Bamboo Fiber-Polymer Composites: Overview of Fabrications, Mechanical Characterizations and Applications

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Abstract The utilization of bamboo fibers in polymer-based composites has expanded in the past few years due to the demand for biodegradable, sustainable and recyclable materials. This article reviews the processing of extracted bamboo fibers and their composites, ultimate mechanical properties/thermal stabilities and corresponding characterizations, as well as the applications. Currently, the challenges regarding bamboo fibers-filled polymer composites involve extraction of high quality bamboo fibers, uniform fiber dispersion/distribution in polymer matrix and/or formation of interphase between matrix-filler phases. Relationships among processing techniques, properties and structural orders are significant to guide the design of future composite.

Keywords Bamboo fibers · Composites · Characterization · Mechanical · Interphase · Application

List of symbols

Materials

BF	Bamboo fiber
BFCP	Bamboo fibers reinforced polymers
CF	Carbon fiber
CFRP	Carbon fiber reinforced polymers
CNT	Carbon nanotubes
GF	Glass fiber
GFRP	Glass fiber reinforced polymers
GP	Graphene platelets
GPRP	Graphene platelets reinforced polymers

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M. Jawaid et al. (eds.), *Green Biocomposites*,
Green Energy and Technology, DOI 10.1007/978-3-319-49382-4_10

HNT	Halloysite nanotubes
MA	Maleic anhydride
MWNT	Multi-wall carbon nanotubes
MTM	Montmorillonite
nCs	Nano-carbons
PA	Polyamide
PANI	Polyaniline
PDDA	Poly(diallyldimethylammonium chloride)
PE	Polyethylene
PET	Polyethylene terephthalate
PI	Polyimide
PP	Polypropylene
PS	Polystyrene
PVA	Polyvinyl alcohol
PVC	Polyvinyl chloride
PU	Polyurethane
UHMWPE	Ultra-high molecular weight polyethylene

Processing

AT	Annealing with temperature
ATT	Annealing with both temperature and tension
LBL	Layer-by-Layer

Characterizations

AFM	Atomic force microscopy
DMA	Dynamic mechanical analysis
DSC	Differential scanning calorimetry
DTA	Differential thermogravimetric analysis
FTIR	Fourier transformed infrared spectroscopy
QCM	Quartz crystal microbalance
ROM	Rule of Mixture
SAXS	Small-angle X-ray scattering
SEM	Scanning electron microscopy
TEM	Transmission electron microscopy
TGA	Thermogravimetric analysis
WAXD	Wide-angle X-ray diffraction

Units

$g \cdot cm^{-3}$	Gram per unit centimeter cube
vol.%	Volume percentage
wt.%	Weight percentage

μm	Micrometers
nm	Nanometers
MPa	Megapasca
GPa	Gigapasca
J	Joules

Symbols

f_c	Herman's orientation factor
φ	Misalignment angle
$\tan\delta$	Dampening parameter
T_c	Crystallization temperature
T_d	Degradation temperature
T_m	Melting temperature
χ_c	Crystallinity degree
H_c	Enthalpy of crystallization
H_m	Enthalpy of melting
E	Tensile/elastic modulus
E'	Storage modulus
E''	Loss modulus
E_f	Tensile/Young's modulus of filled particles
E_m	Tensile/Young's modulus of matrix
σ_f	Tensile/failure stress of filled particles
σ_m	Tensile/failure stress of matrix
σ	Tensile/failure stress (general notation)
σ_y	Yield stress
σ_i	Impact stress
σ_b	Bending stress
ε_t	Tensile/failure strain (general notation)
ε_y	Yield strain (general notation)
V_f	Volume fraction of filled particles
V_m	Volume fraction of matrix

1 Introduction

The requirement for sustainability due to depletion of petroleum resources has stimulated the search for renewable, reusable, and recyclable materials. Currently used synthetic fibers, including high-performance aramid fibers (The National Academies Press 1992; Sikkema et al. 2003; Song et al. 2015a, b, c, d; Song et al. 2012), carbon fibers (Song et al. 2013a, b; Zhang et al. 2013a, b; Meng et al. 2014; Song et al. 2015a, b, c, d; Zhang et al. 2015) and glass fibers (Nishii et al. 1992), have been mixed with both renewable and non-renewable polymers to produce composites. The usages of these composites are still dominating the reinforcement industry (Song et al. 2013a, b); however, the natural fibers as reinforcements have gained much impetus to substitute these synthetic fibers in various applications (Belcher et al. 2001; Beckwith 2008; Faruk et al. 2012; Ren and Li 2013, Aug, 1; Ren et al. 2013). Among these natural fibers, bamboo, banana, coir, cotton, flax, hemp, henequen, jute, kenaf, ramie, and sisal have attracted the most attentions (Faruk et al. 2012; Ku et al. 2011; Koronis et al. 2013). The usages of these fibers greatly depend on the geological locations. For example, bamboo and cotton are abundant in Asia, South America, and Africa; India and Sri Lanka produce 90% of the coir produced every year; and sisal is mainly cultivated in southern Mexico (Beckwith 2008). Banana, flax, hemp, henequen, jute, kenaf, ramie, and sisal, are produced in alternative regions and comparatively, they provide fibers for structural and functional materials, and simultaneously serve as important food resources. The usage of these materials may not only jeopardize sufficient supplies of oil, milk, protein, and vegetable, but can also occupy the existent forests and further damage the environmental soil protection (Faruk et al. 2012). Bamboo, on the other hand, is one of the most natural-abundant crops and has a long application history in living facility and life tools. Practically, apart from bamboo strip based composites (i.e., household storages, furniture, floors, fences, panel, decoration products) it is also optional to extract bamboo fiber (BF) from bamboo trunk in controllable way for structural composites.

Currently BFs are considered as important plant fibers that have great potential in polymer composite industry. Its mechanical robustness, thermal stability, and facile extraction of BFs as well as easy chemical modification have made it versatile in composite industry. The economic value, lightweight, high specific strength, and nonhazardous nature of BFs are among the most attractive and well-known properties of this material. Mechanical characterizations have proven them to possess great potential applications in automobile, aerospace and household usage (Qiu et al. 2012; Li et al. 2012). This contribution will review the processing, characterizations and properties as well as applications of BFs filled polymers, to achieve the goal of better usage of bamboo materials.

2 Fabrication of Bamboo Composites

Polymer-matrix composites, such as carbon or glass fiber reinforced plastics (CFRP or GFRP) have been widely used in industry due to their high strength and stiffness (Song et al. 2013a, b; Chand 2000; Hussain et al. 2006). Nonetheless, when thermoset plastics are involved, it is very difficult to recycle these materials. The thermoplastics, on the other hand, are also unpractical to recycle due to high cost and low quality issues in the current applications. The recycling of polymer/filler composites is mainly related to two ways: dump and calcination. Some dumped fiber reinforced plastics cannot decompose naturally, while others burnt in the furnace may damage the furnace (e.g., glass fiber will cause reduce in net heat and the solid residue in the incinerator will lead to disposal problems). Therefore the usage of reinforcement fibers and choice of fabrication methods should be cautious. Bamboo is abundant in natural resources, especially in Asian and South Africa, because of its fast growing (as fast as a few months) and little protection cost. Bamboo is also called “natural glass fiber” for its high specific strength and stiffness (Okubo et al. 2004). To take advantage of these benefits, it is necessary to review the fabrication procedure, compare their pros and cons, and choose the optimal method.

2.1 Extraction of Bamboo Fibers

BFs are difficult to extract due to the brittleness. This brittleness is caused by the surface-covered lignin. Therefore knowledge of BF composition and structure as well as development of appropriate procedure to extract BFs is of great significance. The chemical composition of BFs is mainly cellulose (74%), hemicellulose (13%) and lignin (10%). Based on the components, 90 wt% is high-glycans. The other 10 wt% includes protein, fat, pectin, tannins, pigments and ash (Low et al. 2006). The presence of lignin provides stiffness and yellow color to BFs. In some applications these limitations in flexibility are not desirable and various chemical treatments have been found to be effective in removing lignin. Non-cellulose components contribute to the strength, flexibility and moisture absorption. Physically, the BFs align uniquely along growth direction, with 2°–10° disorientation angles (Jain et al. 1992).

Both physical and chemical methods have been generally used for BF extraction. Based on several studies listed in Table 1, bamboo extraction generally involves mechanical separation (i.e., cutting, blending, milling, sieving, steam explosion, combing, scrapping, etc.), and/or chemical extraction (i.e., alkali extraction and acid neutralization, fermentation with enzyme, oil soaking, etc.). In both methods, original BFs are necessary to be peeled off the bamboo trunk/strips. The fibers were often peeled off along bamboo length direction. According to Rao and Rao (2007), BFs from combing and scrapping, namely physical separation, break less than those from decorticating and degumming, namely chemical procedure. Later on, the steam explosion technique was found to be a more effective method to extract BFs as compared to other mechanical methods (Okubo et al. 2004). Nonetheless in most mechanically peeled bamboo components the obtained fibers show discrepancies in fiber shape, length and diameter dependent on the processing technique. Other mechanical methods using mechanical devices of miller, blender, and machine have simple processes and high efficiencies (Okubo 2004; Rao and Rao 2007; Thwe and Liao 2003; Bo 2004; Ogawa et al. 2008). Nonetheless due to the roughness and brittleness, BFs produced are scattering in thickness, length, and flexibility, thus have achieved very limited practical applications such as fiberboard.

