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16

The use of bamboo fibres as reinforcements in composites

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Abstract: Bamboos are of notable economic and cultural significance all over the world, especially in South Asia, Southeast Asia and East Asia, being used for building materials, as a source of food source, as a decorative product and as a versatile raw product. Bamboo also has significant potential in composite making due to its high strength, environmentally friendly nature, rapid growing properties, low cost, availability and sustainability. This chapter summarizes production processes for bamboo fibres and their applications in composites. The production of nanocellulose from bamboo fibres is also briefly discussed. Overall, the chapter aims to show the versatility of bamboo fibre in various applications from construction to culinary.

Key words: bamboo fibres, nanocellulose, polymer composites, resin, surface treatment.

16.1 Introduction

As the worldwide demand for fibre grows, sustainable resource management and efficient industrial utilization must collaborate to develop a shared vision for both long-term management of bio-resources and sustainable economic development. Concerns about the environment and ecology have also sparked a new trend towards the use of environmentally friendly materials (Philippou *et al.*, 2001), thus interest in developing natural fibre-based composites is increasing rapidly. Various types of natural fibres have been studied for their application in composites, e.g. bamboo (*Bambusa* spp.) fibres, oil palm (*Elaeis* spp.) fibres, banana (*Musa* spp.) fibres, pineapple (*Ananas comosus)* leaf fibre, coconut (*Cocos nucifera*), coir (*Corchorus* spp.) fibres, jute, dhaincha (*Sesbania* spp.*),* flax (*Linum usitatissimum*), kenaf (*Hibiscus cannabinus*), henequen (*Agave fourcroydes*) and hemp (*Cannabis sativa*) fibres (Islam *et al.*, 2010; Edyham and Hanafi, 2002; Pothan *et al.*, 1997; Devi *et al.*, 1997).

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Bamboo, which belongs to more than 10 genera including about 1450 species ranging from small annuals to giant timber bamboo, is one of the oldest building materials used by mankind (Kamruzzaman *et al*., 2008). It is the fastest growing woody plant in the world and is easily accessible globally. Around 64% of bamboo plantation originates from Southeast Asia, 33% is grown in South America and the rest comes from Africa and Oceania (Bonilla *et al*., 2010). The bamboo culm, or stem, has been made into a diverse range of products from domestic to industrial applications. Examples of bamboo products are food containers, skewers, chopsticks, handicrafts, toys, furniture, flooring, pulp and paper, boats, charcoal, musical instruments, weapons, bicycles, dirigibles, windmills, scales, retaining walls, ropes and cables. With advances in science and technology and the restricted supply of timber, a wide range of technologies have been developed in recent years to process bamboo and make it more durable and usable as a building material.

Bamboo has also gained popularity as a 'green' fibre. It can be cultivated quickly and is a natural fibre (as opposed to popular synthetics like polyester) whose cultivation actually reduces greenhouse gases. Fibres can be made from the leaves, branches and trunks through chemical process, mechanical needling and scraping or through a steam explosion process. It is extremely resilient and durable as a fibre and has served as a foundation structure (Khanam *et al*., 2011; Bhat *et al*., 2011). In studies comparing it to cotton and polyester, it was found to have a high breaking tenacity, better moisture wicking properties and better moisture absorption. Cellulose from bamboo fibres is suitable for processing into viscose rayon, and viscose manufactured from bamboo is promoted as having environmental advantages over wood-pulp viscose. Bamboo is also used as an additive in biopolymers for construction and in many other applications.

To reduce any harmful destruction of the ecosystem and produce low-cost polymeric reinforced composites, researchers are working to manufacture composites using natural fibres which are entirely biodegradable, and consequently the use of bamboo fibres as a reinforcement in composite materials has increased tremendously in recent years. Its structural variation, mechanical properties, chemical modification and thermal properties have made it a versatile material (Amada *et al*., 1996). The cost, availability, light weight, high specific strength and non-hazardous nature of bamboo fibres are its most attractive properties, encouraging researchers in composite technology to work on its development. Production of nanofibrillated cellulose (NFC) from bamboo is a recent development which has many different applications such as nanobiocomposites. There has been extensive research in many fields; engineering, biotechnological (genetic engineering) and cultivation, for example, all aiming to improve the use of bamboo fibres in the composites industry.

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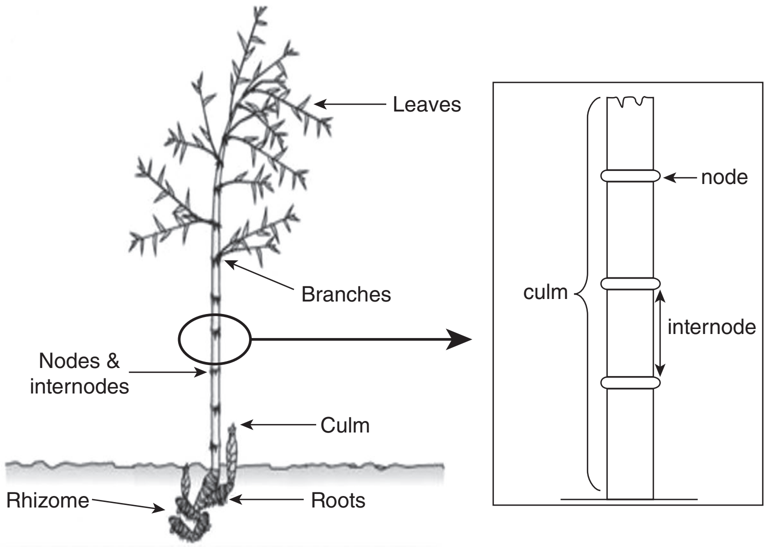

16.1 Structure of a bamboo (Sakaray *et al.*, 2012).

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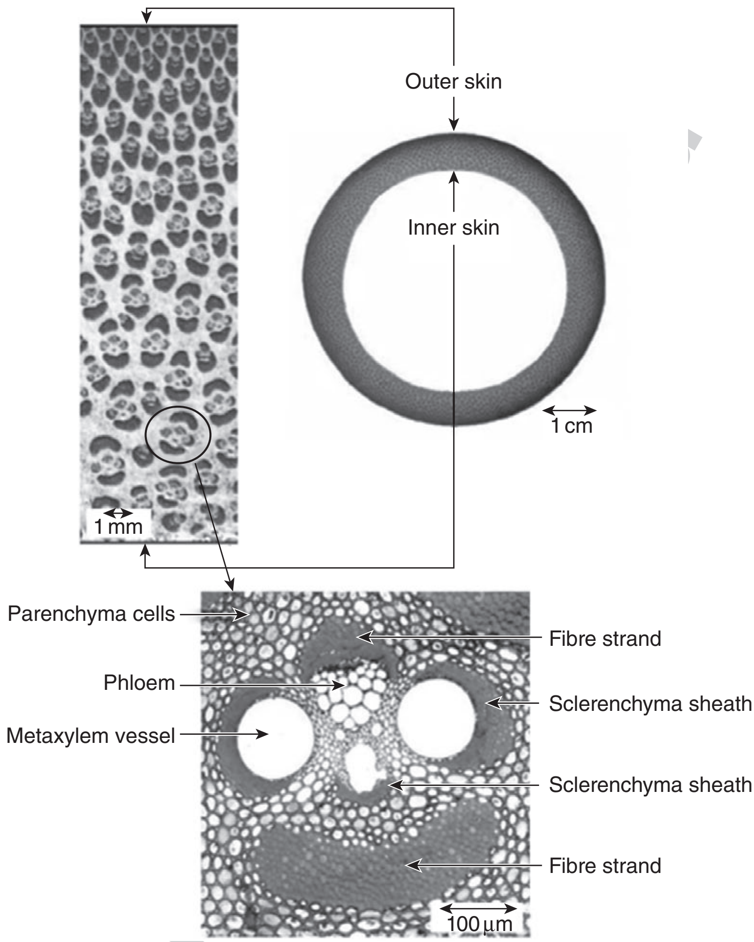
16.2 Structure of bamboo

The main parts of bamboo are the culm, node, internode, leaf and roots. The culm is a hollow stem likely to be cylindrical in shape, while the nodes can be found between the culms along the entire length of bamboo, acting as a disc inserted between each section of culms (Mwaikambo, 2006) (Fig. 16.1). These nodes play an important role in preventing buckling when the bamboo is bent (Amada *et al.*, 1996).

