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Review

A Sustainable and Biodegradable Building Block: Review on Mechanical Properties of Bamboo Fibre Reinforced PLA Polymer Composites and Their Emerging Applications

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Abstract: The development of bamboo fibre (BF) reinforced poly lactic acid (PLA) BF-PLA composites has been growing fast among the natural fibre reinforced composites (NFRCs) over the past few years. BF-PLA composites have gained significant interest as sustainable alternative materials for the engineering and industrial sectors. BF-PLA composites are getting popular due to their remarkable features such as eco-friendliness, biodegradability, recyclability, low cost, low specific weight, and improved mechanical and thermal properties. In this paper, a schematic review of the BF-PLA composites was conducted in terms of mechanical properties (i.e., tensile properties, flexural properties, and impact strength), thermal characteristics with and without chemical treatment, and creep behaviour. Moreover, the sustainability aspects, including biodegradability and recyclability of BF-PLA composites, have been discussed based on various manufacturing methods. In addition, the utilization of BF-PLA composites in the additive manufacturing industry, sustainable packaging, structural, dielectric, and automotive applications are also described to make elevations toward future research and industrial implementations or commercialization. Furthermore, the effects of 3D printing parameters on the mechanical and physical properties of printed BF-PLA objects have been summarized. Significantly, this paper highlights the limitations and future perspectives of the BF-PLA composites.

Keywords: Additive manufacturing, Bamboo-PLA composites, Mechanical properties, Thermal characterization, Recyclability

Introduction

Plastic usage is widespread due to its magnificent properties, such as lightweight, inexpensive, substantial, flexible, and corrosion-resistant high thermal and electrical insulation properties [1]. Most of the plastics are produced from petroleum and chemical-based products known to be toxic [2]. Another issue is plastic waste or plastic pollutants, which may be a potential threat to human health, especially if the food chain is contaminated [3]. However, the plastics are primarily non-biodegradable, and a long time is needed to degrade [4]. Therefore, alternative materials for plastic are needed and required to answer that situation. Accordingly, there is a crucial need for environment-friendly plastics that are degraded normally and produced from renewable resources, also to address the global environmental and waste management problems and begin a more sustainable society [5]. The challenge is not only to replace them but also to create and provide the materials with the appropriate mechanical, physical, thermal performance characteristics and to minimize the cost for the final products [6].

The utilization of natural fibres as reinforcement is one of the sustainable alternatives to satisfy the critical demands. Since natural fibres are biodegradable, eco-friendly, cost-effective, and offer high specific strength and stiffness, low density, lower dermal and respiratory irritation, better insulation properties, etc. Natural fibres are classified as plant-based and animal-based [7]. Plant-based natural fibres are bamboo, flax, coir, hemp, jute, sisal, kenaf, pineapple, and ramie, and animal-based fibres are silk, wool, etc. Natural fibres are feasible to replace synthetic fibres [8-11]. Compared to most synthetic fibres, natural fibres offer good specific mechanical properties, economical to manufacture, are easier to handle, and require only around 20-40 % of the production energy [12]. The utilization of natural materials and modern manufacturing techniques minimizes construction waste and maximizes energy efficiency toward the concept of sustainability [12]. The increased global demand and the percentage growth of applications of NFRCs [13] are shown below in Figure 1.

Green composites are extracted from renewable resources, for example, starch, sugar, vegetable oils, and soy oils reinforced using natural fibres; PLA is the regular type used [14-16]. Sujaritjun *et al.* proved BF as the most effective reinforcement compared to other fibres such as vetiver grass fibre and coconut fibre reinforcements [17]. Several studies have been performed on the development of green composites based on BF and PLA resin composites as well as the improvement of thermal and mechanical properties with various surface modification treatments [18] and the effect of using different types of bamboo fibres [19]. For

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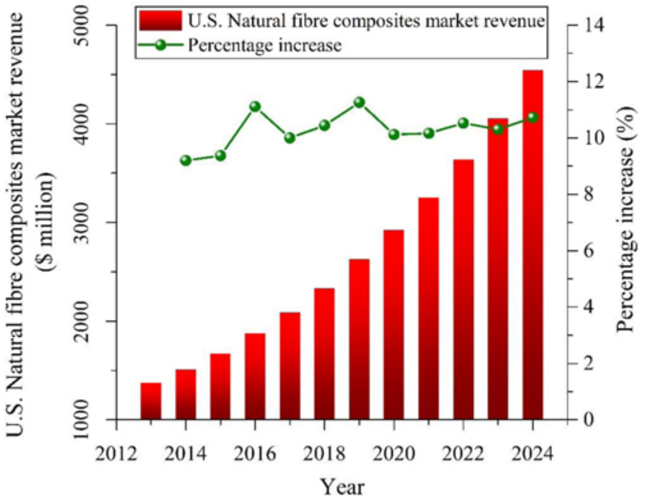


Figure 1. Demand and increase rate of NFRCs from 2013-2024.

example, double melting behaviour [20], the impact of molding conditions on the mechanical properties of bamboo-rayon continuous fibre reinforced PLA composites [21], the effect of cooling rate and hot-press temperature on thermal and physicomechanical properties [22], the impact of bamboo flour grafted lactide on the compatibility interface [23] and influence of polyethylene glycol on mechanical properties of BF-PLA composites [24] had been studied. However, various surface modification treatments alkali (NaOH), alkali-silane coupling agent (NaOH-KH550), had been applied to enhance the mechanical and thermal properties of BF-PLA composites [17,25,26]. Moreover, the influence of low-concentration NaOH solution pre-treatment on the properties of BF-PLA composites had been looked over [27]. Furthermore, different BFs such as nonwoven membrane [28] bamboo charcoal particles had been used in reinforcement to enhance the impact resistance of biodegradable polymer [29]. The outcome of nano-SiO_2 on the interfacial harmony and properties of PLA-grafted-BF PLA composites [30] and MA on BF-PLA composites [31] had been probed. Mechanical, thermal, and morphological properties of bamboo cellulose nanowhiskers (BCNW) PLA bio-composites [32], flame-retardancy of recycled bamboo chopstick fibre-reinforced PLA green composites [33] had been investigated. Liu *et al*. had performed a comparative study on six wood plastic composites (WPCs) made of organo-montmorillonite-modified fibres and PLA [34]. Preparation and characterization of PLA-g-BF based on in-situ solid-phase polymerization [35] and the interfacial compatibility of BF-PLA composites in-situ solid phase grafting [36] had been studied. The tensile and flexural properties of PLA-based hybrid natural composites reinforced with bamboo, coir and kenaf fibres [37], morphological properties of hybrid composites based on PP-PLA blend reinforced by BF [38] had been investigated. Furthermore, a study on physicochemical properties of electron beam irradiated bamboo powder (BP) and BP-PLA composites had been conducted [39]. Few previous studies related to BF-PLA composites and their applications are summarized in Table 1.

Table 1. Previously used BF-PLA composites, their merits, demerits, and applications

Material	Manufacturing process	Benefit	Drawback	Application	Reference
BF, PLA, MA, DCP	Mechano-chemical compositing	Eco-friendly, 100 % renewable materials	-	Industrial	[181]
BF, PLA, MFC from wood	Hot pressed	Biodegradable	-	Engineering	[182]
BF, PLA, PBS, LDI	Compression molding	Environment-friendly	-	Toys, furniture, flooring, electronic hardware, disposable products	[145]
BF, PLA	Conventional hot pressing	Green composite	Low thermal conductivity than that of woods	-	[183]
BF, PLA, NaOH	Hot-pressing	Environment-friendly, high strength, low density, low cost, easy to manufacture	-	Indoor panel	[111]
WBF, PLA	Hot-press molding	Excellent energy absorption capability, green laminate, fully biodegradable	-	Engineering, structural	[51]
BF, PLA, CG, MDI	Twin-screw extruder	Green composites, low cost, improved thermal properties, the environmentally friendly recycling process	The tensile reduced by 20.1-54.3 % and flexural strength reduced by 24.53-60.1 % than of PLA with the increment in natural fillers	Building interior materials, industrial purpose	[100]
BF, PLA, Cloisite 30B nanoclay	Compression molding	Enhanced mechanical properties, significant improvement (26.58 %) in impact strength	-	Dielectric	[184]

Table 1. Continued

Material	Manufacturing process	Benefit	Drawback	Application	Reference
BF, PLA sheets, PP sheets	Hydraulic press heating	Improved thermal resistance i.e., heat deflection temperature increased by 23-34 % than PLA	Should avoid high humidity environments	Packaging	[116]
BF, PLA, AP, VM, MA, AA	Melt-compounding, compression molding	Biodegradable	-	Applicable in different areas of modern life	[185]
BCF, PLA, KH560, MA, NaOH, ethanol, DCP	Mini-extruder, mini-injection molding	Chemical modifications improved the mechanical properties (Young's modulus increased by 34.6 % than of untreated)	KH560 treatment slightly decreased the crystallinity, virgin BCFs decreased mechanical properties	Industrial	[186]
BF, PLA	Compression molding	Eco-friendly, sustainable	-	Sustainable packaging	[62]
BF, n-HA, PLGA, KH550	Solution mixing method	Biodegradable	-	Bone, and bone fracture internal fixation materials	[90]
SEBF, PLA, NaOH	Hot-pressed	Similar strength as glass fibre reinforced plastics, three times higher strength than that of mild steel	Tensile strength and Young's modulus were about half of those of E-glass fibre	Automotive, interior	[49]
BF, PLA	Manual lay-up	Environment-friendly, high performance, low cost	Applications in aerospace are very restricted	Structural, energy, automotive	[65]
PLA, A-151, BCNW	Solution cast	Bio-nano-composite	Tensile strength and modulus reduced with silane treatment	Engineering	[118]
PLA, BC, HNO_3, NaOH	Co-rotating twin-screw mini-extruder	Extend the application of bamboo-char in polymer composites	-	Polymer composites	[187]
BF, PLA, NaOH	Compression molding, hot-pressing	Biodegradable, natural composite	-	Industrial	[102]
BF, PP, PLA, MAPP, NaOH, KH550, Isocyanate	Co-rotating twin-screw extruder	Biodegradable, recyclable, low cost, catalyst-free, improved mechanical properties with BF modification	Addition of untreated BF decreased the impact and flexural strength	3D printing	[103]
BF, PLA, TA-ESO solution	Reactive blending	Fully bio-based composites	-	Automobile interior parts, containers, furniture, food packaging	[124]
BC, PLA	Compression molding	Tensile modulus enhanced with the addition of BC particles	The addition of BC decreased tensile strength, elongation at break, and shear viscosity	Food packaging	[188]
BSSFs, starch, PLA, NaOH, KH550, MAH	Molding method	Green, low-cost, biodegradable composites	Dimension stability and biodegradability had not been considered	Replace traditional single-phase or multiphase materials	[108]
rBF, PLA	Filament purchased	Sustainable, better extrusion properties, superior post-printing modeling ability, versatile texture	Mechanical failure or adhesive failure, bubbles, cracks, local deformations	Fused deposition modeling	[106]
BF, PLA	Filament purchased	Environment-friendly, 0 ° raster angle provided optimal flexural, compression, impact, and shear properties	0° raster angle provided fewer tensile properties	Fused filament fabrication	[109]
BCP, PLA, PEG, Recyclostab 411	Compression molding	Retains good dark attire even in UV irradiation, high temperature, humidity	Decreased rheological properties after weathering, phase-separated composites	High-temperature food packaging applications	[189]
BC, PLA, AHP	Melting blending, injection molding, hot pressing	Biodegradable, reduce CO and CO_2 generation, BC boost the flame retardancy	Functional properties for its end-use need to be further verified	Fire retardancy	[190]
BC, PLA, AHP	Melt-blending	Reduce generation of CO, aromatic compounds, and carbonyl groups	Generated much CO_2 and smoke during combustion	Fire retardancy	[191]
MCC from bamboo, PLA, PBS, H_2SO_4	Melt-mixing, hot pressing	Biodegradable, environment-friendly	-	Food packaging	[88]

Graupner *et al*. produced and analyzed the mechanical properties of composites made entirely of renewable materials and reviewed the influence of hemp, cotton, kenaf, and Lyocell (one kind of artificial cellulose fibres) on attributes of PLA based composites [40]. Bajpai *et al*. highlighted the factors and challenges in producing and characterizing PLA-based green composites [41]. Abdul Khalil *et al*. provided a critical review on BF reinforced composites, highlighting the manufacturing and ensuing properties of BFs with polymer matrices based on applications [42]. Liu *et al*. overviewed the properties and structure of BF, how the interface between BF and particular the polymer matrix affects the performance of the final composites and place few strategies on biological, chemical and physical modification of BF [43]. Nurul Fazita *et al*. conducted a review study on natural fibre-biopolymer composites, specially BF-PLA composites intended for sustainable packaging [44]. A review study was carried out to understand and order the behaviour of PLA, and natural fibre reinforced PLA composites and their characteristics based on processing conditions [45]. Also had proved that composites from renewable fibres are similar or sometimes equivalent to composites from synthetic fibres, and various properties and types of natural fibres had been pointed out as a potential alternative to synthetic fibres [45]. Muhammad *et al*. reviewed different fibre extraction processes (mechanical, chemical treatment) of BF; the BF reinforced composites, its manufacturing technique, and applications [46].

From the above literature, it can be postulated that limited research has been conducted on thermo-mechanical properties, sustainability aspects, and applications of BF-PLA composites. Therefore, the main aim of this study is to review the mechanical properties, thermal characteristics, applicability of BF-PLA composites based on different manufacturing techniques to create a benchmark for future research direction and industrialization or commercialization. The biodegradability, recyclability, and few limitations of BF-PLA composites are also considered to ensure environmental sustainability. Moreover, the effects of 3D printing parameters for BF-PLA composites are also highlighted.

PLA Bamboo Fibre Composites

Natural fibre reinforced composites (NFRCs) have gained notable acceptance commercially over the past few years. BF-PLA composites are one of the well-liked NFRCs. BF-PLA composites are not only eco-friendly composites but also inexpensive. The low specific weight, reliable thermal properties, and excellent mechanical strength of BF-PLA composites make it suitable for the engineering and industrial sector.

Polylactic Acid (PLA)

Polylactic acid (PLA) or polylactide is biodegradable [47,48] a versatile thermoplastic polymer produced entirely from renewable resources like potato, sugarcane, sugar beets, corn, and other starch-rich crops [49]. Figure 2 shows the chemical structure, pellets, generation, applications, and recycling process of PLA. The production of PLA requires less water, less energy, and emits less carbon dioxide than traditional polymers, which are petroleum-based [50,51]. PLA has the advantages of compostability, with a favourable melting point of 160-180 °C [52]. PLA is biocompatible [53], has low immunogenicity, offers a large scope of physical and mechanical properties that ease the engineering process, and is so fitted for multiple applications [53,54].