Table 1 Extraction methods of bamboo fibers

Techniques	Year	Details
Physical or mechanical method		
Extruding, cutting and blending (Thwe and Liao 2003)	2003	Bamboo rods were obtained by passing wider strips through an extruder. Short BFs were obtained by cutting these rods into chips, which were then grinded in blender for half an hour
Steam explosion (Okubo 2004)	2004	Bamboo was heated at around 170 °C under 0.8 MPa for 100 min for 8 times, washed and dried
Cracking (Bo 2004)	2005	High-pressure cooking vessel soften bamboo slices, form micro-cracks and delamination by spliting the bamboo through machine, propagate cracks and expand delamination along the fiber direction which lead to bamboo detaching. Then in another external load synergies, the macro-crack of bamboo continues to expand, achieve its interfacial debonding stratified, to obtain crude fiber bamboo
Combing and scrapping (Rao and Rao 2007)	2007	The cylindrical portion of culm is peeled in the longitudinal direction to make strips. The strips are bundled and are kept in water for three days in order to soften them. Gentle beating, scrapping using sharp knife and combing were repeated until individual fibers were separated
Machining center (MC) (Ogawa et al. 2008)	2008	MC program was designed based on cutting theory. Fiber shape, length and diameter can be controlled by the spiral toll path, axial depth of the cut and the vascular bamboo-bundle size
Chemical method		
Decorticating and chemical degumming (Rao and Rao 2007)	2007	The manually decorticated bamboo fibrous strips are dried off in the sun. These strips of fiber contain tissues and gums. After decorticating, the dry fiber is extracted by means of a chemical process of decomposition called degumming, in which the gummy materials and the pectin are removed
Semi pilot scale extraction technique (Chattopadhyay et al. 2011)	2011	Bamboo culms were digested in NaOH/NaS_2/ digestion solution, washed with HCl solution and cold water, and finally dried/blended/grinded into short BFs
Retting (Mounika et al. 2012)	2012	This process involves the action of bacteria and moisture on dried bamboo strips to dissolve and rot away cellular tissues and gummy substances that surround the fiber bundles and strips

On the contrary, chemical method showed comparatively higher efficiency. However, during the chemical of degumming it also leaves out some lignin within the fibers, which weakens the mechanical reinforcement. Although the extraction of

BFs may suffer from deteriorated integrity in the degumming treatments, in most cases the alkali treatment is effective in fiber surface modifications and further improves mechanical stiffness/strength, and subsequent interfacial interactions between polymer and BFs (Das and Chakraborty 2008a, b). Therefore, exploration of softening BF methods, lignin removal technology and special machine development has to be conducted for fine fiber productions.

2.2 Solution Processing Film

In solution processing technique, the BFs are generally dispersed in solvent and then mixed with polymer solution by mechanical mixing, magnetic agitation or high-energy sonication. Subsequently the polymer composites can be obtained by vaporizing the solvent at elevated temperature. This method is considered as an effective measure to prepare composites with a homogeneous BF distribution and often used to fabricate composite films. Epoxy and polyurethane are the thermoset polymers that are usually employed in BFs filled composites by solution mixing. Other polymers such as PS, PVA, PMMA, PVC, and so on can also be prepared in the same method.

2.3 Melt Processing Film

During melt processing, polymers were melted at elevated temperature and mix with extracted BFs. BFs are dispersed within the polymer matrix by rheological shear stress generated from blending the BFs with polymer melt. However, it is known that the BFs can easily be damaged to shorter fibers or defected in some sense. After uniform mixing of the fibers and the polymer matrix, the resultant fiber-polymer matrix mix was shaped from extruder (Phuong et al. 2010), injector (Samal et al. 2009), mold, compounder or roller (Ismail et al. 2002). Pressure sometimes is applied for regular shape and for getting rid of voids.

2.4 In-situ Polymerization Film

Surface modification of cellulose fibers by in situ graft copolymerization has been intensively investigated (Roy et al. 2009; Thakur 2015). The copolymerization can be achieved by various types of polymerization techniques while free radical polymerization, including conventional free radical polymerization (Odian) and reversible deactivation radical polymerization (RDRP) (Matyjaszweski and Xia 2001; Zhang et al. 2014, 2015; Sciannamea et al. 2008), are the most popular methods due to their versatility and simplicity compared to other polymerization techniques. By grafting polymer chains onto the cellulose surface, the adhesion between modified cellulose and polymer matrix could be dramatically increased. Therefore, in situ polymerization is considered as a very efficient method to significantly improve the BFs dispersion and the interaction between BFs and polymer matrix. Generally BFs should be chemically modified to generate suitable functional groups that allow further graft-from or graft-to polymerization. Various monomers, including methyl methacrylate (Yu et al. 2014), poly(ethylene glycol) methyl ether methacrylate (Bao et al. 2011), or methacrylamide (Kushwaha and Kumar 2010a, b, c), have been employed for in situ graft copolymerization to fabricate BFs/polymer composites. Generally the mechanical properties of the resulting composites were improved due to the stronger interfacial adhesion between the BFs filler and polymer matrix.

2.5 *Laminate*

Hand lay-up is usually used to fabricate BF included composites (Chen et al. 2004). In this procedure, BF were extracted carefully and cut into fibers with various lengths. First, the inner surfaces of the mold are sprayed with a thin layer of release agent. Next, the BFs are placed into the mold uniformly at designed concentrations (Chen et al. 2004). Several classic researches regarding laminate layering-up have been summarized in Table 2. Hot pressing with pressure application, melt compounding as well as in situ polymerization methods have been selectively used for various polymers.

In order to bring out the anisotropic nature of BFs, it is important to align BFs in a polymer matrix during processing of BFs/polymer composites. Achieving suitable BFs-polymer matrix interfacial bonding that provides effective stress transfer is another critical challenge for fabrication of BFs based polymer composites especially for BFs/polymer structural composites. In the following sections these issues influencing the mechanical reinforcement efficiencies will be discussed.

Table 2 Processing of polymer/bamboo composites

Literature	Materials	Processing
2004 (Okubo et al. 2004)	PP/bamboo ~41–51 vol. % film	Hot-pressed at 190 °C under 2 MPa for 30 min
2004 (Takagi and Ichihara 2004)	Starch based resin/short BFs	Hot pressing at 130 °C under 20 MPa for 5 min
2008 (Han et al. 2008)	HDPE/MAPE/bamboo	Melt compounding
2011 (Verma and Chariar 2012)	Epoxy/dry bamboo culms lamina	In situ epoxy curing with bamboo culms dispersion

MAPE, maleated polyethylene

3 Mechanical Characterization of BF/Polymer Composites

For polymer/bamboo composites, mechanical enhancement could be achieved through three aspects: (i) well dispersed fillers, (ii) effective interfacial interactions between matrix and fillers and, (iii) preferential alignment of polymer chains/fillers in line with mechanical loading direction. To understand these factors, their influence on final composites' mechanical properties and the optimal test method, a review on static tensile properties, dynamic mechanical behavior as well as tribology is provided here.

3.1 *Mechanical Properties of Extracted BFs*

Static tensile test is a straightforward way to study the reinforcement effects (Song 2014). To understand the mechanical reinforcement efficiency, basic properties of BF were listed in Table 3, as compared to other natural fibers and commercial fibers. Among the most popular natural fibers, flax, hemp, jute, kenaf, ramie, and sisal fibers were extensively researched and employed in different applications. But nowadays, abaca, bagasse, coir, oil palm, pineapple leaf, and rice husk fibers are gaining interest and importance in both research and applications due to their specific properties and availability. Among all of them, bamboo shows distinguished mechanical properties, with even higher specific modulus and strength than glass fiber. Materials with high specific stiffness and specific strength are likely to have special merit in applications in which weight will be a critical factor. Because the values of Young's modulus and tensile strength used for the charts calculations were found to be different in every study, the generally used values were marked in ranges. In parallel to that occurrence, the variation of values in the physical properties of the fibers is attributable to different harvesting seasons, ages and/or regions of the planet.

One disadvantage of BF is its poor adhesion to most polymers because of the relatively high moisture absorption. Therefore surface modification or interphase formations become necessary to improve stress transfer from filled BFs to polymer matrix. It is found that alkali treatment influences bamboo mechanical properties (Das and Chakraborty 2008a, b). The important modification achieved with alkaline treatment is the disruption of the hydrogen bonding in the network structure, thereby increasing the surface roughness and interfacial area. An optimal NaOH/water solution of 20% improves BF in tensile strength from 25 to 200 MPa, flexural strength 100–400 MPa, and corresponding toughness from 0.1 to 0.35 MPa, despite a drastic drop in failure strain from 18 to 5%. Improvements in tensile modulus from 1.5 to 7.5 GPa, and flexural modulus from 3.5 to 5.5 GPa also reach maximum when BF was dipped in 20% concentration alkali. Higher alkali concentration will cause a NaOH penetration, material swelling and bamboo

Table 3 Mechanical properties of BFs as compared to other natural fibers and commercial fibers

