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Review

Bamboo fibre reinforced biocomposites: A review

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ABSTRACT

The reduction in harmful destruction of ecosystem and to produce low cost polymeric reinforced composites, the researchers are emerging with policies of manufacturing the composites using natural fibres which are entirely biodegradable. These policies had generated safe strategies to protect our environment. The utilization of bamboo fibres as reinforcement in composite materials has increased tremendously and has undergone high-tech revolution in recent years as a response to the increasing demand for developing biodegradable, sustainable, and recyclable materials. The amalgamation of matrix and natural fibres yield composite possessing best properties of each component. Various matrices used currently are soft and flexible in comparison to natural fibres their combination leads to composite formation with high strength-to-weight ratios. The rapid advancement of the technology for making industry products contributes consumer the ease of making a suitable choice and own desirable tastes. Researchers have expanded their expertise in the product design by applying the usage of raw materials like bamboo fibre which is stronger as well as can be utilized in generating high end quality sustainable industrial products. Thereby, this article gives critical review of the most recent developments of bamboo fibre based reinforced composites and the summary of main results presented in literature, focusing on the processing methodology and ultimate properties of bamboo fibres with polymeric matrices and applications in well designed economical products.

1. Introduction

The soaring prices of raw materials for engineering and standard plastics, the future sustainability of natural reservoirs and threat to environment have forced to use natural redeemable materials for development and fabrication of polymer composites [1,2]. The use of synthetic fibres had dominated the recent past of reinforcement industry; however the natural fibre reinforcement had gained much impetus to substitute this synthetic fibre in various applications [3]. The combination of natural fibres with polymer matrices from both non renewal (petroleum based) and renewal resources used to produce polymer composites that are competitive with synthetic composites is gaining attention over the last decade [4]. Biodegradable plastics and bio-based polymer products from renewal resources can form sustainable and eco-friendly products than can compete and capture current market which is dominated by petroleum based products [5]. Researchers have exploited both softwoods as well as hardwoods to extract the fibres for reinforcement in various composites [3]. For some developing countries, natural fibres are of vital economic importance: for example, cotton in some West African countries, jute in Bangladesh and sisal in Tanzania [1].

The countries where there is scarcity of forest resources, agricultural crops have been utilized for developments and research on polymer composites. Bamboo is one of the agricultural crops which can be exploited for the design and development of polymer composites [6]. Bamboo is found in abundance in Asia and South America. In many Asian countries bamboo has not been explored fully to its extent although it is considered as natural engineering material. This sustainable material has evolved as backbone for socio-economical status of society as it takes several months to grow up. Traditionally bamboo has been used in various living facility and tools, which owes to its high strength to its weight. This property is due to the longitudinal alignment of fibres. In practice, it is mandatory to fabricate the bamboo based composites in addition to the extraction of bamboo fibres in controlled way from bamboo trees [7,8]. The bamboo fibres are naturally possessed with finer mechanical properties, but are brittle in nature as compared to other natural fibres due to the extra lignin content covering the bamboo fibres.

Presently bamboo is considered important plant fibre and has a great potential to be used in polymer composite industry. Its

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structural variation, mechanical properties, extraction of fibres, chemical modification, and thermal properties had made it versatile for the use in composite industry [9,10]. On the basis of earlier reports, bamboo has 60% cellulose with high content of lignin and its microfibrillar angle is 2–10°, which is relatively small. This characteristic property has made bamboo fibre as fibre for reinforcement in variety of matrices [9,11]. A variety of methods have been developed by researchers to extract the bamboo fibre for reinforcement of composites. Alkaline treatment was used as a tool for facilitation of bamboo fibre extraction and optimizes separation of bamboo fibres for preparation of bamboo fibre reinforced polymer composites [12,13]. Researchers investigated the changes occurring in fine structure of bamboo fibre due to treatment with different concentration of alkali solution [14]. In an interesting study, researchers investigated effect of mercerization of bamboo fibres on mechanical and dynamical mechanical properties of bamboo composites [15,16]. The common approach towards fabrication of composites from bamboo is to obtain better properties as compared to synthetic fibres. Bamboo fibres used as filler and twin-screw extruder was used for compounding of bamboo and biodegradable polymer for fabrication of bamboo reinforced polymer composites [9]. In another study, researchers used orthogonal bamboo fibre strip mats for fabrication of bamboo fibre reinforced epoxy and polyester composites by using hand lay-up technique [17,18]. Dried bamboo fibres were used for preparation of short bamboo fibres reinforced epoxy composites and their chemical resistant and tensile properties with fibre length have been studied [19]. Researchers used bamboo belongs to species of Bambusa Paravariabilis, which grows abundantly in Asia for development of bamboo fibre reinforced polypropylene composites [20]. In an interesting study, bamboo which commonly grown in Singapore and can be abundantly throughout Southeast Asia was used together with E-glass fibres as reinforcement in the hybrid composites [21]. Researchers studied the effect of fibre length on the mechanical properties of polymer composites by using starch resin and short bamboo fibres [22].

A considerable effort has been made by researchers in good use of bamboo fibre as reinforcement in polymer composites. Bamboo fibres extracted from raw bamboo tress by steam explosion technique used for development of eco-composites and evaluated mechanical properties of bamboo fibre reinforced polymer composites [23]. Biodegradable and environment-friendly green composites developed by utilizing micro/nano-sized bamboo fibrils possessing moderate strength and stiffness [24]. Flexural properties of bio-based polymer composites made from bamboo and biodegradable resin were evaluated and it compared with kenaf composites [25]. They also calculated flexural modulus by Cox's model that incorporates the effect of fibre compression were in good agreement with experimental results. Morphological and mechanical properties of bamboo flour filled HDPE based composites were investigated in respect of crystalline nature of maleated elastomer modifier, combined EPR-g-MA and PE-g-MA modifier systems and loading rate of bamboo flour in the presence of combined modifier [26]. Researchers investigated thermal properties of jute/bagasse hybrid composites and observed that thermal properties of hybrid composites increased by increasing char residue at 600 °C [27]. Polypropylene/polylactic acid/bamboo fibres blend composites were fabricated and morphological, and thermal properties of blend composites compared with neat polymers [28].

The presence of different functionalities particularly hydroxyl groups in the bamboo fibres would lead to the weak interfacial bonding between fibres and the relatively hydrophobic polymers, therefore researchers have tried to improve these properties by different interfacial treatments [29]. The strengthening effects on the bamboo fibres containing various matrices such as polystyrene, polyester and epoxy resins have been extensively studied. The economic value, light weight, high specific strength and non hazardous nature of bamboo fibres are among most attractive properties of this material which makes researchers to work in the direction of composite technology. Therefore, it can be revealed that bamboo fibre based composites have potential use in automotive industry, can replace the non-renewable, costly synthetic fibres in composite materials, particularly in the automotive industry and including household sectors. Presently an ecological threat has forced many countries to pass laws for using 95% recyclable materials in vehicles. The current era is the time for using natural fibres, particularly bamboo fibre based composites in daily lives. The extensive research from every field either engineering, biotechnological (genetic engineering), cultivation, etc. are trying to make one goal of utilizing these bamboo fibres in better way in composite Industry.

2. Socio-economic aspects of bamboo and bamboo fibre reinforced composites

The diversity of bamboo is itself reflected by its number of species, there are roughly 1000 species of bamboo found word wide. Bamboo grows very fast rather it is better to say extremely fast growing grass. Since, ancient time's bamboo has been utilized in many Asian countries as well as South America for centuries. Bamboo can be considered an ecological viable substitute for commonly used wood in many ways. Bamboo attains maturity in 3 years as compared to wood which takes almost more than 20 years. After maturity tensile strength of bamboo is comparable to mild steel. The growth rate of bamboo is unbelievable, the known fastest bamboo grows vertically two inches per hour and in some moso bamboo species the height of 60 feet is achieved only in 3 months, thus the cutting down this substitute wood would not affect the ecological balance at all. Trade for bamboo and bamboo products is growing very rapidly, the reason for market value of bamboo is shortage of wood production in many countries and bamboo is best option to substitute wood in terms of growth factor [30]. The business and trade of bamboo and its products either house hold materials, panels or decorating products has a collective effect on both global environment as well as economic development. Although the export trade of raw bamboo materials showed a decrease from US $ 61 million in 2001 to US $ 45 million in 2009, the decrease in export of bamboo may be due to the domestic utilization of bamboo. The China is highest exporter to USA and EU (Table 1).

The farmers are primary benefiters for growing and harvesting the bamboo. The good source of income from growing and harvesting the bamboo has polished their basic skills in terms of cultiva-

Table 1
Bamboo export and import trade flow. *Source*: http://trade.inbar.int/Home/Analysis.

