass transition and melting temperature) were found to be improved after the chemical treatments; it was attributed to the improved interfacial adhesion between the fibre and the matrix [54].

4 Conclusions and Future Perspective

In this article, factors influencing the mechanical and thermal properties of composite reinforced with bamboo fibres were reviewed. It could be observed from studies that strength and modulus of the composite were dependent upon the physical characteristics of the fibre such as fibre diameter, fibre loading, fibre orientation in the composite and presence of other natural fibres in hybrid form. Compatibility between the natural fibres and polymer matrix is also pivotal for achieving superior mechanical and thermal properties. Modification of the fibre surface with alkali, silane and acetylation was found to improve the wettability between the bamboo fibre and various polymer matrices. Alkali treatment removes fibre constituents such as cellulose, hemicellulose, lignin, etc. and leads to micropores or fibrillation on the fibre surface leading to better mechanical interlocking. Further, the chemical modification also improves the thermal stability especially the glass transition and melting temperatures of the composites by improving the interfacial adhesion between the fibre and the matrix. Silane acts as a coupling agent and forms a covalent chemical bond between the fibre and matrix. Maleic Anhydride, when mixed with thermoplastic polymers acts as a compatibilizer and improves the fibre-matrix bonding leading to improvement in the mechanical and thermal properties of the composites. Based on the studies and the reports it is sure that bamboo fibres can find enormous potential in the future in engineering applications.

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Free Vibration Analysis of Bamboo Fiber-Based Polymer Composite

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Abstract The present work aims to study the free vibration and damping properties of pure bamboo bioepoxy composites (B), pure basalt bioepoxy composites (b), and bamboo/basalt fiber reinforced hybrid bioepoxy composites. The pure and hybrid composites were fabricated by hand layup technique with different layering sequences such as BBBB, bbbb, BbBb, BBbb, BbbB, and bBBb. Experimental modal analysis was performed to obtain the natural frequency and the damping characteristics of the fiber reinforced composites. Variations in the natural frequency and

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damping characteristics were noticed with different layering sequences of the fiber in the composites. For instance, a higher natural frequency was obtained when bamboo fiber was stacked on the top surface and an enhanced damping behavior was noticed when basalt fibers were used as skin layer in hybrid composites. Numerical analysis was performed and the results were compared with the experimental results.

Keywords Bamboo fiber · Basalt fiber · Hybrid composites · Free vibration test · Natural frequency · Damping

1 Introduction

The need for bio-based composite materials is increasing rapidly in the industrial sector after the implementation of the various pollution norms around the world [16]. Many researchers are working on the development of the new combinations of composites with synthetic and natural fibers [6, 9, 15]. The investigations on synthetic fiber-based composites are slowly diminishing due to their negative effect on the environment. On the other hand, the usage of natural fibers in composite materials is slowly increasing, and lots of explorations had been witnessed in the past decade. This shows their positive impact on the environmental aspects. Industrial sectors like the automotive, construction, aviation, packaging, marine, and manufacturing use natural fiber based composites for different applications [25, 29]. Even though many cheaper alternatives have been identified to replace the synthetic fibers, still the synthetic polymers/resins systems are dominating because of the high cost of the bio-based polymers. However, material scientists are working rigorously towards the development of cheaper natural-based resins [29].

In this scenario, bio-based composites and some of their significant properties such as, mechanical, thermal behavior, water absorption, vibration, and damping, need to be studied at a broader level. Mechanical, thermal and sorption properties of bio-based composites are well investigated by many researchers. However, the vibration and damping characteristics of bio-based composites still need more exploration. Damping is an effect that reduce the vibratory motion. The damping coefficient of the material indicates the material's response to the unwanted shocks or vibrations. The high damping coefficient will diminish unwanted shocks or vibrations very quickly. In other words, it measures how quickly the unwanted shocks or vibrations weaken. It is one of the essential properties where researchers need to work on; improvement in these properties in natural fiber-based composites can potentially replace many conventional materials used in different industrial sectors [13].

The vibrational study on fiber reinforced composite materials started in the earlier 1950s, when the development of the synthetic fiber composites was booming. Nevertheless, vibrational studies on natural fiber reinforced composites were reported only in the last decade and still needs further exploration. Further, finite element analysis of the fiber composites was also conducted using computer code earlier, in which the three-dimensional finite element analysis of rubber like materials was made under the different conditions. This revealed that the fiber orientation, fiber length, and fiber volume fraction could influence the vibrational behavior of the composite materials [28].

The vibrational properties of coconut sheath and glass fiber reinforced polyester composites using the impact hammer technique was reported earlier [21]. The natural frequency of hybrid composites was influenced by the addition of clay content, whereas the maximum increase of dynamic properties was reported up to 3wt%. Recently researchers investigated the effect of varying the fiber stacking sequence on dynamic properties of coconut sheath (C)/banana (B) fiber reinforced polyester composites [23]. The CBC layering sequence exhibited the most significant damping factor. It was evident that the properties of the hybrid composites can be improved by varying the fiber stacking sequences. Researchers also investigated the vibrational properties of the coconut sheath (C) and sisal (S) fiber reinforced polyester composites. The composites containing more wt.% of coconut sheath than the sisal fiber (i.e., CCS) displayed an increased natural frequency [12].

The investigation on the effect of varying the layering sequence of the coconut sheath (C) and sansevieria cylindrica fiber (S) reinforced polyester composites showed that fibers possessing higher tensile modulus positioned as skin layer in hybrid composites (i.e., CSC) produced an increased natural frequency [1]. Researchers examined the dynamic properties of short fibers such as sisal and banana in polyester matrix composites by varying the fiber lengths and fiber loadings. The maximum damping was observed at 4 mm/40wt% for the banana, and 5 mm/40wt% for the sisal fiber reinforced composites. It was ascribed to the fiber surface morphology variations between the two natural fibers [11]. In another work, a comparative study was reported on flax woven sheath and glass fiber reinforced epoxy composites. The composites reinforced with flax fiber exhibited improved damping property than the composites reinforced with glass fiber [18]. Recently the dynamic properties of banana and jute fiber reinforced hybrid polyester composites were investigated. The highest damping was observed in huckaback (i.e., type of woven) woven composites due to their improved interaction between the fiber and matrix [19]. The effect of fiber orientation on the vibration properties of sisal fiber reinforced polyester composites showed that the higher natural frequency was obtained by orienting the fibers in 0° as skin layers, while the lowest natural frequency was found for fibers with 90° orientation placed at the top and bottom surfaces of sisal fiber reinforced composites [26].

In this present work, an attempt was made to study the free vibration, and damping properties of completely biobased hybrid composites having bioepoxy as the matrix and natural fibers such as bamboo and basalt as the reinforcement materials. The hybrid composites were fabricated with four-layered sequences by using the woven bamboo and woven basalt fiber. The fabricated hybrid composites were tested for natural frequency and damping with the effect of different layering sequences.

Table 1 Properties of bioepoxy matrix and hardener

Bioepoxy matrix		Hardener (SD surf clear)	
Aspect/colour	Clear liquid	Aspect/colour	Liquid/clear
Storage	2-years, crystallization free	Typical reactivity	Standard
Viscosity (m.Pa.s ± 20%) at 25 °C	800	Viscosity (m.Pa.s ± 20%) at 25 °C	40
% bio-based Carbon content	50–58	% Bio-based Carbon content	0
Density @ 20 °C ± 0.005	1.198	Color (Gardner)	1 max
Refractive index @ 25 °C + 0.5%	1.5350	Density @ 20 °C ± 0.005	0.958

Table 2 Properties of bamboo and basalt fiber [8, 22]

Properties	Bamboo fiber	Basalt fiber
Density (kg/m^3)	910	2800
Tensile modulus (GPa)	35.91	89
Tensile strength (MPa)	503	2800
% Elongation	1.4	3.15

2 Experimental

2.1 Materials

The bioepoxy matrix (SR Greenpoxy 56®), a produce having 56% of its molecular structure coming from the plant origin, was kindly gifted for the research work by Sicomin epoxy systems, France. The weight ratio of bioepoxy and hardener was 100:37. The salient properties of the bioepoxy matrix and the hardener are presented in Table 1. Bidirectional bamboo fiber mat and basalt fiber mat were used in the present study. These fibers were purchased from local sources in North Bangkok, Thailand. The properties of the fibers are presented in Table 2.

2.2 Fabrication of Composites

In this present study, the different combinations of bamboo/basalt fiber reinforced hybrid composites (Fig. 1) were fabricated by hand layup technique. The bioepoxy and the SD surf clear were mixed in the weight ratio of 100:37. The mould was coated with silicone spray for easy removal of the test samples. After the application of the releasing agent, the fibers were layered as per the designated combinations. The epoxy and the hardener mixer were poured between the fiber layers to improve

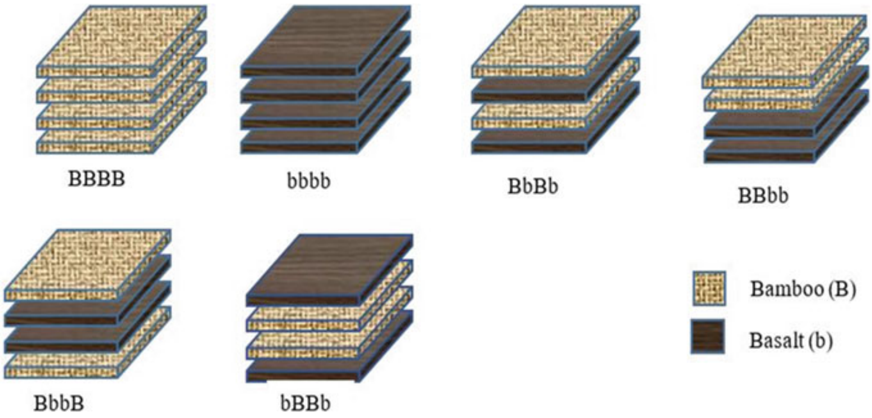

Fig. 1 Different layering sequences of bamboo/basalt fiber reinforced bioepoxy hybrid composites

the infiltration into the reinforcement and to enhance the fiber settlement. Then the excess mixer was removed carefully by a roller, and the steel mould was closed on top. The mould was left for curing for the next 24 h at room temperature, followed by post-curing at 80 °C for 2 h.

2.3 Modal Analysis

Modal analysis of the bamboo/basalt fiber reinforced hybrid composites was performed by impact hammer technique (Kistler model 9722A500), and the test was conducted according to ASTM E756—05 (2017).

3 Results and Discussion

3.1 Natural Frequency and Damping Behavior of Woven Fiber Reinforced Hybrid Composites

Modal analysis is used to study the dynamic behavior of any material such as natural frequency, damping, and mode shape. The dynamic properties depend upon many factors such as weight of the material, stiffness, area, moment of inertia, etc.[23]. Understanding these dynamic behavior helps in formulating new materials for vibration and noise applications such as aerospace, automotive, golf clubs, tennis rackets, civil structures, biomechanical, and acoustical instruments. The design of structural applications requires a reduction of resonance amplitude and increasing the fatigue

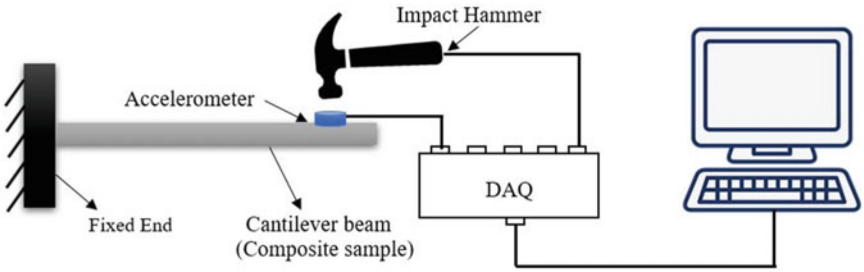

Fig. 2 Schematic diagram of free vibration experimental setup

life of the structures due to the near-resonant vibrations under the sudden applied load or force.

A free vibration test is a commonly accepted technique. A schematic representation of the vibration set up is shown in Fig. 2. In this experiment, the impact hammer was used to apply a force at the free end of the composite sample, whereby the composite sample was fixed like a cantilever beam. Due to this excitation, the response of the composite sample was received with an accelerometer attached at the free end of the sample (shown in Fig. 2). Consequently, the calculated frequency response function (FRF) generated the information about (i) the natural frequency and (ii) the damping [5]. If any sample or object vibrates equivalent to the natural frequency, the vibration amplitude of the object could increase predominantly which would lead to failure.

The FRF is referred to as the ratio of output response of the material to the applied force. The response of the material could be displacement and velocity or acceleration. These measurements acquired by the Fast Fourier Transform (FFT) analyzer or data acquisition system (DAQ), coupled with some software (e.g., DEWESoft) that could perform the FFT [27].

As an example, the measured response of the composite sample (BBBB) is presented in Fig. 3a, where the amplitude was changed continuously (i.e., increment and decrement in amplitudes at various points as sweep up in time). It could be ascribed to the rate of change of oscillation of the input force. Besides, the response of the composite sample was amplified as the applied force with the rate of oscillation that reached closer and closer to the resonant frequency (i.e., the natural frequency) of the composite sample and reached a maximum when the rate of oscillation was at the resonant frequency of the composite sample. The time data were then taken and transformed into the frequency domain with the help of DAQ, which could compute the FRF. As an example, the FRF of BBBB is presented in Fig. 3b, which shows the peak values corresponding to the stiffness of the BBBB fiber reinforced composites.

Generally, a deformation pattern occurs when applying a force that matches the natural frequency of the sample. If the force matches with the first natural frequency, it corresponds to the first bending deformation (Mode I), and if the force matches with the second natural frequency, it is referred to as the first twisting deformation (Mode II). Similarly, for the third natural frequency, it is referred to as the second

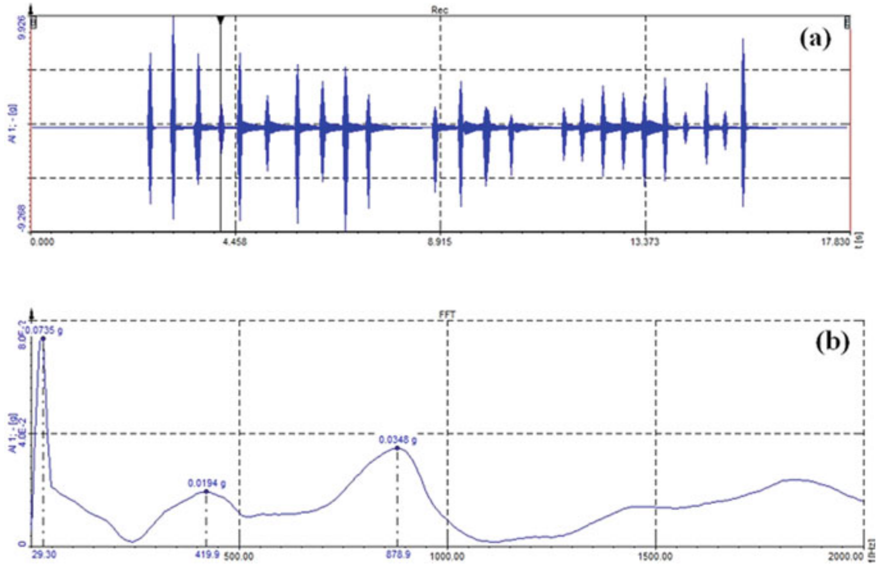

Fig. 3 **a** Increasing the rate of oscillation and, **b** frequency response function (FRF) of pure bamboo fiber reinforced composites (BBBB)

bending (Mode III) deformation. All the deformation patterns are also called a mode shapes of the composite sample [27].

Nowadays, the fiber reinforced composites are found to be promising alternatives for conventional materials. This could be attributed to their high specific stiffness, high specific strength, and tailorable properties. Moreover, the fiber reinforced composites have more viscoelastic nature than the elastic nature, which can exhibit higher damping [3, 24]. Hence, they are vastly recommended for high-performance applications.

Damping is a noteworthy factor in analyzing the dynamic characteristics of fiber reinforced composites. The damping could be enhanced by using active and/or passive damping control systems [7]. The active damping control system needs (1) sensor and actuators (2) source of power and (3) a compensator, which can give better performance under the vibratory conditions. While the passive damping requires (1) the use of structural changes (2) damping materials and/or (iii isolation method; the passive damping control system uses the materials' inherent ability to dissipate vibrational energy. Furthermore, the system complexity is considered to be lesser in the case of the passive control system. Hence it is effectively contributing to improving the reliability of structures [7].

The improvement of damping characteristics of fiber reinforced composites is typically based on micro-mechanical and macro-mechanical approaches. In the micro-mechanical approach, the improved damping could be achieved by optimizing (1) the fiber $[\frac{length(L)}{diameter(D)}]$ ratio and the fiber orientation (2) the fiber interaction (3) the fiber to matrix interface bonding and (4) the fiber coatings. While the macro-mechanical approach involves (1) lamina orientation (2) coupling effect (3) damping tape (i.e., a viscoelastic material sandwiched) (4) co-cured damping layers (5) lamina hybridization and lamina layering sequence [3].

In general, the damping is measured by using the vibration test of small-sized samples, where the samples are subjected to (1) flexural vibrations (2) extensional and/or torsional vibrations. For example, the damping of BbbB composites was measured by the half-power bandwidth method (as shown in Fig. 4). Figure 4 shows the intersection of the line obtained from the FRF curve. The maximum amplitude was obtained from the peak of the FRF curve, and the half-power points were obtained from 3 dB below the peak curve of the respective mode when the logarithmic scale was used and $\frac{1}{\sqrt{2}}$ of the peak value was used for the linear scale, as shown in Fig. 4. Hence the damping (ξ) was calculated based on Eq. (1) by the half-power bandwidth method [11].

$$\xi = \frac{\Delta\omega}{2\omega n} \tag{1}$$

where

$\Delta\omega$ bandwidth
ωn natural or resonant frequency.

The first three modes of natural frequencies were calculated by using the free vibration test, and the values are presented in Table 3. From Table 3, it is evident that the natural frequency of the BBBB and the bbbb were 29.3 Hz and 19.53 Hz, respectively. This could be due to the higher mass of basalt fiber than the bamboo fiber

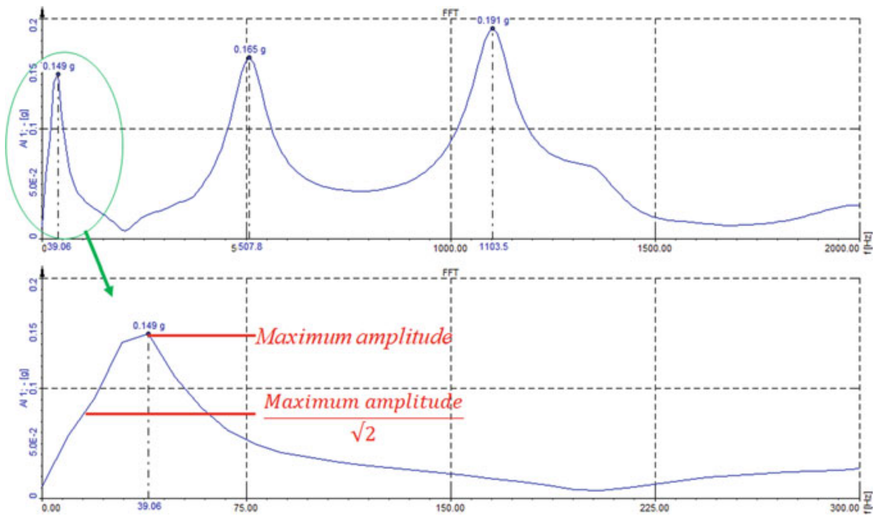

Fig. 4 Damping calculation of BbbB composites from the half-power bandwidth method

Table 3 Free vibrational characteristics of the bamboo/basalt fibers reinforced hybrid bioepoxy composites

Layering sequence	Natural frequency (Hz)			Damping		
	Mode I	Mode II	Mode III	Mode I	Mode II	Mode III
Bioepoxy	29.3	195.3	449.2	0.12948	0.01942	0.00845
BBBB	29.3	419.9	878.9	0.20446	0.01427	0.00682
Bbbb	19.53	449.2	878.9	0.14546	0.00632	0.00323
BbBb	39.06	410.2	986.3	0.09390	0.00894	0.00372
BBbb	39.06	546.9	849.6	0.06235	0.00445	0.00287
BbbB	39.06	507.8	1103.5	0.08047	0.00619	0.00285
bBBb	29.3	449.2	1103.5	0.14274	0.00931	0.00379

for a constant fiber length [17, 22]. Further, the mass of the basalt fiber was increased by the addition of bioepoxy for fabricating the basalt fiber reinforced composites. Owing to this inertial effect, an increase in stiffness of basalt fiber composites was dominated by the mass of the basalt fiber; hence, a reduction in the natural frequency could be witnessed.

It can also be observed from Table 3 that the combination of bamboo and basalt fiber reinforced hybrid composites exhibited higher natural frequencies than the pure fiber reinforced composites (i.e., BBBB and bbbb). It could be due to the improved interfacial adhesion between the bamboo fiber, basalt fiber, and the bioepoxy matrix. A tensile test was conducted according to ASTM: D 3039–08 for examining the reasons for such higher natural frequency possessed by the hybrid composites. From the tensile tests, it was revealed that the tensile strength of hybrid composites had ranged between 72 and 94 MPa, whereas the BBBB and bbbb were found to be 38 and 154 MPa, respectively. The improvement in the interfacial adhesion between the hybrid fibers (i.e., bamboo and basalt) and the bioepoxy was witnessed by obtaining an intermediate behavior between the tensile strengths of BBBB and bbbb. Similar studies were done on coconut sheath and banana fiber reinforced polyester hybrid composites, and the results reported that the hybrid composites produced higher natural frequency than the pure fiber reinforced composites [23]. In another study, coconut sheath/sisal fiber/polyester composites showed higher natural frequency than the pure fiber reinforced composites, i.e., coconut sheath/polyester and sisal fiber/polyester composites [12].

Table 3 shows the damping values of the pure fiber, and the hybrid fiber reinforced bioepoxy composites. It can be observed from Table 3 that the BBBB composites exhibited higher damping (0.20446) than the bbbb composites (0.14546). It is well known that the fibers and bioepoxy possessed elastic behavior and viscoelastic behavior, respectively. Further, it is expected that the bamboo fiber could intake more amount of bioepoxy during fabricating their corresponding fiber layered composites when compared to the basalt fiber reinforced composites. This is due to the larger diameter of bamboo fiber (10–30 μm) than the basalt fiber (9–24 μm) [10, 30].

Accordingly, the bamboo fiber reinforced composites (BBBB) could exhibit more viscoelastic nature, which resulted in increased damping.

When hybridizing the two fibers (i.e., bamboo and basalt) with bioepoxy, the damping values were found to be decreased significantly. According to Chandra et al. [3], the interfacial bonding between the fiber and matrix would influence the mechanical and damping properties. Further, the authors reported that the enhanced interaction between the fiber and the matrix could support to transfer the loads effectively as well; it could lead to enhance the mechanical properties. However, there was no help in terms of improving the damping properties. Henceforth, the hybrid composites exhibited lesser in damping than the pure fiber reinforced composites.

Figure 5 shows the comparison of damping results available from the earlier reported literature with the present work. From Fig. 5, it can be observed that the combination of bamboo and basalt fiber reinforced hybrid composites was found to be superior to the earlier reported studies [2, 4, 14, 20]. Hence these hybrid composites could be a potential replacement for low and medium load structural applications.

In the numerical study, the bamboo and basalt fiber reinforced hybrid composites were modeled by ANSYS Workbench R17. The frequency was set up between 0–1100 Hz, and the element type was chosen as BEAM188. Furthermore, the material properties such as Young's modulus and density were given based on the experimental test results. The experimental and numerical results of the bamboo/basalt fiber reinforced composites were shown in Table 4. It showed a good agreement between the experimental and numerical results. Then the mode shapes (such as Mode I, II, and

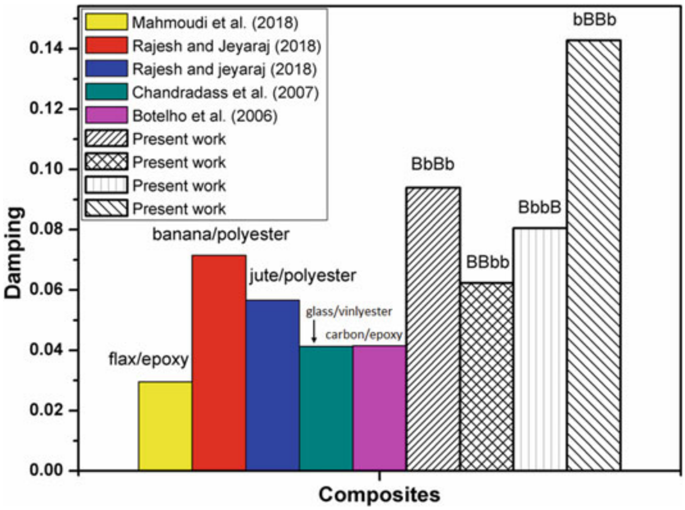

Fig. 5 Damping of different types of composites from available studies [2, 4, 14, 20]

Table 4 Comparison of experimental natural frequencies with numerical results

Layering sequence	Natural frequency (Hz)					
	Experimental			Numerical		
	Mode I	Mode II	Mode III	Mode I	Mode II	Mode III
Bio epoxy	29.3	195.3	449.2	29.844	224.25	438.37
BBBB	29.3	419.9	878.9	47.717	315.69	878.91
bbbb	19.53	449.2	878.9	49.945	330.5	874.08
BbBb	39.06	410.2	986.3	56.298	372.49	985.22
BBbb	39.06	546.9	849.6	45.162	298.84	844.95
BbbB	39.06	507.8	1103.5	40.009	700.17	1368.8
bBBb	29.3	449.2	1103.5	30.575	535.06	1046

III) of bBBb hybrid composite obtained from the commercial software ANSYS were given in Fig. 6a–c, whereas the composite was modeled in cantilever beam condition.

Conclusion and Future Perspective

- The bamboo and the basalt fiber reinforced hybrid bioepoxy composites were fabricated by hand layup technique with four different layering sequences.
- The experimental test (i.e., free vibration technique) was performed to estimate the dynamic characteristics such as natural frequency and damping of the pure and the hybrid fiber reinforced composites.
- The natural frequencies increased by changing the layering sequences between the bamboo and basalt fibers in bioepoxy. Nevertheless, the hybrid composites showed no significant changes in Mode I while the pure fiber reinforced composites (i.e., BBBB, bbbb) exhibited higher damping than the hybrid fiber reinforced composites.

Based on the results attained from the present work, the developed hybrid composites could be used in structural applications where the improved dynamic characteristics are anticipated.

Further work is necessary to eliminate the errors in FRFs due to the added transducers or mass loading effects. These errors need to be eliminated before they are used for any further analysis purposes.

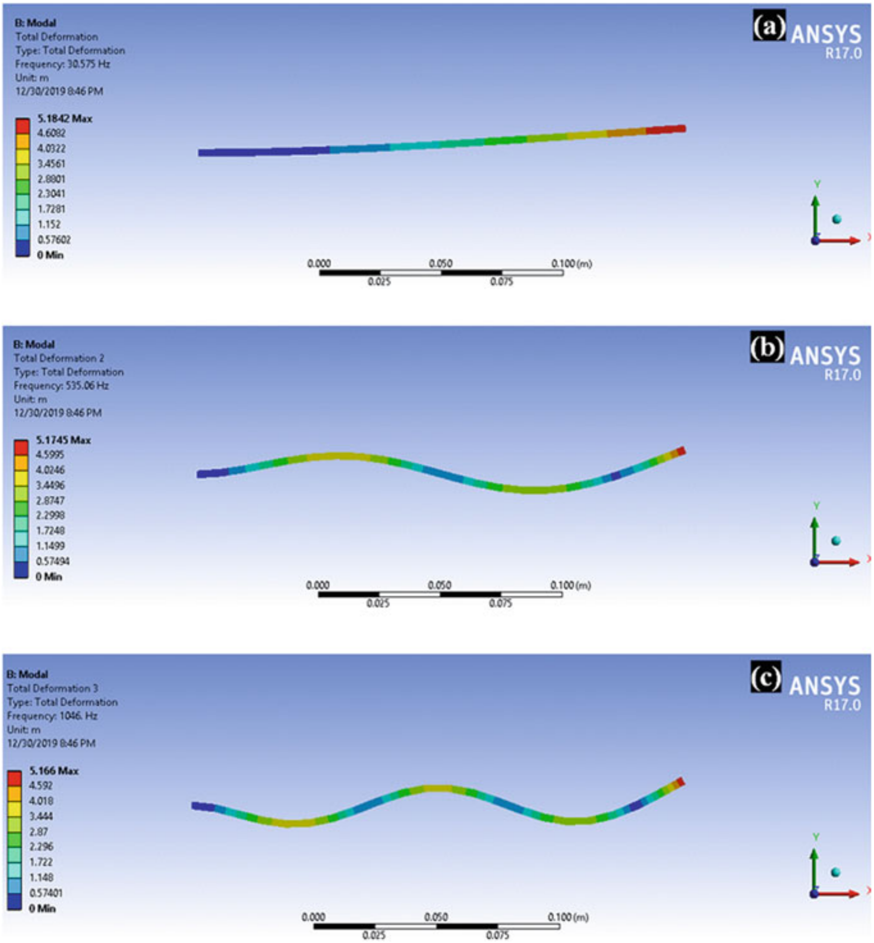

Fig. 6 The first three modes of bBBb fiber reinforced bioepoxy hybrid composites. **a** Mode I, **b** Mode II and **c** Mode III

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Effect of Chemically Treated Bamboo Fiber Reinforcement on the Dielectric Properties of Epoxy Composites

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Abstract In the present investigation, the bamboo fiber incorporated epoxy-based composites were manufactured with chemically treated and raw bamboo cellulose fibers. The electric modulus, dielectric constant, alternating, and direct current conductivity investigations were performed to justify the dielectric properties of bamboo fiber reinforced epoxy laminates. The electric modulus and dielectric properties of the epoxy composites were measured from traditional impedance analyzer equipment. The dielectric behaviors were characterized by frequency function (0.01 Hz to 1 MHz) for the range of temperatures between 30 and 150 °C. The conductivity, volume resistivity, dissipation parameter, and dielectric constants of ERRBT epoxy composites were higher than that of ERSBT, and ERSABT epoxy composites. The activation energy, volume resistivity, and dissipation parameter reduced with the increment in frequency under all the range of temperatures. The combined salt and alkaline treatment decreases the water absorption capacity in bamboo cellulose fibers and hence enhances the dielectric and thermal insulation characteristics of the epoxy laminates. Also, the investigation of the adhesion of cellulose fiber in the polymer

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matrix with the scanning electron microscope (SEM) showed higher compatibility of bamboo cellulose fibers with the epoxy matrix.

Keywords Bamboo cellulose fiber · Dielectric constant · Dissipation parameter · Electric modulus · Epoxy composite · Volume resistivity

1 Introduction

The advantages of plant cellulose fiber incorporated polymer composites (PCFRP) when compared with synthetic fiber, pure polymer and wood laminates has been well established, because of biodegradability, usage of raw materials, resistance from impact, lower coefficient of thermal expansion (CTE), modulus, lower dielectric constant, and flexibility [1, 2]. In addition, they have other superior characteristics which contains low price, lower density, low machine wear, renewable in nature, lower device abrasion, less skin and respiratory problems, abundant in different forms through the world, higher fiber aspect ratio and sound absorption [3–7]. The reinforcement of plant cellulose fiber into the polymers offer researchers an opportunity to fabricate PCFRP laminates that possibly challenge the recently developed materials in nature which have better mechanical characteristics, and similarly it can be applied for different dielectric applications such as switches, printed circuit boards, connectors, household plugs, cable pillar, cables, solder mask, etc.[8]. Moreover, they have certain possible applications in the creation of back seat, arm rest, and packaging trays [9, 10].

The polymers played as an efficient insulator but utilization is restricted to bearing dielectric applications. Hence, investigations on dielectric characteristics of PCFRP laminates expect higher importance [11]. The applications in dielectric acquire lower CTE and dielectric constant for successful employment. For illustration, the FR-4 PCB based materials have dielectric constant value around 4.6 under frequency of 1 MHz and lower CTE [12]. Primary limitations of plant cellulose fibers were lower resistance from weathering and hydrophilic in nature which negatively influence the polymer matrix/cellulose fiber interface that tends to strength loss, delamination and degradation of laminates [13, 14]. Due to hydrophilic nature of plant cellulose fibers, it should be physically or chemically treated to create them more suitable with the hydrophobic polymers (thermoplastic and thermosets) [13]. Many scientists have recorded enhancement in dielectric characteristics of plant cellulose fibers when treated with alkaline solution with distinct concentration of sodium hydroxide (NaOH) [15, 16]. Depend on its intrinsic characteristics, principle of plant fracture and ultra-structure, the bamboo cellulose fiber provides a hard engineering composite material and desirable plant cellulose fibers when compared to other familiar plant fibers such as henequen, kenaf, sisal, coir, flax, hemp, etc.[17]. The bamboo and other cellulose fibers applied in European based automobile industries. In laminates, it is generally suitable to align cellulose fibers for improved dielectric and structural characteristics [18]. It is usually, very hard, if not impractical, to attain excellent arrangement of cellulose fibers. Orientation of cellulose fibers in the polymer based composites is mainly depend on the different conditioning processes.

Furthermore, the utilization of plant cellulose fibers in dielectric applications has become more familiar. The plant cellulose fibers reinforced polymer based composites have been utilized as dielectric materials in transformer parts, microchips, switches, connectors, circuit boards, terminals, etc. Hence, the investigation of dielectric characteristics of plant cellulose fiber reinforced polymer based composites are very important [19]. The various properties of dielectrics are dissipation factor, dielectric constant, volume resistivity and conductivity which are essential for the successful utilization of these types of materials. These characteristics are mainly based on the different parameters like physical texture, chemical composition, structure and microstructure of the materials [20].

The thriving attention in the advancement of electrically conductive based polymer laminates, because of the principle that plant cellulose fibers reinforced polymer laminates not only played as an efficient insulator but also offer higher mechanical characteristics for field bearing conductors [21]. Thus, the investigations on the electrical characteristic of the plant cellulose fiber reinforced polymer based laminates are very essential. The various dielectric properties like dissipation factor, and dielectric constant of different plant fiber composites have been investigated by different scientists. Paul et al. [22] have determined the influence of different chemical treatments such as acetylation, stearic, potassium, and alkali treatment on sisal fibers incorporated low density polyethylene laminates. It was found that the dielectric loss and constant values of the laminates were reduced with an outcome of chemical treatment process. The volume resistivity of the treated fibers reinforced polymer composites were observed as higher when compared with untreated fiber reinforcement. The influence of temperature, orientation of cellulose fiber, and frequency on dielectric characteristics of sisal based polymer laminates has been studied and found there is a decrement with the rise of temperature on the dielectric characteristics of sisal fiber incorporated polymers [8, 23]. Shinoj et al. [24] have investigated the influence of cellulose fiber treatment and fiber loading on dielectric characteristics of oil palm fiber incorporated linear low density polyethylene based laminates. They recorded an increment in dielectric constant of the laminates with the effect fiber loading and reduced the dielectric constant under higher fiber concentration and alkaline treatment. Fraga et al. [25] evaluated the relationship between dielectric nature and water absorption capability of the jute fiber polyester laminates and found that there is a decrement in dielectric constant value with the increment in water and higher frequencies for laminates. Sreekumar et al. [26] examined the electrical characteristics of the sisal fiber based polymer laminates and showed an improvement in dissipation factor, loss parameter and dielectric constant with the fiber concentration under the higher range of frequencies.

However, it is well-established that the plant cellulose fiber and polymeric resins both have different surface characteristics. From the region, the plant cellulose fibers show a larger hydrophilic characteristic, highly polar because they are made up of cellulose, hemicellulose and lignin content, which includes strongly hydroxyl bonds (polarized). Hence, these kinds of cellulose fibers are intrinsic and incompatible with hydrophobic polymers [27]. The incompatibility may leads to complete wetting of cellulose fibers, which limits the uniform distribution within the resin and produce weak dielectric, thermal and mechanical characteristics. The chemical surface treatments on the plant cellulose fibers improves the compatibility within the polymer matrix and cellulose fibers, which tends to laminates with stronger interface that results in efficient stress transfer between the incorporating cellulose fibers and polymer matrix [28, 29]. The chemical surface treatments may produce the cellulose fiber cell walls more stable, decrease water absorption capacity and improves the resistance from micro-organisms damage. But, there is no such investigation on chemical treatment using both sodium chloride (NaCl) and NaOH on bamboo fiber which is utilized as reinforcement material to epoxy polymer. The aim of the present investigation is to observe the influence of combined NaCl and NaOH treatment on the dielectric characteristics of the bamboo fiber reinforced epoxy polymer composites. In this chapter, the dielectric constant, dissipation factor, volume resistivity, and dielectric relaxation were examined under ranges of frequency and temperature.

2 Materials and Methods

2.1 Materials

The polymer resin matrix applied in thin present investigation was epoxy resin (ER) polymer supplied from Sakthi fiber glass, Tamilnadu, India. The polymer resin contains two constituents as epoxy (LY 556) and hardener (HY 951). During the fabrication process, a low viscosity epoxy polymer was mixed with hardener in the ratio of 10:1 to convert the liquid into solid film.

2.2 Chemical Treatment on Bamboo Fiber

A cultivated Assam bamboo species of Bambusa Tulda was utilized in this present investigation. The culms of bamboo was sectioned into small pieces of average dimensions as 4 mm (diameter), 20 mm (length), and 1.2 mm (thickness) and cleaned with fresh water, denoted as raw bamboo sample (RBS). A salt solution was prepared using NaCl and fresh tap water at the ratio of 1:5 under 6 pH and the bamboo fibers were soaked for 48 h in atmospheric condition, and then dried in sunlight for 360 min., which is considered as SBT (salt solution treatment on bamboo) [28]. After the SBT, the bamboo fibers were again treated with 1 N NaOH solution under room temperature for 6 h. Consequently, the combined treated bamboo fibers were completely rinsed and washed with distilled water to eliminate the residues of alkali, till it attains the 6 pH, is denoted as SABT (combined salt and alkaline treatment on bamboo). Then, the extracted bamboo fibers were dried in electric furnace for 60 ± 2 °C for 24 h. All the three different types of bamboo fibers were placed in the industrial miller to obtain the fine particles and separated from 150 μm (average size) micro mesh.

2.3 Bamboo Fiber Epoxy Composites

An ultrasonic assisted wet-layup technique has selected for the manufacturing of epoxy composites reinforced with chemically treated or untreated bamboo fiber to attain uniform dispersion of fibers within the matrix [30]. The three types of extracted bamboo fibers such as RBT, SBT, and SABT of each 10 wt% were reinforced in the epoxy polymer and stirred with the help of ultrasonictaor probe (24 kHz of frequency and maximum power). During the curing process, the hardener has been added and stirred with mechanical agitator for complete immersion. A load of 50 kN has been applied on the top surface of the mould to ensure the complete soaking of fibers within the polymer resin. The post curing of bamboo fiber reinforced polymer composites was performed at 80 °C in electric furnace for 24 h.

2.4 Epoxy Composite Characterization

2.4.1 Dielectric Properties

The dielectric properties measurements were performed in HP LCR impedance analyzer and 16451B dielectric test fixture, the observations of the investigated specimen taken over the range of temperature between 30 and 150 °C with the frequency ranges from 0.01 to 1 MHz according to the ASTM D150-11 standard. The fabricated bamboo fiber reinforced epoxy composites was sectioned into square-shaped part as 25 and 5 mm length and thickness respectively. The experiment was conducted five times for every composite sample and average value was measured.

2.4.2 Morphological Properties

The morphological properties of the epoxy composites reinforced with chemically treated and untreated bamboo fibers examined under room temperature by FE-SEM, Hitachi, Europe instrument. A plasma gold ion sputtering of some thickness in nano meters ws produced on the epoxy composite specimen surface to provide charge and observed with an accelerating voltage of 15 kV. These examinations were carried out on the cross-section surface of the epoxy composites, which is fixed 90° to the axis of the fiber, so that the cross-sectional aspects could be examined.

3 Results and Discussion

3.1 Dielectric Properties

The dielectric properties of a bamboo fiber reinforced polymer composites mainly based on the polarize-capability of its components (i.e. micro fibers and polymer matrix) and are committed primarily by interfacial, dipoles, interfacial, and polarizations from electronics [31, 32]. The capability of composite material to save charge and become polarized followed by an extrinsic field of electricity is termed as dielectric constant, whereas the dissipation parameter is the ratio between the power distributing in the circuit and electrical power dissipated in the material. In this context, it can also be defined as the measurement of energy from the source of electricity which can be modified into heat that applied as an insulator [21, 31]. The loss parameter is generally applied to explain the losses produced during the transmission of industrial energy and circulation which can be termed as the mean power parameter for the given time period.

3.1.1 Dielectric Constant and Dissipation Factor

The dielectric characteristics of pure epoxy polymer and chemically treated and untreated bamboo fiber reinforced epoxy polymer composites was performed from room temperature to 150 °C for frequencies ranging between 0.01 and 1 MHz. The curves of frequency dependent of the dissipation parameter and the dielectric constant in the epoxy polymer matrix and its ERRBT, ERSBT, and ERSABT composites for different range of temperature between 30 and 150 °C with an increment of 20 °C are presented in Fig. 1a–h. The overall increment in dielectric constant with temperature under lower frequency range and reduction of the characteristics with the rising frequency were examined. For pure epoxy polymer, the dissipation parameters also showed the appearance of two relaxations, which based on the frequency and temperature, whereas the bamboo fiber reinforced epoxy composites exhibited only one relaxation. In this context, these relaxations were correlated with the glass transition for higher range of frequencies and polarization electrode for lower frequency range when there is an increment in temperature. Then latter it was assigned to the glass-rubbery transition of the polymer based composites. The maximum peak of relaxation also transferred to the higher range of frequencies by increasing the temperature, which tends to reduction in relaxation time and also maximum shifting under higher range of frequencies [33].

In the condition of ERRBT, ERSBT, and ERSABT composite, the relaxation associated with the influence of conductivity above glass transition temperature, the dissipation parameter graphs showed the relaxation which is assigned to the Maxwell–Wagner-Sillars (MWS) effect [8]. This relaxation was the outcome of the aggregation of charge within the polymer matrix and bamboo fibers which consisting different dielectric constants and conductivities. Hence, the improvement of these

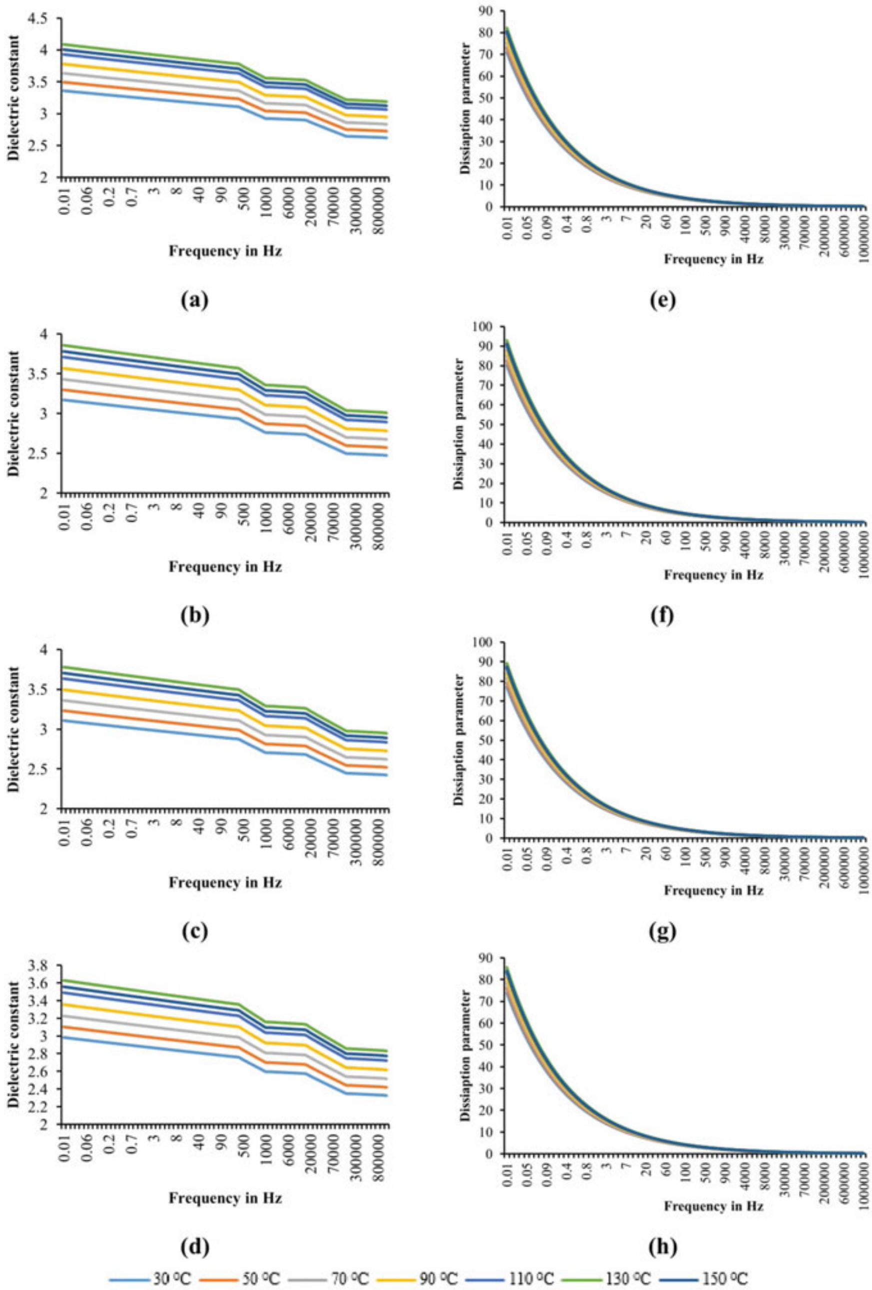

Fig. 1 Bamboo fiber reinforced epoxy composites, Dielectric constant. **a** ER, **b** ERRBT, **c** ERSBT, **d** ERSABT, and dissipation parameter, **e** ER, **f** ERRBT, **g** ERSBT, and **h** ERSABT

relaxation above glass transition temperature augmented the intensity of dielectric constant when the increment in temperature. It is also observed that the previous experimentation on relaxation of molecules in an anisotropic laminate depend on the acrylic polymer and hydroxypropyl cellulose displayed that under lower frequencies, the ionic conductivity controlled the dielectric spectrum of the laminate. In this condition, the bamboo fiber is treated with NaCl and NaOH solution which is comparably lesser conductivity than the raw bamboo fiber. The reason may be assigned to the electrical properties of the elements of the epoxy composites (conductivity and dielectric constant of fibers and polymer matrix) to be less distinct for the display of MWS polarization, so the elimination of the MWS peak from the dissipation curves, as shown in Fig. 1h, which leads to slow improvement in dielectric constant under higher range of temperature and lower frequencies when compared with ERRBT, and ERSBT composites, could be described. The reinforcement of bamboo fibers in the polymer matrix, leads to reduction in dissipation parameter intensity and this was augmented in reverse in the ERRBT composite. It is also examined that the introduction of heat increases the insulation temperature which increases its degradation, hence bamboo fibers reinforcement improves the thermal insulation properties in epoxy composites. The relaxation which was already observed in the epoxy polymer, was entirely sketched from the conductivity effect in the condition of ERSBAT composite and by interfacial polarization in the condition of ERSBT composite. However, in the condition of ERSBAT, and ERSBT composites, the constant temperature of the dissipation parameter in the similar range of temperature exhibited an improvement in the presence and intensity of relaxation peak which is ascribed with the interfacial polarization for the epoxy based composites. The similar results were examined in Okrassa et al. [34] in which the cellulose relaxation corresponds to its glass transition which is also not appeared in the dielectric spectrum. This characteristics was comprised with the appearance of string hydrogen bonds within the chains of cellulose [35].

3.1.2 Volume Resistivity

The volume resistivity of bamboo fiber reinforced epoxy composites is formulation of cellulose microfibrillar angle, crystalline, cell (size, number, and shape), chemical constituents, presence of amorphous components, applied voltage, concentration of impurity and moisture. The graphs of volume resistivity as temperature function for ER, ERRBT, ERSBT, and ERSABT composites are presented in Fig. 2a–d respectively. It is observed that volume resistivity reduced with increment up to 80 °C, and remains constant after this temperature ranges between 80 and 130 °C.