Fibers	Literature	Physical properties		Mechanical properties				
		Density (g/cm^3)	Diameter (μm)	Tensile Modulus (GPa)	Tensile strength (GPa)	Average specific modulus (GPa/(kg·m^{-3}))	Average specific strength (GPa/(kg·m^{-3}))	Average tensile strai (%)
BFs								
Bamboo	2004 [a](Okubo et al. 2004), 2007 [b](Rao and Rao 2007) 2008 (Das and Chakraborty 2008a, b), 2011 (Osorio et al. 2011)	0.60–1.50	88–250	Up to 43	Up to 0.8	44.90–67	0.55–1.00	1.3
Natural fibers								
Abaca	2002 (Shibata et al. 2002), 2007 (Munawar et al. 2007), 2009 (Bledzki et al. 2009), 2009 (Rahman et al. 2009)	1.50	10–30	12	0.40	8.00	0.26	0.03–0.10
Bagasse	2006 (Cao et al. 2006), 2007 (Zheng et al. 2007)	1.25		17	0.07–0.29	13.60	0.23	0.3
Banana	1982 (Hatakeyama et al. 1982), 2002 (Joseph et al. 2002), 2006 (Sapuan et al. 2006), 2007 (Rao and Rao 2007)			17–85	0.60–0.80	2.50–22	0.44	3.36
Coconut	1963 (Betrabet et al. 1963), 2007 (Rao and Rao 2007)			2.50	0.50	2.17	0.43	20.00
Cotton	2008 (Kim et al. 2008a, b)	1.50–1.60	20	5–13	0.29–0.60	5–13		7–8
Coir	1982 (Hatakeyama et al. 1982), 2003 (Wambua et al. 2003)	1.20		4–6	0.18	3.3–5	0.15	30

(continued)

Table 3 (continued)

Fibers	Literature	Physical properties		Mechanical properties				
		Density (g/cm^3)	Diameter (μm)	Tensile Modulus (GPa)	Tensile strength (GPa)	Average specific modulus (GPa/($kg \cdot m^{-3}$))	Average specific strength (GPa/($kg \cdot m^{-3}$))	Average tensile strai (%)
Curaua	2004 (Gomes et al. 2004)	1.38	66	11.8	0.5–1.15	8.56	0.36–0.83	3.7–4.3
Date (A)	2007 (Rao and Rao 2007)			1.91	0.46	1.99	0.48	24
Flax	1997 (Hornsby et al. 1997), 2000 (Garkhail et al. 2000)	0.60–1.10	50–100	20–70	0.35–1.04	50–70	0.33–1.73	2.7–3.2
Hemp	2003 (Wambua et al. 2003)	1.10–1.48	120	35–70	0.39–0.90	47.29–63.6	0.26–0.82	1.6
Henequen	1991 (Cordemex 1991), 1999 (Canche-Escamilla et al. 1999), 2004 (Herrera-Franco and Valadez-Gonzalez 2004)		180	10–16	0.43–0.57	10–16		3.7–5.9
Jute	1982 (Hatakeyama et al. 1982), 2000 (Hill and Abdul Khalil 2000)	1.30	260	13–26.5	0.40–0.80	7.69–23.1	0.31–0.62	1.5–1.8
Kenaf	2003 (Wambua et al. 2003)	1.31	106	26.50	0.43–0.52	19.85–38.17	0.38	1.5–1.8
Oil palm	1997 (Sreekala et al. 1997), 2004 (Jacob et al. 2004)	0.80–1.60	2.6–4	3.20	0.25	40	0.31	0.8–1.6
Palm	2007 (Rao and Rao 2007)			2.70	0.38–0.77	2.67	0.37	13.71
Pineapple	1997 (Devi et al. 1997), 1999 (Luo and Netravali 1999)	0.80–1.60		1.44	0.40–0.63	25–29	0.80	2.4–14.5

(continued)

Table 3 (continued)

Fibers	Literature	Physical properties		Mechanical properties				
		Density (g/cm^3)	Diameter (μm)	Tensile Modulus (GPa)	Tensile strength (GPa)	Average specific modulus (GPa/(kg·m^{-3}))	Average specific strength (GPa/(kg·m^{-3}))	Average tensile strai (%)
Ramie	2003 (Wambua et al. 2003)	1.50	34	9.40–22	0.40–0.94	24–32	0.21	3.6–3.8
Sisal	2003 (Wambua et al. 2003), 2007 (Rao and Rao 2007)	1.50	50–80	8–10.40	0.57	8–10	0.39	2.0–5.45
Vakka	2007 (Rao and Rao 2007)			15.85	0.55	19.56	0.68	3.46
Commercial fibers								
Glass fiber	1992 (Nishii et al. 1992)	2.50	9–15	70	1.20–1.50	28	0.6	1.9–3.2
Carbon fiber	1997 (Tang and Kardos 1997), 2013 (Song et al. 2013a, b)	1.40	5–9	230–240	4.00	130–171.4	2.86	1.4–1.8

[a] Tested bundle samples containing 100 fibers

[b] BFs extracted using physical method and chemical method

hemi-cellulose depletion. These factors will contribute to softening and frangibility (Das and Chakraborty 2008a, b). Instead, studies according to Gassan and Beldzki (1999) and van de Weyenberg (2005), 3% of NaOH is enough to remove surface waxy materials and impurities on the surface of the fiber. As a result, this increases the fibers' wetting ability, the aspect ratio, and the effective area that comes into contact with the matrix, which will further improve the mechanical interlocking at interface. The removal of the cementing constituents of hemicelluloses, a less dense and less rigid interfibrillar region, allows the fibrils to re-arrange along the fiber major axis during tensile deformation and hence improving some properties of the fiber bundles, which in turn influence the properties of the final composites. Alkali treatment effects studied by several authors (Rong et al. 2001; Das et al. 2006; Mukherjee and Satyanarayana 1984) have been shown to make the mechanical properties of composites become higher than that of untreated versions.

3.2 *Reinforcement and Interfacial Interaction Efficiency from Static Tests*

Static tests are straightforward to examine the interaction between polymer and BFs. The alkali treated BFs have included into polymers to examine their reinforcement efficiency (Kushwaha and Kumar 2009a, b, 2010a, b, c). This would allow for a larger degree of chemical modification on BFs. To improve the stress transfer between BFs and polymer, an interphase adhesion was improved by forming covalent bonds between the –OH group of the fiber and the –COOH group of the maleic anhydride (Kushwaha and Kumar 2010a, b, c). An optimal 5% NaOH solution treatment on BFs exhibited best compatibility with epoxy. Tensile and flexural strength were extensively studied and the enhanced results were attributed to the less water uptake by the composites. In addition, the alkali treatments make the composites more durable. In another recently published work (Kushwaha and Kumar 2010a, b, c), several different chemicals (i.e., maleic anhydride, permanganate, benzoyl chloride, benzyl chloride, pre-impregnation treatment) were used to modify the BF to estimate various mechanical, physical and morphological properties of bamboo reinforced polyester composites (Kushwaha and Kumar 2010a, b, c). It was concluded that different modifications of BF show variations in mechanical, physical and morphological properties of bamboo reinforced polyester composites.

Tensile and flexural tests have been effective in estimating the interfacial interactions between polymer and BFs. Depending on the polymer and material treatments, properties may vary from one to another. For example, tensile tests showed an increase in tensile strength and a decrease in modulus for maleic anhydride-treated bamboo epoxy composites (Kushwaha and Kumar 2010a, b, c). The improvement in tensile strength signifies the interaction efficiency increases; while the deteriorated modulus may be due to the swelling and partial removal of lignin and hemicellulose in BFs. As well known, lignin contributes to the stiffness and modulus. These phenomena have also been observed in SEM images. On the contrary, opposite trend was observed in another study that the tensile modulus increases while fracture strength decreases in BF/rubber composites (Ismail et al. 2002). In this study, bonding agents were used to improve interfacial interactions; SEM and curing time measurements also showed consistent trend.

Flexural strength is a combination of the tensile and compressive strength, which directly varies with the inter-laminar shear strength. In flexural testing various mechanisms such as tension, compression, shearing, buckling, etc. take place simultaneously. The loading in flexure causes normal stresses in the direction of fibers and shear stresses in the plane perpendicular to the load. Composites when loaded in flexure can fail the tension either longitudinally or transversely, or shear in the matrix, interface or fiber. In three-point flexural test, failure occurs due to bending and shear failure. The lower strength of the inter-laminar resin should account for the fact that flexural strengths of the laminates are lower than tensile strengths. Therefore an increase in only tensile modulus and flexural modulus in composites were found to be related to a better chemical bonding between the maleic anhydride modified bamboo and polyester (Kushwaha and Kumar 2010a, b, c), while an improvement in both tensile strength and modulus of the acrylonitrile-treated fiber-reinforced thermosetting resins correlated to the enhanced chemical bonding and minimized defects in BFs (Kumar and Kushwaha 2009).

The study of interfacial bonding also improves the understanding about moisture absorption in final composites (Qiu et al. 2011, 2012). The aim of these studies is to visualize the hydrophobic character of bamboo based reinforced composites in order to support the current demand of utilization of bamboo in outdoor applications. The moisture regaining greatly weakens the interfacial stress transfer from BF to polymers therefore becomes an important illustrator in evaluating composites' mechanical stabilities (Kumar and Kushwaha 2009). For example, silane treatment resulted in reduction of water adsorption and has been studied regarding their effects on moisture reduction degree (Kushwaha and Kumar 2009a, b, 2010a, b, c). Among the many silanes used in this study, amino functional silane showed best results with epoxy resins, and triethoxy derivative gave better results than trimethoxy amino slicanes; however, the best water absorption results were achieved by both alkali and amino-propyltriethoxy silane treated bamboo epoxy composites. Later on in a similar study (Kushwaha and Kumar 2010a, b, c), no alkali treatments were conducted to compare the results. It was observed that amino-propyltriethoxy silane exhibited better results than amino-propylthiemthoxy, for same reason due to enhanced adhesion between BFs and polymer matrix.

