

Review Article

Mechanical and Thermal Properties of Bamboo Fiber–Reinforced PLA Polymer Composites: A Critical Study

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In the past few years, a new passion for the growth of biodegradable polymers based on elements derived from natural sources has been getting much attention. Natural fiber-based polymer matrix composites offer weight loss, reduction in cost and carbon dioxide emission, and recyclability. In addition, natural fiber composites have a minimal impact on the environment in regards to global warming, health, and pollution. Polylactic acid (PLA) is one of the best natural resource polymers available among biodegradable polymers. Natural fiber–reinforced PLA polymer composites have been extensively researched by polymer researchers to compete with conventional polymers. The type of fiber used plays a massive part in fiber and matrix bonds and, thereby, influences the composite's mechanical properties and thermal properties. Among the various natural fibers, low density, high strength bamboo fibers (BF) have attracted attention. PLA and bamboo fiber composites play a vital character in an extensive range of structural and non-structural applications. This review briefly discussed on currently developed PLA-based natural bamboo fiber–reinforced polymer composites concentrating on the property affiliation of fibers. PLA polymer–reinforced natural bamboo fiber used to establish composite materials, various composite fabrication methods, various pretreatment methods on fibers, their effect on mechanical properties, as well as thermal properties and applications on different fields of such composites are discussed in this study. This review also presents a summary of the issues in the fabrication of natural fiber composites.

1. Introduction

Over the last few decades, there has been a tremendous interest in the potential use of natural fibers to replace synthetic fibers. Natural fibers are commonly employed as reinforcing materials in composites owing to their exceptional physical and chemical

characteristics and positive environmental impact [1]. The continuous and rigid phase is called a matrix, and the discontinuous and intense phase is known as reinforcement. Fibers are the primary load-carrying members, with the matrix around them maintained in the right place. The fibers that transfer the loads resist environmental damage caused by high temperatures and

TABLE 1: Physical and mechanical properties of polylactic acid [15].

Properties	Unit	Value
Density	g/cm^3	1.21–1.25
Melt density	g/cm^3	1.0727
Glass transition temperature	$^{\circ}\text{C}$	45–60
Melting temperature	$^{\circ}\text{C}$	150–165
Tensile strength	MPa	21–59
Elongation at break	%	2.5–7.0
Young's modulus	MPa	350–3500
Shear modulus	MPa	1287
Poisson's ratio	—	0.36
Yield strength	MPa	70
Flexural strength	MPa	106
Notched Izod impact	J/m	26
Rockwell hardness	HR.	88
Ultimate tensile strength	MPa	73
Percent of elongation	%	11.3

TABLE 2: Physical and mechanical characteristics of bamboo fiber [28].

Characteristics	Unit	Amount
Solid density	g/cm^3	0.91–1.4
Tensile strength	MPa	270–615
Young's modulus	MPa	17–36

humidity [2]. In the past decades, fibers extracted from natural resources have emerged to replace the regular high-strength processed fibers to develop a new category of natural fiber-reinforced polymer composites [3].

Natural fibers are categorized based on their source in the plant, like leaves, bast, fruit, seeds, and wood [4]. Bamboo is the fast-growing and most prominent member of the grass family. Bamboo fibers (BF) are environmentally friendly, with fast-growing and reformed carbon dioxide from the environment, making them one of the most impressive plant fibers [5]. Bamboo's benefits pave the way for its lightweight, high strength and modulus, good stiffness, and biodegradability [6].

The general public's increased environmental awareness and use of petroleum-based products have led to a significant increase in the use of PFRCs in commercial applications. New materials made entirely of renewable resources are being developed as a result of limiting the emissions of greenhouse gases into the environment and growing awareness of the limited availability of fossil fuels [7]. Global challenges namely economic, environmental, and health concerns are consistently driven scholars to replace the utilization of plastics [8]. In contrast natural fibers have some drawbacks as supplements. Therefore, there is a limited number of matrix options to choose among the polymers [9]. Polylactic acid (PLA) polymers, also known as polylactides, have recently been commercialized for products requiring biodegradability [10].