The structure of bamboo culm has been described over the years in great detail and most publications dealing with bamboo have focused on its anatomical structure (Parameswaran and Liese, 1980; Liese, 1998; Gritsch and Murphy, 2005; Jiang, 2007). Unlike wood, bamboo has no rings in its culm; it mainly consists of epidermis, cortex, ground tissue and lacuna. The vascular bundles which are made up of slerenchyma fibres, vessels and phloem are widely embedded in parenchymatous ground tissues (Londoño *et al.*, 2002) (Fig. 16.2). These bundles play the same role as reinforced fibres in composite materials. The fibres are characteristically thick-walled at maturity and the high tensile strength of bamboo tissue is attributed mainly to their multilayered cell wall structure (Gritsch *et al.*, 2004). The sieve tube and vessel which build up the vascular bundle are responsible for transporting nutrients and water. Jiang (2007) reported that the culm consists of about 52% parenchyma cells, 40% fibres and 8% conducting tissue. The vascular bundles are widely distributed from the periphery



16.2 Crosssection of the bamboo culm (Chaowana, 2013).

towards the inner section of the culm; however, their concentration, size and shape vary. The fibre bundles are smaller and denser when closer to the periphery compared to the inner section of the culm (Grosser and Liese, 1971; Silva *et al.*, 2006). The fibres which are strongly lignified are mainly responsible for the mechanical properties of bamboo fibres (Alvin and Murphy, 1988). According to Liese (1998) the structure and anatomy of the bamboo culm has a large impact on its physical properties as well as its uses. For example, the mechanical properties of the culm are determined by its specific gravity, which depends mainly on the density and diameter of the fibres and the thickness of the fibre cell walls and makes it suitable for use as a building material.

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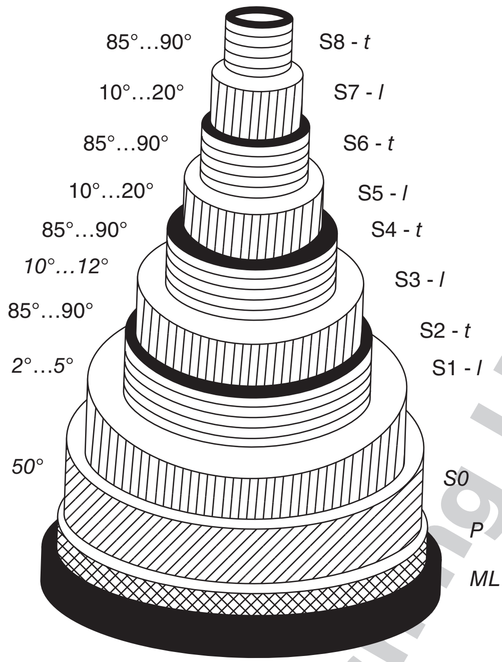

16.3 Polylamellate structure of a thick-walled bamboo fibre (ML = middle lamella, P = primary wall, S = secondary wall) (Liese, 1985).

Parameswaran and Liese (1980) reported that bamboo fibre consists of a multilayered or 'polylamellated' cell wall structure (Fig. 16.3). The lamellation consists of alternate broad and narrow layers with different fibrillar orientation. In the thick layers the fibrils are oriented at a slight angle to the fibre axis, whereas the thin ones generally show a more transverse orientation. This cell wall structure is very important because it determines the mechanical properties of the fibres (Osorio *et al.*, 2010). Fibre characteristics such as diameter, cell wall thickness and number of cell wall layers have been shown to vary according to their location in the culm and within vascular bundles, as well as to the maturity of the culm (Parameswaran and Liese, 1976; Murphy and Alvin, 1992).

16.3 Chemical properties of bamboo

Table 16.1 shows the compiled database for the chemical composition of bamboo. In general, the major chemical constituents of bamboo are cellulose, hemicelluloses and lignin, accounting for over 90% of the total mass, which is similar to wood (Jain *et al.*, 1992). According to Fengel and Wegener (1984) the α-cellulose content in bamboo is 40–50%, comparable with the

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Table 16.1 Chemical composition of bamboo

Bamboo species	Holocellulose (%)	Cellulose (%)	Lignin (%)	Extractives (%)	Ash (%)	Reference
Phyllostachys makinoi	79.9	45.3	25.5	–	–	Fengel and Shao (1984)
Phyllostachys edulis (Riv.)	–	44.5	20.5	–	2.4	Amada *et al.* (1996)
Yunnanicus bamboo	70.3	52.7	25.5	5.7	2.3	Feng *et al.* (2003)
Whangee bamboo	70.2	52.4	23.2	7.2	1.8	Feng *et al.* (2003)
Dendrocalamus asper	74.0	–	28.5	5.5	1.5	Kamthai (2003)
Gigantochloa scortechinii	67.4	–	26.4	3.4	1.3	Kassim *et al.* (1992)
Phyllostachys pubescens	71.7	–	23.6	4.6	1.4	Li *et al.* (2007)
Schizostachyum zollingeri	71.6	–	21.4	2.5	–	Nor Aziha and Azmy (1991)
Bambusa vulgaris	67.1	50.2	23.9	–	1.3	Nahar and Hasan (2012)

reported α-cellulose contents of softwoods (40–52%) and hardwoods (38–56%), which makes bamboo a suitable raw material for the pulp and paper industry. According to Mwaikambo and Ansell (2001) cellulose is the most important component for composite fabrication as higher cellulose content leads to increased stiffness and therefore greater suitabilty for resin reinforcement. The high lignin content of bamboo contributes to its high heating value and its structural rigidity with the latter making it a valuable building material (Scurlock *et al.*, 2000). Lignin also facilitates reactivity, which allows a better response to chemical modification (Mwaikambo and Ansell, 2001). The high ash content for some bamboo species can adversely affect tool knife wear during machining operations and pulp processing (Mohmod, 1993). The ash content of bamboo is mostly silica along with metals such as calcium and potassium. According to Taj *et al.* (2007) its chemical makeup contributes to the overall properties of the fibre and the composition varies for different types of fibre. Usually the chemical content of bamboo changes with the age of the bamboo, the cellulose content in particular decreasing as the bamboo matures. Thus, it directly affects the chemical composition of bamboo fibre. Meanwhile, non-cellulosic

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components also contribute to fibre properties such as strength, flexibility, moisture and even density (Abdul Khalil *et al.*, 2012).

16.4 Mechanical properties of bamboo

The mechanical properties of plant fibres depend on their physical, chemical and morphological properties such as fibre orientation, cellulose content, crystal structure and diameter or cross-sectional area of the fibre (Munawar *et al.*, 2007). The mechanical properties of plant fibres are much lower compared to those of the most widely used equivalent reinforcing glass fibres. However, because of their low density, the specific properties (property-to-density ratio), strength and stiffness of plant fibres are comparable to the values for glass fibres (Taj *et al.*, 2007).

Bamboo is one of the most popular cellulose fibre resources that are abundantly available. Bamboo shows great potential as a sustainable structural material as well as for use in textiles due to its shorter maturity cycle and high cellulose content (Wan and Ko, 2009). Chaowana (2013) reported that the mechanical properties of bamboo fibres are extremely unstable due to its variable density and moisture content, it being a heterogeneous and anisotropic material. It is well established that the mechanical properties of bamboo culm improve with age (Liese, 1985; Li, 2004). Improved mechanical properties in mature bamboo are correlated with increased specific gravity, due to anatomical changes in the vascular bundles (Mohmod, 1993). The number of vascular bundles per unit area of the stem remains unchanged over its life cycle; however, the number of fibre cells with thickened secondary walls increases within the vascular bundles (Li *et al.*, 2007). The fibre cell wall consists of highly crystalline cellulose fibrils wound spirally in a matrix of amorphous hemicellulose, lignin and pectin which act mainly as bonding agents (Biagiotti *et al.*, 2004). The mechanical properties of some bamboo species selected from several studies are presented in Table 16.2.