Top exporters		Top importers	
Country	US $ million	Country	US $ million
Canada	3	Turkey	7
South Africa	3	Norway	8
Mexico	3	India	9
Nigeria	8	Mexico	9
Hong Kong, China	9	South Africa	12
Malaysia	14	Hong Kong, China	13
Myanmar	15	Russia	19
Singapore	18	Switzerland	20
Thailand	18	Rep. of Korea	25
Philippines	30	Australia	26
USA	30	Singapore	31
EU-27	54	China	40
Vietnam	84	Canada	54
Indonesia	269	Japan	194
China	1034	USA	254
		Eu-27	230

tion, handle the pressure if there is some loss in marketing of bamboo, and enrich them with empowering ability. The ecological system is directly related to bamboo plantation, it helps in reducing landslides, soil erosion, and an unproductive land can be converted into productive land. The livelihood of poor rural farmers is boosted by bamboo cultivation skills. The protection of degraded land and environment can be well established by cultivating the bamboo, not only this food security can be evolved by intercropping the bamboo with other food plants. The bamboo cultivation requires least investments; the investment is needed for bamboo propagation, land and manpower. The socio-economic benefits in terms of raw materials cultivation or product development (Furniture, flooring, bamboo based composites, fencing, decoration, etc.) leading to production of long lasting consumer goods is no doubt contributing to a greater extent in developing the economic values of many countries [30] The depletion of natural resources and fast increasing prices of crude oil have triggered the interest in utilizing the bamboo in composite technology. Imposing the strict laws to design the eco-friendly consumer goods is forcing industries to develop the methodology of using regenerable resources for fabrication of composites; bamboo is one among the best resources which can be used as reinforcing agent in composites instead of using glass fibres which directly depend on the depleting natural resources [31]. The researchers are looking for the greener solution of this environmental threat. The easy availability of bamboo has stimulated a new era of composite industry. A step towards policy making and technological initiatives need to speed up to use bamboo composites in public interest in order to avoid the use of wood. The evolution in bamboo based composites in house hold things, transportation, construction have moulded the bamboo economics into new direction while benefiting the common people both economically as well as socially. The promotion of bamboo based composites have generated new avenues for employment, all over world the policies are being made to develop interest among common masses by implying different policies for example exempting bamboo composites from excise duties [32].

3. Bamboo fibres

3.1. Global distribution of bamboo

The bamboo is grown in various continents of the world, it has been divided accordingly; Asia–Pacific bamboo region, American bamboo region, African bamboo region and European and North American region (Table 2). The Asia–Pacific bamboo region is the largest bamboo growing area in the world. In Asian countries, bamboo is known by different names, In China it is known as "friend of people", "wood of the poor" in India, "the brother" in Vietnam [33,34]. FAO provided the data of bamboo production at global level as shown in Fig. 1. In Asia, large area of bamboo is occupied by six countries viz. India, China, Indonesia, Philippines, Myanmar, Vietnam and others. Globally among sympodial and monopodial, sympodial type of bamboo dominates major part [30]. The extensive awareness of bamboo plantation in China has lead to an increase in monopodial bamboo by about 30%.

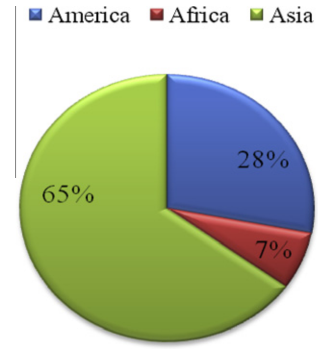


Fig. 1. World percentage of bamboo from different continents [30].

3.2. Extraction of bamboo fibres

The bamboo fibre is obtained from bamboo tree and it is divided into two kinds of fibre according to different process flow and method: Natural original bamboo fibre and bamboo pulp fibre (namely bamboo viscose fibre or regenerated cellulose bamboo fibre). Original bamboo fibre is directly picked up from natural bamboo without any chemical additive, using physical and mechanical method. In order to differentiate from bamboo pulp fibre (bamboo viscose fibre), we call it as original bamboo fibre or pure natural bamboo fibre. But bamboo pulp (viscose) fibre belongs to regenerated cellulose fibre as chemical fibre. Broadly there are two types of processing to obtain bamboo fibres viz. mechanical processing and chemical processing. Both processes initially include splitting of bamboo strips, which is followed by either mechanical processing or chemical processing depending upon the further use of bamboo fibres. Chemical processing includes initial alkali hydrolysis (NaOH) to yield cellulose fibres. Alkali treated cellulose fibres are then passed through carbon disulphide via multi phase bleaching. Most of the manufactures use this process as it is least time consuming procedure to yield the bamboo fibres.

However, in mechanical process, the initially crushed bamboo is treated by enzymes leading to formation of spongy mass and by the help of mechanical comb fibre technology, individual fibres are obtained. This method is environment friendly as compared to chemical process, although it is less economic process. Researchers reported detailed method of fibre extraction and it was divided into rough and fine bamboo preparation [35]. The rough bamboo fibres were obtained by cutting, separation, boiling and fermentation with enzymes of bamboo. While as to obtain fine bamboo, the steps followed are boiling, fermentation with enzyme, wash and bleach, acid treatment, oil soaking and air-drying. The detailed outline is given in Fig. 2.

3.3. Chemical composition and structure of bamboo fibres

The chemical composition of bamboo fibre constitutes mainly cellulose, hemicelluloses and lignin. These components are actually same high-glycans, and make about 90% of total weight of

Table 2
Bamboo regions along with countries [30].

Bamboo region	Countries
1. Asia–Pacific	China, India, Burma, Thailand, Bangladesh, Cambodia, Vietnam, Japan, Indonesia, Malaysia, Philippines, Korea and Sri Lanka
2. American bamboo region (Latin America, South America and North America)	Mexico, Guatemala, Costa Rica, Nicaragua, Honduras, Columbia, Venezuela and Brazil
3. African bamboo region	Mozambique, Eastern Sudan
4. European countries	England, France, Germany, Italy, Belgium, Holland. United States and Canada have introduced a large number of bamboo species from Asian and Latin American bamboo-producing countries

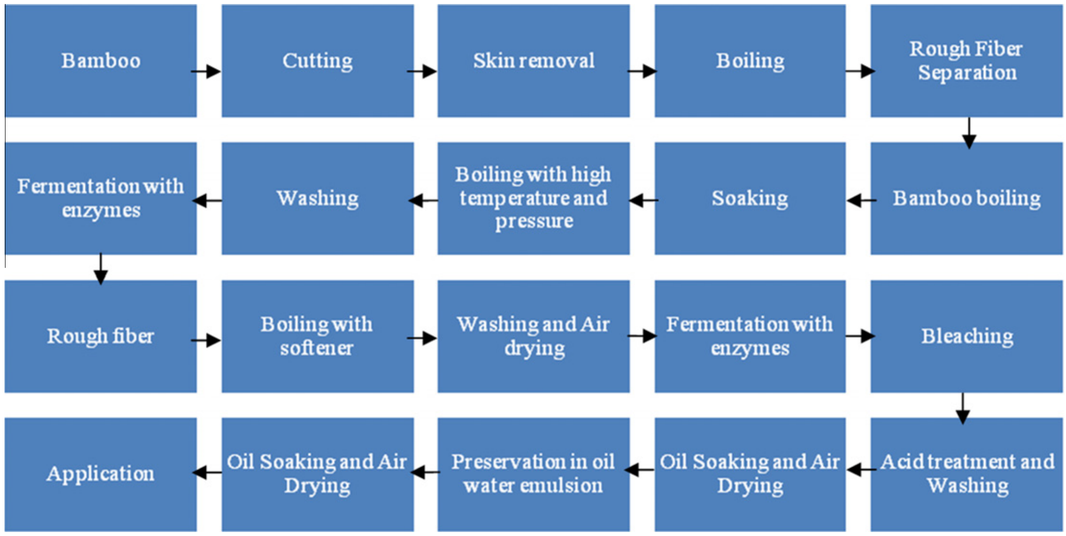


Fig. 2. Extraction of rough and fine bamboo fibre [35].