This study reviews recent advancements in biodegradable polymer composites, explicitly bamboo cellulose

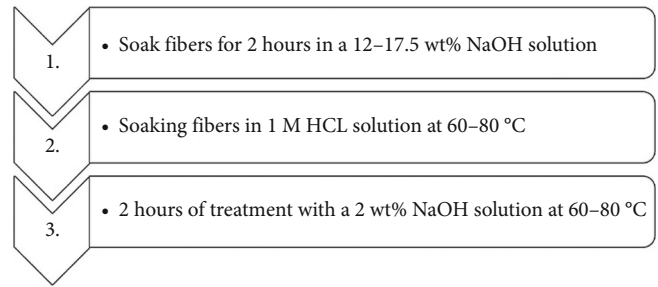


FIGURE 1: Alkaline treatment procedure [37].

fibers-reinforced PLA composites. It concerns the effect of bamboo cellulose fiber reinforcements and modifiers or compatibilizers on mechanical and thermal properties.

2. Materials and Methods

2.1. Polylactic Acid. PLA could be the most encouraging candidate in the family of biopolymers because of its built-in properties like biodegradability, better mechanical properties, transparency, and simple processability in most equipment [11]. PLA is the thermoplastic aliphatic polyester having lactic acid as the monomer. It could be synthesized by microbial fermentation of corn or potato starch [12]. The backbone formula for PLA is $(\text{C}_3\text{H}_4\text{O}_2)_n$ or $[-\text{C}(\text{CH}_3)\text{HC}(=\text{O})\text{O}-]_n$. PLA can be made through direct condensation polymerization, azeotropic dehydrative condensation, and lactide polymerization. High molecular weight PLA is commonly made via the ring-opening polymerization route [13]. PLA is a co-polymer comprising poly(L-lactic acid) and poly(D, L-lactic acid), made from L-lactides and D, L-lactides, respectively. Lactic acid generated from biological sources comprises a predominance of L-isomer compounds [14]. The essential physical and mechanical properties are given in Table 1.

PLA polymers with exceptionally high L-isomer content tend to be crystalline. Moreover, glass transition temperature (T_g), melting temperature (T_m), and crystallinity lessen with diminishing L-isomer content [14]. T_g and T_m can play a significant role, when analyzing the properties. Above the T_m , the polymer gets melted and starts flowing [16]. This flow increases the chain movement of the polymer, which leads to the mechanical properties being almost reduced to zero. If the polymers are processed above melting temperature, the viscosity of the polymer is reduced dramatically, which improves the processability. This process temperature range for PLA would be 190 $^{\circ}\text{C}$ –250 $^{\circ}\text{C}$ [17]. PLA-based polymer's mechanical characteristics can be significantly varied, from soft polymers to high-strength and stiff materials. When better mechanical qualities are required, semicrystalline PLA is recommended [18]. PLA's mechanical characteristics and crystallizations depend heavily on the polymer chain's molecular weight and chemical composition [19].

Biodegradation of polymer occurs via breakups in the leading chains or branch chains of macromolecules. Hydrolysis, thermal activation, photolysis, bioactivities, and oxidation are all factors that contribute to polymer degradation

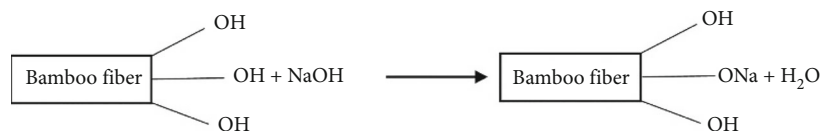


FIGURE 2: Chemical reaction during alkaline treatment [38].

[20]. PLA is most popular because of its degradation behaviour. PLA degradation primarily depends on molecular weight, crystallinity, purity, temperature, and pH [17]. PLA degradation occurs within a few days under high temperature and high moisture conditions. PLA degradation starts with hydrolysis and ends with a bacterial action on the remaining fragmented particles [21].

2.2. Bamboo Fiber. The fundamental benefit of natural fibers is the long-term sustainable supply and easily degraded, so it is safer for the environment than synthetic fibers [22]. Unlike other natural fibers, bamboo is good for environment, with fast growth and a high rate of carbon dioxide fixation, making it the most significant plant fiber. Bamboo has many benefits, like biodegradability, lightweight, high strength, and stiffness [23]. These properties cause bamboo to be used traditionally to manufacture utensils. Bamboo can also be employed as a reinforcement if fibers are extracted in a controlled manner [24].