16.5 Cultivation of bamboo, fibre extraction and surface modification

The major steps in producing natural fibres for use in plastics include:

- Harvesting the fibre-bearing plants
- Extracting the fibres
- Further processing the raw fibre to meet the required purity and performance for use in plastic composites.

The fibre extraction procedures depend on the type and portion of plant from which the fibres are derived (e.g. bast, leaves, wood) as well as the

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Table 16.2 Mechanical properties of bamboo fibres

Species	Density (g/cm^3)	Diameter (μm)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)	Reference
Dendrocalamus membranaceus	1.38	366	639–813	33	2–7.5	Defoirdt *et al.* (2010)
Bambusa vulgaris	1.03–1.21	–	106–204	–	–	Monteiro *et al.* (2011)
–			575	27	–	Mwaikambo (2006)
Guadua angustifolia	1.44	156	811	46.4	1.9	Trujillo *et al.* (2010)
–	0.6–1.1	–	140–230	11–17	3.6–3.8	Kang and Kim (2011)
Bambusa vulgaris	–	–	882	33	3.9	Nahar and Hasan (2012)

required fibre performance and economics (Rao and Rao, 2007). Bamboos grow to their maximum height and diameter in a few months and are harvested at 4–6 years old (Wang, 2012). Different types of bamboo material can be produced during harvesting, including mat, sliver and veneer. Harvested bamboo should be split with a machete, hand splitting knives or a splitting machine, and bamboo strips are milled out from the bamboo wall. The removal of nodes is essential to ensure an even thickness of sliver. The knots (inner and outer) are removed manually using a sharp knife or width-sizing machine. This process is followed by either mechanical or chemical processing depending upon the subsequent use of the bamboo fibres (Abdul Khalil *et al.*, 2012).

All the previous reports regarding the extraction of fibres from bamboo have mainly concentrated on mechanical, chemical and combined chemi-mechanical procedures (Deshpande *et al.*, 2000; Das and Chakraborty, 2008). Chemical processing includes initial alkali hydrolysis to yield bamboo fibres. Most manufacturers use this process as it is less time consuming (Abdul Khalil *et al.*, 2012). However, bamboo fibre is also extracted mechanically. In the mechanical process, the woody parts of the bamboo plant are crushed and then natural enzymes are used to break the bamboo walls into a soft mass, enabling the natural fibres to be mechanically combed out and spun into yarn (Erdumlu and Ozipek, 2008). Conventional methods of compression moulding technique (CMT) and roller mill technique (RMT) were explored for mechanical separation (Deshpande *et al.*, 2000).

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The average diameter of fibre extracted by RMT is finer than with CMT, but the latter technique produces fibres with a higher average strength (Deshpande *et al.*, 2000). Another method used to separate bamboo fibres is the steam explosion method. In steam explosion, the water contained in bamboo is heated under high temperature and pressure and the pressure is then rapidly released to the atmosphere, so that the water evaporates, shattering the parenchyma inside the bamboo (Ochi, 2012). This method is more environmentally friendly compared to the chemical process; however, it is rarely used because it is expensive. A combination of chemical and mechanical methods has also been used for the extraction of bamboo fibres. In recent research by Anyakora (2013) bamboo fibres were impregnated with 'white liquor' and the softened sample converted into fibre by mechanical action, followed by thorough washing, screening and drying. The extracted fibres were separated, re-washed and dried in a forced-air circulation type oven.

The ultimate quality of a bamboo composite mainly relies on a proper combination of reinforcement (bamboo fibres) and binder (matrix or resins). Surface treatment before fabricating the composite is essential to induce bridging between the fibre and polymer matrix (Chen *et al.*, 1998). Natural fibres are hydrophilic; hence several researchers have carried out studies on surface treatment of bamboo fibres. Generally, surface treatments include alkali or acid and silane treatment. A recent study by Ma and Joo (2011) is the most promising one to date, showing that the tensile strength of bamboo/polylactic acid (PLA) composite increased to 88.83 MPa with silane coupling after plasma (CAP) treatment, an increase of 71.2%, and the interfacial shear strength (IFSS) improved by 87.4%. Chen *et al.* (1998) claimed that acetylation treatment is the most effective way to increase the moisture resistance of bamboo fibre. Liu and Hu (2008) reported that the modification of bamboo fibres with sodium hydroxide concentration under 11% results in a slight increase in its crystallinity index. Biodegradable fibreboard was also prepared from bleached bamboo fibres modified with cationic guar gum by Han *et al.* (2013). An increase in tensile strength and strain were observed in the treated fibre as well as improved thermal stability compared to the pure fibre. Surface treatments for bamboo fibres are still limited and further detailed studies are needed. Table 16.3 shows the effect on bamboo fibre after surface treatment.

16.6 Properties of bamboo fibre-reinforced polymer composites

Bamboo fibre-reinforced polymer composites have been developed by various researchers using bamboo fibres in the form of strip, culm or woven mat or hybridizing bamboo with synthetic fibres such as epoxy, polyester,

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Table 16.3 Effect of surface treatments on bamboo fibre

Treatment	Effect on bamboo fibre	References
Mercerization(alkali treatment)	De-waxing, remove the impurities such as matter that contained oil and grease to improve the wetting ability when spreading resin over bamboo fibre surface; reduce the weight of bamboo fibre; surface roughness of fibre increases; diameter of fibre decreases; percentage of crystallinity increased because of the removal of cementing materials which leads to better packaging of cellulose chain; lignin, fat, protein and non-water-soluble ingredients removed.	Deshpande *et al.* (2000), Mohanty *et al.* (2001), Das and Chakraborty (2008), Kang and Kim (2011)
Silane treatment	Silane coupling agent cuts down the amount of hydroxyl groups and improves the crosslinkage between fibre and matrix; increases the impact fatigue strength of composite; improves the thermal and mechanical properties of composite.	Kushwaha and Kumar (2010b), Bao *et al.* (2011), Kang and Kim (2011)
Silane coupling after plasma (CAP) treatment	Bamboo surface etching helps in increasing surface roughness and hence improves the binding of matrix.	Ma and Joo (2011)
Silane coupling during UV irradiation (CDU)	Alter the surface structure of the bamboo fibre and active binding site, which helps in improving the mechanical properties of composite.	Ma and Joo (2011)
Isocyanate silane treatment	Amino (NH_2) and cyano groups (CN) contained in amino and isocyanate silanes, which strengthen the crosslinking of cellulose and coupling agent in bamboo fibres.	Tung *et al.* (2004)
Acetylation	Moisture uptake ability decreases; alter the fiber surface structure by substituting the hydrogen atom on fibre surface with acetyl group to reduce the polarity and hence helps in fibre–matrix interaction; increase the micropores on the acetylated surface which helps to improve the bamboo/resin interaction.	Phuong *et al.* (2010), Chen *et al.* (2011)

Continued

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Table 16.3 Continued

Treatment	Effect on bamboo fibre	References
Acrylation	Maleic anhydride treatment improves the tensile strength, modulus and impact strength of composite by proposing better bonding due to the crystallization which happens on the surface of bamboo fibre.	Chen *et al.* (1998)
Thermal treatment	Optimum temperature of thermal treatment ranging from 140–220°C increases the dimensional stability of bamboo in the existence of moisture meanwhile the mechanical properties are unaffected.	Colla *et al.* (2011)
Oxidization treatment	Potassium permanganate ($KMnO_4$) is used as an oxidant to form cellulose radical from MnO_3^- ions and increase the surface roughness of bamboo.	Chen *et al.* (2011)

unsaturated polyester, phenolic, vinyl ester, polypropylene, polylactic acid, natural rubber, Novalac and polyethylene resins. Table 16.4 sets out the work on bamboo fibre-based polymer composites.