bamboo fibre. The other constituents are protein, fat, pectin, tannins, pigments and ash. These constituents play important role in physiological activity of bamboo and they are found in cell cavity or special organelles. The chemical composition of the bamboo fibre is given in Fig. 3 [36]. Usually the chemical content of bamboo changes with age of the bamboo, particularly cellulose content keeps on decreasing while age of bamboo is increased so directly it directly affects the chemical composition of bamboo fibre. The lignin is considered to provide stiffness and yellow colour to bamboo fibres. Different treatments cannot remove all the lignin content of the bamboo fibres, as lignin has been found quite resistant to various alkalis. Non cellulosic components have enough contribution to fibre properties such as strength, flexibility, moisture, and even density [37]. The unidirectional arrangement of bamboo fibres in tissues and cell wall structure of bamboo is one of unique property of bamboo [38–40]. Bamboo fibres possess alternate broad and narrow polylamellate structure with alternating broad and narrow lamella as compared to sandwich like structure of wood fibre [41,42]. One the characteristic of ultra structure of bamboo fibre is variation in arrangement of cellulose fibrils along their longitudinal axis. The alternate narrow and broad layers have different arrangement of cellulose microfibrils, with large microfibril angle in narrow layers and low microfibril angle perpendicular and parallel to the main cell axis, respectively [41]. The lignin plays important role and is present in different concentration in different layers of cell wall. In addition, hemicellulose, phenolic acids (e.g. ferulic and *p*-coumaric acids), are responsible for covalent bonding in the cell wall structure. This variation of different components across the cell wall provides novel design to bamboo fibre wall, enhancing its various mechano-physical properties [38,43,44]. Recently, two researchers reported extensive studies on structure of bamboo fibre of different species and investigated the cell wall structure of different bamboo species [45,46]. A study on bamboo species *Guadua angustifolia* revealed the presence of irregular form and more precisely beam shaped pattern of bamboo fibres (Fig. 4) [45]. Their size was found to depending upon the position across the cell wall. However, irrespective of position of bamboo fibre across the cell wall, a fibre with pentagonal or hexagonal, arranged in a honeycomb pattern was observed.

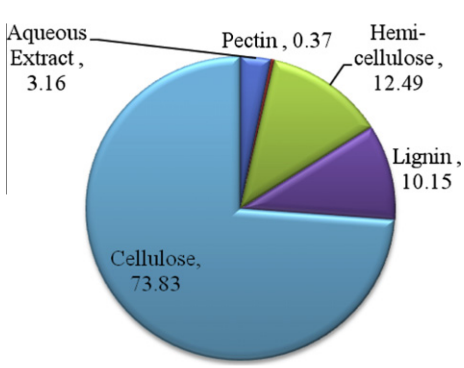


Fig. 3. Chemical constituents of Bamboo fibre [36,37].

The morphology of bamboo fibres revealed the clean surface of bamboo fibre with no apparent damage, the roughness found at surface will help in fibre matrix bonding, the main utilization of bamboo fibres (Fig. 5). They also reported the insight about the fibre dimensions of different species of bamboo fibre obtained from different position of respective bamboo culms (Fig. 6) [46]. The polylamellate structures do not exist in the cell wall of the fibres of the normal wood. Based on its anatomical properties, ultra structure and plant fracture mechanism bamboo establishes itself as a superior natural fibre.

4. Eco bamboo fibre composites

Scientists have welcomed the move of imposing regulations for better and safer environment and had given a new direction to researchers towards generation of new ideas in eco-composite technology [47–49]. Eco-composite can be defined as composites with better environmental and ecological advantages over synthetic or conventional composites. Eco-composites can be fabricated from natural fibres or variety of natural polymers and polymer matrices. This field has gained enough popularity in recent years and keeps on increasing day by day, although much has not been achieved yet.

4.1. Polyester based bamboo fibre reinforced composites

Natural fibre composites had gained much attention in structural applications in recent years. But this natural material is extremely difficult to be produced. Thus, defected material with different degree of cracks may occur during service. Therefore, it is necessary to understand how these difficulties may be overcome. It has been

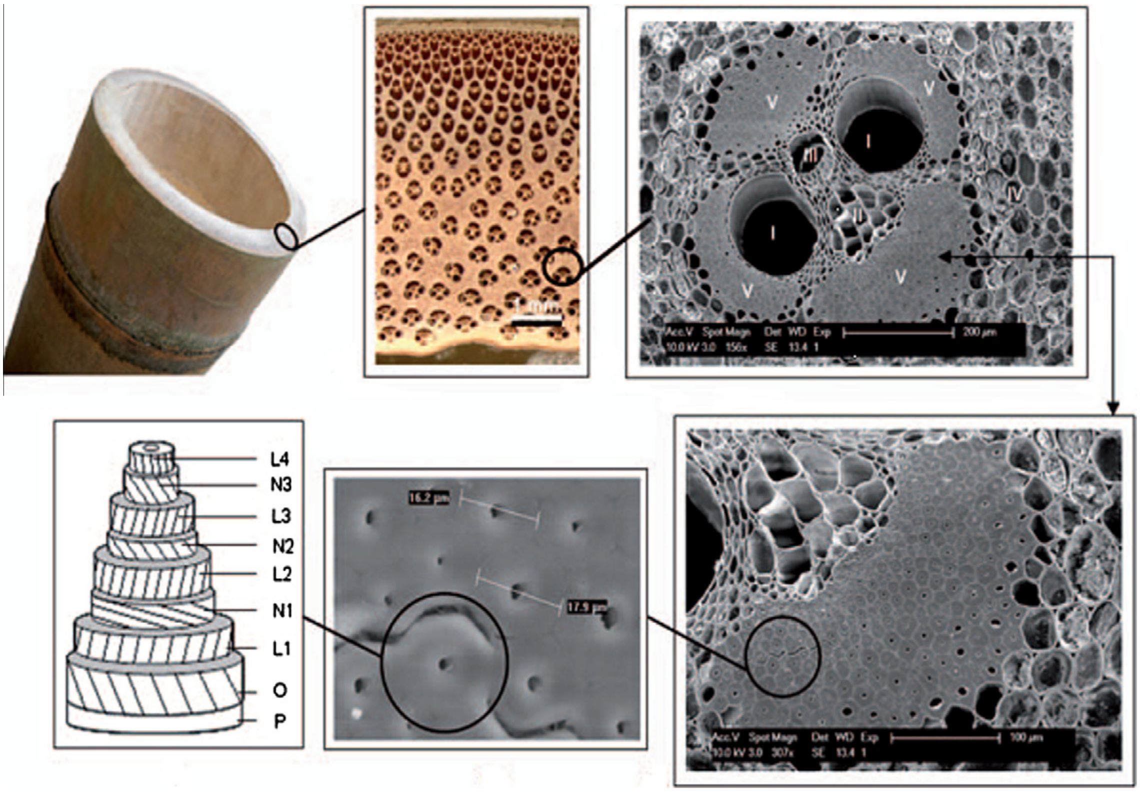


Fig. 4. Bamboo microstructure [45].

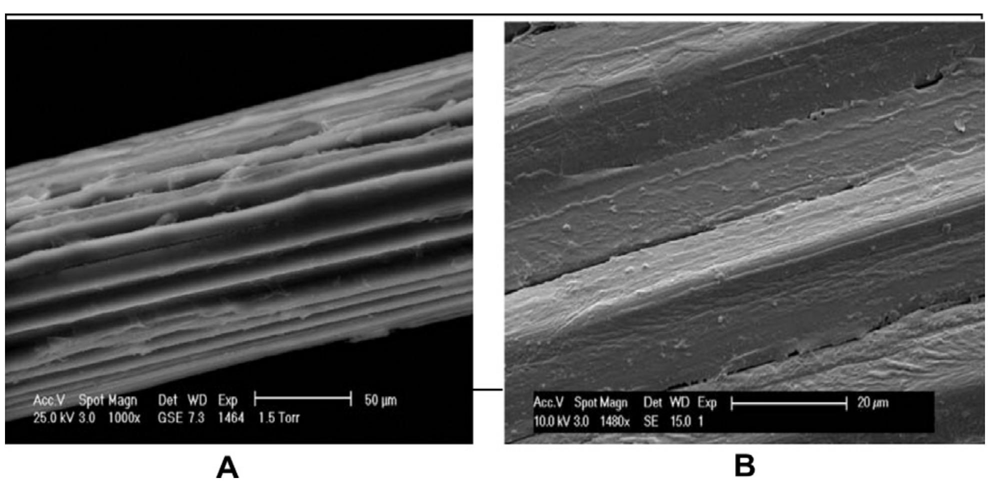


Fig. 5. (A) SEM images of bamboo (*G. angustifolia*) fibre bundle after mechanical extraction. *Note*: The fibre bundle is composed of several elementary fibres, and (B) SEM images of bamboo (*G. angustifolia*) showing the roughness of the fibre bundle after mechanical extraction [45].

reported that toughness of a brittle polymer for example, polyester can be improved through natural fibre reinforcement [50]. In an interesting study, researchers have selected the bamboo fibre to study the fracture behaviour of bamboo fibre reinforced polyester composites [51]. These composites were characterized by different approach utilizing a technique known as LEFM approach. In another study, they reported comparison study on bamboo and other fibres used as reinforcement in polyester matrix [52]. They developed a composite material of high strength and light weight applications. Effect of different properties viz mechanical and water absorption of bamboo reinforced polyester composites have been reported [53]. In order to yield better properties results they have physically modified the bamboo fibre by different concentration of NaOH. Tensile and flexural strength were extensively studied and the enhanced results were attributed to the less water uptake by the composites by alkali treatments making them more durable. In another recently published work, they used different chemicals to modify the bamboo fibre to estimate various mechanical, physical and morphological properties of bamboo reinforced polyester composites [54]. They concluded that obtained results from various modifications of bamboo fibre show variation in mechanical, physical and morphological properties of bamboo reinforced polyester composites.