A suitable procedure for extracting controlled bamboo fibers from bamboo trees must be developed to reap the benefits of bamboo fibers [25]. However, bamboo fibers with excellent mechanical qualities are difficult to come by [26]. The bamboo fibers are covered with lignin, so they are brittle compared to other natural fibers. As a result, a planned technique should be followed to extract bamboo fibers used as a reinforcement in composite materials [27]. The physical and mechanical characteristics are listed here in Table 2.

Bamboo's chemical constituents are primary cellulose, hemicellulose, and lignin. Bamboo contains 60% cellulose and a significantly higher percentage of lignin, 32% [29]. Bamboo is a natural fiber that can become a composite fiber. Higher mechanical property is also a priority for the usage of bamboo fiber [30]. Besides, natural fiber-reinforced composite waste is also environmentally friendly [31].

2.3. Extraction of Bamboo Fiber. According to Roslan et al., the end forms of the composite will be determined by the bamboo fibers extracted in various forms. Composites are laminated as fiber-reinforced, short or arbitrarily oriented fiber, or sandwich structure composites based on the extracted fiber [29]. The bamboo is anisotropy in behaviour, which decreases the required energy to remove bamboo fibers [32]. Strips, flakes, long fiber, short fiber, powder, particles, and nanocellulose fibers are popular forms of extracted bamboo. In contrast, only a few researchers have performed the bamboo fiber extraction process to investigate the characteristics of bamboo fibers-reinforced composites. Eventually, several methods have been used as chemical, mechanical, or a combination of both techniques to extract bamboo fibers based on their industrial application [33].

2.4. Surface Treatment of Bamboo Fiber. Although several physical, mechanical, and biochemical approaches have been proposed, bamboo fiber manufacturing still needs harsh surface treatment [34]. Surface pretreatments can improve the compatibility of natural fibers, minimizing the demand for synthetic fiber-based composites [34]. Natural fiber-reinforced composites have limited applicability due to their lack of bonding with other materials, low melting temperature, and poor resistance to water absorption. Fiber pretreatments can change the fiber surface chemically, reducing water absorption, and upsurging the roughness of the surface [35].

Several types of natural fiber surface treatment methods are used, such as silane treatment, acetylation treatment, alkaline acid treatment, maleated coupling agents, acrylation, and acrylonitrile grafting. Alkaline treatment is the most common method for fiber treatment. Increasing the concentration of NaOH over the particular limit adversely affects the properties of bamboo fibers. The addition of NaOH improves the ductility of the brittle composite [36]. The step followed by an alkaline treatment is given in Figure 1. The possible chemical reaction occurs in the bamboo fiber during alkaline treatment, as shown in Figure 2.

The interaction of fiber is improved by employing maleic anhydride, which results in a strong covalent bond established in the polymer-fiber interface by affecting the hydrophilic nature of the natural fiber. Free-radical chemistry was involved in mediating PLA during the interaction [44]. The mechanical characteristics of fibers can be enhanced when maleic acid is used to produce the matrix for aiding a strong bond with fiber. Silane is another popular approach to treating fibers by interacting with the hydrophilic and hydrophobic ends of fibers with different functional groups. When subjected to heat, sunshine, wet conditions, and radiation, the functional and mechanical properties of bamboo fibers deteriorate. The degradation can be avoided through the treatment of fiber surface with silane [53], [54]. An alkaline treatment removes excess cellulose, and contaminants from the outer surface of fibers during mercerization. Depolymerization of cellulose takes place in the short fibers. The bamboo fiber's specific surface area gradually increased and peaked. The specific surface area decreased gradually because of the decomposition of cellulose during alkaline treatment [42, 48, 52].

ESO monomers are incorporated as toughening agents into PLA. TA-ESO is used to form a tonic acid cross-linked rubbery phase inside the continuous PLA matrix, which improves the toughness of the PLA [41, 50]. Many other researchers have used lysine-diisocyanate and dopamine hydrochloride. Physical treatment utilizing an electron beam to treat bamboo fibers has significantly affected the

TABLE 3: Fiber treatment of bamboo fiber material.