16.6.1 Bamboo fibre-reinforced polymer composites

Gupta *et al.* (2011) studied potential uses of bamboo fibre in polymer composites (Fig. 16.4) and measured the effect of various parameters on the mechanical and erosion wear performance of bamboo fibre-reinforced epoxy composites. The results indicated that the erosion wear performance of the epoxy matrix improves quite significantly with the addition of bamboo fibres. Tensile, flexural and impact properties increased with fibre loading and displayed maximum values at 40 wt% fibre, 30 wt% fibre and 20 wt% fibre loading, respectively. The researchers recommended the potential use of bamboo fibre for low-cost housing components, pipes carrying coal dust, industrial fans and helicopter fan blades. In another study, alkali- and silane coupling agent-treated bamboo fibres were reinforced into the epoxy matrix to study the effect of surface modification on tensile and impact properties of bamboo–epoxy composites under controlled conditions (Lu *et al.*, 2013). Alkali-treated bamboo fibre-reinforced polymer composites displayed a 34% and a 31% increase in tensile strength and elongation at break respectively, while silane-treated bamboo fibre resulted in a 71% increase

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Table 16.4 Reported work on bamboo fibre-reinforced polymer composites

Fibre	Matrix	References
Bamboo	Epoxy	Lu *et al.* (2013), Gupta *et al.* (2011), Rajulu *et al.* (2004)
	Polylactic acid (PLA)/ poly(butylene succinate) (PBS)	Lee and Wang (2006)
	Polyester	Wong *et al.* (2010), Prasad and Rao (2011)
	Natural rubber	Ismail *et al.* (2002)
	Polypropylene (PP)	Phuong *et al.* (2010), Lee *et al.* (2009), Chen *et al.* (1998), Okubo *et al.* (2004), Chattopadhyay *et al.* (2011a, b)
	PP, MA-grafted PP, polyvinylidene fluoride, and polyethylene terephthalate	Fuentes *et al.* (2013)
Bamboo husk	Epoxy	Shih (2007)
Bamboo culm	Epoxy	Verma and Chariar (2013)
Bamboo strip	Epoxy	Shin *et al.* (1989)
	Vinyl ester	Chen *et al.* (2009, 2011)
	Polyester	Das and Chakraborty (2009a)
	Novolac	Das *et al.* (2009), Das and Chakraborty (2007, 2009b)
Bamboo fibre/ strip mat	Epoxy	Nirmal *et al.* (2012), Kushwaha and Kumar (2009, 2010a, b)
	Polyester	Kushwaha and Kumar (2009, 2010a)
Woven bamboo mat	Polylactic acid (PLA)	Porras and Maranon (2012)
	Epoxy	Kumar *et al.* (2011), Kushwaha and Kumar (2011)
	Polyester	Kushwaha and Kumar (2011)

in tensile strength and a 53% increase in elongation at break as compared to untreated composites.

Short bamboo fibre-reinforced epoxy composites were fabricated with different fibre loadings and the void content, density and percent weight reduction of these composites were determined (Rajulu *et al.*, 2004). In an interesting work, Lee and Wang (2006) investigated the effect of lysine-based diisocyanate as a coupling agent on the tensile, water resistance and interfacial adhesion properties of bamboo fibre-reinforced poly(lactic acid) and poly(butylene succinate) biocomposites. The thermal degradation of both bamboo composites was lower than those of the pure polymer matrix,

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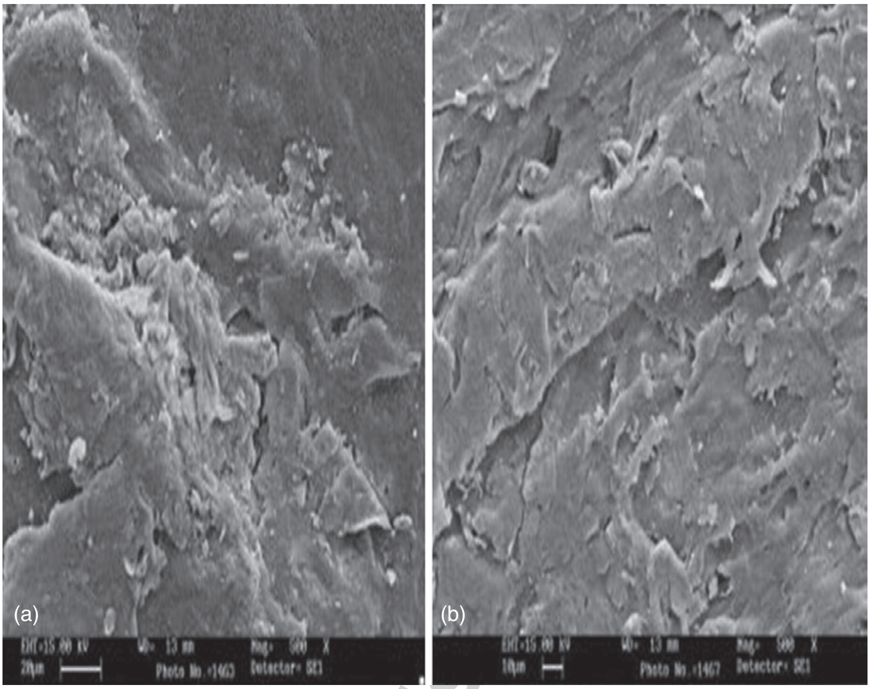

16.4 SEM micrographs of bamboo fibre–polypropylene interface: (a) without maleic anhydride grafted polypropylene (MA-*g*-PP) and (b) with MA-*g*-PP for 50 vol% of bamboo fibre (Chattopadhyay *et al.*, 2011a, © 2010 Wiley Periodicals, Inc.).

but enzymatic biodegradability indicated that both composites could be quickly decomposed by enzyme, although the addition of lysine-based diisocyanate delayed the degradation.

In another study, the fracture and morphological behaviour of short bamboo fibre-reinforced polyester composites was investigated and the results indicated that the highest fracture toughness was achieved at 10 mm/50 vol% fibre-reinforced composite, with a 340% improvement compared to pure polyester (Wong *et al.*, 2010). Prasad and Rao (2011) conducted a study comparing bamboo to jowar and sisal fibres as reinforcement fibres in a polyester matrix and determined that the developed composite material can be used in different applications. Bamboo fibre-reinforced natural rubber composites were prepared and the mechanical properties of composites with and without bonding agent were studied (Ismail *et al.*, 2002). The results showed that interfacial bonding between bamboo fibre and natural rubber was enhanced by the addition of the bonding agent and their composites displayed enhancement in tensile modulus and hardness.

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Bamboo fibre-reinforced polypropylene (PP) composites were prepared using compatibilizer (Chen *et al*., 1998). The results indicated that 24% bamboo fibre loading-treated composites displayed better mechanical properties and that the newly developed composites were lighter, more water-resistant, cheaper, and with tensile properties more than three times higher than those of current commercial products. PP composites developed using steam-exploded bamboo fibres demonstrated better tensile properties compared to mechanically extracted bamboo fibre-based PP composites (Okubo *et al*., 2004). Bamboo fibre-based PP composites were produced at 10, 15 and 50 vol% fractions of bamboo fibre and studied for their degree and rate of aerobic biodegradation by a specially designed experiment (Chattopadhyay *et al*., 2011a). In another work, Chattopadhyay *et al*. (2011b) fabricated short bamboo fibre-reinforced PP composites by incorporating chemically modified bamboo fibres at various loading percentages. The results indicated that thermal stability and functionality of composites improved with modification of the bamboo fibres. Phuong *et al*. (2010) have reported on the fabrication of bamboo fibre-reinforced recycled polypropylene composites via direct melt blends using a twin-screw extruder. The effects on the mechanical, thermal, rheological and morphological properties of composites by alkaline and acetylation treatment of bamboo fibres were investigated.

In another study, the effects of coupling agent and filler loading on the mechanical and thermal properties of bamboo–PP biocomposites were studied and it was observed that the treatment of bamboo fibres with coupling agents affects their physico-mechanical, thermal and morphological properties (Lee *et al*., 2009). Another work on bamboo–PP composites indicated that composites prepared with modified polypropylene resin showed drastic changes in their mechanical properties (Mohanty and Nayak, 2010; Sano *et al*., 2002). Fuentes *et al*. (2013) used an integrated physical–chemical–mechanical approach to study the effect of adhesion on the mechanical strength of bamboo fibre-reinforced PP, MA-grafted PP, polyvinylidene fluoride and polyethylene terephthalate. Results indicated that physical adhesion improved interfacial and longitudinal strengthening of bamboo polyvinylidene fluoride composites as compared to the other thermoplastic matrices used in this study.