PLA has been used in various applications including biomedical [53,55,56], tissue engineering [57], additive

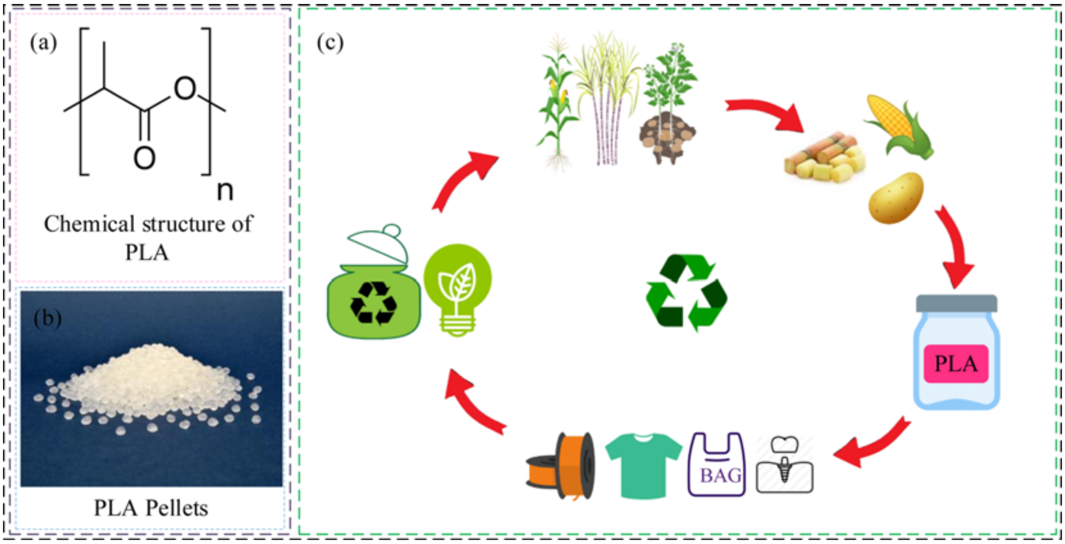


Figure 2. (a) Chemical structure, (b) pellets, and (c) production, recyclability, and applications of PLA.

Figure 3. Different applications of PLA.

manufacturing or 3D printing [58-60] sustainable packaging [61,62], textile [63,64], structural [65], automotive [66], tissue engineering [67], drug delivery [67], technical items [47] and also has great potential for surgical masks (FFP2 and KN95/N95 filters) especially during COVID-19 pandemic [68]. The main application areas of PLA are mentioned in Figure 3.

Moreover, PLA is suitable as a polymer matrix [65,69,70] for the reinforcements with natural fibres and can be manufactured by extrusion, compression molding, injection molding, thermoforming techniques [71]. Although PLA has potential advantages and numerous fields of applications, PLA has few technical restrictions also including low rigidity, poor degradation rate in the normal environment, less cellular interaction, and inflated hydrophobicity; which minimizes its water absorption capacity [72-75].

Advantages from Bamboo Fibre (BF)

Bamboo is a giant grass [76], grows all over the world except Europe and Antarctica. China has the most abundant bamboo resources globally with an area of over 4210000 hector·meters^2 which is about 2.8 % of China's total forest land [77]. Moreover, the higher mechanical property, such as the tensile strength of bamboo (391-1000 MPa), is greater than steel (400-481 MPa). However, the culm of bamboo is 20 times sustainable compared to the ordinary western building materials such as concrete, steel, and timber in their natural form [76,78]. One earlier study showed that bamboo is a reliable replacement for steel reinforcement, which could minimize the cost of housing applications, especially in regions where bamboo is more economical than steel [79]. The results from [80] showed that the usage of bamboo would not only act as a viable alternative for wood-plastic composites (WPCs) but also enlarge the commercial employment of bamboo and the evolution of cleaner, greener, and sustainable products. In terms of environmental issues, bamboo is considered eco-friendly because it comes from fully renewable resources.

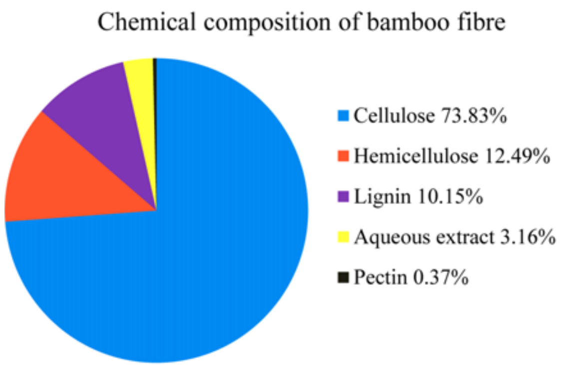
Furthermore, the bamboo forest has a promising carbon storage potential (higher than tree or wood), mainly when the bamboo culms are modified into substantial products after harvesting. The sequestered carbon will not remit quickly to the atmosphere because of the increased lifespan of durable bamboo products. Thereby it has significant role in carbon sequestration as well as has a supreme impact in mitigating climate change effects [81]. Caron saving percentage of different bio-composites is shown in Table 2.

Table 2. Bio-composites and amount of carbon savings

Bio-composites (BCs)	Carbon savings (%)	Reference
Cellulose fibre BC	16.3-18.7	[70]
Hemp fibre BC	10-50	[70]
Cotton fibre BC	40	[70]
Kenaf fibre BC	9.2-10.7	[70]
Bamboo fibre BC	45.6	[192]
Rice husk	39.1	[192]

For germs protection, bamboo fibres are antibacterial. So, bamboo fabrics do not irritate the skin and minimize the risk of allergies [82]. Chemically bamboo contains cellulose of 73.83 %, hemicellulose of 12.49 %, lignin of 10.15 %, aqueous extract of 3.1 %, and pectin of 0.37 % [44]. The chemical composition of bamboo and different types of bamboo fibres are shown in Figure 4. BFs are organic, recyclable, biodegradable, sustainable, eco-friendly and cost-effective. However, the water absorbency of BF is high [6] and so has facilitated the production of biodegradable, cost-effective, eco-friendly, recyclable, and sustainable materials. The potential of bamboo fibre extraction, mechanical properties, thermal characteristics, structural variation, and chemical modification make it appropriate for use in the composite industry [46]. However, mechanical testing results from previous studies showed that BFs have the capability of the mechanical product [6].

Moreover, it is a suitable replacement for conventional fibres, such as carbon and glass, in composites material [83]. The U.S. Department of Energy report demonstrated that to produce a BF mat, the energy consumption is a small fraction (17 %) of the energy required for the glass fibre [84]. However, bamboo has gained substantial interest owing to its high strength-to-weight ratio [42]. Bamboo is one of the fastest-growing plants, requires less water, and needs no use of pesticides or herbicides. Also, the bamboo fibre surface is smooth and round, and its length to diameter ratio is high. Furthermore, BF is two times lighter; also stronger and stiffer than glass fibre because Young's modulus of BF is about 12 % higher and elongation at break for BF is up to 22 % larger than E-glass fibre [44,85]. Three types of BFs can be obtained; long fibres, short fibres, and



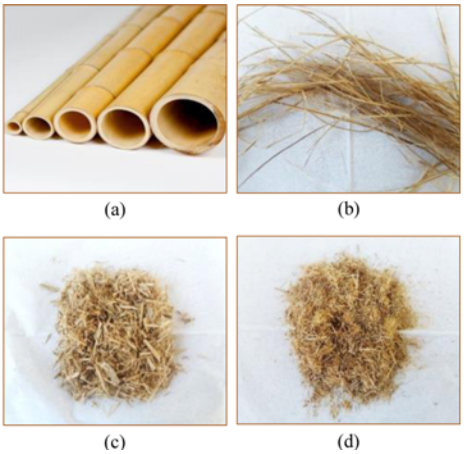


Figure 4. Chemical composition of bamboo (left) and bamboo fibres, reproduced from [86] under Creative Commons Attribution 3.0 licence (right).

Table 3. Comparisons among natural fibres, glass, and metal

Properties	Natural fibre	Glass fibre	Metal
Health risk when inhaled	No	Yes	Yes
Renewable	Yes	No	No
Recyclable	Yes	No	Yes
CO_2 neutral	Yes	No	No
Biodegradable	Yes	No	No
Energy consumption	Low	High	High
Density	Low (0.8-1.1 g/cm^3 for BF)	Twice than natural fibres (2.5 g/cm^3 for E-glass)	Higher than natural fibres (4.52, 7.26 g/cm^3 for titanium, stainless steel, respectively)
Cost	Low (1.90-2.25 $ per kg for BF)	Costly than natural fibres (1.0-4.80 $ per Kg for E-glass)	Expensive than natural fibres (titanium per kg 4.1 $ in April 2021)
Biocompatible	Yes	Yes	Yes (titanium , stainless steel, cobalt-chromium alloy, and its alloys)

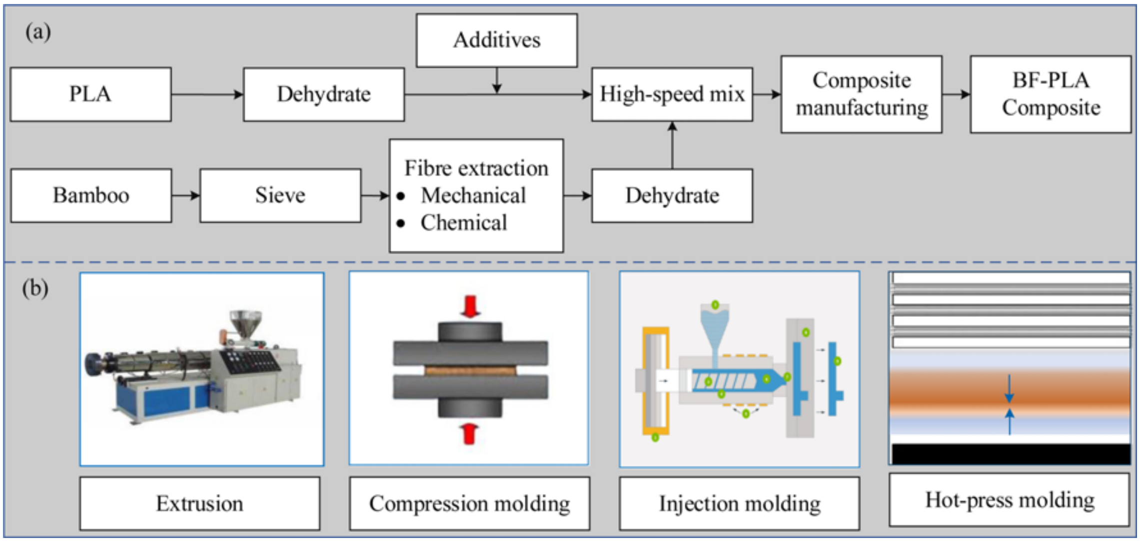


Figure 5. (a) Generation process of BF-PLA composites and (b) common methods for manufacturing.

powder [86], as shown in Figure 4. Natural fibres offer several advantages over glass fibres, and metal. The merits and demerits of natural fibres, glass fibres, and metal are shown in Table 3.

Production of BF-PLA Composites

Various manufacturing techniques such as compression molding [87], hot-press molding [51,88], extrusion with a twin-screw extruder [24,89] injection molding [24], solution mixing [90], solution casting [91] have been used to produce BF-PLA composites. Figure 5 represents different manufacturing methods of BF-PLA composites.

Characterization of BF-PLA Composites

Mechanical Properties of BF-PLA Composites

Reinforcement with natural fibres is now popular owing to their outstanding mechanical properties, lightweight, and low cost. Mechanical properties of few natural fibres, especially bamboo, flax, kenaf, hemp, sisal, ramie, jute, sisal, bamboo, bagasse, and abaca are better than synthetic fibres [92]. Mechanical properties of few natural fibres are shown in Table 4.

The mechanical properties can be determined by tensile properties, flexural properties, and impact strength. All of those properties depend on several factors [93], which are as following

- The type of natural fibre - bamboo, flax, hemp, jute, etc.
- Fibre orientation - Normally, the alignment of fibres in the composites affects the tensile strength of composites [94,95]. The better the fibers' orientation, the higher the strength of reinforced composites [94].
- Type of the polymer matrix - PLA, acrylonitrile butadiene styrene (ABS), polypropylene (PP), etc.
- Type and percentage of fillers (if used)
- Percentage of fibres in the composites - The mechanical strength (impact strength) of the BF-PLA composite decreases with the addition of BF [94]. At 20 wt% of BF, the BF-PLA composites had the optimal mechanical properties [24].
- The shape of the fibre - which may be cylindrical, spherical, or rectangular cross-sectioned prisms or platelets.
- Fibre separation, extraction, and treatment process (chemical, mechanical) - KH improved the compatibility between BF and PLA matrix, also has a prime role in the mechanical properties of BF-PLA composites [94]. In terms of both NaOH and KH treated BF reinforced PLA composites, tensile modulus and strength were increased [94]. While the flexural modulus was improved crucially with the addition of KH treated BF [94]. A significant stress transfer between the fibre and polymer is suggested by the increase in the modulus [96,97]. The mechanical properties of NaOH treated BF-PLA composites increased compared to the untreated BF-PLA composites [24]. Graft-modified BF enhanced the interfacial harmony of BF and PLA, also the tensile and flexural properties of BF-PLA composites [36].
- Manufacturing methods or techniques - compression molding, hot-press molding, twin-screw extruder, injection molding, solution casting, etc.
- Types and percentage of additives - Synthesis plant ester, epoxidized soybean oil, ethanol, etc.
- Mixing sequence of fibre, matrix, and additives - Mixing all the materials simultaneously results in the severe aggregation after extrusion, wire feeding difficulties, and blocking. To enhance processing efficiency, the PLA particles should be first added with additives to attach the liquid to the surface of PLA and next bamboo powders should be mixed through a high-speed mixer, which ensures well-proportioned wire and has better surface quality [98].

Table 5 represents the comparison of mechanical behaviour among PLA-based natural fibre composites.

Table 4. Natural fibres and their mechanical properties [44,70]

Natural fibre	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)
Bamboo	391-1000	48-89	1.9-3.2
Flax	800-1500	60-80	1.2-1.6
Hemp	550-900	30-70	1.6
Kenaf	295	21-60	2.7-6.9
Banana	529-914	27-33.8	5.3
Palm oil	248	3.2	2.5
Pineapple	170-1627	60-83	1-3
Cotton	287-597	6-12.6	3-10
Jute	393-700	10-55	1.5-1.8

Tensile Properties of BF-PLA Composites

The tensile moduli of BF-PLA composite increased with NaOH treatment, and the tensile strength of BF-PLA composites also increased with NaOH solution and KH550 specifically; the tensile strength was double than that of the BF-PLA composite containing untreated BF [18]. The reinforcement of BF in the weft direction improved the tensile properties of BF-PLA composites [51]. When the NaOH treatment had been done for 3 hours, the tensile modulus, tensile strength, and elongation at break of BP-PLA composites increased by maximum values of 406.41 MPa, 44.21 MPa, and 6.22 %, respectively [27]. The poor fiber-matrix compatibility and voids of the bamboo yarns affected the tensile strength, and the obtained experimental values for tensile strength of BF-PLA composites were lower (36 % in the warp and 24 % in the weft directions) than theoretical [99]. The tensile strength was reduced to 54.3 % compared to pure PLA by the increment

Table 5. Mechanical properties of PLA based natural fibre reinforced composites [65,99]

Natural fibre and content	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Flexural modulus (MPa)
BF 51 % (weft)	77.58	1.75	149	1200
BF (warp)	80.6	5.92	-	-
BF (weft)	61.9	5.17	-	-
Jute 15 %	44	0.88	65	3559
Jute 40 %	100.5	9.4	-	-
Flax 30 %	55	8.3	-	-
Kenaf textiles	82.28	-	-	-
Cellulose fibre from recycled newspaper 30 %	47.7	6.3	113.4	9700
Abaca 30 %	74	8.032	124	7890
Cellulose 30 %	44	5.846	72	6510
Hemp	73.0	-	102.0	-
Banana 40 %	78.6	7.20	65.4	-

of the natural fillers, and the mechanical strength was improved from 34.6 to 54 MPa by the addition of coupling agent MDI [100]. Molding pressure of 1 MPa and molding temperature of 190 °C were identified as optimal molding conditions with molding time of 4 minutes that led to securing the significant tensile strength ratio [21]. With 1 % of MAH, the tensile strength of the BP-PLA composite reached a peak value of 47.6 MPa and elongation at break of 6.22 % [31]. NaOH-treated BF's tensile strength was similar to those of usual strong natural fibres such as flax and hemp fibres [49]. The obtained tensile strength of kenaf-bamboo-coir-PLA composites was 187 MPa, which was about 20 % higher than bamboo-coir-PLA and 78 % higher than kenaf-coir-PLA composites while Young's moduli of all three composites were low, varying from 6.0 to 7.5 GPa [37]. With 15 phr PLA-g-glycidyl methacrylate (PLA-g-GMA), the tensile strength and tensile modulus of the BF-PLA composite material were improved by 135 % and 44 %, respectively [101]. The specific Young's modulus of the BF-PLA composite was twice than that of the E-glass/epoxy composite [65]. At 2 phr of BF-g-LA content, the tensile strength of BF-PLA/BF-g-LA composites was 55.3 MPa, i.e., increased by 30 % [23]. After chemical modification of BFs by NaOH, the tensile properties significantly improved, tensile strength increased by 49 %, and elongation at break by 84 %, compared to the untreated one [102]. When 5 % maleated polypropylene (MAPP) was applied, the tensile strength of BF-PP-PLA composites reached 33.73 MPa with an increase of 13 %, compared to the composites without MAPP [103]. Reinforcing PLA filament with short BFs where length (l) over diameter (d), $l/d=4-5$ the modulus increased by 91-230 %, on the contrary the dust-like fractions increased up to 39 % only [104]. Graft-modified treatment of BF increased the tensile strength by 19.3 % and elongation at break by 30.1 % [105]. Tensile testing of BF-PLA composites revealed that the reinforcement of 20 % recycled BF caused mechanical or adhesive failure since the interface between fibre and matrix was not strong enough [106]. Tensile properties of ultrafine bamboo-char (UFBC) reinforced BP-PLA bio-composites were mainly influenced by the interfacial compatibility of the ternary system [107]. The tensile strength of BSSFs-starch-PLA ternary composites raised maximum values of 33.1 MPa with 20 wt % BSSFs [108]. Figure 6(a) shows tensile test specimen of pure PLA, BF-PP-PLA, and BF-PLA composites [103,109].