After this temperature range, the epoxy composites starts degrading thermally and volume resistivity exhibits anomalous nature. When the frequency increments, the volume resistivity exhibits a reduction because of interfacial polarization with the heterogeneity of system [18]. Volume resistivity of ERSABT composites is comparably higher than the ERSBT and ERRBT composites, due to the formation of stronger interfacial bonding within the matrix and bamboo cellulose fibers. The hydrophilic behavior of raw bamboo fiber is important for the higher alternating

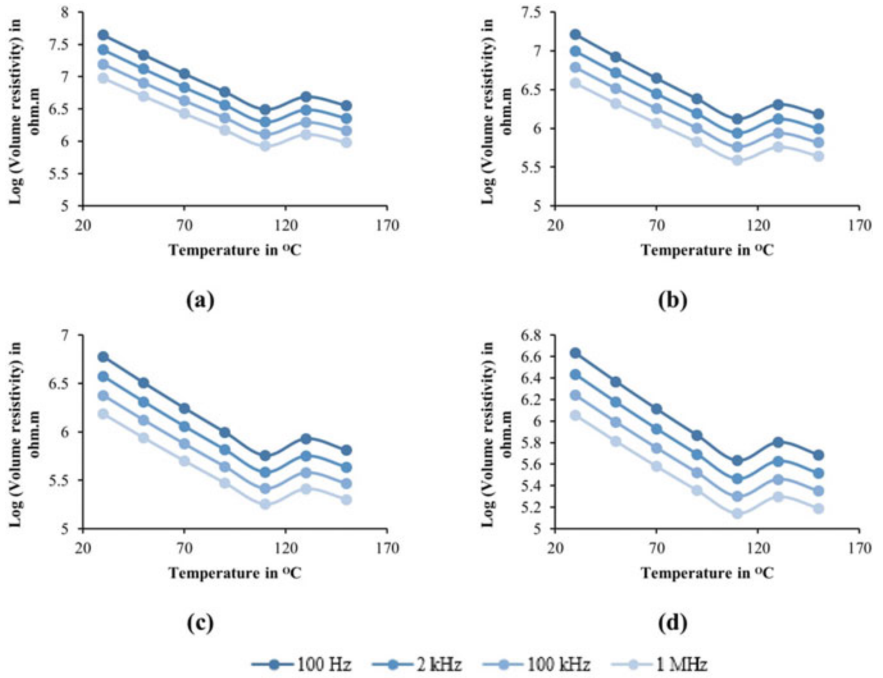

Fig. 2 Volume resistivity of bamboo cellulose fiber reinforced epoxy composites. **a** ER, **b** ERRBT, **c** ERSBT, and **d** ERSABT

current conductivity and dielectric constant when compared with chemically treated one.

3.1.3 Electrical Conductivity

The present investigation deals with direct & alternating current conductivity of epoxy laminates. The alternating current conductivity dependent on the temperature for ER, ERRBT, ERSBT, and ERSABT composites are shown in Fig. 3a–d respectively. The chemical surface modification of bamboo fibers in epoxy composites modifies the complete structure of composites, due to alternating current conductivity value alters with chemical composition of fibers. Under the lower range of temperatures, the alternating current conductivity values mainly based on significant frequency. Furthermore, with rise in temperature, relaxation considered & conductivity on frequency also get decreased.

Figure 4a–d exhibits the conductivity variation with frequency and temperature for ERRBT, ERSBT, and ERSABT composites respectively. Frequency characteristics of conductivity under the given range of temperature in ERRBT, ERSBT, and ERSABT laminates classified in two sections as alternating and direct current

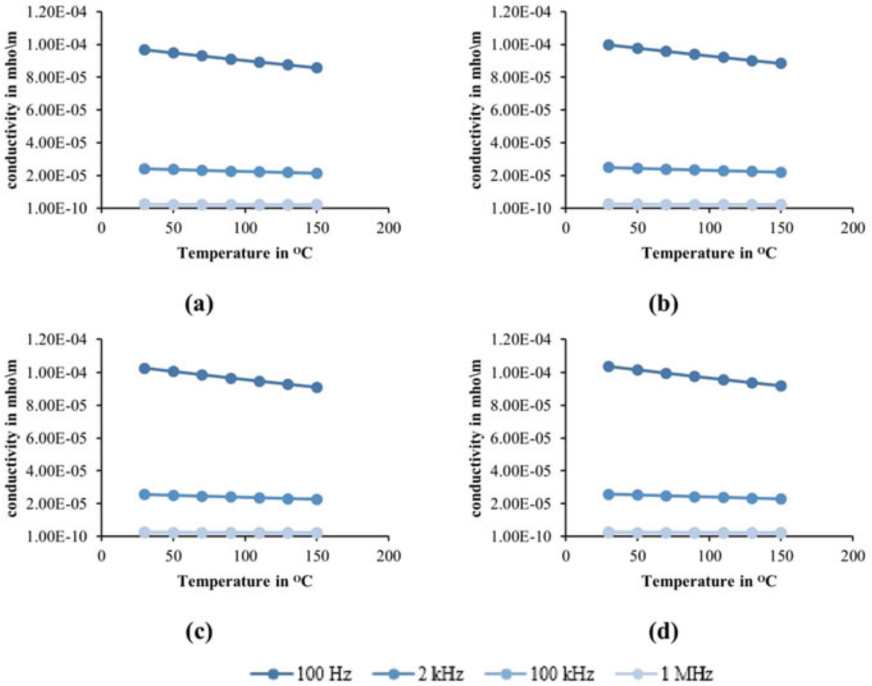

Fig. 3 Temperature dependence of alternating current conductivity at different frequencies. **a** ER, **b** ERRBT, **c** ERSBT, and **d** ERSABT

conductivity and obtained from Eq. (1) [18].

$$\sigma(\omega) = \sigma_{dc} + A\omega \tag{1}$$

where Aω and σ_{dc} depicts the frequency dependent & independent conductivity.

Under lower range of frequencies, the specimen exhibit a different plateau which presents direct current conductivity of epoxy laminates under distinct temperatures. At higher frequency range, the spectrum show a strong distribution because of the limited movement of hydroxyl ions & contaminations in structures presents alternating current conductivity.

The Arrhenius graph of reciprocal of temperature (absolute) vs conductivity in logarithmic scale is presented in Fig. 5a–d. Direct & alternating current activation energy quantities estimated from Arrhenius graphs were 0.35 and 0.31–0.22 eV for ERRBT laminates. Activation energy for direct current conductivity is high while comparing with alternating current conductivity, because of transportation/mobility of charge carriers through large distances under the lower frequencies. Furthermore, under higher frequency range, the principal of relaxation has been taken place, in which movement of charge is limited to neighboring lattice parameters. The conductivity activation energy values of bamboo fiber reinforced epoxy laminates are given

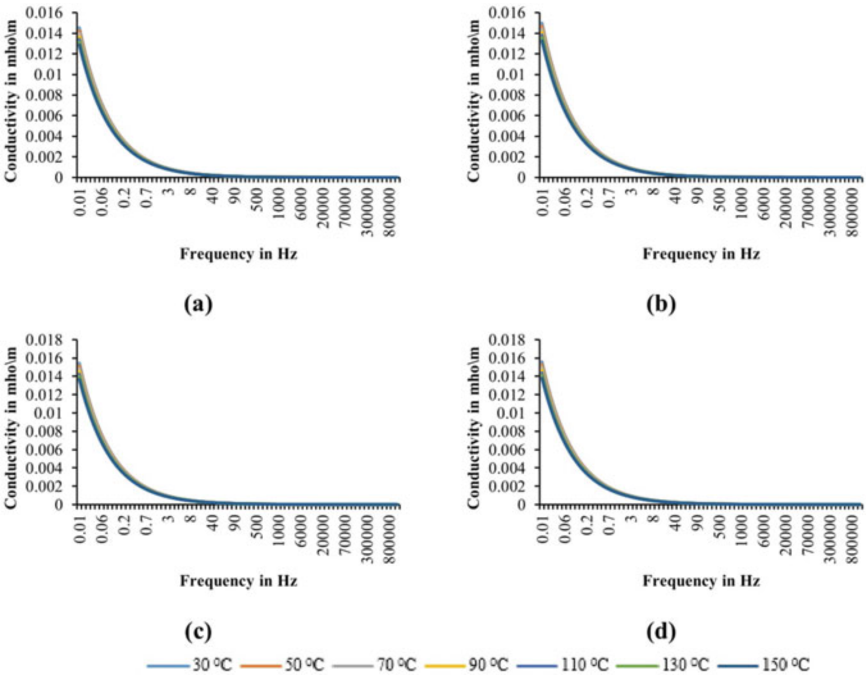

Fig. 4 Alternating current conductivity under different temperature for bamboo fiber epoxy composites. **a** ER, **b** ERRBT, **c** ERSBT, and **d** ERSABT

in Table 1. Activation energy showed decrement from 0.34–0.18 eV with the rise in frequency for ERRBT composites in the frequency ranges between 100 and 100 kHz.

Energy prescribed for process of relaxation is smaller than movement of charge carriers through large spaces, this higher energy conduction energies are examined under lower range of frequencies when compared with higher frequencies. In principle, the conductivity of bamboo fibers is primarily low, because of the absorption of water molecules from the surface of the cellulose fiber [8]. The complete experimental process was performed under the similar exterior case as the room temperature was reported as 30 ± 1 °C. With the effect of salt and combined treatment, the regions of inter fibrillar removes lignin and hemicellulose content, which become less solid and dense, thereby creating the fibers more suitable for realigning, recrystallization and reorientation. The elimination of hemicellulose and lignin tends to fibrillation, cutting down the fiber bundles into small piece, which improves the efficient surface area possible to contact with the polymer matrix [18].

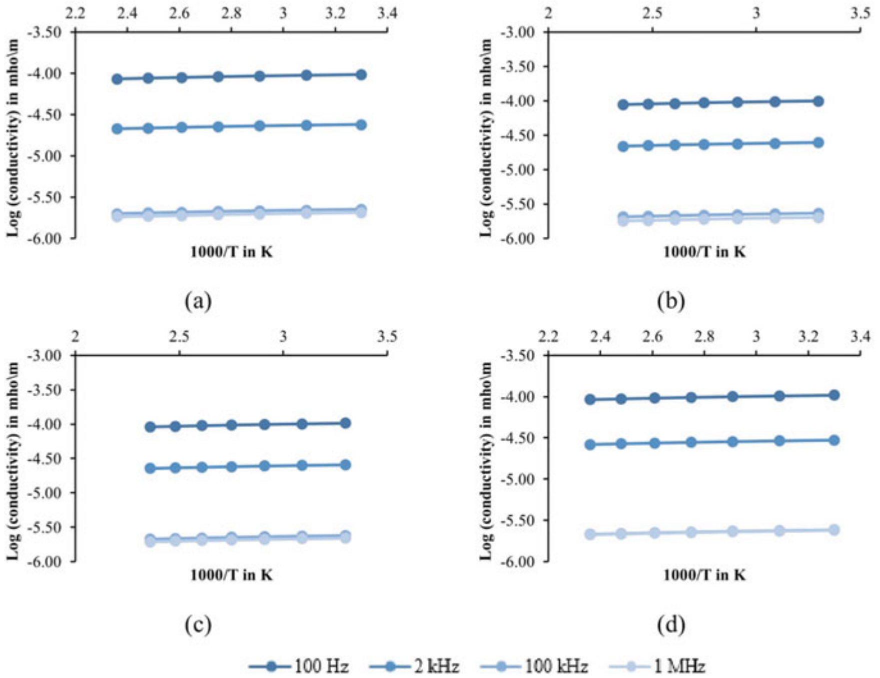

Fig. 5 Reverse temperature dependence of alternating current conductivity for bamboo fiber epoxy composites. **a** ER, **b** ERRBT, **c** ERSBT, and **d** ERSABT

Table 1 Conductivity activation energy of bamboo cellulose fiber epoxy composites

Frequency	Activation energy in eV			
	ER	ERRBT	ERSBT	ERSABT
100 Hz	0.45	0.44	0.41	0.35
2 kHz	0.35	0.34	0.32	0.27
100 kHz	0.28	0.27	0.25	0.22
1 MHz	0.23	0.22	0.21	0.18

3.1.4 Electric Modulus

Electric modulus examination broadly applied to investigate the dielectric nature of the composites. Generally, the dielectric characteristics of epoxy composites increased with the effect of polymer matrix and fiber interaction. The movement of charges could be considered with dipole reorientation, displacement of charge, and formation of space charge. To understand the electrical characteristics of a given polymer matrix and bamboo fiber combinations must be extracted out. Electric modulus is acquaintance to structural properties of shear modulus described by McCrum et al. [36]. Electric modulus can be termed as a benefit method to interpret

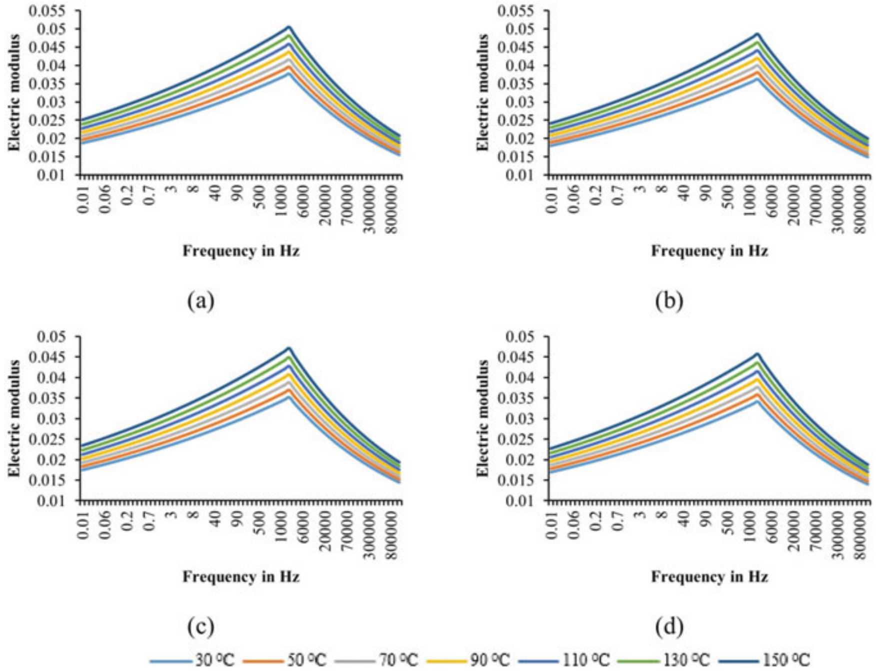

Fig. 6 Electric modulus curve of bamboo cellulose fiber reinforced epoxy composites. **a** ER, **b** ERRBT, **c** ERSBT, and **d** ERSABT

the solid relaxation characteristics that fluctuation in large amount of real component of dissipation parameter and dielectric constant under lower range of frequencies are reduced [37]. The wide peaks of electric modulus as a frequency function for ER, ERRBT, ERSBT, and ERSABT composites are shown in Fig. 6a–d.

3.2 Morphological Properties

The SEM examination was performed to analyze the interface between bamboo fiber and epoxy polymer matrix in the composite materials. The SEM images of the epoxy composites are shown in Fig. 7a–c for ERRBT, ERSBT, and ERSABT composites respectively. Figure 7a presents the microstructure of cross-sectional view of the ERRBT composites that the fibers are randomly distributed in the epoxy matrix and individual partition of fibers were not observed in single form. In Fig. 7b, a closer examination of the interface in the image of the ERSBT composites showed good contact between the epoxy matrix and bamboo fibers than that in the condition

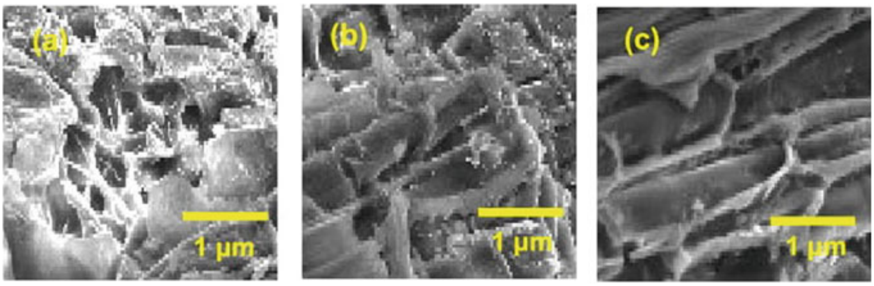

Fig. 7 SEM micrographs of the bamboo cellulose fiber reinforced epoxy composites. **a** ERRBT, **b** ERSBT, and **c** ERSABT

of NFRUP composites investigated by Kumar et al. [18]. A narrow and tiny voids around the fiber which may leads to cracking in the ERSABT composites, due to the propagation of fatigue crack resistance based on the adhesion between the epoxy polymer and bamboo fiber, which decreased the dissipation factor and dielectric constant values. A closer glance at the ERSABT composites cross-sectional aspects showed in Fig. 7c determined an identical adjacent contact in the interfacial region within the epoxy matrix and bamboo fibers when compared with ERRBT and ERSBT composites.

4 Conclusion

The impedance spectra have been utilized to justify the dielectric characteristics of chemically treated and untreated bamboo cellulose fiber reinforced epoxy composites. The ERSABT composites have higher dielectric characteristics when compared with ERRBT and ERSBT composites. The dissipation parameter and dielectric constant of bamboo fiber reinforced epoxy composites were observed reduced with higher frequencies. The reason may be assigned to the decrement in the polarization of components that appeared in the bamboo cellulose fibers. Volume resistivity was observed to reduce the effect of chemical salt and alkaline treatment process. When compared with other bamboo composites, the ERSBT composites exhibits higher volume resistivity due to it has a comparably smaller microfibrillar angle and a lower concentration of cellulose. From this analysis of dielectric characterization, it exhibits that these price efficient bio-based epoxy composites could be applied for dielectric applications.

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Bamboo Fiber Reinforced Concrete Composites

M. Ramesh, C. Deepa, and Arivumani Ravanan

Abstract The construction industry in most countries is considered to be the main consumer of energy and materials. Many research attempts concentrate on the use of renewable and sustainable materials in this area in an effort to ensure future generation sustainability. Because of higher steel costs and non-renewability, efforts are now being made to provide a sustainable low-cost alternative through the use of naturally available material. This increases construction prices exponentially and also damages the environment by producing large quantities of greenhouse gases. And, in the future, cheap and affordable infrastructure needs to be developed based on the bio-friendly building materials. A series of observational experiments, test the feasibility of using bamboo as concrete reinforcement. The reinforced bamboo can significantly strengthen the mortar and reduce the overall weight of the laminate due to its high strength to weight ratio. This chapter examined the potential for structural applications of bamboo fiber enhanced composites.

Keywords Bamboo fiber · Concrete composites · Pulping · Biodegradability · Durability

1 Introduction

The choice of products in this period of industrialization is based primarily on the cost and form of facility used for production or storage. Industrialized products, including ordinary cement and steel, find applications in all industries and the world a road leads to. Advanced materials such as synthetic polymers, fibers and alloys have been developed in the second half of the twentieth century. For the construction of load bearing buildings, reinforced concrete is mostly used in steel. Concrete is

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often reinforced with steel bars to increase the carrying capacity of its low tensile load. Nonetheless, due to higher steel prices and non-renewability, attempts are now being made to provide a sustainable alternative at low cost through the use of locally available materials [1]. Several scientists are therefore making attempts to provide a low-cost, renewable steel alternative. Several scientists have been exploring the possibility of using plant fibers as structural materials in concrete in this regard. Therefore, a low cost and renewable material such as bamboo, which apparently has some physical characteristics of metal, is considered.

Bio-composites with natural fibres, low density, low cost, low energy consumption and CO_2 neutralization [2, 3]. Among the natural fibers, due to its exceptional strength-to-weight ratio, particular attention should be paid to bamboo fibre, which results in an active strength comparable to low-carbon steel and glass fiber [4, 5]. Because of its high strength-to-weight ratio, it is widely used as scaffolds and wall proportioning. Bamboo's tensile strength is very high and the ultimate tensile strength for some of its species is the same as the yield strength of mild steel, whereas the strength to the specific weight ratio is six times greater than that of steel. Bamboo can take both tension and compression like steel bars, whereas many other plant reinforcement materials cannot carry compression loading. In addition, the energy needed to produce one cubic meter of bamboo per unit of stress is 50 times lower than the energy required by steel. Because of these characteristics, bamboo has attracted the attention of many researchers for use in concrete. There have been many promising studies that have shown diverse use of bamboo for construction [1].

Bamboo fiber characteristics include: high strength and biodegradability and three times higher production of O_2 than other plants. Given their many benefits, natural fiber reinforced composites were considered potential candidates for structural applications, such as low-cost residential buildings in developing countries [6]. Bamboo is a promising fiber to be used as a pulping and reinforcing raw material, taking into account its rapid growth, its position as a major non-wood forest product and wood replacement, its worldwide abundance and relatively low cost compared to other vegetable resources. Several scientists have worked as new modern building materials to grow bamboo and bamboo items. Reinforced concrete from bamboo has a long history of civil engineering research and applications [7]. Various composite bamboo components such as composite slabs, walls, beams and columns are used for the construction of beam-column frame structures or for the assembly of large panel structures with a rigid connection or other reliable connections [8, 9].

2 Bamboo

Bamboo is a natural grass-like perennial plant and one of the world's fastest growing woody plants [10]. About 75 genera and 1250 bamboo species are found in various countries around the world. Bamboo is a rapidly growing wood that belongs to the Poaceae family of grass, composed of cellulose fibers embedded in a matrix of lignin. Bamboo is a giant grass which grow at a phenomenal rate of growth of

91 cm per day, according to the world record Guinness Book. Bamboo has a major economic advantage as it grows in full in a few months and is abundantly available in tropical and subtropical regions. In addition to releasing fresh oxygen into the air, the processing of each ton of bamboo absorbs about one ton of atmospheric CO_2. Bamboo is found to be approximately 50 times more energy-efficient than steel in terms of the resources needed to produce them. Bamboo is elastic, lightweight, has outstanding tensile strength and a very good weight to strength ratio, making it extremely effective against high-speed winds and earthquakes.

Bamboo is a wood-like plant belonging to the family of grasses, consisting of a cylindrical hollow shoot, or culm. This culm is covered with a waxy surface that prevents the escape of moisture. The culm has raised ridges called nodes at intervals, from which branches are offshooting. The plant grows from a multitude of underground stems and roots called rhizomes. Some species can grow up to 30.5 m in height, with a diameter as wide as 305 mm. In just three or four years, it achieves its maximum intensity and reaches maturity within five years. In addition, bamboo culm needs only 3–6 years of maturity in order to achieve optimum strength for structural applications [11]. Bamboo is characterized as a natural resource that is renewable, biodegradable and energy-efficient, with great potential as a building material that is sustainable. Compared to conventional materials such as cement, wood and metal, it has a high strength to weight ratio [4, 12–15]. Bamboo's large applications in civil engineering are limited by its dimensional instability due to humidity, inadequate adhesive binding, difficult connections due to its irregular shape, insufficient knowledge of modern bamboo structure layout and lack of official design codes and standards.

2.1 Bamboo as a Structural Material

Bamboo is distinguished by its high potential as a sustainable structural building material as a biodegradable and energy-efficient natural resource [16]. Several scientists have devoted themselves as new modern building materials to the production of bamboo and its products. Number of studies have been carried out to look for such unusual construction materials. The number of materials such as kevlar, polyester, carbon fibres, metal alloys has been regarded as a building material over the past few decades. Nonetheless, the manufacturing of such products is a complex process that cannot be produced from the local materials and technologies at the minimum level. In order to resolve the problem of housing shortages, which is predominant for people living below the poverty line, it is essential to develop building technologies that can be used from the materials available locally to construct building components such as beams, columns, slabs and walls at a much lower cost than traditional building materials [17]. An curious feature of bamboo is that the shoot's diameter coming out of the soil is the biggest diameter it ever grows to. Given this high growth rate, the bast fibers, or so-called wood fibers, still need four to five years to mature. Bamboo's

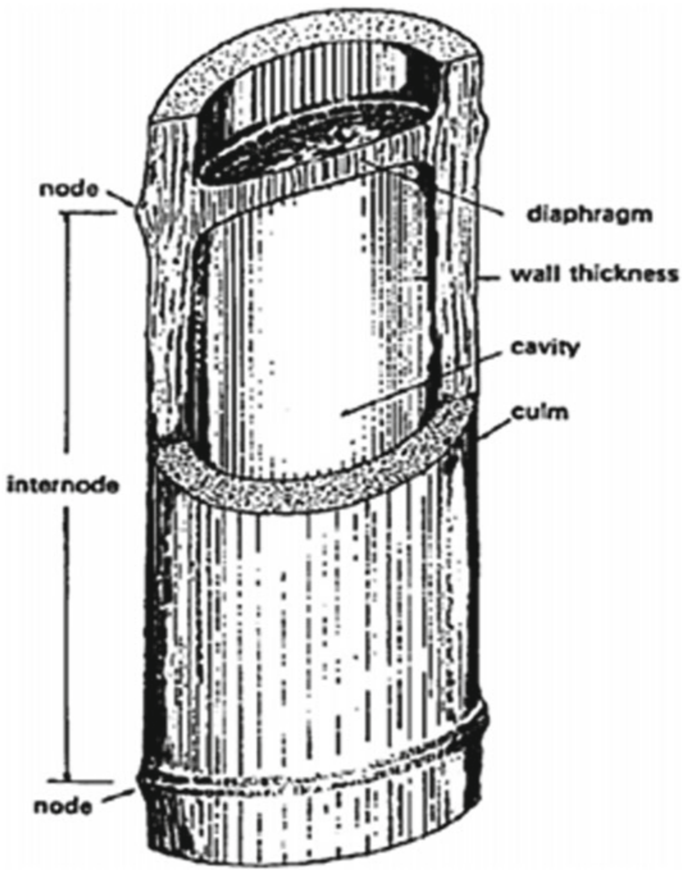

Fig. 1 General features of a bamboo culm [18]

general physical characteristics are shown in Fig. 1 [18]. The relation between steel and bamboo is discussed in Table 1.

2.2 Bamboo Composites

Bamboo's growing industrial and environmental importance requires more comprehensive statistics to be developed on bamboo resources, use and trade. Bamboo is a highly efficient material in its natural shape. Bamboo easily becomes a possible reinforcement product for structural use with these additional parameters in mind. Bamboo is a building material that is widely used, particularly in Asian countries. Activities are suppressed in rural areas or even in small towns as a result of consumers preferring manufactured goods, among other consequences, and renewable resources

Table 1 Comparison of different properties between bamboo and steel [17]

S. No	Property	Bamboo	Steel
1	Density (Kg/m^3)	515–817	7850
2	Modulus of elasticity (N/mm^2)	0.6–21.41 × 10^3	2 × 10^5
3	Tensile strength (MPa)	100–400	130–140
4	Compressive strength (MPa)	25–100	110–130
5	Bending strength (MPa)	70–300	0.5–0.7
6	Factor of safety	3.5–4	1.15
7	Ratio of tensile strength to weight density (m)	31,800–32,200	5300–5400

are lost and cause permanent pollution. Bamboo composites are currently used in a wide range of fields, including aerospace, chemical, industrial, electrical, hydraulic, nautical and mechanical engineering [19]. In this sense, it becomes evident that ecological materials meet such fundamental requirements, using agricultural by-products such as rice husk, coconut fibres, sisal and bamboo, thus minimizing energy consumption, preserving non-renewable natural resources, reducing pollution and maintaining a healthy environment.

The building industry has undergone many changes and has become familiar with the use of composite materials. Houses were built using natural short straw fiber mixed with clay as ancient brick material, which can be described as a good example of natural fiber reinforced composite. The daunting complexity of the concrete structures repair and the demanding tasks involved with repairing and replacing old and heavy concrete or cement structures have prompted the construction industry to follow the techniques of using plastic composites reinforced with synthetic fiber. Given the advantages of synthetic fiber composites, it is not possible to reuse these materials [20]. New hybrid composites of bamboo and glass fibers have been developed and are being used to produce high-strength and termite-resistant artificial panels. Adding bamboo to fresh concrete can increase the concrete matrix's ductility. The energy required to produce 1 m^3 per unit stress projected in practice was compared with that of bamboo for materials commonly used in civil construction, such as steel or concrete. It has been found that 50 times more energy is needed for steel than for bamboo. Bamboo's tensile strength is relatively high, reaching 370 MPa. In tensile loading applications, bamboo is an attractive alternative to steel. This is because the tensile strength ratio to bamboo's specific weight is six times that of steel. Recent advances in composite bamboo materials can be a viable bamboo concrete reinforcement product discussed in this chapter.

2.3 Selection of Bamboo for Composites

Chow studied the performance of bamboo as a building material in the early 1900s [21]. Bamboo and bamboo fragments of small diameter were used as reinforcement material for concrete applications in this research. However, only after the 1950s, elaborate research began with research projects on bamboo as concrete reinforcement. Problems such as concrete de-bonding, water absorption, fungus attacks, and thermal expansion coefficient are prevalent and not much further research was conducted. Ghavami later started several mechanical experiments using bamboo as concrete reinforcement in 1995. Bamboo has been found to significantly increase the composite's load bearing strength. For building purposes, that shows a distinct brownish green color, only those bamboos should be used. This will mean that the crop is mature and at least three years old. Selection is to be done in such a way that we get the longest large diameter culms, the culms are usually short at the top of the bamboo and the thickness often decreases to a considerable degree, so culms from the bamboo base are preferred. It is important to avoid bamboos that are cut in spring or early summer; these culms are generally weaker due to increased fiber moisture [22]. Bamboo has continuously attracted the attention of scientists and engineers to be used as reinforcement in cemented composites due to its superior properties such as high strength to weight ratio, high tensile strength and other considerations such as low cost, easy availability and harmless to the environment during operation [23]. Bamboo's main disadvantages in its natural form are its poor bond with concrete, low elasticity modulus, high tendencies of water absorption, low durability, and low fire resistance. Some of these deficiencies can now be substantially improved by treating the bamboo appropriately [24].

3 Bamboo Concrete

Much early interest in concrete from bamboo is attributed to the U.S. Navy and its interest in rapid construction in South East Asia after the World war II. The continued shortage of steel in the first half of the twentieth century led to further research into bamboo and many other materials for their potential construction. Bamboo-reinforced concrete work involved structural testing and Glenn's design of prototype buildings [25]. He provided a set of findings from the test results obtained as well as principles of design and construction for the use of bamboo canes and splints as concrete reinforcement. He highlighted issues such as (i) high deflection, low ductility and early brittle failure of reinforced bamboo concrete beams under load,(ii) reduced ultimate load capacity compared to reinforced steel elements; (iii) bonding problems associated with excessive bamboo cracking and swelling; and (iv) the need to use asphalt emulsions. For concrete beams with 3–4% bamboo reinforcement, it is recommended that a bamboo tensile stress of 34–41 MPa be based on maximum stress values of 55–69 MPa. Ultimately, to keep the beam deflection below 1/360 of the length, an appropriate bamboo tensile stress is recommended for reinforced elements between 20 and 28 MPa. Brink and Rush [26] promulgate an encouraging stress approach to the development of reinforced concrete for bamboo, comparable to the contemporary ACI 318 [27] reinforced concrete approach. They proposed an acceptable 28 MPa bamboo tensile stress based on an ultimate 124 MPa capability and 0.34 MPa bond strength. For serviceability requirements, a bamboo elasticity of 17.2 GPa is recommended.

Research on cemented and polymeric composites using bamboo and other natural materials as reinforcement highlights common problems such as biodegradability, manufacturing and thermal compatibility of bamboo and matrix material. A final issue that could potentially affect the bonding performance of bamboo is the thermal expansion coefficient that is affected by the moisture content; and is as much as five times lower in the longitudinal direction than that of concrete or steel, but two times higher than that in the transverse direction. The reported longitudinal thermal expansion for bamboo ranges from 2.5 to 10 °C; the transverse direction is about an order of magnitude higher [28–30].

3.1 Properties of Bamboo Concrete

Bamboo's mechanical properties and its availability in developing countries have resulted in its empirical use in concrete structures as reinforcement. It can support both tension and compression parallel to fibers like a steel rod, whereas many other materials cannot withstand compression loading [31]. Bamboo is a generally hollow, anisotropic, natural material with high physical and mechanical properties varying throughout the section and along the culm. Bamboo density varies with standard values spanning from 500 to 800 kg/m^3 through the cross section. In modes of failure dominated by longitudinal tension, bamboo usually exhibits a fragile behavior. The variability of bamboo's longitudinal mechanical properties is close to that of wood, having variance coefficients between 10 and 30% [29, 32]. While bamboo is a material with exceptional mechanical properties, its use in concrete is an ill-considered idea with major problems in terms of toughness, strength and rigidity and does not always meet the environmentally friendly requirements [29].

3.2 Durability

Bamboo's resilience is closely linked to its natural composition. Bamboo consists of cellulose, hemicellulose, and lignin, as with other lignocellulosic materials. The chemistry of these bamboo components changes with age and/or after harvesting, resulting in a cycle of cell death and tissue deterioration [29]. Unlike wood, bamboo is vulnerable to insect and mold attacks and environmental degradation. Its durability depends on the species type, age, condition of conservation, treatment and curing.

When cutting bamboo in the bamboo grove, cure should be initiated. There is a strong relationship between insect attacks and starch rates plus bamboo culm humidity. Bamboo receives a variety of treatments, including spot curing, immersion, heating, or smoke, to reduce the starch content. Sustainable infrastructure requires creative and cost-effective methods to reduce processes of deterioration such as curling, oxidation, water and chloride permeability that affect the durability and serviceability of cement composites [33].

For various reasons, drying bamboo is essential to its conservation. Low moisture bamboo is less prone to mould attacks, particularly if the moisture content is less than 15%. Bamboo's physical and mechanical properties increase with its moisture content decreasing. Bamboo to be handled with a preservative must be dry to help penetrate and achieve better results and minimize transport costs. Bamboo's durability depends heavily on the preservative treatment methods in accordance with basic requirements: its chemical composition should not affect the bamboo fiber and should not be washed out by rain or humidity once it is injected. The preservative can be applied using simple systems such as leave transpiration, immersion, impregnation, modified Boucherie method, Boucherie method to state-of-the-art cauldron equipment and special vacuum or pressure chambers [34].

3.3 Water Absorption

One of the bamboo's major drawbacks is its water absorption when used as concrete reinforcement. Several species have studied the capacity of bamboo to absorb water. Different biological studies have stated that bamboo has a high water absorption ability, as shown in Fig. 2a, dimensional variations of untreated bamboo due to water absorption may cause micro- or even macro-cracks in cured concrete. Bamboo swelling pushes away the concrete and the bamboo loses its moisture after the healing process and shrinks almost back to its original size, leaving vacuum around itself. The swelling and shrinking of bamboo in concrete restricts the use of bamboo as a steel replacement in concrete. Figure 2b shows the use of epoxy in splints of bamboo [22]. Akeju and Falade [35] used bamboo bitumen and sand coating to reduce their water absorption potential and used this to improve the beam and column components.

3.4 Bonding Strength

Another important factor is bonding between bamboo and concrete, particularly when the concrete member is loaded The bond between bamboo reinforcements and concrete matrix is formed mainly by means of key mechanisms; adherence to the concrete matrix; creation of residual compressive stress due to concrete shrinkage at the reinforcement and concrete interfaces; and friction due to surface roughness of reinforcements. Bonding creates a shear resistance with reinforcement at the matrix

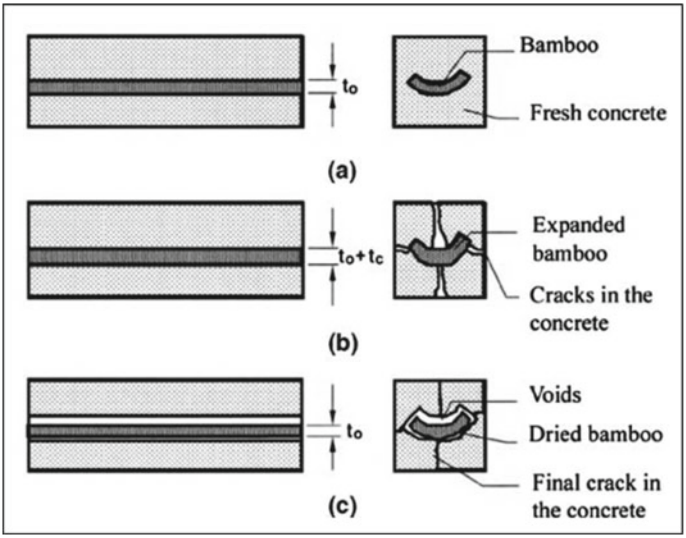

Fig. 2 Behaviour of bamboo as reinforcement in concrete: **a** bamboo in fresh concrete, **b** bamboo during curing of concrete and **c** bamboo after cured concrete [18]

interface [36]. Bonding between concrete and reinforcing material avoids the slippage of the reinforcement. The factors responsible for the bond strength are the elastic properties of the cement matrix, the compressive frictional forces on the surface of the reinforcements due to concrete shrinkage and shear resistance, and the roughness of the reinforcements [22]. The bonding properties of raw bamboo splits in concrete, chemically modified and untreated, were studied. This showed that an epoxy resin coating of two components improves the bonding of raw bamboo reinforcement up to 5 times compared to uncoated bamboo and steel.

A series of pull-out experiments examined bamboo and concrete bond behaviour for the first time. This research resulted in a special bamboo strip profile and surface treatment combined with maximum bond strength under uniaxial loading. This bamboo strip is also used in concrete slab panels as the central reinforcement. Through experimental testing of concrete slab panels, the viability and effectiveness of this particular bamboo profile used as reinforcement was investigated. Test results showed that the load carrying capacity and the deformation capacity were increased when the proposed bamboo strip is used as reinforcement in concrete slab panels compared to plain cement concrete and reinforced cement concrete slabs [37]. To understand the bonding behavior of the newly developed concrete bamboo-composite reinforcement, series of pull-out tests were conducted to find a suitable technique for reinforcing the bond between concrete matrix and bamboo-composite reinforcement [36, 38]. Through reinforcement pull-out test, the bonding between concrete and bamboo for 3 product types has been developed. Sand rolled bamboo rebar, G.I rolled bamboo rebar and coir rolled bamboo rebar as shown in Fig. 3a are the 3 types of products. The test was conducted in an Indian-standard universal

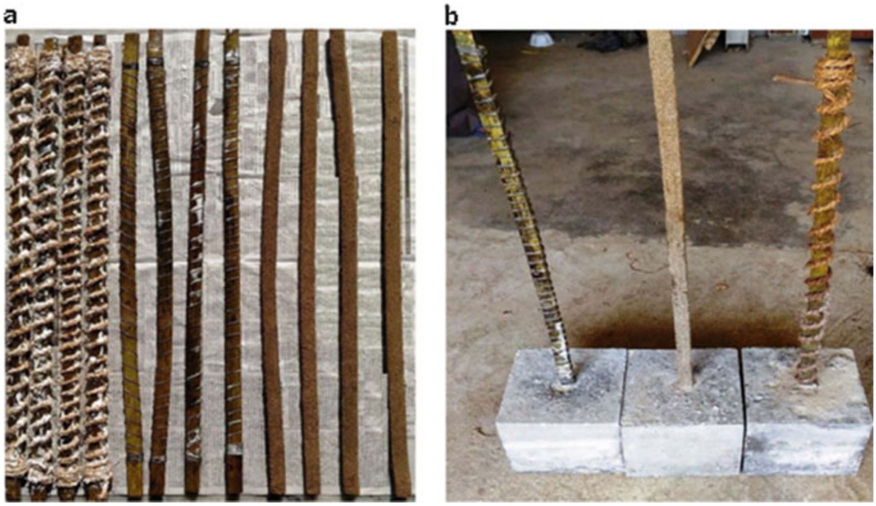

Fig. 3 **a** Bamboo bars with various frictional properties; **b** specimen for reinforcement pull-out test [22]

testing machine. The reinforcements with different bonding properties were placed into three different cubes of 15 cm × 15 cm × 15 cm dimensions as shown in Fig. 3b. The bonding shear stress can be calculated as:-

$$\tau_b = \frac{F_m}{L * S}$$

where, F_m is the pulling load applied, L is the length of bonded interface and S is the perimeter of the bamboo splint. It was found from the test that G.I rolled bamboo rebar offers higher bonding shear stress compared to coir rolled and sand rolled bamboo rebar i.e. G.I rolled rebar bonding shear stress is 1629 times that of sand rolled rebar and 1147 times that of coir rolled rebar respectively [22].

3.5 Tensile Strength

Bamboo, one of the oldest building materials called high tensile strength, is used as the main structural component for these low cost houses [22]. The tension is very strong and the tensile strength varies from species to species. It can be found in bamboo an average tensile strength of 50–75% of that of steel or sometimes even more. The test specimen has an average 250 N/mm^2 tensile resistance. The test was carried out in a universal testing machine; the results obtained from the test are shown in Fig. 4. It can be seen from the plot that although bamboo has high tensile strength, unlike steel, it lacks ductility [22].

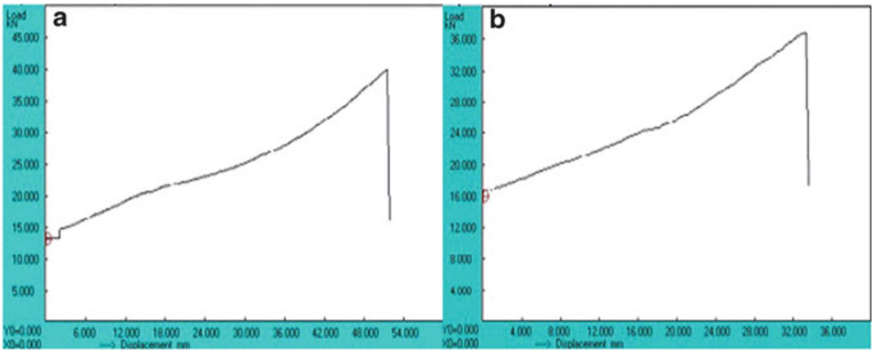

Fig. 4 Load versus displacement plot of tensile strength test bamboo specimen **a** 16 mm bamboo splint; **b** 20 mm bamboo splint [22]

3.6 *Compressive and Split-Tensile Strength*

Concrete is known for its high compressive strength and low tensile strength as the most common material on earth. To increase the tensile strength of concrete, the incorporation of bamboo fiber into reinforced concrete [39] becomes common. Details of compressive and split-tensile forces are shown in Fig. 5. The strength properties of the mixes increased with the healing period, this trend is a norm in concrete composites. This growth was caused by the accelerated hydration of cement in the presence of moisture. The reference mix (Mc) reported the highest compressive strength of 28 days, with a strength of 7.28% compared to the m-sand concrete (M2). The mix 2 slowly gained strength until 14 days when the early strength of other mixes quickly developed. This may have been due to the addition of fly ash, which possibly

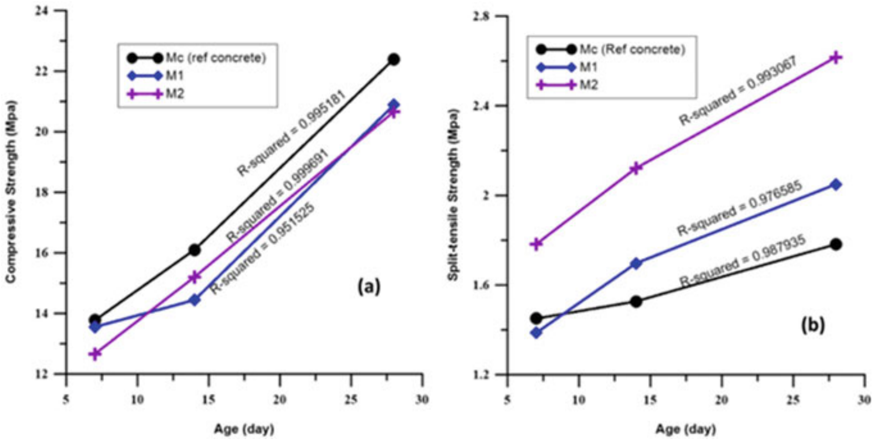

Fig. 5 Strength development with days **a** compression, **b** split-tensile [40]

disrupted the hydration in the mix. In mix 2 (M2), which has an equal combination of river sand and m-sand as fine aggregate, the highest 28-day tensile strength was obtained for split tensile strength. The effects of mixed cement with fly ash help block micro-pores in the concrete matrix aggregates. Usually, the main pores of the aggregate particles are usually broken along the fault surface during the splitting tensile test. Therefore, it can be concluded that these types of admixtures are good in concrete when high tensile strength and compressive strength are needed. In addition, for all the mixes considered, statistical regression models using the best fit curve for both compressive and split tensile strengths were calculated [40].

3.7 Flexural Strength

The bamboo-based ferrocement slab panel's flexural activity has been examined. The writers used bamboo strip skeletal in one-way slabs along with chicken wire mesh as protection in this investigation. The impact of cement replacement with fly ash and slab thickness variation was studied. The results of the slabs tested under monotonically increasing uniformly distributed flexural load indicate that the first crack load and ultimate loads were similar in both slabs [41] type. For example, the flexural performance of bamboo reinforced concrete slabs with styrofoam as an infill panel has been examined. It was reported that slabs casted with the combination of bamboo reinforcement and expanded polystyrene infill panel becomes light in weight by 27%, with 6% decrease in load carrying capacity [42]. Three-point loading flexural strength test is conducted according to ASTM C1341-13 standards. Tests were carried out by an Instron testing machine, with 100-kN load cell, on the 7th day after curing. The test span to depth ratio was 13:1, and the crosshead velocity was 0.47 mm/s. Strain was measured by crosshead displacement. The flexural strength gained by the samples (Mc, M1 and M2) over 28-day period is presented in Fig. 6. The concrete bamboo reinforced sample slightly gained more flexural strength than other composites. The implication of this was that there exist a perfect gripping

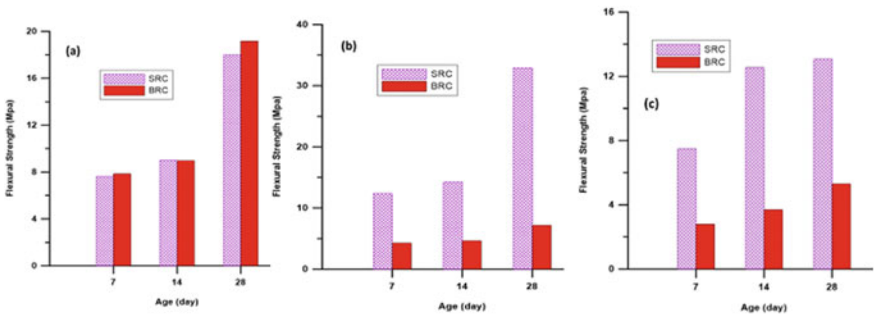

Fig. 6 Flexural strength development over 28 days **a** reference (Mc), **b** mix 1 (M1), **c** Mix 2 (M2) [40]

between the concrete matrix and the bamboo strip. Thus, the resistance of concrete further complemented the appreciable tensile strength of bamboo strip [40].

The preparation and flexural properties of bamboo fiber reinforced mortar laminate was done by Yao and Li [23]. The laminate was a sandwich plate combined with reformed bamboo plate and cement mortar sheet. Test results showed that the reformed bamboo plate can greatly strengthen the fiber reinforced mortar and reduce the total weight of the composite, and the flexural strength values of the laminate can be improved to greater than 90 MPa.

3.8 Impact Strength

The effect of bamboo diameter and slab thickness on impact strength of slab panels were studied during the experimentation. It is reported that there exists a linear relationship for first and ultimate crack strength with respect to bamboo diameter and slab thickness in both type of concrete mix. The impact strength of the bamboo reinforced concrete slabs compared to conventional concrete slabs needs further investigation. The performance of bamboo concrete slab panels subjected to impact loading was investigated. In this work, oil palm shells are used as substitute to conventional aggregate inside concrete mix with cement in the ratio of 0.45 and 0.6. The impact strength for first crack was mainly influenced by bamboo diameter but it is even more sensitive to slab thickness [43].

3.9 Fatigue Strength

An effort to evaluate the fatigue behavior of a cement base composite reinforced with bamboo pulp in the proportion of 6% of the dry cement weight was taken. Bend specimens of the composite were subjected to three point bending and the corresponding S–N curves were determined and then modelled according to Manson-Coffin type formulation. Fatigue data obtained using notched bend specimens showed a great deal of scatter and hence could not be reasonably modelled [6, 44]. Finally, it is worth mentioning that the fatigue behavior of the concrete indicated value the range between 0.0559 and 0.0575. This is seen to be consistent with the fatigue resistance exponent obtained in the present study for the bamboo reinforced cementitious composite.