Fiber	Fiber size	Fiber treatment/additive/compatibilizer	References
Bamboo fibers	30–60 mesh	Untreated	[39]
Bamboo fibers	500 μm long and 70 μm in diameter	Lysine-diisocyanate (LDI)	[40]
The bamboo fiber	Average diameter 192 μm and width 21.2 μm .	Epoxidised soybean oil (ESO)	[41]
Bamboo particle	250–425 μm	Alkaline treatment	[42]
Bamboo flour	80–120 mesh	Compatibilizer-PLA-g-glycidyl methacrylate (PLA-g-GMA)	[43]
Bamboo particles	200–400 μm	Alkaline treatment. Maleic anhydride compatibilizer (MAH)	[44]
Bamboo fiber	40–60 mesh size and length up to 380 μm	Dopamine hydrochloride (DA) Alkaline treatment	[45]
Bamboo powder	74–178 μm	Nanocalcium carbonate Micro-crystalline cellulose (MCC) Cellulose nanofibers (CNF)	[46]
Bamboo powder	3–5 μm	Physical treatment using an electron beam	[47]
Bamboo cellulose nanocrystals	200–500 nm long and 10 nm in diameter	Alkaline treatment NaOCl and lastly with NaOH	[48]
Bamboo fiber	500 μm long and 70 μm in diameter	Esterified maleic anhydride (e-MA)	[49]
Bamboo particle	126 μm	Tannic acid-crosslinked epoxidized soybean oil (TA-ESO)	[50]
Bamboo cellulose fiber	8 μm width and 500 μm length	Alkaline treatment The silane treatment (KH560)	[51]
Bamboo cellulose nanowhiskers	<150 μm	Alkaline treatment	[52]
Bamboo cellulose nanowhiskers	10–20 and 1–5 μm	Trimethoxysilane (A-189)	[53]
Bamboo cellulose nanowhiskers	<150 μm	Alkaline treatment. The silane treatment A-189	[54]
Bamboo cellulose nanowhiskers	<150 μm	Alkaline treatment	[55]
Bamboo micro-fibrils	8–10 μm diameter and 3–4 mm length	Alkaline treatment	[56]
Ultrafine bamboo-char	30 μm	HNO ₃ aqueous solution Alkaline treatment	[57]
Bamboo cellulose nanowhiskers	<150 μm	Alkaline treatment Triethoxyvinyl silane (A-151)	[58]
Ultrafine bamboo-char	1000 mesh	Untreated	[59]
Bamboo fiber	<150 μm	Alkaline treatment	[60]
Bamboo flour	<150 μm	Alkaline treatment	[61]
Bamboo fibers	200 μm	Alkaline treatment	[62]
Bamboo fabric	Yarn thicknesses warp 50 tex and weft 71.4 tex	—	[63]
Bamboo fabric	—	—	[64]
Bamboo strip mats	—	Alkaline treatment	[65]
Bamboo fiber	5 mm	Alkaline and silane treatments	[66]
Bamboo pulp	—	NaOH treatment	[67]
Bamboo fiber	—	Alkaline treatment	[68]
Bamboo fiber	—	Alkaline treatment	[69]
Bamboo fiber	—	Alkaline treatment	[70]

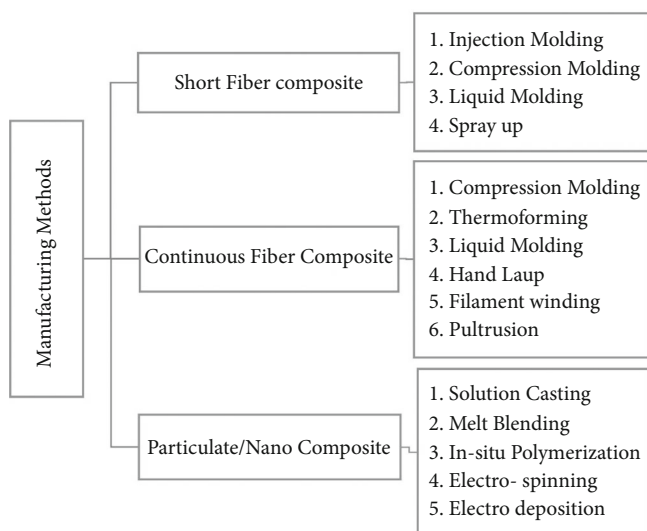


FIGURE 3: Manufacturing process for PLA polymer composite fabrication [66].

composite because of the uniform distribution around the matrix [40, 45, 47]. The advancement in mechanical characteristics with the inclusion of treated fibers were added to PLA matrix indicates that there is enhanced surface compatibility that makes stress transmission possible. This is in contrast to untreated fibers. Treated fibers removed the hemicellulose, pectin, and lignin bonding elements from fiber, which display advanced thermal permanency comparing to untreated fibers. Since the alkali treatment may remove the coupling components like hemicellulose, pectin, and lignin from fibers, it enhances the thermal stability of the composite than untreated composites [68]. Table 3 shows the extensive literatures on fiber treatment.