16.6.2 Bamboo husk fibre-reinforced epoxy composites

Morphological analysis of bamboo husk-reinforced composites reveals that modified fibre displays better fibre and matrix interfacial bonding compared to untreated fibres, and thermal resistance and mechanical properties are enhanced by the addition of coupling agent-treated fibres or untreated powders (Shih, 2007). Results also indicated that the storage moduli of

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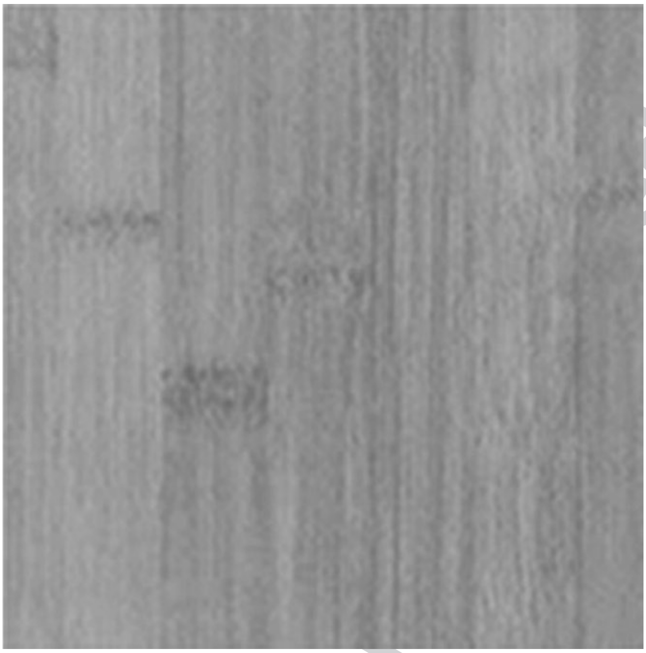

16.5 Bamboo laminated epoxy composite (reprinted from Verma and Chariar, 2013, © 2013 with permission from Elsevier).

epoxy were enhanced with the addition of 10% coupling agent-treated fibres and untreated powders.

16.6.3 Bamboo culm-based epoxy composites

Verma and Chariar (2013) fabricated four-layered laminated bamboo epoxy composites (LLBC) using thin laminas obtained from dry bamboo culm and epoxy resin. Experimental and theoretical values of stiffness and strength of LLCB were evaluated and compared with four-layered unidirectional laminated bamboo composites (HLLBCs). The results show that the stresses and strains obtained using a constitutive equation of laminate at macroscopic scale are lower than the experimental failure limit of LLBCs. An example of bamboo culm-based composite is shown in Fig. 16.5.

16.6.4 Bamboo strip-based polymer composites

Shin *et al*. (1989) and Corradi *et al*. (2009) used bamboo strip to fabricate unidirectional bamboo–epoxy laminates of varying laminae number and

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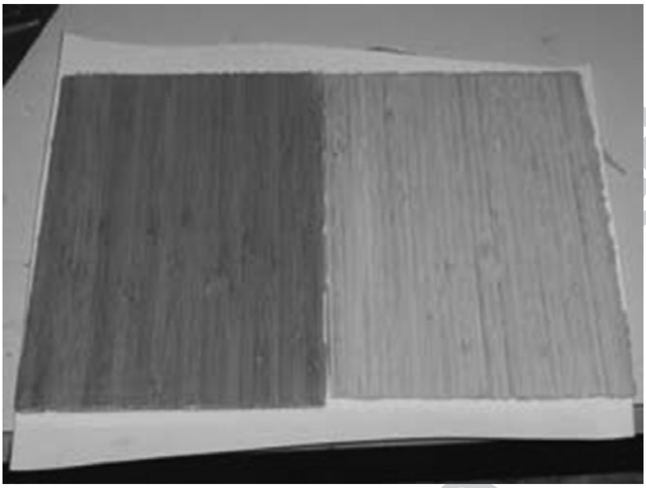

16.6 Bamboo strip-based composite (Corradi *et al.*, 2009).

evaluated their tensile, compressive, flexural and interlaminar shear properties as shown in Fig. 16.6. The moisture sorption characteristics of bamboo strips and their influence on the interfacial shear strength of bamboo–vinyl ester composites were also investigated (Chen *et al.*, 2009). The results showed that relative humidity influenced the interfacial shear strength of composites and water immersion caused an accumulated loss of interfacial strength. A further study on bamboo strip-reinforced vinyl ester composites has been carried out to compare the effect of different chemical treatments (silane, alkali, oxidation and acetylation) on their ability to absorb moisture and the results showed that acetylation treatment was the most effective (Chen *et al.*, 2011). Das and Chakraborty (2009a) developed bamboo–polyester composites by hand lay-up technique using untreated strips and bamboo strips treated with alkali for 1 h at different concentrations, e.g. 0, 10, 15, 20 and 25%. The bamboo fibre strip and polyester composites with 20% caustic-treated strip reinforcements and 60% filler loading displayed the greatest improvement in mechanical properties.

In another study, bamboo strips were mercerized with varying concentrations of NaOH (10, 15, 20 and 25%) and made into bamboo strip based novolac composites (Das and Chakraborty, 2007). Das *et al.* (2009) investigated how alkali treatment of bamboo strips affected the thermal and weathering properties of the unidirectional bamboo strip Novolac resin composites. The results showed that the composites with treated bamboo strips showed better weathering and thermal stability compared to the untreated ones. In a further study, Das and Chakraborty (2009b) reported on the dynamic mechanical and thermal properties of untreated and treated

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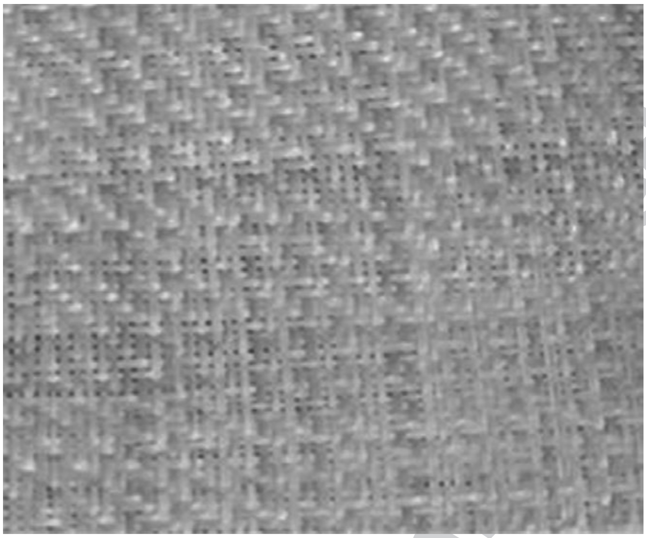
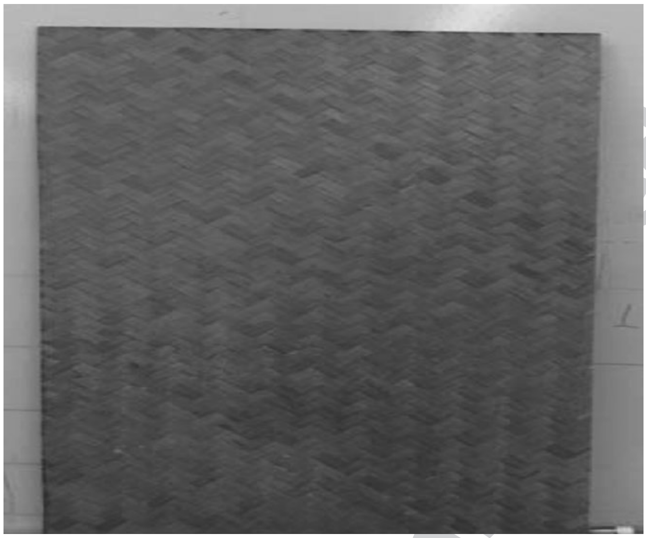


16.7 Three bidirectional roving bamboo fibre (Gupta *et al.*, 2011).

bamboo strip-reinforced Novolac composites. The results indicated that 20% alkali-treated fibre composites had the best dynamic mechanical properties and differential scanning calorimetry analysis revealed that alkali treatment of the bamboo strip imparted better thermal stability to the composites as compared to the untreated one.