3.10 Morphology Analysis

The morphologies of untreated and alkali-treated bamboo fibers are shown in Fig. 7a, b, respectively. Compared with untreated, alkali treatment leads to a more open or

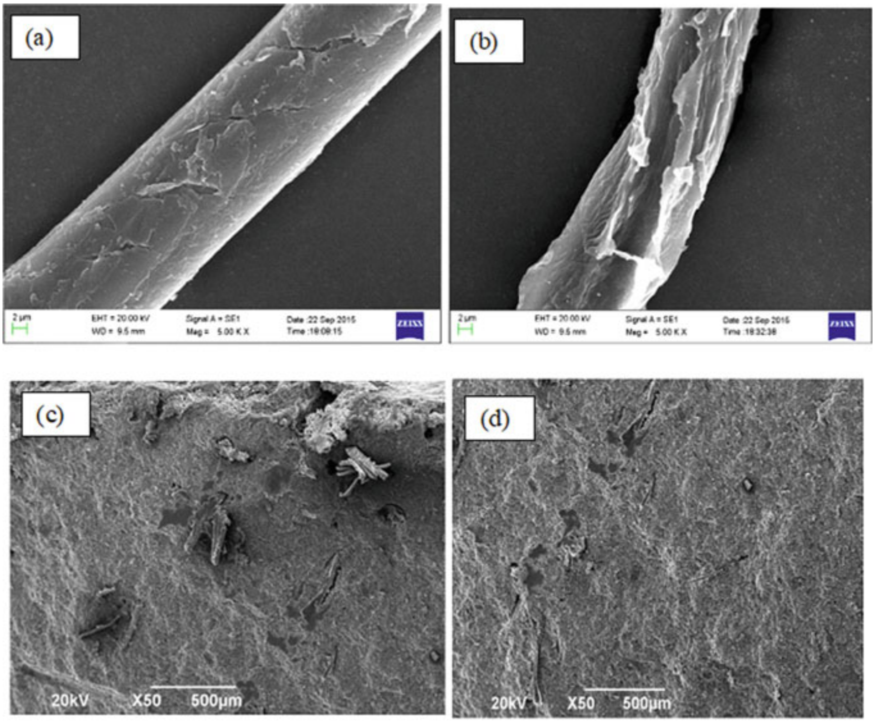

Fig. 7 SEM micrographs of bamboo fibers: **a** untreated; **b** 10% alkali treated; **c** fractured surfaces of cement with 0.5% untreated fibers; and **d** fractured surfaces of cement with 0.5% treated fibers [45]

rough fiber surface, probably resulting in an increased fiber cement bonding and greater energy dissipation during composites failure due to a larger fiber failure surface area [45]. Figure 7c, d show the fractured surfaces of the cement with 0.5% untreated and 0.5% alkali-treated bamboo fiber at low and high magnification, respectively. As shown in images, the cement with 0.5% untreated fiber shows a bunch of individual fibers. This should be caused by the strong inter-fiber hydrogen bonding, which resists dispersion of the individual fiber. Inhomogeneous distribution of fibers would yield bulk and surface flaws. The cement with alkali-treated fiber shows a fine and uniform dispersion of the fibers. Uniform dispersion of treated fibers would inhibit the crack propagation resulting improved mechanical properties of the fiber reinforced mortar. It can be seen that the matrix of cement closely enwrap treated bamboo fiber, and treated fiber homogeneously distributed in cement matrix without obvious phase interface and the aggregation of treated fiber on fracture surface. This indicated that better adhesion is formed between the alkali-treated fiber and the cement matrix. This may be attributed to the fibril-exposed surface, cement precipitation into the fiber cavities and the interfacial bond formed between the cellulose chain of bamboo fibers and calcium based hydrated product of the cement [45].

4 Life Cycle Assessment of Bamboo Concrete

Many of the references cited in this chapter premise bamboo reinforcement for concrete as a green or sustainable alternative to steel reinforcement. This section attempts to quantify this claim using life cycle assessment (LCA), a well-established methodology used to assess the whole life environmental impacts and/or cost of products and services [46]. With the aim of providing a benchmark for the selection of bamboo as reinforcement in concrete structures and comparing their environmental impact, a LCA analysis has been carried out. The software Open LCA was used in combination with the EcoInvent V3 database and the environmental impact evaluation method IPCC2013 [29]. The data for bamboo composites and transport distances were calculated using the methods developed by Escamilla and Habert [47–49]. This method allows for the generation of three scenarios combining the production efficiency of construction materials and the potential transport distances. The bamboo culms are assumed to be only boric acid treated and a structural epoxy surface treatment is assumed to enhance bond. The transport of construction materials was considered to be primarily road transport. The production of the bamboo reinforcements will have emissions of the order of 2000 kgCO_2eq, almost twice the emissions resulting from the production of the steel reinforcements. This increase is attributed to the considerably greater amount of concrete necessary to meet the load carrying requirement of the functional unit.

The increase effects both concrete materials production and transportation. The emissions savings achieved by replacing the steel reinforcement with bamboo are surpassed by the emissions from the additional concrete. Considering only the bamboo reinforcement; the emissions contribution from the bamboo reinforcement is minimal, but the emissions from transportation of bamboo are much greater than the materials savings achieved by replacing steel; this conclusion was arrived [49, 50].

5 Industrial Applications of Bamboo Concrete

The usage of bamboo-reinforced concrete in primary structural members, certain related applications may be practical provided issues of durability, dimensional stability and bonding between bamboo and concrete are addressed as discussed in this chapter. Bamboo splints may be an alternative for crack control reinforcement for slabs on grade provided at least 3% bamboo is used. Such slabs are designed to remain uncracked and/or are provided with control joints to permit only controlled cracking. Light cement bamboo frame panels, known colloquially as bahareque construction are well established [51]. This construction is a modern technique utilising composite shear panels constituted of a wall matrix of bamboo or metal lath nailed onto a bamboo framing system, plastered with cement or lime mortar render. This method works well because the stresses in the wall matrix are very low. This method of construction is recognised and promoted by ISO 22156. Bamboo splints has been proposed as reinforcement for masonry construction. Due to the role masonry reinforcement plays, some researchers consider bamboo reinforcement as suitable to reinforce hollowcore masonry in non-seismic environments [18].

Javadian et al. [36] have proposed the use of a heat treated, densified engineered bamboo composite for concrete reinforcement. The resulting composite strips to be used as concrete reinforcing bars, the composite strips are coated with epoxy resin and sand is broadcast on to this as a means of enhancing bond. The bond capacities ranged from 2.42 to 3.65 MPa in direct pull-out tests which was reported to be about 80% of comparable steel reinforcement bond strength. Such engineered bamboo composite reinforcing rods hold promise for overcoming many of the obstacles associated with using bamboo as concrete reinforcement. Till now no LCA or similar comparison with steel has been made to document assertions of sustainability. Nonetheless, it is clear that the additional processing, energy and the resins used on their production will have a significant impact on environmental impact and cost. Finally, bamboo fiber reinforced concrete has been proposed and demonstrated by several researchers [52–54].

6 Conclusion

Bamboo reinforced concrete stands to be a good option in the sustainable development of civil engineering construction. Many researches has been carried out in this field which helps us in understanding that use of bamboo in reinforced concrete has a vast scope. In order to expand the application of bamboo in building structures, bamboo concrete composite structures are discussed in this chapter.

- Bamboo is a ductile reinforcing material having some appreciable tensile strength,
- which makes it suitable as a substitute for steel. Due to its strongly bonded particles, bamboo can be an excellent material for members subjected to compression and bending.
- A poor bonding of bamboo with concrete with alternative material can be a factor, because bamboo on its own has good strength and ductility.
- Performance of bamboo fiber composite in concrete pore water solution, indicating the ability of bamboo to retain its mechanical properties in the alkaline environment of a concrete matrix.
- It can be concluded that bamboo provides a high tensile strength of 250 N/mm^2 or higher which actually depends on the area of cultivation, type of species and cross-sectional area. An improved flexural performance of bamboo composite beam has been observed with the increase in number of days of curing period and increase in the size of bamboo rebar.
- Although the aim of the study is to increase the flexural strength but in practical case with the increase in span of the beam the mid span deflection increases which

is also an important criterion when serviceability limit state is considered, thus reduction of mid span deflection is another major area of research.

- Design, fabrication and evaluation of properties of bamboo revealed the bamboo-reinforced concrete composite to be a potential sustainable green material for construction.
- It is noted that bamboo is a cheap and replenishable agricultural resource and abundantly available in some countries. Thus, it would be expected that the low-cost bamboo reinforced constructional and housing products have a widely market in future.

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Characterization and Properties of Biopolymer Reinforced Bamboo Composites

Laila El Foujji, Khadija El Bourakadi, Abou el kacem Qaiss, and Rachid Bouhfid

Abstract The development of novel sustainable eco-friendly materials gained increasing attention, in order to minimize the dependency on fossil fuels. Biopolymers and derivatives are among the chosen materials due to their natural origin, diversity and abundant character as well as being environmentally friendly thanks to their biodegradability. Biopolymers are complex biochemical units that vary due to their structures, they are synthesized from plants or living organisms. The advantages of these natural polymers are biodegradability and renewability, but used alone, they have low mechanical properties. To overcome this drawback, using composite materials which have a wide spectrum activity in industrial and engineering fields seems as an interesting choice. Recently, for composite manufacturing, interest shifted towards using fibers stemming from natural resources as reinforcements, because of their environmental benefits. Using a biodegradable matrix and a bio-resourced filler would result in a completely biodegradable composite. The available naturally occurring reinforcements are based upon jute, sisal, flax, hemp, and kenaf etc. We will be interested in the use of bamboo fibers as reinforcing fillers for biopolymer composites. Bamboo fibers own one of the most desirable combinations of low density (1.4 g/cm^3) and good mechanical properties allowing them to compete with glass fibers in terms of specific stiffness and strength at similar volume fractions. In this chapter, we will present the latest biopolymers used in composite and nanocomposite materials and their main properties and characterization screening their combination to various types of bamboo fillers, starting from the raw materials to nanoscale dimensions and, we will show some main applications in interesting domains.

Keywords Bamboo · Biopolymers · Composites · Nanocomposites · Characterization

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1 Introduction

Each year, the development progresses in science and technologies led to a huge number of polymers and polymer by-products. However, the main majority of the synthesized polymers are from fossil fuel origins, which make them non-biodegradable materials, and with the absence of the best treatment methods, they become environmentally harmful wastes [1]. In addition, the shortage of oil and fossil fuels has been a problem for many years and raises concerns all around the globe. It also greatly affects the field of chemical industry. For example, a 2012 statistic study showed that the annual plastics production is around 200 million tons [2]. Therefore, it is necessary to find new renewable and environmentally friendly raw material alternatives to replace fossil fuel resourced ones. An interesting good approach is to produce polymers from agricultural sources [3], polymers issued from renewable resources, biomass in particular, have received a rising attention lately due to their environment friendly impact. This class of polymers have two important properties, which are biodegradability and biocompatibility, that are mostly investigated regarding several applications such as medical issues [4]. Through the previous two decades, major advances have been done on developing biodegradable polymer materials for several applications [5], some applications of biodegradable polymers include food packaging, packing foams, disposable food service items and health care products, at the present, most of these products are produced from polystyrene or polyethylene. They also become wide ranging vital materials in the implantable applications, such as dental and orthopedic devices, drug delivery systems and tissue engineering scaffolds [6]. The use of biopolymers (such as starch, chitin, cellulose…) with other components is an interesting choice in order to bring them new properties or at least, improve their intrinsic properties. Composites and nanocomposite materials the strategy to be followed to reach the previous goal. The mix between biopolymers and fibers to improve some properties, should not alter the biopolymers' biodegradable and environment safety properties. The advantage of natural bio-sourced fibers over inorganic ones (such as glass fibers…) is their reduced cost. Other properties also include low density, high specific density/resistance ratio, low abrasiveness, along with biodegradability and renewable origin [7]. Bamboo is an interesting source of fibers, it's a fast growing tree, and has an abundant global production of about 30,000 kt each year, the stiffness and strength of bamboo fibers are closely similar to this property of glass fibers and hard woods [8]. Bamboo fibers present favorable physical and mechanical properties compared to natural fibers and have been proposed for reinforcing different polymer matrices including polylactic acid [9]. The cellulose is the main constituent of bamboo fibers, about 57%, followed by the lignin content by approximatively 25% and the humidity is present at 8.5%. Nanocellulose is gaining a great deal of attention, it typically has a 5 to 50 nm width and an important specific surface area. Enormous advancements and considerable interest on cellulose nanofiber were seen in the last decade owing that to renewable character, low density, advantageous mechanical properties, availability, and diversity of sources. The use of cellulose nanofibers from bamboo pulp as a reinforcing phase in natural rubber have been studied and proven to have superior values of tensile strength compared to early reports on natural rubber [10]. Cellulose whiskers or nanocrystals extracted from bamboo are another important type of reinforcements, an improved yield of 88% of cellulose nanocrystals extraction was established by simultaneous mechanochemical activation and phosphotungstic acid hydrolysis, Short rod-like cellulose nanocrystals were elaborated and showed higher thermal stability and displayed a web-like network structure that could provide higher reinforcing capability for composite materials [11].

2 Polymers and Biopolymers

The polymer is a word that descends from the Greek term "many parts", it's the main constituent of plastic and elastomer materials. Large molecules or macromolecules that are made and composed of repeated monomers chemically joined and bonded into long chains result in obtaining polymers [12]. Thanks to their numerous properties, natural polymers, and synthesized ones play a ubiquitous role in everyday life [13]. The chemical industry produces enormous quantities of synthetic polymers in order to assure the material needs for product diversity, including coatings, films, paints, and structural plastics. Yet, in the previous several decades, the development of eco-friendly and sustainable products to lessen the dependence on the attenuated fossil fuels, which is the source of most plastics, knew a major increase. The rapid growth of the demand for removing petroleum-derived plastics from our eco-system has been an impetus to the research on bio-friendly polymers [14]. Biopolymers are the alternative solution for this problematic issue, currently considered as a potential class of materials and among the most investigated ones [15]. Biopolymers are extracted from various natural resources. A summarize of biopolymer classification is shown in Fig. 1.

2.1 Classification and Characterization of Natural Biodegradable Biopolymers

The classification of biodegradable polymers is not usually an easy task. They can be sorted according to many criteria. Starting from their chemical composition, synthesis and processing methods, their economic importance and application. These classifications provide useful and different information [17]. To categorize biodegradable polymers called biopolymers based on their origin, we can find two groups: natural polymers issued from natural resources and synthetic polymers.

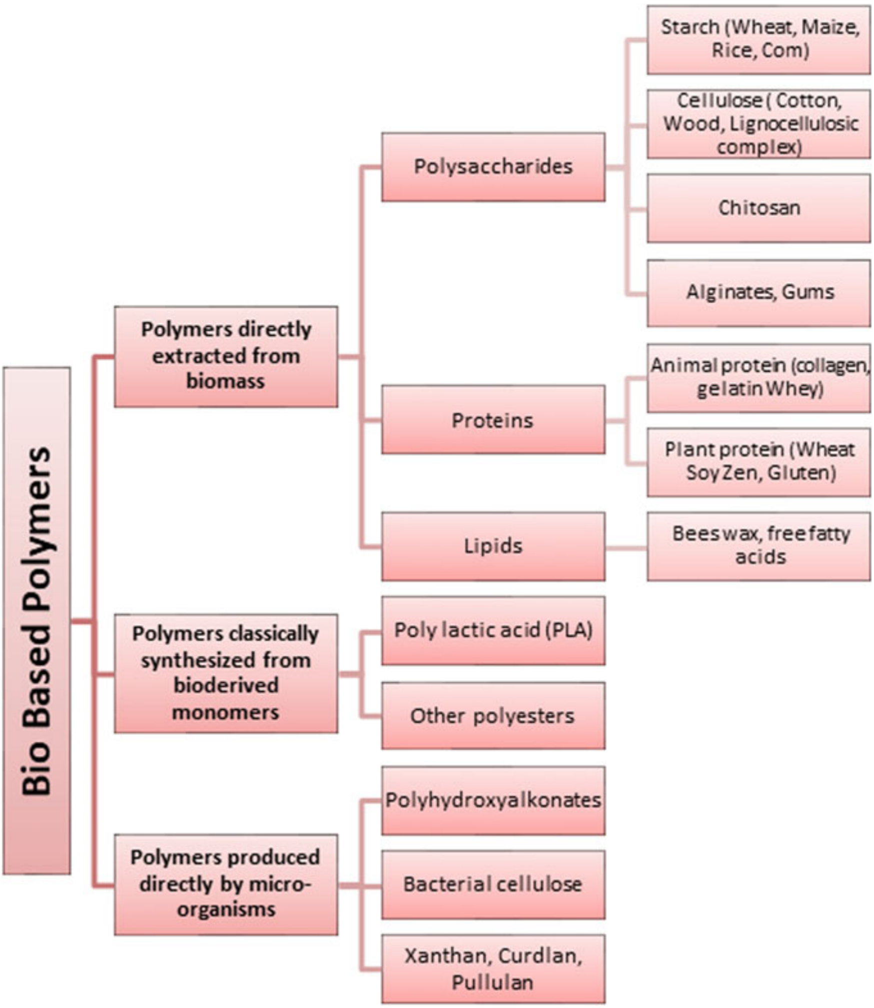


Fig. 1 Classifications of bio based polymers [16]

2.1.1 Carbohydrate Polysaccharides

Polysaccharides are made of several monosaccharides linked together via glycosidic bonds. It's the largest component of the biomass, its value is expected to exceed 90% of the carbohydrate mass in nature [18].

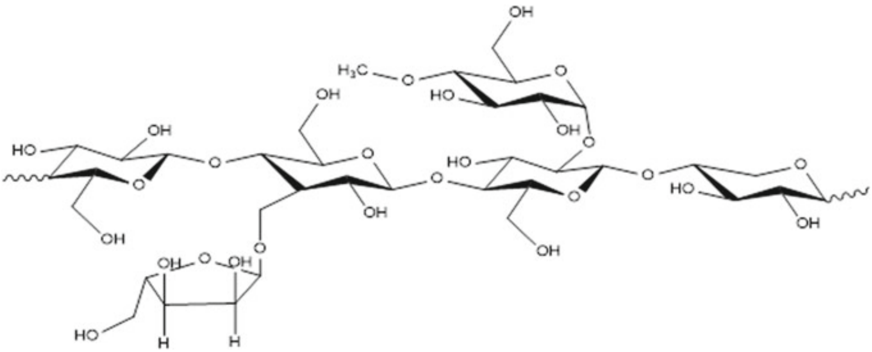


Fig. 2 Hemicellulose structure

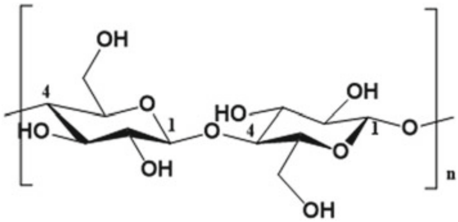
Microbial and Animal Polysaccharides

Microbial polysaccharides are renewable resources materials made by microorganisms, and they have both characteristic of biocompatibility and biodegradability, such as alginates/alginic acid. Thanks to their high properties for thickening, stabilizing, emulsifying, and gelatinization, they are used in many industrial fields as additives, such as the synergic effect seen between polysaccharides and particle gel on the thickening and oil recovery [19]. Many potential natural polysaccharides are used in the drug delivery systems, the widely used one is chitin and its derivative. Chitin is a widespread biopolymer, located in large quantities in marine animals, especially on the animals' outer skeleton such as insects and crustaceans [20]. Chitosan have gained important attention thanks to the fact of being biodegradable, biocompatible and to their non-immunogenicity and non-toxicity [21].

Hemicellulose

In general, hemicellulose is a pentose-based polysaccharide [22], that forms the cellulose-hemicellulose network thanks to its attachment by hydrogen bonds to the cellulose microfibrils, which guarantees the rigidity and strength of the plant tissues [23]. The hemicellulose structure was first elucidated as arabinoxylan oligosaccharides with diferulic acid cross-linkage in moso bamboo shoots, the thermal degradation was observed to occur at 200–300 °C for 4-year-old moso bamboo. Figure 2 shows the hemicellulose structure. The hemicellulose includes xylans, xyloglucans, glucomannans and mannans, and it plays an important role in plant tissue configuration [24].

Fig. 3 Structure of cellulose



Cellulose

One of the top polysaccharides contributing at a fast rate to engineer multifunctional bio-based materials, is the cellulose, especially at its nanoscale forms. Cellulose is a linear chain of glucose molecules having a flat ribbon-like conformation, its repeat unit consists of two anhydroglucose moieties joined together 1–4 glycosidic bond as shown in Fig. 3, n is the polymerization degree which found to vary between 10,000 and 15,000 depending on cellulose source [25]. Cellulose is extracted from plant using chemical, mechanical or enzymatic methodologies, we will focus later on, on some important applications of this polysaccharide, but as a first important application, we can cite the manufacture of a fully bio-based conductive separator made from cellulose polysaccharide for application as a separator in electrolyte polymers in fuel cells [26]. The pretreatment of bamboo with cold sodium hydroxide and urea lead to some structural and morphological changes, providing high reactive cellulose that found and important application in the bioethanol production [27].

Starch

Starch is ranked among the three more abundant polysaccharides on earth, along with cellulose and chitin. But it is the only used material as main carbohydrate storing system of green plants, while chitin and cellulose are structural polysaccharides. Starch is collected in amyloplasts organelles and can be stored for a long period of time, and it's used generally in food [28].

Chitin

Chitin is the second largest carbohydrate resource for the production of fuels issued from bio-sourced origin and of some chemicals, the sustainable and efficient conversion of chitin makes it an attractive material [29]. Chitin is constituted by sequences of *N*-Acetyl-*D*-glucosamine through a β linkage, its structure is shown in Fig. 4 it is the second abundant biopolymer in nature after the cellulose. Among the applications of chitin is its use in the manufacture of films used on board surfaces to prevent the bacterial growth in perishable food packed in starch-based treated board [30].

Fig. 4 Chitin structure

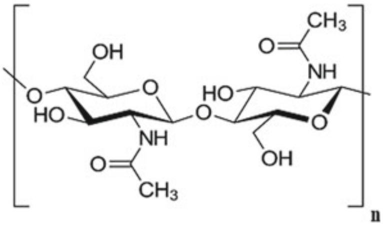
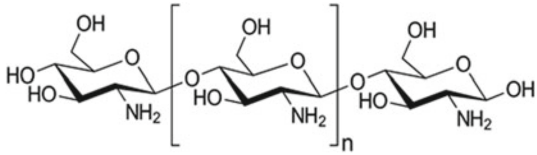


Fig. 5 Chitosan structure



Chitosan

Chitosan is a linear cationic biopolymer, ranked in the second position of the most abundant natural biopolymer after cellulose. It has a similar structure to cellulose; the only difference is the type of attached group to carbon 2 [31]. The chemical structure of chitosan is shown in Fig. 5. This polysaccharide is built from 4-linked-β-2-amino-2-deoxy-glucopyranose residues, some of which are *N*-acetylated as shown in Fig. 5.

Chitosan biopolymer have a wide spectrum of use, an important application is its use as a coating agent of several nanoparticle materials, such as polymer, lipid and metal nanoparticles. An efficient coating process is confirmed, as well as, many physicochemical and biological advantages that were brought by the chitosan-coating, like physicochemical stability, improvement of tissue/cells interaction, controlled releasing time and increase in the bioavailability and efficacity of drugs [32].

2.1.2 Animal and Plant Sourced Proteins

Many proteins extracted from animals exist, for example gelatin, collagen and whey. The collagen, another abundant and natural biopolymer that has many applications in the biomedical and non-biomedical fields, this biopolymer can be extracted from fish waste using ionic liquid as a green pretreatment route [33]. Gelatin is another biopolymer with interesting properties, it can for example be applied as a coating layer to stabilize surfaces by increasing the steric barrier and it shows interesting anti-angiogenic and antibacterial activity [34]. Many plant proteins are used in chemistry fields (wheat gluten, soya, zein, caesin…), for example functional commercial soy proteins are often affected due to their natural high molecular weight but a controlled enzymatic hydrolysis reaction of these proteins can improve both the technical functionality of these proteins and numerous of their bioactive properties like providing good emulsion activity and gelling ability [35].

2.2 Synthesis and Properties of Synthetic Biopolymers.

Synthetic biopolymers have been developed, primarily in response to perceived uncertainty in the continuing supply of fossil raw materials from the 1970s oil crisis, they are mostly developed for biomedical and agricultural applications, Among these synthetic biopolymers, we cite polylactic acids or polylactide, that indicates the same biodegradable aliphatic polyester, polyhydroxyalkanoates, polyhydroxybutyrate, polyglycolide, polydioxanone, polyvinyl alcohol…. Synthetic biodegradable biopolymers have been developed, typically for biomedical and agricultural applications [36]. The biopolymer production capacity in 2011 sorted by type is presented in Fig. 6.

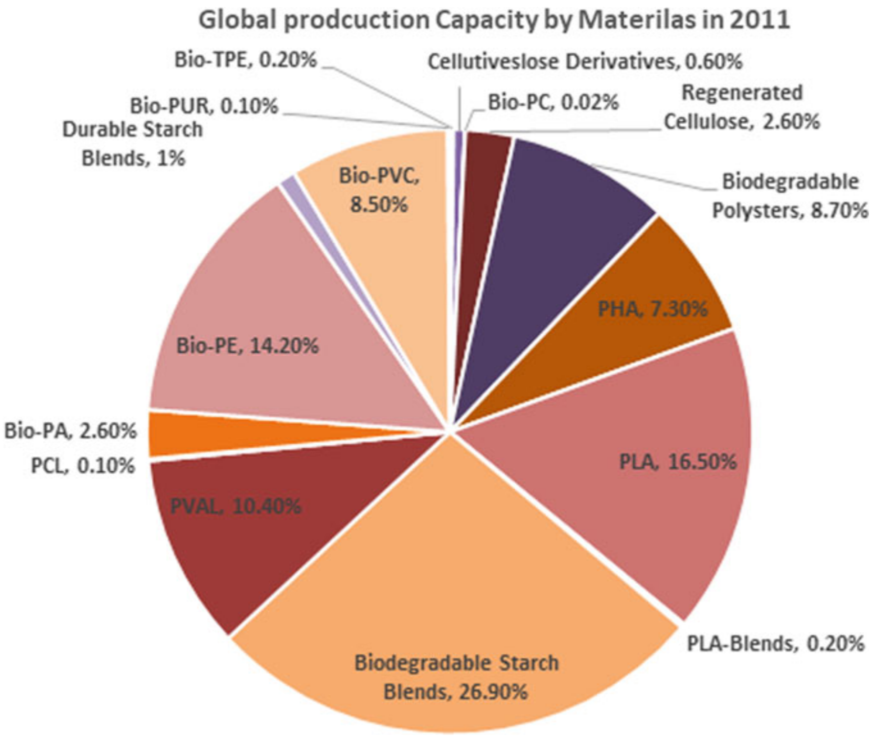


Fig. 6 Biopolymer production capacity in 2011 by type [37]

3 Bamboo and Bamboo Fibers

Bamboo received expanding attention in the previous two decades thanks to its economic and environmental values [38]. Bamboo (*Bambusa arundinacea*) is a woody, perennial, evergreen plant that belongs to the Poaceae-Graminae, considered to be the fifth-largest known ubiquitous family of monocotyledonous flowering plants, containing all lower grasses along with some giant members. Numerous chemical compounds are found in the leaves of bamboo and have an important therapeutic activity against a number of diseases and play a vital role as antioxidants. Leaves mainly consist of benzoic acid, hydrocyanic acid, glutelin protein, flavonoids, proteolytic enzymes [39]. The general composition of bamboo culm is shown in Fig. 7.

3.1 Sources of Bamboo

Bamboo is one of the most important and substantial green renewable resources, it is an easily flourishing plant, a cursory obtainable fibrous plant that can be used as an alternate for the unsustainable synthetic fibers in the biodegradable polymer, it offers a great potential alternative to wood [41]. Globally, bamboo is widely available in about 1662 species and 121 genera, and it is distributed over a large number of biogeographic regions, commonly found in Africa, Asia, some parts of Europe and America [39].

3.2 Bamboo Fibers Extraction

Bamboo fibers are extracted mainly by mechanical methods to avoid much black liquid release [42]. The bamboo fibers extraction methods are important to maintaining particular properties of bamboo fibers, the use of a machining center to

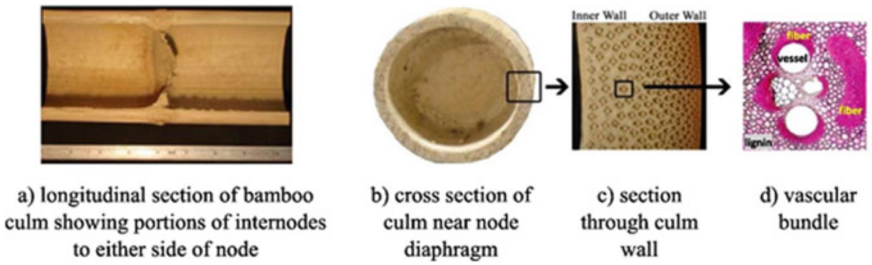


Fig. 7 Anatomy of bamboo culm showing functionally graded distribution of fiber in culm wall [40]

end-mill the bamboo culm, for example, results in obtaining high-quality, straight bamboo fibers without any thermal damage [43]. The treated bamboo may be made into huge durable structural elements that will have the potential ability to become transformative large-scale building materials. Laminated bamboo, for example, is a promising structural engineered material, generally made by improving the material's durability [44]. Raw bamboo fibers can be used as microscopic reinforcement agents, these fiber bundles of 125–210 μm in diameter were used as reinforcement agents of a polymer matrix made of maleic anhydride polypropylene. Commercialized bamboo chips (3 × 2 cm) using were filtrated and were the source of the bamboo bundles, using a mesh sifter machine. The tensile strength of the bamboo bundles was as high as that of the jute fiber [45]. In another case, using untreated and alkali-treated continuous bamboo fibers were studied to compare their properties, these fibers were incorporated into an epoxy matrix. The characterization showed that the strength of bamboo fibers was reduced with the alkaline treatment, however, the alkali-treated fiber-reinforced composites acquired better tensile strength than those with untreated bamboo fibers [46]. Bleached bamboo fibers are another branch of fibers that have some important characteristic, for instance, a comparative study on the compatibility of unbleached and bleached bamboo-fibers with the Linear low-density polyethylene matrix, showed better properties of the bleached fibers in terms of tensile strength and less water uptake, which assure an improved compatibility of these fibers conjointly with a better wettability with the apolar matrix [47].

3.3 Mechanical and Morphological Properties of Bamboo Fibers

3.3.1 Tensile Strength

The usual longitudinal tensile strength of Moso bamboo single fibers ranges from 1.43 to 1.69 GPa, what makes it significantly higher than nearly all the previously published data. High-strength bamboo strip used to reinforce composite materials with a maximum tensile capacity of approximately 180 MPa were fabricated using the hot press method [48]. Table 1 shows some physical properties of some natural fibers [49].

Table 1 Physical properties of some natural fibers

Sl. No.	Fiber name	Density g/m^3	Tensile strength (MPa)	Young's Modulus (GPa)	Specific strength MPa/g m^{-3}	Specific modulus GPa/g m^{-3}	Failure strain (%)
1	Bamboo	800	441	35.9	551	44.9	1.3
2	Jute	1300	370	22.7	281.6	17.5	1.4
3	E-glass	2500	2400	70	900	28	–

3.3.2 Scanning Electron Microscopy

The morphologies of untreated bamboo fibers and alkali-treated bamboo fibers are shown in a and b of Fig. 8, respectively. Alkali treatment leads to a more open or uneven rough fiber surface which results probably in an increased fiber-material bonging due to a larger fiber surface area [50].

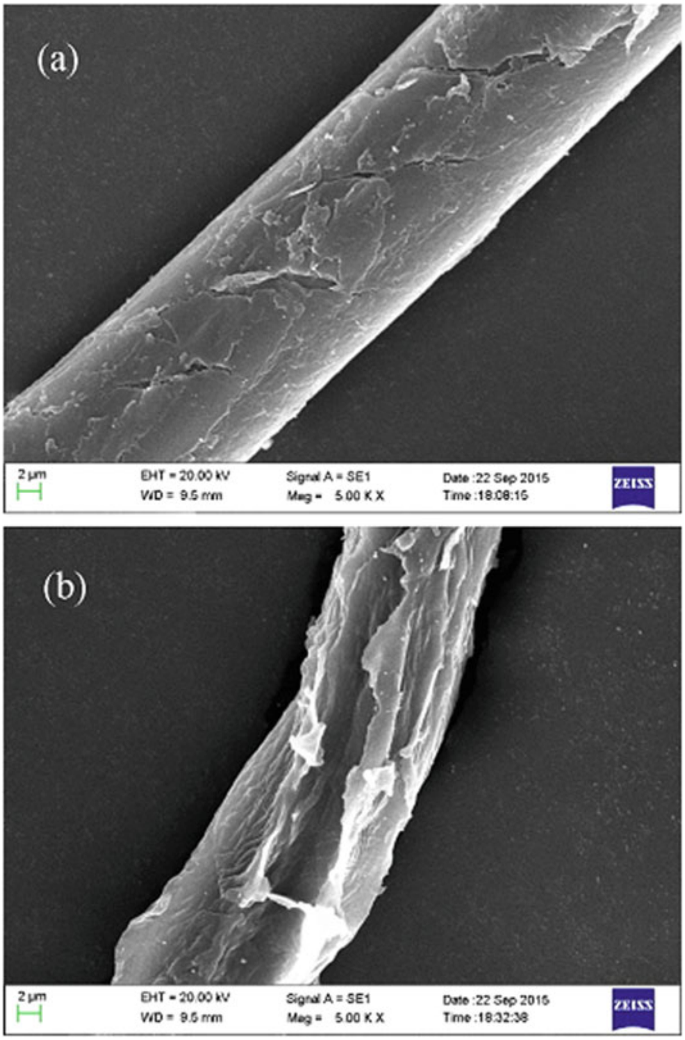


Fig. 8 SEM micrographs of the bamboo fibers: **a** untreated bamboo fibers; and **b** 10% alkali treated bamboo fibers

3.3.3 Fourier Transform Infrared Spectroscopy

The Fourier transform infrared spectroscopy (FTIR) is a powerful technical tool that is used to recognize and confirm the presence of certain functional groups belonging to the modifying agent used during the modification and also the mechanisms of interaction between materials [51]. Fourier transform infrared spectrums of treated samples that were presented elsewhere [52] comparing raw to bleached and caramelized fiber have only some subtle differences that exist between these treated sample and the raw one, observed shifts in the bleached material compared to the raw Moso bamboo were attributed to the bleaching process oxidizing the aromatic rings of the phenolic groups in the lignin (1230 cm^{-1}) and to hydroxyl groups in the polysaccharides (1047 cm^{-1}). The FTIR spectra from another study [53] of original bamboo, microwave liquefied residue, bleached residue, alkali treated residue, and cellulose nanofiber are presented in Fig. 9. They are showing the important absorbance peaks that distinguish the original bamboo which have characteristic bands such as 1735 cm^{-1} for hemicellulose and 1230 cm^{-1} for lignin, from the liquefied one, where an absorbance band appears at 1203 cm^{-1} and attributed to S=O vibration revealing the introduced sulphate groups during the microwave process because of the use of sulfuric acid as the catalyst. The other characteristic absorbance bands of lignin (1596, 1506, 1456, and 1230 cm^{-1}) were absent in the spectrum of the bleached residues.

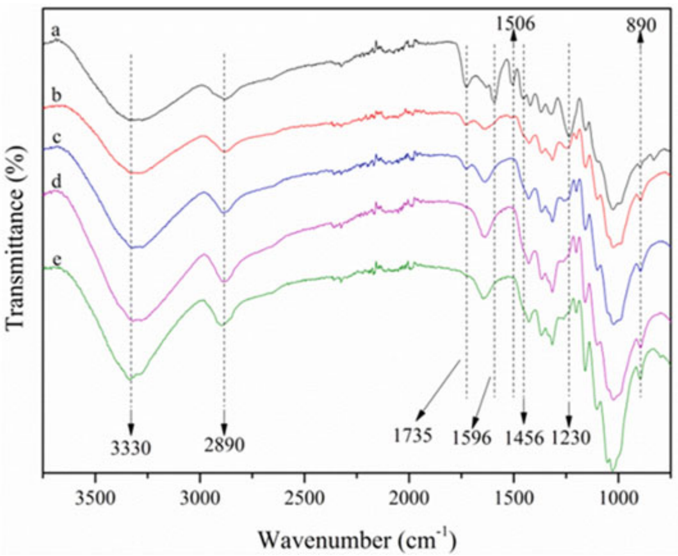


Fig. 9 FTIR spectra of **a** original bamboo, **b** microwave liquefied residue, **c** bleached residue, **d** alkali treated residue, and **e** cellulose nanofiber [53]

4 Properties of Bamboo and Cellulosic Bamboo Fibers

4.1 Bamboo Based Nanofibrillated Cellulose

The bamboo was studied as micro and nano reinforcement agent in polymeric matrices, including thermoplastics such as polyethylene, polypropylene, different polyesters, and other semicrystalline polymers, hybrid composites such as that of polypropylene and polylactic acid, macro reinforcement in thermosets and polyester resins [55]. The hierarchical structure of bamboo fibers is described in Fig. 10. Nanofibrillated Cellulose is the cellulose fibers that have been fibrillated to reach the agglomeration stage of many cellulose microfibril units, nanofibrillated cellulose has a nanoscale diameter (at least one dimension should be less than 100 nm) and a typical length of several micrometers [56]. Cellulose nanofibrils can be derived from the bamboo plant using eco-friendly ultrasonic treatment process, which provides a high aspect ratio of isolated nanofibrils [57]. Appropriate pretreatments of cellulosic fibers are important parameters to consider for promoting hydroxyl groups accessibility, increasing inner surface, alter crystallinity, and break cellulose hydrogen bonds and therefore, boost the reactivity of the fibers, among the mechanical processes used to isolate nanofibrillated cellulose, we can cite: High pressure homogenization, grinding, cryo-crushing, micro-fluidization, steam explosion, ball milling and high intensity ultrasonication [56, 58].

Chemical modification on cellulose fibers is mainly used to facilitate cellulose nanofibers production and decrease energy consumption, among the first used strategies of introducing negative charges on the cellulose fibers surface is the oxidation, using 2,2,6,6-tetramethyl-1-piperidinyloxy (TEMPO) [59], the newest research on TEMPO oxidation for cellulose nanofibrillation focused on coexisting salts, where a

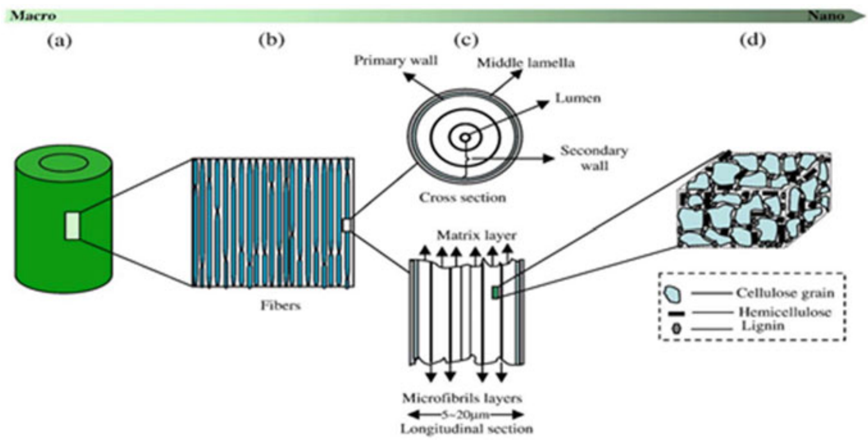


Fig. 10 Hierarchical organization of bamboo fibers over different length scales [54]

portion of NaBr was replaced by Na_2SO_4, providing both cheaper cost and leads to the same carboxylic content. Phosphoarylation is another way of introducing negative charges on cellulose fibers, it's a new emerging chemical pretreatment. Many other chemical modification processes exist (enzymatic, sulfoethylation, cationization, ozonation…) [60].

4.2 Bamboo Cellulose Nanowhiskers

Cellulose microfibril is a semicrystalline polymer, it is constituted of a disordered region called amorphous region and a highly ordered called crystalline region [61]. While acid hydrolysis treatment is applied to cellulosic microfibrils, it allows the dissolution of cellulose amorphous domains. During this process, hydronium ions pierce the cellulose chains in the amorphous domains promoting the hydrolytic cleavage of the glycosidic bonds and liberating individual crystallites. The resulting material is called cellulose whiskers, but other terminologies are used such as cellulose nanocrystals, cellulose nanowhiskers, or nanocrystalline cellulose [62]. A mechanochemical approach of manufacturing bamboo cellulose whiskers via the dissolving action of phosphoric acid on cellulose microfibrils was applied, this leads to high yields bamboo cellulose nanocrystals thanks to the swelling effect of phosphoric acid on microfibrils, allowing them a better disintegration [63]. Decreasing the size of a material from the microscale to the nanoscale have a major effect on its properties, they change and they are expected to drive new potential applications. The main impacted properties by this change are reported below:

4.2.1 Specific Surface Area

The specific surface area is a property of solids defined as the total surface area of a material per unit of mass, since the nano-dimensions of the structural elements leads to a high surface area, the reported large specific surface area of cellulose nanocrystals is estimated to be more than 100 $m^2\ g^{-1}$ and even up to several hundreds of $m^2\ g^{-1}$ [64]. The addition of sulfuric acid to bamboo fibrils separated the cellulose whiskers instantly. After a 3 h treatment using a 65 wt% sulfuric acid, bamboo whiskers showed the maximum specific surface area of 14.225 $m^2\ g^{-1}$, while after a 4 h treatment with a 55 wt% sulfuric acid treatment, the specific surface area of the whiskers reached 13.355 $m^2\ g^{-1}$. Cellulosic hydrolysis degree varied in acid concentration and processing time, more pores led to a larger specific surface area, but an excessive treatment dissolved the cellulose and the specific surface area may decrease [65].

4.2.2 Aspect Ratio

Aspect ratio is defined to be the length to width (L/W) ratio, it is a predominant factor in the morphological characterization of cellulose nanowhiskers, usually, sphere-tended nanoparticles exhibit a low aspect ratio value ($\geq$1), but close to 1. A study on cellulose nanocrystal prepared by using sulfuric, hydrochloric, phosphoric, and a mixture of acetic and nitric acid solutions showed good aspect ratios ranging from 1 to 28 [66].

4.2.3 Mechanical Properties

The mechanical modulus of cellulose nanomaterials is doubtlessly their main asset.

The cellulose is a ubiquitous structural polymer that gives its mechanical properties to higher plant cells. The tensile modulus of native cellulose crystals for example can be estimated to range between 56 and 220 GPa, with an average value of 130 GPa [67].

4.2.4 Thermal Properties

The thermal properties of cellulose nanoscale materials are low because of its low thermal stability, and this might affect their use, especially sulfuric acid-hydrolyzed nanocrystals [62].

4.2.5 Morphological Properties

Bamboo cellulose nanocrystals exhibited a large length-to-diameter ratio (L/D) and had rod-like shapes (Fig. 11), the fibrillated bamboo cellulose nanocrystals had a higher surface area and better cross-linking characteristics when used as nanofillers. The bamboo cellulose nanocrystals had an average length, diameter and L/D ratio of 455 nm, 12 nm and 37, respectively [68].

5 Composites and Nanocomposites Based on Bamboo

A composite material is a multiphase material formed from a combination blend of materials which vary in the composition or in the form and remain bonded together, and retain their identities and properties. Composites maintain an interface between components and act in concert to provide improved specific or synergistic characteristics that cannot be obtainable by any of the original components acting alone [69].

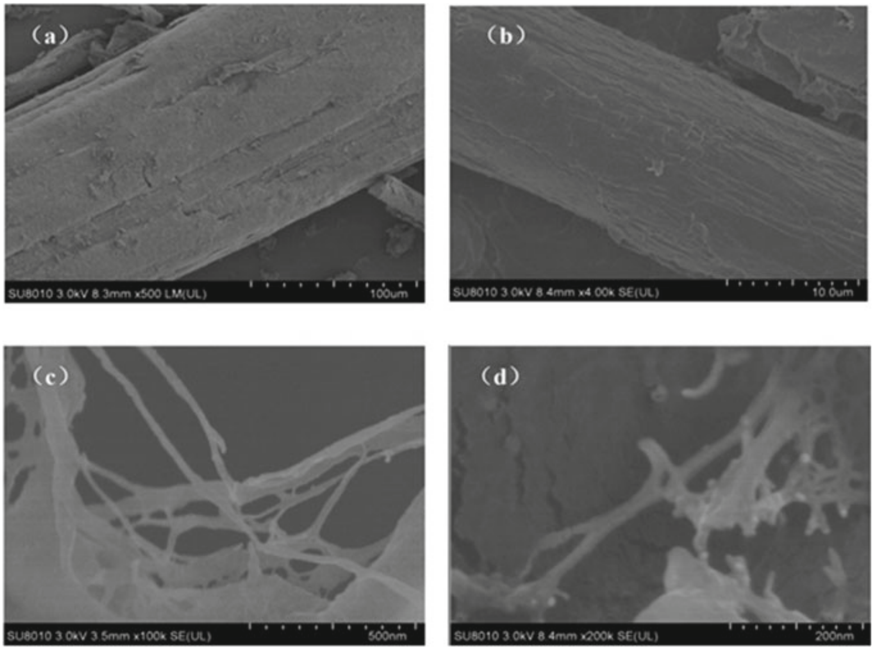


Fig. 11 SEM Micrographs of bamboo cellulose with different treatment: **a** raw bamboo particles; **b** alkali treated; **c** 55 wt% H_2SO_4 4 h; **d** 65 wt% H_2SO_4 3 h [68]

In the present era, researchers cannot think about the development without developing new materials with exciting properties to meet the increasing and diverse demand of both industry and society [70]. Composite materials are materials consisting of a fibrous phase generally a reinforcing fiber providing high mechanical properties for example, incorporated in a continuous phase (matrix). Depending on the type of matrix, composites are classified as polymeric, metallic, or ceramic [71]. Nanocomposites show great promise as they can provide the necessary stability and processability for important application.

5.1 Characterization of Composite Materials

5.2 Physicochemical Properties of Composites and Nanocomposites

Dramatic changes in the physicochemical properties of composites and nanocomposites can occur, due to the fillers or reinforcement agents, physical and thermal properties can increase or decrease according to the amount and nature of the fillers,

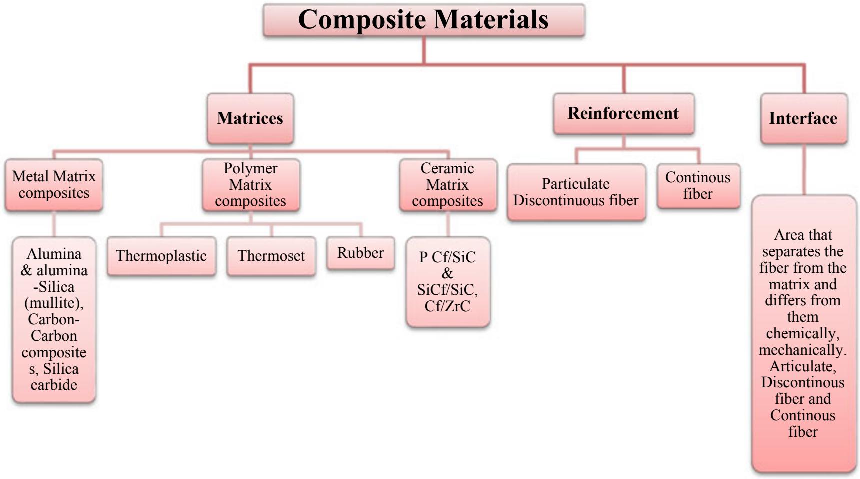


Fig. 12 Composite materials and types of constituents [69]

as well as many other properties such as mechanical behavior, along with some critical issues like the poor bonding, poor wettability, and the degradation at the interface between fiber/matrix which is usually caused by a hydrophilic and hydrophobic effect [72]. Some main components of composite materials are described in the Fig. 12.

5.3 Manufacturing Processes

Manufacturing processes of composites and nanocomposites are crucial steps to consider in the materials elaboration process. For instance, the damage of the fiber during manufacturing present a main reason of the decrease of the composites' strength, as well as other properties, The suitable manufacturing processes must be utilized to transform the materials to the final shape without causing any defect of products, for example the injection moulding of composites is a process where a measured amount of mixture which contains the molten polymer and fiber is forced into mould cavities [73]. Another process is the Compression moulding, many studies were conducted on the possibility of using natural fibers as filler mixed with renewable polymers to form a new class of biocomposites through compression moulding process, it's the preferred process thanks to its simplicity and fast processing cycle [74]. Hot processing favorable for simple flat samples because only two hot plates are needed to compress all fiber and matrix together simultaneously, then heat was applied, and the last process is resin transfer moulding [72].

6 Bio-based Polymers Matrices Reinforced Bamboo Composites

Chitosan is an exciting biodegradable, biocompatible and non-toxic polymer, it is commercially available and indeed widely used in composites as a matrix, in a recent study, the manufacturing and characterization of bio-nanocomposite films using chitosan as matrix, which was reinforced with bamboo or montmorillonite nanofibers was done. The solutions were prepared by dissolving crab shell chitosan in a glacial aqueous acetic acid following the described specific concentration and under the described conditions, the prepared films were elaborated by the casting technique. A comparison of cassava starch and chitosan as matrix polymers was established, showing some better response to nanostructure process of cassava starch, while in another hand the use of bamboo nanofibers showed a good interaction between the polymer matrix and the nanofibers, and the use of montmorillonite nanoparticles and bamboo nanofibers improved the low mechanical resistance of chitosan films and improved also its poor barrier properties [75]. In another study poly lactic-co-glycolic and nanohydroxyapatite and bamboo fibers were combined as a ternary composite by solution mixing method, the effect of the bamboo fibers content was investigated, it has an important impact on crystallization behavior, interface structure and mechanical and thermal properties. 5 wt% of the bamboo fibers showed the ultimate benefits for both crystallization and mechanical properties [76]. Another study investigated the mechanical and thermal properties of an aged composites based on polypropylene, ethylene-propylene-diene monomer and talc reinforced with bamboo fibers. Again, adding bamboo fibers increased significantly flexural and tensile modulus and the fatigue life, while decreased the elongation at break and impact strength. A compatibilizer was also used and it influences positively only tensile and flexural strength, but it has a negative effect on tensile elongation at break and impact strength of the material [77].