2.5. Bamboo Fiber-Reinforced Polymer Composites. The cost-effective and effective manufacturing method is crucial in manufacturing fiber-reinforced polymer composites. The quality of the composite has been highly dominated by the manufacturing method. Due to the interest in manufacturing methods, there has been more emphasis on the advancement in the characteristics of composites [71]. Figure 3 represents the different manufacturing methods for different size of natural fibers.

Varying fiber parameters like fiber size, fiber orientation, and production processes define the success of optimized composite materials for effective use in specific applications [72]. It is essential to understand the physical, mechanical, electrical, and thermal properties of fiber-reinforced composites for their effective utilization. Because of their essential mechanical qualities, polymer composites are utilized in numerous application domains [73]. Manufacturing methods of PLA-based bamboo fiber composites are given in Table 4.

Melt blending and compression moulding are commonly used in thermoplastic composite preparation methods. Although the impact of the manufacturing method on the properties of the resulting composite has not been

reported, it is considered that the process leads to a better distribution of fibers [43, 52–54]. Another method that is often employed is twin-screw extrusion. In the usage of this approach, rotational speed and temperature have a leading effect on the degree of crystallinity, mechanical properties, and thermal properties of the polymer composite [44–46]. During high temperatures, the shear force generated by the twin-screw harms the fiber and lessens fiber length and width. However, the tensile properties of PLA composite by twin-screw extruder have higher values than the PLA composites made by melt compounding and compression moulding methods [58]. Film stacking is yet another frequently used technique, comprising compression on a layer of polymer films and fiber for a significant time. It has been observed that this moulding technique seriously influences the tensile properties of the PLA composite [62]. Some other researchers have used batch mixers, reaction kettle, solution casting, direct melting and solidification, and in situ polymerization methods [49, 60].

3. Properties of Bamboo Fiber-Reinforced PLA Polymer Composites

3.1. Mechanical Properties of Bamboo Fiber-Reinforced PLA Polymer Composites. Many studies have been written about the effects of bamboo fiber-reinforced PLA polymer composites. Table 5 briefly summarises the mechanical properties of bamboo fiber-reinforced PLA composite. Yang et al. stated that bamboo fibers show impressive reinforcing benefits on PLA composites mechanical and thermal characteristics. The bending strength and elastic modulus of bamboo fiber-reinforced PLA composite were increased by increasing bamboo fiber amount up to 60 wt% [39]. Lee and Wang found that specific tensile properties and water resistance were greatly improved by using di-isocyanate as a coupling agent in composite manufacturing. It enhances the bonding of polymers with fibers [40].

The 0.5 ESO-treated composites achieved the ideal mechanical properties. Compared with untreated bamboo fiber/PLA composite, the treated fiber composite's tensile strength, elastic modulus, and fracture strain improved by 97.9%, 6.3%, and 110.1%, respectively [40]. The alkaline-treated PLA-reinforced bamboo particle (BP) composite's tensile, fracture strain, and bending properties were increased by 20.56%, 64.44%, 37.92%, 37.30%, and 28.94%, respectively, when compared to the untreated BP-reinforced PLA composite. After alkali treatment for 3 hours, the mechanical characteristics of the composite are reduced slightly due to poor bonding between the PLA and bamboo, reduction in specific surface area, and partial damage to the fiber structure [41]. The tensile strength and modulus of elasticity increased by 44% and 135% by adding a 15-phr PLA-g-glycidyl methacrylate compatibilizer. With the inclusion of 15-phr of compatibilizer, the impact strength of the composite was enhanced to 14.5 kJ/m². It is due to the bamboo fibers (BF) dispersed uniformly in the composite incorporating a compatibilizer [42]. The tensile strength of alkali-treated composites was improved and marked as 44 MPa. The highest tensile strength value was 47.60 MPa for the

TABLE 4: Bamboo fiber–reinforced PLA-based polymer composite production methods.