Flexural Properties of BF-PLA Composites

The flexural properties of the chemically treated BF-PLA composites highly depend upon the amount of BF and the types of treatment content. For instance, flexural moduli increased with the rising of BF content. However, the flexural moduli increased with NaOH treatment, and the flexural strength also raised with NaOH and silane coupling agents [18]. After 3 hours of NaOH treatment, the maximal flexural modulus and flexural strength of BP-PLA composites were 4.50 GPa and 83.85 MPa, respectively [27]. Biodegradable BF-PLA composites offered extremely inflated flexural strength of 273 MPa, with fibre content of 70 % and molding temperature of 160 °C [110]. The flexural properties increased with increasing BF content up to 40 % and then reduced [111]. When weft direction BF reinforcement was used, the flexural properties of PLA increased, i.e., flexural strength by 3.43-47.35 % and modulus by 11.32-112.43 % [51]. With 0.5 % MAH, maximum flexural modulus 4.65 GPa, and flexural strength 72.61 MPa were obtained while flexural performances were reduced by further increasing MAH content [31]. The flexural strength was reduced by 24.53-60.1 % compared to pure PLA by incrementing the natural fillers while, with the addition of coupling agent MDI, the mechanical strength was improved by 70.5 % [100]. The flexural strength of bamboo-coir-PLA

Table 6. Flexural properties of BF-PLA composites [110,112,113]

Natural fibre (%)	Plastic	Temperature (°C)	Density (gm/cm^3)	Flexural strength (MPa)	Flexural modulus (GPa)
BF 50 %	PLA	120	1.26	191.52	3.23
BF 50 %	PLA	140	1.29	199.00	5.43
BF 50 %	PLA	160	1.30	197.60	5.89
BF 50 %	PLA	180	1.29	158.97	5.78
BF 50 %	PLA	200	1.16	106.38	5.32
BF 0 %	PLA	160	1.24	44.50	0.73
BF 30 %	PLA	160	1.29	148.08	3.69
BF 70 %	PLA	160	1.28	273.28	6.83
-	PLA	61-62	1.255	65	-
-	ABS	81	1.06-1.08	77	2.48
-	PC	-	1.20	83-97	2.28-2.35
-	PE	-	0.94	34-39	1.00-1.55
-	POM	-	1.41	94-110	2.62-3.38
-	PP	-	0.90	41-55	1.17-1.73
-	PS	-	1.05	23-69	1.10-2.69

(206 MPa) and kenaf-bamboo-coir-PLA (199 MPa) were higher compared to that of kenaf-coir-PLA composites, about 20 % and 16 %, respectively [37]. With 5 % MAPP, the flexural strength of BF-PP-PLA composites reached 47.18 MPa, i.e., increased by 11.7 % than the composites devoid MAPP [103]. The flexural strength of the BF-PLA composites also improved by 19.3 % with the graft-modified treatment of BF [105]. The flexural properties of UFBC reinforced BP-PLA bio-composites were largely dependent on the crystallization behaviour [107]. At 20 wt % of BSSFs, the flexural strength of BSSFs-starch-PLA ternary composites reached peak values of 50.3 MPa [108]. Flexural properties of BF-PLA composites and several plastics are listed in Table 6.

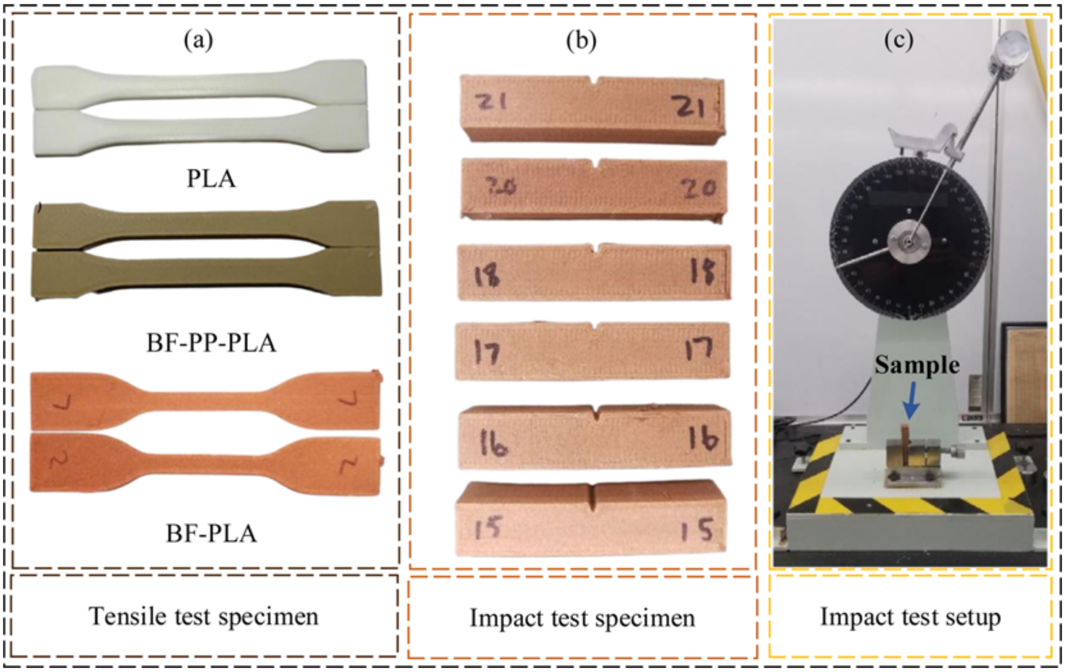


Figure 6. (a) Tensile specimens adapted with permission from [103], Copyright 2018, Society of Plastics Engineers, (b) impact test specimen of BF-PLA composites, and (c) experimental setup for impact testing (reproduced from [109] under (http://creativecommons.org/licenses/by/4.0/)).

Impact Strength of BF-PLA Composites

The impact strength of NFRCs varies with the fibre type, content, and chemical surface modification techniques. The increase in natural fibre content decreased the impact strength (maximum of 23.8 % for BF) of PLA-based composites, while the impact property improved by 40 % than neat PLA with the flexible epoxy surface treatment [114]. BF proved to be a more effective reinforcement than vetiver grass fibre and coconut fibre reinforcements [114]. The Izod impact energy of the BF-PLA composites was found to be 6.53±0.23 kJ/m^2 with 40 mass% of micro-fibril BF content and decreased for further increase of micro-fibril BF [111]. With the BF reinforcement in the weft direction, the impact properties of PLA increased by 57 % than of PLA matrix [51]. BF-PLA-Cloisite 30B nano-clay-based laminated hybrid composite was produced using the film-stacking method, and the impact strength was improved by about 26.58 %, compared to virgin BF-PLA composites [115]. The impact strength of BF-PLA composite in warp direction was increased by 240 % compared to pure PLA [99,116]. With 2 phr of BF-g-LA content, the impact strength of BF-PLA-BF-g-LA composites was increased by 27 % and reached at 9.56 kJ/m^2 [23]. The Charpy impact strength of BF-PLA composites was 126 J/m, while for pure polymers was 37.5 J/m [116]. For BF-PP-PLA composites, at 5 % MAPP, the impact strength increased by 23.5 % compared to the composites without MAPP and reached 3.15 kJ/m^2 [103]. The impact test specimen of BF-PLA composites and impact test setup are shown in Figures 6(b) and 6(c), respectively.

Thermal Characteristics of BF-PLA Composites

Thermal behaviour also has a vital role in the practical applications of any composites [117]. Various testing methods, such as differential scanning calorimetry (DSC), differential thermogravimetry (DTG), thermogravimetric analysis (TGA), Vicat softening point test (VST), are performed to investigate the thermal characteristics. The thermal decomposition temperature of BF-PLA composites was raised with PLA-g-glycidyl methacrylate (GMA) [101]. The BF-PLA composites with titanate coupling agent treatment (NaOH-1 % NDZ201) had significant thermal stability among the NaOH, NaOH-KH550, and NaOH-NDZ201 surface treatment [25]. The glass transition temperature (T_g) and crystallinity reduced from 45.6 °C/30.33 % to 33.6 °C/13.23 % with 16 wt% A-151 treatment [118]. A thermal analysis had performed to show the difference in T_g for two types of PLA plasticizer (cPLA1 and cPLA2), which specified cPLA1 as more significant for 3D printing since the T_g for cPLA2 was too low, i.e., 27.1-27.6 °C for cPLA2 and 37.6-41.9 °C for cPLA1 [104]. NaOH treatment reduced the thermal stability for BF-PLA composites by 16.74-28.86 % than PLA [24]. Graft-modified treatment improved the overall thermal stability of the BF-PLA composites relative to the unmodified form, i.e., crystallinity increased by 5.14 % [105]. Both DSC and X-ray diffraction (XRD) revealed that the NaOH treated BF functioned as nucleating agents and caused harm to the polymer crystallization [102]. However, TGA indicated the superior thermal stability of NaOH treated BFs [102]. The starch-polypropylene (PP) based BF reinforced composites were fabricated through injection molding and extrusion techniques, which concluded that adding a certain amount of BF can enhance the thermal stability of resultant composites [119]. The degree of crystallinity (X_c) is calculated by the equation (1)

$$X_c = \frac{\Delta H_f}{\Delta H_0} \times 100\% \tag{1}$$

where, ΔH_f denotes the heat of fusion, ΔH_0 represents the heat of fusion for 100 % crystalline of the composites [119]. Table 7 presents different methods of thermal characterization of BF-PLA composites with and without chemical modification.

Creep Behaviour Analysis of BF-PLA Composites

Creep behaviour refers to the tendency of a polymer to bend under extrinsic loads, mainly with the temperature rises. In an earlier study, the creep resistance and mechanical properties of BF-rPLA composites were investigated. The BF-rPLA composites were manufactured using the compression molding technique and exhibited the ultimate creep resistance at 60 wt% of fibre among all the BF-rPLA composites, and then reduced with increasing the fibre by more than 70 wt%. That study also highlighted that the modulus of all BF-rPLA composites decreased around 27-40 % within 30 years [87]. The creep curves of BF-rPLA composites in a normal time scale and the creep master curves at a reference temperature (20 °C) are shown in Figure 7.

Sustainable Aspects of BF-PLA Composites

Natural fibre reinforced composites (NFRCs) or green composites or bio-based products derived from reinforcement with the renewable resources possess recyclability and triggered biodegradability (i.e., would degrade easily after disposal in composting conditions but remain stable in an intended lifetime) with environmental acceptability, and commercial feasibility are referred as "sustainable" bio-based products or composites [120]. The schematic representation of sustainability is shown in Figure 8. Fazita *et al.* concluded BF-PLA composite as eco-friendly and sustainable in product packaging [62]. Due to bamboo's excellent structural, mechanical properties, and environmental advantages, it is considered a primary building material for sustainable construction [76]; also, bamboo has a high potentiality to be developed as sustainable raw material for composites [86].

Table 7. Thermal characterization of BF-PLA composites

Composite	Fibre (%)	Chemical treatment	Characterization	Result	Reference
BF, PLA	0, 10, 20, 30, 40, 50	MAH, DCP	DSC	X_c enhanced with the addition of BF as well as BF-e-MA in non-isothermal crystallization	[181]
BF, PLA, PBS	10, 20, 30, 40, 50	LDI (coupling agent)	DSC, TGA	X_c increased and enthalpy decreasd in both composites with increasing LDI	[145]
BF, PLA	60	-	Hotwire method	BF-PLA composites had low thermal conductivity comparable with that of woods	[183]
BF, PLA	-	NaOH, stream exploded, mechanically (rolling and cutting)	DSC	The heat resistance and thermal properties improved with the addition of BF	[193]
BF, PP, PLA	35	MAH-g-PP	DSC	At ratio of 48.75:13:35:3.25 for PP:PLA:BF: MAH-g-PP optimal thermal properties were obtained, similar phenomena had found for rheological and morphological properties also	[38]
BF, PLA, Talc	1	no	DSC	BF had a minor effect on the X_c, while the talc played a significant role	[20]
BF, PLA	10, 20, 30	NaOH, KH	TGA	Silane treated BF-PLA composite showed better thermal and mechanical properties relative to delignified BF-PLA composite	[18]
BF, PLA, CF, WF	2, 8	-	DSC, DMA, VST, TGA		[194]
WBF, PLA	-	no	TGA (on BF yarn)	The BFs are stable until around 220°C	[51]
BF, PLA	50	no	DSC	Thermomechanical properties of BF-PLA composites highly depened on the process parameters	[22]
BF, PLA, Cloisite 30B nano-clay	-	NaOH, HCl	TGA	Increased thermal stability	[184]
BF, CG, PLA	30	MDI	TGA	The thermal characteristics were enhanced by the coupling agent	[100]
BP, PLA	30 wt	NaOH	DSC	Treated BP offered better interfacial compatibility and a higher X_c	[27]
BCF, PLA	2 wt	NaOH, KH, MA, grafting, ethanol, DCP	DSC	The crystallinity enhanced with NaOH treatment while slightly decreased after KH treatment, T_g for all composites were slightly higher compared to pure PLA	[186]
BF, PLA	15 wt	PLA-g-GMA	TGA	Thermal decomposition temperature increased with the addition PLA-g-GMA	[101]
BF, PLA, PP sheet	-	no	DSC, TGA	Increased the thermal stability of both PLA and PP	[116]
BF, PLA	10, 20, 30	NaOH, KH and acrylation, MA grafting	TGA	Both AA and MA enhanced the thermal characteristics of BF-PLA composites	[185]
BP, PLA	-	NaOH, MAH	DSC	T_g was improved, whereas X_c was reduced at 0.5 % MAH and opposite was true for excessive MAH	[31]
BF, n-HA, PLGA	10	NaOH, KH	DSC	Different surface modification treatments had significant impact on crystallization behaviour of PLGA	[90]
BF, PLA	-	no	DSC	BF had minimal effect on T_g and T_m both for recycled and virgin BF-PLA composites	[62]
rBF, nano-clay, PLA	-	KH, NaOH	TGA	The enhancement for heat distortion temperature raised up to 102 %, also improved thermal stability significantly	[33]
BF, lactide, PLA	15	BF-g-LA (compatibilizer)	TGA	Thermal decomposition temperature was increased	[23]