6.1 Morphological and Structural Characterization of Nanocomposites

Nanocomposite materials can be characterized using several tools, in the following part examples of nanocomposites materials characterization studies will be presented. A research paper on poly(lactic acid) (PLA)/bamboo cellulose nanowhiskers (BCNW) bionanocomposite material exhibits improved high toughness but a low modulus, in order to surpass this drawback, new fillers of silane surface-modified based ultrafine bamboo-char were used. The elaborated materials were films made by solution casting method using different amount of reinforcements ranging from 0.25 to 4 wt%.

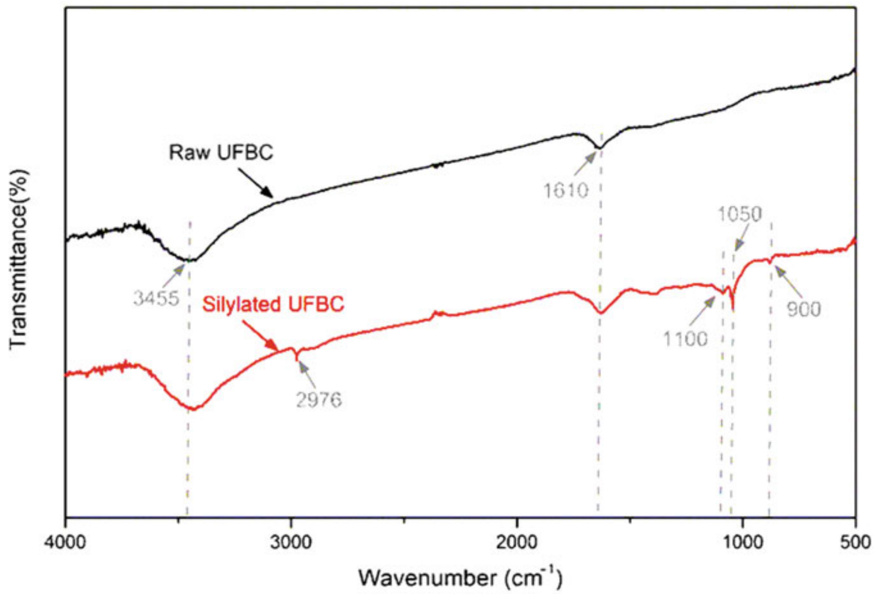


Fig. 13 FT-IR spectra of raw ultrafine bamboo-char (UFBC) and silylated UFBC

6.1.1 Fourier Transform Infrared Spectroscopy

At first, an important technical characterization tool to be used is the Fourier transform infrared spectroscopy, in this example, and in order to assure the surface modification of the ultrafine bamboo-char using silane, Fig. 13 makes a clear statement of that modification by the appearance of an absorption band at 2976 cm^{-1} equivalent to the silane group [78].

6.1.2 Scanning Electron Microscopy

Scanning electron microscopy (SEM) is used in order to observe the uniformly dispersion of the fillers, confirmed again in the Fig. 14, the micrographs of bionanocomposite surface exhibited more pits and cavities than the binary system of PLA/BCNW. Which is due to the presence of UFBC/PLA around the biochar particles and formed small cavities all around the particles resulting in a core–shell dispersion structure, UFBC were dispersed uniformly in the PLA matrix and the two phases had a good interface effect [78].

After proving the modification and the incorporation of the fillers, mechanical properties of the composites were evaluated, the surface modified UFBC did successfully reinforce the PLA/BCNW bionanocomposites, a higher tensile strength was reached (18.87 MPa) along with improved tensile modulus (272.24 MPa), the ideal UFBC content was 0.25 wt% assuring an elongation at break value of 165.8% [78].

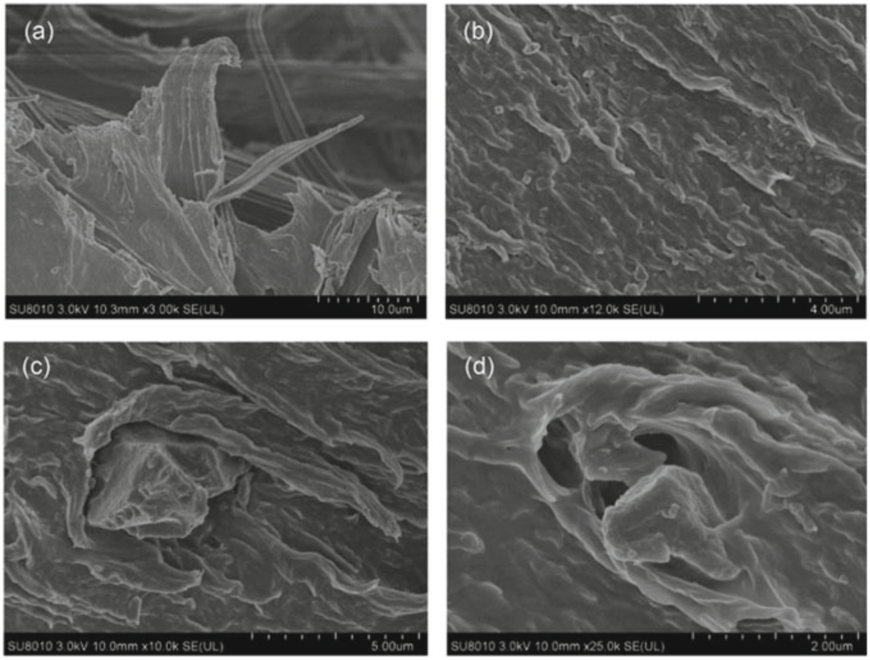


Fig. 14 Fractural surface of PLA/BCNW/UFBC bionanocomposites, **a** 0.25%, **b** 0.5%, **c** and **d** 0.5% UFBC in PLA

Another study was focused on the borer powder of bamboo which can be an be considered as an excellent starting material for manufacturing cellulose nanocrystals in both a low-cost and using an environmental-friendly way, the chemical composition of uninfected bamboo powder and borer powder has not been changed significantly, so cellulose nanocrystals (CNC) and carboxylated cellulose nanocrystals (CCN) were prepared, the crystallinity of the CNC and the CCN nanofibers are significantly improved after a series of chemical treatments, that is up to 69.84 and 62.75%, respectively [79].

6.1.3 X-Ray Diffraction Analysis

The crystallinity improvement of the nanofibers (CCN or CNC) compared to the borer powder is also shown in the same study [79], this property of CCN and CNC makes them eventually used to improve mechanical properties of composite materials, based on the fact that mechanical properties, especially the tensile strength modulus is massively dependent on the crystallinity property. Another study [11] presented the X-Ray diffraction analysis (XRD) of other bamboo based cellulose samples. All the cellulose samples present four diffraction peaks at $2\theta = 15°$, 16.5°, 22.7°, and 34.8°, corresponding to the (110), (110), (200), and (004) crystallographic planes of the monoclinic cellulose demonstrating that the crystalline type of CNCs is remained after the nanocrystallization process. Compared to bamboo pulp, an increase of the crystallinity index for CNCs is seen and which is explained by the degradation of amorphous regions and disordered regions of cellulose. As mentioned previously, a higher crystallinity index in CNCs is associated with higher tensile strength and thermal stability, which is expected to be beneficial for producing high strength composite materials.

6.1.4 Thermal Analysis of Nanocomposites

To characterize the thermal properties of bamboo pulp and of its derivative cellulose nanocrystals (CNCs), The initial thermal decomposition of bamboo pulp is 313 °C compared to 322 °C for CNCs, the maximum degradation temperature follows the same path, where for CNCs the temperature is increased to 348 °C compared to 338 °C for the pulp. All of these results indicate that the thermal stability of CNCs is higher than that of cellulose raw material, due to the fact that the thermal stability of cellulose is affected by crystalline order [11].

7 Applications of Bamboo Cellulose Nanocrystals

The use of bamboo cellulose nanocrystals as alternate to bacterial cellulose for wound dressings seems to be an interesting application of these materials, a prior study highlighted interesting properties of cellulose nanocrystals, such as their ability and capacity of absorbing water along with their strong antibacterial activity. The *in-situ* single approach was adopted for the elaboration of this bionanocomposites, where the formation and simultaneous impregnation of silver nanoparticles onto cellulose nanocrystals matrix were carried out. The elaborated bionanocomposite was found to significantly enhance the *in-vivo* skin tissue repair by decreasing the production of inflammatory cytokines and increasing fibroblast proliferation, angiogenesis, and finally tissue neoepithelization and regeneration in less than 14 days by favoring collagen deposition [80].

Hybrid materials made of bamboo cellulose nanocrystals and zinc oxide were elaborated. Using solely water solvent in mild temperature (80 °C), this facile green-route one step synthesis provided materials with various morphologies (nearly spherical, thin sheet and flower-like shapes) depending on pH values. These materials were subjected to several applications, they were used to absorb methylene blue and malachite green dyes, they showed high removal capacity (93.5 and 99.0% respectively) reaching 91.5% and 97.8% respectively withing the first 5 min. These materials were also tested to investigate their antibacterial activity. The spherical like hybrid materials actually showed high ratios reaching 91.4–99.8% against *Escherichia coli* (gram positive) and *Staphylococcus aureus* (gram negative) as shown in Fig. 15 [81].

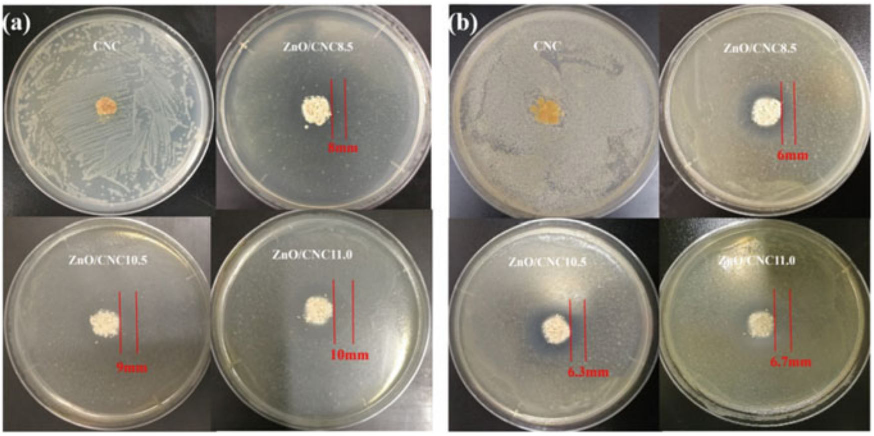


Fig. 15 Antibacterial ability of CNC and ZnO/CNC hybrids against **a** *E. coli* and **b** *S. aureus*

Poly(3-hydroxybutyrate)/cellulose nanocrystal films were elaborated in order to test their barrier and migration ability while they are in contact with food products, the extraction source of cellulose source was bamboo stems, the nanocomposites were elaborated using the solvent exchange cum solution casting evaporation technique, the oxygen transmission rate of these films was dropped dramatically by 65% even at low cellulose nanocrystals loading of 2 wt% compared to neat poly(3-hydroxybutyrate). These materials seem to be promising materials for various applications in the field of food packaging [82].

Some other nanocomposites were elaborated based on glycerol plasticized starch, and in order in reinforce these materials, bamboo based cellulose nanocrystals were used, the latter material was prepared using a combination of sulfuric acid and HNO_3–$KClO_3$ hydrolysis which led to several geometries depending on the concentration of the acidic media. Tensile strength and Young's modulus of these nanocomposites, was much higher than their counterparts for glycerol plasticized-starch without bamboo crystals, these results were due to the effect of the size of cellulose nanocrystals, and to the reduced water uptake.

8 Conclusion

The addition of bamboo fiber in biopolymeric materials represents a promising route, as it improves the overall properties of the composite and nanocomposite materials. The increase in mechanical properties was engendered by the high properties of the bamboo extracted nanofibrils and nanocrystals (modulus, tensile strength), but many other parameters must be taken into consideration, such as the fiber size, surface modification, fiber content, coupling additives, etc. because they also influence the mechanical properties as well as other characteristics of the composite and nanocomposite (thermal stability, crystallinity, water absorption, etc.). The realization of a composite material with the best possible properties, thus passes through the control of all these parameters.

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The Effects of Culm Nodes on Bamboo Fiber Properties

Mohammad Irfan Iqbal and Rashed Al Mizan

Abstract A Chinese poet once wrote, "Man can live without meat, but he will die without bamboo" because of its multifunctional and ecofriendly in nature. It has recently entered the textile and composite sector with some attractive labels such as 'green'. The current commercial manufacturing methods of bamboo fibres and its reinforced composites are mainly based on removal of nodes portion of bamboo culm. This method generates a high amount of solid waste materials and hence the term 'green' becomes questionable. This research investigates the effects of culm nodes on fibre properties. In this study an approach to produce fibres from bamboo strips along with nodes has been reported. SEM analysis and X ray diffraction is done to get idea of surface morphology and crystallinity of bamboo fibre along with node respectively. The surface of bamboo fibre which have node was comparatively rough than the fibre in internode portion. It was reported that the bamboo fibres along with nodes had a lower crystalline than internodes fibres. The finding implies that the separation of fibres from bamboo strips along with nodes is difficult. In order to use these bamboo fibres for textile and composites applications fibre properties such as fineness and tenacity were examined. It was revealed that the fibres without node have high fineness and higher tenacity compared with node fibres. It is assumed that the single fibre length of this bamboo species is not enough for conventional spinning. However, spinnable length was achieved as fibre bundles.

Keywords Bamboo fibre · Characterization · Nodes · Green

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1 Background

In the recent decades, Bamboo fibers has been one of the major interesting research subjects due to its multifunctional and ecofriendly nature [1]. It is considered one of the biggest grass plants in the world. It has always belonged to the Poaceae family, a sub-family of Bambusoideae It has more than 1250 species within 75 genera in the world [2], mainly grown in tropical and subtropical areas. China is one of the hubs of bamboo growth, having about 400 species of 50 genera. The estimated area of bamboo growth has gone beyond 4.21 million ha [3]. Bamboo plantation can be done in very hard climatic conditions by maintaining green harvesting processing. It is also well acknowledged for its easy and faster growing nature amongst the scientist and farmers [4]. Bamboo plants are also popular due to its hard and heavy-duty in nature. It is one of the ancient structural materials used by humankind [5]. It has been always used in household products. Now, owing to changes in processing technology and enhanced market demand, it has been expanded to industrial applications recently [6]. It is an intimate part of the daily lives of people in nations where bamboo is scarce in resources and is therefore handled with excellent regard. As plentiful natural resource in China, bamboo has been utilized in many purposes such as agricultural, craftwork, housing and structural for many centuries; however, textile fiber from bamboo has gained attention recently due to its unique properties suitable for apparel industry [7]. To utilize bamboo based fiber in the textile and apparel sector in China two ways can be considered [8]. One method is to process natural fiber from bamboo by means of physiochemical action and the other method is the making of regenerated fiber from bamboo pulp widely known as semi synthetic bamboo fiber [9].

The annual output of bamboo fibers is almost 40,000 tones and is accelerating significantly [10]. Generally, bamboo fibers are made from “Moso” the world’s largest bamboo [4]. Though bamboo is well valued and widely used in life, the development of bamboo fiber is most current [11].The utilization of bamboo fiber for apparel purpose is a twentieth century development, started by several Chinese company [11]. The first contemporary bamboo textile process was developed by Beijing University [12].

The successful extraction of the bamboo fibers and because of modern bleaching technology [13], lead to create commercially available bamboo fabrics for readymade garments, finds potential market in Europe and America. Subsequently, the methods of engineering bamboo fabrics have been in progress, bringing new innovations in fiber processes. The entire processes are natural which, retain the organic heritage of the product.

Philipp Lichtenstadt in 1864 has been made bamboo textile reported by Nayak and Mishra [11]. The practice is quite similar to the procedure use nowadays to manufacture regenerated bamboo cellulose, [14]. The U.S. patent #41,627 dated, 16 February 1864 which deals with the process for “disintegrating the fiber of bamboo, so as to use it in manufacturing cordage, mats, cloth, or pulp for paper.” There is another U.S. patent #87,295, dated 23 February 1869 which also discusses on the improvement of bamboo fiber preparation. One more document has been delivered in 1881 for mixing bamboo fiber with wool and spinning into a modern bamboo yarn [11].

The chemical compositions of bamboo fibers are mainly cellulose (60%), hemicellulose and lignin (32%) [15]. Culm, node, internode, leaf and roots are the main parts of bamboo (Iqbal et al.). The culm is a hollow stem cylindrical in shape consists of nodes along the entire length of bamboo, acting as a disc introduced between every segment of culms [16] (Fig. 1). These nodes portion play a significant role in avoiding buckling of bamboo culm [17]. Many researchers reported that these node portions have a mechanical function for instance: improving the stiffness and strength of the bamboo fibre. It has been suggested: "Bamboo node is crucial to improve stiffness and stability of the slender bamboo Culm during growth" [18]. There is a consensus among botanists that the biomechanics of the plant have been governed by the nodes. Studies have found that properties of node portions varied from those of bamboo internodes [19]. The effects of different species, age, location, and portion of bamboo culms can influence processing procedures and performance of end products [20]. Previous studies have reported that the bamboo consists of about 52% parenchyma cells, 40% fibers and 8% conducting tissue [21]. The strongly lignified bamboo fibers can influence the mechanical properties of end products [22]. The structure and anatomy of the bamboo culm has a great influence on its physical properties reported by Liese [23].

The research to date has tended to focus on extraction of bamboo fibers only in internode portions rather than along with node points. In this chapter we are going to take a closer look into the effect of culm nodes on fiber properties. There are some advantages to the development of bamboo fiber for textiles and composites. First, bamboo fibers are an environmentally friendly fiber, which is renewable, fast growing, degradable, and does not occupy cultivated land. Next, the exploitation

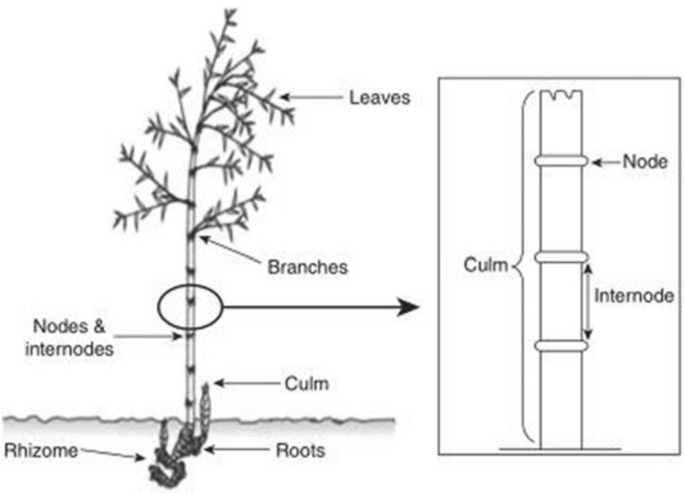

Fig. 1 Structure of a bamboo [24]

of the abundant bamboo resources can be of significant economic benefit in hilly areas. In addition, the bamboo fiber can make up for the lack of natural textile fiber available in China and it may replace partial need for synthetic fibers used in garments and furniture fabric. Moreover, bamboo and the bamboo fibers are very competitive in price. Bamboo fibers have potential as a sustainable alternative for glass fibers also. Besides these the beneficiary characteristics of bamboo and its products are worth noting. The natural antimicrobial ability along with smoothness, hypoallergic and deodorant properties. Moreover, high water absorption with fast drying property caused by the existence of large number of micro cracks with grooves on the bamboo plant surface making them suitable products for higher breathability and thermo regulating properties than other natural fiber such as cotton and hemp. It has a high durability in comparison to other fibers, UV protection abilities (SPF 15); a high sorption of dyes and better color clarity; bamboo fabrics have low shrinkage; bamboo fiber does not essential to be mercerized to obtain natural luster; clothes made from bamboo fiber are more wrinkle resistant than cotton and can be ironed at lower temperatures; bamboo products are biodegradable [4].

Bamboo fiber has a long list of application possibilities. Sports clothing industry could be a potential place for bamboo fiber due to its antibacterial and temperature-regulating features. Because of its smooth hand and UV protection nature makes it ideal material for summer (Zakrzewski). A most noticeable escalation in bamboo fiber use can be seen in yoga and fitness clothing [4]. For these reasons, once the conception of the bamboo fibers appeared, it has drawn increasing attention from many international organizations and countries, especially within China. Unfortunately, there is always a debate in every case because of the bamboo fibers are short and rigid in reality that it would be difficult t spin them for apparel uses [25]. Hence, studies into bamboo fiber are very active among the researchers. Research activity currently divided in two groups. One is for structures and property analysis of bamboo fiber and another one focuses on extraction methods of bamboo fiber. In the beginning, most scientist worked on the analysis of the structures and properties of bamboo fibers and development of bamboo fabrics [9, 26–28]. Testing results have showed that the structures and properties of the bamboo fiber are similar to those of ramie [9, 29]. But there is no measurable research in the field of manufacturing and characterization of 100% bamboo yarn by taking fibers from different sections of bamboo culm in China as well as in the research world. In this chapter work an overview has been taken in order to make bamboo fibers by taking node and without node of bamboo Culm.

Bamboo also has noteworthy prospect in composite manufacturing because of its high strength, green nature, fast growing properties, low cost, availability and sustainability. To save the ecosystem and produce cost effective fiber reinforced composites, researchers are working to manufacture composites using natural fibers by replacing less environment-friendly fibers (e.g. glass fiber). The cost, availability, light weight, high specific strength and safe nature of bamboo fibers are its most attractive properties,, encouraging researchers in composite technology to work on its development. There is also limited work in the development of bamboo fiber reinforced composite along with nodes. The chapter suggest that bamboo fibers along with nodes could be a potential material for various purposes. However, available studies have hardly addressed the extraction and use of bamboo fibers along with nodes for composite and textiles applications. Most of the previous studies focuses on only utilization of bamboo with only internode portions.

2 Literature Review

The apparel industry is considered as one of the major polluters organization because of using hazardous and pollutants raw materials and chemicals during fiber production. Even cotton, the most demanded and usable natural fiber, has been marked as one of the most non-'green' crops because of the use of enormous quantity of water and pesticides during its harvesting period [30]. Consequently, the price of cotton is also increasing dramatically. Therefore, it is necessity to look for new renewable resources for apparel fiber production. Bamboo species has been considered as one of the green and abundant crops in nature due to its fast growth rate, excellent carbon sequestration activity, and needs for little water along with no pesticides requirement (Austin et al. 1970; Liese 2009). However, the current commercial manufacturing process of bamboo fibers involve the removing of nodes portion generates large quantities of wastes and hence it is questionable to label bamboo textiles or composites as 'green' products. It is therefore necessary to develop a fresh technique for the production of textile fibers from raw bamboo crops together with nodes. Recently, the use of bamboo species in apparel products, composite materials [31] and cosmetics goods has rapidly growing. This is entirely due to the consumer perception for bamboo based products as an eco-friendly material [32] and the potential functionality and sustainability that bamboo can add, including UV-absorbing, antibacterial and moisture regulation. In general, processing bamboo crops into fibers along with nodes in an environmentally friendly way is challenging [33]. This is usually due to the fact that the extraction and separation of bamboo fibers depends on the change in the orientation of cellulose micro fibrils and the presence of a big quantity of gummy material lignin (~28%) [34].

For apparel fiber processing the ultrasonic treatment has been recently recognized as one of the green methods [35–38]. Bio based methods for instance, enzymatic and bacterial are also eco-friendly and thus extensively used in the apparel industry for fiber processing.[39–44]. The usually used enzymes for bast fiber processing are cellulase, xylanase, pectinase and mannanase [45, 46]; among them, the use of cellulase is remarkable [47, 48].

In this chapter, an investigation was carried out to process bamboo strips into fibers that retain the node portions of raw bamboo plants. Ecologically benign methods such as Ultrasonication, enzyme treatment was used to process bamboo into fiber.

3 Experimental

3.1 Materials

The bamboo strips used as the starting materials were procured from local markets in the middle part of China with a typical length of 74 cm. The strips had an average length of 74 cm. The average distance between the nodes was 20, 16.5 cm at the top and 20 cm at the bottom. The width and thickness of bamboo strips were 4.7 mm and 1.8 mm respectively. The strips were classified into two categories: without nodes or only internodes and with nodes in middle of strips. Reagent grade sodium hydroxide (NaOH), 35% hydrogen peroxide (H_2O_2), Cellulase enzymes (9012-54-8) and acetic acid (CH_3COOH) from Aladdin Industrial Corporation, China were used.

3.2 Methods

3.2.1 Fiber Extraction Procedures

Figure 2 shows the flow chart of production process of bamboo fibers along with nodes. In this method, bamboo strips were used as a starting material. First, bamboo strips cut into 50 mm small pieces and treated mechanically with pressing and hammering to accelerate the reaction rate in defibrillation and degumming. An ultrasonic bath (KQ-50DE) was used for ultrasonic treatment. An oil bath (DF101S) was used for boiling the samples with acetic acid (2%) followed by ultrasonic treatment.

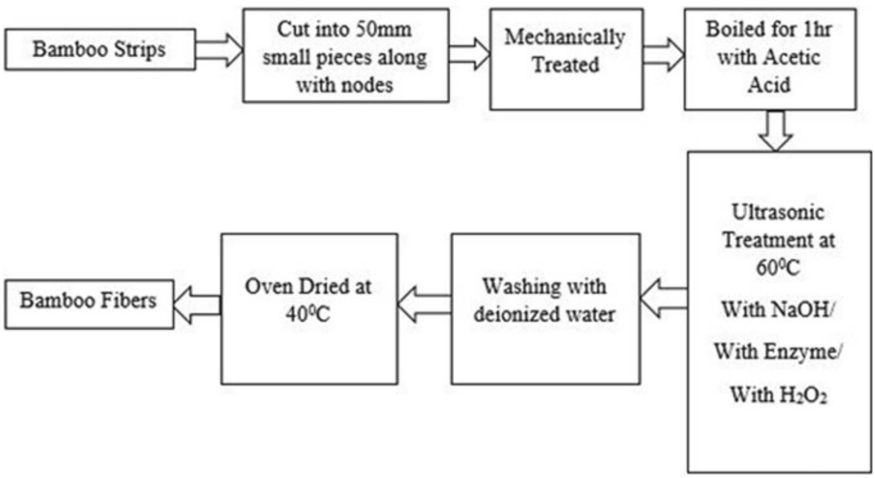

Fig. 2 Production process of bamboo fibers along with nodes

Three separate chemicals, namely, NaOH (100 g/l), enzyme (20%) and H_2O_2 (10%) were used for degumming independently. For the degumming with enzyme, bamboo strips in deionized water were treated with cellulase enzyme for 4 h at 60° C and pH 7 prior to ultrasonic treatment. Then the processed fibers were filtered and washed with deionized water and the fibers were subsequently dried in oven at 40 °C for 18 h.

3.2.2 Characterization of Fibre

Fibre fineness: The linear density in tex was measured by dividing the mass of specimens by their known length [49, 50]. For fineness 3 samples were considered and their averages were reported.

Tensile Testing: Fibre tenacity in CN/dtex was determined using an electromechanical tensile machine, ASTM D 3379-75 Standard was followed to determine tensile properties. The gauge length was 10 mm and the cross-head speed was 20 mm/min. The tests were carried out until the materials got broken. The samples with Jaw break were not taken into consideration for the analysis. For tensile property 100 samples were considered randomly and their averages were reported.

3.3 Surface Morphology

A scanning electron microscope (JEOL, voltage: 20 kV) was used to investigate the surface morphology of the bamboo fibers. Before observation, the samples were coated in gold by ion sputtering.

3.4 X-ray Diffraction Measurements

Crystal orientation of raw bamboo fibers specimens along with node were characterized by X-ray diffraction measurements using an X-ray diffraction measuring instrument. The degree of crystallinity, Xc, was estimated using the Segal method [51] (Eq. 1) which is widely used for cellulosic materials:

$$Xc = \frac{I_{002} - I_{am}}{I_{002}} \times 100\% \quad (1)$$

where I_{002} is the peak intensity from the (002) lattice plane ($2\theta = 22.6°$) and I_{am} is the diffraction intensity of amorphous phase represented at $2\theta = 19°$.

Table1 The properties of bamboo fibers

Bamboo fibre	Fineness(tex) ± STD	Tenacity(cN/dtex) ± STD
Without node	20 ± 4	71 ± 6
With node	50 ± 2	82 ± 10

4 Results and Discussion

4.1 The Properties of Bamboo Fibre

The tenacity and fineness of the bamboo fibers with nodes and without nodes are shown in Table 1. The average value of Tenacity and Fineness of fibers with nodes and without nodes are 50tex, 82cN/dtex and 20tex, 71cN/dtex respectively. It can be found from the Table 1 the fibers without node have high finness but lower tenacity compared with node fibers. In contrast to earlier findings, no evidence of bamboo fibers extracted from bamboo strip along with nodes is found. This result may be explained by the fact of unique morphological and anatomical characteristics of nodes [52] that allows that contribute to the variation in fiber fineness and tenacity.

4.2 Fibers Appearance

Figure 3a, b shows SEM images of an extracted fiber without node and with node respectively. The SEM images 3a indicate that the fiber without node gives the most uniform fibrous morphology. However, the fibers were found in bundle form and had very rough surfaces, unsuitable for textile applications.

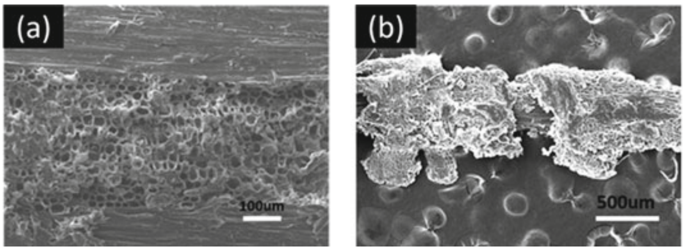

Fig. 3 **a** SEM photograph of bamboo fiber without node **b** SEM photograph of bamboo fiber with node

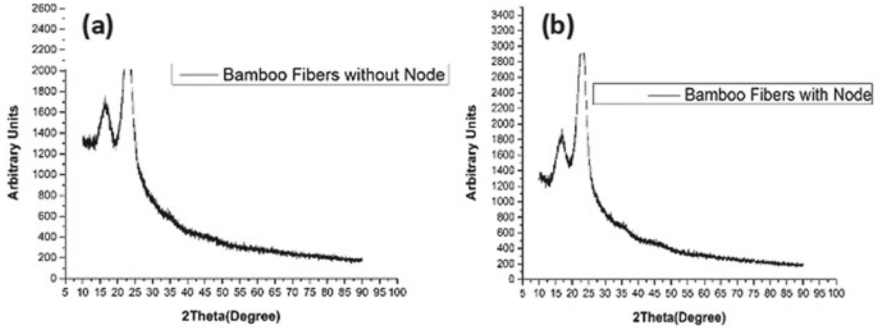

Fig. 4 XRD spectrum of **a** bamboo fibers without node and **b** bamboo fibers with node

4.3 Crystallinity of Processed Bamboo Fiber

The orientation of polymer chain in bamboo fiber can be observed from XRD pattern in Fig. 4. There are several mechanical properties and suitability of end use, depends upon this molecular direction. In Fig. 4a, the XRD pattern of bamboo fibers without nodes showed, where the diffraction peak indicates the evidence of cellulose in the bamboo.

In this XRD pattern the corresponding peak around 22° and 16° are the strong evidence of cellulose-I crystal structure. The pattern also gives the evidence of crystalline region in bamboo fiber by giving the corresponding peak in arbitrary intensity. Moreover, the boarded background of the XRD pattern gives proves of amorphous region in the respective bamboo. However, the crystallinity of the bamboo fiber without node was calculated as ~86% which was finely supported by morphology. On the other hand, the XRD pattern of bamboo fibers with nodes showed in Fig. 4b. This pattern gives a similarity with former pattern, rather than giving an intensity difference. The intensity difference of this XRD spectrum provides the evidence of reducing crystallinity, which was stated as ~66% in this portion. In same way, it can also be sated the increase of molecular disorientation of bamboo fibers with nodes portion. From Fig. 5, it is clearly showing; some route develops in the node portion.

During the initial stage of this route development can affect lignocellulose deposition in this portion, which is also a reason of this molecular disorientation in the node portion. However, the increase of amorphousness will be adventitious for textile production, due to facilitation of dye ability and water absorption. In contrast, node in bamboo fiber also gives a hinder to produce single fiber in real.

5 Conclusions

In this chapter, a new approach to process bamboo strips into fibres along with nodes was investigated. The bamboo Fibres were extracted from bamboo strips with the

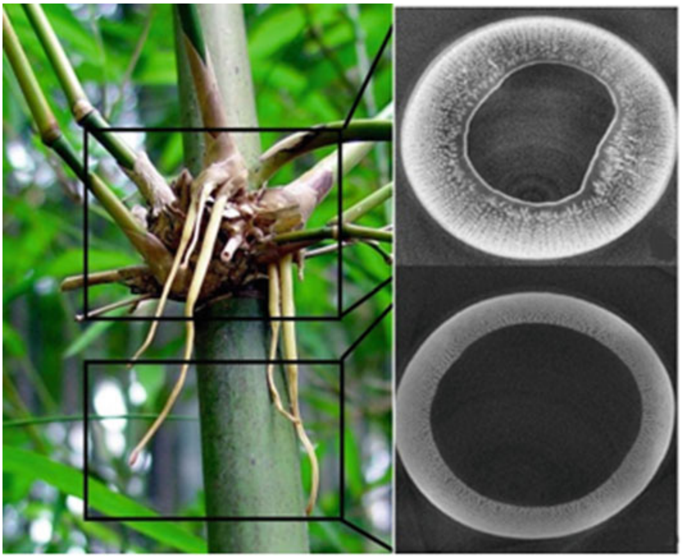

Fig. 5 Route and branch develops in the node portion with their CT-scanned images. Adapted with permission [53]

aid of Mechanochemical method. The manufacturing process was considered as eco-friendly due to the avoidance of environmentally hazardous chemicals and the use of H_2O_2. The bamboo Fibres processed using this manufacturing method having the properties of single fibres was not suitable for existing conventional textile spinning. In this study, it was shown that the single Fibre length of this bamboo species is 3–5 mm. This short length is not suitable for conventional textile spinning. However, there are many applications of these short fibres. Some of the examples are:

- The short Fibres can be used as reinforcement components in plastics [54] and composites [55].
- The short Fibres can be made spinnable by blending with other textile fibres. The short Fibres add UV blocking and antibacterial functions to the fabrics. The antibacterial property can be used in medical textiles such as bandages.
- The short Fibres can be used to make bamboo paper sheeting with UV blocking and antibacterial functions.

The short fibers can be used as a precursor of ultrafine bamboo powders. Bamboo powders can be blended in various host materials to give UV blocking and antibacterial functions [33]. Because of the high solubility of ultrafine powders, they can also be used to produce regenerated or blended fibers, membranes and other functional materials [56–60].

However, fibers with spinnable characteristics for making yarn were obtained as fiber bundles. The fibers produced using this method will be useful for many applications in the textile, plastic, composites and medical industries.

The bamboo fibers along with node had the highest tenacity but lower fineness and crystallinity from the internode fibers. It was found that node fibers were not suitable to process into single bamboo fiber due to less crystalline structure.

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Futuristic Prospects of Bamboo Fiber in Textile and Apparel Industries: Fabrication and Characterization

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Abstract In recent years, the textile market is proposed to have new types of fibers and yarns. The expansion of eco-friendly fabrics with organic, bio-degradable, and environmentally friendly nature is the current trend to reduce the carbon footprints as well as a carcinogenic effect caused by various synthetic materials. Ecofriendly fabrics possess natural characteristics that are user-friendly, cost-effective, and less harmful nature. The market demand for such fabrics is increasing with the consciousness of the consumer. Bamboo textiles provide a remarkable opportunity for developing sustainable and socio-economically significant textiles in the future. This chapter describes the fabrication and characterization methods for bamboo-based textiles and their futuristic prospects in the textile and apparel industries.

Keywords Natural fiber · Bamboo · Textile fiber · Bamboo weave · Bamboo fabric · Bamboo textile

1 Introduction

Natural fibers were explored to humans from different plant and animal sources for thousands of years back. At present, the exploration of natural plant fibers is increased due to its potential in various fields, including textile and apparel industries. Specific industries were making use of sustainable products for diverse end applications.

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However, the textile industry has poor pathway records in social and ecofriendly concerns. Bamboo textile has an excellent opportunity to provide sustainable textile products. There are two main advantages of bamboo textiles processing such as bamboo is a natural eco-friendly, non-harmful material and which can act as raw material that regulates sustainable government policies [1, 2].

Nowadays, the textile industry has mainly focused on utilizing renewable and recyclable resources as well as environmental friendly processes to pledge the demand, more comfort, healthier, and eco- friendly products [3]. Bamboo the "Green Fiber" has extended the reputation and evoked the interest of investigators to develop textile products for protection, comfort, and environment-friendly assets. Bamboo fiber is one of the new inventions in the textile industry since bamboo is a fast-growing plant, unlike cotton, which is a widely used cellulose enriched material and without need any pesticides to grow the plants. The fiber which is obtained more abundant and cheaper from the natural resource like bamboo is another advantage. The bamboo plant is grown in tropical climates, and it is harvested after 3–4 years. This plant is widespread throughout Asian, Latin American, and African countries. *Heterocyclic* is a species known as *Moso* bamboo, which is the most commonly used bamboo for fiber extraction for textile applications [4, 5].

Bamboo fiber from most of the species possess characteristics such as excellent tensile strength, UV protection, anti-bacterial, bio-degradability, moisture absorption property, breathability, and drying behavior [6, 7]. In SEM analysis, the cross-section of bamboo fiber had shown small voids like structures called the lumen, unparalleled micro-structures, and different micro gaps. Bamboo fiber clothing has high air permeability that can absorb and evaporate human sweat quickly. Besides, its anti-bacterial and eco-friendly nature make it a suitable material for the manufacturing of textiles along with other apparel and socks [8].

2 Processing of Bamboo Fibers

In the textile industry, bamboo is processed by two kinds of manufacturing methods that are mechanical and chemical processing (Fig. 1). It is required more efficient equipment for the extraction of bamboo fiber on an eco-friendly basis, and this process having a negative impact also since it may cause health issues like an allergy to labors [9–11].

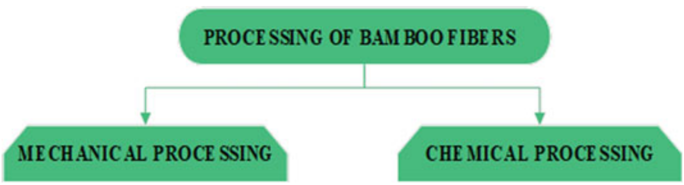


Fig. 1 Processing methods for bamboo fiber

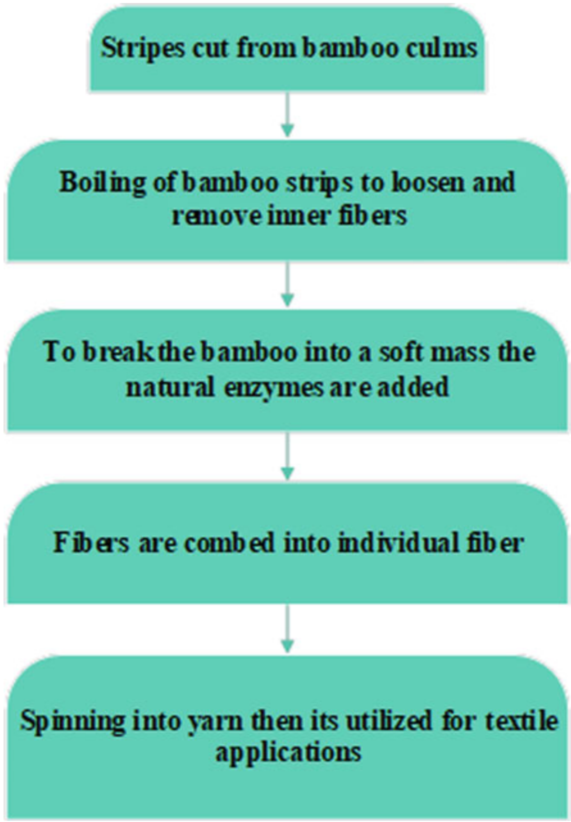


Fig. 2 Extraction and mechanical processing of bamboo fiber

2.1 Mechanical Processing Method

During mechanical processing, the bamboo is crushed into pulp, followed by natural enzymes that are used to form a soft material, and after that, the fibers are combed out. Then the fiber is spun into yarn, and the yarn is converted into bamboo fabric products [12]. The mechanical process for making bamboo fibers and yarn that are ramie-like method is demonstrated in Fig. 2.

2.2 Chemical Processing Method

The most common method used to extract bamboo fiber in the textile industry is chemical processing. In this process, the bamboo culm is treated with chemicals to obtain renewed bamboo fiber, and then it can be again processed with more chemical agents to make fine yarn to convert them into fabrics. All parts of the bamboo plant can be turned to usable fabrics through this chemical treatment method. Primarily, the bamboo culm collected can be treated with caustic soda for softening, then the steps pressing, aging, ripening, degassing, and acid treatment to be carried out (Fig. 3). After the process of cutting filament fibers into staple fibers, they are further subjected to necessary final treatments, and the dried, baled fibers are then direct for spinning.

However, the chemical process requires additional labors and cost expensive compared to the mechanical method. Some chemical processing methods are not eco-friendly while some provide more economical and sound environmental impacts. Furthermore, the chemical techniques involve low energy consumption and easy control over fiber properties when compared to steam explosion and mechanical methods [14]. Hence, this method of the manufacturing process is rarely used in the apparel industry for bamboo fiber processing [15]. There is also a third category of bamboo fiber, which falls under chemically manufactured bamboo fiber are bamboo

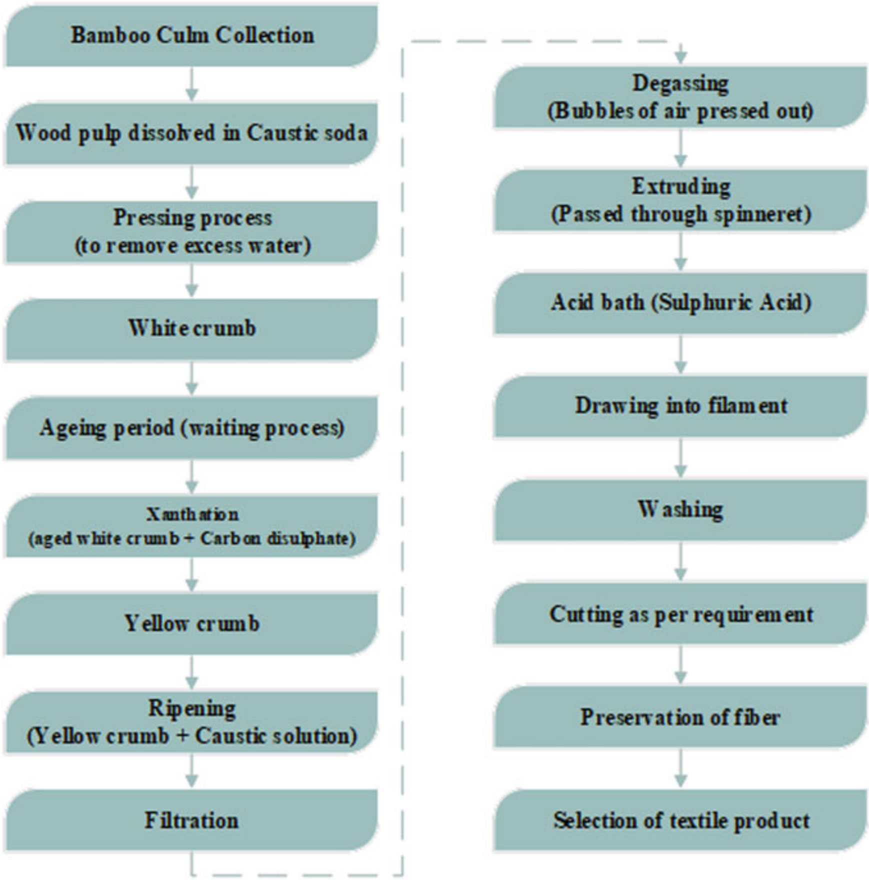


Fig. 3 Extraction and chemical processing of bamboo fiber

charcoal. When using bamboo charcoal in the form of nano-particles, the charcoal powder is mixed with the liquid of viscose spinning [16, 17].

3 Properties of Bamboo Fibers and Their Products

Properties of the bamboo fibers are inconsistent for the extraction, processing, and time owing to decrease cellulose content with aging [18]. Moreover, the method of extraction of fiber found as a significant factor in defining the characteristics of the end- product. The manufacturing of bamboo pulp fiber follows a technique similar to that of viscose production since it is quite easy to predict the structure and properties of the same. Distinct methods possess the different potential to remove lignin, which contributes stiffness and yellowing of bamboo fibers. Simultaneously, the non-cellulosic components also affect fiber properties like strength, density, moisture absorbency, flexibility, etc. [19, 20].

The fabric woven out of mechanically extracted fibers has a rough and stiff feel, whereas, the one woven out of viscose-type chemical process holds a very soft handle and excellent drape. Another difference is reflected in terms of strength and durability, which is higher in the case of mechanically processed fibers. These differences can be attributed to the alteration in the physical form of the fiber during chemical processing, which leads to the modification of molecular orientation within the fiber, and also its degree of polymerization. Even though the bamboo viscose fiber is essentially the same in chemical nature as its raw form, the yarns and fabrics manufactured out of both behave differently (Table 1).

4 Yarn

Moving on from fiber to yarn level, the mechanical process is used to comb out the natural fibers to get individual fibers, and then the spinning of the yarn process is carried out. In the textile industry, yarn is arranged in the form of a continuous strand of staple or filament fibers, which is more suitable for weaving, knitting, or non-woven. Also, relatively the cross-section of the yarn shows the twist or fiber filament, and also yarn is a textile product of considerable length [17, 30]. The yarn is twisted with one or more yarns to ensure added value or create aesthetics. The fibers with a finite length of yarn are called staple fibers. Nowadays, continuous filaments are also used to construct yarns. Filament yarns tend to be smoother, lustrous, uniform, harsher, and less absorbent. While spun yarns have hairy surface and are more uneven in appearance, lower luster, softer, and more absorbent. The Spun yarn is mostly used in many woven and knitted fabric products.

Table 1 Important chemical and mechanical properties of bamboo fibers in comparison with some other natural fibers [10, 21–29]

Types of fibers	Cellulose (wt. %)	Lignin (wt. %)	Moisture (wt. %)	Tensile strength (MPa)	Elongation at break (%)	Density (g/cm^3)
Bamboo	60.8	32.2	–	615–862	3	0.91
Coir	36–43	41–45	8	593	7.8	1.2
Banana	63–68	5	10–12	600	3.36	1.38
Sisal	67–78	8–11	10–22	511–635	3–7	1.5
Jute	61–72	12–13	12.5–13.7	393–773	1.5–1.8	1.3
Hemp	70–74	4–6	6.2–12	690	1.6	1.47
Kenaf	31–39	15–19	–	930	–	1.45
Flax	71	2.2	8–12	500–1500	2.7–3.2	1.5
Ramie	69–76	0.6–0.7	7.5–17	400 – 938	3.6–3.8	1.5
Cotton	85–90	0.7–1.6	7.85–8.5	287–800	7–8	1.51–1.60
Nettle	53–86	3.5–9.4	–	–	–	1.5
Pineapple	81	12.7	–	144	14.5	1.44–1.56
Okra	60–70	0.6–0.7	–	–	–	–
Silk	–	–	–	252–528	20–25	–
Wool	–	–	–	122–175	25–35	–

4.1 Yarn Manufacturing Process

A number of processes are employed for converting bamboo fiber into yarns, which involves the removal of stable fibers, alignment of fibers and then spun the yarn. Depending upon the machinery/setup present in the spinning mill, along with the manufacturing process, influences the quality of the yarn produced. The yarn manufacturing process from bamboo fiber is depicted in Fig. 4 (Table 2).

4.1.1 Opening, Blending, and Cleaning

The first process of the spinning mill is opening the fiber from the bales. The opening and blending processes ensure the reliability and uniformity of the blended fiber, are shown in Fig. 5. Fiber is blended and then passed in between many spike rollers to open further the fiber clusters, followed by cleaning is done to remove the impurities, which may cause severe quality issues in the end product. A blending of various fibers is done to improve the functional properties and also to enhance the aesthetic quality of fabric [16].