Matrix	Fiber	Production method	References
PLA	Bamboo fibers	Hot pressing and cold pressing	[39]
PLA	Bamboo fibers	Batch mixer and compression moulding	[40]
PLA	Bamboo fibers	Twin-screw extruder	[41]
PLA	Bamboo particles	Vulcanization moulding machine hot pressing	[42]
PLA	Bamboo flour	Melt blending and compression moulding	[43]
PLA	Bamboo particles	Co-rotating twin-screw extruder	[44]
PLA	Bamboo fiber	Co-rotating twin-screw extruder and hot and cold press	[45]
PLA	Bamboo powder	Co-rotating twin-screw extruder	[46]
PLA	Bamboo powder	Twin-screw extruder	[47]
PLA	Bamboo cellulose Nanocrystals	Melt mixer and hot press	[48]
PLA	Bamboo fiber	Batch mixer and hot pressing	[49]
PLA	Bamboo fiber	Twin-screw extruder	[50]
PLA	Bamboo cellulose fiber	The mini-extruder and injection moulding	[51]
PLA	Bamboo cellulose nanowhiskers	Melt blending and vacuum drying	[52]
PLA	Bamboo cellulose nanowhiskers	Dried at room temperature	[53]
PLA	Bamboo cellulose nanowhiskers	Dried at room temperature	[54]
PLA	Bamboo cellulose nanowhiskers	Dried at room temperature	[55]
PLA	Bamboo micro-fibrils	Hot pressing	[56]
PLA	Ultrafine bamboo char	Twin-screw mini-extruder	[57]
PLA	Bamboo cellulose nanowhiskers	Melt blending and vacuum drying	[58]
PLA	Ultrafine bamboo-char	Double roll lab-scale compounder	[59]
PLA	Bamboo fiber	Hydrothermal reaction kettle	[60]
PLA	Bamboo flour	Hydrothermal reaction kettle	[61]
PLA	Bamboo fibers	Twin-screw mini-extruder	[62]
PLA	Bamboo fabric	Film stacking procedure	[63]
PLA	Bamboo fabric	Film stacking procedure	[64]
PLA	Bamboo fibers	Co-rotating intermeshing twin-screw extruder	[65]
PLA	Bamboo fiber (pulp)	Hot pressing	[66]
PLA	Bamboo fiber	Hot and cold pressing	[69]
PLA	Bamboo fiber	Compression moulding	[70]

1.0% MAH compatibilizer used in the composites. These results reveal that MAH enhanced the compatibleness of PLA and bamboo. This was used to transfer the stress produced by PLA to bamboo particles by stretching the polymer composite [43].

After the alkaline treatment, the flexural strength improved by 16.1%. The tensile strength was enhanced by 34.4% of the PLA/alkaline-treated dopamine modified bamboo composites. Alkali treatment enhances the bamboo fiber surface area, also used for high dopamine reaction with the matrix material [44]. Combining nano CaCO_3 , MCC, and CNF with PLA/BP composite filaments enhances the tensile strength based on the lattice arrangement. Stress transfer can be more effortless through hydrogen bonding and uniformly dispersed in the new lattice arrangement [45].

The unirradiated bamboo powder influences the mechanical properties of the PLA polymer composites because of the weak bonding with the PLA [46]. The tensile strength and fracture strain values are increased with

increases in cellulose nanocrystals up to a specific limit. Even the distribution of cellulose nanocrystals increases the surface roughness of the fiber and acts as a load-carrying element [47]. The fiber–matrix interface contains a low TA cross-linked, epoxidized soybean oil by forming a flexible interface layer between fiber and PLA. The TA-ESO oligomer was a toughening phase within PLA that contributed to significantly higher break elongation, tensile strength, and impact strength [50]. The Scanning Electron Microscope (SEM) image of bamboo cellulose fiber and NaOH-treated bamboo cellulose fiber is shown in Figure 4. The surface of the untreated cellulose fiber was heavily contaminated by amorphous cellulose and impurities. After being treated with NaOH solution, the cellulose fibers may remove the impurities and had ordered surface.