Table 7. Continued

Composite	Fibre (%)	Chemical treatment	Characterization	Result	Reference
BF, RWF, PLA	5, 10, 20, 30, 40, 50	Acetone, CH2Cl2, UI, A171	DSC	With the increasing content of fibres, T_g and T_m of BF-PLA composites enhanced first and then reduced, but reverese phenomena had been ovserved for RWF-PLA composites	[195]
BF, PLA	-	no	TGA, DSC	The innovative mechanical extraction process can be used in the industrial level	[65]
BCNW, PLA	-	NaOH, $NaClO_2$, AA, H_2SO_4, (3-mercaptopropyl) (A-189)	DSC, TGA	The thermal degradation stability, The T_g, and crystallinity decreased remarkably after treatment	[196]
BF, PLA	40 wt	DA, NaOH	DSC, TGA	Thermal stability improved significantly with synergistic treatment	[26]
UFBC, BP, PLA	UFBC (0, 1.0, 2.5, 5.0, 7.5, 10.0, 12.5 wt) BP (0, 30, 29, 27.5, 25, 22.5, 20, 17.5)	no	DSC	X_c enhanced with the increment of UFBC and reached to 42.2 %, slightly decreased at UFBC of 5.0 wt%	[107]
BF, PLA		NaOH, NaOH-KH550, NaOH-NDZ201	DSC, TGA, VST	Thermal characteristics of BF-PLA composites improved with surface modified treated BF compared to both pure PLA and untreated BF-PLA composites	[25]
BF, PLA	-	NaOH, grafting	DSC, TGA	The grafting modification improved the overall thermal performance of PLA-g-BF composites	[35]
BCNW, PLA	-	NaOH, $NaClO_2$, H_2SO_4, A-151	TGA, DSC	Thermal properties including T_g and crystallinity decreased remarkably after treatment	[118]
BCNW, PLA	0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 wt%	NaOH, $NaClO_2$, H_2SO_4, ultrasonically treated, uranyl acetate	DSC	At 2.5 wt% of BCNW, the optimal T_g and cold crystallinity were obtained for BCNW-PLA composites	[91]
BF, PLA	-	NaOH	TGA, DSC	Superior thermal stability	[102]
BF, PLA	-	NaOH, Grafting, glycerol, tributyl citrate, formamide	DSC, TGA	The optimal thermal stability was found when the ratio of glycerol: tributyl citrate: formamide was 2:3:1	[197]
BSSFs, starch, PLA	0, 10, 20, 30, 40 wt	NaOH, KH550, MAH	TGA	The addition of BSSFs might lessen the thermal stability	[108]
BCNW, PLA		KH, $NaClO_2$, NaOH, H_2SO_4, A-151, A-1100, A-174, A-189	DSC	T_g and crystallinity decreased after the surface modifications	[32]
BP, PLA	5, 10	Electron beam	DSC	Improved the thermal properties, impact strength and overall mechanical performance	[39]
BF, PLA	10, 20, 30, 40	TA-ESO solution	DSC	TA-ESO content from 5 to 20 wt% promoted the crystallization of PLA	[124]
BF, PLA	-	NaOH, glycerol/formamide/ tributyl citrate, Grafting	DSC, TGA	Improved the final thermal stability	[36]
BF, PLA	10,15,20,30	NaOH, PEG	TGA, DSC	The increment of BF content reduced thermal stability	[24]
BF, PP, PLA	0, 10, 20, 30	NaOH, KH, Isocyanate, NaOH and isocyanate treatment	TGA, DSC	MAPP enhanced thermal stability, chemically modified BF has better thermal stability	[103]
BCP, PLA	50 wt	PEG, Recyclostab 411	DSC, TGA	Improved thermal stability while no significant effect had been found for the weathering condition in case of thermal stability	[189]
BC, AHP	5, 15, 25, 35	Derived from [190]	DSC, TGA	Thermal decomposition decreased significantly with the addition of AHP	[191]
BF, PLA, nano-SiO_2	-	NaOH	TGA	Maximal thermal stability was obtained for 1.5 % of nano-SiO_2	[30]
MCC from bamboo, PLA, PBS	0.5, 1, 1.5 wt	Acid hydrolysis technique (to extract MCC), H_2SO_4	TGA, DTG, DSC	MCC enhanced the crystallinity, and thermal stability	[88]

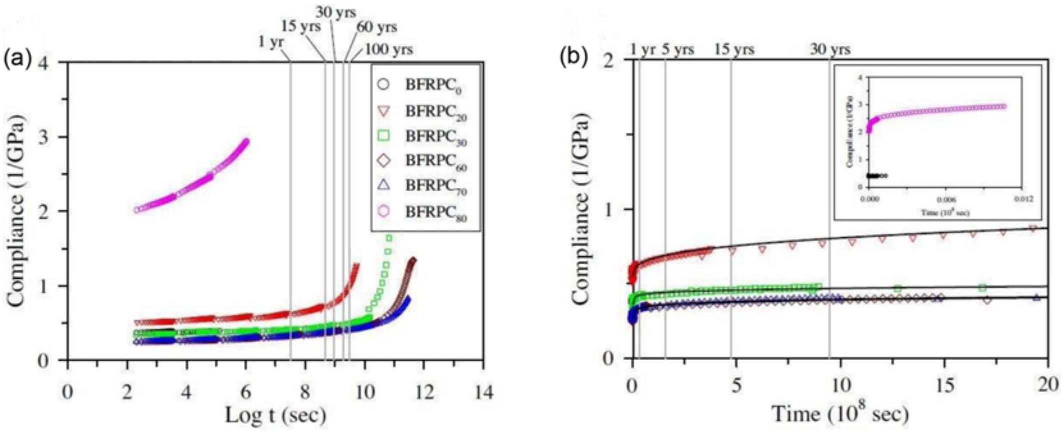


Figure 7. Creep master curves of various BF-rPLA composites: (a) in a normal time scale, (b) at 20 °C temperature (Adapted with permission from [87], Copyright 2015, Elsevier).

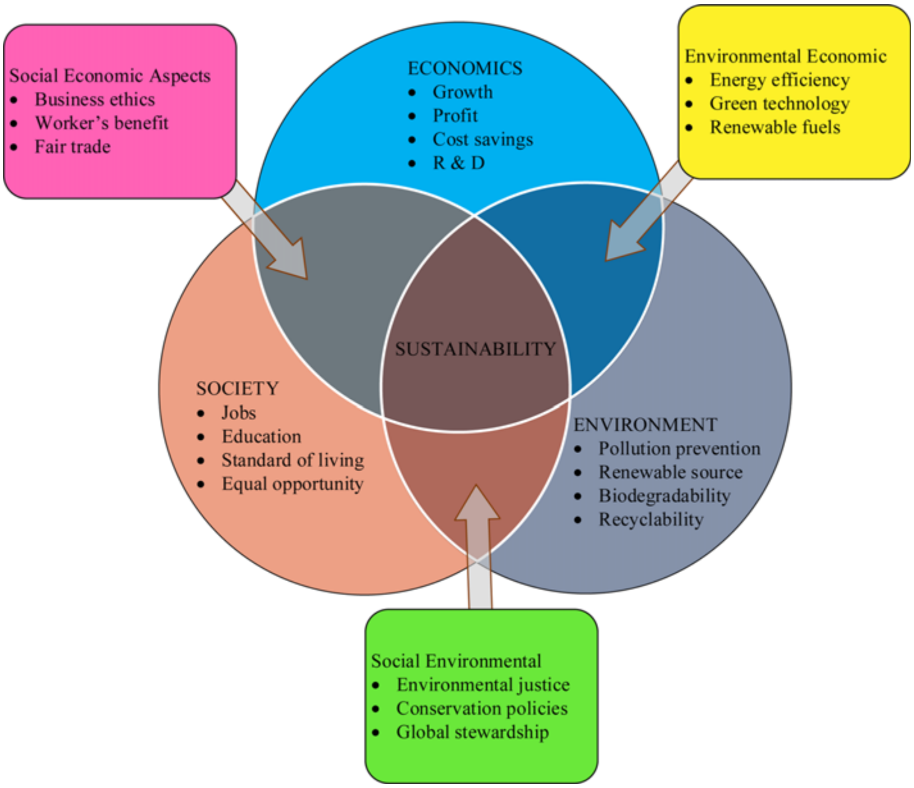


Figure 8. Concept of sustainable composites.

Biodegradation of BF-PLA Composites

Biodegradability refers to the ability of materials or composites to completely break down into water (H_2O) and carbon dioxide (CO_2) through the action of natural microorganisms, like algae, bacteria, and fungi, and no ecological harm occurs during the process [5,121]. Different test methods such as soil burial and compost conditions, tests with river or sea water, aerobic tests are used to determine the biodegradability of composites. The degradation rate of aerobic tests with water and compost conditions is faster than the soil burial test. It is required to measure the weight loss of composites to calculate the degradation rate. The weight loss of the composite can be determined by equation (2),

$$\text{Weight loss } (\%) = \frac{W_0 - W_1}{W_0} \times 100 \tag{2}$$

where W_0 denotes the sample weights before biodegradation

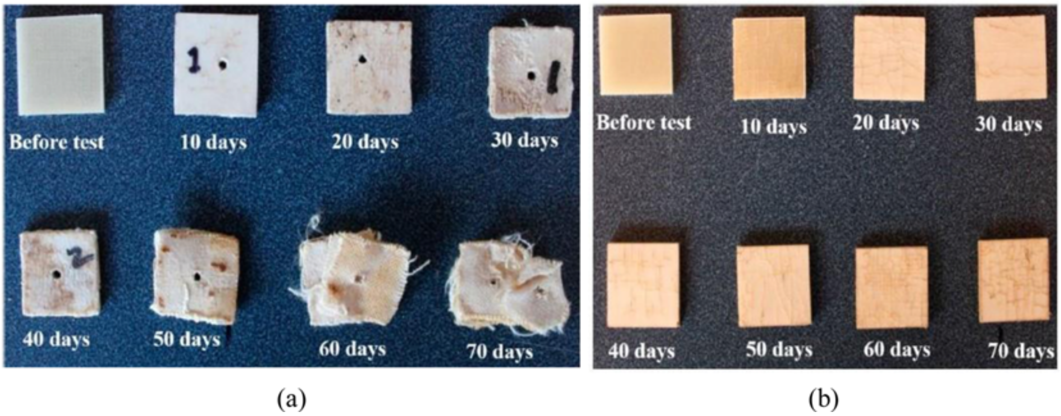


Figure 9. Biodegradation of BF-PLA composites; (a) under controlled composting conditions and (b) in open environment (reused from [62] under (http://creativecommons.org/licenses/by/4.0/)).

test and W_1 represents the sample weights after the biodegradation test.

To develop biodegradable composites, BFs might potentially be a viable applicant as reinforcements [102]. A study was performed to analyze the biodegradability of BF-PLA composites for sustainable packaging, and the results indicated that the degradation rate of BF-PLA composites decreased with the reinforcement of BF [62]. Wang *et al*. fabricated 100 % biodegradable composites for industrial applications by reinforcing PLA with NaOH treated BF [102]. The BF-PP-PLA composites demonstrated the advantages, including low cost and biodegradability [103]. Adding a certain mass of BF can enhance the biodegradation rate and thermal stability of the starch-PP-BF composites [119]. The natural aging of BF-PLA composites (prepared by injection molding process) was serious and needed to

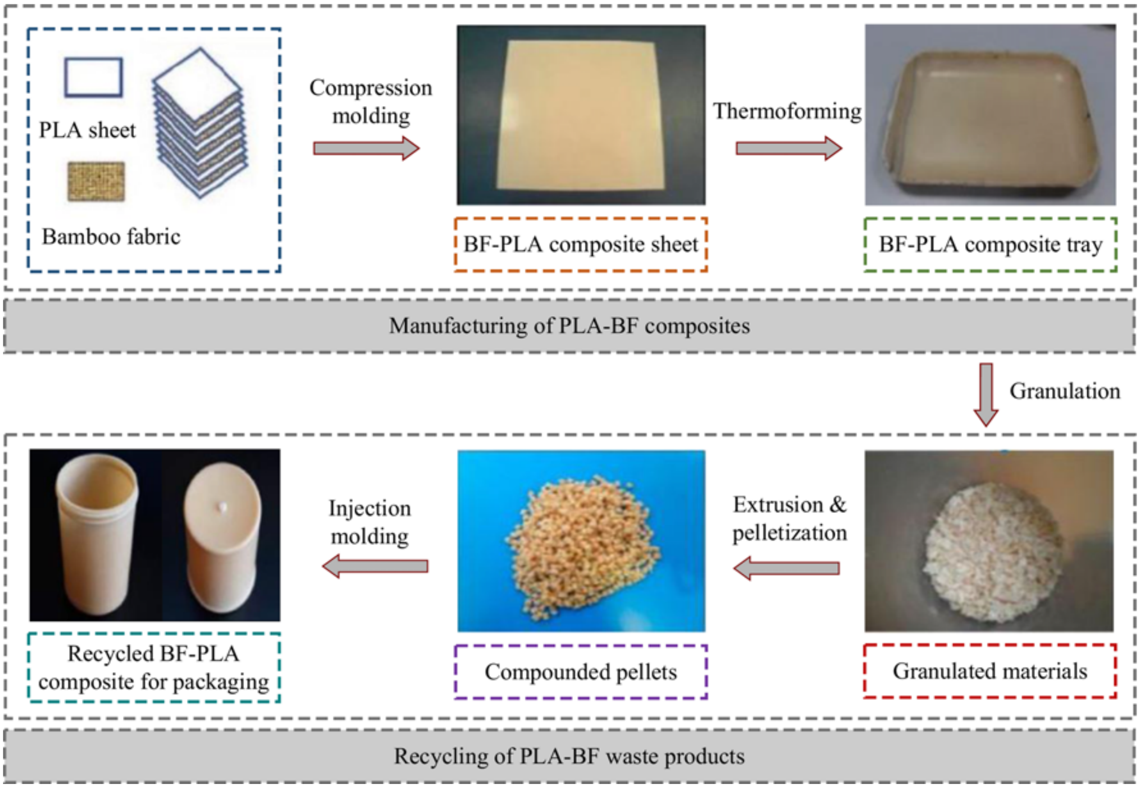


Figure 10. Manufacturing and recycling of BF-PLA composites (reproduced from [62] under (http://creativecommons.org/licenses/by/4.0/)).

adopt certain technical means to further improve the composites outdoor use performance as the impact strength and tensile strength were reduced by 75.8 % and 69.6 %, respectively, after aging for 137 days [122]. Figure 9 shows biodegradation of BF-PLA composites both under controlled composting conditions and naturally.