Maleic anhydride treatment improved the mechanical (Modulus of elasticity and flexural modulus) as well as water-resistant properties (water uptake) of bamboo–epoxy composites, similar

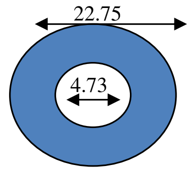
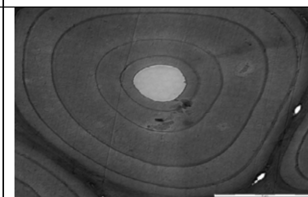
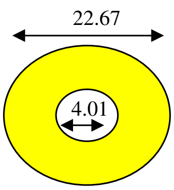
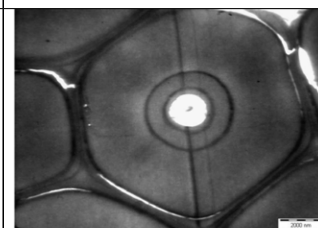
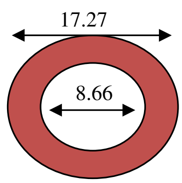
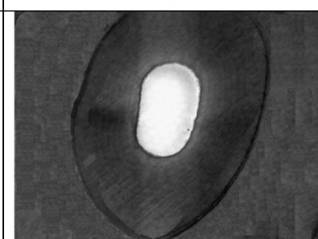
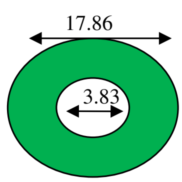
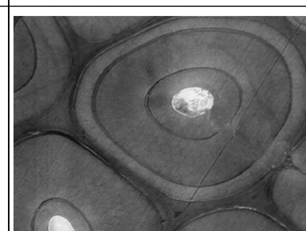
Species	Fiber and Lumen diameter (μm)	Fibre length (μm)	TEM image for individual fiber
G. brang		1910	
G.levis		2040	
G.scortechinii		1745	
G.wrayi		1799	

Fig. 6. Fibre dimensions and TEM images of different species of bamboo [46].

trend was observed in the properties of other chemically modified (permanganate and benzoylation treatments) bamboo fibre polyester composites. They supported their findings of mechanical properties by observing the scanning electron microscope (SEM) images which revealed that fibre-polyester bonding was improved by using modified bamboo fibres in composites. Previous research investigated acrylonitrile treated bamboo fibres reinforced composites and observed that acrylonitrile treated bamboo fibres affected the tensile, flexural, and water absorption properties of composites [55]. They also studied morphological properties of composites, it exhibited fractured surfaces due to arose tension, enough quantity of residual resin occurred on the surface with gaps between the cells. Further study, they reported water absorbing properties of bamboo reinforced polyester composites [56]. In this study mercerized bamboo fibres, modified by various silanes were carried out to observe the changes in water up taking capacity of composites. The main aim of their study was to visualize the hydrophilic character of bamboo based reinforced composites in order to support the current demand of utilization of bamboo in outdoor applications. In another study, researchers reported the use of extracted bamboo fibres as reinforcement for polymers [12]. The overall objective of this work was to investigate the fibre extraction from bamboo strips and the use of these bamboo fibres as reinforcement for polymers, utilizing both chemical and mechanical means to obtain the bamboo fibres. The developed polyester bamboo reinforced composites were analyzed to yield information about tensile strength and morphological properties.

Researchers developed bamboo reinforced polyester composites by hand lay-up technique and bamboo strips used were treated by alkali prior to further studies [57]. They also studied effect of bamboo fibre loading variations on mechanical properties of bamboo reinforced polyester composites and observed best results at 60% fibre loading. The interaction between matrix and bamboo fibre was supported by fourier transform infrared spectroscopy (FT–IR), and revealed that hydrogen bonding is main cause of interaction between the fibre and matrix. The fractured surfaces with varied degree of topography were visualized by SEM studies. Bonding interaction between the polyester and modified bamboo was observed with least pull out of cellulose fibrils. As it is evident that natural fibres are sensitive to alkali treatment and hence it get dissolved during treatment which makes fracture in the fibre from the lumen, longer cellulose fibre pull-out from hemicellulose–lignin matrix was reported in this study. The mechanical, thermal, and morphological properties of polycaprolactone and bamboo fibre composites were evaluated [58]. In order to attain the homogeneity between matrix and the bamboo fibre, the maleic anhydride grafted polycaprolactone was used for the study. The mechanical (Tensile and elongation at break) properties of bamboo fibre/maleic anhydride grafted polycaprolactone composites enhanced as compared to the bamboo fibre/polycaprolactone composite.

4.2. Epoxy based bamboo fibre reinforced composites

The adhesive wear and frictional performance of bamboo fibre reinforced epoxy composites were studied [59]. It reported that wear performance of bamboo fibre reinforced epoxy resin composite had excellent wear resistance, as compared to neat epoxy. The friction performance of bamboo fibre reinforced epoxy composite was enhanced by almost 44% at low sliding velocity for anti parallel orientation as compared to the higher sliding velocity. Morphology of these composites exhibited superior orientation in antiparallel direction as compared to other directions. This observation was attributed to high shear resistance incurred by the bamboo fibre that influenced the wear and friction for the different sliding velocities. Another study reported about mercerized the bamboo fibres to yield the bamboo fibre-reinforced epoxy composites [60]. The resulted composites possess of two fibre orientations parallel and perpendicular to the electric field was achieved. The effects of fibre alignment and alkali treatment on the dielectric properties of bamboo fibre epoxy composites and to evaluate the performance of a standard laminating resin was their main concern on the basis of structural concern. The dielectric, electric modulus, AC, and DC conductivity studies were carried out to explain the dielectric behaviour of bamboo epoxy composites. These characteristic properties such as high volume resistivity, good mechanical properties and less cellulose content and small microfibrillar angle of bamboo fibre makes bamboo fibre reinforced epoxy composites as cost effective biocomposites used for dielectric application. In an interesting study, researchers investigate the effect of silanes on mechanical properties of bamboo fibre–epoxy composites [56]. They prepared two sets of bamboo–epoxy composites, one with silane treatment bamboo mats and the other with silane treatment mercerized bamboo mats. The mechanical properties such as tensile strength, elastic modulus, flexural strength and flexural modulus were evaluated and it was observed that silane treatment improved the tensile and flexural strength but addition of silane treated mercerized bamboo leads to the significant reduction of the strength. Morphologies, mechanical and thermal properties of bamboo husk reinforced composites were investigated [61]. SEM studies revealed that morphology of fibres modified by coupling agents were better in the compatibility with polymer matrices perspective as compared to untreated fibres. It was reported that these composites have high storage modulus and glass transition temperature. Developed a novel mechanical extraction process to obtain long bamboo fibres and were used to fabricate epoxy reinforced structural composites [45]. They mentioned that treatment of fibres by alkali provides a plus point for favouring the bond with the matrix as this treatment removes organic and other impurities form the fibres hence enhances the interfacial bonding. The flexural and Young's modulus was also calculated theoretically and good results were obtained for fibre/matrix adhesion and fibre alignment. The effect of different derivative of silanes in addition to alkali treatment on water absorption properties of bamboo epoxy composites were extensively carried out [62]. Both alkali as well as silane treatment resulted in reduction of water absorption. The results obtained by them were attributed to improved fibre–matrix adhesion, resulting from the alkali and silane treatment. The main cause of less water absorption is greater hydrophobicity developed by treatment of bamboo fibres. Among the different silanes used in this study amino functional silanes provided best results with epoxy resins. Triethoxy derivative gave better results than trimethoxy amino silacanes, however, the best water absorption results were achieved by alkali and aminopropyltriethoxysilane treated bamboo–epoxy composite. In their study, a similar type of study was carried out with no alkali treatment was given to bamboo fibres [63]. The amino silanes have reduced the water absorption capacity of bamboo reinforced epoxy composites to greater extent as compared to untreated fibre composites. It was observed that aminopropyltriethoxy silane exhibited good results for bamboo–epoxy composites than the aminopropyltrimthoxy silane. Similar explanation stated as above was justified for the results obtained in this study, which indicates the better adhesion ensured better adhesion between epoxy matrix and bamboo hence leading to reduced water absorption in composites. Aminopropyltriethoxy silane treated bamboo fibre composite yielded good results against water absorption, and was supported by their lowest diffusion coefficient values. The overall performance of fabricated composite depends on various physico-mechanical properties particularly void content. It reported a short bamboo fibre reinforced epoxy composites and their density, void content, and percent weight reduction from the matrices [64]. The void content directly depends on the fibre content used, and it was observed that void content of these composites keep on decreasing with increasing fibre content. Similar trend was observed with density of these composites. A linear relationship was observed for weight reduction for these composites as function of matrix with linear increase, hence generating light weight composites.