The interfacial interactions were not only studied in thermoset polymers but also in thermoplastic composites. PP as matrix is an example. Instead of modifying BFs, some researchers found that modified polymer matrix could be used for reinforcement in composites. The maleic anhydride grafted PP (MA-g-PP as shown in Table 4) was included as compatibilizer in order to improve adhesion between BF and polymer matrix (Chattopadhyay et al. 2011). The direct effects of different maleic anhydride concentrations and modification of BF on various physical and mechanical properties of PP composites suggested that both concentration and

Table 4 Mechanical properties of BF/polymer composites

References	Sample (polymer/% CNT)	Mechanical properties			
		Elastic modulus (GPa)	Strength (GPa)	Strain (%)	Toughness
Thermoset composites					
2003 (Saxena and Gowri 2003)	Polyester/68% Bamboo composite	8.2 ± 1.8	101.8 ± 2.8		
	Polyester/69% Bamboo composite with surface treatment	9.8 ± 2.4	112.2 ± 2.2		
	Epoxy/60% Bamboo composite	7.8 ± 3.8	112.8 ± 1.4		
	Epoxy/60% Bamboo composite with surface treatment	8.2 ± 2.1	144.8 ± 0.7		
2002 (Ismail et al. 2002)	Rubber	1.3	0.020	750	
	Rubber/50 vol.% BF	4.5	0.004	190	
2010 (Wong et al. 2010)	BF	5.96 ± 0.43	0.518 ± 0.051	10.4 ± 0.2	
	Resin	2.0–4.5	0.040–0.090	2	0.5
	Resin/40 vol.% BF	3.8	0.062		1.7
2010 (Kumar and Kushwaha 2009)	Polyester/bamboo	4.2	0.074		
	Polyester/1 h acrylonitrile treated bamboo	8.4	0.097		
	Polyester/5 h acrylonitrile treated bamboo	5.8	0.087		
	Epoxy/bamboo	6.736	0.086		
	Epoxy/1 h acrylonitrile treated bamboo	9.9	0.125		
	Epoxy/5 h acrylonitrile treated bamboo	9.0	0.102		
2011(Prasad and Rao 2011)	Polyester	0.63	0.0315		
	Polyester/40 vol.% Jowar	2.75	0.124		
	Polyester/40 vol.% Sisal	1.90	0.0655		
	Polyester/40 vol.% bamboo	2.48	0.126		

(continued)

Table 4 (continued)

References	Sample (polymer/% CNT)	Mechanical properties			
		Elastic modulus (GPa)	Strength (GPa)	Strain (%)	Toughness
Thermoplastic composites					
1997 (Okubo et al. 2004)	PP	5	0.032		
	PP/0.5% MA-g-PP/50 vol.% BF	6	0.036		
2002 (Thwe and Liao 2002)	PP				
	PP/30 vol.% BF	2.5	0.015		
	PP/10% MA-g-PP/30 vol.% BF	2.6	0.0165		
	PP/10 vol.% GF/20 vol.% BF	2.7	0.016		
	PP/10% MA-g-PP/10 vol.% GF/20 vol.% BF	2.8	0.0175		
	PP/20 vol.% GF/10 vol.% BF	2.9	0.017		
	PP/10% MA-g-PP/20 vol.% GF/10 vol.% BF	3.0	0.0185		
2003 (Thwe and Liao 2003)	PP/10% MA-g-PP/20 vol.% BF	2	0.0205		
	PP/10% MA-g-PP/15 vol.% BF/5 vol.% GF	2.6	0.023		
2004 (Takagi and Ichihara 2004)	Starch		0.010		
	Starch/10% BF		0.020		
	Starch/20% BF		0.026		
	Starch/30% BF		0.036		
	Starch/40% BF		0.040		
	Starch/50% BF		0.042		
[a]2004 (Okubo et al. 2004)	PP	0.018	0.23		
	PP + ~50 wt% BF1	0.004 ± 0.00	0.030 ± 0.00	1.21	
	PP + ~50 wt% BF2	0.005 ± 0.00	0.035 ± 0.002	1.18	

(continued)

Table 4 (continued)

References	Sample (polymer/% CNT)	Mechanical properties			
		Elastic modulus (GPa)	Strength (GPa)	Strain (%)	Toughness
[b]2008 (Samal et al. 2009)	PP	0.586	0.032		
	PP/10%BF	0.710	0.036		
	PP/20%BF	0.813	0.038		
	PP/30%BF	1.240	1.240		
	PP/1%MA-g-PP/30%BF	1.423	0.047		
	PP/3%MA-g-PP/30%BF	1.550	0.0485		
	PP/1%MA-g-PP/15%BF/15%GF	1.491	0.0545		
	PP/3%MA-g-PP/15%BF/15%GF	1.520	0.0583		
[c]2008 (Kim et al. 2008a, b)	PVC/5%P[(SMA)-b-(SAN)]/55 wt% bamboo flour	9	0.036		
	PVC/10%P[(SMA)-b-(SAN)]/55 wt% bamboo flour	11	0.037		
	PVC/15%P[(SMA)-b-(SAN)]/55 wt% bamboo flour	13	0.044		
	PVC/20%P[(SMA)-b-(SAN)]/55 wt% bamboo flour	15	0.047		
[d]2008 (Han et al. 2008)	PE	0.83 ± 0.06	0.021 ± 0.001		
	PE + 30 wt% BF +3.5 wt% MA-g-PE	2.45 ± 0.29	0.029 ± 0.001		
2010 (Mohanty and Nayak 2010)	HDPE	0.153	0.0214		
	HDPE/10% BF	0.330	0.0189		
	HDPE/20% BF	0.758	0.0220		
	HDPE/30% BF	2.674	0.0255		
	MA-g-HDPE/30% BF	2.878	0.0285		

(continued)

Table 4 (continued)

References	Sample (polymer/% CNT)	Mechanical properties			
		Elastic modulus (GPa)	Strength (GPa)	Strain (%)	Toughness
2010 (Wong et al. 2010)	Polyester	2.0–4.5	0.04–0.09	2	0.4–0.6
	BF	5.96 ± 0.43	0.52 ± 0.005	10.4 ± 0.2	
	Polyester + BF	1.1–3.8			1.1–1.7
2011(Chattopadhyay et al. 2011)	PP	0.56 ± 0.004	0.0245 ± 0		
	PP/30 vol.% BF	1.357 ± 0.009	0.0258 ± 0		
	PP/MA-g-PP/30 vol.% BF	1.370 ± 0.006	0.0374 ± 0		
	PP/40 vol.% BF	1.776 ± 0.008	0.0263 ± 0		
	PP/MA-g-PP/40 vol.% BF	1.527 ± 0.008	0.0428 ± 0		
	PP/50 vol.% BF	1.721 ± 0.010	0.0290 ± 0		
	PP/MA-g-PP/50 vol.% BF	1.633 ± 0.011	0.0503 ± 0		
	PP/60 vol.% BF	1.643 ± 0.012	0.0255 ± 0		
	PP/MA-g-PP/60 vol.% BF	1.586 ± 0.008	0.0465 ± 0		

[a] BF2 has more single BF separations than BF1

[b] GF, glass fiber

[c] P[(SMA)-b-(SAN)], Poly(styrene-co-maleic anhydride)-block-poly(styrene-co-acrylonitrile)

[d] MAPE, maleated polyethylene. MA-g-PP, maleic anhydride grafted PP

modification play significant roles in tailoring the properties. The mechanical properties are listed in Table 4. In addition, in this study SEM morphology studies, TGA thermal behavior and FTIR spectra analyses revealed better bonding pattern, respectively. In another study, the effects of the chemical treatment of BF surface (alkaline and acetylation) on fiber structure and composite mechanical, thermal, rheological properties have been investigated (Phuong et al. 2010). Mechanical properties in treated BF incorporated composites as compared to those without treatment showed increases, related to increased adhesion at interphase.

Similarly, in hybrid composites where both BFs and other fibers were included, compatibilizer showed exactly increasing trend in mechanical properties as compared to those without compatibilizer. In one study, use of MA-g-PP in PP matrix results in moderate improvement in tensile modulus and strength of BFRP, while substantial improvement in flexural modulus and flexural strength of BFRP and BGRP were seen (Thwe and Liao 2002, 2003). The researchers believed that MA-g-PP could be utilized in enhancing the better interaction of hydroxyl groups on BFs. The SEM images were used to examine the morphology variations. Voids were observed to decrease greatly due to the impregnation of polymer matrix into BFs. For this reason, tensile strength due to less defects density and modulus due to the more perfect structure were improved to a great content. The same mechanism was applied in HDPE composites. The composites treated with maleic anhydride grafted polyethylene (MA-g-PE) exhibited improved mechanical properties, which confirmed efficient fiber/matrix adhesion. Dynamic mechanical analysis showed that the storage modulus increased in the untreated and especially in treated composites as compared with original high-density polyethylene (HDPE), indicating an increase in the rigidity of the matrix polymer with reinforcement. Optimum stress transfer at the interface region by forming chemical bonds between the fibers and the matrix has been widely accepted as a primary mechanism of the stiffening reasons.