Recyclability of BF-PLA Composites

In previous research, BF-PLA composites were produced by compression molding, and thermoforming technique was applied to employ those resultant composites in sustainable packaging. Later the composites were then recycled through granulation, extrusion, and pelletization methods. Again sustainable products for packaging were fabricated from recycled BF-PLA composites by injection molding. That study concluded that the resultant BF-PLA composites had sufficient thermal stability and mechanical rigidity to be reused and recycled potentially [62]. Also, the BF-PP-PLA composites include the advantage of recyclability [103]. Figure 10 represents the manufacturing and recycling process of BF-PLA composites.

Applications of BF-PLA Composites

Bamboo PLA Composites for Sustainable Packaging

The incredible characteristics of plastic, such as cheap availability, lightweight, long-lasting, flexible, corrosion-resistant high thermal and electrical insulation properties [1], make it suitable for packaging applications. However, the usage of plastics causes serious pollutant emissions [44]. Usually, plastic packaging is thrown away after using it once and results in continuous waste flow. One of the key approaches to minimizing this waste is using biodegradable polymers or natural fibres in reinforcement with non-biodegradable polymers as packaging materials. Some major features of packaging products are biodegradability, heat deflection temperature, impact resistance, physical properties, and recyclability [44]. PLA is a common type of biodegradable thermoplastic polymer, has been generally used as planting cups and plastic bags [123]. NFRCs, especially BF-PLA composites, have been employed for packaging, which are environment friendly, renewable, and can replace the plastics efficiently [92]. However, BF-PLA composites have superior impact strength and thermal resistance compared to virgin PLA [116]. Thus, BF-PLA composites have great potential to be used in sustainable packaging [62,116]. A comparative study on the functional characteristics of BF-PP and BF-PLA composites intended for packaging applications had done in earlier research. Results indicated that Charpy impact strength for both BF-PP and BF-PLA was increased than that of the virgin polymers. A similar trend was obtained from drop weight impact tests also. From the DSC, TGA, and heat deflection temperature analysis, it was proven that the addition of BF influenced the thermal resistance positively. In terms of water absorption, BF-PP composites revealed lower water absorption (7.3 %) compared to BF-PLA composites (13 %) [116]. One previous review study discussed various effective properties and examples of packaging products to investigate the potentiality of BF-PLA composites for sustainable packaging applications [44]. The obtained BF/TA-ESO/PLA ternary bio-composites had great potential applications such as containers and food packaging [124]. The MCC-PBS-PLA composites can be considered suitable material for packaging applications where MCC was extracted from bamboo [88]. The applications of BF-PLA composites in sustainable packaging and structural field are shown in Figure 11.

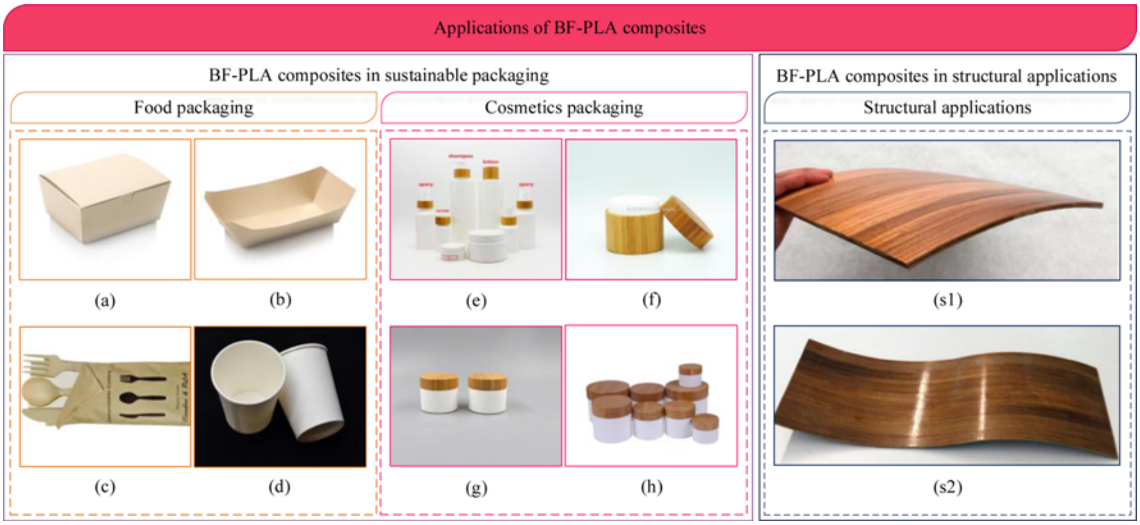


Figure 11. Some conventional packaging products of BF-PLA composites; (a) lunch box [125], (b) food tray [126], (c) cutlery set [127], (d) coffee mug [128], (e-h) cosmetic jar packaging [129,130], (s1-s2) structural applications of BF-PLA [65].

Structural Applications of Bamboo Fibre-filled PLA Composites

Bamboo culm (bamboo in natural form) demonstrates around 20 times more sustainability than common western building substances such as concrete, steel, and timber in several applications [78]. Bamboo has significant potential as a building material mainly for organic-shaped buildings also become a reliable building material like concrete and steel. It is easy to lithe and bend the bamboo while used as a structural material. Therefore, bamboo can be used reliably and responsibly [131]. A biodegradable BF-PLA composite was manufactured for structural applications. The fully biodegradable BF-PLA composite was manufactured by manual lay-up and then melting, where the heating temperature was 185 °C for 20 minutes to avoid the degradation of bamboo. A meager amount of PLA resin (3.5 %) was used to bond the mechanically extracted bamboo strips through Resin Film Infusion (RFI), where the BF content was 63 % and lignin 33.5 % [65]. That BF-PLA composite showed compressive strength (approximately 187 MPa·cm^3/g) similar to aerospace composites, about 84 % of the specific tensile strength. In Young's modulus, BF-PLA (38 GPa·cm^3/g) was more than double that of E-glass/epoxy (18 GPa·cm^3/g). The flexural strength (about 273 MPa·cm^3/g) was near E-glass/epoxy (270 MPa·cm^3/g approximately). However, the in-plane shear strength (around 8 MPa·cm^3/g) was too lower in comparison to that of E-glass/epoxy (about 33 MPa·cm^3/g) due to the gaps between strips and poor adherence between the matrix and fibre [65]. Besides offering good mechanical behaviour, BF-PLA might be considered a viable alternative to wood-reinforced materials, aluminium alloys, and E-glass/epoxy composites [65].

BF-PLA Composites in Automotive Applications

The application of NFPCs (Natural fibre reinforced polymer composites) in transportation diligence has become inexorable due to lightweight, superior properties, less cost of production, and suitability to many products [93]. NFRCs have been applied in the automotive sector widely. The replacement of glass fibre with reinforcement of natural plant fibres in plastic polymers has gained significant popularity. While the common natural plant fibres are bamboo, kenaf, cotton, flax, banana, wood, bust, coir, jute, hemp, rice straw, wheat straw, sisal, tomato, potato, and ramie, etc. [132-135]. The benefits of using NFRCs are mainly owing to their lightweight instead of their renewable sources or natural origin [135]. Materials experts estimated that advanced composites might create 50-67 % lighter auto-body in comparison to a similar-sized auto-body made from steel, with a mass reduction of 40-55 % for an aluminum and mass reduction of 25-30 % for an optimized steel auto-body [14,136]. However, according to estimation, vehicle weight influenced the fuel consumption around 75 %, while fuel efficiency increased about 6-8 % with each 10 % reduction of vehicle weight. Furthermore, emission of CO$_2$ reduced (20 g/km) for every 100 kg reduction in the weight of automotive [137]. Figure 12(b) represents the automotive part (door trim) made by bamboo composite material.

NFRCs are mainly employed in automotive interior parts due to their comparatively low mechanical properties and inherent moisture sensitivity. Generally, interior parts such as dashboard, indoor panels, floor mats, fillers, seatbacks, liners, storage bins, and package shelves are manufactured with NFRCs. Also, NFRCs can be applied to few exterior parts of vehicles. For example, abaca reinforced composites have been used in bumpers, spoilers, spire tire covers, load floors, seat frames, fender components, etc. The utilization of flax-polyester composites, especially in engine and transmission enclosure, can help in sound insulation. Recent research had been done to expand the potentiality of NFRCs in automotive applications, flax-acrodur with soaked flax tape in fast molding parts, flax-vinyl ester composites in hoods, and hemp-PP composites in decking and interior parts in vehicles [137,139,140]. Also, kenaf-epoxy composites in spall liners, pine-maple flour reinforced nylon composites in under hood parts, palm-phenolic resin composites in brake pads [95,141-143]. Furthermore, bamboo-polyurethane (BF-TPU) composites in door panels can be used for sound

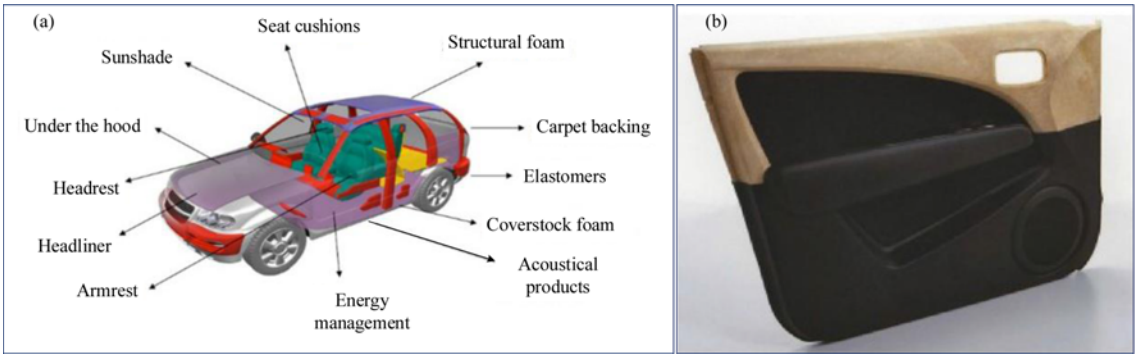


Figure 12. (a) Automotive parts that can be made with composites [138] and (b) door trim prototype of bamboo composite. Adapted with permission from [42], Copyright 2012, Elsevier.

Table 8. NFRCs in the automobile sector

Natural fibre	Automotive part	Brand name	Vehicle	Reference
Abaca	Spare tire well	Mercedes-Benz	A-Class, two-door coupe vehicle	[14]
Jute	Door panels	Mercedes-Benz	E-class vehicles	[14]
Kenaf	Spare tire cover	Toyota	RAUM 2003	[14]
Bamboo	Interior components	Mitsubishi Motors	-	[14]
Soy	Seat foams	Toyota	RAV4	[14]
Wheat straw	Inner lid and storage bin	Ford	2010 Flex crossover vehicle	[14]
Prepreg	Lower door panels	BMW	7 Series sedan	[14]
Flax	Engine and transmission enclosures	Mercedes-Benz	Travego travel coach model	[14]
Bamboo	Door panels	Fiat	-	[135]
Mixed flax/sisal	Door trim and Panels	Audi	A2 midrange car	[198]

absorption [144]. Because of high mechanical properties, BF-PLA composites are considered viable materials for industrial applications, commonly in automotive and energy applications [65]. From one earlier study [49], the obtained tensile strength of BF-PLA composites was significantly comparable to that of glass fibre reinforced plastic composites. Moreover, the particular strength of final BF-PLA composites was three times higher than that of mild steel. Thus BF-PLA composites can be a sustainable alternative to common glass fibre reinforced composites for automotive interior parts, including door trim panels, luggage compartment floor, and load floor [49]. The obtained BF/TA-ESO/PLA ternary bio-composites had great potential for automobile interior parts [124]. The implementations of NFRCs in the automobile industry are shown in Table 8.

Other Applications of BF-PLA Composites

Since bamboo is one of the economical raw materials, the usage of bamboo panels has expanded significantly in the secondary structural sector, mainly as flooring, building application, and sports [65]. BF-PLA and BF-PBS composites have potential applications, including flooring, furniture, disposable products (one-way), toys for children, and hardware for electronic products [145]. Bamboo with polyester can be used as footwear [146], biomedical appliances [146] dielectric materials [147,148]. Bamboo and wood fibres based composites are used to produce various instruments for musical applications [149]. One earlier study overviewed different types of natural fibres based composites used for dielectric applications [147]. The NaOH and KH treatments with nano-clay filler enhanced BF reinforced composites' mechanical and dielectric properties [115,150]. The obtained BF/TA-ESO/PLA ternary bio-composites had great potential applications such as furniture [124]. Table 9 presents the dielectric properties of NFRCs, including BF-PLA composites.

Bamboo PLA Composites for Additive Manufacturing

Three-dimensional printing (3DP) or additive manufacturing (AM) [151,152] is a fast rapid prototyping process and has been growing at an exponential rate in the last few years. AM has gained significant interest because of its sustainability, simplicity, low cost, waste remediation, and ability to produce complex shapes without any modifications [153]. This fast-emerging technique allows fabricating products directly from computer-aided design (CAD) or computed tomography (CT) scan under computer control [154].

The 3D printing technology has found various applications, including automobile, aerospace, building, architectural design, metal and alloy, digital art, telecommunication, electronics, biomedical equipment, bone tissue engineering, sports, textile, apparel, and fashion industry [153,155,158-161]. Figure 13 illustrates the schematic, types, and applications of 3D printing.

ASTM classified 3DP into seven categories: material extrusion, powder bed fusion, sheet lamination, vat photopolymerization, directed energy deposition, binder

Table 9. NFRCs intend for dielectric applications

Natural fibre	Polymer	Dielectric constant	Frequency	Chemical treatment	Reference
BF	PLA	4.5-14	100 Hz-1 MHz	Nano-clay, mercerization	[115]
BF	Epoxy	5-7	0-1 MHz	NaOH, KH	[150]
Palm sugar	Epoxy	8-24	1 kHz	NaOH	[199]
Chicken feather fiber	Epoxy	3.4-5.4	10 kHz-1 MHz	EPON 862, Epikure W	[200]