4.3. Phenolic resin based bamboo fibre reinforced composites

Researchers investigated the effect of mercerization of bamboo fibre on physical, mechanical and thermal behaviour (weathering behaviour, % water uptake, % thickness swelling, and thermal stability) of bamboo fibres reinforced novolac resin composites (Fig. 7) [65]. The effect of mercerization of both treated and untreated on properties of composites were evaluated. Earlier reports clarified that these modification improve various properties such as wetting ability, interfacial strength, mechanical properties, weathering and thermal properties of the composites [19]. The weathering behaviour, water absorption, humidity and UV exposure along with dimensional changes of fabricated composites were carried out for different duration and atmospheric conditions. They reported that better thermal properties were observed after alkali treatment due to better interfacial interaction between alkali treated bamboo fibres and novalic resin. As per their evaluation, they hypothesized that alkali treatment makes fabricated composites more thermally stable up to certain range of temperature and at particular concentration of alkali. In addition, moisture absorption at 100% humidity was considered to be depending on interfacial bonding. The Dynamic mechanical analysis (DMA) of a composite material directly depends on various factors e.g. fibre content, compatibilizer, additive, orientation of the fibre and the mode of testing plays important role. There are various studies reported earlier in which these study has been utililized [66–68]. Similar studies on dynamic mechanical and thermal properties of novolac–bamboo fibre composites were reported [69]. Prior to composite fabrication the bamboo fibres were treated with alkali and it shows that obtained properties were affected by the concentration of alkali used. Thermal degradation studies revealed that alkali treatment of the fibre imparts better thermal stability to the composites as compared to untreated one. FT–IR and DMA observations suggested that best results were obtained for 20% alkali-treated fibre composites. The fabricated bamboo fibre reinforced novolac composites were characterized for their visco-elastic properties and it was best technique which provides the most appropriate information about the glass transition temperature as

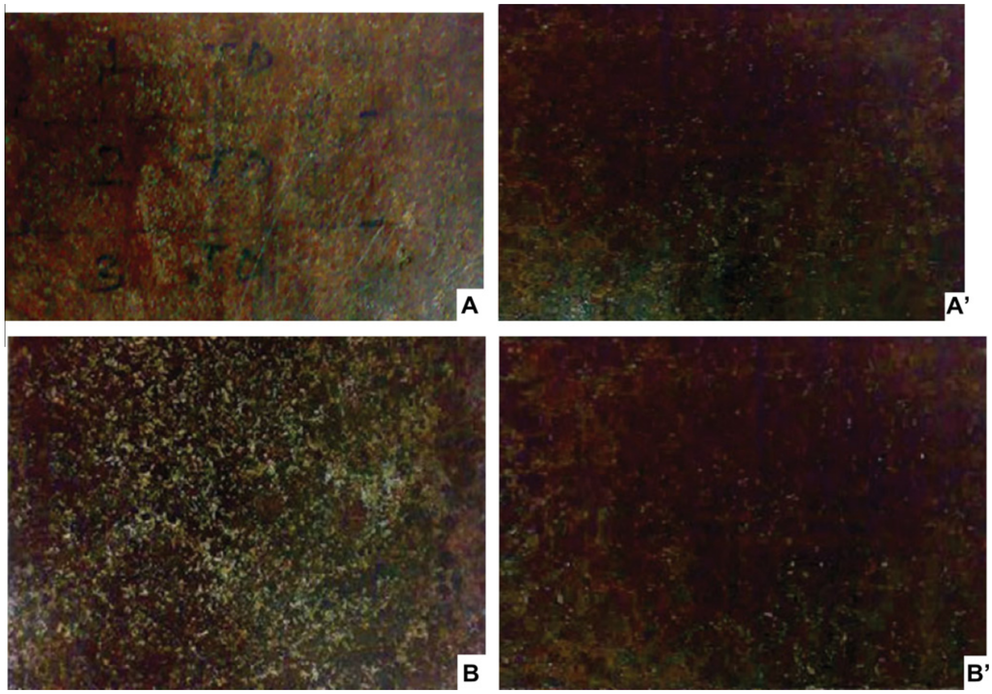


Fig. 7. Photograph of untreated bamboo strips-novolac resin composites sheet (A) before UV exposure; (B) after 75 h UV exposure; Photograph of 20% alkali treated bamboo strips-novolac resin composites sheet (A') before UV exposure; (B') after 75 h UV exposure [65].

compared to differential scanning calorimetry (DSC). The thermal stability was enhanced by using more concentrated solution and with best properties was observed at 20% alkali treatment. In another research, it reported about impact test and fracture energy of bamboo/novalac composites [70]. Bamboo fibres were treated with varied concentration of NaOH ranging from 10–25% and it revealed that fracture energy increases for composites made from untreated bamboo strips as compared to mercerized bamboo strips (Fig. 8). The developed composite has better impact strength along the fibre direction. It is known that bamboo possess weak strength across its length, and study provides potential outdoor applications of bamboo/novolac resin composites. The effect of mercerization of bamboo strips was already reported in previous study which elaborated mechanical and morphology properties of bamboo/novolac resin composites [16]. The changes in fibre structure as well as surface topography were best at 20% alkali treatment of manufactured composites, as the concentration of alkali was increased in modification of fibres, the resultant mechanical properties of composites started diminishing.

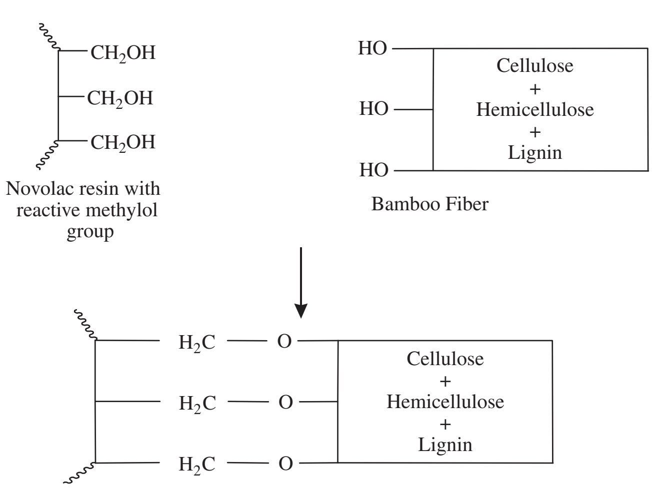


Fig. 8. Probable reaction scheme of bamboo and novolac resin [70].

4.4. Polypropylene based bamboo fibre reinforced composites

Researchers worked on Boro Baash, a Bangladeshi bamboo to obtain composites with uni and omni directional fibres (Figs. 9 and 10) [71]. The novel designed composites were fabricated according to earlier report [72]. As per their observation they consider the strength of bamboo as results of cohesive strength between sclerenchyma fibres instead of tensile strength of the fibres themselves. This strength was exploited for the fabrication of composites with novel design. They made a comparative study of strip thickness, width, and orientation of strips on mechanical and sound dampening properties of bamboo fire reinforced polypropylene composites with that of jute–polypropylene composites. Results revealed better composite properties than jute based composites.