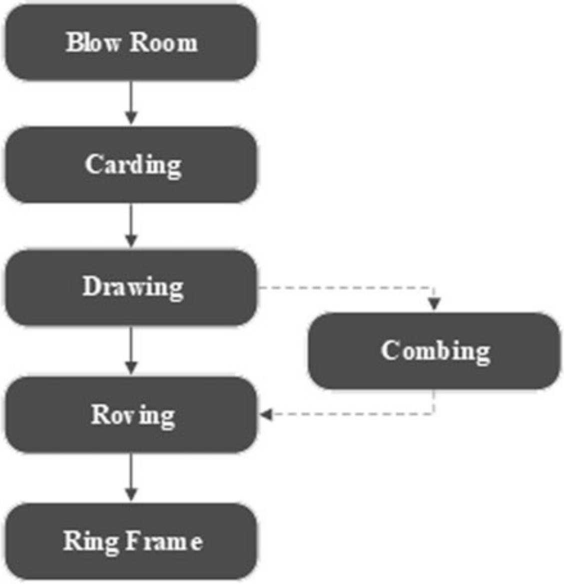


Fig. 4 Flow chart of yarn manufacturing process

4.1.2 Carding

The carding machine used to separate and clean the fibers; bypassing fibers between three different rollers. Then the overlapping fibers are converting to a single continuous strand is called 'sliver' Notably, a large number of short fibers and neps are removed during this process, as shown in Fig. 5 [17].

4.1.3 Drawing

The process of drawing assists in blending fibers and smooth down. In this process, the number of fibers present in the slivers is reduced with the desired linear density. The uniformity or evenness of the slivers can be improved through this drawing process.

4.1.4 Combing

Improving the quality of the sliver, the final short fibers, neps, and other impurities are removed via the combing process. The functions of the combing process are aimed to obtaining good quality of yarns. Comparing carded and yarn, combed yarns are better in quality. The fineness, strength, evenness/uniformness of the yarn can be improved by removing short fibers, which helps further alignment of the fibers.

Table 2 Functional properties of bamboo fibers compared with other fibers [10, 29, 31–41]

Fibers	Absorbency	Elasticity	Recovery	Strength	Wicking ability	Comments
Bamboo	Hydrophilic, 13%	14–24%	–	22–25 cN/tex	Poor	New fiber, natural antibacterial, biodegradable
Cotton	Good, hydrophilic, 8.5%	Poor, 3–10%	74%	Good, 20–43 cN/tex	very poor	Slow to dry
Wool	Good, hydrophilic, 13%	Good, 20–40%	high, 99%	Fair, loses 20% strength when wet	Good	Slow to dry
Silk	Good, hydrophilic, 11%	Good, 20%	Poor	Good strength in dry state	Good	Challenging to care in use
Viscose rayon	Hydrophilic, 13%	Good, 15–30%	82%	Fair to good, 18–26 cN/tex	Poor	Difficult to launder
Lyocell	Good, hydrophilic, 12%	12–16%		High, 37–45 cN/tex	Poor	
Polyester	Poor, hydrophobic, 0.4–0.8%	Good, 19–23%	Good, 97%	High	Faster than cotton	most popular. cheap, easy to care for
Polyamide	Fair to poor, 4–4.5%	Good, 26–40%	Good, 100%	Very high strong fiber	Better than polyester	More expensive than polyester fibers
Polypropylene	Very poor hydrophobic, <0.1%	Good, poor than polyester	Good, poor than polyester	High	Excellent	Lightest among synthetic fibers, unable to be dyed
Acrylics	Hydrophobic, 1–2%	Good 25–46%	Good, 92–99%	Fair strength, 20% weaker when wet	Good	Tend to pill during wear

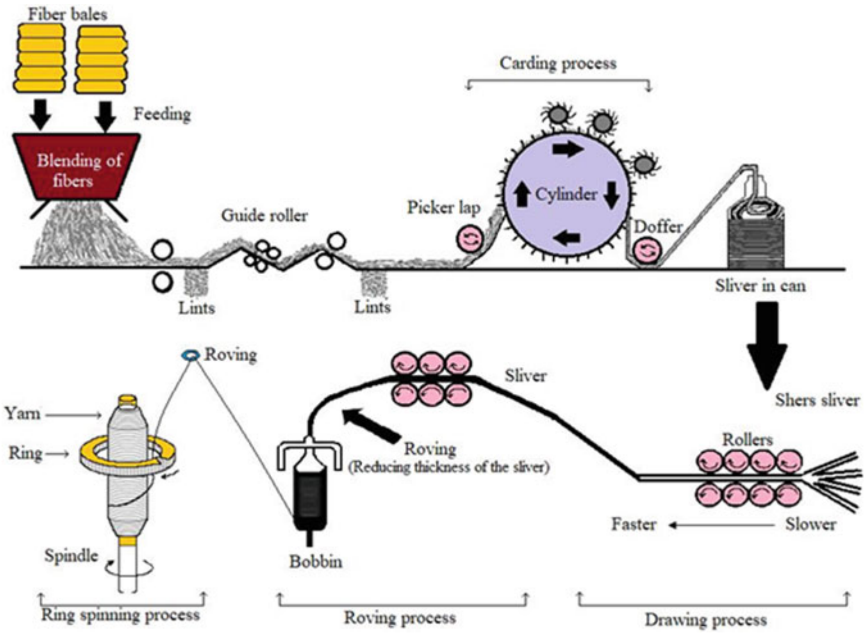


Fig. 5 Process flow of Spinning

4.1.5 Roving

This process is to reduce the thickness of the sliver to get finer strand before spun into yarn is shown in Fig. 5. To keep the fibers together, a small amount of twist is applied to the soft strands of combed and carded fibers and freed of foreign matters, which are the feed for the next spinning process. There are two types of twisting used in this process, such as S-Twist and Z-Twist.

4.1.6 Spinning

The spinning of bamboo fiber is similar to viscose fiber spinning. Humidity is an important factor that needs to controlled while bamboo spinning. During the drawing and roving process, more fly is produced in the bamboo fiber. So it is recommended to keep the humidity ranges from 65 to 70% and low temperature approximately 25 °C. To enhance the humidity properties of bamboo fiber, vapor treatment to be applied before starting the process. The cohesion properties are weak for bamboo fiber, so it is required to keep a high coefficient of the twist with low carded web and roving tension [13, 42, 43]. Three main spinning systems used to convert the fibers into yarn.

They are:

- Ring spinning method
- Rotor spinning method
- Air-jet spinning (vortex) method.

Ring Spinning Method

The ring spinning method is one of the spinning techniques where the final yarn count needed to draw out the roving, by rotating the spindle twist are inserted to the fibers and yarn is wounded on a bobbin. These three stages took place continuously and simultaneously. For producing a ring-spun yarn, the new processes (winding and roving) are required and slower in the production process. So the ring-spinning process is comparatively expensive. Ring-spun yarns have a fixed twist structure, excellent tensile properties, and are versatile in that any count can be spun. Yarns with optimum characteristics can be produced, and this method is also simple [44].

Rotor Spinning Method

The sliver web is fed into the machine and where the sliver is combed to individualize by the opening roller. In the rotor, the fibers are deposited along with the groove of air current and centrifugal force, deposits where they are evenly scattered. The spinning action of the rotor allows the twisting of fibers together, and from the center of the rotor, the yarn is drawn continuously. The resulted yarn is clean from any defects, and then yarns are wound onto packages.

Air-Jet Spinning (Vortex) Method

To produce a unique structure with a distinct way of yarn formation air-jet spinning machine is used. Fiber wrapping is achieved by holding fibers together parallel of the core to spun a fascinated yarn. The sliver web is fed into the machine, and the final count of yarn is further drawn out through high pressured air rotating vortex twisting. The yarn obtained is clear and free from wound or defects, are ready for the fabrication process.

4.1.7 Winding

The winding section is comprising of two elements, such as spindle and a flyer. A spindle is a long metal shaft that acts as a guide and a conveying element for the flyer. To insert a twist in the roving process flyer is a specialized attachment attached in the roving frame. In the bearing, the low end of the spindle is attached, which gets the train of gears from its drive and transfers it into the flyer. The flyer is fixed around the shaft at the spindle, which is derived from a separate set of gears independently. An empty hollow package made of wood or plastic is arranged on this shaft. Where, the winding is the process of transferring the one package of spinning yarn into another large package (cone, spool, pirn, etc.).

5 Properties of Yarns

The physical properties of ring spinning yarns made from 100% regenerated bamboo, and 50:50 bamboo/cotton blends are discussed here. The diameter of yarn and hairiness reduce mechanical properties such as tensile strength, elongation, and evenness are found to be increased because the blending proportion of the bamboo fibers increases in yarns. It is found that there is increasing the percentage of bamboo fiber up to 50:50, the tenacity reduced is ascribed to the differentiation in breaking strength and elongation of bamboo fibers. The fiber and yarn characteristics of bamboo fiber are quite similar to those of viscose rayon fiber. On the other hand, its natural anti-bacterial characteristic, high air, and moisture permeability, ensuring breathability in particular knitted goods, are distinctive characteristics of bamboo. The high elongation value and moisture absorption capacity of bamboo fiber can result in high shrinkage after refurbishing. For this reason, world-leading sports clothing brands are incredibly attentive in bamboo fiber opine [6, 17].

The yarn count and yarn twist are the two parameters that influence the thermal resistance and water vapour permeability of the fabric [45]. The amount of air layer decreases simultaneously when there is an increase in the fiber per unit area as the weight increase. In addition, the thermal conductivity of entangled air is lower than the thermal conductivity values of fibers. The fabric obtained higher porosity values are made from the finer yarns could be ascribed to the fabric made from finer counts having lower thermal conductivity [46]. The textiles materials made from bamboo yarn possess high absorbency, antibacterial, and soft feel. Compared to conventional fiber, bamboo fiber is very hydroscopic and absorbs more water. The breathability and coolness are the other remarkable outstanding characteristics of bamboo fabric.

Table 3 Properties of bamboo yarn in comparison with some other textile fibers yarn [8, 13, 17, 30, 43, 57, 59]

Fiber	Yarn count tex	Blend ratio	Weight (g/m^2)	Thickness (mm)	Porosity (%)	Optical porosity (%)	Loop length Mm	Cover factor
Bamboo	36.60	100	220	0.69	60.26	11.84	3.68	1.65
Wool; polyester	38.90	43:57	222	0.75	78.14	7.89	3.38	1.85
Wool; polyester	42.20	48:52	236	0.75	76.76	6.37	3.46	1.88
Wool; polyester	38.90	61:29	225	0.72	73.84	6.08	3.54	1.76
Wool	40.00	100	204	0.72	78.37	6.39	3.61	1.75
Wool; bamboo	56.60	35:65	270	0.83	67.01	8.47	4.39	1.71
Wool; bamboo	38.30	52:48	210	0.74	73.56	13.91	3.72	1.67
Wool; bamboo	46.10	60:40	236	0.75	71.76	9.91	3.90	1.74
Polyester	44.40	100	220	0.77	79.24	5.01	3.44	1.93
Cotton	30	100	210	0.69	62.06	12.97	3.56	1.45

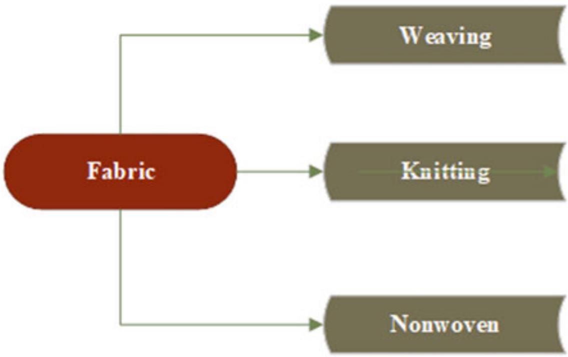
6 Bamboo Fabric

Fabric is a flexible textile structure usually made of threads. The clothing fabric of ancient man dating back to thousands of years was made directly from fibers. Primitive methods of making fabric involve applying heat, moisture, and physical force to animal fibers. These processes interlock the fibers and make a fabric. Fabrics may be made either by weaving or knitting. The process of making fabric by the interlacement of two sets yarn strands is known as weaving, and the process of making fabric by interloping of threads is known as knitting.

6.1 Bamboo Fabric Manufacturing Process

There are three processes that are employed to manufacture fabrics from bamboo yarn. They are knitting, weaving, and nonwoven (Fig. 6).

Fig. 6 Fabric manufacturing process from yarn



6.1.1 Knitting Technology

The knitting process is used for inter looping of yarns to form the fabric. Knitted fabric is characterized by the direction of wales and courses yarn that runs vertically and horizontally. There are many advantages of knitting in the aspect of the end product is economical and relatively fast performance together with the comfortness of the wearier. Knitted garment are more elasticity, good permeability, and high moisture absorption that reduces some possible functional and performance properties. The comfortness and performance properties of the knitted products such as tight T-shirts, summer wear, socks, and gloves. There are two techniques used to form knitting technology, such as warp and weft knitting [16, 43, 47, 48].

Weft Knitting Process

Weft knitted fabrics can be produced either in the flat or tubular form. Generally, the weft knitting fabric has high elasticity and high drapability, which is more suitable for a huge range of textile applications. For outer and inner garments, the weft knitted fabric is more suitable because of its porous nature and comfortness. There are four types of machines available for weft knitting, which are (i) Circular knit machine, (ii) Flatbed knit machine, (iii) Fully fashioned knit machine, and (iv) Hosiery knit machine. The latch needles are fitted in the cylindrical form in the circular knitting machine (Fundamental elements of knitting machines are the hooked needle and a thin strip of a sinker). Inside the cylinder, guide synchronized timing cams are fitted to trace the movement of latch needles in a loop formation.

Warp Knitting Process

The warp knitting is length-wise, through the intermeshing of loops in the form of wales direction. In this process, the loops formed on the knitting needles are column-wise, remain in the knitting mode. Compared to the weft-knitted fabric, which is not easy to ravel out the warp knitted fabric, is the main advantage of warp-knitted cloths. However, these fabrics are less stretchable as the weft knitted fabrics. Two types of warp-knitting machines are used commercially. They are.

I. Tricot knit machine
II. Raschel knit machine.

6.1.2 Production of Weft Knitted Fabrics

The increase of the weft knitting industry with modern machines to produce a wide range of product designs shows the potential of bamboo yarn. The knitting machine selection is purely based on fabric type or products. Machine productivity is an important factor to be considered in selecting a knitting machine, which is influenced by the circumferential speed, a number of feeders of the machine, the diameter of the cylinder, and machine efficiency [7, 11, 49–55]. The appearance, characteristics, dimensional stability, fashion, and eco-friendly trend increases the demand of using regenerated fibers and their blends with cellulose fibers like cotton. For the weft-knitted fabrics with effective production, proper selection of knitting yarn is very important. The properties such as yarn count, twist, evenness, knitting ability, winding behavior, friction and moisture content have a bearing on selection of a knitting yarn. Basic machine factors such as diameter, needle gauge, and number of feeders, knitting bed and take down systems are to be considered while selecting fabrics to produce in the knitting machine [56].

6.1.3 Single Jersey Structure

The plain knitted fabric is described as prominent visibility of face loops structure at the right side of the fabric and visibility of back loops at the wrong side of the fabric. It is furthermore signified as a single jersey fabric (single fabric). Single jersey fabric is very smooth even at the technical face and with the face side limbs formed at the column of fabric in V shape alongside wales. There is a more significant appearance of the fabric is emerged when the fabric is produced using different colour yarns as the design of the single jersey has a basic repeating pattern. The backside appearance of the fabric highlighted using an alternative different coloured yarn by the formation of interlocking semi-circles columns with an aid needle head loops and singer base loops.

6.1.4 Rib Structure

Upright cord-like appearance is formed by the intermeshing of vertical rows of wales, alternatively in the face and backside of rib fabric. The vertical row of wales is intermeshed with another loop in the opposite direction at the backside of the fabric, and hence the fabrics having a similar appearance at the front and backside. The stitch of the rib structure occurs in both planes of the fabric, and thus it is called double jersey fabric. Predominantly the face and backside of the fabric have to face loop appearance at 1 × 1 rib fabric unless the fabric is elongated to make the visibility of the back loops in-between the surface. The thickness of the 1 × 1 rib is increased in double, and the width of the rib fabric is around half of the plain knitted fabric theoretically. But the elastic recovery of 1 × 1 rib fabric is increased by double as compared to plain jersey knitted fabric. Generally, the widthwise elastic recovery of the 1 × 1 rib fabric is around 30% compared with single jersey knitted fabric.

6.1.5 Interlock Structure

The interlock structure is formed by combining two 1 × 1 rib structures, and it is the derivative of the rib knit structure. Both sides of the interlock structure have a similar single jersey face side appearance. As it has reversed mesh combination, the stretch-ability of the fabric is very less as compared to plain and rib kit fabrics, and it has a very smooth appearance at eight sides of the fabric [47]. The vertical column of the loop of direction yarns on the front and backside are exactly reverse to each other, and the loops are intermeshed together. The interlock knit structure is a derivation of the rib structure form in which two sets of threads are consecutively intermeshed by the cylinder and dial needle and shot and long needles for the formation of the interlocking structure occurs. The movement of individual needles of interlock knitting the machine is controlled by a jacquard mechanism to create enlarged and complicated knot structures [57].

6.2 Weaving Technology

Two sets of yarn strands are interlaced to each other at a right angle are known as woven fabric. The yarn runs in the lengthwise direction are known as warp, and the yarn runs in widthwise direction are called the weft yarns. The thick edges of the fabric, which are produced in the manufacturing process of woven fabric, are known as selvages. Weaving is the method of interlacing the warp and filling yarns to form a woven fabric. The warp yarns are runs parallel to each other, and fabric runs in lengthwise or the direction along with the weaving machine [58]. To directions of fabric without selvedge in the fabric, the grainline is passed parallel to both directions. For example, 45 ° diagonal directions of woven fabric are termed as bias. The bias direction of the stretchability is high. The drapability of the woven fabric is good in the bias direction (Table 4).

6.2.1 The Manufacturing Process of Woven Fabric

The weaving is the process of making the fabric on the loom, and such woven fabric manufactured from the machine is called a loom. The process sequence is described in detail below.

(a) The warp yarn is wounded in a huge roller, which is located in the lower back of the warp beam. To get a desired width of the final fabric, the yarn per inches is pre-determined depends upon a number of yarns present in the warp beam. To have warp stripes in the fabric, according to the stripes pattern, preferred the colored yarns are ties in the beam.
(b) The warp yarns pass via the harnesses, which have many vertical wires called heddles, each with an eye within the middle. In one heddle, each warp yarn is threaded through that eye. The purpose of the harness is to decrease or raise the warp yarns to create an opening or shed for passing the weft yarn. In the loom, a minimum of two harnesses are required, and the number of harnesses is increased because the structure of the fabric design becomes more complicated. The odd numbers of yarns are attached to one harness in a simple loom, and the second harness is attached as an even number of yarns. When the first harness is raised, the odd numbers of yarns are lifted to form a shed, and this process is known as shedding.
(c) By using a boat-shaped device, the weft yarn is inserted in the shed is called a shuttle, which carries the yarn continuously on a bobbin or pin. The weft yarn is inserted through other devices such as air or water jets are known as shuttle less looms, which is called picking.
(d) The reed is used to push the filling yarn into the previously woven fabric at a point are known as fell. The reed is a frame that is made up of a number of vertical wires and with the metallic comb. Once the weft yarn is inserted to make the fabric more compact, the reed is pulled by the weaver is called as beating up.

(e) Finally, the woven fabric is wounded into the cloth beam, which is located in the loom near to the weaver is known as take up.

6.2.2 Motions of Loom

- Primary operations

1. Shedding: In this process, separation of the upper and lower layer of warp shed forming a shed through which the weft yarn is passed.
2. Picking: Weft yarn is inserted into the shed is done in this process.
3. Beating: Pushing of the recently laid weft yarn against the cloth.

- Secondary operations

1. Let Off: The more warp yarn is supply by the slow unwinding of the warp beam.
2. Take Up: The interlaced fabric is wound up onto the cloth beam. The secondary processes, i.e., simultaneously take up and let off happen.

6.2.3 Basic Weaves

Figure 7 shows all about weaving technology for various products. The warp and weft yarn is interlaced in different ways to get a variety of structure is known as a basic weave.

A weave may be characterized by its repeat unit present in the fabric. Basic weaves are those that require a minimum number of warp and weft yarns to constitute their repeat units, e.g., plain weave needs just two warp and two weft yarns. To make different kinds of fabrics, many types of weaves are used, such as cambric, poplin, matt, satin, velvet, towels, denim, etc. There are three basic weaves, such as plain,

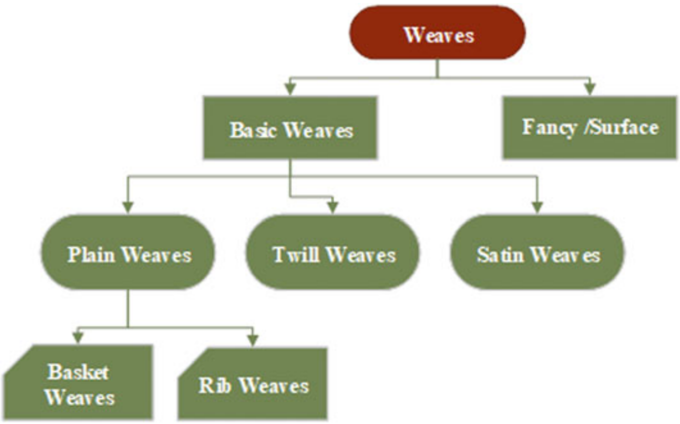


Fig. 7 Weaving technology

Twill, and Satin weave and all other weaves combinations and variation of this basic weaves.

Plain Weave

Plain weave is a basic tightest weave structure and also the most widely used weave. In this case, the warp and weft yarns are interlaced to each other at the right angle, i.e., one up one pattern is followed, which means each weft filling yarn goes above one warp yarn, and under successive the warp yarn and the same repeated patterns are followed for rows to produces a checked effect. The plain weave fabrics reversible until one side of the fabric is making as a face by finishing or printing. Plain weave structures do not ravel easily, and it has less absorbency compared with other weaves. The plain weave structure is used in blankets made by thin yarns and fine cambries fabric, a grey fabric made extremely fine [60].

- Rib Weave fabrics: the rib effect is produced in fabric by using large-diameter filling yarn compared to warp yarn. There are two types of rib weaves, such as warp rib and weft rib structure. By inserting two yarns in the shed, which form the 2 × 2 rib structure. Similarly, for weft rib also. The warp rib is identified prominently in the weft direction, and the weft rib is obviously identified in the warp direction. Example: Bengaline, ottoman, faille, poplin, broadcloth, taffeta.
- Matt or Basket Weave fabrics: Basketweave is extending both warp and weft direction of plain weaves structure. To produce matt weave, one single ends two or more ends is working and then two or more picks in the shed. Grouping of both warp and weft direction of yarns in an irregular manner, which produced irregular matt weave. Example: Flat duck, hopsacking, Panama are other examples.

Twill Weave

Diagonal lines are produced on the front, or the backside of the fabric is known as twill weave. For creating the new effects in the twill fabric, the direction is varied, such as broken twill weave, herringbone twill weave structure, and pointed twill weave. High strength and compact weaving of the fabric are the main characteristics of this type of fabric.

Satin Weave

The characteristics of satin weave are smooth, shiny, and slippery on the surface of the fabric are created long floats present on its structure. The surface of the fabric seen more warp yarn has resulted in the fabric. The shiny effects of the fabric are reflected in light by using these yarns. Satin weave requires 5–12 harnesses in the loom. Moreover, less twisted yarns are used to making these types of yarns compared to other weaves. All these together give a soft, smooth, and shiny appearance to the fabric. The satin wave processing is demonstrated through Fig. 8.

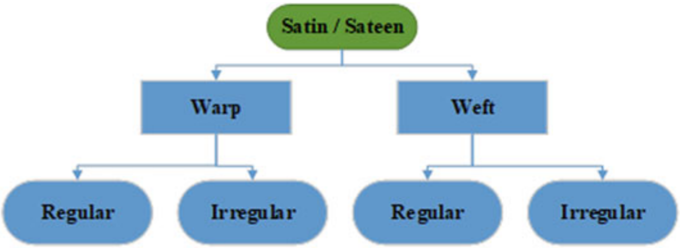


Fig. 8 Processing of satin weaves

6.3 Nonwoven Fabrics

Nonwoven is a process of converting fabric directly from fiber, and also this process is invented before spinning and weaving process earlier days. The process of entanglement of fibers by applying heat, pressure, and moisture to make the fabric is known as felting. Nowadays, nonwoven fabrics are extensively used in technical textiles, and especially in the medical textiles sector, it protects against biological agents. Finishing is given to nonwoven materials to improve the properties of the materials such as repellent against water, microbes proof, and anti-bacterial resistance that has been developed for applications. For example, surgical face masks, hygiene gowns, drapes for hospitals etc. There are three methods used to manufacturing the nonwoven fabric, namely Hydro-entanglement, thermal bonding, and Melt blown. However, bamboo fiber has wide market demand in the field of textile healthcare and hygiene fabrics such as an inner layer of the sanitary napkin, surgical masks, mattress, and because of the antibacterial nature of the bamboo fabric it is used in food-packing bags.

7 Properties of Fabric

Basically, the bamboo is anti-bacterial in nature, so it fights against microbes and pathogens; relatively, the fiber is smooth and soft with low pilling resistance and also anti-wrinkling, due to the micro gaps the bamboo fiber has high moisture absorption. Compared with the cotton fabric, in order to dye the bamboo fabric, it requires less amount of dyestuffs at the desired level because the absorption properties of the dyestuff are better, good to colour fastness, and show the colour better. The chemical components of bamboo are more significant, so it's providing extraordinary fungal and bacterial resistance. Due to their unique properties such as stretchability, open structure, and contour to the body shape without restricting the movement, the weft knits techniques are widely used in the apparel industry. The production technique is effortless and compared to other knit fabric structure costs, is low, wide product range, and high level of clothing comfort are influences the growing interest for weft knits.

Prakash et al. [62] examined the relationship between the linear yarn density and a stitch length of the single- jersey-knitted bamboo fabrics for thermal properties. It is found to be increasing in linear density, and stitch length affects the thermal comfort properties of the fabric. So that the value of thermal properties was compared and it was found that it is due to the fineness of the fabric, the thermal resistance and thermal conductivity of the fabric are decreased. The relatively both water-vapour and air permeability values increase simultaneously, there is increasing in linear density and the stitch length (Table 4).

The GSM and thickness of the fabric of all linear densities of yarn are decreased because of increasing in bamboo fiber content. The thermal properties of the fabric are affected due to the presence of more bamboo fiber. It is concluded that depend upon the fibre content present in the fabric affects the thermal properties, air permeability, and relative water vapour permeability properties and the yarn essential the linear density of the fabric [43, 62]. It is also established that the blending of cotton fiber with bamboo fiber for producing single jersey knitted fabric to improves moisture management properties. As the moisture content of bamboo fiber is more in nature,

Table 4 Properties of bamboo knitted fabric in comparison with some other textile fibers fabrics [16, 41, 47, 61]

Types of fibers	Blending ratio	Types of fabric	Areal density (g/m^2)	Thickness (mm)	Thermal conductivity (W m^{-1} K^{-1}) × 10^{-3}
Bamboo	100	Single jersey	185	0.50	45.04
Cotton	100	Single jersey	149	0.47	55.27
Merino wool	100	Single jersey	139	0.35	24.59
Polyester	100	Interlock	168	0.61	–
Modal	100	Single jersey	133	0.59	
Wool; Bamboo	52:48	Two-layer, interlock	253.00	0.90	30.54
Wool; Polyester	60:40	Two-layer interlock	161.80	0.82	–
Nylon; Elastane	92:8	Single jersey	214.20	0.80	–
Modal	100	Pique	151	1.64	59.94
Cotton	100	Pique	176	0.833	55.86

the absorption rate of the fabric is improved at the maximum level altogether. The fiber fineness and light in the weight of bamboo fiber the air permeability of the bamboo fabric are increased enormously. The busting strength of the knitted fabric is considered significant for improving the durability of cotton bamboo knitted socks and gloves material [62]. The fineness and strength of plain weave are extremely high as the plain weave has more amount of interlacement and binding points between warp and weft, and there is a restriction of displacement and slippage of warp and weft yarns when it undergoes any stress during use. Woven structure fabric fabrics have the preeminent eminent history in the textile application as these fabrics are produced by strong interlacement and binding of two sets of warp and weft yarns mutually [63]. The fabric tensile, tearing and bursting strength, thickness, stiffness, stability, porosity, filtering quality and abrasion resistance of fabrics are influenced by the fabric particulars such as ends per inch, picks per inch, warp and weft count and areal density and the cover of the fabric at a greater level. The characteristics of the fabric are the primarily prejudiced warp and weft yarn density and also weave construction. For achieving more quality parameters such as good fabric strength and durability of the fabric considering fabric particulars, areal density and cover is considered significantly [64].

Medical textile, which is under technical textiles, is significantly used in healthcare and hygiene disposable and non-disposable products manufacturing such as surgical gown, mask, surgical drape, towels, gloves, baby diapers, sanitary napkins and they are mainly used in clinics and houses. Bamboo fiber has an exceptional characteristic that helps in the ideal manufacturing of health care products. Bamboo fiber is excellent in moisture absorbency and has the capability to absorb time times of water on its own weight [48]. The abrasion resistance of bamboo, fabrics are higher as compared to cotton fabrics. Natural sterilization, moisture vapor transmission, and quick-drying properties of bamboo fabrics are excellent. Sanitary materials such as a baby diaper, absorbent pads, adult napkins, and towels manufactured using bamboo are highly absorbent, soft, and not causing any skin allergies.

8 Dyeing and Finishing of Bamboo Textile

During dyeing and finishing, the pretreatment process, such as light sergeing, enzyme desizing, moderate bleaching, and semi-mercerizing, should be applied to the bamboo fabric. Which is applied to avoid strong conditions and use small mechanical tension?

1. **Sergeing**: It is a process that is carried out in a moderate condition.
2. **Desizing**: It is a process used to remove the sizing materials in the fabric, and it should be consolidated, the desizing rate should be over 80%.
3. **Scouring:** For pure bamboo fabric, there is no need for scouring process, sometimes wash it with a little amount of alkaline soap solution. In case the bamboo fiber is blended with other fiber that fabrics need scouring.

4. **Bleaching**: It is a process that removes coloring matter and also brightening the fabrics.
5. **Mercerizing**: this process is carried out to give lustreness to the fabric and bad anti-alkaline. However, in order to increase the absorbance capacity to dyestuff.
6. **Dyeing**: It is a process of coloring the gray fabric with active dyestuff, the alkali should be less around 20 g/L, and the temperature should not exceed more than 100ºC. The low temperature and light tension are applied in this drying process to cure the fabric.

9 Scope of Bamboo in the Textile and Apparel Industries

Bamboo textile products demand very high in the market because of their physicochemical, thermal, and mechanical properties along with natural antibacterial, bio-degradable, high moisture absorption, UV protective, and breathable behavior. Comfort, cooling nature, and luxurious feel are the additional features of bamboo fabrics over other materials. Currently, there is an increasing demand for bamboo fibers in fact of their application in apparel such as underwear, sportswear, t-shirts, gloves, and socks. Hygienic products like sanitary napkins, absorbing pads, masks, bandages, and surgical gown are manufactured by bamboo fibers that enhance its market value to a large extent. The acceptability of bamboo fabrics in medical, textile, and apparel industries increases due to their good functional performances also [1, 65, 66]. Moreover, the competence of bamboo fiber with other available materials with respect to various unique, promising properties confirms its merit for extensive future uses in textile and apparel industries using further advancements.

10 Conclusion

The futuristic of natural fiber-based textile products depend upon the products that have reduced environmental and social problems during their entire lifetime. As a significance of the unique properties of bamboo products, the textile and apparel industry has established a remarkable mark on it. The merits of the usage of bamboo fiber in the textile industry are breathability, ease of processing, high functionality, and beauty. This chapter mainly focused on the processing of the bamboo fiber, manufacturing of bamboo fabric along with its industrial demand. Further scope in this area point towards the prospects of using bamboo products in both the textile and apparel industry, to maintain the environmental quality along with social welfare.

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Bonding Mechanism and Interface Enhancement of Bamboo Fiber Reinforced Composites

Asrafuzzaman, Kazi Faiza Amin, Ahmed Sharif, and Md Enamul Hoque

Abstract Nowadays, the utilization of natural fiber-reinforced polymeric composites has increased due to its eco-friendly nature. Among all the natural fiber reinforced polymer composites, bamboo fibers have caught attention as reinforcement in the polymeric matrix due to its superior mechanical properties, sustainability, and recyclability. The bonding mechanism of the polymeric matrix, bamboo fiber reinforcement, and their interface plays a critical part in governing the properties and performance of the formed composite materials. Factors like moisture content and lignin tend to reduce the interfacial adhesion between matrix and reinforcement phases resulting in the formation of defects and loss of strength that degrades the quality of the composite materials. That is why the enhancement of interfacial bonding/adhesion is required to ensure optimal properties of bamboo reinforced composite materials. This article summarizes the chemical treatments and the interfacial agents such as mercerization, use of compatibilizers, and silane treatment that are employed to enhance the interfacial adhesion which eventually leads to an improvement of strength in tension, stiffness, flexural strength, interfacial shear strength and so forth.

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Keywords Bamboo fiber · Bonding mechanism · Interfacial adhesion · Mercerization · Compatibilizer · Silane treatment · Interfacial shear strength

1 Introduction

With the advent of nanotechnology, the nanoparticle-reinforced composites (called nanocomposites) have been developed as advanced materials [1–6]. Likewise, natural fibers have shown great potentials nowadays in producing eco-friendly green composites for wider areas of applications [7–11]. They are known for their biodegradability and enhanced properties. Among the natural plants, bamboo is quite advantageous because of its' high growth rate, ability to fix carbon-di-oxide emission to the environment, lightweight, and high specific strength [12]. Bamboo fibers caught special attention owing to their longevity, mechanical characteristics, recyclability as well as their utilization as reinforcement in composite materials [13]. Earlier work on bamboo protective coatings with phenolic, epoxy, and styrenated coatings showed perfect adhesion between bamboo fiber and coating materials. However, work reported on the bamboo fiber-reinforced composite is very limited and a thorough study is required [14]. It has been suggested that some of the issues pose obstacle to the widespread use of bamboo fibers as reinforcement of composite matrix such as low moisture resistance, inadequate mechanical and chemical characteristics, current extraction procedure of bamboo fiber from bamboo culm is not suitable for manufacturing business [13]. The study found that the poor interfacial bond amid the matrix and bamboo fiber leads to the de-bonding of the composite on aging which results in poor mechanical and chemical properties. Hence, arises the concern for improving the interface of the bamboo fiber – composite matrix to meet the required property requirements [14].

2 Bamboo Structure

Bamboo culms are hollow, and several diaphragms divide each culm from inside, which are observed like rings from outside. The portion between rings is known as "Internode" where branches grow [12]. The bamboo culm contains vascular bundles that are attached in parenchyma tissue. The vascular bundles are kept in the longitudinal direction by the parenchyma tissue. It is observed that a high amount of vascular bundles is present near the outside culm of the bamboo whereas their percentage reduces on the inner side culm [13]. The fiber strand comprises of various fundamental fibers (mostly hexagonal and pentagonal shape) where nano-fibrils are aligned and attached with hemicellulose and lignin. Vascular bundles delimit culm strength. Hence, a suitable method is required to isolate the parenchyma tissue from the fiber strands and vascular bundles without any detrimental impact on the fibers which are extracted [13]. Figure 1 exhibits the components of a bamboo culm.

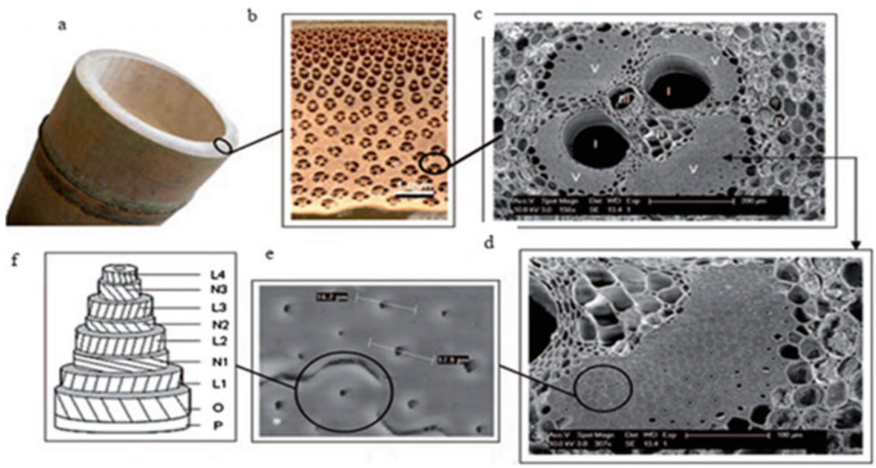

Fig. 1 **a** Culm of a bamboo, **b** Bamboo culm cross-sectional view, **c** Vascular bundle, **d** Fiber strand, **e** Elementary fibers, **f** Model of polylamellae structure of bamboo [15]

2.1 Bamboo Fibers (BF)

Bamboo has the combined characteristics of grass and wood. They are quite robust (specifically longitudinally) because a resilient fiber bundle infiltrates their body from the base to the topmost part albeit bamboo pulp being shorter than ∼2 mm. So, the ordinary length of bamboo fiber is around 2 mm plus the regular diameter is 10–20 µm [16]. Hemicellulose, lignin, and cellulose consist of bamboo. Around half of the total chemical constituents are cellulose and hemicellulose. They are present as holo-cellulose. Lignin is also present in abundance. It provides the role of a binder and performs as the matrix for the cellulose fibers. Lignin participates in load-bearing actions as a fundamental part of the composite [17]. Other than these two constituents, bamboo contains starch, de-oxidized saccharide, fat, and protein [18]. Bamboo fibers also referred to as 'natural glass fiber' are getting more and more consideration from the researchers [19].

3 Bamboo Fiber Reinforced Polymer Composites

In general, BF is used as reinforcement for polymer composites. Inherently, BF is hydrophilic, while polymers are hydrophobic. Owing to the incompatibility in terms of their polarity structures, it is quite difficult to formulate a feasible composite having superior interfacial bonding [16]. Various approaches i.e. physical treatment (solvent extraction, heat treatment), physio-chemical treatment (laser, ultra-violet bombardment), and chemical modification have been endeavored to make lingo-cellulosic molecules of fiber and hydrocarbon-based polymers compatible to each other [20, 21]. It is well established that bamboo fiber can be used as a reinforcement for thermosetting composites, thermoplastic composites, rubber/elastomeric composites, and biocomposites.

3.1 Bamboo Fiber Reinforced Thermosetting Composites

These composites are composed of BF fibers which are large in size. Post-curing under a particular load is required for the preparation of the thermosetting composites. Phenolic resin, epoxy, and unsaturated polyester are the most commonly used thermoset polymer matrices for this type of composite [22].

3.2 Bamboo Fiber Reinforced Thermoplastic Composites

Unlike thermoset composites, short BF fibers are used for thermoplastic composites. Polymers (petroleum-based) that are chosen to be used as matrix material are polypropylene (PP), polyethylene (PE), nylon, and polyvinyl chloride (PVC). The short fibers are dispersed in the matrix in a random orientation. As a result, they exhibit isotropy [22].

3.3 Bamboo Fiber Reinforced Rubber/Elastomeric Composites

Rubber/elastomeric composite reinforced with short BF has several advantages including design flexibility, stiffness, damping, process economy [23].

3.4 Bamboo Fiber Filled Bio Composites

The use of BF in biocomposites is a recent practice. Biomass-derived biopolymers are utilized as matrix material. The most commonly used biopolymer matrices are polylactic acid (PLA), polybutylene succinate (PBS), protein, polycaprolactone (PCL), and starch [24].

4 BF-Polymer Matrix Interfacial Bonding Mechanism

The property and performance of any plant fiber (including bamboo fiber) composite rely on the bonding mechanism at the interface. The interface area of the matrix and the reinforcement has a prime role to play in controlling the performance of the material. The composite interface is created by the coupling of the fiber and matrix, which is, in essence, a region of structural, compositional, and property gradients, usually ranging in breadth from one atomic layer to many micrometers. Processes occurring at the different levels of the interface (macroscopic, atomic, and microscopic) are closely related. To accurately comprehend the interfacial phenomena, it is extremely important to understand the order of incidents happening at mentioned levels. Stress transfer between matrix and bamboo fiber is controlled by the interfacial region [25]. The molecular synergy at the interface as well as the thickness and strength of the interfacial region regulate the effectiveness of load transference [26].

Inter-diffusion, electrostatic adhesion, chemical reactions, and mechanical interlocking are the most common interfacial bonding mechanisms. All of these mechanisms are mutually responsible for adherence and typically one of them prevails [25]. Due to Van der Waals forces or hydrogen bonding, intimate intermolecular interaction occurs between fiber molecules and the polymer that causes inter-diffusion [22]. Adsorption and diffusion are two sub-stages of the adhesion mechanism. The first stage is governed by spreading and penetrating while the second stage indicates good wetting leading to inter-diffusion of fiber and matrix. The fiber-matrix compatibility controls the magnitude of the diffusion process [27]. For electrostatic adhesion, two opposite charges are formed at the interfacial region. Those are responsible for the adhesion of fiber and matrix. The chemisorption reactions form chemical bonds (ionic bond and atomic bond) between matrix and fiber (Fig. 2).

The mechanical interlocking phenomenon occurs when the holes, crevices, or other irregularities of the fiber are infiltrated by the matrix and the fibers get locked to the matrix mechanically [25]. It is seen that increasing surface roughness, increases the contact area for adhesion thus favoring mechanical interlocking [27]. Moreover, increasing mechanical interlocking displays potential improvement of bonding mechanism [25].

5 Controlling Factors of Interfacial Characteristics of BF Composites

5.1 Moisture Absorption

Under natural humidity situations, BF soaks a substantial quantity of moisture and thus it is known as a hydrophilic material. Moisture sorption hysteresis of BF is comparable to other natural fibers for instance hemp and flax [28]. The mechanical performance of the bamboo is affected by the absorption capability of BF. Moreover,

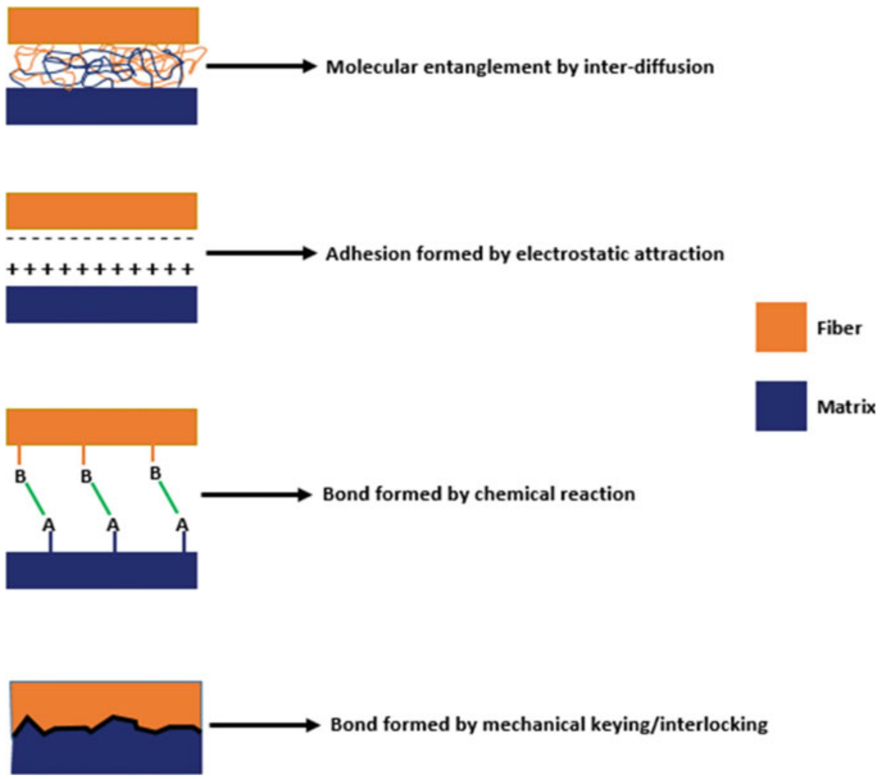

Fig. 2 Types of bonding mechanisms in the interfacial region

poor adhesion between BF and water-repelling polymers (matrix) is observed due to moisture absorption [16]. Moisture has a detrimental effect on the polymeric matrix and the fibers. Moreover, the matrix-fiber interface can also be impaired due to the presence of moisture. Ultimately, poor stress transference from the matrix to reinforcement is observed. The cycle of deterioration begins when the cellulose fibers are swollen. It produces stress at the interface. As a result, micro-cracks appear in the matrix around the swollen fibers exacerbating the water absorption and weakening the interface. Intermolecular hydrogen bonding is formed with the fibers due to the absorbed water and thus interfacial adhesion is reduced. At the same time, water leaches out the soluble constituents from fibers. This occurrence eventually results in de-bonding at the interface. The study showed that due to moisture absorption extensibility of BF is increased but elastic modulus is decreased whereas the tensile strength remained unaffected. The effect of moisture absorption on interfacial shear strength (IFSS) was inspected for bamboo fiber—vinyl ester matrix composite. The IFSS in 20°C and 60% humidity was only 50% of what was achieved under dry conditions. For composites developed under 80–90% humidity conditions, negligible interfacial strength was observed. Significant damage to interfacial shear strength was observed for BF-vinyl ester matrix composite due to water absorption. Ultimately, the IFSS was reduced by 38% [22].

5.2 Presence of Lignin

Bamboo fiber contains 32.2% lignin approximately, which is greater than the percentage of lignin in other natural fibers [17]. Studies have found that bamboo strips containing lignin lead to ineffective interfacial adhesion [22]. Defects are formed due to poor interfacial adhesion and as a result, the composite lacks strength [16].

6 Treatments to Enhance Interfacial Adhesion of BF Reinforced Composite

Interfacial bonding/adhesion is the prime concern for producing BF reinforced composites having optimal properties. Various studies have conducted engineered enhancement of interfacial adhesion between BF and matrix materials. In turn, it leads to an effective increase in composite properties like tensile strength, flexural strength, interfacial shear strength (IFSS), stiffness, and many more. Different chemical treatment procedures, interfacial agents, filler materials, and bonding agents affecting the enhancement of the interfacial adhesion will be discussed below.

6.1 Alkaline Treatment or Mercerization

Alkaline treatment, namely mercerization, removes lignin and other unwanted constituents and thus helps to reduce the acrid aroma of BF. It forms cellulose micro- or nanocrystals that have irregular fiber surfaces due to the removal of amorphous cellulose from the cellulose fiber bundle. Hydroxyl groups in bamboo fiber are activated due to mercerization. The enlarged surface area results in better interfacial adhesion. Ultimately, the tensile and thermal properties of the composite are improved [22]. Usually, a NaOH solution (aqueous) is used to perform this treatment. The study showed that PLA (polylactic acid) composites containing delignified BF provide better tensile strength and bending modulus than a PLA composite with untreated BF. This improvement was ascribed to the surface alteration and the enhancement of the interface adherence between the BF and PLA matrix [29]. However, it is observed that superfluous alkali treatment results in excessive delignification that results in weakening and deterioration of the fiber being treated [25]. Alkali treatment (greater than 15%) proved to be detrimental to composite properties [30, 31].

6.2 Compatibilizer or Maleated Coupling Agents

Maleated coupling agents showed promising results in enhancing interfacial adhesion. The hydroxyl group of the plant fiber is removed by the maleic anhydride (MAH) group and thus reducing its' hydrophilic tendency [25]. Additionally, a C–C bond is formed with the matrix. Improved adhesion is attained by the creation of covalent bonds at the interface between coupling agents and fibers along with molecular entanglement amid polymeric matrix and coupling agents [32]. Due to this treatment, the surface energy of fibers and matrix become closer resulting in improved wettability and enhanced adhesion at the interfacial region [33]. As a compatibilizer/coupling agent for the BF/PP composite, maleated polypropylene (PP) is the most frequently used. Studies showed that incrementing the content of MAH results in a little improvement in impact strength and modulus but the augmented degree of maleation increases tensile strength substantially [34].

Bamboo pulp fiber-reinforced composites showed improved strength and modulus but reduced toughness due to the addition of maleic anhydride grafted PHBV8 (Poly(3-hydroxybutyrate-co-3-hydroxyvalerate)) as compatibilizer. Isocyanates, MDI (Methylene diphenyl diisocyanate) are common compatibilizer used in BF reinforced composites. The fracture surface of PHBV8/bamboo pulp fiber composites with and without pMDI (Poly methylene diphenyl diisocyanate) is shown in Fig. 3. Without pMDI, a significant amount of fiber pullout is detected. This proved inadequate interfacial adhesion. However, interfacial bonding becomes strong due to the presence of pMDI and fracture surfaces show that all fibers are broken. Improved interfacial adhesion reduces the chance of fiber de-bonding and hinders the fiber pull out. Moreover, it enables higher stress transference between fiber and matrix and thus improves the modulus and the tensile strength of the composites [22]. The toughness of the composite is diminished owing to the interruption of fiber pull out, a key energy dissipation source throughout the composite deformation [36]. Therefore, the addition of compatibilizer helps to improve flexural and tensile strength, while the ductility of the composite is reduced.