16.6.5 Bamboo fibre/strip mat-based polymer composites

The adhesive wear and frictional properties of bamboo fibre mat-reinforced epoxy composites were studied and results (see Fig. 16.7) showed that they had excellent wear resistance compared to neat epoxy (Nirmal *et al.*, 2012). Two sets of bamboo fibre mat-reinforced epoxy composites were fabricated in another study, one with silane-treated bamboo mats and the other with silane-treated mercerized bamboo mats (Kushwaha and Kumar, 2010a). It was observed that silane treatment improved the tensile and flexural strength of bamboo–epoxy composites but by contrast the addition of silane-treated mercerized bamboo led to a significant reduction in strength. Kushwaha and Kumar (2010b) also carried out a study to establish the effect of alkali and silane treatment on water absorption properties of bamboo matting-reinforced epoxy composites and discovered that both alkali and silane treatment resulted in a reduction of water absorption. The same researchers reported on the reinforcement of modified (alkali-treated) bamboo strip matting into epoxy and polyester matrix developed bamboo



16.8 Woven bamboo mat composite (Bäcklund, 2011).

fibre-reinforced plastic (BFRP) composites (Kushwaha and Kumar, 2009). Bamboo mats were treated with 1, 2, 5, 10, 15, 20 and 25% concentration of NaOH in distilled water for 30 min at 20°C (room temperature). This morphological study showed that 5% NaOH-treated bamboo strip mat exhibited better compatibility with the epoxy and polyester resins than the untreated bamboo, and treated bamboo-reinforced polyester composites displayed 69% higher tensile and 59% higher flexural strength. The same researchers also investigated the effect of acrylonitrile treatment of bamboo mats on bamboo-reinforced epoxy and polyester resin composites and observed that treatment of bamboo mats improved the tensile, flexural and water absorption properties of both composites (Kushwaha and Kumar, 2010a).

16.6.6 Woven bamboo mat-reinforced polymer composites

The dielectric behaviour of woven bamboo strip mats/epoxy composites (Fig. 16.8) was studied with dual fibre orientation (parallel and perpendicular) to the electric field (Kumar *et al.*, 2011). This study determined the effects of fibre alignment and alkali treatment on the dielectric properties of woven bamboo strip mats/epoxy composites and evaluated the structural performance of a standard laminating resin. The physical, thermal and mechanical properties of bamboo fabric-reinforced PLA composites were investigated by Porras and Maranon (2012). The results revealed that the tensile, flexural and impact properties of PLA increased when weft-direction bamboo fabric reinforcement was used, and bamboo fabric-reinforced PLA composites showed excellent ability to absorb energy, which could be exploited in structural engineering applications. In another recently published work, woven bamboo mats modified by maleic anhydride, permanganate, benzoyl chloride and benzyl chloride were used as reinforcements in epoxy and polyester matrices to estimate the physical, mechanical and morphological properties of bamboo-reinforced polyester/epoxy composites (Kushwaha and Kumar, 2011). The results obtained showed variations in the mechanical, physical and morphological properties of bamboo-reinforced polyester/epoxy composites.

16.7 Applications of bamboo composites

Design is a creative process that aims to establish the quality of a variety of objects, processes, services and systems throughout their life cycle. According to Pawlak (2008) design is a key factor of innovative humanization technology and an important factor in cultural and economic exchange. Research in material processes such as bamboo contributes to good design because it is concerned with factors such as safety, aesthetics, functionality, consumer acceptance and the potential impact on the environment. Indirectly it contributes to the development of products based on human values, whether in a physical or a cognitive sense (O'Grady and O'Grady, 2006). Most products are designed to take account of a diversity of factors such as safety and comfort without adversely affecting the ecology and without being more expensive (Rodgers and Milton, 2011).

This section describes the potential and explores the different types of biocomposites from various materials that are often associated with and used in design. The era of hybrid products formed over decades has continued to attract the world market until now when biocomposite material has proven its quality and importance to life cycle assessment (LCA) (Vogtländer *et al.*, 2010).

Compared to other materials, bamboo furniture is long-lasting and unique in general appearance but with similar strength to other wood-based furniture (Suhaily *et al.*, 2012). The growth rate of bamboo is an advantage as it is one of the fastest-growing plants and has a tensile strength comparable to that of mild steel. Normal bamboo will grow upright and can reach heights over 18.3 metres in only a few months. Bamboo is easily cultivated and does not affect the environment if cut frequently compared to trees grown for solid wood (Kowaluk *et al.*, 2011). Many researchers have already shown that modern furniture using biocomposite material such as bamboo fibre can create something unique, outstanding and biodegradable compared to solid wood materials (Brower *et al.*, 2009; Leao *et al.*, 2010). Wood consumption in line with population has increased every year. However,

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bamboo biocomposites are a new alternative material for wood-based industries and many researchers are developing panel products from bamboo fibre.

The integrated materials process determines the most suitable type of design material taking into account various factors such as its impact on nature and the community, technology, price, durability and sustainability. Bamboo is stronger when bent and glued under pressure, making bamboo plywood a very good deck and an ideal pilot material for furniture, interiors, transport and construction. Over the last few years, researchers have demonstrated that bamboo is an excellent material, capable of producing a variety of quality products as shown in Table 16.5 (Gabrielsen and Kristensen, 2004). Now, with the development of science and technology in the use of bamboo biocomposites, consumers need to be reassured about their quality and durability compared to other materials (Riley, 2003).

In little more than a decade, bamboo flooring has become a serious contender in the hardwood flooring market and some believe that bamboo plywood is next. Nowadays, bio composites in the production of various bamboo products for the construction industry and interior design have a high demand in the global market because both consumers and manufacturers realize their importance in supporting continuing efforts to encourage sustainability. Their success proves that the hybrid material bamboo can surpass other types of materials in various aspects, physical, mechanical and aesthetic. Lighter laminated bamboo can be used to create unusual effects and bamboo joinery can be bent or straightened by heating and clamping as demonstrated in the work of Colombian architects Simon Velez and Oscar Indalgo (Adams, 1998). Various types of bamboo-based products have been successfully commercialized, from ceilings, walls, floors, window frames and doors to stairs and home decor accessories.

For example, PlybooSport bamboo flooring has been designed using bamboo biocomposites for high-impact use in gym and basketball courts and is widely used in countries and regions such as the United States, Mexico, Europe and Canada (Smith and Fong, 2010). Now that bamboo flooring has grown beyond niche market status it is beginning to attract more scrutiny, especially in interior design. This is further enhanced by its excellence as an innovative material and has attracted recognition from various quarters with evidence of excellent designs made from bamboo material, for example the unique palm-shaped bamboo dome designed and built by Binh Duong and Vo Trong Nghia.

Bamboo furniture making is increasing gradually as the wood-based manufacturing industry is threatening the environment with its destruction of the forests. However, one major problem associated with bamboo is its huge wastage, especially through open burning, which creates its own

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Table 16.5 Innovative design and applications from bamboo fiber biocomposites in various categories

Category	Name of product	Inventor/Designer	References
Interior design	Bamboo Flooring For Basketball Court 	Smith and Fong	Smith and Fong (2010)
	Bamboo Dome, Vietnam 	Vo Trong Nghia	Vo Trong Nghia (2010)
Building and construction	Kontum Indochine Café, Vietnam 	Vo Trong Nghia	Vo Trong Nghia (2010)
Furniture design	Infinity Bench 	Andrew Williams and Tom Huang	Williams (2010), and Huang (2007)
	Hangzhou Bent Bamboo Stool 	Min Chen	Min Chen (2013)
Automotive components	Renault Mégane Bio-Concept car 	Cloth seats, floor mats, dashboard, door panels, etc.	Pro-Shift, (2010), Makinejad *et al.*, (2009)

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burden on the environment. Bamboo has significant waste residues as both ends of bamboo poles cannot usually be used due to fungal attack and non-uniform diameter. It has been reported that in some cases about 15 cm must be cut and removed from each end. With advances in technological development, researchers have succeeded in producing composites from bamboo waste. This has enabled furniture designers to demonstrate that bamboo materials are not only resilient and pliable, but tremendously powerful in internal and external conditions.