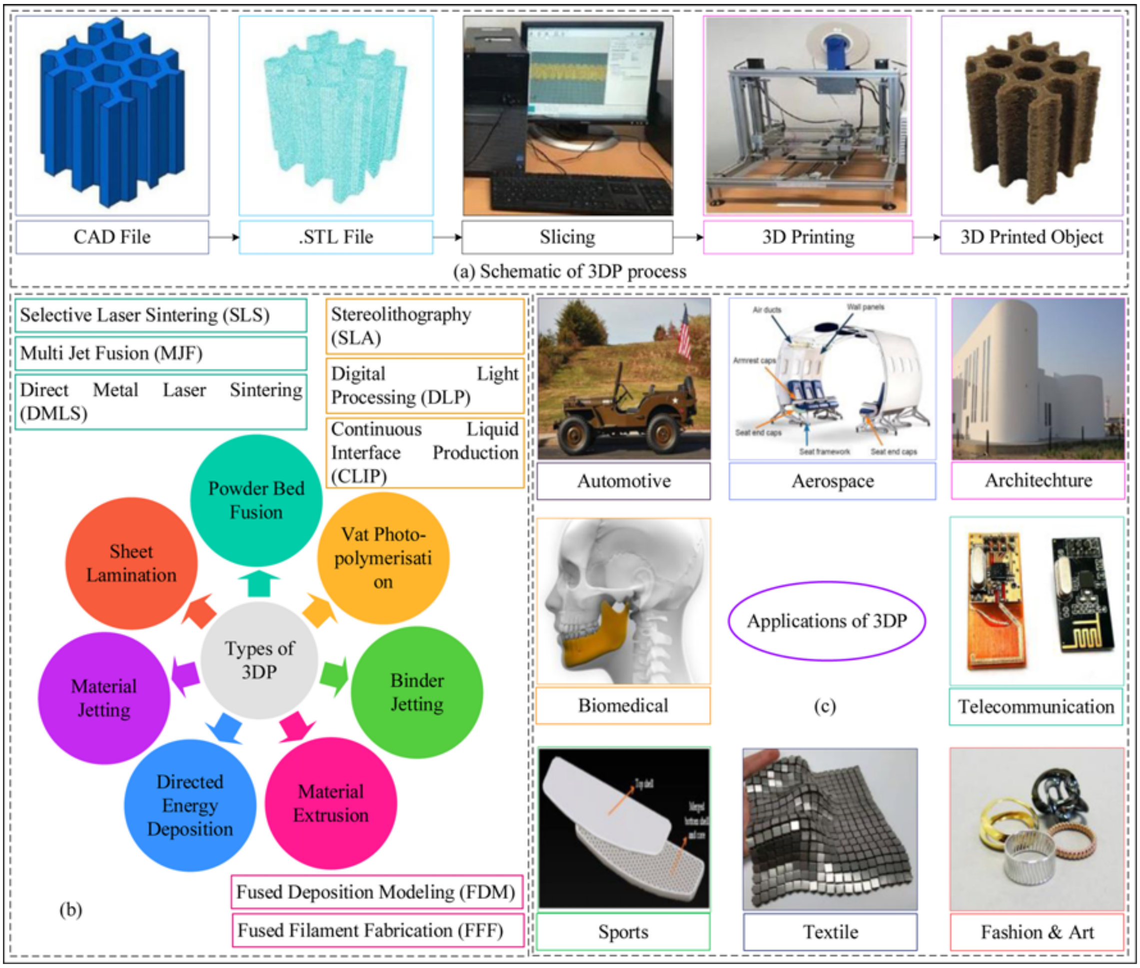


Figure 13. (a) Schematic, (b) types, and (c) applications of 3D printing (automotive [160], aerospace [161], architecture [162], fashion & art [163], biomedical [164], telecommunication [165], textile [166], sports [167]).

jetting, and material jetting [168]. There are several methods of 3D printing such as fused filament fabrication (FFF) or fused deposition modeling (FDM) (based on material extrusion); stereolithography (SLA), digital light processing (DLP), and continuous liquid interface production (CLIP) (based on vat photopolymerization); direct metal laser sintering (DMLS), selective laser sintering (SLS), and multi-jet fusion (MJF) (based on powder bed fusion) [168,169]. FDM was first developed by Stratasys in Eden Prairie, Minnesota [170]. FDM provides optimum strength-to-weight ratios, excellent chemical and thermal resistance to the functional prototypes and 3D printed parts. It is easy to design and assemble FDM 3D printers at a low cost and is thus known as personal 3D printers [171]. FDM 3D printing methodology has been commonly used because of its affordability, simplicity, reliability, material availability, and minimal wastage [171]. In FDM, a filament (commonly made of plastics or wax materials) is extruded via a nozzle, and the 3D objects are printed layer by layer on the printing bed through the deposition of the filament material.

The nozzle has resistive heaters to keep the filament at a temperature just aloft to its melting point to flow smoothly through the nozzle and create the layers. Each layer is piled onto the previous layer until the whole part is fabricated [170]. FDM utilizes strong, engineering-grade materials like PLA, acrylonitrile butadiene styrene (ABS), polyamide, polycarbonate (PC), polyethene (PE), polypropylene (PP), polyurethane (TPU), polyvinyl alcohol (PVA), acrylonitrile styrene acrylate (ASA) and investment casting wax [170,172]. Printable filaments for FDM 3D printers can be made from a variety of thermoplastic materials. Most commercially available thermoplastic filaments are not biodegradable and sometimes may not be safe for human health. So production of biodegradable, non-toxic, sustainable, recyclable, low-cost filaments for 3D Printing has become one of the leading issues for AM. Currently, innovative research has been found in producing new environment-friendly, cost-effective filaments using natural fibres such as

Figure 14. Filaments for 3D printing: (a) PLA and (b) BF-PP-PLA. Adapted with permission from [103], Copyright 2018, Society of Plastics Engineers.

wood, bamboo, flax, kenaf, coir, sisal as an alternative sustainable material. Natural fibre reinforced composite materials are sustainable and greener alternative to the field of additive manufacturing. Implementing natural fibres alternative to synthetic fibres to produce the filaments for 3D printing can minimize the gas emissions linked to the manufacture of the synthetic fibres [173]. Due to abundant resources of bamboo, fast growing rate, great water absorbency, antibacterial properties, lightweight, low-cost, durability, higher tensile strength bamboo has greater efficiency for the development of FDM filaments. However, PLA is a biodegradable plastic that is made from corn. Innovative research has focused on producing new composite materials based on PLA reinforced with BF. Different studies on bamboo PLA composites intend for additive manufacturing are shown in Table 10.

Where wt% was calculated by the equation (3),

$$\text{wt\%} = \frac{\text{weight dry fibers after dissolving}}{\text{filament weight}} \tag{3}$$

Figure 14 shows FDM filaments for 3D printing made with pure PLA and BF-PP-PLA composites.

Nowadays, few natural fibre reinforced FDM filaments are available commercially, which are listed in Table 11.

Where the percentage of BF in the filament material was calculated using equation (4) [109],

$$\frac{\rho_{composite} - \rho_{matrix}}{\rho_{reinforcement} - \rho_{matrix}} = \%\ of\ filler\ material \tag{4}$$

Effects of 3D Printing Parameters on Printed Objects

It has been proofed that the mechanical properties of 3D printed objects highly depend upon the printing parameters [174,175]. There are certain printing parameters such as the nozzle diameter, nozzle type, printing temperature, infill density, layer height, raster angle, deposition geometry [109], extrusion velocity, printing speed, air gap, etc. which significantly influence the mechanical properties of 3D printed objects [98,106,174,176]. Appropriate adjustments of parameters are required for smooth printing using BF-PLA composites [98]. Tensile strength increases appreciably with a larger nozzle diameter; higher layer thickness, higher extrusion, and filling velocity reduced the build time while the surface roughness increased [174]. Moreover, the printing parameters can affect the surface roughness as well. The surface roughness leads to worsening if wall thickness or and layer height increases [177]. The printing process was

Table 10. Bamboo fibre reinforced filaments for Fused Deposition Modeling (FDM) 3D Printer

Natural fibre	Plastic	Additives	Extruder	AM method	Result	Reference
BF (20 wt%)	PP PLA	MAPP MDI IPDI AR,KH	Co-rotating twin-screw extruder	Injection molding	The thermal stability of final composites reduced with the increment of MAPP At 5% MAPP the flexural, tensile, & impact strength increased by 11.7, 13, & 23.5 %, respectively BF-PP-PLA composites were potential for 3D printing	[103]
BF+FF (15 wt%)	PLA	cPLA1 cPLA2	Co-rotating twin-screw extruder	-	Reinforcement of short BF with PLA filament enhanced the modulus by 91-230 % The dust-like fractions raised up to 39 % only	[104]
BP (20.1, 19.99, 20.02 %)	PLA	PEG600 DOP Synthesis Plant Ester Epoxidized Soybean Oil	Conical twin-screw extruder	3D Printing	The ideal proportion of PLA and BP was 5:2 along with plasticizer of 2 %, lubricant of 2 %, and the extrusion temperature was 180 °C	[98]
rBF (20 %)	PLA	-	-	3D Printing	Mostly fill density and deposition geometry influenced the elasticity	[106]
BF (11.8 %)	PLA	-	-	3D Printing	Raster angle of 0 ° was suitable for each properties except tensile	[109]
BF (10, 20, 30)	PLA	Ethanol, 3-Aminopropyl triethoxysilane	Extruder	3D Printing	The optimal BF-PLA bio-composites for manufacturing 3D printer filament was used in a mixture ratio of 10:90	[201]

Table 11. Commercially available natural fibre reinforced FDM filaments

Natural fibre	Filler percentage	Plastic	Filament name, company	Reference
Bamboo	11.8	PLA	eBamboo, eSUN, China	[109]
Bamboo	20	PLA, PHA	- ColorFabb, Netherland	[202]
Recycled bamboo	20	PLA	BambooFill, ColorFabb, Netherland	[106]
Recycled wood	15	PLA, PHA	- ColorFabb, Netherland	[202]
Bamboo/Bamboo fill	-	PLA	- ColorFabb, Netherland	[70]
Pine/Wood fill	-	PLA	ColorFabb, Netherland	[70]
Recycled wood	-	PLA, PHA	WoodFill fine	[202]
Recycled wood	40	PLA	Laywoo- D3	[202]
Wood	40	PLA	Bilby 3D	[202]
Cedar fibre	40	PLA	EasyWood	[202]
Cellulose	40	PLA	Laywood	[202]
Dried crop residues	-	PLA	Jinghe, China	[70]
Cherry wood or lay wood	-	PLA	CC Products, Germany	[70]

Table 12. 3D printing parameters for BF-PLA composites

Printing speed (mm/sec)	Extrusion speed (mm/min)	Printing temperature (°C)	Nozzle temperature (°C)	Printing bed temperature (°C)	Nozzle size (mm)	Printing thickness (mm)	Support angle (degree)	Reference
50	41	-	195	-	-	0.25	60	[98]
30	31	-	195	-	-	0.15	20	
30	25	-	190	-	-	0.2	50	
60	-	-	230	50	0.6	0.2	-	[109]
40	-	200	-	50	-	-	-	[106]
40-60	-	-	180-200	40-60	-	-	-	[103]
60	60-80	-	215	90	-	-	-	[201]

smooth and steady with a nozzle diameter of 0.4 mm, and a printing thickness of 0.20 mm-0.40 mm for bamboo powder (0.27 mm in size) [98]. Impact energy absorption and ductility effectively relate to the raster angle orientation. Raster angle of 0 ° orientation was efficient among the four orientations (0 °, 90 °, 0 °/90 °, and -45 °/45 °) for all aspects, except tensile properties [109]. Table 12 represents the printing parameters of bamboo-based FDM filaments for the existing literature.

Restrictions of 3D Printing with BF-PLA Composites and Future Recommendation

As mentioned above, bamboo contains cellulose of 73.83 %, hemicellulose of 12.49 % [44]. However, cellulose materials can decompose thermally before melting and become flowable when heated. Thus cellulose materials are considered infeasible for 3DP [178]. Different chemical modification processes (NaOH, KH), grafting, electron beam, compatibilizer have been employed to resolve this issue. For example, using partially liquefied cellulose in NaOH/urea solvent system, an ultra-strong, lightweight, flexible, and thermally insulated structure was manufactured through 3DP successfully [179]. Contrastingly, the nanocellulose hydrogels, cellulose esters, cellulose solutions in ionic liquids, MCC, can be used to fabricate high quality, stable 3D structures [178,180]. MCC also improves thermal crystallinity [88]. Significant research should be done to create a benchmark for 3DP using cellulose-based materials in the upcoming future.

Limitations of BF-PLA Composites

Although natural fibres offer several advantages like low cost, low density, biodegradability, high strength, better insulation, less dermal and respiratory irritation, etc. A major disadvantage regarding natural fibres is their poor interfacial compatibility with plastic polymers because of their hydrophobic feature. This hydrophilic nature results in irregular distribution of fibres in the polymer matrices. The irregular growth conditions of fibre can change the mechanical properties [16]. Moreover, lower durability, higher moisture absorption, lower mechanical properties, inferior fire resistance, difficulties to process compared to synthetic fibres, and variation in quality and price reduce the applicability of natural fibres [12]. Several studies have been conducted to resolve these issues through different chemical surface modification treatments of natural fibres to minimize the water absorption and enhance the interfacial bonding of fibre and matrix [12,16]. Morales *et al*. concluded that the applications of BF-PLA composites in the aerospace industry are minimal [65], and Rawi *et al*. suggested that the possible packaging applications with BF-PLA composite should avoid a high humidity environment [116].

Conclusion

In this review, various manufacturing processes of BF-PLA composites were summarized. The mechanical properties, thermal characterization, sustainability aspects, and applications of BF-PLA composites were also discussed. Moreover, the uses of BF-PLA composites in additive manufacturing, effects of 3D printing parameters were mentioned. Furthermore, few limitations of BF-PLA composites were reported. The following interfaces can be extracted from the current study.

1. The mechanical properties and thermal characteristics of BF-PLA composites remarkably depend upon the different fibre extraction processes, surface modification, or chemical treatment such as NaOH, silane coupling agent, and uses of coupling agent.
2. The weft direction BF reinforcement improves the tensile properties of PLA. The specific Young's modulus of the BF-PLA composites was double in magnitude than that of E-glass/epoxy composites. The mechanical properties of BF-PLA composites can be improved significantly after graft-modified treatment of BF. On the other hand, reinforcement of recycled BF can cause mechanical failure.
3. The thermal stability decreases with the NaOH treatment. On the other hand, the graft-modified treatment enhances the overall thermal stability of the resulting BF-PLA composites compared to the unmodified form. However, the thermal decomposition temperature of BF-PLA composites was enhanced with the inclusion of PLA-g-glycidyl methacrylate (GMA).
4. At 60 wt% of BF, BF-rPLA composites offered optimal creep resistance and flexural properties among all the BFRPCs. However, these characteristics were decreased with more than 70 wt% of BF fibres.
5. The degradation rate is reduced with the reinforcement of BF in the PLA matrix. However, a 100 % natural biodegradable BF-PLA composite material can be obtained for industrial purposes with the reinforcement of NaOH-treated bamboo fibres.
6. BF-PLA composites have great potential (thermal stability and mechanical strength) to be reused and recycled.
7. The 3D printing parameters such as speed, temperature, layer thickness, nozzle size, supporting angle significantly affect the mechanical strength and surface roughness of the printed BF-PLA parts.
8. BF reinforcements with PLA influenced the thermal, mechanical, electrical properties and feasibility of the composites. Therefore, BF-PLA composites are suitable for application in various sectors, including automotive, construction, sustainable packaging, dielectric items, and musical specialties.
9. The applications of the BF-PLA composites are restricted in the aerospace industry. Possible packaging applications of BF-PLA composites should avoid a high humidity environment.

Finally, this study has great potential for future research and industrial applications or commercialization of BF-PLA composites. It also has a positive impact related to sustainability and environmental issues.

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References

1. J. Ruan, J. Huang, B. Qin, and L. Dong, *ACS Sustain. Chem. Eng.*, **6**, 5424 (2018).
2. R. C. Thompson, C. J. Moore, F. S. V. Saal, and S. H. Swan, *Philos. Trans. R. Soc. B Biol. Sci.*, **364**, 2153 (2009).
3. R. H. Waring, R. M. Harris, and S. C. Mitchell, *Maturitas*, **115**, 64 (2018).
4. C. Andreeßen and A. Steinbüchel, *Appl. Microbiol. Biotechnol.*, **103**, 143 (2019).
5. T. Iwata, *Angew. Chemie - Int. Ed.*, **54**, 3210 (2015).
6. M. K. S. Besi, *Aust. J. Basic Appl. Sci.*, **7**, 247 (2013).
7. S. Nunna, P. R. Chandra, S. Shrivastava, and A. K. Jalan, *J. Reinf. Plast. Compos.*, **31**, 759 (2012).
8. R. Malkapuram, V. Kumar, and Y. S. Negi, *J. Reinf. Plast. Compos.*, **28**, 1169 (2009).
9. H. Ku, H. Wang, N. Pattarachaiyakoop, and M. Trada, *Compos. Part B Eng.*, **42**, 856 (2011).
10. A. Athijayamani, M. Thiruchitrambalam, V. Manikandan, and B. Pazhanivel, *Int. J. Plast. Technol.*, **14**, 104 (2010).
11. M. M. Ahmed, H. N. Dhakal, Z. Y. Zhang, A. Barouni, and R. Zahari, *Compos. Struct.*, **259**, 113496 (2021).