6.3 Silane Treatment

Silane (SiH_4) is an inorganic substance. Two reactive groups are present in silane coupling agent. The alkoxysilane group interacts with hydroxyl rich fiber while the other is left to react with the matrix. Silane tends to react with water (absorbs moisture) to form silanol. The formed silanol further reacts with the hydroxyl group integrated to the cellulose, hemicellulose, and lignin molecules in the filler through ether linkage with the elimination of water. In contrast, hydrophobic molecules of silane are capable of reacting with a polymer matrix [37]. Because of covalent bonding between fiber and matrix, the hydrocarbon chain formed by the silane restrains swelling of

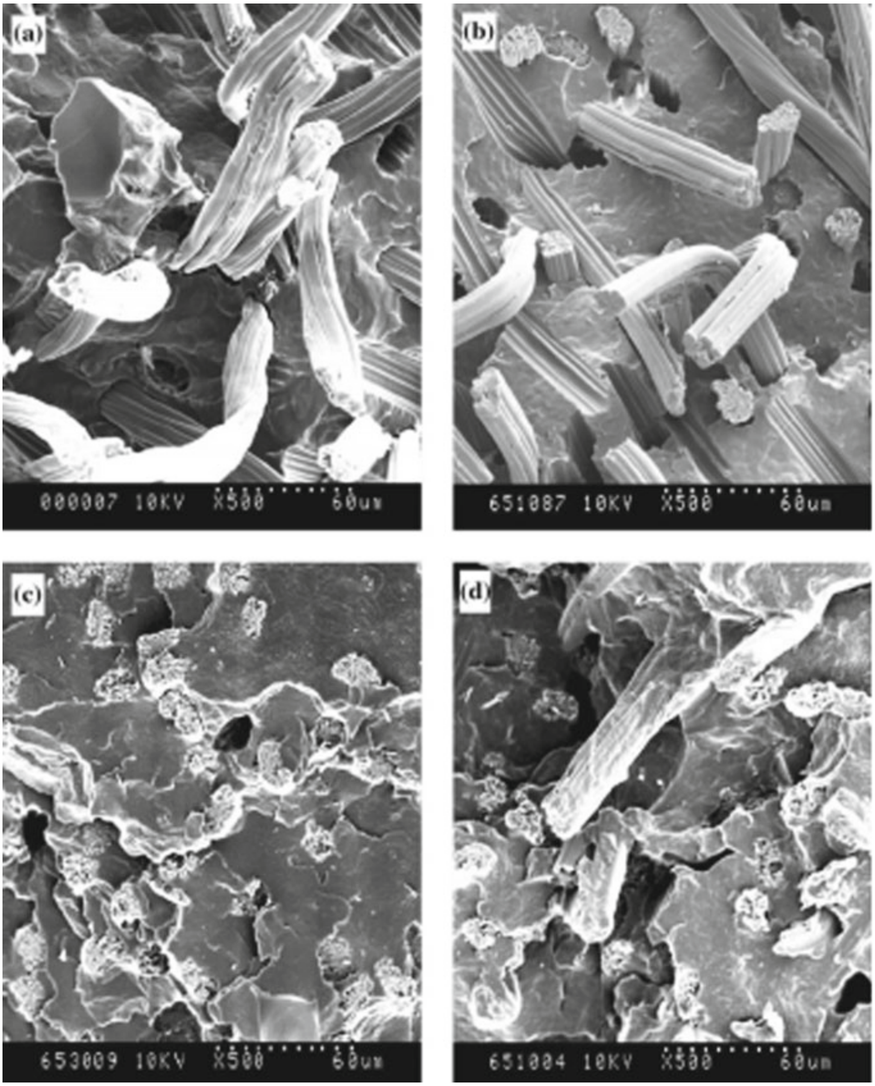

Fig. 3 SEM images of tensile **a**, **c** and impact **b**, **d** fracture surfaces of PHBV8/bamboo pulp fiber (80/20 w/w) composite without pMDI **a**, **b** and with pMDI **c**, **d** [35]

the fiber by getting entangled and cross-linking of the networks [33, 38]. Furthermore, the presence of hydrocarbon chains is anticipated to have an impact on the fiber wettability and chemical affinity of the matrix and thus enhancing interfacial properties [25]. The amine groups of 3-aminopropyl triethoxysilane are favorable for increasing the adhesion at the interface of PLA (Polylactic acid)/ BF composites [22].

To enhance fiber-matrix interface adhesion, numerous other physical and chemical procedures are utilized. Some of them are acetylation, benzoylation, acrylation, permanganate treatment, argon plasma treatments, etc. [22].

7 Scientific Studies and Research on Interface Enhancement of BF Reinforced Composites

7.1 Alkali Treatment on BF Reinforced Polyester Composites

Wong et al. [39] studied two types of bamboo fibers: treated with NaOH concentration (1, 3, and 5%) and untreated. Interfacial shear strength (IFSS) of the fiber with polyester matrix at dissimilar embedment length of fibers were also studied.

For the characterization of the morphology of the fiber (before and after the tests), SEM (Scanning Electron Microscopy) was utilized. Both strength and stiffness were increased according to the result. Besides, higher NaOH concentration and longer embedment length showed increased IFSS. Figure 4a, b shows the effect of NaOH concentration and fiber embedment length on IFSS.

However, It is necessary to remember that enhancement will be saturated after a certain proportion of alkali treatment [39].

7.2 BF Filled Rubber Composites with Bonding Agents

Ismail et al. [23] studied the adhesion between BF and natural rubber by the addition of bonding agents. In this study, phenol–formaldehyde and hexamethylene tetra-amine were used as bonding agents. SEM characterization of the tensile fracture surface showed that the presence of the bonding agent resulted in better interaction between fiber and rubber matrix interfacial adhesion.

7.3 BF Reinforced Poly Lactic Acid (PLA) Composite with Micro-Fibrillated Cellulose (MFC)

The study of [40] showed that small addition (10%) of MFC obtained from the wood pulp with the PLA/BF composite gives enhanced fracture toughness due to better interfacial adhesion and intertwined MFC fibers prevent the progress of cracks through the interface. Figure 5 exhibits a representative stress–strain curve of PLA/BF/MFC, PLA/BF, and PLA resin composites.

It is quite clear from the graph that the addition of MFC content with PLA/BF composite enhanced interfacial adhesion thus increasing bending strength and elastic

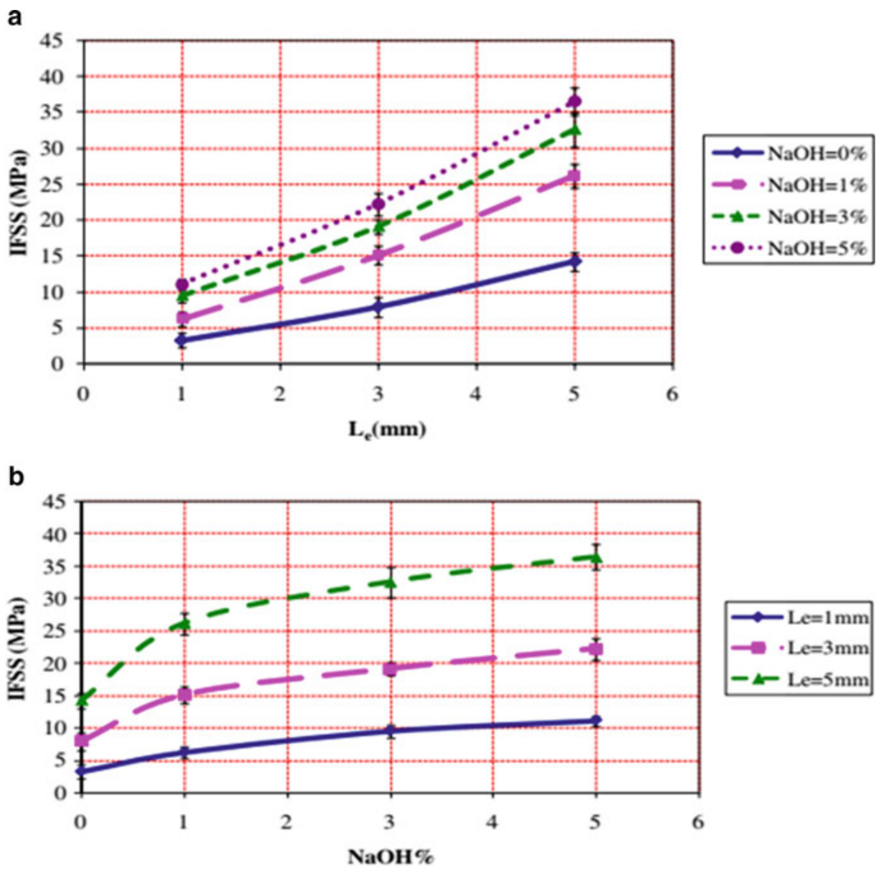

Fig. 4 **a** The outcome of fiber embedment length to IFSS for treated and untreated fibers. **b** The outcome of alkali treatment to IFSS at different fiber embedment length [39]

modulus. Nevertheless, the increasing ratio is insignificant for the sample with MFC content over 10% in weight.

Figures 6a, b display the fracture surface of PLA/BF and PLA/BF/MFC composites. Countless fiber pullouts are observed for PLA/BF composites, which is detrimental for interfacial adherence between matrix and fiber while only a small number of fiber pullouts are detected in the case of PLA/BF/MFC.

Moreover, high interfacial shear strength (IFSS) is observed (Fig. 7) due to the addition of a minor quantity of MFC in PLA/BF composites that also prevents interfacial failure.

In the case of PLA/BF, as soon as a crack reaches bamboo fiber, it propagates alongside the interface giving low fracture toughness. Improvement of fracture toughness was observed due to the addition of MFC with PLA/BF composite since intertwined MFC prevents crack progression along with the interface. Consequently, no

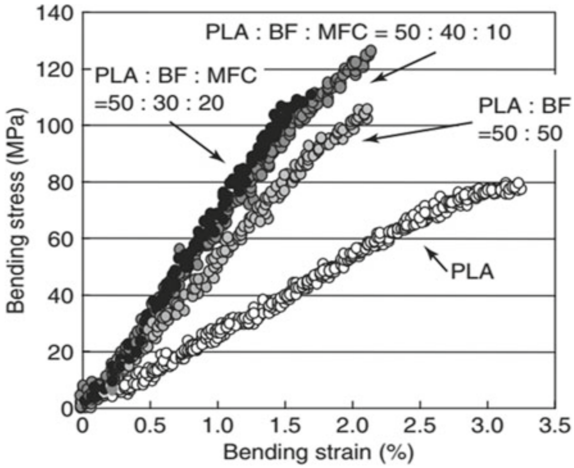

Fig. 5 Stress–strain profiles of PLA, PLA/BF and PLA/BF/MFC composites [40]

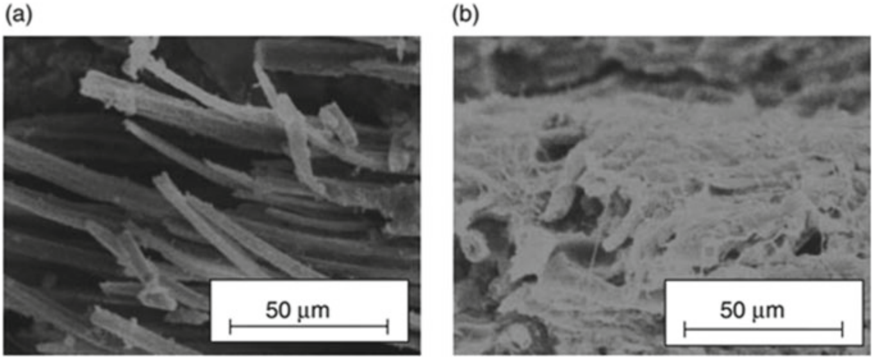

Fig. 6 Fractography of **a** PLA/BF (50:50) composite and **b** PLA/BF/MFC (50:40:10) composite [40]

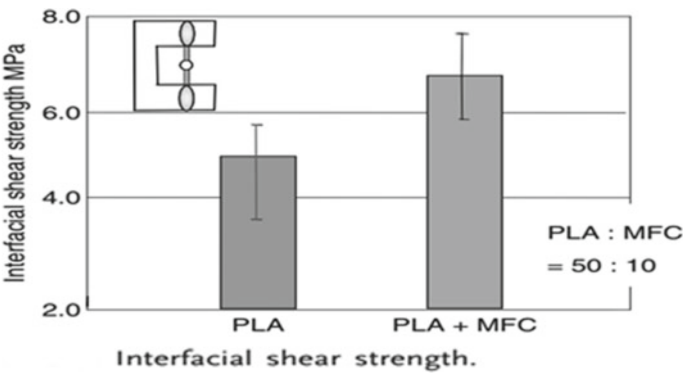

Fig. 7 Interfacial Shear Strength of PLA composite and PLA/BF/MFC composite [40]

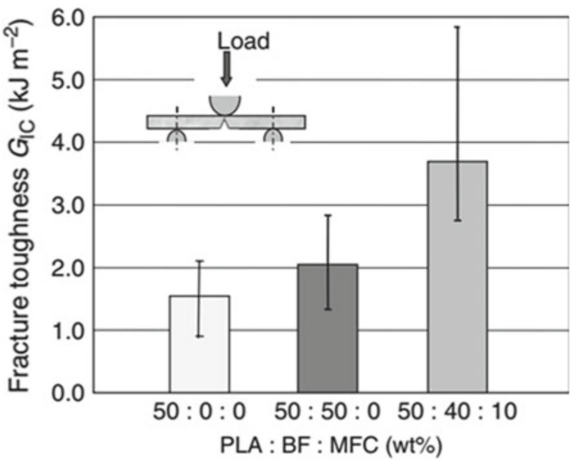

Fig. 8 Graphical representation of fracture toughness of PLA, PLA/BF and PLA/BF/MFC composites [40]

de-bonding occurs. Figure 8 shows the fracture toughness of PLA, PLA/BF, and PLA/BF/MFC composites.

Another study by [41] showed the effect of alkali-soaking treatment, silane coupling treatment, and maleic anhydride grafting treatment of the cellulose fiber on the mechanical characteristics of bamboo cellulose fiber reinforced PLA composites. Improved strength and modulus were observed for alkali soaked composite in comparison to the untreated specimens. Enhanced impact toughness and ductility are observed by silane treatment which is are higher than those of PLA composite filled with pristine bamboo cellulosic fibers. Maleic anhydride grafting showed a moderate effect on ductility and rigidity. SEM observation as well as FTIR spectrum analysis concluded that interfacial interactions amid fibers and matrix were enhanced due to all the above-mentioned modifications.

7.4 BF Reinforced Unidirectional Epoxy-Based Composite

Wang et al. [42] studied epoxy-based composite reinforced with BF which are chemically treated with NaOH solution of 1, 4, and 7% concentration at room temperature causing an increase in tensile strength of the composite by 17.78, 45.24, and 28.92% respectively. The addition of NaOH solution removes pectin, hemicellulose, and part of the lignin of bamboo fibers [43]. As a result, a large number of micro-fibrils on the fiber surface are exposed ensuring promising interaction with the epoxy resin matrix. So, interfacial adhesion enhancement improves tensile performance. However, at 7% NaOH concentration, the micro-fibril structure was damaged and interfacial adhesion became weak.

Toughness is dominated by interfacial adhesion too. It was also observed that with an increasing percentage of NaOH solution (1, 4, and 7%), elongation at break of composites increased respectively by 15.92%, 23.32%, and 41.70%. Fracture surface morphology indicates that with the increase of NaOH percentage, the fiber pullout phenomenon reduces due to better interfacial adhesion. However, a 7% NaOH solution causes the formation of disordered micro-fibrils, which is harmful to interfacial performance. Figure 9 shows the interfacial morphology of BF reinforced epoxy-based composite treated with numerous alkali concentrations. As shown in Fig. 9a, complete fiber pullout from the matrix occurred displaying poor interfacial adhesion. Figure 9b indicates the dispersion of fibers and an effective increase in the surface area of the fiber leading to improved interface adhesion. Figure 9c shows that broken fibers are firmly fixed in the epoxy resin indicating a well-bonded interface. Figure 9d also shows a well-bonded interface but some fiber pullout occurs due to the presence of disordered micro-fibrils in the fiber surface.

The IFSS also increased by 30.79, 100.30, and 53.66% in the sample treated with 1,4, and 7% NaOH solution. In the case of, 7% concentration, cellulose crystal structure is damaged hence the decrease of IFSS. Moreover, the flexibility of the epoxy-based molecular chain is limited after the NaOH treatment which results in a

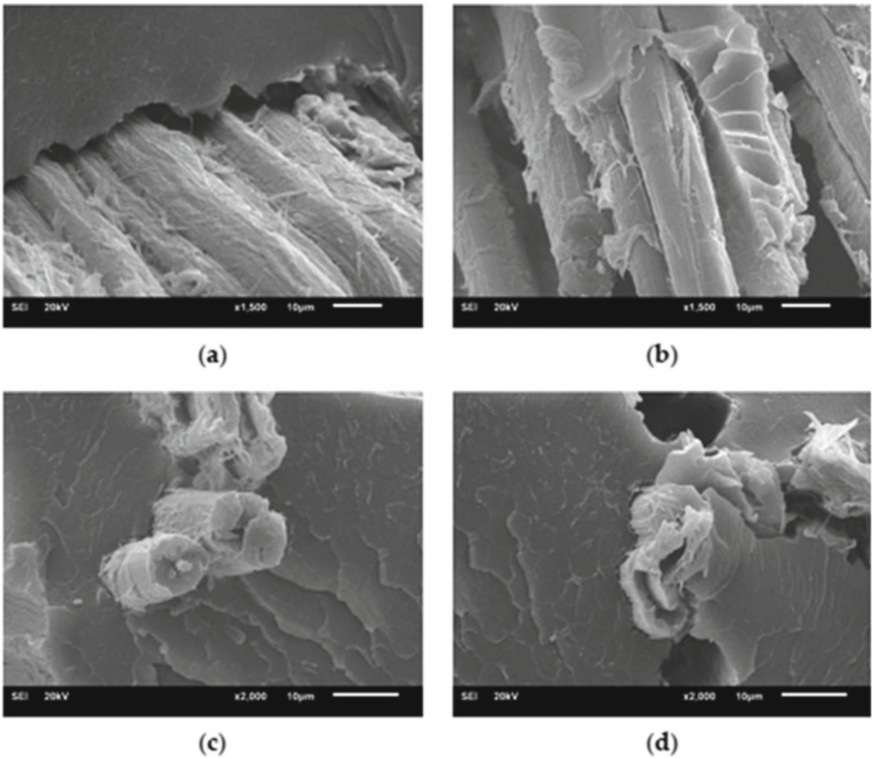

Fig. 9 Interfacial morphology of BF reinforced epoxy based composite treated with numerous alkali concentrations of **a** 0% **b** 1% **c** 4% and **d** 7% [42]

higher glass transition temperature, T_g. They determined that this treatment improves decomposition temperature and exhibit enhanced thermal stability due to the better interfacial adhesion.

7.5 Interfacial Adhesion of BF Reinforced Thermoplastic Composites

Improved mechanical properties are already obtained with BF reinforced composites with a thermoset matrix. Good chemical bonding at the interface and low viscosity of the resin is attributed to this improvement [15]. However, they are neither biodegradable nor recyclable thus having a serious environmental impact. In search of eco-friendly BF reinforced polymer composites, Fuentes et al. [44] integrated the physical–chemical-mechanical methodology to study the influence of interfacial adhesion on the mechanical behavior of BF reinforced thermoplastic composites. Maleic anhydride grafted polypropylene (MAPP), polypropylene (PP), polyvinylidene-fluoride (PVDF), and polyethylene terephthalate (PET) are used as a thermoplastic matrix in this study. PP, MAPP, PET, PVDF composites reinforced with BF showed increased interfacial shear strength. Among the four of them, PVDF displayed best amalgamation of high work of adhesion, wetting parameters along with a positive spreading co-efficient assisting to attain a better wetting of the molten thermoplastic on the bamboo fiber. This is a direct result of strong physical adhesion at the interface owing to the presence of a highly basic component on the bamboo fiber's surface and a highly acidic component of PVDF. Moreover, the relatively high total surface energy of both the matrix and fibers also attributes to this factor.

7.6 Cotton Shaped BF Reinforced Maleic Anhydride Modified Polypropylene (MAPP) Composites

Okubo and Fujii [19] observed the interfacial adhesion development of BF reinforced MAPP composites. They used the steam explosion technique for extracting bamboo fiber and compared its' properties with mechanically extracted bamboo fiber. The study showed the modulus and tensile strength of PP based composites using steam-exploded fibers improved by 30% and 15%, correspondingly, owing to the good impregnation of the matrix into fibers and reduction of several voids, compared to mechanically extracted bamboo fiber PP composites.

The fiber extracted by the steam explosion method appeared as cotton fiber. They stated to it as "Bamboo Fiber Cotton (BFC)". It is shown that the MAPP based Bamboo Fiber Cotton Eco-Composites (BFCEC) gives better strength as well as modulus compared to MAPP based Bamboo Fiber Eco-Composites (BFEC), which clearly indicates enhanced interfacial adhesion.

7.7 *BF/Epoxy and BF/Polyester Composites with Polyester Amide Polyol (PEAP) as Interfacial Agent*

Saxena and Gowri [14] examined the effect of PEAP on the BF as an interfacial agent and observed the properties of BF/Epoxy and BF/Polyester composite. The flexural and tensile strength of both the composites were improved owing to the PEAP treatment on BF. The polyester amide polyol acts as a bridge between the resin matrix and the fibers. The polyester amide polyol is attached to the fiber surface (containing surface reactive protons) due to hydrogen bonding.

This interaction is responsible for better wetting to the resin during application followed by chemical bonding. There is a further possibility of hydrogen bonding between PEAP treated fiber and resin matrices which in turn enhances fiber-matrix interface adhesion. Figure 10 shows the stress elongation curve of BF/epoxy and BF/Polyester composite in a treated and untreated condition. Evidently, the presence of PEAP improved the tensile strength of both types of composites.

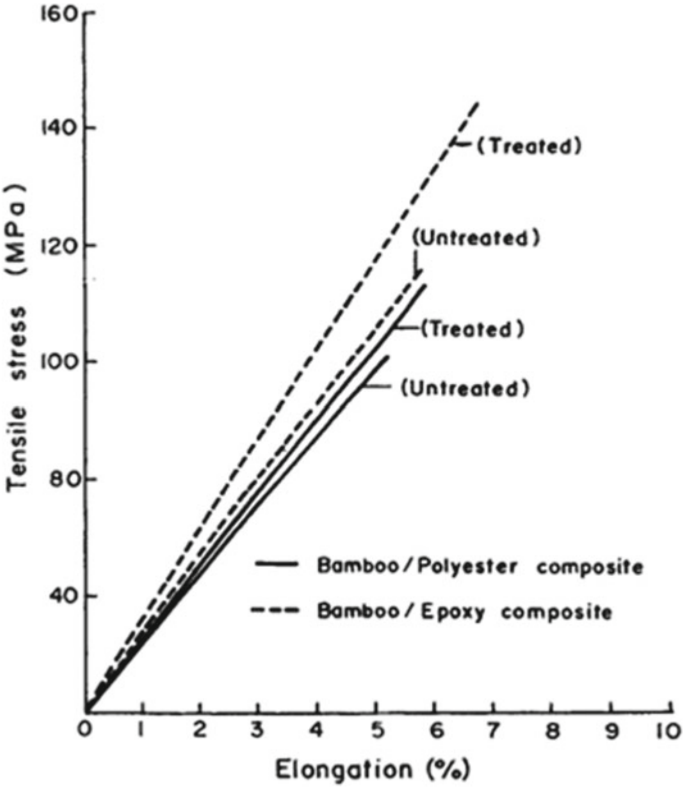

Fig. 10 Stress-elongation plot for bamboo composites untreated and treated with PEAP [14]

Another important characteristic, observed from this study is the reduction of water absorption percentage of BF with the addition of PEAP as an interfacial agent. Introduction of hydrophobicity to the fiber surface attributes to this phenomenon. The surface-treated composite absorbs less moisture/water than untreated composites, owing to the cross-linked interface region formed by the reaction between PEAP and resin matrix. Thus, interfacial adhesion enhancement reduces the moisture-induced degradation of the composites.

8 Conclusions and Future Perspectives

It is undeniable that interfacial adhesion between bamboo fiber and polymer matrix is a crucial part in determining the properties of composites. Modification of the interface through various physical, chemical, and mechanical treatments has resulted in enhanced strength, modulus, IFSS, water absorption capacity, toughness, ductility, etc. Due to the improved properties, the range of industrial and commercial applications of BF reinforced polymer composites is expanding substantially. However, there are many scopes for further investigation and innovation in this field to overcome the probable challenges ahead.

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Lifecycle Assessment of Thermoplastic and Thermosetting Bamboo Composites

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Abstract This chapter reports on the lifecycle assessment of the thermoplastic and thermosetting polymers composites reinforced with bamboo fibers. Several research works have reported that the bamboo reinforced polymers composites are biodegradable with environmental friendliness characteristic. Several chemical surface functionalization techniques have enhanced the properties of bamboo reinforced polymer composites.

Keywords Composites · Lifecycle assessment · Bamboo · Thermoplastic polymers · Thermosetting polymers

1 Introduction

For a comfortable life, human required useful and novel materials; and for this, exploration for the new materials had been already started from a long time. Various new

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materials were continuously developed and discovered through the stage of twentieth century and composites have identified as one of the materials, which revolutionized the concept of high strength and toughness. Therefore, the composites have become an essential component of our life and can be easily available everywhere in engineering industries, for example spacecraft, rubber tire, asphalt, etc. Bricks made from the straw and mud is amongst the classic examples of composites of past time. Composite is defined as the resultant material fabricated through the combination of two or more materials (having different chemically/physically states that may be polymers, metals and ceramics) to develop the superior properties as compared to the parental components (material which is present in a comparatively large amount as compared to other components in the domain) [1–5]. Bones, woods, muscles, tissues, teeth, etc. are the common examples of composites that are found in nature. Most commonly used composites consist of fibers or particles reinforced in the matrix domain. Composites are any multiphase materials that are made up of two or more chemically dissimilar elements, which have a discrete interface that separates them. In composites, continuous phase surrounds one or more discontinuous phases. Generally, the discontinuous phase is relatively stronger and harder than the continuous phase elements and is known as the reinforcement, whereas the continuous phase is called as the matrix [6–10]. The purposes of matrix in composite materials are to transfer the loads to reinforcements, protect the reinforcements from the surrounding environment and to keep the reinforcements in the desired orientation and location; whereas the function of reinforcements in composites are to give strength, stiffness and enhance the other mechanical properties [11–15]. A judicious combination of reinforcing phase and matrix direct a composite material having the modulus and strength similar to or even superior to than those of the usual metallic materials [16–20]. The physical and mechanical characteristics of composites can further be modified by adding certain additives and fillers.

Nowadays, the bio/green composites have become an area of interest to composites scientists and industries; and several experimental researches are going on in this area [21–24]. Green composites are a special class of bio-composites that have caught the attention as an alternative solution to the petroleum derived materials which may cause several environmental problems. In case of green composites, both the reinforcement and matrix are derived from the natural renewable resources [25, 26]. Green composites are termed as green because of their sustainable and biodegradable properties, so it can be simply decomposed without causing any harm to the environment. Nowadays various experiments and research works are performed to enhance the mechanical and other desirable properties of green composites so that their applications can be expanded. This becomes particularly essential to discuss the significant works connected to the area of biodegradable composites and their properties.

Earth has a very limited resources and over exploitation of these resources result in the depletion of non-renewable resources. This gives rise of the environmental crises, which may be slow (sometime unnoticeable) but highly significant to the human beings. Moreover, the growing issue of environment pollution, reduction in the cost of raw material, and the demand of renewable resources for the fabrication of composites, results in shifting of the researcher's interest towards the natural fibers. Due to their good thermo-mechanical properties, nowadays the application of natural fibers as a reinforcement material in thermoplastic and thermosetting composites have gained a quite a bit of interest [27]. Natural fibers are further divided into three major groups depending upon their source of extraction. Natural fibers which were extracted from the plants are known as the cellulose fibers; fibers which were extracted from the animals are known as the protein fibers and fibers which were extracted from the minerals are known as the mineral fibers [28, 29]. On a chemical note, the major components of the natural fibers are the cellulose (semi crystalline polysaccharides) in which D-glucopyranose units are linked together by b-(1-4)-glucosidic bonds; hemicelluloses (branched and fully amorphous polysaccharides) mostly consisting of D-pentose sugars units strongly bonded with the cellulose fibrils through hydrogen bonding; lignin (highly complex structure and amorphous) consisting of the aromatic alcohol units such as coumaryl alcohol, coniferyl alcohol and sinapyl alcohol; pectin (a heterogeneous polysaccharide); waxes and other water soluble materials [30]. Cellulose fibrils are the major component that provides strength to the fiber. Plant fibers are further divided into the stalk, grass, fruit, wood seed, leaf and bast, out of which the bamboo belongs to the family of grass known as the Bambusoideae [31].

2 Overview of Bamboo: Production to the Fiber Extraction

Out of all the natural fibers, the bamboo fiber (regenerative cellulose fiber) is one of the mostly used fibers become of its availability and low production cost. In India, bamboo (belongs to the Gramineae family) is the largest cultivated crop of about 11.4 million hectares, and China being the second largest of about 5.4 million hectares. Considering worldwide geography, there is around 1200 species (such as the bambusa balcooa, bambusa bamboos, bambusa nutans, etc.) and 90 genera of bamboo covering about 36 million hectares land (about 3.2% of the total forest area) [32]. Majorly concentrated in the Asia (about 65%), Arica and Latin America; due to the better heat, monsoon climate and water availability [32]. On the other hand, there are some species of bamboo which also found in the cold regions. Depending upon the height of the bamboo, their species are classified into the 3 major groups: dwarf species grow only a few centimeters; medium size species grow up to few meters; and the giant species grow up to 30 m (having diameter of about 30 cm). Except in rock strewn soils, the bamboos can be grown on different soils, mostly on a pH level of 4.5–6 and drained sandy soil to clay soil is required for its plantation. Propagation of bamboo normally occurs through the rhizomes or culms cutting. Seeds can also be used for propagation, but the availability is very rare. Tissue culture, seeds, air-layering, wildings and offsets are the methods for procuring planting material or bamboo.

Bamboo structure consist of hollow cylinder known as culm, which is having several diaphragms from inside and outer appearance looks like the rings. Internodes are defined as the spacing between the two rings which varies from species to species [33]. Characterizations of bamboo species is one on the basic of vascular bundles, and also play an important role in providing the strength to culm [34]. As we go up to the upper most section, bamboo culm diameter decreases that result in increase of the vascular bundles density. Therefore, the strength of base section is lower than the top section [35]. Chemically the bamboo fiber consist of cellulose, hemicelluloses and lignin; these components constitute of about 90% of the total weight and act as major building block which provides strength to the bamboo fiber. Moreover, the physiological activities depend upon the other constituents such as the fat, tannin, pectin, protein, pigments and ash [36]. Cellulose content of bamboo fiber keeps on decreasing with increase in age, which results in decrease in its strength. Lignin provides the yellow color and stiffness to the bamboo fiber; it is also resistance to the alkali medium.

3 Bamboo Fiber Extraction

3.1 Mechanical Extraction Process

One of the most popular methods is the steam explosion method. In this method, the plant stalks were disintegrated into the fiber bundle by treating them with the hot stream (120–180 °C temperature) under certain pressure and then the rupture of rigid structure biomass fiber is done with the help of an explosive. It is one of the cheapest method with relatively low energy consumption to disintegrate the cell walls of the bamboo. But this method is not sufficient enough to produce single fiber and about 25–210 μm diameter bundles were produced that were dark and rigid [37]. Another method is crushing in which the small pieces of bamboo were cut through the help of roller crusher. Then with the help of pin roller, the coarse fibers were extracted from the small pieces. After that the fat and unwanted materials were removed by boiling at 90 °C for a period of 10 h and finally it is dried in the dehydrator [38]. But this process only yields the short fibers [39]. Another technique is the grinding, the procedure involves soaking of bamboo culm without nodes for a period of 24 h. Then these drenced strips were cut into small pieces. After that the small bamboo chips were cut when passing the strips through extruders. With the help of high speed blender these chips were then grounded for 30 min to fabricate the bamboo fibers. Finally, dried into an oven for 72 h after the size separation of fibers [40]. Another similar method was rolling. In this process, the bamboo strips were soaked for 1 h in water and then passed through a rolling mill at low speed with some pressure. Then rolled strips were again soaked in for 30 min and separation of fiber is done using a blade. The oldest method is retting, in which the bamboo strips were soaked for long periods of time for about 3 days minimum, and then beaten and scraped with sharp blades [41].

3.2 Chemical Extraction Process

Most commonly used chemical method was retting with an acid or alkali. In this method, the bamboo strips were dipped into a NaOH solution at different normality mainly by 1 N concentration, as per many researchers heated around 70 °C for several hours [42, 43]. Treated strips were then passed through the press machine and then finally separated. After that it is then washed properly and dried in an oven. Lignin is also soluble in acidic solution; therefore some researchers also used trifluoracetic acidic [44]. To reduce the water content and lignin in the fibers, some chemical assisted natural retting method is also used. In this method, the bamboo slices were immersed into a $Zn(NO_3)_2$ solution at different concentrations for long duration at 40 °C temperature [45].

4 Lifecycle Assessment of Bamboo Polymer Composites

Lots of scientific studies have been performed on characterization of bamboo reinforced polymer composites that includes mechanical, thermal, fracture, water absorption, visco-elasticity, morphology, tribological, chemical and wear [40, 46–104]. Lifecycle assessment scrutiny has been performed for various composites [105–127]; but for the bamboo reinforced polymer composites it is very limited [128–132]. Li et al. [128] evaluated the glued-laminated bamboo's environmental impact on a life cycle assessment ground. The outcome shows that the processing of glued-laminated bamboo contributes remarkably to the eutrophication potential, acidification potential, global warming potential and photochemical ozone creation potential; whereas the resource depletion and ozone depletion are affected by urea-formaldehyde resin adhesive, amongst which urea was the major contributor. Recently in 2018, Chang et al. [129] utilized the life cycle assessment approach to investigate the production chains that produces plybamboo. They reported that the bleached glue-laminated bamboo boards have a lower environmental impact than their heat-treated counterparts. Gu et al. [130] in their study revealed that the bamboo fiber reinforced composites are generally more eco-friendly than the flax fiber reinforced composites. Earlier in 2003, Thwe and Liao [131] showcased the environmental effects on bamboo-glass/polypropylene hybrid composites. They specifically reported that the environmental degradation process of bamboo fiber reinforced composites can be delayed by adding a small amount of glass fiber. Hung et al. [132] provided the natural weathering properties of acetylated bamboo plastic composites and indicated that the durability and decay resistance of bamboo plastic composites can be enhanced through the acetylation process of the bamboo reinforcement.

5 Conclusion and Future Perspective

Lifecycle assessment scrutiny has been performed for various thermosetting and thermoplastic bamboo composites; but at the same time there is a whole lot of studies left to be done on the bamboo based natural matrix composites.

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Conflicts of Interest "There are no conflicts of interest to declare by the authors."

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Applications and Drawbacks of Bamboo Fiber Composites

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Abstract The plant fiber-reinforced polymer composites have been utilized broadly in various engineering fields in recent times, because of its comparative benefits such as sustainability and recyclability. They have shown interest in different fields of engineering, as it is the capability to provide lower weight materials against metallic and synthetic materials. In recent years, both synthetic and metallic materials are presented replaced with plant reinforced polymer composites in many automobile components manufacturing industries. Among the different types of natural fibers, bamboo is one of the most fast-growing renewable resources and possesses huge potential to utilized as feedstock material to the biorefinery. In this present investigation, a new wind turbine blades are fabricated from bamboo fiber reinforced polymer composites to improve the annual generation of electricity. Both structural and aerodynamic factors are examined as design parameters in the optimization process. The design of airfoil also employed in optimization procedures to enhance structural and aerodynamic characteristics from airfoil theory. Blade element momentum theory is applied to determine aerodynamic characteristics and classical laminate theory is

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used to calculate mass per unit length and stiffness of the section. A techno-economic model also developed and showed that there is a decrement in the cost of blade material. The results also depict that the structural, aerodynamic, and techno-economic performance of the newly developed wind turbine blade is enhanced as compared with conventional plastic.

Keywords Aerodynamic · Bamboo fiber · Epoxy nanocomposites · Structural · Techno-economic analysis · Wind turbine blade

1 Introduction

The utilization of synthetic fibers has controlled the present past of reinforcement application, whereas natural fiber reinforcement showed a good alternative to replace synthetic fibers from different applications [3]. Bio-based polymers and biodegradable plastic products from renewal sources could produce eco-friendly and sustainable products than the present market which is regulated from petroleum-based products [15]. Researchers have utilized both hard and softwoods to extract the fibers as reinforcement materials in many composite applications [3]. In certain developing countries, the plant fibers have crucial economic importance, such as cotton, jute, and sisal in some African, Bangladesh and Tanzania respectively [11]. The various nations where there is a lack of forest sources and crops from agriculture have been applied for the research and development of polymer-based laminates. Bamboo is one type of agricultural crop, which was for the development, and design of polymer laminates [4]. Bamboo fiber is observed as an abundant material in South America and Asia. In Asian, the fibers not been depicted full to its extent as it is noticed as nature-based material. These types of materials involved as the backbone for the social and economic background of society as used to take many months to cultivate.

Currently, the bamboo fiber is considered as an essential plant fiber with higher potential to utilized as reinforcement material in composite industries. Its mechanical characteristics, fiber extraction, variation in structural properties, modification in chemical constituents, and thermal characteristics create it versatile for application in polymer material company [16]. The various types of techniques have been developed by scientists for the extraction of bamboo fiber as reinforcement material in composites. The alkaline treatment is applied as a method for the extraction of fiber from bamboo and optimizes the bamboo fiber separation for the production of bamboo fiber-based polymer composites. The scientists studied the modifications possessed in the fine structure of bamboo fiber because of the treatment with different content of alkali solution [6]. Thermoplastic polymer and bamboo fibers blended laminates were manufactured, and thermal and microstructural characteristics of hybrid composites compared with pure polymers [27]. The trade and business of bamboo products as panels, household materials, decorating products have an informative impact on both economic and overall environment advancement.

The depletion of non-renewable energy sources has become a significant problem throughout the world. The production of renewable energy, usually the generation of power from wind observed as a vital energy source. It is noted that electricity produced from the turbine is proportionate to the swept volume of rotor blades. The large wind turbines tend to average wind speeds with increases in the height of the tower. In the year 1980s, conventional wind turbine sizes raised from approximately 50 kW with a diameter of rotor (10–15 m) as compared with conventionally 5 MW turbines with a diameter of rotor (120 m) [7, 21].

Presently, the design technique for the massive scale of the wind turbine blade is classified into two divisions as structural and aerodynamic performance. Both aerodynamic and structural performance affects the external geometry and internal configurations, respectively. The most common technique is to model outer shape, to improve the extraction of power and efficiency of structural characteristics. The architectural and aerodynamic optimization techniques have been preferred broadly in many investigations [8, 24]. Benini and Toffolo [1] preferred a method to optimize wind turbine by comprising a multi-objective algorithm and BEM (Blade Element Momentum) theory. Their motive is the potential trade-off within the annual production of energy and energy costs. Xudong et al. [25] conducted an optimization on wind turbine blades based on aero-elastic code and BEM theory to reduce the cost of energy. The design parameters of the wind turbine blade were a twist, chord, and thickness dispersion with a fixed diameter of the rotor. The structural optimization for wind turbine blade design also considers stability, strength, vibration, and price [17, 26]. The finite element method (FEM), which can transform factors like materials characteristics, angle of the fiber, specific thicknesses of layer, and internal geometry configuration from parametric modeling process. One method to optimize wind turbine blades to decrease their total weight. The lightweight blade not only reduces the load for complete turbine systems but also contains certain remunerative advantages. Hu et al. [10] investigated structural optimization to decrease the weight of the blade and the cost of material. Liao et al. [14] applied FAST (wind turbine blade software) and PSO (Particle Swarm Optimization) method to determine structural characteristics and decrease the total weight of the blade, respectively. Zhu et al. [28] comprised the PSO method and FEM to minimize the total weight of 1.5 Mega Watt (MW) blade. Zhu et al. [29] applied FEM for structural analysis, BEM concept for aerodynamic examination, and multi-target genetic procedure to verify the effectiveness of optimization technique. The design parameters were twist and chord distribution, several layers, location of shear webs and spar cap to minimize blade weight and maximize annual energy production.

Generally, the polymers composites reinforced with glass fibers are mainly applied for the fabrication of wind turbine blades. The polymers incorporated with carbon fiber has improved the structural characteristics of the blades as well as it attained higher cost than other synthetic and natural fibers [5, 18]. For the architectural design challenge, tip deflection and structural stability should meet the necessary design constraints—the aerodynamic problem to express higher energy from the mean speed of wind regions. The present investigation aims to design a technique combining structural and aerodynamic optimization on bamboo fiber wind turbine blades applied in lower wind speed regions. By enhancing structural and aerodynamic characteristics of the wind turbine blade, the manufacturing process and shape of geometry are fixed as design parameters. More necessarily, initiating airfoil design in the process of optimization could grant to both structural and aerodynamic characteristics. The motive is to deal with the design procedure to collect optimal characteristics of wind turbine blades mainly focused on airfoils. Every airfoil is highly influenced by structural and aerodynamic performances of wind turbine blade section, due to optimization concentrates on each part of the blade. The primary target is to enhance the structural and aerodynamic performance of the fabricated wind turbine blade. This chapter investigates on blade sections fabricated from bamboo fiber polymer composites and airfoils design simultaneously containing structural and aerodynamic combined optimization and techno-economic analysis.

2 Materials and Methods

2.1 Fabrication of Bamboo Fiber/Al-SiC Epoxy Nanocomposite for Wind Turbine Blade

Firstly, bamboo fiber was supplied from Composite Research Center, Ambattur, India. The Fibers was soaked in sodium chloride (NaCl) solution for 48 h under atmospheric condition (40 ± 3 °C temperature and 1 atm pressure). After the soaking process, the fibers were treated with 0.1 N NaOH solution. Finally, treated bamboo fiber was converted into nano form using industrial grinder and nanoparticles separated from nanomesh (average size 50 nm), termed as bamboo nanofibers (BNF).

In step 2, aluminum alloy (Al6061 1 μm) and silicon carbide (SiC, 150 μm), purchased from Carborundum Universal Kochi, India, and the particles are combined in horizontal type of high energy ball mill, by selecting balls to powder weight ratio, milling speed and time as 10, 200 rpm and 180 h respectively. The nanoparticles of an average size of 52.74 nm were separated from nano sieve. Two different types of epoxy nanocomposites were fabricated, as BNF and BNF/Al-SiC. In these type of nanocomposites, the matrix is an epoxy polymer (LY556), and hardener (HY951) both are comprised in the ratio of 10:1 by reinforcing either 10 wt.% of BNF or both BNF/Al-SiC. An ultrasonicator probe has been utilized to achieve uniform dispersion of nanoparticle in epoxy polymer under an ice bath to avoid overheating. The sonication was performed for 120 min, frequency of 24 kHz, and electrical power of 400 W as per the manufacturer standard. After the fabrication of epoxy nanocomposite, the sample was placed in a muffle furnace for 24 h under 60 ± 2 °C to remove the residual stress and moisture content.

2.2 Nanocomposites Characterization

The mechanical characteristics of epoxy hybrid nanocomposites were determined in terms of tensile and Rockwell hardness. The tensile property of hybrid epoxy nanocomposites was tested in Tinius Olsen (H-50kN), Universal testing machine according to ASTM D 3039/3039 M-17 under the crosshead speed of 2 mm/min. The test was performed at room temperature (30 ± 2 °C). Rockwell hardness of the composite materials also measured using Wilson Wolpert Hardness Tester, according to ASTM D 785-08 standard with an indenter load of 3 kg and dwell for 15 s. The density of the epoxy hybrid nanocomposites was measured using ASTM 1505-10 standard under room temperature and atmospheric pressure. The characteristics of a new type of composite materials are shown in Table 1.

Table 1 Material properties of BNF epoxy, and BNF/Al-SiC epoxy nanocomposite material as compared with glass fiber epoxy

Property	BNF epoxy	BNF/Al-SiC epoxy	Glass fiber epoxy
Density in kg/m^3	1139.52	2377.68	2069.47
Superficial hardness in kgf/mm^2	29.02	106.23	92.46
Elastic modulus in x-direction (E_x) in MPa	1404.00	3942.00	3431
Elastic modulus in y-direction (E_y) in MPa	1047.60	1868.40	1626.2
Elastic modulus in z-direction (E_z) in MPa	1047.60	1868.40	1626.2
Shear modulus in xy-direction (G_{xy}) in MPa	594.00	842.40	733.2
Shear modulus in yz-direction (G_{yz}) in MPa	442.53	627.59	546.23
Shear modulus in xz-direction (G_{xz}) in MPa	594.00	842.40	733.2
Tensile strength in x-direction (T_x) in MPa	441.56	730.13	635.49
Tensile strength in y-direction (T_y) in MPa	17.55	29.02	25.26
Tensile strength in z-direction (T_z) in MPa	17.55	29.02	25.26
Shear stress in xy-direction (τ_{xy}) in MPa	34.15	85.71	74.60
Shear stress in yz-direction (τ_{yz}) in MPa	19.90	49.97	43.49
Shear stress in xz-direction (τ_{xz}) in MPa	34.15	85.71	74.60

Table 2 Geometry of baseline wind turbine blade

Span position in m	Twist in deg	Chord in m	Thickness in %	Airfoil
2	18	2.5	100	Circle
14.7	10.5	3.64	45	DU00-W2-401
18.5	7.3	3.21	40	DU00-W2-350
27.8	2.9	2.46	35	DU97-W2-300
52.3	−1.65	1.18	30	DU91-W2-250
67	−1.7	0.04	25	DU93-W2-210

Table 3 Characteristics of wind turbine

Class of wind	III
Power (rated) in MW	5
Speed of wind (rated) in m/s	9
Wind speed (cut in) in m/s	3
Wind speed (cut out) in m/s	20
Blade number	3
Ratio of tip speed (design)	10.7
Diameter of rotor in m	122.3
Type of control	Various speed and pitch
Power coefficient (maximum)	0.463
Pre-bend under tip of blade in m	2.5

3 Model of Wind Turbine Blade

A general 5 MW horizontal axis low-speed wind turbine blade has been selected for a present this investigation. The wind turbine blade fabricated from BNF epoxy, and BNF/Al-SiC epoxy has an approximate weight of 9600 kg, and 13,552 kg respectively. The wind turbine blade baseline is explained from the distribution of twist, chords, and chosen airfoils. The details of each factor influenced by the wind turbine blade are shown in Tables 2 and 3.

4 Aerodynamic and Structural Model Description

Glauret [9] described the BEM concept comprising the blade element theory with momentum theory. The momentum theory targeted to examine both tangential and axial inducing speed by initiating angular and axial induction parameters—blade element theory assigned to estimate the aerodynamic load effecting on every element of the blade. The induced speed affects the angle of attack of the airfoil, which is acquired in the wind turbine blade and hence influences the aerodynamic loads. The

BEM methods provide a method to determine the aerodynamic characteristics of blade elements using the iteration process. They have an effect on incited speed around the tip of the blade. Hence, Prandtl's tip loss elimination has been included to simulate the rotor of a wind turbine blade is employed [26]. To collect the aerodynamic characteristics of a wind turbine blade, both drag and lift constants of an airfoil in every section of the blade is essential to adopt. Rfoil software has been applied to design the airfoil characteristics, due to XFoil does not have good agreement with tunnel experiments under a higher angle of attack. The classical laminate concept (CLC) has been introduced in the design technique to determine the characteristics of composite material blades. CLC model can evaluate the overall effectiveness of a structured wind turbine blade fabricated from composite laminates. Bir [2] generated a pre-processor PreComp software using FORTRAN to determine the blade structural characteristics, which mainly depend on CLC. The PreComp requires certain input documents as interior architectural layout, the shape of the blade, and composite materials characteristics. Moreover, PreComp offers specific interior geometry and a conventional layup of materials. In this investigation, PreComp is used to determine the structural features of different sections of the blade.

The Blade element momentum code is confirmed among the aerodynamic design of the wind turbine blade with 61.5 m (length) and rated power of 5 MW. Aerodynamic characteristic is performed by employing wind speed between 3 and 20 m/s and tip speed ratio of 10.6 [26]. The density of air considered as 1.215 kg/m^3 whereas the tilt and cone angles of the blade were eliminated. Aerodynamic performance of NACA series airfoils collected by reviewing RFoil software for particular Reynold's number. The power graph evaluated from the BEM code shows the rated wind speed as 8 m/s. Hence prediction from blade element momentum code for present investigation contemplated as acceptable. CLC code employed in PreComp is confirmed at structural characteristics of geometry and layup scheme of a wind turbine blade due to the power distribution of blade areas as restricted. All stiffness for every direction and mass per unit length of wind turbine sections is estimated by employing blade shape with length ranging from 12.4 to 61.5 m. Figure 1a, b displays the comparison between mass per unit length and stiffness distribution estimated by CLC code employed in PreComp. As observed in Fig. 1, the distribution of stiffness in every section and weight per length are in the right consistency with the modeled wind turbine composite blade.

5 Description of the FE Model

Finite element design of conventional wind turbine blade fabricated from APDL (ANSYS software) using BNF epoxy, and BNF/Al-SiC epoxy, as explained in the above section. The maximum deflection in blade tip for BNF epoxy and BNF/Al-SiC epoxy are estimated as 5.15, and 3.97 m. These blades tip deflection is comparably lower than the conventional ones, as observed from Yang et al. [26] under the rated speed of 8 m/s.