NaOH pretreated fibers delivered with the maximum stiffness. The KH560 modification provided the good ductility to the composites. Maleic anhydride compatibilizer balances stiffness and ductility enhancements, resulting in the

TABLE 5: Mechanical properties of bamboo fiber-reinforced PLA composite.

Fiber	Fiber addition (wt %)	Best combination (wt%)	Modifiers	Addition (wt %)	Tensile strength (Mpa)	Tensile modulus (Gpa)	Flexural strength (Mpa)	Flexural modulus (Gpa)	Impact strength (kJ/m ²)	Elongation at break (%)	Reference
Bamboo fibers	10-50	—	Lysine-diisocyanate	30	30	3.4	—	—	—	2.8	[40]
Bamboo fibers	20	—	Epoxidised soybean oil	—	52	2.15	—	—	—	3	[41]
Bamboo particles	30	—	Alkaline treatment	—	44.21	0.668	—	—	—	6.22	[42]
Bamboo flour	15	—	PLA-g-glycidyl meth acrylate	—	60	6.3	—	—	14.5	—	[43]
Bamboo particles	30	—	Alkaline treatment and maleic anhydride compatibilizer	—	47.60	—	72.5	4.5	—	—	[44]
Bamboo fiber	40	—	Dopamine hydrochloride and alkaline treatment	—	39.51	2.17	64.25	4.53	8.43	—	[45]
Bamboo fiber	0-60	30	Esterified maleic anhydride	10	35	3.058	—	—	—	—	[49]
Bamboo particle	0-50	20	Tannic acid-crosslinked epoxidized soybean oil	0.5	65	1.7	—	—	6.3	6.5	[50]
Bamboo cellulose fiber	2	—	Alkaline, silane treatment	—	72	2.6	—	—	4.9	11	[51]
Bamboo cellulose nanowhiskers	1-4	3	Trimethoxy silane treatment	8	20	0.340	—	—	—	32	[52]
Bamboo char	0-4	—	Silane treatment	—	20	0.300	—	—	—	30	[53]
Bamboo cellulose nanowhiskers	2.5	—	Trimethoxy silane (A-189)	16	13	0.110	—	—	—	200	[54]
Bamboo cellulose nanowhiskers	0-4	2	Alkaline treatment	—	11	0.430	—	—	—	2.5	[55]
Bamboo microfibrils	0-50	40	Alkaline treatment	—	37	1.20	—	—	—	—	[56]
Ultrafine bamboo char	2.5	—	Alkaline treatment	15	65.36	1.012	—	—	16.05	5.36	[57]
Bamboo cellulose nanowhiskers	2.5	—	Triethoxyvinyl silane.	4	18.5	3.2	—	—	—	125	[58]
Ultrafine bamboo char	0-40	30	Untreated	—	14	0.550	—	—	21	2.5	[59]

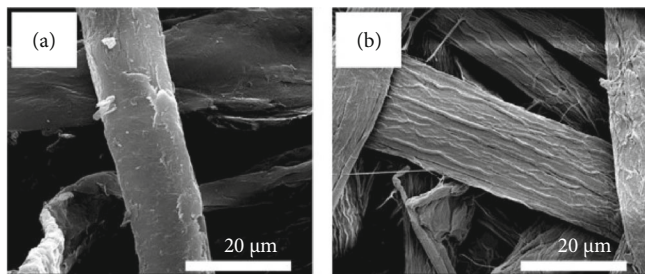


FIGURE 4: SEM micrograph: (a) untreated bamboo cellulose and (b) NaOH-treated bamboo cellulose fiber. (Reproduced with permission from Elsevier, license number: 5191770249047) [51].