For example, a piece of furniture called the Hangzhou Bent Bamboo Stool designed by Min Chen is made of 16 layers of thin bamboo veneer (Chen, 2013), the sections of bamboo being bent into an arc shape and glued together at the end, producing an effect like ripples on a water surface. It demonstrates the ability of each bamboo veneer layer to withstand a heavy load while offering flexibility to the user. Young designers Andrew Williams and Tom Huang have collaborated to create the Infinity Bench using bamboo strip construction (Williams, 2010; Huang, 2007). The Infinity has two hollow tubes, one large and one small, made with bamboo strips of the same size arranged closely together using adhesive on the outside and inside to ensure the strength of the design.

Building materials are selected based on three important criteria (van der Lugt *et al.*, 2005):

- Functionality
- Technical qualities
- Cost.

Sustainability has also been included as one of the criteria as the issue of environmental building materials has become important. Now, all organizations and institutions must comply with the construction and manufacturing criteria in each project. This is because the construction industry is also causing environmental damage, and recycling, sustainable production and use of renewable resources have to be considered in the development of new materials.

Unique architecture and distinctiveness apply where the whole structure of the building is made using bamboo, proving that bamboo materials have high strength comparable to metals. Moreover, the dynamic shape adds to the building's aesthetic quality. For example, the Kontum Café Indochine by Vo Trong Nghia Architects is a restaurant without walls, enabling a seamless view and maximizing the flow of air into the building in the summer, rendering air-conditioning unnecessary (Vo Trong Nghia, 2010). Built using a bamboo roof structure, it consists of 15 units of an inverted cone creating a space with a unique character.

The industrial revolution in transportation began in 1930 with the use of natural fibres in the construction of car interiors. Famous car inventor

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Henry Ford led the way in this important era in the automotive manufacturing world because of his use of materials made from natural fibres. Studies have shown that the low cost of natural fibre materials makes them very suitable for use in automotive parts (Proemper, 2004; Makinejad *et al*., 2009). The use of bamboo in the car industry continues to grow rapidly, especially in Europe and Southeast Asia. Now, bamboo-based innovation continues to be the choice of researchers globally because it promises excellent performance at minimal cost. In 2006, the European Union (EU) and Asian countries supported this by issuing guidelines for the global car manufacturing industry. The guidelines instruct all car manufacturers to produce automotive plastic reinforced with natural fibre. In addition, the European Union (EU) has set a target that recycled materials must make up 80% of manufactured products with that figure increasing to 95% in 2015.

Recent research has developed bamboo mat veneer composite (BMVC) hybrid in vehicles and trains. Natural fibre composites with thermoplastic and thermoset matrix have also been widely used in the manufacture of door panels, rear seats, headliners, package trays and dashboards by car manufacturers such as Audi, BMW, Peugeot, Volvo, etc. (Proemper, 2004). This is because natural fibres such as bamboo have been proven to reduce weight and cost and have the advantage of being recyclable. In aeronautics research, the kite and early aircraft were built using materials made from bamboo fibre because it is light, very strong and able to withstand wind resistance. The Philippines created a plane made entirely of bamboo during World War II (Proemper, 2004).

16.8 Sustainable and renewable products from bamboo composites

In the proliferation of the global bamboo manufacturing industry, three main factors should be given priority in relation to product life and sustainable development, as shown in Fig. 16.9:

- Ecological
- Economic
- Social–cultural.

There needs to be a balance between society's increasing demand for products, preservation of the forest, diversity of material resources and benefits, and the impact of culture. Previous research results show the use of bamboo composites can sustain economic and social-cultural factors, both locally and globally, and has a far less detrimental effect on the ecosystem. Consumer awareness can be achieved by evaluating the environmental impact of the entire life cycle of a product, from raw material through manufacture to final disposal.

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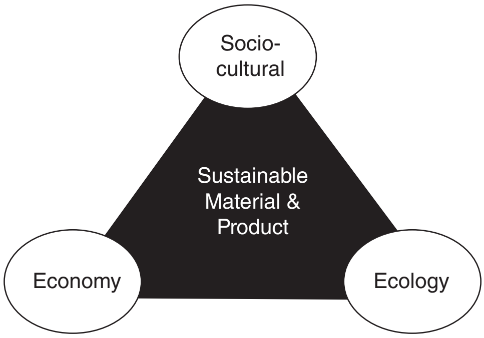

16.9 Three elements to support the sustainable product.

Like any other resource-based industry, the constant supply of raw material is important to ensure its continued existence. Over the years, the industry has observed a decline in the quantity and quality of bamboo. As a result, it has been forced to accept inferior quality bamboo which has led to problems in meeting consumers' specifications. The cultivation of bamboo through proper management is essential to ensure a continuous supply of high-quality raw material. The feasibility of planting bamboo under rubber and forest plantation has been studied. Either small-scale rubber holders or larger estates growing rubber could adopt the practice. However, growing bamboo in plantations still encounters management problems that need to be solved. Governments may have to play a part in land acquisition or long-term lease of land to make bamboo plantations more attractive. A form of the rural development scheme for rubber planting used in peninsular Malaysia may be a good model to follow.

The bamboo industry can improve the quality of the environment through reduced CO_2 emissions and almost zero net greenhouse gas emissions. Environmental issues are increasingly important and an issue of international debate. Bamboo materials can be an exciting challenge leading to new solutions through technology and research that are both economic and ecologically sustainable. Problems such as the lack of material resources due to forest fires, drought and an annually increasing world population are the main reasons why researchers have focused their attention on the development and design of new materials from bamboo fibre (Wagner *et al.*, 2010). The ability to see the potential of biocomposite bamboo products as part of the culture and heritage of the world could also lead to the development of innovative products (Zhang *et al.*, 2001). In addition to its product versatility, bamboo has other benefits such as being less susceptible to erosion, helping to reduce deforestation and being readily disposable without harming the environment compared to other materials.

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Bamboo's natural strength is unmatched by modern materials such as steel and plastic.

The bamboo industry offers the best opportunity for sustainable economic development for biocomposite fibres, which are produced at minimal cost and will bring a new evolution in the world of supply chain and manufacturing (Zuo *et al.*, 2001). Bamboo cultivation requires minimal cost or care, bamboo being fully grown in 3–4 years compared to other types of plants that require 5–30 years to mature. The short period to maturity of bamboo ensures a cycle of optimal supply of good quality raw materials at all times.

Problems of waste disposal and environmental damage have raised concerns about the costs of commercial market production recently. Low-impact materials like bamboo are necessary to diversify the market by providing an alternative choice of material resource. This could increase potential new markets in developing sustainable global solutions (Ljungberg, 2005). To realize sustainable economic development, we need to take into account the costs associated not only with the goods such as the cost of the raw materials and production, but also other factors such as reputation, trends, environmental protection and natural resources. Bamboo also has a better variety of mechanical uses and anti-bacterial applications, making it an excellent resource for the development of a sustainable product (Kar and Jacobson, 2012).

Design is a practical activity and is part of our culture and current research. New product design can make an important contribution not only to products and services required by a creative community, but also for the development of materials (Lane and Flagg, 2010). Bamboo-producing countries of the world such as China and India have many sources of bamboo and various bamboo species (van der Lugt *et al.*, 2012). The world is faced with many serious problems such as global warming, acid rain, soil erosion, the financial crisis and extinction of flora and fauna habitat which are caused by profit-oriented manufacturing. Over the years, materials such as bamboo have proved to be innovative in global production, satisfying the current desire to develop sustainable products without forgetting traditional culture. In other words, materials and design are very much needed in maintaining quality of life because they reflect the values of our culture over the years, especially in the furniture manufacturing industry, construction of houses and buildings, appliances, jewellery and other industries (Steffen, 2007).