12. D. B. Dittenber and H. V. S. GangaRao, *Compos. Part A Appl. Sci. Manuf.*, **43**, 1419 (2012).
13. Grand View Research, “Natural Fibre Composites Market 2018-2024”, https://www.grandviewresearch.com/industry-analysis/natural-fiber-composites-market (Accessed May 12, 2021).
14. G. Koronis, A. Silva, and M. Fontul, *Compos. Part B Eng.*, **44**, 120 (2013).
15. Ford, “Integrated Sustainability and Financial Report 2021”, https://corporate.ford.com/microsites/sustainability-report-2020/index.html (Accessed May 12, 2021).
16. N. M. Aly, *IOP Conf. Ser. Mater. Sci. Eng.*, doi: 10.1088/1757-899X/254/4/042002 (2017).
17. W. Sujaritjun, P. Uawongsuwan, and W. Pivsa-art, *Energy Procedia*, **34**, 664 (2013).
18. J. T. Kang and S. H. Kim, *Macromol. Res.*, **19**, 789 (2011).
19. K. Wang, T. Wu, Y. Shih, and C. Huang, *Polym. Eng. Sci.*, **48**, 1833 (2008).
20. Q. F. Shi, H. Y. Mou, L. Gao, J. Yang, and W. H. Guo, *J. Polym. Environ.*, **18**, 567 (2010).
21. S. Kobayashi, K. Takada, and D. Song, *Adv. Compos. Mater.*, **21**, 79 (2012).
22. T. L. Wu, Y. C. Chien, T. Y. Chen, and J. H. Wu, *Holzforschung*, **67**, 325 (2013).
23. X. Y. Song, M. Wang, Y. X. Weng, and Z. G. Huang, *Polymers*, **9**, 323 (2017).
24. H. Long, Z. Wu, Q. Dong, Y. Shen, W. Zhou, Y. Luo, C. Zhang, and X. Dong, *J. Appl. Polym. Sci.*, **136**, 47709 (2019).
25. G. Hu, S. Cai, Y. Zhou, N. Zhang, and J. Ren, *J. Reinf. Plast. Compos.*, **37**, 841 (2018).
26. J. Lin, Z. Yang, X. Hu, G. Hong, S. Zhang, and W. Song, *Polymers*, **10**, 403 (2018).
27. S. Qian, H. Mao, K. Sheng, J. Lu, Y. Luo, and C. Hou, *J. Appl. Polym. Sci.*, **130**, 1667 (2013).
28. H. A. Le Phuong, N. A. Izzati Ayob, C. F. Blanford, N. F. Mohammad Rawi, and G. Szekely, *ACS Sustain. Chem. Eng.*, **7**, 11885 (2019).
29. M. Ho and K. Lau, *Mater. Lett.*, **136**, 122 (2014).
30. Y. Zuo, K. Chen, P. Li, X. He, W. Li, and Y. Wu, *Int. J. Biol. Macromol.*, **157**, 177 (2020).
31. S. Qian, H. Mao, and E. Zarei, *J. Polym. Environ.*, **23**, 341 (2015).
32. Y. Ma, S. Qian, L. Hu, J. Qian, C. A. Fontanillo Lopez, and L. Xu, *Polym. Compos.*, **40**, 3012 (2019).
33. Y. Wang and Y. Shih, *J. Taiwan Inst. Chem. Eng.*, **65**, 452 (2016).
34. R. Liu, M. Liu, S. Hu, A. Huang, and E. Ma, *Holzforschung*, **72**, 735 (2018).
35. Y. Zuo, W. Li, P. Li, W. Liu, X. Li, and Y. Wu, *Ind. Crop. Prod.*, **123**, 646 (2018).
36. W. Li, X. He, Y. Zuo, S. Wang, and Y. Wu, *Int. J. Biol. Macromol.*, **141**, 325 (2019).
37. R. B. Yusoff, H. Takagi, and A. N. Nakagaito, *Ind. Crops Prod.*, **94**, 562 (2016).
38. Z. Ying-chen, W. Hong-yan, and Q. Yi-ping, *Bioresour. Technol.*, **101**, 7944 (2010).
39. A. Kumar and V. R. Tumu, *Compos. Part B Eng.*, **175**, 107098 (2019).
40. N. Graupner, A. S. Herrmann, and J. Müssig, *Compos. Part A Appl. Sci. Manuf.*, **40**, 810 (2009).
41. P. K. Bajpai, I. Singh, and J. Madaan, *J. Thermoplast. Compos. Mater.*, **27**, 52 (2014).
42. H. P. S. Abdul Khalil, I. U. H. Bhat, M. Jawaid, A. Zaidon, D. Hermawan, and Y. S. Hadi, *Mater. Des.*, **42**, 353 (2012).
43. D. Liu, J. Song, D. P. Anderson, P. R. Chang, and Y. Hua, *Cellulose*, **19**, 1449 (2012).
44. M. R. Nurul Fazita, K. Jayaraman, D. Bhattacharyya, M. K. Mohamad Haafiz, C. K. Saurabh, M. Hazwan Hussin, and H. P. S. Abdul Khalil, *Materials*, **9**, 435 (2016).
45. A. S. Getme and B. Patel, *Mater. Today Proc.*, **26**, 2116 (2019).
46. A. Muhammad, M. R. Rahman, S. Hamdan, and K. Sanaullah, *Polym. Bull.*, **76**, 2655 (2019).
47. M. Murariu and P. Dubois, *Adv. Drug Deliv. Rev.*, **107**, 17 (2016).
48. W. Ali, A. Mehboob, M.-G. Han, and S.-H. Chang, *Compos. Struct.*, **245**, 112322 (2020).
49. R. Sukmawan, H. Takagi, and A. N. Nakagaito, *Compos. Part B Eng.*, **84**, 9 (2016).
50. E. T. H. Vink, K. R. Rabago, D. A. Glassner, and P. R. Gruber, *Polym. Degrad. Stab.*, **80**, 403 (2003).
51. A. Porras and A. Maranon, *Compos. Part B Eng.*, **43**, 2782 (2012).
52. C.-C. Chen, J.-Y. Chueh, H. Tseng, H.-M. Huang, and S.-Y. Lee, *Biomaterials*, **24**, 1167 (2003).
53. B. Tyler, D. Gullotti, A. Mangraviti, T. Utsuki, and H. Brem, *Adv. Drug Deliv. Rev.*, **107**, 163 (2016).
54. Q. Wei, G. Wang, M. Lei, Y. Guo, Y. Song, T. Lu, and Y. Wang, *Polymer*, **176**, 159 (2019).
55. F. Alam, V. R. Shukla, K. M. Varadarajan, and S. Kumar, *J. Mech. Behav. Biomed. Mater.*, **103**, 103576 (2020).
56. S. Liu, Y. Zheng, Z. Wu, J. Hu, and R. Liu, *Polymer*, **211**, 123093 (2020).
57. D. Jiang, F. Ning, and Y. Wang, *J. Mater. Process. Technol.*, **289**, 116952 (2021).
58. M. Leite, J. Fernandes, A. M. Deus, L. Reis, and M. F. Vaz, 3rd International Conference on Progress in Additive Manufacturing (Pro-AM 2018), 2018.
59. Y. Wang, M. Lei, Q. Wei, Y. Wang, J. Zhang, Y. Guo, and J. Saroia, *J. Mater. Sci.*, **55**, 5064 (2020).
60. H. Saniei and S. Mousavi, *Polymer*, **196**, 122467 (2020).
61. S. Sharma, *Sustain. Food Packag. Technol.*, doi: 10.1002/9783527820078.ch4 (2021).

62. M. R. N. Fazita, K. Jayaraman, D. Bhattacharyya, M. S. Hossain, M. K. M. Haafiz, and H. P. S. Abdul Khalil, *Polymers*, **7**, 1476 (2015).
63. M. H. Kudzin and Z. Mrozińska, *Polymers*, **12**, 768 (2020).
64. A. Cayla, F. Rault, S. Giraud, F. Salaün, V. Fierro, and A. Celzard, *Polymers*, **8**, 331 (2016).
65. A. P. Morales, A. Güemes, A. Fernandez-Lopez, V. C. Valero, and S. de La Rosa Llano, *Materials*, **10**, 1 (2017).
66. C. Ciofu, S.-N. Mazurchevici, D. Maldonado-Cortes, L. Pena-Paras, D. I. Q. Correa, and D. Nedelcu, *Int. J. Mod. Manuf. Technol.*, **11**, 83 (2019).
67. N. Iqbal, A. S. Khan, A. Asif, M. Yar, J. W. Haycock, and I. U. Rehman, *Int. Mater. Rev.*, **64**, 91 (2019).
68. H. He, M. Gao, B. Illés, and K. Molnar, *Int. J. Bioprinting*, **6**, 309 (2020).
69. B. P. Chang, A. K. Mohanty, and M. Misra, *RSC Adv.*, **10**, 17955 (2020).
70. V. Sekar, M. H. Fouladi, S. N. Namasivayam, and S. Sivanesan, *J. Eng. (United Kingdom),* doi: 10.1155/2019/4546863 (2019).
71. A. Gregorova, M. Hrabalova, R. Wimmer, B. Saake, and C. Altaner, *J. Appl. Polym. Sci.*, **114**, 2616 (2009).
72. R. M. Rasal, A. V. Janorkar, and D. E. Hirt, *Prog. Polym. Sci.*, **35**, 338 (2010).
73. S. Farah, D. G. Anderson, and R. Langer, *Adv. Drug Deliv. Rev.*, **107**, 367 (2016).
74. A. Ferrández-Montero, M. Lieblich, J. L. González-Carrasco, R. Benavente, V. Lorenzo, R. Detsch, A. R. Boccaccini, and B. Ferrari, *Acta Biomater.*, **98**, 114 (2019).
75. Y. Huang, C. Cai, Z. Wei, P. Wang, L. Deng, Y. Wang, and Y. Fu, *J. Mater. Process. Technol.*, **292**, 117052 (2021).
76. R. Manandhar, J. H. Kim, and J. T. Kim, *J. Asian Archit. Build. Eng.*, **18**, 52 (2019).
77. J. Fu, X. Li, W. Gao, H. Wang, A. Cavaco-Paulo, and C. Silva, *Biocatal. Biotransformation*, **30**, 141 (2012).
78. P. Van Der Lugt, A. Van Den Dobbelsteen, and R. Abrahams, *J. Bamboo Ratt.*, **2**, 205 (2003).
79. J. G. Moroz, S. L. Lissel, and M. D. Hagel, *Constr. Build. Mater.*, **61**, 125 (2014).
80. S. A. Bahari and A. Krause, *J. Clean. Prod.*, **110**, 16 (2016).
81. X. Song, G. Zhou, H. Jiang, S. Yu, J. Fu, W. Li, W. Wang, Z. Ma, and C. Peng, *Environ. Rev.*, **19**, 418 (2011).
82. bamboodetective, “13 Little-Known Bamboo Facts: Why Bamboo Fabric is so Popular?”, https://bamboodetective.com/13-little-known-bamboo-facts/ (Accessed May 12, 2021).
83. A. U. M. Shah, M. T. H. Sultan, M. Jawaid, F. Cardona, and A. R. A. Talib, *BioResources*, **11**, 10654 (2016).
84. P. Peças, H. Carvalho, H. Salman, and M. Leite, *J. Compos. Sci.*, **2**, 66 (2018).
85. D. U. Shah, B. Sharma, and M. H. Ramage, *Int. J. Adhes. Adhes.*, **85**, 15 (2018).
86. I. F. Ridzqo, D. Susanto, T. H. Panjaitan, and N. Putra, *IOP Conf. Ser. Mater. Sci. Eng.*, doi: 10.1088/1757-899X/713/1/012010 (2020).
87. T. C. Yang, T. L. Wu, K. C. Hung, Y. L. Chen, and J. H. Wu, *Constr. Build. Mater.*, **93**, 558 (2015).
88. M. Rasheed, M. Jawaid, B. Parveez, A. Hussain Bhat, and S. Alamery, *Polymers*, **13**, 465 (2021).
89. G. Gamon, P. Evon, and L. Rigal, *Ind. Crops Prod.*, **46**, 173 (2013).
90. Y. Li, L. Jiang, C. Xiong, and W. Peng, *Ind. Eng. Chem. Res.*, **54**, 12017 (2015).
91. S. Qian, H. Zhang, W. Yao, and K. Sheng, *Compos. Part B Eng.*, **133**, 203 (2018).
92. K. N. Keya, N. A. Kona, F. A. Koly, K. M. Maraz, M. N. Islam, and R. A. Khan, *Mater. Eng. Res.*, **1**, 69 (2019).
93. N. Karthi, K. Kumaresan, S. Sathish, S. Gokulkumar, L. Prabhu, and N. Vigneshkumar, *Mater. Today Proc.*, **27**, 2828 (2019).
94. M. S. Huda, L. T. Drzal, D. Ray, A. K. Mohanty, and M. Mishra, *Prop. Perform. Nat. Compos.*, doi: 10.1533/9781845694593.2.221 (2008).
95. R. Yahaya, S. M. Sapuan, M. Jawaid, Z. Leman, and E. S. Zainudin, *Def. Technol.*, **12**, 52 (2016).
96. A. K. Mohanty, M. Misra, and L. T. Drzal, *J. Polym. Environ.*, **10**, 19 (2002).
97. A. K. Mohanty, M. Misra, and G. I. Hinrichsen, *Macromol. Mater. Eng.*, **276**, 1 (2000).
98. D. Zhao, X. Cai, G. Shou, Y. Gu, and P. Wang, *Key Eng. Mater.*, **667**, 250 (2016).
99. N. F. M. Rawi, K. Jayaraman, and D. Bhattacharyya, *J. Reinf. Plast. Compos.*, **32**, 1513 (2013).
100. B. S. Baek, J. W. Park, B. H. Lee, and H. J. Kim, *J. Polym. Environ.*, **21**, 702 (2013).
101. Y. N. Wang, Y. X. Weng, and L. Wang, *Polym. Test.*, **36**, 119 (2014).
102. F. Wang, S. Zhou, M. Yang, Z. Chen, and S. Ran, *Polymers*, **10**, 401 (2018).
103. H. Long, Z. Wu, Q. Dong, Y. Shen, W. Zhou, Y. Luo, C. Zhang, and X. Dong, *Polym. Eng. Sci.*, **59**, E247 (2019).
104. D. Depuydt, M. Balthazar, K. Hendrickx, W. Six, E. Ferraris, F. Desplentere, J. Ivens, and A. W. Van Vuure, *Polym. Compos.*, **40**, 1951 (2019).
105. W. Li, X. He, Y. Zuo, S. Wang, and Y. Wu, *Int. J. Biol. Macromol.*, **141**, 325 (2019).
106. J. A. Taborda-Ríos, O. López-Botello, P. Zambrano-Robledo, L. A. Reyes-Osorio, and C. Garza, *J. Reinf. Plast. Compos.*, **39**, 932 (2020).
107. S. Qian, Y. Tao, Y. Ruan, C. A. F. Lopez, and L. Xu, *J. Mater. Res.*, **33**, 3870 (2018).
108. M. Guan, Z. Zhang, C. Yong, and K. Du, *J. Appl. Polym. Sci.*, **136**, 47899 (2019).