The bamboo strips–polypropylene (PP) composites possess considerably high flexural properties. This characteristic property makes them suitable to replace nowadays most used glass fibre in automotive industry. Among other natural fibres, composite of polypropylene using pineapple leaf fibre, banana fibre, and bamboo fibre were studied for their degree and rate of biodegradation properties by specially designed experimental set up [73]. They observed that degradation of bamboo–PP composites had taken place in the areas where fibre remains attached to matrix in terms of physical forces. SEM results revealed that if bamboo fibres are exposed they got damaged while fibres embedded deep in the matrix are almost unaffected (Fig. 11). Thus, they observed that renewable resources such as bamboo fibre can be used as reinforcing agents in synthetic polymers and reducing the polymer content used in manufacturing the neat composites therefore reduce the generation of waste non-biodegradable polymers. In another research, they reported preparation of short bamboo fibre reinforced poly-

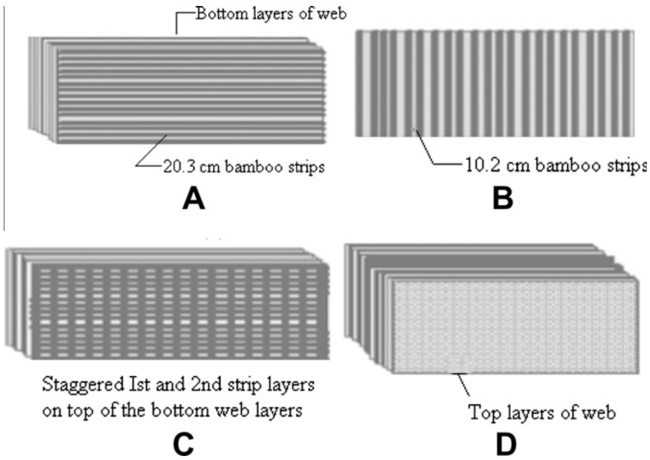


Fig. 9. (a) Layering of 20.3 cm bamboo strips on the bottom stack of web layers, (b) laying of 10.2 cm strip layer on top of the 20.3 cm strip layer, (c) after completing all six layers of strips in the alternate fashion, and (d) laying the top stack of web layer [71].

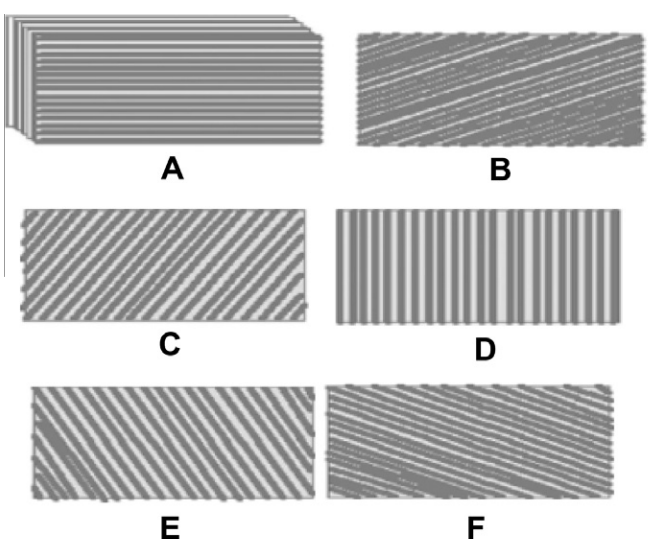


Fig. 10. Orientation of bamboo strips on web, (a) 0°, (b) 30°, (c) 60°, (e) 90°, (f) 120°, and (g) 150° [71].

propylene composites with various loadings percentages of chemically modified bamboo fibres [74].

In this study they have chosen maleic anhydride grafted polypropylene, which was supported as compatibilizer in order to improve adhesion between fibre and matrix. The direct effects of different percentage and modification of bamboo fibre on various physical and mechanical properties of PP composites indicated that both percentage and modification plays important role in varying these properties. SEM, thermogravimetric analysis (TGA), and FT–IR analysis results revealed that fracture surfaces, thermal stability and functionality of composites with modified bamboo fibres exhibited a better results and bonding pattern, respectively. The effect of alkaline and acetylating agents on morphology of bamboo fibre–polypropylene was reported [75]. The recycled polypropylene resin was used for this study. Various properties viz. mechanical, thermal, rheological property, morphology, and miscibility were extensively studied. The comparison of alkaline and acetylating treatment showed that mechanical properties of bamboo fibre–PP composites were improved. Similarly adhesion between bamboo fibre and polypropylene matrix was enhanced. In terms thermal stability a decrease in melting temperature was monitored. In addition, rheological experiments revealed that for modified bamboo fibre–PP composites rheological values are directly depended on fibre content used. Subsequent alkaline treatment and silane treatment is among the latest trends used during these days for manufacturing of composites to attain best results. In another study, they also observed that bamboo fibres and PP as the polymer matrix yields better mechanical strength for polymer composites [76]. In addition to chemical modification, filler loading of bamboo fibre also affects the physico-mechanical, thermal and morphological properties of bamboo fibre reinforced PP composites (Fig. 12).

Instead of modifying the bamboo fibres, other researchers tried modified polypropylene matrix for reinforcement of bamboo fibres [8]. They believed that polypropylene modified by maleic anhydride can be utilized in enhancing the better interaction of hydroxyl groups on bamboo fibres [20,21,77–79]. The increased mechanical properties of composites were reported as compared to conventional composites. The SEM studies carried out depicted the decrease in void content was observed in modified bamboo composites due to strong impregnation of resin matrix. The impregnation of polypropylene in composites of steam exploded bamboo fibres showed a tremendous increase in tensile strength and modulus again assigned the same reason of being presence of less number of voids. Mechanical properties of some bamboo fibre based

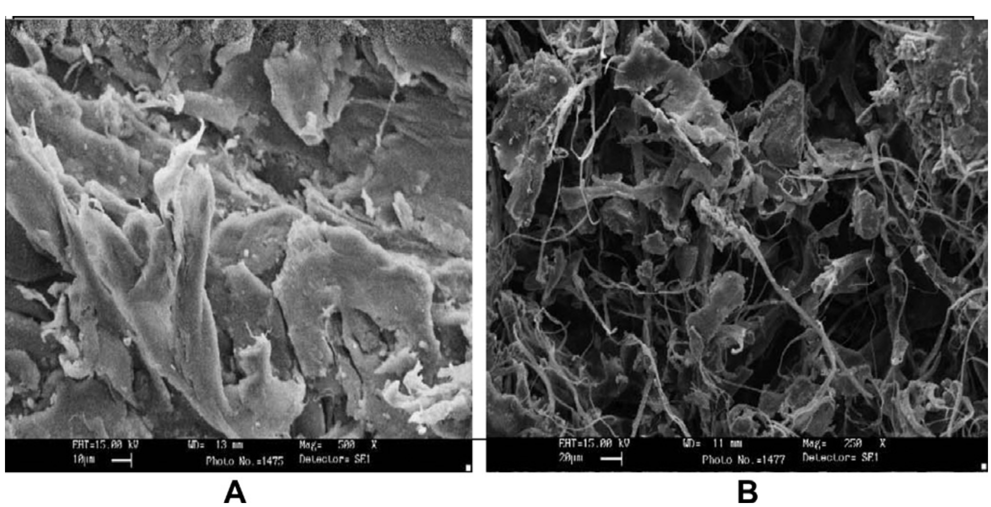


Fig. 11. (A) SEM micrographs of partially biodegraded bamboo fibre–PP interface, (B) SEM micrographs of partially biodegraded bamboo fibre–PP fractured surface [73].

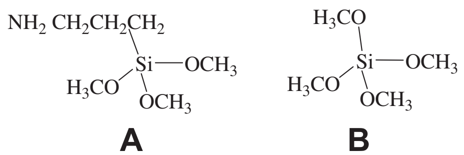


Fig. 12. Chemical structures of (a) aminopropyltrimethoxysilane, and (b) tetramethoxy orthosilicate [76].

reinforced composites is given in Table 3. In other work, researchers extensively studied the mechanical properties of bamboo reinforced with modified polypropylene resin and drastic changes were observed in these properties was observed [84,85]. The extent of adhesion and surface treatments were reported in these studies revealed that adhesion became well after this treatment. In another report a maleic anhydride grafted polypropylene was used in fabrication of composites with enhanced mechanical properties [20]. The tensile strength was found much more as compared to commercial wood pulp composites. They further speculated that such composites have a potential application as a new wood substitute.

4.5. Poly vinyl chloride and Polystyrene, based bamboo fibre reinforced composites

The interfacial adhesion is one of the important properties which improve the bonding between matrix and the fibre. Recently reported work on interfacial strength between poly(vinyl chloride) (PVC) and bamboo flour in PVC/bamboo flour composites observed improved in properties by using novel coupling agents [86]. They coupling agents were generated by one pot synthesis. The increased content of coupling agent used increases the morphological and mechanical properties of composites. Their observation revealed that coupling agent favours the affinity property between fibre and polyvinyl matrix by lowering down the interfacial tension. The SEM studies revealed better dispersion of fibre into PVC matrix due to increased amount of coupling agents used. The enhancement in mechanical properties was also indication of strong bonding between matrix and bamboo fibre. The tensile strength and chemical resistance of bamboo fibres treated with alkali and coated with polystyrene and polyurethanes systems was carried out [87]. The combination of different matrixes leads to increase in tensile properties and similar trend was observed in chemical resistance of bamboo composites. The different matrix system can be favourable matrix for making composites of bamboo, and hence can be utilized commercially.