16.9 Future trends

A huge amount of research has been devoted to nanoscale-related technologies in recent years. This research revolution is significant, bringing about a new generation of composite processes and products with improved

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and unique properties. Technology is enabling the industry to manipulate matter at the atomic level so that its physical and chemical properties (e.g. stability, hardness, conductivity, reactivity, optical sensitivity, melting point, etc.) can be manipulated to improve the overall properties of conventional materials.

Cellulose nanofibres are found in the cell wall of bamboo fibres, acting as the framework of a biocomposite made of the matrix substances lignin and hemicellulose. These nanofibres have lateral dimensions of a few nanometres and are comprised of a bundle of cellulose molecular chains arranged parallel to the longitudinal direction of the nanofibres (Nakagaito *et al*., 2011). Chang *et al*. (2012) produced bamboo nanofibres using hot-compressed water (HCW) treatment and disc milling. Bamboo nanofibres were also successfully prepared using chemical pretreatment combined with high-intensity ultrasonification (Chen *et al*., 2011).

Over the years, the use of nanocellulose as reinforcing agents in paper and nanocomposites, membranes and films for filtration and packaging, stabilizing and texturing agents in cosmetics and food additives, wound dressings, artificial blood vessels, scaffolds for tissue engineering and drug delivery systems, among others, has been reported (Ioelovich and Figovsky, 2008; Taokaew *et al*., 2013). However, applications of nanocellulose are still increasing due to its physical and mechanical properties. Cellulose nanocrystals, whiskers and nanofibres can be designed for a great variety of applications, ranging from medical to technological. Nanocomposites comprising nanoparticles and nanofibres are expected to be a major growth area in the plastics industry. According to Wagner *et al*. (2010) polymers reinforced with as little as 2–6 percent of nanoparticles exhibit dramatic improvements in properties such as the following:

- Thermomechanical properties
- Light weight
- Dimensional stability
- Barrier properties
- Flame retardancy
- Heat resistance
- Electrical conductivity.

Nanofibre composites are also used for making flexible circuits, solar panels and other electronics devices (Giri and Adhikari, 2013). This application potentially offers the benefits of reduced energy consumption together with more competitive pricing compared with conventional materials (Fan *et al*., 2011).

Research developments have shown the possibility of increasing paper strength by the addition of nanocellulose particles or nanofibrillated cellulose (Ioelovich and Leykin, 2004). Henriksson *et al*. (2008) reported

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that nanopapers made from nanofibrillated cellulose have higher mechanical properties than conventional papers formed by the beating process. Recent research by Sehaqui *et al.* (2010) successfully developed a smooth and optical cellulose/inorganic hybrid nanopaper. They found that optical transparency and high tensile strength are demonstrated in 200 mm diameter nanopaper sheets, indicating well-dispersed nanofibrils.

Additionally recent advances in nanocellulose support different aspects of medical developments including the following (Kalia *et al.*, 2011):

- Skin transplants for burns and wounds
- Drug release systems
- Blood vessel growth
- Scaffolds for tissue engineering
- Stent covering
- Artificial organs
- Bone reconstruction.

Interestingly, a great variety of biomaterials have been developed recently (Fig. 16.10). Researchers from Chalmers University of Technology and the University of Gothenburg have shown that nanocellulose stimulates the formation of neural networks (Fig. 16.10(a)). This is the first step towards creating a three-dimensional model of the brain that could elevate brain research to a totally new level. Recently, MIT Chemical have discovered that arrays of billions of nanoscale sensors have unique properties that could help pharmaceutical companies produce drugs more safely and efficiently. Using these sensors, researchers were able to characterize variations in the binding strength of antibody drugs which hold promise for treating cancer and other diseases. A bionic ear (Fig. 16.10(d)) using nanoparticles has been developed by a scientist at Princeton University that can hear almost 1,000,000 times better than the normal human ear. The technology, which seamlessly interweaves biological components and sensitive electronic devices into a single bionic structure, could have a range of applications in regenerative medicine.

Currently, a team of researchers from the University of Pennsylvania has shown that nanoscale particles of the semiconductor cadmium selenide can be 'printed' or 'coated' on flexible plastics to form a flexible circuit (Fig. 16.10). This technology could pave the way for new kinds of devices and pervasive sensors which could have biomedical or security applications. Meanwhile, researchers at the Indian Institute of Technology in Madras have developed a \$16 nanoparticle water filtration system (Fig. 16.10) which is the first to combine microbe-killing capacity with the ability to remove chemical contaminants such as lead and arsenic. The system can be customized to rid water of microbial contaminants, chemical contaminants or both, depending on the user's needs.

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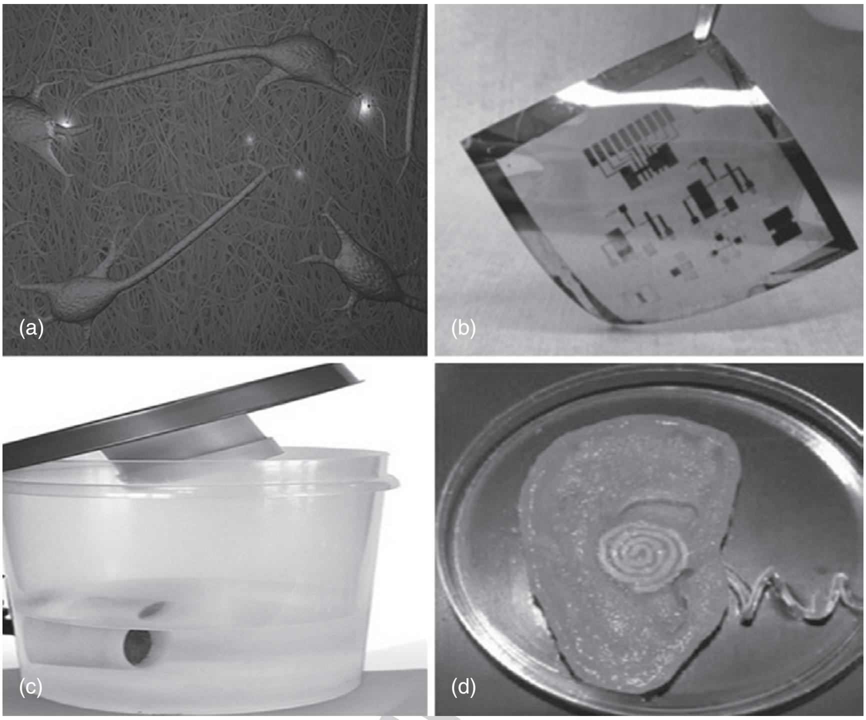

16.10 Examples of future applications of nanotechnology: (a) nanocellulose that stimulates the formation of a neural network; (b) flexible circuit; (c) water filtration system; and (d) bionic ear (Gatenholm, 2013; Kim *et al.*, 2013; Gravotta, 2013; Anon, 2013).

16.10 Conclusions

The use of bamboo fibres in various applications has opened up new avenues for both academics and industrialists in designing sustainable building blocks. The fabrication of bamboo fibre-based composites using different matrices has developed cost-effective and eco-friendly biocomposites. These composites are likely to find more and more applications in the near future. To design such composites, a thorough investigation of the fundamental, mechanical and physical properties of bamboo fibres is necessary. Thus, this chapter has attempted to gather information on bamboo fibre processing and analyse its properties and applications for different composites. Current researches on bamboo fibre-based composites are in terms of either fibre modifications or their mechano-physical, thermal and other properties; however, the ultimate goal of fully utilizing the bamboo fibre is still some way off.

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Further research is required to overcome the obstacles currently facing the advanced application of bamboo fibres in composites as well as in outdoor applications. Researchers worldwide are working to address and overcome these, and efforts to develop biocomposites and nanobiocomposites from bamboo fibres with improved performance for global applications are an ongoing process.

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