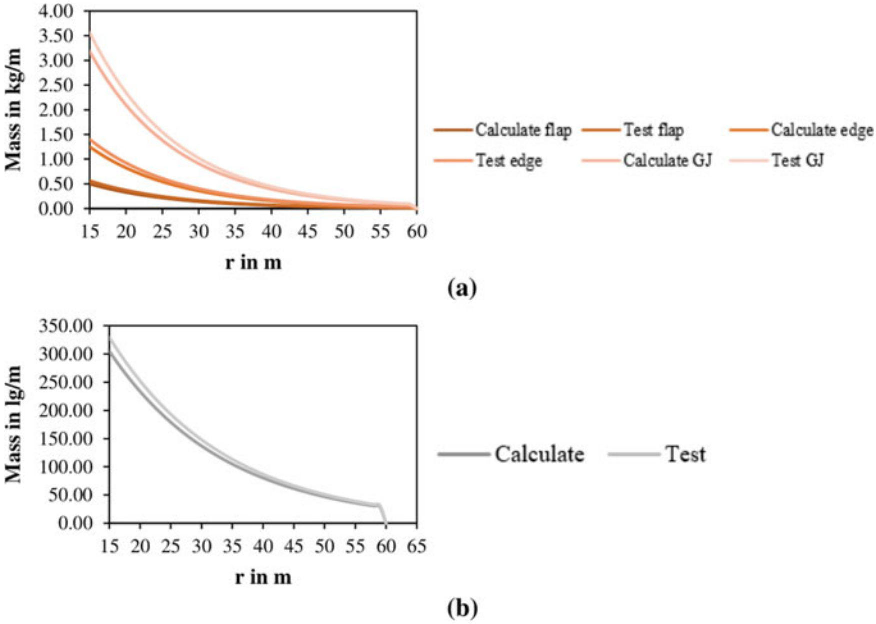

Fig. 1 Comparison between mass per unit length and stiffness distribution collected original blade and CLC code

6 Optimization Process and Modeling

This investigation targeted to suggest the combined aerodynamic and structural optimization techniques to enhance the characteristics of wind turbine blades applied in lower wind speed regions. Aerodynamic characteristics of blades acquire lower load and good AEP (Annual Energy Production). Structural features require smaller deformations and lower weights of the wind turbine blade. The architectural and aerodynamic characteristics are influenced by each other, and hence, the optimization technique should be combined. Airfoil theory is used to form specific designs of airfoils, and quantities of chord and twists were estimated from BEM simultaneously. Then, CLC and BEM concepts are used to determine structural and aerodynamic characteristics for every cross-section and can be optimized separately.

PSO method is one of the popular ways which broadly applied to resolve the issues and can determine overall optimum conditions [23]. The design procedure initiates the PSO method, finite element software (ANSYS), RFoil, BEM, and PreComp code. Three modules combined in particle swarm optimization procedure by employing MATLAB software, a structural examination from PreComp, aerodynamic analysis depend on RFoil and BEM code and validation of extreme strength from ANSYS. Figure 2 displays the optimization flow chart using a particle swarm optimization technique. The aerodynamic parameters are applied to regulate the profiles of the airfoil and structural parameters to control the number of layers and configuration in

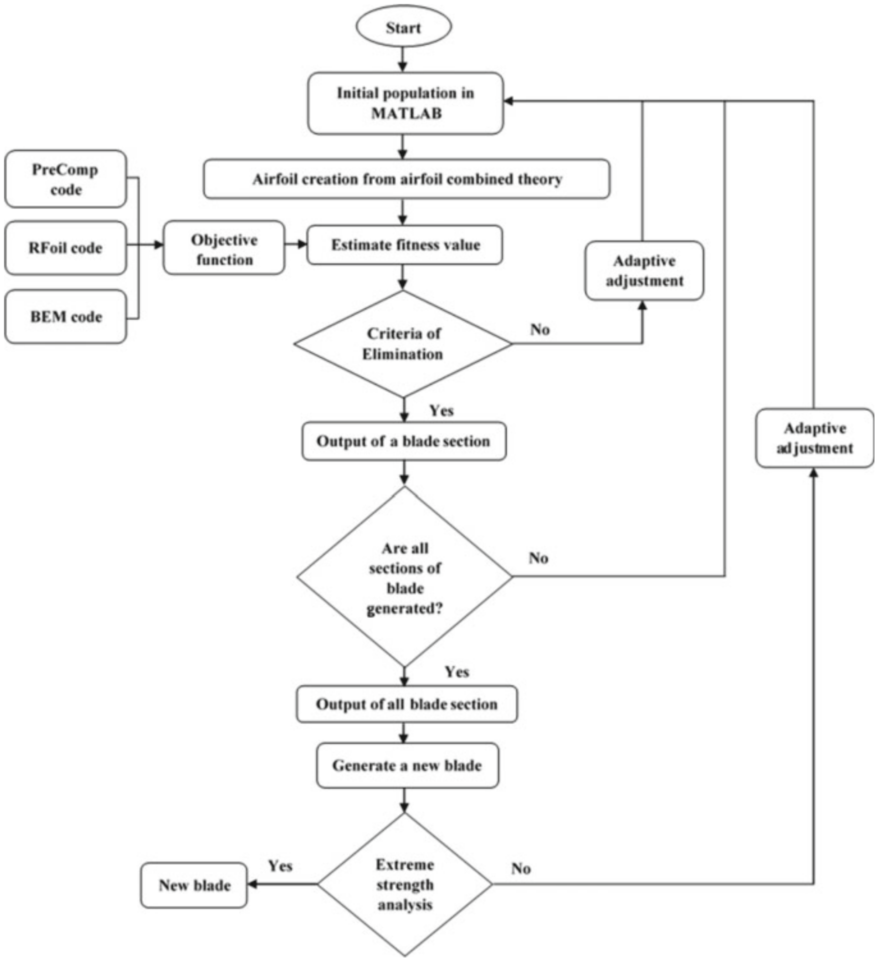

Fig. 2 Optimization process flow chart

every section of the wind turbine blade. The BEM concept is applied to estimate the twist and chord for each airfoil in the design procedure and determine the thrust and torque of each section of the wind turbine blade. Also, the PreComp code selected to determine the stiffness and weight of wind turbine blade parts. The factors such as airfoil, twist angle, length of the chord, interior configuration of blades, material properties and distribution of layup. A wind turbine blade profile made from APDL and performed a finite element method analysis using ANSYS software.

7 Wind Turbine Blade Performance Simulation and Modeling

The power produced by wind turbines mainly depends on the speed of the wind, mechanical, aerodynamic, electrical characteristics, and swept area. A simple mathematical equation generated from MATLAB software to develop a proposed design procedure [12]. The generated model for a wind turbine can be employed in the following three subdivisions, such as mechanical power (mechanical performance), power coefficient (aerodynamic performance), and electrical performance.

7.1 Subsystem of Mechanical Power

The mechanical power of the wind turbines can be determined from Eq. (1)

$$P_m = \frac{1}{2} \times C_p \rho A v^3 \tag{1}$$

where P_m is the mechanical power of wind turbine, A is swept area of the wind turbine, and C_p is the power coefficient of wind, ρ is air density in kg/m^3, and v is the speed of wind in m/s. Torque coefficient (C_Q) and mechanical torque (T_m) determined from Eqs. (2) and (3), respectively.

$$T_m = \frac{P_m}{\omega} = \frac{1}{2} \times C_p \rho A v^2 \left(\frac{R}{\lambda}\right) \tag{2}$$

$$C_Q = \frac{C_p}{\lambda} \tag{3}$$

7.2 Coefficient of Power (Aerodynamic Performance)

The coefficient of power (C_p) depicts the amount of power that can be developed from the wind. C_p is determined by using Eq. (4) [22]:

$$C_p = C_1 \left(\frac{C_2}{\lambda} - C_3 \beta - C_4\right) e^{-\frac{C_5}{\lambda_1}} + C_6 \lambda \tag{4}$$

where $C_1 = 0.5176$, $C_2 = 116$, $C_3 = 0.4$, $C_4 = 5$, $C_5 = 21$ and $C_6 = 0.0068$ are the constant coefficients, β is pitch angle and λ is tip speed ratio [13]. Speed of wind can be calculated from Eq. (5)

$$\lambda = \frac{R \times \omega}{v} \tag{5}$$

where ω is the rotational speed of wind turbine in rad/s, R is the radius of a wind turbine in m, v is the speed of wind in m/s. The factor λ_1 can be expressed from Eq. (6)

$$\frac{1}{\lambda_1} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{6}$$

7.3 Electrical Energy Using Generator

The following procedure in the design procedure is converting mechanical into electrical energy. A permanent magnet generator is designed with six magnetic poles and considered efficient even for the lower speed of rotation. The subsystem has considered for iron, copper losses, electrical, frequency, induced current, induced voltage, efficiency, and total electrical power. Table 4 represents the mathematical formulations to determine the electrical power. All mathematical formulations are shown in MATLAB scriptlet for the determination of total electrical energy [22].

Table 4 Formulations for various factors applied in simulation

Factor	Mathematical formula	Factor	Mathematical formula
Fitch factor	$k_p = \sin\left(\frac{180 P\eta}{2Q}\right)$	Induce current	$I = \frac{P_m}{3 \times E_{LN}}$
Distribution factor	$k_d = \frac{\sin(q\frac{\alpha}{2})}{q \times \sin(\frac{\alpha}{2})}$	Copper losses	$P_{losses}^{Cu} = 3RI^2$
Winding factor	$k_w = k_d k_p$	Iron losses	$P_{losses}^{Fe} = k_h B_{max}^2 f_{elec} + k_c B_{max}^2 f_{elec}^2 + k_e B_{max}^{3/2} f_{elec}^{3/2}$
Mechanical frequency	$f_{mech} = \frac{\omega}{2\pi}$	Total losses	$P_{losses}^{total} = P_{losses}^{Cu} + P_{losses}^{Fe}$
Electrical frequency	$f_{elec} = \frac{\omega}{4\pi} \times p$	Net power from generator	$P_t = P_m - P_{losses}^{total}$
Induced phase voltage	$ELN = \sqrt{2}\pi f_{elec} n\phi k_w$	Efficiency of generator	$\eta = \frac{P_t}{P_m}$
Induced line voltage	$ELL = \sqrt{3}E_{LN}$		

8 Techno-Economic Formulation

A techno-economic model offers price benefit of dissimilar materials or techniques which could be applied to evaluate the feasibility of new schemes depend on technical viability and economic possibilities. Many frameworks and guidelines for techno-economic examination are utilized to present investigation, containing changes to consider for cost parameters combined in wind turbine blades. Techno-economic design concentrates on materials (prices of procured materials, schedule of laminates, scraps, consumables, adhesives), fabrication process (cost of equipment and tooling, infusion factors, time for curing, labor, overhead and electricity price), and disposal (prices for landfill disposal and any recycling opportunity for thermoset polymer wind turbine blades). The techno-economic model established to consider the cost of unique designs (varying blade materials). The assumptions formed during the advancement of the techno-economic model, which did not affect the comparison within different types of polymers utilized in the fabrication of wind turbine blades. A conservative method for composite laminate design considered from the NREL blade and resulting price and weight of wind turbine blade in this designed model may be quietly lower than conventional blades.

The techno-economic model is applied to fabricate blade, which contains bamboo nanofiber, aluminum silicon carbide, polymer systems (resin and hardener), and blade fabrication consumables. Generally, the prices of the material quoted in weight, hence computing the total weight of every component applied in the blade. The model assumes that wind turbine blades fabricated from the wet layup molding process, as this, along with the prepreg lamination process, consider for above 90% of wind turbine blade fabrication throughout the world [20].

However, the waste materials quantities were assumed to be similar for these polymer systems. In the same manner, the 5 wt.% of epoxy nanocomposite material applied in the spar car because the cutting of fabric depends on the design of the wind turbine blade. From recent research, it was presumed that both the wind turbine blades have a similar schedule of laminate. The schedule of laminate for the NREL wind turbine blade developed depends on the actual blade model shown in Fernandez et al. [7]. A little modification to consider for the assumption that wind turbine blades made entirely from BNF and BNF/Al-SiC without any synthetic fibers in the spar caps. The material cost, total weight, and density of these three types of nanocomposite materials ranging between \$100–\$1000, 9600–14,000 kg and 1120–2175 kg/m^3 respectively, which is comparatively lower than conventional equipment (cost of \$2000, the total weight of 14,500 kg and density of 2200 kg/m^3). Material bills show information and depict the comparison of relative prices within BNF epoxy, BNF/Al-SiC epoxy, and the baseline conventional materials. The fabrication process steps with tooling prices, laborer numbers, consumables, capital equipment costs and power requirements for the BNF epoxy, and BNF/Al-SiC epoxy nanocomposite wind turbine blades are shown in Table 5 [17].

The annual fabrication rate of 200 blades depends on labor time per blade and cycle. Presently, this is polymer-agnostic input in the model; moreover, an outcome

Table 5 Fabrication price for model affects all the processes

Factor	Quantity
Annual volume of production	200 blades
Length of wind turbine blade	61.5 m
Labor direct costs	$25 per hour
Materials cutting charge @ 4 labours per station, 40 non-gating hours, and 148 kW of power	$306,000
Trailing and leading edge shear web @ 6 labours per station, 27 non-gating hours, and 310 kW of power	$204,000
Others (spar cap, both low and high pressure skin, assembly, demold, trim, overlay, postcure, root tools and hardware, surface preparation, paint, surface finish, inspection and shipping preparation) @ 4 labours per station, 50 non-gating hours and 172 kW of power	$10,143,800
Effects on costs and salary	32.3%
Mean labor and downtime of equipment	18%
No. of days of working per year	300 annually
No. of hours of working per day	24
Rate of recovery	12%
Recovery life of equipment	120 months
Recovery life of building	384 months
Capital period of working	90 days
Electricity cost	$0.08 per kWh
Building space cost	$700 per m^2
Inflation (expected)	0.48%
Rate of tax (corporate)	18%
Development of research	1.20%

of faster gatting times, the number could increment for thermoset blades. The input factors computed for single processes and stations, designed model drags material information from variable prices—direct labor, material, utility, and fixed prices—tooling, maintenance, equipment, capital cost, and building.

The wind turbine blade and iterative optimization procedure are displayed in Fig. 3. It could be observed the optimum outcomes converged when iteration numbers attain 140 with 16.256 s of computational time.

9 Results of Airfoil Design

After the completion of the optimization procedure, the output contains the length of the chord, airfoils, internal structural configuration, twist angle, and distribution of layup for every section of the wind turbine blade. The aerodynamic characteristics

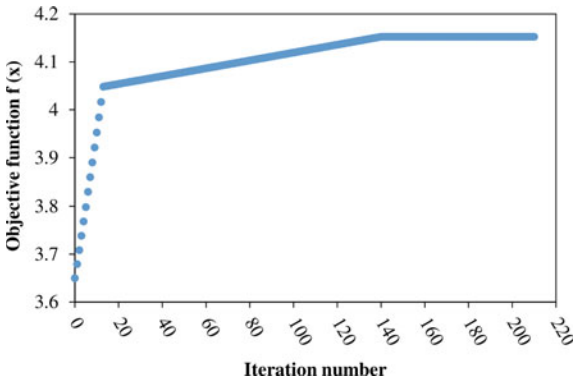

Fig. 3 Iterative course for every section blade under the optimization process

and designed airfoils are compared with NACA 8412 airfoil series shown in Fig. 4a–e. Figure 4a–e display the ratio of lift to drag and profile of airfoils at different thickness compared under actual airfoil in similar operating case.

The NACA 8412 airfoils and lift to drag coefficient of the airfoil in every angle of attack, lift to draft ratio of the optimum airfoil at 25% of thickness lower than actual airfoil under the 8–12 angle of attack. Aerodynamic performance of airfoils outcome in lower thrust and more abundant torque under the optimum twist.

10 Structural and Aerodynamic Design Outcomes of Wind Turbine Blade Section

The internal configuration, distribution of layup, and aerodynamic performance for 23 sections of the wind turbine blade are completed after the process of optimization, which explains all parts of the wind turbine blade. Figure 5 displays the optimum interior configuration of a wind turbine blade at a thickness of 30% and Table 6 exhibits information. The new chord of wind turbine blade under the thickness of 30% compared to the actual one reduces 0.0215 m. Optimum twist increments are 1.6° than the actual one. Smaller chord will tend to decrease thrust and weight. New twist quantity will warranty the airfoil (new) utilized in section may gain more power from wind resources [26]. Table 6 exhibits the structural and aerodynamic characteristics performance of the blade section under 30% of the thickness. In aerodynamic characteristics, the torque of new blades is higher and thrust is lower than actual. It states that the blade section can generate more power and more loads than real ones. From structural performance, stiffness of edge, flap, and GJ wise directions are enhanced and weight per unit of the section is lower than the actual one. Fewer forces and more considerable stiffness will lead to smaller deformations.

Moreover, lower weight can reduce gravity force and improvement in fatigue life. Thrust and torque in ultimate case displays the torque of new wind turbine blade improves and thrust reduces around 26.23% as compared with that of an actual wind

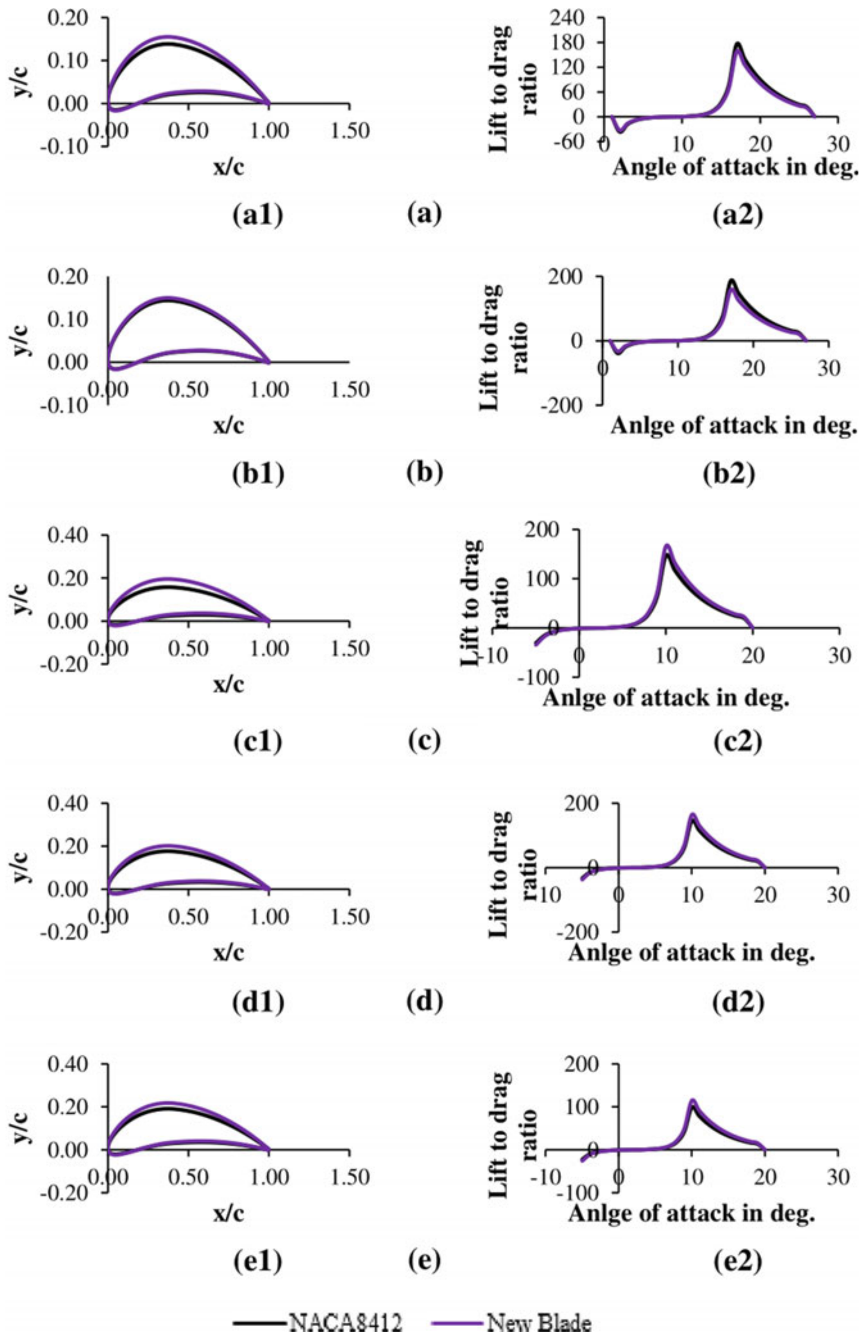

Fig. 4 Comparison of lift to drag ratio and airfoil profiles between actual and optimum condition **a** 40% thickness and Re 5×10^6, **b** 35% thickness and Re 6×10^6, **c** 30% thickness and Re $\times 10^6$, **d** 25% thickness and Re 4×10^6, and **e** 21% thickness and Re 3×10^6

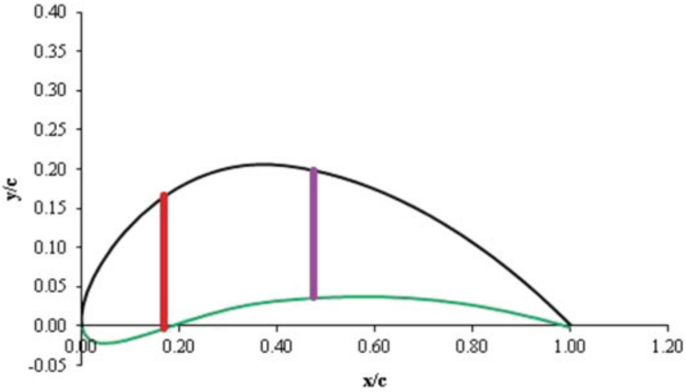

Fig. 5 Structural configuration of wind turbine blade sections under 30% of the thickness

Table 6 Number of layup and configuration details of 30% thickness section of wind turbine blade

	Actual	BNF epoxy	BNF/Al-SiC epoxy
Chord in m	2.45	2.68	2.95
Twist in deg	2.82	3.08	3.39
Width of spar in c^{-1}	0.64	0.71	0.78
Width of web in c^{-1}	0.48	0.52	0.57
UD thickness of spar at suction surface	57.20	62.46	68.87
UD thickness of spar at pressure surface	57.20	62.46	68.87
UD thickness of trailing edge at suction surface	24.96	27.26	30.05
UD thickness of trailing edge at pressure surface	24.96	27.26	30.05
M in kNm	35.10	38.33	42.26
T in kN/m	11.72	12.80	14.11
Weight in kg/m	238.26	260.19	286.85
EI_1 in GPa	0.29	0.32	0.35
EI_2 in GPa	0.93	1.01	1.11
GI in GPa	0.55	0.60	0.67
M_ex in kNm	1183.06	1291.90	1424.32
T_ex in kN/m	451.70	493.26	543.82

turbine blade. About 4.17% improvement when compared with recent literature, Yang et al. [26]. The comparison shows that a new wind turbine blade in extreme cases has higher performance than the actual one.

11 Results of Blade Design

The twist angle and length of the chord distribution of new wind turbine blade required from the optimization process are displayed in Fig. 6a, b, respectively. The optimized wind turbine blade areas are ranging between 45 and 25% thickness sections. The length of a chord of new wind turbine blade reduces slightly, due to the design constraints acquires balance cross-sectional stiffness not lower than an actual blade. The decrement of a chord can tend to lower weight and lighter thrust for wind turbine blades.

Twist of new wind turbine blades in all parts improves because of a new type of airfoils chosen in the design technique. With the increment in a twist, airfoils of every wind turbine blade could generate in the optimum angle of attack and warranty that the wind turbine blade has higher aerodynamic performance. As displayed in Fig. 7a, b the width of the shorter spar requires thicker layers to consider structural constraints like the area from the wind turbine blade under 20 m, around span as compared with conventional wind turbine blade. From 20 to 67 m along the span of

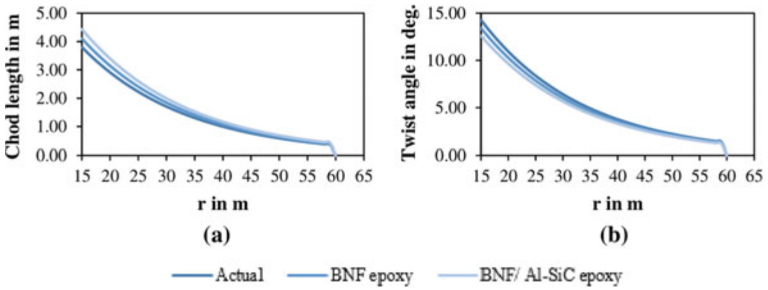

Fig. 6 Comparison of twist angle and chord length distribution between BNF epoxy, BNF/Al-SiC epoxy, and actual wind turbine blade

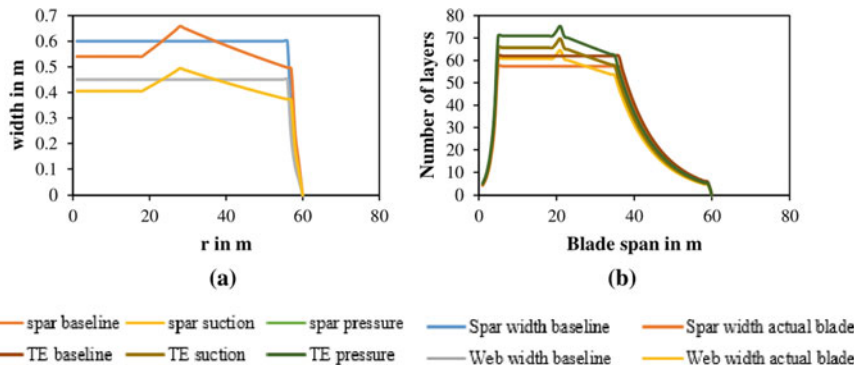

Fig. 7 Distribution **a** web and spar width of baseline and actual wind turbine blade and **b** thickness of baseline and actual wind turbine blade

a wind turbine blade, spar width of the optimum blade and layer spar of optimum blade shorter and thicker than conventional wind turbine blade, respectively. The primary reason is the trailing edge addition, which enhances section characteristics and also has a lower effect on total weight.

12 Structural and Aerodynamic Characteristics of a Wind Turbine Blade

Figure 8a–c exhibit edge, flap and torsional stiffness distribution for new (BNF epoxy, and BNF/Al-SiC epoxy) and actual wind turbine blade. The bending stiffness (section) of the new wind turbine blade improves as compared with the actual one, specifically in the range of length between 13 and 30 m. Hence, the new wind turbine blade has a higher capability of deformation resistance. Figure 8 displays the part of the weight per unit length for the actual and new wind turbine blade. The part of weight per length of the wind turbine blade reduces slightly. The primary reason is the constraint acquires balance stiffness not lower than the actual blade. The total weight of new wind turbine fabricated from BNF epoxy, and BNF/Al-SiC epoxy nanocomposites, decrease by 34.37%, 11.85%, and 6.07% respectively as compared with the actual blade.

Figure 9a, b exhibits thrust and torque distribution for both new and real wind turbine blades. The outcome display the torque of every new wind turbine blade, which is higher than actual, also offers a high amount of generation of electricity. The thrust of every new wind turbine blade lower than real, which reduces aerodynamic

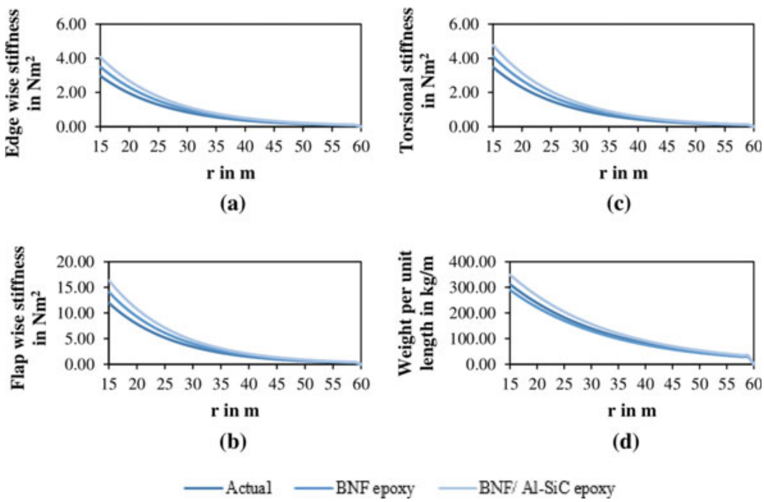

Fig. 8 Structural performance distribution between the actual blade and new blade under optimum condition **a** edge-wise, **b** flap-wise, **c** torsional stiffness and **d** weight per unit length

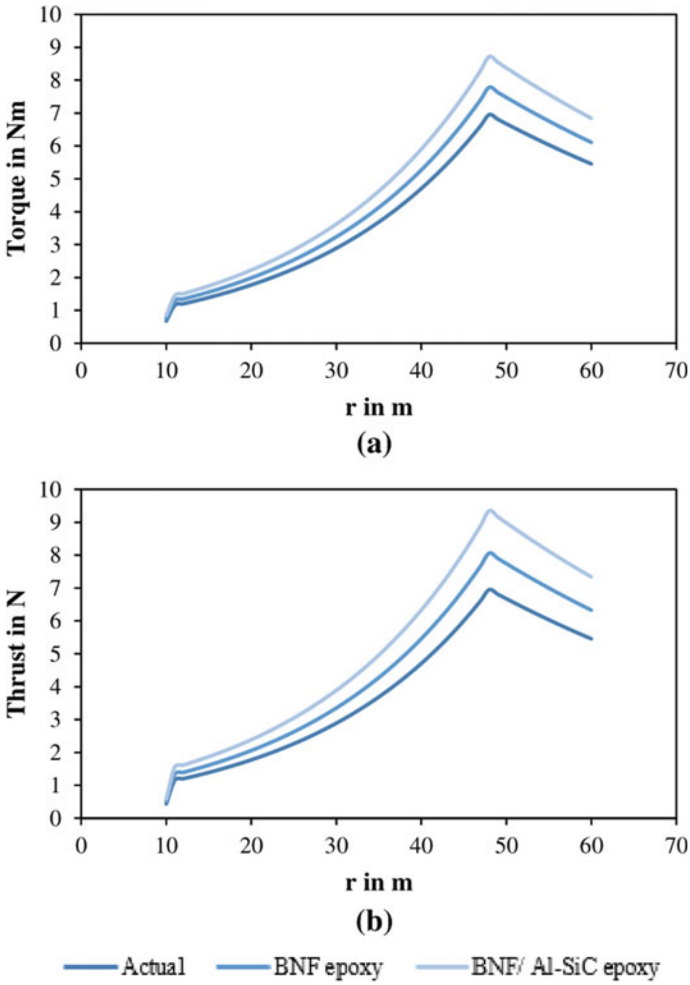

Fig. 9 Thrust force and torque distribution between actual and new wind turbine blade under optimum condition

forces depicting the rotor from wind sources. Figure 10a displays a comparison of power within actual and optimum. While comparing with a real wind turbine blade, the new blade attains rated power under 7.6 and 10.4 m/s lesser than the actual blade. Hence, a new wind turbine blade has a higher performance at the lower speed of the wind and can generate more energy than the real wind turbine blade. The comparison is given in Fig. 10b exhibits that generation of electricity of new wind turbine blade is higher than the actual one. With a yearly average speed of wind of 7 m/s, annual energy generation of blade fabricated from BNF epoxy, and BNF/Al-SiC epoxy nanocomposites are 9.12 GW, and 9.06 GW, with an increment of 9.51%, and 2.75% respectively as compared with existing literature from Yang et al. [26]. The outcomes

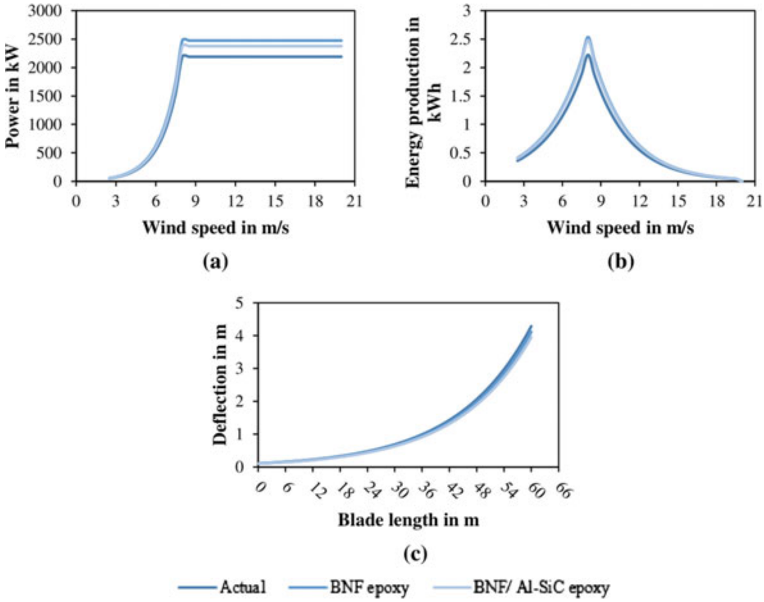

Fig. 10 Comparison of new wind turbine and conventional blade under optimum condition **a** power in kW, **b** energy production in kWh and **c** blade deflection in m

display that a new wind turbine blade has a higher aerodynamic characteristic than actual in lower wind speed. Figure 10c shows a comparison of wind turbine blade deformation between real and newly developed wind turbine blades.

The deflection of a new wind turbine blade fabricated from BNF epoxy and BNF/Al-SiC epoxy nanocomposites is 3.93 m and 3.76 m, which has 27.15%, 30.62%, and 32.77% respectively than recent literature observed in Yang et al. [26]. By employing 2.5 m (pre-bend) under the tip of the blade, real deformations of newly developed blade fabricated from BNF epoxy, and BNF/Al-SiC epoxy nanocomposites has decreased by 4.37 m, 4.26 m and 4.18 m as compared with recent literature by 7.02%, 9.38% and 12.11% respectively. Hence, the new wind turbine blade has higher characteristics in avoiding collisions within the tower and the tip of the blade.

As observed in Fig. 11a, b Tsai-Wu parameters prevailed in 3rd ply of wind turbine blade eliminates first skin, fabricated from polymer nanocomposites (BNF epoxy, and BNF/Al-SiC epoxy). The outcome display that the new wind turbine blade has higher performance in failure criteria due to the aerodynamic performance and structural efficiency.

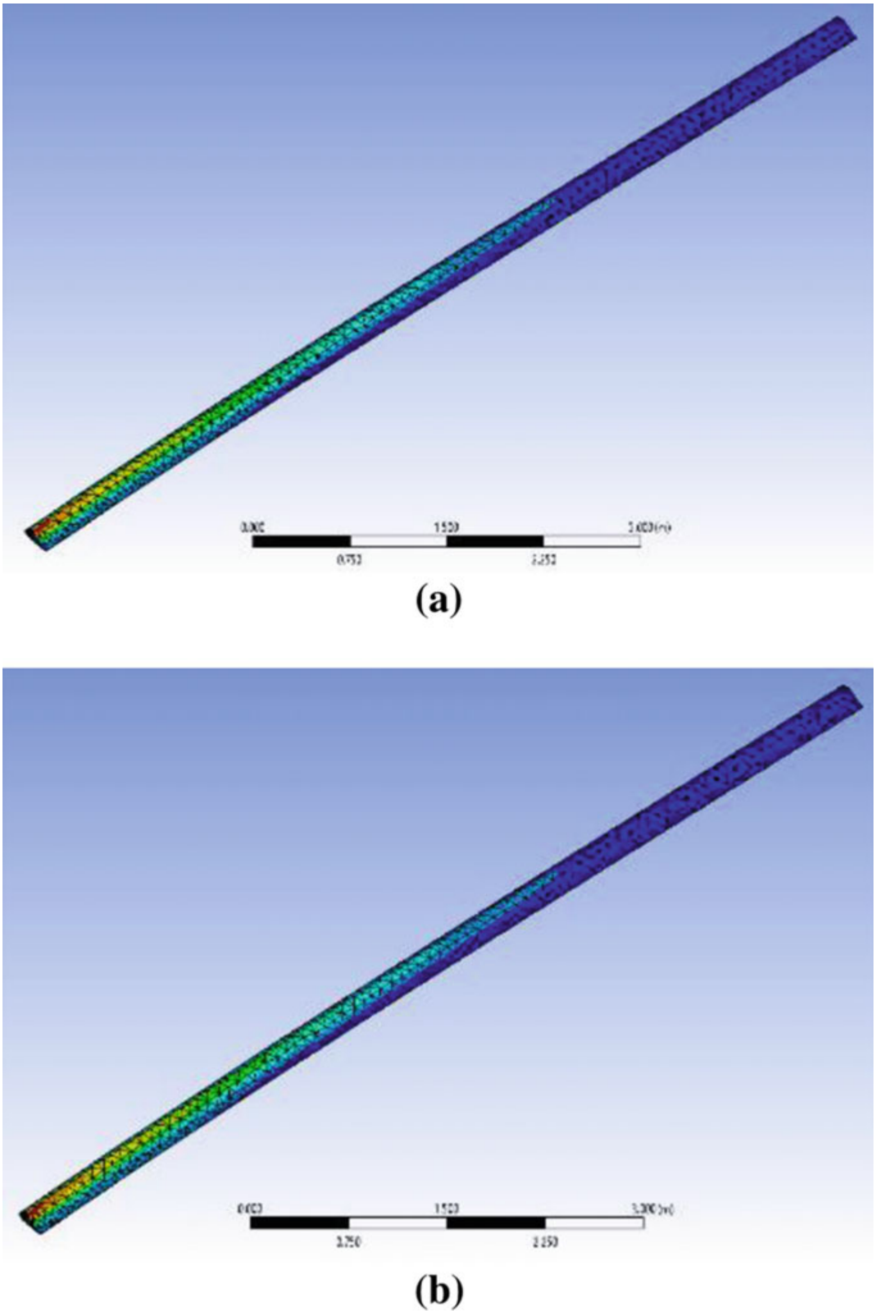

Fig. 11 Tsai-Wu failure parameters of the new wind turbine blade **a** BNF epoxy, and **b** BNF/Al-SiC epoxy

13 Techno-Economic Analysis

The price of the wind turbine blade of length 61.5 m is estimated using techno-economic model as 12.41 \$/kg for epoxy polymer which is slightly lower than the expected price for conventional wind turbine blade manufacturer in the United States of America and signify a 2.3% of decrement in fabrication cost when compared with traditional material of blade shown in Table 7. The nanocomposite materials and direct labor charges are the factors for the contributors to wind turbine blade price. The cost of scrap materials contains 10.6% of materials cost and 3.6% of total manufacturing price with the effect of maximum savings from reduced wastes and higher tolerances, by producing the condition for automation during the fabrication process.

The influence of economic scales are perceived with the same trends down to 200 blades annually (approximately) and within the 200 and 1000 wind turbine blades, the minimal decrement in the total cost. Furthermore, the smaller fabrication of 100 blades, an increment in the price of blades over the scenario of baseline (200 blades annually) by 24%. These observations present the model which does not exhibit any bias in huge-volume fabrication run. Hence it is predicted that the material price occurs in the total amount of the wind turbine blade. These outcomes are similar to the results observed by Murray et al. [17] and Schubel [20].

Table 7 Cost comparison of wind turbine blade fabricated from BNF, and BNF/Al-SiC epoxy nanocomposites

Cost	BNF epoxy	BNF/AlSiC epoxy	Conventional material
Cost of capital	\$36,036.04	\$36,036.04	\$37,837.84
Overhead labour cost	\$11,727.71	\$11,727.71	\$12,314.10
Maintenance cost	\$3411.69	\$3411.69	\$3582.27
Building cost	\$9595.39	\$9595.39	\$10,075.16
Tooling cost	\$4477.85	\$4477.85	\$4701.74
Equipment cost	\$5757.24	\$5757.24	\$6045.10
Utility cost	\$4051.39	\$4051.39	\$4253.96
Direct labour cost	\$69,939.77	\$69,939.77	\$73,436.76
Material cost	\$15,580.77	\$80,570.93	\$80,399.48
Total Cost	\$160,577.85	\$225,568.01	\$232,646.41

14 Conclusion and Drawbacks

This investigation adopted a technique for the fabrication of wind turbine using novel polymer nanocomposite materials. The following conclusions have been derived. The 2D airfoil was transferred into 3D structural-aerodynamic wind turbine blade and established in the particle swarm optimization method. The aerodynamic properties of every airfoil production depicted by RFoil software. The structural performance and aerodynamic loads of different sections of the blade are created and determined from CLC and BEM models. This technique is successful in incrementing in annual energy from 2.5 to 9.61% as compared in recent literature by considering a change in airfoils profile, twist and chord distribution along the span of the wind turbine blade. The higher stiffness values tend to lower deflection, and the wind turbine blade's total weight decreased from 5 to 34% by reducing chord length and mass per unit length. From the techno-economic model, the BNF epoxy, and BNF/Al-SiC epoxy nanocomposites can decrease the total cost of the blade by 5.1% when compared with the conventional one. Thus, the utilization of bamboo fibers epoxy nanocomposites in the wind turbine blade is shown higher aero-structural characteristics and the most cost-efficient solution.

From the wide applications of bamboo fiber-reinforced composites in construction, sports, automotive, aerospace, railway industries, and other miscellaneous products, these materials provide significant problems in full-scale usage and their development. Various major problems are poor moisture resistance, lower mechanical characteristics, lower fire resistance, varies with the type of fiber and its processing methods. Another important issue is associated with the advancement of bamboo fiber-reinforced composites is adhesion between matrix and fiber, which has the highest effect on delamination. The machining of these types of bamboo composites, also challenging due to delamination and fiber pullouts, are the general issues examined by investigators during the machining applications [19].

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Bamboo/Bamboo Fiber Reinforced Concrete Composites and Their Applications in Modern Infrastructure

Kazi Faiza Amin, Asrafuzzaman, Ahmed Sharif, and Md Enamul Hoque

Abstract Bamboo is a renewable, eco-friendly, green material that grows perennially all over the world. Being a material of low cost, lightweight, and high strength to weight ratio compared to steel, bamboo caught great attention of the researchers to use it as a sustainable reinforcement in concrete. The use of bamboo in construction had started in ancient times. However, the practice of using bamboo as a reinforcement in concrete is still at its nascent age. This chapter addresses the assessment of bamboo reinforced concrete composite in infrastructural performance as a substitute for steel-reinforced concrete. Bamboo/bamboo fiber reinforced concrete beams and slabs have shown promising results to be used as the infrastructural components. It is evident from the studies that the bamboo has superior mechanical properties. However, still some issues need to be resolved such as durability, interface bonding in concrete, and stiffness. Further in-depth research work is required to establish the usability of bamboo as reinforcement in concrete infrastructure.

Keywords Bamboo fiber · Green material · Eco-friendly · Concrete · Modern infrastructure

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1 Introduction

Socio-economic and environmental awareness strongly encourages the proper use of natural resources [1]. Among the natural resources, bamboo is considered to be one of the fastest-growing plants on the earth. Bamboo fiber is sourced from its stem and it has an annual worldwide production of 10,000,000 tons [2]. Thus it has caught special attention owing to its reusability, mechanical characteristics, sustainability as well as its utilization as reinforcement in composite materials [3]. As a construction material bamboo has been used for centuries in certain areas of the world but its use as a reinforcement in concrete had received little consideration [4]. In 1964, a feasibility test of using bamboo as the reinforcing material in concrete elements that were precast was done out at the U. S. Army Engineer Waterways Experiment Station [5]. Recently, bamboo has been considered for reinforcement in soil–cement pavement slabs [6]. Owing to its' availability in subtropical and tropical regions, this replacement is generally cost-effective as bamboo is much cheaper than steel reinforcements [7]. Besides, due to its superior properties such as low weight to strength ratio, high tensile strength, hollow cylindrical shape, high Maxwell's strength, less expenditure, easy availability, and environment affability during service, bamboo is persistently becoming appealing to scientists and engineers for its use as reinforcement in concrete in construction industries [8]. Nevertheless, it is imperative to note the restrictions of bamboo reinforcement; specifically, its low elastic modulus and high water absorption rate are limiting factors in many reinforcements uses.

2 History of Bamboo Reinforced Concretes

The utilization of natural fiber as reinforcement has gained prominence since the 1990s [9]. However, the implementation of bamboo as a reinforcement in concrete is not a new idea. Hou-Kun Chow was the first to test the raw bamboo with a small diameter as reinforcing materials in concrete at MIT in 1914 [10]. Afterward, in 1935, the researchers from Stuttgart examined the possible utilization of raw bamboo in concrete. Unfortunately, they were unsuccessful in using full-scale owing to the debonding of bamboo from the matrix of concrete because of water absorption that led to swelling [11]. In another instance, Clemson university carried out extensive research in 1950 by employing bamboo culms of small diameter as concrete reinforcement [11]. However, most of the bamboo reinforced concrete structures collapsed soon after the construction owing to swelling and shrinkage of the raw bamboo and deterioration over time because of the fungal and pest attacks [10]. More recently, the work on bamboo reinforcement in concrete was performed in Brazil between 1995 and 2005 [12–14]. To determine the most suitable species to be used as reinforcement in lightweight concrete beams, seven species of bamboo were studied. The outcome of this research evidenced that significant load-bearing capacities were obtained by the concrete beams with bamboo compared to non-reinforced beams. Moreover, strength parallel to steel-reinforced concrete was also observed [10].

Early studies indicated the use of bamboo bars or bamboo splints as reinforcement in concrete [7]. From the test results of these studies Glenn [15] expressed a set of deductions along with construction codes using splints and bamboo canes as reinforcing material in concrete. Glenn emphasized problems concerning bamboo reinforcement such as (a) low ductility, premature brittle failure, and high deflection; (b) lower ultimate load capacity in comparison to structures that are reinforced with steel; (c) problems associated with bonding such as swelling and extreme cracking of bamboo; and, (d) the requirement for using asphalt emulsions. Glenn recommended the usage of bamboo reinforcement up to 4% in a concrete beam considered the tensile stress of bamboo is between 34 and 41 MPa and allowable stress values for concrete beams are between 55 and 69 MPa. Another study promulgated a permissible stress methodology for producing bamboo reinforced concrete similar to the existing method for steel-reinforced concrete [4]. Geymayer and Cox acknowledged the exceptional and restricted adhesion behavior of bamboo and recommended that the bond strength of the reinforcing bar should be 44 N/mm. A significant number of research articles based on bamboo reinforced flexural specimens ratify the rudimentary standard of the design approach suggested by Geymayer and Cox [4]. Albeit specific analysis of bond was not included in these experiments, they endorsed coating of bituminous paint with sand to be used as a topcoat for the treatment of bamboo splint reinforcement [16]. In separate studies, Ghavami and Maity concluded the importance of providing minimal bamboo reinforcement and suitable surface treatment for bonding improvement [13, 17]. Furthermore, Ghavami observed that compared to unreinforced concrete beams, the ultimate capacity of beams reinforced with splint bamboo (3% addition) increased four-fold [13]. However, no characteristic dissimilarity concerning bamboo or steel-reinforced beams performance was apparent in those investigational studies [7]. The findings of research on the use of bamboo from the last century until today imply that green bamboo is a possible replacement for steel in reinforced concrete structures [10]. However, problems such as durability issues, swelling due to absorption of water, concrete and bamboo possessing dissimilar coefficient of thermal expansion, green bamboo being easily affected by the alkaline nature of concrete, along with the inadequate adhesion in between concrete matrix and green bamboo are still major concerns that require further study and research [10].

3 Comparison Between Bamboo-Reinforced and Steel-Reinforced Concretes

The most common reinforcement used in concrete is steel which is very different in contrast to bamboo reinforced concrete. Major dissimilarities amid traditional reinforcing steel and bamboo are mentioned below:

1. Steel and bamboo are completely different materials based on their ductility and brittleness. Steel is considered ductile whereas bamboo is elastic brittle in nature. As a result, allowable stress is limited to the bamboo-based margin of safety design [7].
2. Compared to steel, bamboo has a 10% less longitudinal tensile modulus and strength [18]. Due to the low modulus, serviceability concerns such as deflections and crack control are quite important and naturally administer design even though the permissible strength is very low [7].
3. Anisotropy is one of the major characteristics of bamboo that leads to intricate interactions with contiguous concrete. For example, (a) the thermal expansion coefficient of bamboo varies in comparison to that of steel and concrete, which have an effect on the consistency with the surrounding concrete and have a major influence on the composite bond behavior. (b) Dimensional instability and consequent requirement of specific treatment to prevent moisture transmission make bamboo dissimilar to steel. Non-uniform dimensional stability (transversely and longitudinally) leads to the anisotropic property [7].
4. Though corrosion does not affect bamboo, exposure to (a) inconsistent hygrothermal surroundings; and (b) an alkali rich atmosphere increases vulnerability to deterioration. In an embedded concrete climate both the mentioned conditions are prevalent [7].
5. Due to vulnerability to termites and fungal attacks, bamboo quickly degrades when subjected to a high level of humidity which does not happen in the case of steel [7].