3.3 *Composite Mechanics*

An understanding of the intrinsic mechanical properties of BFs will help the estimation of composites' mechanical behavior. A simple calculation method is modified Rule-of-Mixture (ROM) by taking filler length and orientation factor into consideration,

$$E_c = E_m V_m + \eta_o \eta_l E_f V_f \tag{1}$$

where E and V stand for the modulus and volume fraction for composites (i.e., E_c and V_c) and fibers (i.e., E_f and V_f). Here orientation factor, η_l and length efficiency factor, η_o were defined based on Krenchel's method (Cox 1952) and shear lag theory (McCrum et al. 1997),

$$\eta_o = \frac{\int_0^{\frac{1}{2}\pi} I(\varphi)\cos^4\varphi d\varphi}{\int_0^{\frac{1}{2}\pi} I(\varphi)d\varphi} \quad (2)$$

It is often assumed that the distribution of rods, *I(φ)* as a function of φ, can be described by a Gaussian or Lorentzian distribution. η_o is 0 for perpendicular distribution to loading axis, 1 for unidirectional along loading direction and 0.325 for randomly distributed particles. *I(φ)* have been measured in polarized microscope, Raman (Young et al. 2010; Blighe et al. 2011), and X-ray diffraction (Song et al. 2015a, b, c, d; Chen et al. 2004; Pichot et al. 2006) as well as scattering (Zhou et al. 2004) techniques.

Researches have studied effects of BF loading variations and also orientation effects on mechanical properties of bamboo reinforced polyester composites. The relationship is also plotted in Fig. 1, assuming a polymer modulus of 5 GPa, BF modulus of 40 GPa and volume fraction/orientation factor of a range between 0 and 1. It can be observed that the optimal design of advanced composites is to improve both parameters of orientation and volume fractions. The effects of loading effects on mechanical properties have been widely studied. The optimal parameters were reported to be 60 vol.% (Das and Chakraborty 2009), 50 vol.% (Okubo et al. 2004), 40 vol.% (Wong et al. 2010; Prasad and Rao 2011) or even lower down to 30 vol.% (Han et al. 2008) and 20 vol.% (Thwe and Liao 2002). The optimal concentration

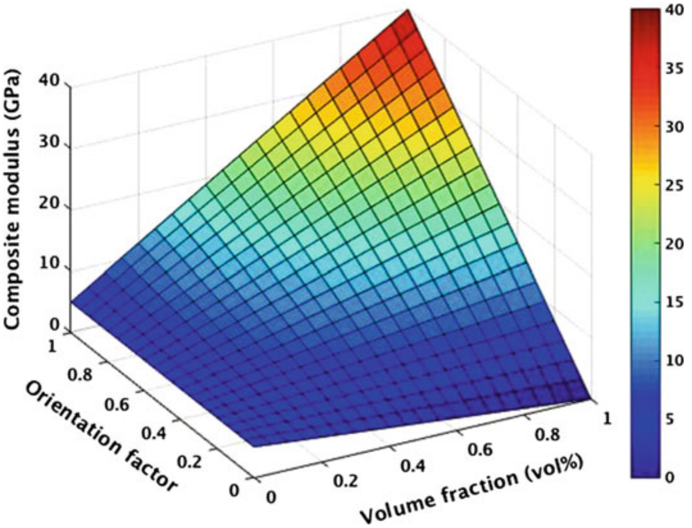

Fig. 1 Composite modulus as a function of parameters of both orientation factor and volume fraction

greatly depends on processing techniques, which determines both dispersion of BF and interaction between BF and polymer matrix.

Uniform dispersion of BFs in polymers is also a fundamental challenge. In fact, no matter what preparation method is adopted, the main purpose is to uniformly disperse BFs within a polymer matrix and obtain composites with as high as intrinsic properties. In general, several factors that influence the dispersion of BFs in a polymer matrix have to be considered in the preparation process of BF/polymer composites. The tightly bundled structure of BFs during growth process and the attraction between single BFs by van der Waals force and hydrogen bonding during processing make BFs themselves hard to be separated. So it is even more difficult for BFs to be separated from one another within the polymer matrix in mixing stage. These factors prevent BFs from being well dispersed within polymers. The obtained BF/polymer composites are poor in their mechanical performance and the intrinsic properties of the composites cannot be achieved. As shown in Sect. 3.1 and Table 1, presently, there are two main kinds of bamboo extractions to improve their dispersion within a polymer matrix: mechanical separation and chemical treatment. However, laborious work is required in mechanical separation, in addition to the scattering size in obtained bamboo fibrils. Chemical treatment may be more facile and practical processing technique considering the time needed and homogeneity in final composites. For example, the maleic anhydride grafted polycaprolactone was used to obtain even distribution of BFs in polymers. The mechanical properties were found to be much enhanced in composites as compared to control samples (Su and Wu 2010). Nevertheless, BFs treated by different surfactants may decrease the contact between BFs, and thereby reduce the stress transfer efficiency properties of BF/polymer composites (Kushwaha and Kumar 2010a, b, c). Silane treatments were studied about their effects on composites' mechanical properties. Take one study for another example; two sets of samples including silane treatment only and siliane treated simultaneously mercerized bamboo. Tensile and flexural properties were examined. It was observed that the silane treated bamboo showed comparable properties to untreated bamboo while the silane treatment after mercerization improved only the flexural modulus, and at the same time decreased the tensile modulus, tensile strength and flexural strength (Kushwaha and Kumar 2010a, b, c).

The interaction between these two phases can be determined by FTIR (Das and Chakraborty 2009), and revealed that the main cause of interaction is due to hydrogen bonding. The fractured surfaces with varied degree of topography were visualized by SEM studies. Bonding interaction between bamboo and polymers was observed with least pullout of fibers. The shear-strength as fiber was pulled out from polymers is a standard for evaluating the interaction between these two phases. Research has shown that the shear strength ranges between polymers (i.e., epoxy, PMMA) and carbon nanotubes of tens to 632 MPa (Chen et al. 2015), and boron nitride of 125–728 MPa. However, interactions between most natural fibers and polymers have not been appreciated and require more attentions.

Preferential orientation is another factor greatly influencing not only mechanical but also electrical properties in final composites (Kumar et al. 2011). The resulted composites possess two fiber orientations, parallel and perpendicular to electrical field. Based on dielectric dissipation factor (tanδ), 0° oriented bamboo/epoxy composites were higher than that of 90° oriented composites. The BF orientations were also examined in flexural tests (Osorio et al. 2011). BFs were first obtained using pure mechanical extraction instead of chemical procedure or high temperature processing. After that alkali treatment was conducted to remove organic and other impurities from the fibers thus enhance the interfacial bonding. BFs were arranged as parallel as possible to make unidirectional samples. The flexural and Young's modulus and strength along longitudinal direction were measured to be much higher than transverse direction. In addition, the strength and modulus were calculated theoretically, which were close to single fiber properties and indicated efficient interfacial interactions.

For length efficiency factor,

$$\eta_l = 1 - \left[\frac{\tan h(na)}{na}\right] \tag{3}$$

$$n = \sqrt{\left[\frac{2G_m}{E_f \ln(2R/d)}\right]} \tag{4}$$

$$a = \frac{l}{d} \tag{5}$$

where G_m is the shear modulus of polymer matrix, $2R$ is the distance from the fiber to its nearest neighbor fiber, l and d mean the length and diameter of the particle.

Researchers studied the effect of fiber length on the mechanical properties of polymer composites by using starch resin and short BFs (Takagi and Ichihara 2004). BFs with 200 μm in diameter and 4–25 mm in length were obtained by steam explosion and then hot pressed with into sheets with starch. At fixed fiber concentration and assumed even dispersion, length efficiency is only dependent on aspect ratio as shown in Eq. 2. Tensile strength and flexural strength in 48 vol.% loaded composites were found to increase constantly from around 10 MPa in matrix up to 50 MPa. However, when fiber aspect ratio drops to 20 (i.e., length of 4 mm and diameter of 200 um), there was no reinforcement effect as composites showed comparable properties with bamboo powder filled composites. Figure 2 also shows clearly how the length efficiency factor changes with parameter *na*. Based on this curve from Eq. 3, shear modulus of 100 MPa, tensile modulus of 40 GPa, and concentration of 48 vol.% generate a value of 0.05 for *n*. A multiplication of aspect ratio of 20 provides a length efficiency of 100%. This is also consistent with the experimental observation that lower length of BF will not reinforce the composites (Takagi and Ichihara 2004). Similarly, this length effect of larger reinforcement from longer fibers in various polymers including polyester (Wong et al. 2010) has been observed.

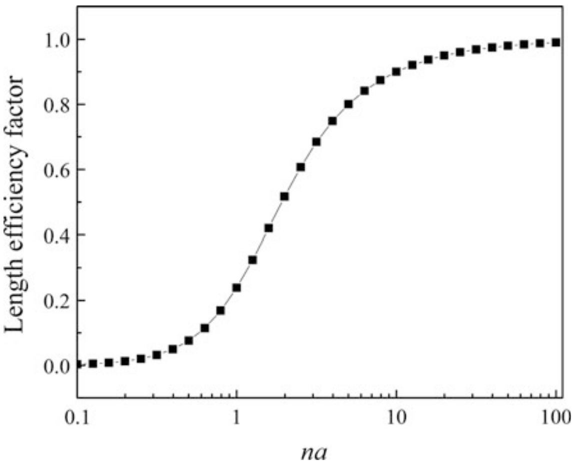

Fig. 2 Length efficiency factor (η_l) as a function of parameter *na*

3.4 Dynamic Mechanical Analysis on Interfacial Bonding Efficiency

DMA provides information regarding rheological/viscoelastic properties of polymeric materials as a function of temperature or frequency. The storage, (E'), and the loss (E'') dynamic moduli as well as dampening parameter (tan δ) are monitored during the temperature sweep test. In contrast to traditional thermal analysis techniques for polymers (e.g., differential scanning calorimetry (DSC), thermal gravimetric analysis (TGA), and differential thermal analysis (TMA)), DMA provides more sensitive characterization of transitions associated with chain movements, molecular relaxations, and their relationship to the interactions between the matrix and filled fibers. The dynamic parameters were ominously influenced by the increase in fiber length, aspect ratio, and orientation as well as loading but not in a geometric progression. Thus DMA is important toward understanding the characteristics for the confined polymer regions as well as other microstructural parameters such as morphology and nature of constituents in polymer composites. The general dynamic mechanical properties of several polymer and polymer based composite materials (i.e., PVA (Park et al. 2001; Nishio and Manley 1988; 2015a, b, c, d), epoxy (Zeng et al. 2014), PMMA (Saha et al. 1996), carbon fiber (Saha et al. 1996), PP (Wielage et al. 2003)) have been previously investigated in details, and reinforced effects of filled particles have been examined. The DMA analyses greatly depend on the composites compositions (i.e., fiber content, concentration, compatibilizer, plasticizer, additive, orientation) and the test mode (i.e., tension, compression, temperature sweep, frequency sweep).