5. Thermal characterization of bamboo fibre reinforced composites

Although a large number of reports based on characterization of plant natural fibre based composites, have been explored tremendously, but the reports on thermal characterization of fibres based composites, particularly, bamboo is quite scare. In this study, thermogravimetric analysis of alkali treated bamboo reinforced novolac resin exhibited better thermal stability as compared to untreated composites [65]. They explained that the better thermal stability was an outcome of interaction of forces between the individual components held together with the novolac resin. After alkali treatment the affinity of fibres towards to water absorption decreases as many of the hydroxyl functional groups responsible for water absorption are occupied by respective soft metal ions and subsequent neutralization generates the new cellulosic bonds between parent cellulose molecules [14,16]. The generation of new bonds makes the cellulose with tightly closed packed system; hence increasing the crystallinity index of alkali treated bamboo leading to higher stability [88]. This caged system upholds the water of crystallization leading to an increase in final temperature. Thermal behaviour like heat deflection temperature of polypropylene based bamboo fibres carried out and reported minor enhancement of thermal properties of bamboo fibre based composites after alkali treatment [74,89–91]. Thermal degradation pattern was different after fibre was introduced although slight improvement in their thermal stabilities was observed. A change in the degradation pattern of the composites was also noticed after fibre incorporation along with slight improvement in their thermal stabilities. Fibre content in composites is one of the important factor which effects thermal property directly. Researchers in one of his comparative biodegradation study explained that partial degradation is a good reason which has direct impact on thermal stability of bamboo composites [74]. The structure properties of bamboo composites and their interrelationship with the various properties like crystal-

Table 3
Mechanical properties of bamboo fibre based reinforced composites.

Bamboo fibre based biocomposites	Tensile strength (MPa)	Young's modulus (GPa)	Flexural strength (MPa)	Flexural modulus (MPa)	Reference
BF (30%) + PP	25.80 ± 60.37	1.357 ± 0.9	45.49 ± 0.88	2077 ± 4	[74]
BF (30%) + MA-g-PP	37.37 ± 0.47	1.37 ± 0.6	56.73 ± 0.49	2929 ± 5	
BF + MA-PP	35.1 ± 2.42	4.69 ± 0.55	–	–	[7]
BF + EP	86.57	–	119.69	11901.11	[53]
BF + EP + NaOH	135.00	–	149.00	9500.00	
BF + PE	126.2	2.48	128.5	3700.00	[52]
BF (30%) + HDPE	25.47	2.674	27.86	2911.70	[80]
BF 30% + HDPE-MA	28.54	2.878	53.76	4313.0	
BF (40%) + IUP	–	–	38.7 ± 4.8	4004.8 ± 216.7	[81]
BF + PE	74	–	107	4373	[56]
BF + EP	86	–	119	11901	[55]
BF + EP/PE	135	–	149	9500	[82]
BF (30%) + PP+	43.96	1240.20	45.42	1920.75	[83]
Bamboo (30%) + PP-MA	46.65	1425.55	52.30	2096.95	
BS (60%) + PP	–	–	19.15 ± 1.4	3.13 ± 0.16	[71]
BF + EP	87	–	107	11901	[53]
BF-EP-NaOH (5%)	135	–	154	9500	

BF = bamboo fibre; BS = bamboo strips; PP = polypropylene; MA-g-PP = maleic anhydride grafted polypropylene; EP = epoxy; PE = polyester; HDPE = high density polyethylene; IUP = isophthalate unsaturated polyester resin.

lization and interfacial morphology have been explained [92]. DSC curves were evaluated to observe the effect of clean matrix and their derivatives. The change from plain matrix to modified matrix has visible effect on the DCS pattern of resulted bamboo composites. The trend was observed due the presence of considered amount of β phase form. Other researchers reported that properties of composites depend on the type of filler used; inorganic fillers can act as β-nucleators thereby leading to generation of huge amount of β form, which directly affects various properties of composites, particularly thermal properties [93,94]. In another study, they considered bamboo fibre as source of β-nucleators [92]. The cause of varied degree of thermal behaviour can be attributed to the enhanced degree of adhesion between the matrix and bamboo fibres, stronger adhesion better thermal stability. Thermal behaviour of modified bamboo reinforced composites with different degree of fibre loading was investigated [76]. They compared thermal behaviour of neat matrix, bamboo and resulted bamboo composites. Weight loss was observed to be directly depended on the fibre loading and maximum peak temperature was directly affected by increased inorganic silane content on the bamboo surface. The kinetics of the recycled polypropylene reinforced bamboo fibre composites was investigated and observed that on increasing the cooling rate both crystallization temperature peak and onset temperature shifted in the lower region [95]. It was elaborated that polymer nuclei at slower cooling rate gets sufficient time to achieve activated state which leads to crystallization at higher temperatures [96]. The crystallization peak temperature at particular cooling rate was found directly proportional to content of bamboo fibre used, which was supported by the phenomenon of heterogeneous ‘nucleation effect’ of bamboo which encourages the crystallization of polypropylene matrix [97–99]. The recycled polypropylene bamboo composites possessed lower values for degree of crystallinity than neat recycled polypropylene which depicts that relative degree of crystallinity of composites required lower cooling rate [100–102].

The effect of bamboo fibres in recycled polypropylene based bamboo composites on melting temperature of the matrix was reported with slight decrease in it and increased crystallization, meaning thereby that amount of bamboo fibres directly affects the thermal property of composites [75]. It has been observed by other researchers also that fibres in composites increase both rate of crystallization as well as crystalline percentage of recycled polypropylenes [103–105]. The presence of bamboo fibre and their different loading percentage has a positive role in increasing the crystallization of recycled resins in the composites which usually takes place at higher temperatures neat recycled polypropylene resin. The nucleation effect is main factor for showing such a behaviour [106,107].

Fig. 13. Various applications of bamboo fibre composites. *Source*: www.composite-deck.com/bamboo-plastic-composite.html, accessed on April 21, 2012.

6. Bamboo fibre reinforced composites and design applications

In recent years the utilization of bamboo has been strengthened to exploit bamboo as non-wood renewable fibre. Agro-forestry has been boosted by this renewable fibre as bamboo attains full growth and maturity in one and 2 years, respectively. The fast growing and renewability of bamboo lead to an evolution in theoretical and applied research on bamboo based products, particularly in housing, furniture, packaging, transport, etc. (Figs. 13 and 14). These composites have replaced traditional wood in terms of indoor as well as outdoor applications. Their strength has been compared with traditional wood and has been found ten times stronger than traditional wood. Developed products from bamboo composites over come deficiency such as dimensional stability, longevity, weather resistant, high impact resistant, low maintenance, non toxic, and low flame spread. in conventional composites and traditional wood.

There are various companies who are involved in utilizing the bamboo composites in day today's life, bamboo composite decking, bamboo composite fencing, bamboo composite deck tiles, bamboo composite railings, bamboo composite dustbins, bamboo composite outdoor furniture, bamboo decking accessories. These products are available in market and made from 70% recycled bamboo fibres and 30% recycled High Density Polyethylene (HDPE). These bam-

Fig. 14. Furniture application of bamboo fibre based composites. *Source*: Shyamasundar K. Bamboo and Bamboo composites – Green Building Materials for housing/construction IPIRTI, Bangalore 560022. www.ipirti.gov.in, www.bamboocomposites.com, accessed on February 18, 2012.

Fig. 15. Bamboo fibre based composite decks. *Source*: www.bamboosurfboardshawaii.com/surfboards.html, accesed on March 11, 2012.