109. S. Landes and T. Letcher, *J. Compos. Sci.*, **4**, 159 (2020).
110. S. Ochi, *Open J. Compos. Mater.*, **05**, 70 (2015).
111. Sujito and H. Takagi, *Int. J. Mod. Phys. B*, **25**, 4195 (2011).
112. S. Kumar, R. Singh, T. P. Singh, and A. Batish, *Mater. Res. Express*, doi: 10.1088/2053-1591/ab66f4 (2020).
113. "Acrylonitrile Butadiene Styrene", https://en.wikipedia.org/wiki/Acrylonitrile_butadiene_styrene (Accessed April 19, 2021).
114. W. Nuthong, P. Uawongsuwan, W. Pivsa-Art, and H. Hamada, *Energy Procedia*, **34**, 839 (2013).
115. V. Kumar, N. K. Sharma, and R. Kumar, *J. Reinf. Plast. Compos.*, **32**, 42 (2013).
116. N. F. M. Rawi, K. Jayaraman, and D. Bhattacharyya, *Polym. Compos.*, **35**, 1888 (2014).
117. Y. Wang, M. Zou, K. Gao, W. Guo, G. Wang, and Q. Tang, *BioResources*, **15**, 6230 (2020).
118. S. Qian, K. Sheng, K. Yu, L. Xu, and C. A. Fontanillo Lopez, *J. Mater. Sci.*, **53**, 10920 (2018).
119. F. Yang, H. Long, B. Xie, W. Zhou, Y. Luo, C. Zhang, and X. Dong, *J. Appl. Polym. Sci.*, **137**, 48694 (2020).
120. A. K. Mohanty, M. Misra, and L. T. Drzal, *J. Polym. Environ.*, **10**, 19 (2002).
121. youmatter, "Biodegradable (Plastic) Definition", https://youmatter.world/en/definition/biodegradable-plastic/ (Accessed May 12, 2021).
122. X. Li, X. Zheng, Y. Wu, W. Chen, and Q. Ling, *J. Funct. Mater.*, **44**, 521 (2013).
123. K. Oksman, M. Skrifvars, and J. F. Selin, *Compos. Sci. Technol.*, **63**, 1317 (2003).
124. W. Liu, J. Qiu, T. Chen, M. Fei, R. Qiu, and E. Sakai, *Compos. Sci. Technol.*, **181**, 107709 (2019).
125. bio.africa, "Luch Box Bamboo PLA", https://bio.africa/product/bio-takeout/lunch-box-bamboo-pla-120mm/ (Accessed May 12, 2021).
126. bio.africa, "PLA Bamboo Food Tray", https://bio.africa/product/bio-takeout/food-tray-bamboo-pla-150mm/ (Accessed February 4, 2021).
127. Bio & Chic, "Bamboo fiber+PLA 4/1 Cutlery Kit with KRAFT bag 6in 50 Pcs per Pack", https://bioandchic.com/6-bamboo-fiber-pla-4-1-cutlery-kit-with-kraft-bag-250kits-fork-knife-spoon-napkin/ (Accessed May 12, 2021).
128. Made in China, "100% Compostable Biodegradable PLA Bamboo Coffee Paper Cups", https://biopoly.en.made-in-china.com/product/XKnxFBadncpP/China-100-Compostable-Biodegradable-PLA-Bamboo-Coffee-Paper-Cups.html (Accessed May 12, 2021).
129. L. Dongyang MS Imp&Exp Co., "Bamboo PLA Jar Packaging", https://www.ms-packing.com/jar/bamboo-pla-jar-packaging.html (Accessed May 12, 2021).
130. alibaba, "100% Biodegradable Bamboo Lid with PLA Corn Starch Material Jar Cosmetic Packaging", https://sker.en. alibaba.com/product/62388273759-806890085/100_Biodegradable_bamboo_lid_with_PLA_corn_starch_material_jar_cosmetic_packaging.html (Accessed May 12, 2021).
131. E. A. Nurdiah, *Procedia - Soc. Behav. Sci.*, **216**, 30 (2016).
132. A. S. Herrmann, J. Nickel, and U. Riedel, *Polym. Degrad. Stab.*, **59**, 251 (1998).
133. K. Jayaraman, *Compos. Sci. Technol.*, **63**, 367 (2003).
134. C. Alves, A. J. Silva, L. G. Reis, M. Freitas, L. B. Rodrigues, and D. E. Alves, *J. Clean. Prod.*, **18**, 313 (2010).
135. M. Li, Y. Pu, V. M. Thomas, C. G. Yoo, S. Ozcan, Y. Deng, K. Nelson, and A. J. Ragauskas, *Compos. Part B Eng.*, **200**, 108254 (2020).
136. G. Davies, "Materials for Automobile Bodies", Butterworth-Heinemann, 2012.
137. J. Thomason, P. Jenkins, and L. Yang, *Fibers*, **4**, 18 (2016).
138. A. Ilyas Rushdana, M. Sapuan Salit, M. Lamin Sanyang, and M. Ridzwan Ishak, *Curr. Anal. Chem.*, https://doi.org/10.1088/1757-899X/368/1/012006 (2017).
139. C. Badji, J. Beigbeder, H. Garay, A. Bergeret, J.-C. Benezet, and V. Desauziers, *Polym. Degrad. Stab.*, **148**, 104 (2018).
140. D. M. Panaitescu, Z. Vuluga, M. Ghiurea, M. Iorga, C. Nicolae, and R. Gabor, *Compos. Part B Eng.*, **69**, 286 (2015).
141. R. Yahaya, S. M. Sapuan, M. Jawaid, Z. Leman, and E. S. Zainudin, *Polym. Compos.*, **36**, 1469 (2015).
142. D. J. Gardner, D. Aydemir, A. Kızıltaş, E. Erbaş Kızıltaş, and G. Gündüz, *Compos. Part B Eng.*, **68**, 414 (2015).
143. G. S. Krishnan, L. G. Babu, R. Pradhan, and S. Kumar, *Mater. Res. Express*, **7**, 15102 (2019).
144. M. Farid, A. Purniawan, A. Rasyida, M. Ramadhani, and S. Komariyah, *IOP Conference Series: Materials Science and Engineering*, **223**, 012021 (2017).
145. S. H. Lee and S. Wang, *Compos. Part A Appl. Sci. Manuf.*, **37**, 80 (2006).
146. L. Kohan, C. R. Martins, L. Oliveira Duarte, L. Pinheiro, and J. Baruque-Ramos, *SN Appl. Sci.*, **1**, 895 (2019).
147. H. B. Bhuvaneswari and N. Reddy, *Adv. Compos. Hybrid Mater.*, **1**, 635 (2018).
148. H. B. Bhuvaneswari, D. L. Vinayaka, M. Ilangovan, and N. Reddy, *J. Mater. Sci. Mater. Electron.*, **28**, 12383 (2017).
149. S. Phillips and L. Lessard, *J. Compos. Mater.*, **46**, 145 (2012).
150. V. Kumar and R. Kumar, *J. Compos. Mater.*, **46**, 3089 (2012).
151. S. M. F. Kabir, K. Mathur, and A. F. M. Seyam, *Compos. Struct.*, **232**, 111476 (2020).
152. M. J. Mirzaali, A. Herranz de la Nava, D. Gunashekar, M. Nouri-Goushki, R. P. E. Veeger, Q. Grossman, L. Angeloni, M. K. Ghatkesar, L. E. Fratila-Apachitei, D. Ruffoni, E. L. Doubrovski, and A. A. Zadpoor, *Compos. Struct.*, **237**, 111867 (2020).

153. S. Chakraborty and M. C. Biswas, *Compos. Struct.*, **248**, 112562 (2020).
154. F. Rengier, A. Mehndiratta, H. Von Tengg-Kobligk, C. M. Zechmann, R. Unterhinninghofen, H. U. Kauczor, and F. L. Giesel, *Int. J. Comput. Assist. Radiol. Surg.*, **5**, 335 (2010).
155. N. Guo and M. C. Leu, *Front. Mech. Eng.*, **8**, 215 (2013).
156. T. Hou, J. Xu, W. S. Elkhuizen, C. C. L. Wang, J. Jiang, J. M. P. Geraedts, and Y. Song, *IEEE Access*, **7**, 94793 (2019).
157. A. Standaert and P. Reynaert, 2018 IEEE/MTT-S International Microwave Symposium-IMS, p.141, IEEE, 2018.
158. K. Ji, Y. Wang, Q. Wei, K. Zhang, A. Jiang, Y. Rao, and X. Cai, *Bio-Design Manuf.*, **1**, 203 (2018).
159. N. Shahrubudin, T. C. Lee, and R. Ramlan, *Procedia Manuf.*, **35**, 1286 (2019).
160. A. A. Hassen and M. M. Kirka, *Mater. Eval.*, **76**, 438 (2018).
161. S. Morgan, "How 3D Printing is Transforming the Aerospace Industry", https://blog.trimech.com/3d-printing-transforming-aerospace-industry (Accessed May 12, 2021).
162. N. Jewell, "World's Largest 3D-printed Building Opens in Dubai after 2 Weeks of Construction", https://inhabitat.com/worlds-largest-3d-printed-building-opens-in-dubai-after-2-weeks-of-construction/3d-printed-building29/ (Accessed May 12, 2021).
163. Sculpteo, "3D Printed Jewelry: Why you Should Start Thinking about it?", https://www.sculpteo.com/blog/2019/06/19/3d-printed-jewelry-why-you-should-start-thinking-about-it/ (Accessed May 12, 2021).
164. Sculpteo, "Medical 3D Printing: Additive Manufacturing for Jaw Reconstruction", https://www.sculpteo.com/blog/2018/03/28/medical-3d-printing-additive-manufacturing-for-jaw-reconstruction/ (Accessed May 12, 2021).
165. News Nano Dimension, "First Ever Fully Functional 3D Printed IOT Communication Device Developed for Use in Smart Homes and Products", https://www.nano-di.com/investor-news/first-ever-fully-functional-3d-printed-iot-communication-device-developed-for-use-in-smart-homes-and-products (Accessed May 12, 2021).
166. All3DP, "3D Printed Fabric: The Most Promising Projects", https://all3dp.com/2/3d-printed-fabric-most-promising-project/ (Accessed May 12, 2021).
167. A. Soltani, R. Noroozi, M. Bodaghi, A. Zolfagharian, and R. Hedayati, *Polymers,* **12**, 250 (2020).
168. J.-Y. Lee, J. An, and C. K. Chua, *Appl. Mater. Today*, **7**, 120 (2017).
169. 3dprinting.com, "What is 3D Printing?", https://3dprinting.com/what-is-3d-printing/ (Accessed May 12, 2021).
170. L. Novakova-Marcincinova, J. Novak-Marcincin, J. Barna, and J. Torok, 2012 IEEE 16th Int. Conf. on Intel. Eng. Sys. (INES), p.73, 2012.
171. G. Ćwikła, C. Grabowik, K. Kalinowski, I. Paprocka, and P. Ociepka, *IOP Conference Series: Materials Science and Engineering*, **227**, 012033 (2017).
172. Y. Jin, Y. Wan, B. Zhang, and Z. Liu, *J. Mater. Process. Technol.*, **240**, 233 (2017).
173. W. Ahmed, F. Alnajjar, E. Zaneldin, A. H. Al-Marzouqi, M. Gochoo, and S. Khalid, *Materials*, **13**, 4065 (2020).
174. L. Yang, S. Li, Y. Li, M. Yang, and Q. Yuan, *J. Mater. Eng. Perform.*, **28**, 169 (2019).
175. B. H. Lee, J. Abdullah, and Z. A. Khan, *J. Mater. Process. Technol.*, **169**, 54 (2005).
176. M. Samykano, S. K. Selvamani, K. Kadirgama, W. K. Ngui, G. Kanagaraj, and K. Sudhakar, *Int. J. Adv. Manuf. Technol.*, **102**, 2779 (2019).
177. M. Pérez, G. Medina-Sánchez, A. García-Collado, M. Gupta, and D. Carou, *Materials*, **11**, 1382 (2018).
178. Q. Wang, J. Sun, Q. Yao, C. Ji, J. Liu, and Q. Zhu, *Cellulose*, **25**, 4275 (2018).
179. J. Jiang, H. Oguzlu, and F. Jiang, *Chem. Eng. J.*, **405**, 126668 (2021).
180. L. Dai, T. Cheng, C. Duan, W. Zhao, W. Zhang, X. Zou, J. Aspler, and Y. Ni, *Carbohydr. Polym.*, **203**, 71 (2019).
181. S. H. Lee, T. Ohkita, and K. Kitagawa, *Holzforschung*, **58**, 529 (2004).
182. K. Okubo, T. Fujii, and N. Yamashita, *JSME Int. J. Ser. A Solid Mech. Mater. Eng.*, **48**, 199 (2005).
183. H. Takagi, S. Kako, K. Kusano, and A. Ousaka, *Adv. Compos. Mater.*, **16**, 377 (2007).
184. V. Kumar, N. K. Sharma, and R. Kumar, *J. Reinf. Plast. Compos.*, **32**, 42 (2013).
185. J. T. Kang, S. H. Park, and S. H. Kim, *J. Compos. Mater.*, **48**, 2567 (2014).
186. T. Lu, S. Liu, M. Jiang, X. Xu, Y. Wang, Z. Wang, J. Gou, D. Hui, and Z. Zhou, *Compos. Part B*, **62**, 191 (2014).
187. S. Qian, W. Yan, S. Zhu, C. A. Fontanillo Lopez, and K. Sheng, *Polym. Compos.*, **39**, E633 (2018).
188. R. Srisuk, L. Techawinyutham, W. Koetniyom, and R. Dangtungee, *Key Engineering Materials*, **801**, 121 (2019).
189. R. Srisuk and L. Techawinyutham, *Polym. Compos.*, doi: 10.1002/pc.25776 (2020).
190. S. Wang, L. Zhang, K. Semple, M. Zhang, W. Zhang, and C. Dai, *Polymers*, **12**, 2217 (2020).
191. S. Wang, L. Zhang, K. Semple, M. Zhang, W. Zhang, and C. Dai, *Polymers*, **12**, 2238 (2020).
192. L. Caldas and V. M. Andreola, *Acad. J. Civ. Eng.*, **35**, 499 (2017).
193. R. Tokoro, D. M. Vu, K. Okubo, T. Tanaka, T. Fujii, and T. Fujiura, *J. Mater. Sci.*, **43**, 775 (2008).
194. Q. Zhang, L. Shi, J. Nie, H. Wang, and D. Yang, *J. Appl. Polym. Sci.*, **125**, E526 (2012).
195. L. Yao, Y. Wang, Y. Li, and J. Duan, *Iran. Polym. J. (English Ed.)*, **26**, 161 (2017).
196. S. Qian and K. Sheng, *Compos. Sci. Technol.*, **148**, 59

(2017).

197. W. H. Li, X. Y. He, S. Wang, B. J. Xu, Y. Q. Wu, and Y. F. Zuo, *Materials Science Forum*, **956**, 201 (2019).
198. A. K. Mohanty, M. Misra, and L. T. Drzal, *Natural Fibers, Biopolymers, and Biocomposites*, CRC Press, 2005.
199. I. Santhiarsa, A. A. Sonief, and E. Marsyahyo, *Contemp. Eng. Sci.*, **7**, 907 (2014).
200. M. Zhan, R. P. Wool, and J. Q. Xiao, *Compos. Part A Appl. Sci. Manuf.*, **42**, 229 (2011).
201. Y. J. Shin, H. J. Yun, E. J. Lee, and W. Y. Chung, *J. Korean Wood Sci. Technol.*, **46**, 107 (2018).
202. V. Mazzanti, L. Malagutti, and F. Mollica, *Polymers*, **11**, 1094 (2019).