To understand the dynamic mechanisms, physical meanings of measured parameters should be understood. The storage modulus relates to Young's' modulus. This data is associated with stiffness or a material and determines how stiff or flexible the material is. It also reflects the materials' capability to store energy applied on it for future mechanical response. Loss modulus relates to the viscous response to mechanical loadings and reflects the material's capability to dissipate energy. In some studies, researchers believe that the loss modulus is sensitive to internal segment motions, transitions, relaxations, morphology variations or phase generations. Here in this section, damping parameter, the ratio between storage modulus and loss modulus will be focused to relate to the microstructure in polymer/bamboo composites. Usually the higher the damping parameter in specific materials with unit phase, the more content of non-elastic components; however in multi-phase composites, this data may be dealt with cautions for its complicated suggestions of phases.

Matrix-fiber interface (interfacial region) condition strongly affects the mechanical properties of composites and quite often its dampening level too. Interfacial bonding in fiber-reinforced composites can be considered to be weak, ideal or strong. Ideal interface plays the role of transferring loads and do not contribute to dampening. Kubat et al. (1990) proposed a parameter A (relative dampening at interface to that of matrix) and interfacial dampening (tan δ) to describe poor adhesion in composites, and Ziegel and Romanov (1973) derived a parameter B to depict strong adhesion that do not contribute to dampening in composites, as shown in Eqs. 6 and 7. The property derived composition and interphase models will be presented in this section.

$$A = \frac{1}{1 - V_f}\frac{\tan \delta_c}{\tan \delta_m} - 1 \tag{6}$$

$$B = \left(\frac{\tan \delta_m}{\tan \delta_c} - 1\right)/1.5V_f \tag{7}$$

where tan δ_m *and* tan δ_c stand for dampening parameters in control and composites and V_f means the fiber concentration.

3.4.1 Three-Phase Model

PVA macromolecules have been found to possess a template growth on nano-filler surface (Minus et al. 2006, 2009, 2010, 2011, 2012, 2013; Song and Minus 2014). This newly formed interphase is playing a role of stress-transfer between polymer matrix and nano-fillers and can be assessed quantitatively by DMA. BFs-containing PVA have been prepared in many research groups (Rao and Rao 2007; Chattopadhyay et al. 2011; Yao and Li 2003; Rajulu et al. 1998, 2004; Cao and Wu 2008; Deshpande et al. 2000; Jain and Kumar 1994; Rao et al. 2010, 2011; Tran et al. 2013) but the interphase formation characterizations have not been found in any DMA analyses. This fractional constrained region of PVA can be computed in the following manner (Song et al. 2015a, b, c, d). According to the linear viscoelastic behavior, the relationship between the energy loss fractions W and dampening parameter tan δ can be given in Eq. 8. It is well known that loss of energy during dynamic tests on pure polymer fibers (i.e. control) mainly arises due to the presence of less constrained and amorphous/low-ordered regions (Menard 2008). This phenomenon can be analyzed by examining the tan δ peak associated with the glass transition region for the polymer material. This peak amplitude diminishes and/or shifts as ordering in the polymer material increases. By assuming a proportional relationship between W and the fractions of amorphous/low-ordered regions (V_a) (Eq. 9) the more constrained/ordered regions (V_c) can be calculated using Eq. 10. The baseline portions pertaining to the amorphous and constrained regions are determined using the DMA tan δ data from the control fibers. Therefore, Eqs. 9 and 10 use the loss fraction from the control fiber ($W_{control}$), where $V_{a\_control}$ is the volume fraction of the unconstrained (lower ordered regions), $V_{c\_control}$ is the volume fraction of the more constrained regions (crystalline regions), and α is the proportionality constant.

$$W = \frac{\pi E''}{\pi E'' + E'} = \frac{\pi \tan \delta}{\pi \tan \delta + 1} \tag{8}$$

$$V_{a\_control} = \alpha W_{control} \tag{9}$$

$$V_{c\_control} = (1 - \alpha) W_{control} \tag{10}$$

It is recognized that for the nano-composite fibers the ordered portion consists of both crystalline ($V_{c\_composite}$) as well as interphase (V_{m2}) regions. Therefore a modification of the constrained regions in composites is included in Eq. 11, where $W_{control}$ and $W_{composite}$ represent the energy loss fraction of the control and composite fiber samples, respectively. These loss fractions are measured from the glass transition peak amplitude. Equation 12 is derived from Eqs. 10 and 11 to determine the ratio $V_{m2}/V_{c\_control}$. This provides an indication for the presence of interphase regions in the composite samples, which go beyond the general semi-crystalline polymer matrix structures present in the control fibers.

$$V_{c\_composite} = V_{c\_control} - V_{m2} = (1 - \alpha) W_{composite} \tag{11}$$

$$\frac{V_{m2}}{V_{c\_control}} = 1 - \frac{W_{composite}}{W_{control}} \tag{12}$$

Figure 3 shows a plot for $V_{m2}/V_{c\_control}$ as a function of filler concentration, where all composite fibers show an increasing presence of interphase regions as compared to the control fibers. Comparison between the Rule-of-Mixture analysis and these DMA measurements (Fig. 3b) indicate that the composite fibers exhibit regions of self-reinforcement (interphase), which enhances stress-transfer mechanisms in the materials (Song et al. 2015a, b, c, d).

The three-phase model described above has actually been studied theoretically before (Chaturvedi and Tzeng 1991), the interphase is referred as distinct third phase between the fiber and bulk matrix with its own viscoselastic properties.

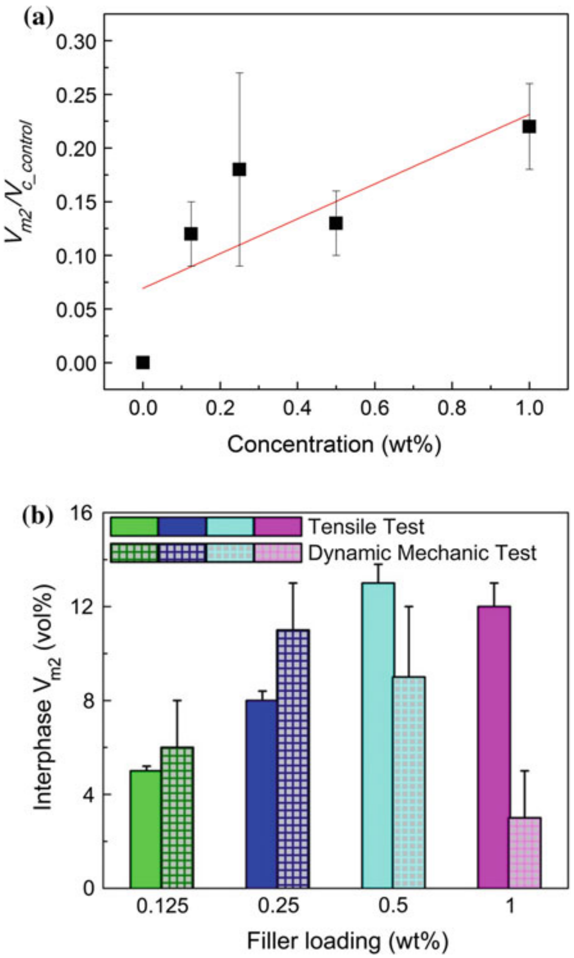

Fig. 3 **a** Plot shows $V_{m2}/V_{c\_control}$ versus the filler loading (wt%). **b** Plot of interphase volume fraction (V_{m2}) predictions for all composites using DMA analysis as compared with measurements from static tensile tests. Interphase growth is shown to increase with filler concentration. (Permission of reprint in this book was grated from John Wiley and Sons)

Parametric study indicate that the fiber aspect ratio, the elastic modulus and dampening properties of the interphase materials appear to be dominant parameters which significantly influence the dynamic stiffness and viscoelastic dampening properties of the three phase composite system. The main drawback of the model is that the input data for the interphase, i.e., geometric and material properties of interphase have been interpolated and no experimental values are available (Chaturvedi and Tzeng 1991).

3.4.2 Two-Phase Model

The interfacial interaction between the filler and the polymer matrix in a two-phase model can also be studied by correlating dampening parameter and interaction efficiency. The theoretical estimation has been observed experimentally.

$$\frac{\tan \delta_{control}}{\tan \delta_{composite}} = 1 + 1.5V_f B \tag{13}$$

$$B = \left(1 + \frac{\Delta R}{R_o}\right)^3 \tag{14}$$

where the term $\frac{\Delta R}{R_o}$ is the relative increase in particle diameter for spheres, V_f represents the volume fraction of the fillers, B is the intercalation parameter describing the interfacial adhesion between the fillers and the polymer matrix quantitatively. A larger value of B means a better interaction between the two phases.