Fig. 16. Prototype of door trim that is made of bamboo composite material. *Source*: Use of Bamboo Fibre in Automobile materials by Mitsubishi Motors Co. www.japantechniche.com/2008/12/01/use-of-bamboo-fibre-in-automobile-materials-by-mitsubishi-motors-co/, accessed on March 28, 2012.

boo composites have been design with special characteristics maintaining their shape, termite resistance, high thermal stability, easy handling and installation. The end users are getting enough benefit from these bamboo based composites both in terms of cost. Recently reported works investigate the laminated bamboo lumber (LBL) for structural applications [108]. Although, the effort made for fabricating the LBL successful, however better understanding of effects on strength properties are to be well understood. The development of cost effective methodology, eco-friendly, less utilization of renewable building materials, reduction in pollution and conservation of energy has been well affected by present days bamboo based composite industry. The other application of bamboo composites are water sports for example decks (Fig. 15). Bamboo based composites used for water surfing are commonly known as surfboards. These surfboards are light weighed with particular design and water proof surfaces. These decks are multilayered bamboo boards with epoxy matrix with specialty over glass boards so that it cannot get bends thus maintaining its shape for long uses. Recently bamboo based composites have been used in making a prototype by Mitsubishi Japan. They have used polyurethane resin to develop such prototype. This product was developed by Mitsubishi in order to reduce the production cost of the materials used currently and emission of CO_2 by using plant based materials (Fig. 16). Instead of potential benefits of advanced composites, these are not considered as primary choice for materials used in automotive applications. A broad change from economic perspective is needed in advanced composites; the only option is use of plant natural fibres. Bamboo can serve as an excellent source to replace the existing crises of cost and availability of raw material.

7. Comparison of bamboo fibre reinforced composites with conventional composites

Bamboo fibres are well known for strong, stiff, inferior microfibrillar angle with the fibre axis and thicker cell wall and are considered as ''nature's glass fibre'' [109]. The production of large quantity of synthetic fibre reinforced composite, e.g. glass/carbon fibre reinforced polymer composites, conventional composites and petroleum based plastics have posed serious threat to ecosystem. The disposition or recycling of glass fibre reinforced composites is not easy and safe for environment, even after recycling these thermoplastic composites, very fewer fractions of them is incinerated. Furthermore, synthetic fibres are have high density (1–2.8 gm/cm^{-3}) than natural fibres (0.5–1.5 gm/cm^3); therefore various products made from them used in different industries affects directly the weight of those components, thus thereby increasing consumption of petroleum [110,111]. These daily encountered problems has to make a shift to development of sustainable and eco-friendly materials, mainly materials derived from the plant source which have a capability of rapid growth, bamboo fibres will be one of the leading examples as these fibres are derived from the sources which is known for its rapid growth and sustainable nature. Researchers as well as industries are working hard to replace conventional and synthetic materials with eco-friendly materials such as bamboo fibres, being one of the sustainable and economical materials to be exploited in field of biocomposites [112–114]. Biodegradable and sustainable biocomposites can be produced from bamboo fibres for indoor and outdoor applications to replace materials/products generally fabricated from glass fibres based composites and conventional composites. Bamboo fibre based polymer composites possess high strength to weight ratio, dimensional stability, durability, and amenability to be engineered to any complex shape or size at low cost of production as compared to conventional composites. Recently technology involved to process hybridization and reinforcement of bamboo fibres with glass, jute, oil palm, coir and other fibres compounding or mixing with matrices and fabricated advance composites with high mechanical and thermal properties [1]. Bamboo fibre based hybrid composites can process under controlled temperature and pressure to obtain a class of products having superior properties than the individual components.

Many researchers have reported comparative studies based on different properties of bamboo fibre based biocomposites, and glass fibre based composites. Researchers stated that bamboo fibres can replace up to 25 wt.% of glass fibres without lowering mechanical properties of glass fibre based composites [81]. They observed that quantity of bamboo fibres loading gradually increases the modulus and strength of fabricated biocomposites. In this study, they also explained hybridization of bamboo fibres with glass fibres and observed that decrease in stiffness with marginal increase in bamboo fibre loading due to poor interfacial bonding [115]. In another interesting work, researchers tried to modify the resin in order to get better comparative results of bamboo fibre and glass composites [83]. The obtained results were tabulated on the basis of collective effect of bamboo and glass fibres. The thermal properties of hybrid composites were enhanced due to the presence of bamboo and glass fibres, and it attribute to hybridization effect and fibre/matrix interface bonding. Researchers studied the effect of alkali treatment of bamboo fibre on tensile properties and chemical resistance of individual and mixed bamboo–glass fibre reinforced composites [116]. They revealed that mixing of fibres directly affect the tensile properties of composites. However, hybrid composites possessed better properties than bamboo fibre composites, which they ascribed due to the low amorphous cellulose components from bamboo fibres due to the strong acids and base treatment. In another previous work they reported fabrication of bamboo-glass composites, and studied flexural and compressive properties of bamboo-glass composites [117]. They hypothesized prior to fabrication that treatment of bamboo fibres with alkali enhances the binding capacity of fibres to the matrix. The mixing of bamboo fibres with glass fibres directly enhanced the mechanical properties of bamboo composites. Thus, these studies reveals that there is ample opportunity for bamboo fibres to replace or reduce the utilization of glass fibre content in composites and conventional composites, and to be utilized commercially on industrial scale. The comparative properties of bamboo fibre, glass fibres, and bamboo/glass fibre reinforced polymer composites are illustrated in Table 4. It's clear from Table 4 that mechanical and physical properties of bamboo fibre reinforced epoxy composites are comparable to glass fibre reinforced epoxy composites.

Table 4
Comparative properties of bamboo fibre based reinforced composites.

	Comparative properties								
		Tensile strength (MPa)	Tensile modulus (GPa)	E (%)	Flexural strength (MPa)	Flexural modulus (GPa)	Density kg/m^3	Specific heat J/kg K	Reference
Fibre	BF	500–575	27–40	1.9–3.2	100–150	10–13	1200–1500	1000–1250	[118,120]
	GF	124–150	7–10	2.5–4.8	110–150	5–9	2350–2500	796–810	[119,121]
Composites	BF–EP V_f 65%	87–165	3–15	1.7–2.2	107–140	10–12	1160–1250	–	[17,53,121]
	GF–EP $V_f = 65\%$	180–220	5–10	2.7–3.5	195–250	7–12	1960–2020	–	[119]

E = elongation at break; BF = bamboo fibre; GF = glass fibre; EP = epoxy; V_f = volume fraction (the ratio of fibre to matrix ratio V/v).

8. Conclusion

The exploitation of bamboo fibres in various applications has opened up new avenues for both academicians as well as industries to design a sustainable module for future use of bamboo fibres. Bamboo fibres have been extensively used in composite industries for socio-economic empowerment of peoples. The fabrication of bamboo fibre based composites using different matrices has developed cost effective and eco friendly biocomposites which directly affecting the market values of bamboo. To design such composites thorough investigation of fundamental, mechanical, and physical properties of bamboo fibres are necessary. Thus, this review has made an attempt to gather information for both basic properties of bamboo fibre based composites as well as their economic utilization. The scientists all over the globe have conducted a wide range of studies with novel ideas to provide basic support to working as well as employing communities. Current research on bamboo fibre based composite using both basic as well as applied science either in terms of modification, mechano-physical, thermal and other properties. But, the ultimate goal of utilizing the bamboo fibre to its full extent is far behind than its projected milestone, particularly in Malaysia, although other countries such as India and China have moved far ahead in utilizing bamboo fibre in socio-economic way. The sustainable future of bamboo based composite industry would help in utilizing the bamboo in a way other than usual traditional mode. The effective characterization of bamboo fibre as well as bamboo fibre based composites should be more advance in terms of analysis and testing. In this review article we have tried to gather the information about the analysis and testing methods used. However, scientist already done lot of works on bamboo based composites but it still required to do more research and innovation in this area to overcome potential challenges ahead. These things will make life easy for both urban as well as rural people who are more depended on synthetic based composites.

9. Future developments in bamboo fibre reinforced composites in advance technology

The sustainable tomorrow for future generation lies with the present industrial development towards eco efficiency of industrial products and their process of manufacturing. High performance, biodegradable materials and renewable plant materials can form new platform for sustainable and eco-efficient advance technology products and compete with synthetic/petroleum based products presently dominated in market which are diminishing natural petroleum feedstock. Natural fibres and biocomposites made from natural sources integrate the sustainable, eco-friendly and well designed industrial products which can be replace dominance of petroleum based products in future. Bamboo fibre is obtained from a source which is known for its renewability in terms of fast growth and better mechanical properties. The utilization of bamboo fibre for fabrication of biocomposites by using advance technology transforms future of coming generation. The well designed and engineered products from the bamboo fibre can help in making new revolution to sustain our natural resources. Thereby, based on this brief review the bamboo fibres can be utilized for advance and engineered product development for different applications. It will be an alternative way to develop the biocomposites which can be particularly used for daily needs of common people whether it is house hold furniture, house, fencing, decking, flooring, and light weight car components or sports equipments. Their low cost, easy availability and aesthetic designs will be the main driving force to transform the depended present to sustainable future.

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