4 Surface Treatment and Bonding Issues in Bamboo-Reinforced Concretes

Pretreatment of natural fibers can play a major role in increasing bonding strength [19]. Bamboo, being a natural fiber also needs surface treatments to ensure proper bonding that is required for adequate stress transfer between reinforcement and concrete. This guarantees that the reinforcing bars do not slip comparative to the underlying concrete mandatory for their performance as a composite. The bond formation process defines the anchoring of the reinforcing bars and controls the crack pattern and stiffness. Numerous problems occur due to a lack of adequate anchoring ability, in general on beam-column joints, cantilever brace, lap splices in conventional construction architecture [20]. Commonly, pull out tests are required to measure the bond strength between concrete and reinforcing material. However, specific pull out test methods for bamboo are unavailable [20]. As a result, successful measurement of bond strength is limited. Besides, many problems such as contraction/shrinkage, absorption of water, variety of species, etc., have an impact on the effectiveness of bamboo in cement composites. Through micro cracks in concrete, moisture is absorbed by green bamboo from the concrete and the adjacent atmosphere. This results in bamboo swelling, which causes local internal tension and degrades the underlying concrete [20]. Also, moisture reduction causes bamboo shrinkage contributing to the formation of cavities. Owing to this constant process of shrinking and bulging (swelling) of bamboo, the appropriate bond between concrete and bamboo cannot be formed which imposes a significant constraint on its use as reinforcement instead of steel [13]. Chemical treatment is therefore required to make the bamboo surface impervious and to augment the bond strength proposed by various researchers for the construction of different structural components. A summary of them is presented in Table 1.

Table 1 Summary of bamboo surface treatment to enhance reinforcement with concrete [20]

Investigations by researchers (chronologically)	Treatment processes
Glenn [15]	Emulsion of asphalt
Kankam et al. [16]	Bitumen
Ghavami [13]	Negrolin (asphalt-water based paint) Negrolin mixed sand Negrolin mixed sand and wire Sikadur 32 Gel (epoxy adhesive)
Terai and Minami [21]	Synthetic resin Synthetic rubber
Sakaray et al. [22]	Water-resistant coating
Javadian et al. [23]	Epoxy coating (water-based) Epoxy coating (water-based) mixed with fine sand Epoxy coating (water-based) mixed with coarse sand Exaphen (aromatic intermediate of polyol used as adhesive) Exaphen mixed with coarse sand Enamel
Nindyawati and Umniati [24]	Water-resistant paint interspersed with sand
Dey and Chetia [25]	Epoxy coated bamboo (sand rolled) Epoxy coated bamboo (coir rolled) Copper chrome boron
Mali and Datta [26]	Bondtite (epoxy) chemical adhesive with sandblasting process

5 Recent Studies on Bamboo/Bamboo Fiber-Reinforced Concrete Structures

Natural fibers have emerged as a popular choice for reinforcement in composite materials [27]. Numerous research studies are done to identify the potential of bamboo reinforcement in concrete to be used in structural components. Some of the important studies and their findings are summarized here. In this context, Chow studied bamboo splints (small diameter) as of reinforcement for concrete beam installations that yielded promising performance [28]. The bamboo used as a reinforcement in the life-sized building was studied by Glenn [15]. However, he noted that, in theory, the findings were feasible but, due to numerous bamboo-related drawbacks, the building fell down within a couple of days. Mansur and Aziz [29] carried out several experiments using a woven mesh consisting of bamboo splints on cement composites. Their research work showed that mesh shaped bamboo improved the ductility and toughness of the mortar and also enhanced its bending, impact, and tensile strength. In another study, the effect of using bamboo reinforcement on a two-way concrete slab was performed. Higher tensile strength was documented for seasoned bamboo relative to unseasoned bamboo. They recommended using less than 4% bamboo reinforcing for concrete constructions. They proposed that additional research should be undertaken to determine the lasting properties of bamboo [22]. A study by Janssen [30] demonstrated the drawbacks of the use of bamboo in a structure made of concrete. The detected drawbacks were adhesion strength, a sleek wall of the culm, and absorption of water in the bamboo. Among all the drawbacks, inadequate bonding was found to be the main concern. Terai and Minami [31] have researched the usage of bamboo as support in pillars and beams. They found that the bamboo reinforced beam had an identical cracking configuration to that of conventional reinforced beams. Maity [17] compared the non-reinforced columns and beams with bamboo reinforced counterparts. It has been established that 8% of bamboo reinforced columns provide identical strength and performance as the conventional RCC (Reinforced Cement Concrete) columns. Puri et al. [32] built a mesh shaped bamboo reinforced wall panel. They noted that the flexibility of the walls increased owing to the bamboo mesh addition. Furthermore, the wall production cost can be substantially reduced by up to 40% and the dead load can be decreased by up to 56% relative to traditional brick walls, they concluded. The experimental assessment of the concrete slab panel reinforced with bamboo was studied by Mali and Datta [26]. It was reported that the load-bearing and deformation capability of the newly enhanced bamboo slab panel increased compared to the standard PCC (Portland Cement Concrete) and RCC (Reinforced Cement Concrete) slabs. Moreover, the flexural efficiency has shown noteworthy development. The descriptions of various bamboo reinforced concrete structures are given below.

5.1 Bamboo Strip Reinforced Concrete Beams

It has already been established that as an alternative to steel, bamboo due to its' low-cost, can be utilized as a reinforcement in concrete for building construction. Budi et al. [33] studied the flexural properties of V-notched bamboo strip reinforced concrete beams (Figs. 1 and 2). They used a specific bamboo for this purpose known as Ori bamboo (*Bambusa arundinacea*). The result of the flexural test revealed several important findings. Both the V-notched bamboo reinforced beams and steel-reinforced beams exhibited flexural tension failure that was evidenced from the vertical cracks originating from the tensile regions of the concrete beam specimens. None of the beam specimens showed shear failure, however.

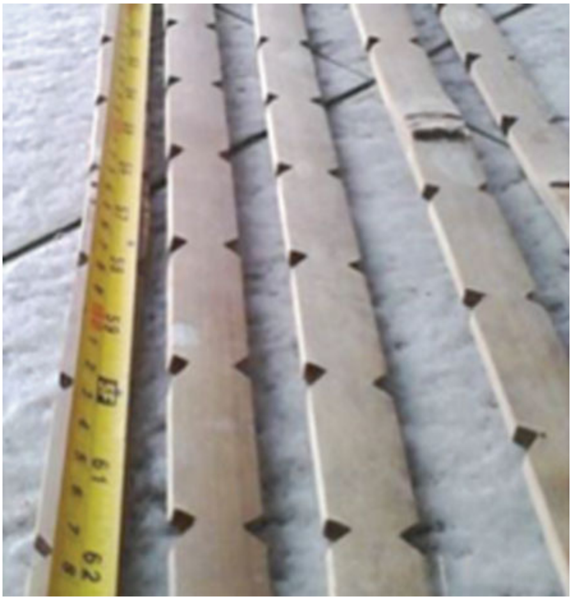


Fig. 1 V-notched bamboo strips bars [33]

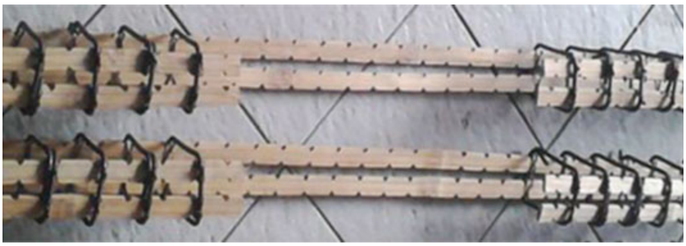


Fig. 2 A model of notched bamboo strips in the concrete beam [33]

This study further observed that the analytical moment is lower than the experimental flexural moment. Ultimately, the shortening of the notch distances of the bamboo strip in the tensile region improved both the analytical and experimental moments (Fig. 3). They summarized that the ultimate moment of resistance improved owing to the increased quantity of notches. This increase in the number of notches also enhanced the beam's failure loads. They concluded that the utilization of bamboo strip notches as stress reinforcements can escalate the flexural capability of concrete beams.

In another study, Budi and Rahmadi [34] used Wulung bamboo as reinforcement in concrete to examine the flexural properties. In this case, too, the efficiency of the notched bamboo strip reinforced concrete beam was improved in comparison to the bamboo reinforcement without the notch. Bamboo strips with different types of patterns such as plain strip, wired strip, and corrugated strip (Figs. 4 and 5) were used as reinforcement in concrete to study the flexural properties and compared with the conventional steel-reinforced concrete by Qaiser et al. [35]. The goal of

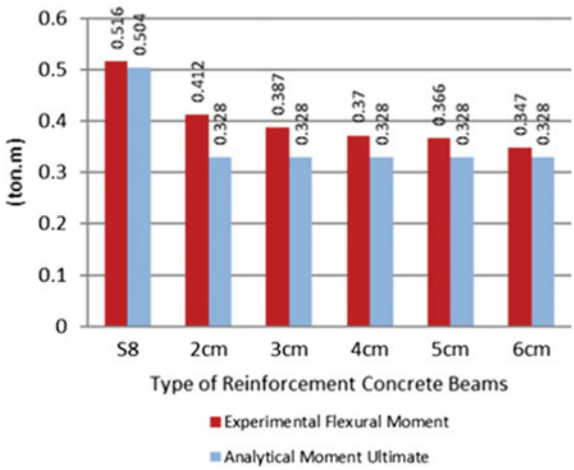


Fig. 3 A comparison chart of experimental flexural moment and analytical moment ultimate [33]

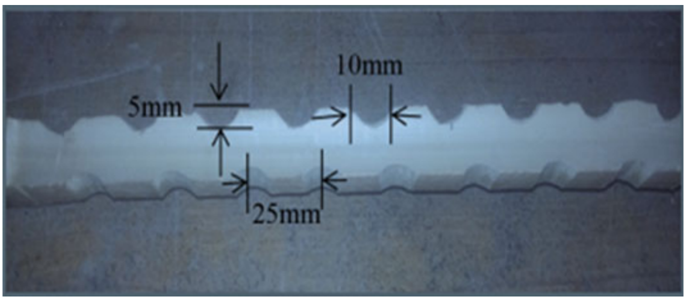


Fig. 4 Semi-circular corrugated bamboo strips [35]

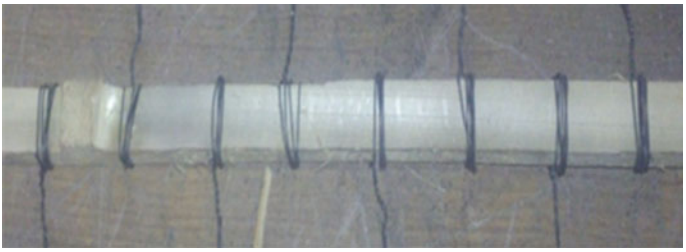


Fig. 5 Wire-wrapped bamboo strips [35]

their investigation was to establish various kinds of bamboo reinforcement strip mechanics as well as to find out how the action of bamboo in strengthened beams are influenced by the mentioned patterns under the circumstances of pure bending.

In this experiment, strips (specimens) of 3 types were arranged. The first type included an unaltered bamboo strip specimen. Half-circular corrugated strip of bamboo of 25 mm, 10 mm and 5 mm pitch, width, and depth respectively, formed the second category specimen and the final category of the specimen (bamboo strips) comprised of thick tie wire (2 mm) enclosed bamboo strip having a pitch of 25 mm pitch and allowance of 10 mm. Figures 4 and 5 illustrate the samples.

The pullout test result is summarized in Table 2 that specifically indicates that the bond strength of the simple strips was weaker than that of the treated bamboo samples. Wired bamboo provided slightly more slip resistance relative to plain strips, but displayed comparatively lower values than the strips that are corrugated. This analysis indicated that semi-circularly corrugated strips had the highest slip resistance of all types of samples.

The load–deflection curves for different notched bamboo reinforced samples are demonstrated in Fig. 6. The slip resistance for wired samples demonstrated that the wire was attached to the concrete covering the strip and provided a large amount of slip resistance that was as high as 17% relative to the simple bamboo strips. On the contrary, corrugated strips display a bond strength increase of as much as 80

Table 2 Pullout strength test observations [35]

Description	Specimen No.	Failure force (N)	Bond stress (MPa)	Mode of failure
Crude bamboo (plain)	1 2 3	2950 2930 2925	0.160 0.159 0.153	Slippage
Corrugated bamboo	1 2 3	5404 5300 5123	0.293 0.287 0.278	Breakage
Wired bamboo	1 2 3	3429 3515 3323	0.185 0.190 0.180	Slippage

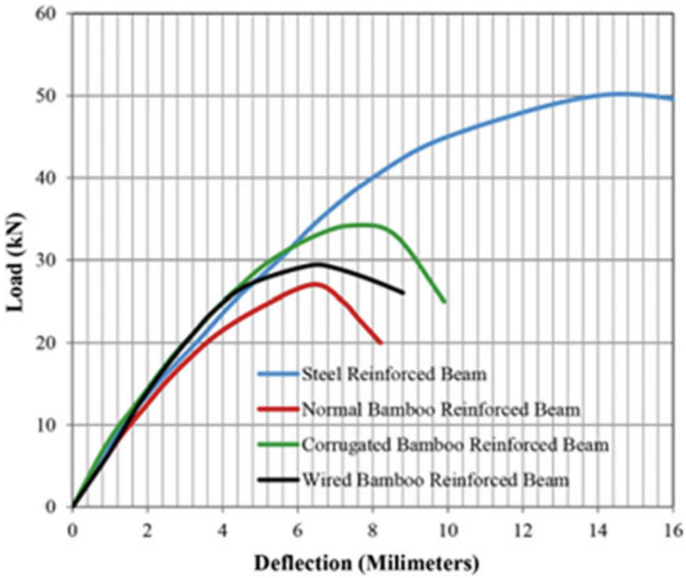


Fig. 6 Load–deflection profiles for several concrete beams [35]

percent relative to plain strips. This may be attributed to the fact that concrete filled the indentations and reinforced the bonding.

Further comparison of their final loading capacity showed that the wired bamboo reinforced specimen indicated an 11% increase and the corrugated reinforced bamboo specimen exhibited around 80% increase as compared to the plain bamboo reinforced beam [35]. Based on their research they concluded that bamboo can theoretically be used as a steel substitute where it comes to impermanent or low-grade infrastructure in underdeveloped areas where the supply of steel is minimal and where it is very costly to construct buildings with steel reinforcement. However, further research work is essential for a conclusive decision on the utilization of bamboo as an infrastructural material.

5.2 Concrete Beam Reinforced with Bamboo Fiber

For steel-reinforced concrete, once the strain (tensile) exceeds the extreme level, a state of tension develops in that region and it cracks. As a result, the vapor of water and destructive ingredients move in and thus, the reinforcement corrodes which in turn, impairs the concrete. Dewi et al. [36] studied the addition of Ori bamboo fiber in the tension region. The fibers were paint coated and sand-covered to avert hygroscopic characteristics and to increase fiber weight to stop it from floating when embedded

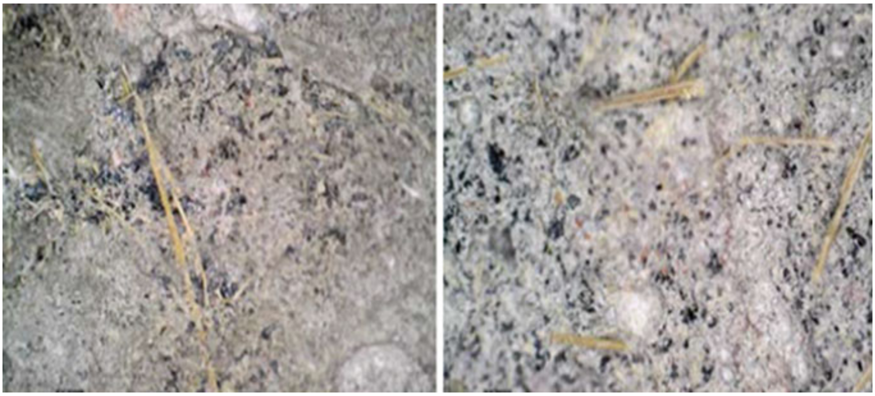


Fig. 7 Bamboo fiber embedded in concrete [36]

in the concrete mixture (Fig. 7). The result showed that the bamboo fibers minimized the concrete crack length and improved the post-cracking load efficiency of the beam.

In this experiment, they varied the amounts of bamboo fiber contents to 40 g/volume and 150 g/volume. The Load–deflection curves of the specimens were compared and showed a noteworthy result (Fig. 8).

The figure showed that the crack load increased owing to the addition of fiber. Compared to concrete (without fiber) and specimen with 150 g fiber content, the specimen with 40 g fiber content displayed a higher load-carrying ability. They established that the increase in fiber content beyond a certain amount reduces the load efficiency of the beam significantly. The beam deflection and crack widths are summarized in Table 3. Bamboo fiber addition reduced the crack width of the reinforced concrete beams, in turn, reducing crack growth and propagation. Moreover, it also increased the post-crack load-carrying capacity. However, increasing fiber content to a certain amount (150 g) could cause a reduction of workability and quality of concrete.

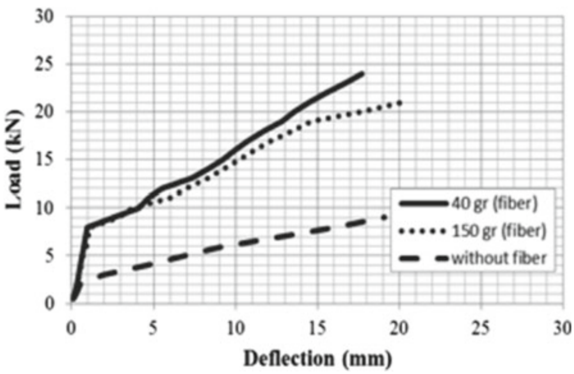


Fig. 8 The illustration of load–deflection profiles with alteration of fiber amount [36]

Table 3 Comparison of crack behavior of bamboo reinforced concrete with normal concrete [36]

Amount of fibers	Width of crack (average) (mm)	Average deflection (mm)
40 g	4.67	15
150 g	5.33	18
Without fiber	11	20

5.3 Bamboo Reinforced Concrete Masonry Shear Walls

The utilization of Tonkin cane bamboo as reinforcement in the concrete masonry wall was studied by Moroz et al. [37]. Figure 9 indicates such an illustration.

They compared this bamboo reinforcement with the conventional steel reinforcement and observed the possibility of utilizing bamboo as a replacement to steel as reinforcement in buildings in areas where bamboo is more cost-effective than steel. They reported that the bamboo reinforcement in shear walls of concrete blocks resulted in improved shear efficiency and ductility relative to unreinforced masonry. The introduction of vertical bamboo reinforcement even without horizontal counterparts delivered increased shearing capability. At the same time, parallel to unreinforced masonry, it also provided ductile failure. However, they specifically mentioned that steps must be taken to avoid the accumulation of bamboo moisture in the cement matrix.

As expected, the ultimate strength of two of the walls was decreased due to swelling. They expressed that bamboo reinforcement having cracks in the longitudinal direction has to be fully water-resistance such that moisture penetration through cracks is hindered to stop swelling. So, they suggested that splints must be cut from

Fig. 9 Typical bamboo bond in-wall specimens [37]

bamboo in such a way to exclude cracks in the longitudinal direction to avoid this complication. However, they could not provide any long term properties of masonry walls that are reinforced with bamboo.

In another study, the energy and thermal performances of an innovative lightweight bamboo-steel wall structure were investigated by Li et al. [38]. In their study, a prototype housing was built utilizing a steel bamboo-composite wall that was fabricated before and a simulated experiment was undertaken to find out its performance enhancement in comparison to widely used brick wall structures in cold and hot season in China. The reinforced steel-bamboo wall consisted of multiple layers comprising of expanded polystyrene, cement mortar, carbon steel, bamboo plywood, and wool as demonstrated in Fig. 10. The bamboo layer depth, the void within the framework, and the carbon steel were cautiously designated to develop the structural firmness such as improved load-bearing capacity, rigidity, and ductility. The mineral wool was utilized as insulation material as it has better thermal and flame-resistant characteristics plus it is ideal for cavity filling [39, 40]. The steel-bamboo wall with high thermal output as well as increased U values (Thermal Transmittance) was observed with the help of simulation analysis suggesting a lesser heating requirement in the winter.

Also, it had shown high tolerance to outdoor temperature variations that led to lower indoor temperatures throughout the summer night and thus decreases the need for cooling energy. However, according to the sensitivity analysis, the effect of the choice of insulation materials on energy savings is important. Therefore, materials with low thermal conductivity were recommended to attain a high energy performance. They recommended further investigation to assess the energy and thermal efficiency of this steel-bamboo construction framework in various environments and at varying rates of natural ventilation (air infiltration).

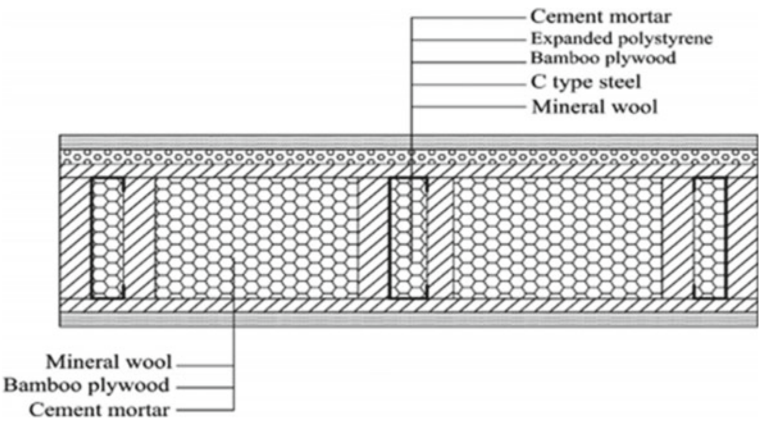


Fig. 10 Cross-sectional view of a wall structure composed of steel-bamboo composite [38]

5.4 Lightweight Bamboo Reinforced Slabs

Bending/flexural performance of bamboo-steel composite slabs was studied by Li et al. [41]. Moso bamboo (*Phyllostachys pubescens*) of thickness 10–25 mm was used. This type of slabs is used in a concrete framework and ground flooring in China. The composite slabs consisted of cold-rolled thin-walled steel channels and Moso bamboo (Fig. 11). The composite slabs were manufactured using three types of connections: adhesive joint connection, self-tapped screw connection, and stability enhanced joint with bamboo laths bonded on both sides of cold-rolled steel channels.

They studied the prospective use of bamboo-steel reinforced slabs to be utilized as slab flooring. They noted that the steel channel buckled and caused the failure of the adhesive-bonded slab but the slab reinforced by self-tapped screws indicated greater bearing capability. Moreover, the composite slabs connected by self-tapped screws and bamboo laths showed improved bearing capacity, rigidity, and strength.

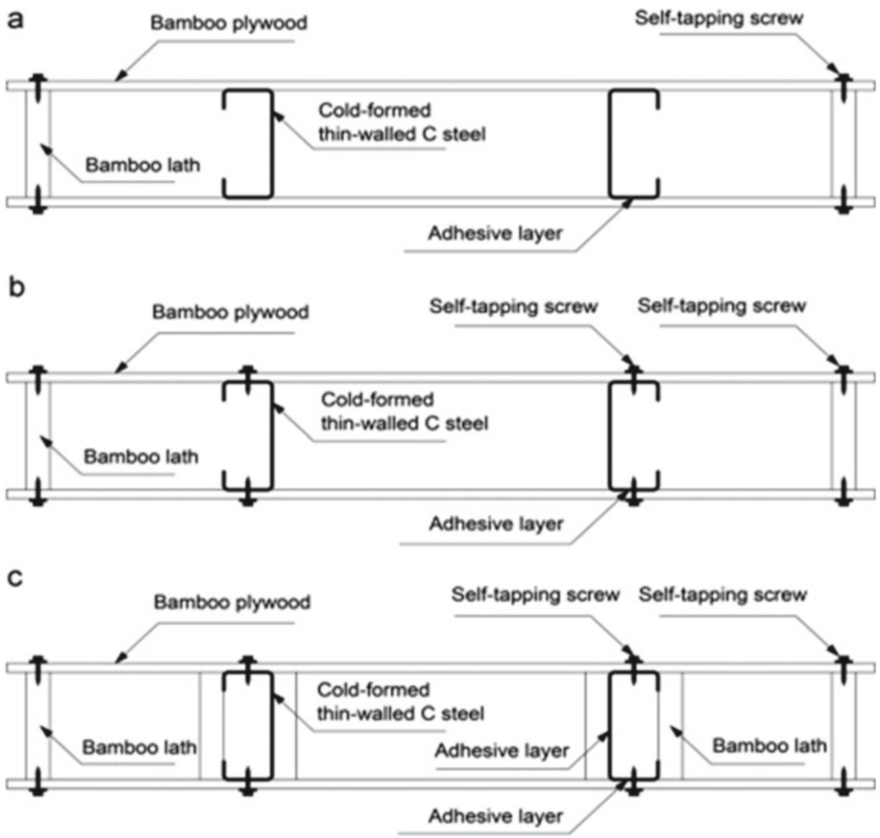


Fig. 11 Schematics of bamboo–steel composite slabs. **a** Adhesive joint connection, **b** self-tapped screw connection, and **c** bamboo laths bonded on both sides of cold-rolled thin-walled steel [41]

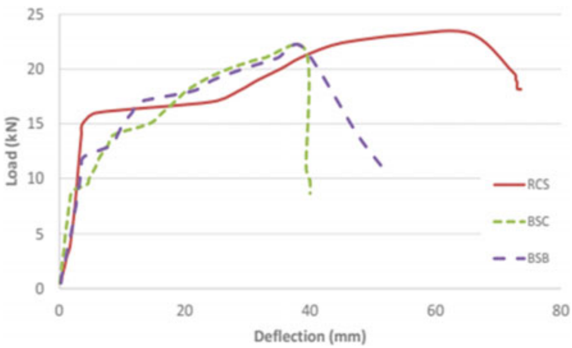


Fig. 12 Load–deflection profiles of RCS, BSC, and BSB slab specimens [42, 43]

The outstanding mechanical characteristics of this type of slabs conformed with the basic specifications of the floor slabs. They concluded that this type of composite slabs were preferable to wood or concrete slabs in low rise buildings.

Wibowo et al. [42, 43] examined the structural performance of lightweight bamboo reinforced concrete slabs with Styrofoam infill panels also known as EPS (expanded polystyrene) to be used in architecture and building construction. The slab samples consisted of three kinds of bamboo reinforced concretes such as BSC (with EPS infill panel and concrete stud), BSB (with EPS infill panel and bamboo stud), and RCS (regular RC slab). The load–deflection curve of the three specimens delivered a promising result as presented in Fig. 12. The load capacity of the RCS sample was 23.2 kN, whereas the samples with EPS infill panel e.g. BSC and BSB showed 21.6 kN, and 22 kN, in that order. As a result, bending strength reduced by 6% owing to the addition of EPS infill but compared to regular slabs they were around 27% lighter. They concluded that slab performance was enhanced since the weight was decreased while the strength dropped by an insignificant amount. However, further studies were suggested to strengthen the load–deflection mechanism of EPS infilled panel reinforced bamboo slabs due to reduced ductility complications.

Chithambaram and Kumar [44] studied the bending characteristics of fly-ash integrated Ferro-cement slab panels reinforced with bamboo. As a substitute for cement in concrete, fly-ash can be used. To determine the impact of fly-ash on the bending behavior of Ferro-cement hybrid slabs, 40 mm and 50 mm thick test panels were considered. They inferred that for both slabs the primary crack loads and ultimate loads were identical and all the slabs exhibited a significant ductility prior to the final flexure failure as observed in Figs. 13 and 14. According to their recommendation, the use of bamboo and fly-ash as substitutes for steel and cement respectively can be beneficial for roof slab panels. They suggested that sustainable use of fly-ash and bamboo waste could preserve the environment without hampering slab panel's structural integrity.

In another experimental study, polyvinyl waste (PW) as a fractional substitution of fine aggregates were utilized to investigate the structural behavior of foamed concrete slab strengthened with bamboo reinforcement [45]. Strength in compression, growth pattern of crack, load–deflection performance, and the ultimate moment

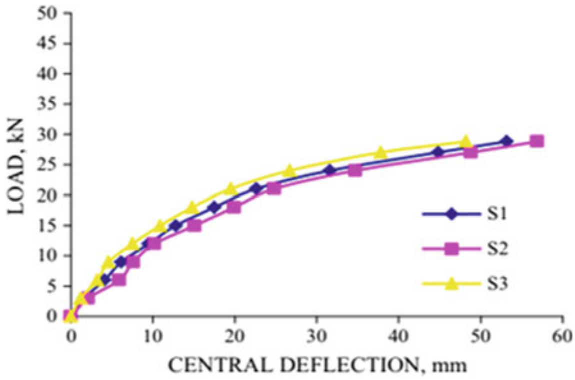


Fig. 13 Load–deflection profile of Ferro-cement slab (40 mm thickness) without fly-ash; S in the figure refers to bamboo reinforced cement mortar Ferro-cement slab [44]

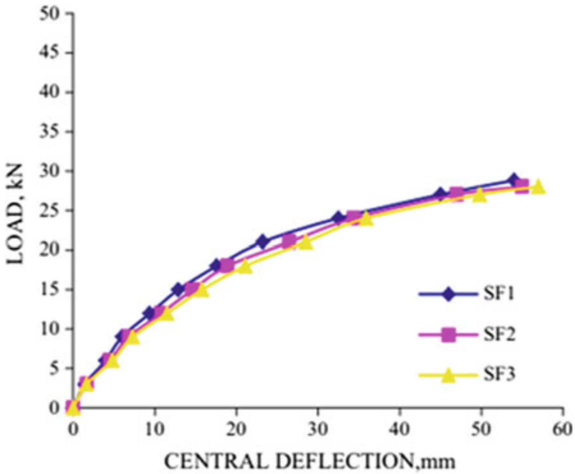


Fig. 14 Load–deflection profile of fly-ash integrated Ferro-cement slab (40 mm thickness); SF in the figure refers to bamboo reinforced fly-ash cement mortar Ferro-cement slab [44]

characteristics were analyzed. The polyvinyl waste (PW) addition instead of sand increased the strength in compression of the foamed aerated concrete samples. PW showed a densifying effect on the substance matrix. They recommended that densification augmented as the percentage of PW increased instead of sand. It was noticed that there was a significant improvement in compressive strength with an increasing amount of sand substitution with PW at various time of curing (Fig. 15).

In addition to compressive strength, all the samples with PW as a fractional substitute of sand demonstrated failure by shear bending compared to diagonal shearing for the slab samples with 0% PW in the mix. Moreover, lower values of deflection were reported for samples with polyvinyl waste as a fractional substitute of sand. Higher failure loads were observed for a high proportion of PW (Fig. 16). Based on their experimental result on the bending moment, they also concluded that an increased amount of sand replacement with PW caused better flexural efficiency of the slab samples.

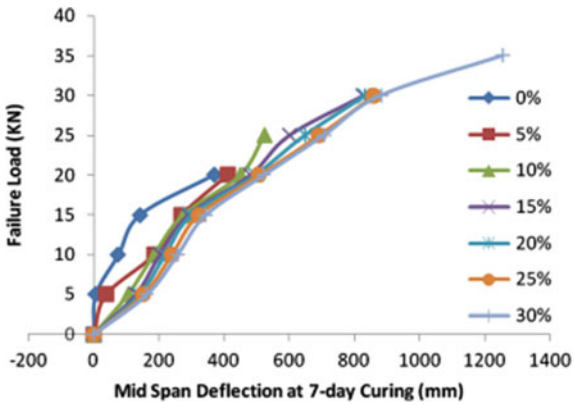


Fig. 15 Relation of percent sand replacement with PW on the compressive strength on the foamed aerated concrete [45]

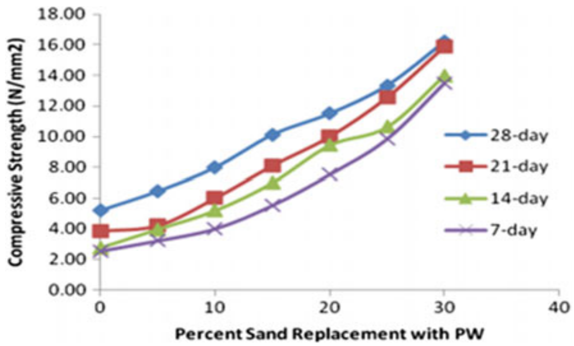


Fig. 16 Load–deflection profile for slab specimens [45]

In another research effort, the combination of bamboo culm/strip with self-compacted concrete slabs (SCC) was studied [46]. The primary objective of this research was to inspect the impact of longitudinal bamboo reinforcement on the ultimate flexural capabilities of bamboo reinforced self-compacted concrete (BRSCC) slabs. Self-compacted concrete, a modern type of concrete manufacturing technology, also provides various economic benefits over traditional standard concrete (NC). In the case of SCC, there is no necessity for mechanical vibration, because the key prerequisite inside the construction mixture is to have a concrete matrix of high fluidity [47, 48]. Since there is no need for mechanical vibrators, the operational cost of construction projects will be reduced. For the NC test specimen, a blend of cement: fine aggregates: coarse aggregates in 1:1.5:3 ratio and for the SCC test specimen, a blend of cement: fine aggregates: coarse aggregates in 1:2.7:1.8 were used. The species of bamboo that was utilized as reinforcement was Bambusa vulgaris. Bamboo reinforced SCC slabs exhibited decreased post-cracking stiffness than NC slabs, and they explained that due to the existence of a comparatively lower amount of coarse aggregate. They observed that for a very small amount of reinforcement (longitudinally), the deformation capacity of the reinforced bamboo SCC and NC slabs can be improved. They also mentioned that the failure performance of bamboo reinforced SCC slabs was significantly better than those made from the standard concrete. Lastly they concluded that bamboo combined with SCC mixture can be applied as reinforcement in concrete slabs to be used in countryside building that can prove to be a fruitful substitute for attaining and upholding sustainability.

Another investigation by [49] assesses the integration of bamboo fiber (instead of bamboo culm/splint) in the self-compacting concrete. They have confidently concluded that to improve concrete load-bearing capability (post-cracking), strength, and ductility, the bamboo fibers can be used as a novel fiber in SCC. They have added that incorporating bamboo fibers of 1.0% by weight produces a substantial improvement in long-term compression and split tensile strength in concrete as well as flexural properties. According to them, the average increase in the strength showed that 1% of the fiber inclusion is the optimal fiber value for a specific aspect ratio from the compressive and split tensile strength view.

The strength of bamboo reinforced slabs was also studied by Suppiah et al. [50]. They compared the bamboo reinforced slabs with steel reinforcement and slabs lacking any reinforcement. According to their test results, they recommended using the Bamboo Vulgaris family as reinforcement instead of steel in low-cost construction. They concluded that coal tar creosote-treated bamboo showed increased strength characteristics and impedes fungus attacks. Furthermore, it produces lesser load carrying capability and greater deflection than the steel-reinforced panels. In a similar study, Semantan bamboo (*Gigantochloa scortechinii*) was used as reinforcement in the slabs [51]. It was evident from the analysis that a higher percent of reinforcement was able to account for more loads. The analysis also found that cracking happens much later than those with a lesser proportion of bamboo reinforcement.

It is already established that usage of bamboo (splint/fiber) as reinforcement in concrete slab lowers the weight of the concrete composite. To make it more economical Wibowo et al. [42, 43] used Styrofoam lamina filler with bamboo reinforced concrete slab to make it more lightweight. They recommended the use of Styrofoam as a panel filler inside the concrete to lessen the self-weight of the concrete and to enhance the sustainability of the structural elements. Moreover, Styrofoam is an environmentally friendly and recyclable material, which is an added advantage. The flexure strength test was performed on Styrofoam lamination filled bamboo reinforced concrete slab. The outcome revealed a 15% reduction in flexural strength but a 20% reduction in weight relative to standard reinforced concrete slabs of the same dimension. According to their recommendation, it would give good performance in real-world infrastructural design as the bending capacity of normal concrete structures when designed with minimal reinforcing materials are generally much greater than the prerequisite amount. Nonetheless, they added that such lightweight concrete structures had unsatisfactory deformation capability and strength as a result, they are quite prone to earthquake damage. So, they recommended further investigation to address the issue.

5.5 Bamboo Panel Incorporated Thermally Insulated Roof Slab System

One of the biggest problems of traditional reinforced concrete roof slab is the thermal disquiet in the adjacent area below the roof slab. Utilization of synthetic materials such as polystyrene which is thermally insulative showed promising results providing thermal comfort. However, it has a negative environmental impact. Hence it is necessary to find an eco-friendly insulation system for the concrete roof slab. Chandra et al. [52] in their study tried to develop an innovative roof slab insulation design that utilizes a layer of bamboo due to its thermally insulative property and assess the effectiveness of the slab insulation system in tropical climatic conditions. Since it is already established that the thermal insulation property of bamboo is quite good [53], they researched the consequence of air trapping by cutting the bamboo (transversely) and determined the outcome of the number of bamboo layers in the concrete slab and its thickness. One of the fabricated model using the bamboo insulation system is shown in Fig. 17.

To analyze thermal performance, 25, 50, and 75 mm insulation thickness was proposed, and to determine the outcome of the number of layers, they examined two layers of 37.5 mm bamboo [52]. A visual illustration of the structural arrangement similar to Nandapala and Halwatura system [54] is shown in Fig. 18.

Their analysis found that 25 mm insulation thickness displayed maximum thermal efficiency and that ultimate thermal efficiency is not influenced by several layers of bamboo. Besides, 25 mm insulation thickness showed a substantial amount of heat drop. They calculated that compared to the slab without insulation (125 mm thick), the ultimate heat gain decrease owing to the 25 mm insulation thickness was 53% (the heat flow graph obtained from their experiment is shown in Fig. 19).

Fig. 17 Bamboo insulated concrete slab system [52]

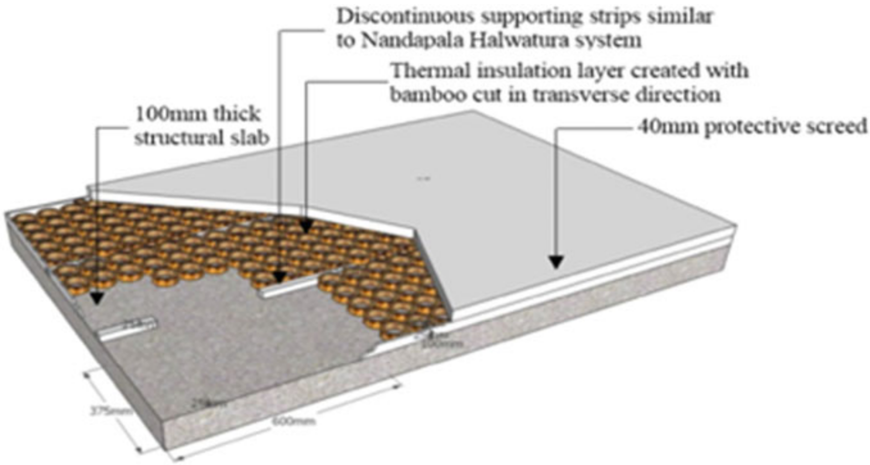
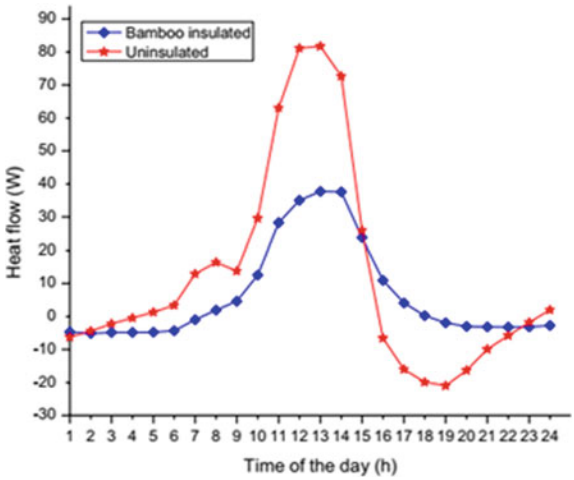


Fig. 18 Schematics of the bamboo insulation layer [52]

Fig. 19 Heat flow of bamboo insulated and uninsulated scenarios [52]



They recommended that the unique thermally insulated concrete slab with 25 mm thickness may be utilized efficiently to guarantee interior thermal comfort. Moreover, due to its potential to endure any stress on the roof, the roof slab with bamboo insulation design is thought to be structurally strong. Moreover, it is considered as a thermally insulated eco-friendly solution [52].

5.6 Bamboo Fiber-Based Composite Reinforced Structural Concrete Beam

Hebel et al. [55] focused on the concept of fabricating bamboo fibers from its culms that are appropriate for structural usage as a unique composite material. The notable feature of this bamboo-based composite reinforcement is that the bamboo fibers cannot absorb water due to epoxy matrix coating hence reduces swelling problems while increasing bonding properties with concrete mix and durability. Moreover, abundant source of bamboo fiber, renewability, biodegradability, and low production cost compared to traditional synthetic fiber materials are added advantages.

Javadian et al. [10] in their experiment investigated the prospect of using the advanced bamboo-composite as reinforcement for the beam of concrete. Moreover, assessment of moisture absorption, bulging, shrinkage, and resistance to chemical attacks were conducted. The bamboo species selected for this research work was "Dendrocalamus asper" also recognized as Petung Putih bamboo widely available in the Java island of Indonesia and used for small housing projects. The epoxy-based thermosetting polymer was chosen for the matrix phase of the bamboo-based composite. The epoxy materials were chosen based on a low amount of volatile organic compounds (VOCs), adequate mechanical properties, and source sustainability. A patented technology was followed to produce the bamboo composite samples that were developed by the authors [56]. For producing the composite samples, the hand lay-up method was utilized. The epoxy resin-infused bamboo fiber packs were positioned into the hot-press mold [10]. Figure 20 shows the bamboo composite sample prepared in their study.

In conjunction with sand particles, a water-based epoxy matrix consisting of two constituents was used. The waterproof system improved the stress transference between concrete and bamboo reinforcement by hindering water and moisture from the interfacial region. Additionally, the introduction of sand aggregates roughened the reinforcement surface. As a result bond strength augmented by generating mechanical keying with the present concrete matrix [23]. The force–displacement graphs for

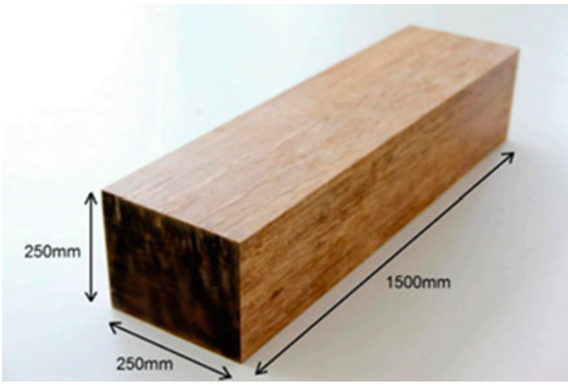


Fig. 20 Bamboo composite concrete beam [10]

non-reinforced and bamboo reinforced concrete beam are shown in Fig. 21a and b, respectively. This model assured that the probability of catastrophic collapse is very low due to cautionary signs of the concrete crushing prior to the ultimate collapse when the rupture of the bamboo-composite reinforcement occurs [10]. The analysis also revealed that the non-reinforced beams went through failure prior to reinforced concrete beams at lesser ultimate failure loads.

The average water absorption characteristics of the composite sample reinforced with bamboo are displayed in Fig. 22. Water absorption has reached a maximum of 0.5%. The poor water absorption rate illustrates the greater hindrance of the composite bamboo specimens to moisture and water penetration, even under intense

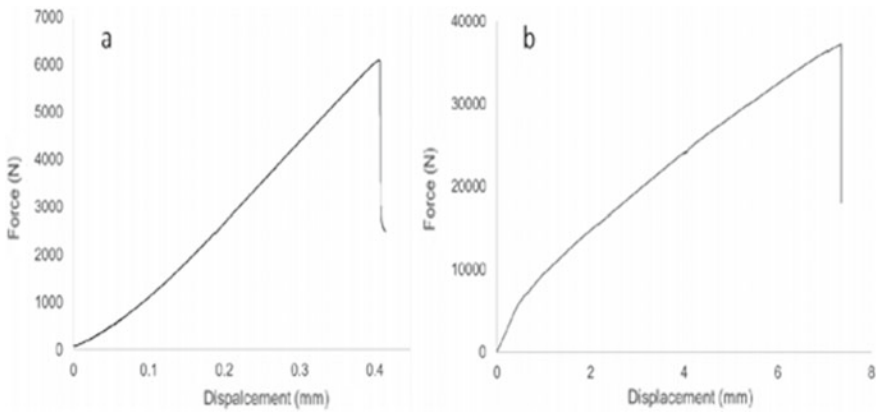


Fig. 21 Force–displacement graphs for **a** non-reinforced and **b** bamboo-composite reinforced concrete beam [10]

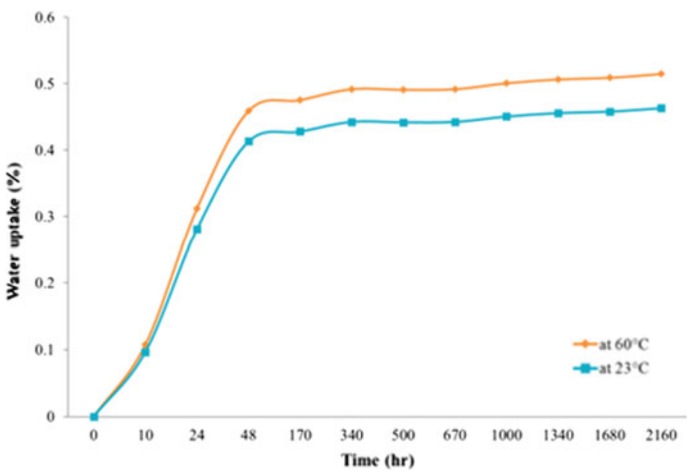


Fig. 22 Water uptake versus time graph for bamboo-composite reinforcement [10]

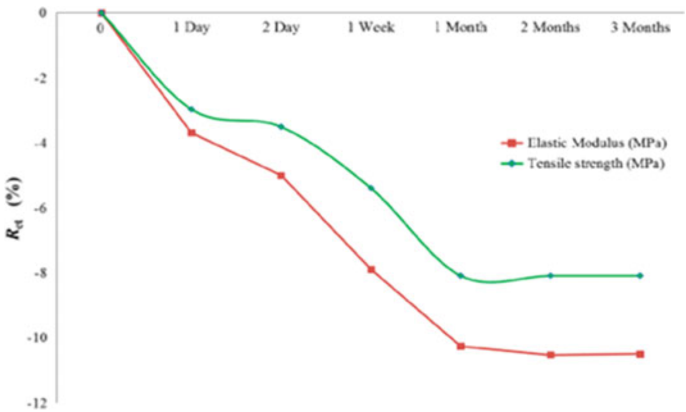


Fig. 23 Relation of elastic modulus and tensile strength with tensile capacity retention [10]

environment. They concluded that the surface of all reinforcements was applied with water-resistant coatings that reduced moisture influx and absorption of water. Two major functions of water-resistant coatings are (i) increasing the adhesion strength of the reinforcement and (ii) preventing the water from permeating into the bamboo-composite reinforcement while in concrete [10].

Moreover, the alkali resistance test of bamboo composite in concrete was carried out to evaluate tensile capacity retention of the concrete [10]. The tensile capacity retention (R_{et}) for the modulus of elasticity as well as the tensile strength of the specimen is displayed in Fig. 23. A similar trend in the reduction of both tensile properties was observed. However, owing to alkaline solution exposure, the elastic modulus was influenced more than the tensile strength. Eventually, the tensile properties reached a stable condition after one-month exposure to the alkaline solution.

Based on this investigation, Javadian et al. [10] recommended that for affordable low-story buildings, bamboo-based composite reinforced concrete could be used. Because the ductility requirement is low for the low-rise buildings and secondary-element failure of those composites delivers adequate cautionary signs of breakdown.

In another study, bamboo fiber vinyl-ester composite plate (BFVCP) was used for the strengthening of reinforced concrete (RC) beams [57]. The outcomes exhibited that the highest tensile strength of the specimen was obtained using the fiber volume fraction of 40%. However, the drawback of this study is due to the short bamboo fiber length which causes insufficient anchorage length bonded along the tension zone of the beam. Consequently, limited improvement in the beam structural capacity was achieved. They recommended that BFVCP may be used for the external strengthening of a weakened beam.

6 Conclusions and Future Perspectives

Reinforced concrete is being used as building materials from the time immemorial. The most prominent reinforcement for concrete for infrastructure construction is steel. However, limited availability of steel in developing and underdeveloped countries, increasing cost and energy associated with steel production, and last but not least, its sensitivity to corrosion raised the concern for finding alternative natural materials for concrete structure reinforcement. Evidently, the utilization of bamboo/bamboo fiber as reinforcement boosts the infrastructural performance. Bamboo reinforced concrete beams and slabs used in masonry walls, roofing, pavement, etc. are showing promising outcomes due to their durability, reduced weight, and environmental friendliness. However, more significant research works are required to assert the potential of bamboo as a reinforcing material for construction infrastructures.

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