This phenomenon has also been taken advantage by creating hydroxylation functional groups on fibers (i..e, halloysite tubes, carbon nanotubes, boron nitride tubes, glass fibers, carbon fibers, as well as natural fibers) to further reinforce the epoxy nanocomposites (Zeng et al. 2014). The calculated interaction parameters for composites without and with hydroxylation were listed in Table 5. The low and negative value in epoxy/p-HNTs indicates a weakly physical interaction between the two phases. However, there is a higher B value in epoxy/h-HNTs, which is ascribed to the hydroxylation group density on the external surface of h-HNTs and led to better stiffening and toughening effects. Similarly, BF, powder, and strip reinforced composites are also applicable from this mechanism (Shih 2007). Dampening parameters and interaction parameters were recalculated and listed in Table 5. It can be shown that the bamboo powder showed the highest interaction efficiency with epoxy matrix (Shih 2007). This is sensible due to the easier dispersion and also interactive area caused by the even bamboo powder distributions. Inversely, BFs were observed to be more difficult to disperse. Appropriate coupling agent (i.e., Z6040) was found to increase the BF/epoxy compatibility and therefore increased its storage modulus, loss modulus and also thermal stabilities.

Mercerization effects on BF composites were also examined using DMA (Das and Chakraborty 2008a, b). The bamboo stripes were treated using varied NaOH concentrated solutions from 10 to 20 vol.% before composite preparations. The storage modulus, and dampening parameter were found to increase with increased alkali concentration in treatments. It was explained that with higher concentration of alkali treatments, more and more non-cellulosic material has been removed, and as a result the polymer matrix can penetrate more in the crevices. As a result of this the amount of matrix by volume has become adequate to dissipate the vibrational energy of molecules properly and therefore the dampening parameter value increases. This is also consistent with the differential scanning calorimetry tests,

Table 5 Dampening parameter of epoxy and HNT reinforced composites

Samples	Concentration (wt %)	Dampening parameter (*tan* δ)	*B*
Pure epoxy (Zeng et al. 2014)	0	0.82	N/A
Epoxy/p-HNTs	4.8	0.84	−0.65
Epoxy/h-HNTs	4.8	0.76	1.78
Epoxy (Shih 2007)	0	0.200	N/A
Epoxy/Bamboo powder	10	0.071	12.11
Epoxy/BF	10	0.120	4.44
Epoxy/coupling agent treated BF1	10	0.125	4.00
Epoxy/coupling agent treated BF2	10	0.114	5.03
Phenolic resin (Das and Chakraborty 2008a, b)	0	0.4755	N/A
Phenolic resin/bamboo strips	25	0.159	7.96
Phenolic resin/10% alkali-treated bamboo strips	25	0.1634	7.64
Phenolic resin/15% alkali-treated bamboo strips	25	0.1638	7.61
Phenolic resin/20% alkali-treated bamboo strips	25	0.1808	6.52
HDPE (Mohanty and Nayak 2010)	0	0.6	N/A
HDPE/20% BF	20	0.4	2.5
MA-g-HDPE/20% BF	20	0.2	10
PP	0	0.17	N/A
PP/30% BF	30	0.15	0.44
PP/2% MA-g-PP/30%GF	30	0.11	1.82
PP/15% BF/15%GF	30	0.14	0.71
PP/2% MA-g-PP/15% BF/15%GF	30	0.08	3.75

Note p-HNTs were prepared using H_2O_2 to remove organic impurities while h-HNTs were further treated using NaOH to form hydroxylation functional groups on HNT surfaces. The pure and composite films were prepared using cast mold method (Zeng et al. 2014). Similarly BFs were treated using coupling agents Z6020 (BF1) and Z6040 (BF2) (Shih 2007)

which showed the highest transition temperature in 20% alkali treated bamboo composites.

Maleic anhydride treatment was examined in a similar way to alkali treatment using DMA. The composites treated with maleic anhydride grafted polyethylene (MA-g-PE) exhibited improved mechanical properties, which confirmed efficient fiber/matrix adhesion (Mohanty and Nayak 2010). In dampening parameter peaks, MA-g-PE-based composites produced a higher magnitude of a peak, which is indicative of the fact that the treated fibers have strongly adhered to the matrix and thereby hindered the mobility of the polymer chain in the crystallites (Table 5).

Hybrid composites of polymers reinforced with bamboo (BFRP) and glass fibers (BGRP) were examined using DMA. This tactic of hybridization allows tailoring the composite mechanics for desirable properties. Maleic anhydride grafted polypropylene (MAPP) has been used as a coupling agent to improve the interfacial interaction between the fibers (i.e., both glass fiber and BF) and matrix (Samal et al. 2009). The tan δ spectra presented a strong influence from fiber content and especially from coupling agent, that is, a great depression of this dampening parameter was observed. This suggests a more robust interfacial interaction. With inclusion of coupling agents at various concentrations, the mobility of the macromolecular chains located in the fiber surface interface reduces with the increase in the fiber–matrix interaction that results in a shift in the glass transition temperature T_g towards higher temperature range and a simultaneous decrease in tan δ. Kuruvilla et al. (Joseph et al. 1993) has also reported that incorporation of short sisal fiber into low-density polyethylene (LDPE), results in an increase in storage and loss modulus, whereas the mechanical loss factor (tan δ) decreases.

Two-phase model and three phase model have also been studied theoretically in micromechanics models (Vantomme 1995). For various longitudinal, transverse, and shear loss factors in composite materials (Epoxy/glass fiber composites), the percentage contribution of dampening from fiber, matrix and interphase are predicted. The three-phase model suggested that in unidirectional laminate, poor adhesion between matrix and fiber would lead to low elastic stiffness and high dampening. The method mentioned above derived the interphase in interphase highly occupied composites; however for a normal quality interphase, more sensitive and accurate dampening measurement methods are needed to identify the contribution from interphase to the overall dampening parameter.

3.4.3 Interfacial Interaction Improvement

Low cost, availability with ease, low density, high specific mechanical properties, less wear or corrosion in processing techniques, and environmentally friendly characteristics of the bamboo reinforcement in polymers have been the primary benefits for their commercialization. Despite these advantages, use of BFs, same as other natural fibers, have been limited mainly due to the poor adhesion with polymer matrix as compared to their synthetic counterparts. Various BF surface treatments have been reported and also summarized in Table 6. The interfacial interaction improvements due to these surface treatments have been achieved in both physical and chemical means.

3.5 Tribology Properties

Besides mechanical properties, tribological performance of fiber reinforced polymer composites is critical to many industrial applications, since composites could be constantly exposed to tribological loadings, e.g. abrasive environments. However, there are considerably fewer studies on tribological properties compared to

Table 6 Interfacial interaction improvement methods for better composites' properties

Year	Techniques	Details
2000 (Deshpande et al. 2000)	Alkali/mercerization treatment	NaOH solutions of various concentrations were examined for optimal properties
2002 (Thwe and Liao 2002)	MA-grafting	The effects of Maleated PP/PE/LDPE/HDPE/polyester on tensile and flexural properties of BF reinforced composites were studied. Polar Maleic anhydride grafted polymers can improve fiber dispersion and interfacial interactin trhough hydrogen bonding between hydroxyl groups of natural fibers and carbonyl groups on the maleic anhydride segment of MA-grated polymers
2003 (Saxena and Gowri 2003)	Polymer bridging effects	The effect of surface treatment on the properties of bamboo/epoxy, and bamboo/polyester composites were studied. An improvement in the properties was observed when the surfaces of BFs were modified with polyester amide polyol, which acts as a bridge between the fibers and polymer matrix
2004 (Kumar and Siddaramaiah 2004), 2009 (Kim et al. 2008a, b), 2011 (Kumar and Siddaramaiah 2005)	Polymer coating	BFs were coated with polymers for more efficient polymer-interphase interactions
2004 (Okubo et al. 2004)	Cellulose enhancer	Use poly-lactic acid and BFs extracted by steam explosion method with micro-fibrillated cellulose from wood pulp as an enhancer
2007 (Shih 2007), 2008 (Han et al. 2008), 2009 (Kushwaha and Kumar 2009a, b), 2010 (Kushwaha and Kumar 2010a, b, c)	Coupling agent/Silane treatments	The effects of various coupling agents on filler dispersion and interfacial interaction were studied
2009 (Kumar and Kushwaha 2009)	Monomer grafting	Acrilonitrile treatments at various durations were examined for property modifications in polyester composites
2010 (kushwaha and Kumar 2010a, b, c)	Both silane and alkali treatments	Silane treatment on mercerized BFs was found to improve the mechanical properties the most as compared to only silane or alkali treatments

mechanical properties (Shalwan and Yousif 2013). The wear and friction performance of BF reinforced epoxy composites were also studied (Nirmal et al. 2012). The introduction of BFs influences the anti-shear properties. The friction performance in composites was enhanced around 44% as compared to pure epoxy. Morphology studies confirmed that the orientation of BFs affects the anti-shear behavior, that is, antiparallel to shear direction causes the most resistant properties compared to random and parallel orientation.

4 Thermal Characterizations

A large number of thermal characterizations of natural plant fiber, including BF, based composites have been reported. The most frequently thermal characterization methods include DSC, TGA, and DMA. The increase of thermal transition temperatures has been observed in epoxy (Shih 2007), PP (Chattopadhyay et al. 2011; Samal et al. 2009), polyester (Mounika et al. 2012) and so on. The better thermal stability is mostly due to an increased interfacial interaction between the reinforcing filler and bulk polymers. At the same time, the good dispersion of BFs will help the dissipation of thermal heat and improve thermal transition temperatures. Mercerization treatments can actually decrease the fibers' affinity to water absorption. As soft metal ions replace original hydroxyl functional groups and subsequent neutralization generates the new cellulosic bonds between parent cellulose molecules, the regaining of water moisture greatly decreased. These changes can easily be detected from DSC and DMA. For example, PP is known for its α- and β-crystalline forms. It was observed that the addition of BF to PP or maleated PP causes an increase in the overall crystallization rate. In addition, a considerable amount of β-crystals were present as long as BFs were introduced while in PP matrices, there were only α-forms (Mi et al. 1997). These evidences can be provided from both DSC and WAXD. The nucleation effect for generating β-crystal from BF is also a significant indicator for improved interfacial adhesion. The crystallization peak temperatures detected from DSC or DMA were found to be proportional to BF content, assuming same heating/cooling rates.

Thermal degradation temperatures, unlike glass transition or crystallization temperatures, which can be detected using either DSC or DMA, are derived from TGA. The degradation behavior of many natural fibers was summarized by Yao and coworkers (Yao et al. 2008). Similar to other natural fibers, BFs exhibit an onset degradation temperature at about 214 °C and a major degradation at around 310 °C. These decomposition characteristics should be carefully considered in the design and manufacturing of BFs reinforced polymer composites. Compared to pure PLA or PBS matrix, BFs-filled PLA or PBS composites show relatively lower onset degradation temperature, which might be attributed to the reduced molecular weight of the polymer matrix after intensive processing. To improve the thermal stability, diisocyanates crosslinkers were added to build up the molecular weight of the matrix. Thermal degradation temperature of the resulting composite was increased. Lee and Wang (2006) Fiber content in composites is one of the most important factors that affect thermal property directly. Another important factor is the silane and similar surface treatments. It was observed in one comparative biodegradation study that partial degradation is a good reason that has direct impact on thermal stability of bamboo composites.

5 Application of BF/Polymer Composites as Structural Materials

The applications of bamboo-based materials have been found traditionally in housing, furniture, packaging, transport cargo and so on. Their advantages include low cost, low maintenance, nontoxic, high abrasion resistance, high impact resistance, and dimensional flexibility. Currently on market, most bamboo composites are mostly PE, PU and PP filled BFs or sheets. The application has been extended from fencing, railings, and outdoor furniture to automobile and sport goods (i.e., car doors and surfboards). This section will review these potential usages in the future.

5.1 Automobile Applications

Automobile industry has shifted to more sustainable constructions, including usage of green composites, mainly due to high efficiency and government regulations. Based on the European guidelines, 95% of the vehicle weight has to be recycled by 2015 (Energy and Polytechneio 2003). In the United States, such requirements have not been regulated. Nonetheless up to now the most recyclable parts are still metallic. Auto-body could be reduced in weight by up to around 70% if currently used steel auto-body is all replaced by composites (Yang et al. 2012); and this is specifically important for the appearing electrical vehicles so as to increase the maximum mile range. One way to reduce the cost and simultaneously balance sustainability is to use degradable materials, including polymer based BF composites. Currently most polymer-based composites contain talc, calcium carbonate, mica, and glass and carbon fibers. Most of the parts are used as trim parts in dashboards, door panels, parcel shelves, seat cushions, backrests and cabin linings.

BFs, like other natural plant fibers, have certain drawbacks before preparing successful automobile parts. For example the tendency to form aggregates during processing, low thermal stability, low resistance to moisture and seasonal quality inconsistencies. Besides, the high moisture adsorption of plant fibers leads to swelling and presence of voids at the interface or porous regions, which will greatly deteriorate mechanical properties and reduces dimensional stabilities. Another advantage is the poor compatibility between fibers and polymers. The polymers used in automobile are thermoset, including mainly epoxy and phenolic, and thermoplastic, mainly PE, PVC and PP. Most of these polymers are hydrophilic while cellulose in bamboo is hydrophilic. For better affinity between these two, chemical treatments by chemicals as coupling agent or compatibilizer are necessary (Ren et al. 2012a, b). Thirdly, the lower thermal stability of BFs also limits the possible processing techniques, such as color change, odor variation, gas generation and mechanical property decreases. Strategies such as coating of high-temperature stable polymer or monomer may be valid modifying this property.

5.2 *Sports Goods*

Application of bamboo composites in sports industry has been well known (Subic et al. 2010). These reinforced composites have been used to produce surfing boards, baseballs, polo balls, etc. The advantages of using Bamboo fibers in sports apparel include their softness, moisture permeability and thermal property. These products are lightweight with particular design and waterproof surfaces. The multi-layered boards are with epoxy matrix with specialty over glass boards. This specialty allows for stiffness and long mechanical durations.

5.3 *Construction and Building Materials*

Application of natural fibers, such as coconut, sisal, jute, ramie bast, eucalyptus pulp, malva, banana, hemp, kenaf bast, flax, pineapple leaf, sansevieria leaf, abaca leaf, bamboo, date, palm, sugarcane fiber and cotton as indicated in Table 4, are being commonly reinforced in the polymer system to complement the certain specific properties in the final product. Among these different natural fibers, hibiscus sabdariffa, henequen, pines, esparto, sabai grass and banana fibers are still some of the unexplored high potential fibers having similar chemical constituents (cellulose, hemicellulose and lignin), mechanical properties and thermal resistance to other more explored natural fibers such as jute, sisal, hemp, bamboo, oil palm. Construction and building materials are the most interesting application area, which relates to enhancing the functional properties of concrete, steel, wood, and glass, as the primary construction materials. The government policy requires the usage of recyclable and reusable materials for sustainable development.

Due to their light weight, high strength, and abundant sources, bamboo fibers composites have been identified as great eco-products for construction industry. Bamboo-based biocomposites are used as structural components or interior design components in buildings. Bamboo is still being investigated as concrete reinforcement for future housing construction due to the low moisture resistance of bamboo mateirals. The topic has been discussed by Aziz and coworkers (Aziz et al. 1981).

6 Potential Concerns of BF and BF-Based Composites

In addition to the advantages of using BFs in polymer-based composites, the disadvantages include their mechanical and thermal performances, their adhesion with polymer matrix and their processing optimizations. First of all in different growing regions or even different season, BFs are not capable to provide consistent physical properties. These properties can vary from both physically and time-dependent based on interchangeable sunshine levels, water supplies, wind levels, thermal history, and soil conditions. Additionally, these variations can also be observed even in the same forest in between the crops. All of these factors result in significant variations in properties in contrast to their synthetic fiber counterparts (such as synthetic carbon fiber, aramid high performance fibers or E-glass fibers as well as natural clay particles). One possible approach to address this issue is to develop new crops or new mixture of hybrid fibers by evenly distributing these varied bamboo seeds or baby crops. Blending fibers provides a barrier against variability in any single fiber crop. And more essentially is to develop processing techniques so that fine and even fibers are obtained before mixing in polymers.

Another major negative issue of BFs is their poor interaction with most of the polymer matrices. The uneven dispersion may lead to uneven distribution of fibers within the matrix and what is worse, the inefficient stress transfer between the polymer and fibers. Most polymers are hydrophobic and natural fibers are hydrophilic, resulting in poor adhesion and ineffective stress transfer at the interface (Ren et al. 2013). BFs are sensitive to moisture, which leads to reduction of mechanical properties and delamination. Moreover, their susceptibility to microbial corrosion, rotting, and long-term storage may also limit the shipment and composite processing. The commonly suggested solution to this problem is to use chemical coupling or adhesion, aimed to improve the interface compatibility by increasing bonding energy between polymer and fillers.

The third drawback of using BFs is their limited thermal stability. The highest processing temperature is around 300 °C, above which the fibers significantly decompose and deteriorate the mechanical properties of the composites. This greatly limites the variety of resins they can be blended with. To avoid the defects or damages caused by processing techniques, the range of thermal treatment temperature and processing time has to be carefully chosen based on the fiber stability.

Last but not the least, the choices of matrix may also require careful considerations from biodegradability. For example, traditional thermosets render the overall products not easily recyclable in addition to their high melt viscosity and less processing ease. On the opposite side, the novel bio-based thermosets, such as plant-oil based resins, can be decomposed in most cases. Therefore it would be preferable to opt for bio-thermoplastics, which do not need polymerization process and may also combine both benefits of recyclability and prospect disposal.

7 Conclusion

The study of bamboo fibers in various applications has opened up new routines for sustainable, recyclable and self-degradable green composites. Various polymer matrices have been taken advantage for fabricating optimal composites with high mechanical performance. To design such composites thorough investigation of fundamental, mechanical, and physical properties of bamboo fibers are necessary. This review has reviewed the extraction of bamboo fibers, fabrication of polymer composites, mechanical characterization and thermal properties, as well as brief information regarding applications. Although basic scientific questions about bamboo fibers and polymer matrices have been answered, the full content of composites' properties has not been fully achieved and a great deal of research efforts are still required to develop the next generation of BFs-based composites.. It is worth believing that the challenges confronted now will lead toward high performance, biodegradable and renewable eco-friendly materials.

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