best overall characteristics [51]. The fracture strain values were raised to 213.81%, 111.26%, 255.27%, and 209.8% following coupling agent treatments of 8 wt% A-151, A-1100, A-174, and 16 wt% A-189, respectively. The elastic modulus and tensile strength of pretreated composites increased slightly as silane concentration increased. A-1100-treated composite is an excellent choice for improving and toughening [52]. 0.25 wt% ultrafine bamboo cellulose enhances the tensile strength by 99.26% and elastic modulus by 104.93%. In addition, the fracture strain decreased to 39.28% when the ultrafine bamboo cellulose exceeded 2.0 wt% because of the accumulation of excess cellulose content [53]. Tensile strength and modulus of elasticity were reduced exceptionally when bamboo cellulose nanowhiskers were silylated. Tensile strength varied little and peaked at 14.03 MPa at 4 wt%, whereas the modulus of elasticity increased marginally from 69.81 to 132.84 MPa as silane content increased. At 4 wt% treated, elongation at break increases dramatically from 12.35 to 250.8% [54]. Tensile modulus and the elongation percentage at break of pure PLA with increasing bamboo cellulose nanowhiskers (BCNW) content. The hydrogen bonding between nanowhiskers and PLA were the primary considerations in the nanowhiskers PLA composite performance. Including a lower amount of bamboo, cellulose nanowhiskers lead to a decrement in tensile modulus by destroying the interaction between PLA molecular chains [55]. SEM images of PLA/bamboo cellulose nanowhiskers composite and their reinforcement effect on surfaces are shown in Figure 5.

After embedding the bamboo micro-fibrils in PLA, polymer tensile strength improved by 100%, and modulus of elasticity increased by 150% with 40% of bamboo micro-fibrils content [56]. HNO_3 modification improved the interfacial adhesion of ultra-fine bamboo cellulose to PLA. It reaches the highest tensile modulus and fractures strain value at 39 wt%. The highest tensile strength of 45.25 MPa was recorded at 54 wt% [57]. The silane treatments of bamboo fiber reduce the tensile properties of the composite. However, fracture strain increased enormously from 12.3 to 213.8% with a 16 wt% silane treatment [58]. Adding bamboo cellulose content increased tensile properties to the highest values, and both declined slightly with a further increase in bamboo cellulose content. Elongation at break decreased with the inclusion of bamboo cellulose at a higher percentage. This tendency occurred due to bamboo cellulose

fiber's very low aspect ratio. The impact strength improved significantly to the highest value of 20.50 J/m with 30% loading. It exceeds 160% when compared to pure PLA [59]. The tensile strength of the PLA-g-BF was lesser than the PLA untreated bamboo fiber composite. This reduction in crystallinity was produced by the polymers binding to the fiber, which destroyed the polymer's crystal structure. However, the fracture strain of the composite was enhanced considerably because of its improved plasticity offered by the PLA [60]. The most significant effect was nearly a 200% increase in strain energy of the PLA composite. Due to this, a considerable deformation is maintained evenly around the bamboo fiber before the crack propagates. This deformation occurs where the highest distribution of the cellulose into the matrix. The composite absorbed a lot of strain energy and resisted crack propagation through the bamboo fiber. A superior enhancement with 1 wt% cellulose content in the reinforced PLA composite was obtained [61].

Increasing the fiber content in the composite increases the tensile modules of the composite and the fiber holds the matrix polymer and restrict the movement of the PLA molecules which enhances the stiffness of the composite [69].

In summary, many PLA polymer-based bamboo fiber composites have been studied for pretreatment and their effect on mechanical performance. The comparison of various pretreatment concentrations for mechanical properties is shown in Figure 6. The tensile properties of the NaOH-treated composite were increased effectively due to the improvement in physical interlock between the polymer and reinforcements.

Compared to other chemicals, in NaOH treatment, increasing NaOH content increases the damage on the surfaces of the fibers, which is used for better adhesion with polymers. In contrast, the elongation at the break of NaOH-treated composites showed a slight decrease attributed to PLA entanglement in fiber pores. The tensile properties of A-151 and A-189-treated PLA composites decreased considerably when silane percentages increased, and the accumulation of molecules also increased. Notably, elongation at break value was appreciably increased by increasing the silane concentrations because the fiber's hydrophilic hydroxyl group was changed with a hydrophobic sulfhydryl group, so the fiber's interfacial properties and PLA were improved. Silane molecules interlocked between fiber and PLA molecules also served as bridging agents. Increases in TA-ESO concentration considerably reduced the tensile properties of the composites. The diffusion of the high concentration of TA-ESO phase within the PLA matrix would damage the PLA molecular structure's integrity of the composites. A high concentration of TA-ESO would reduce the tensile properties of the PLA composite.

3.2. Thermal Properties of Bamboo-Reinforced PLA Composites. Natural fibers are very sensitive to the thermal effect. It urges researchers to analyse the thermal properties of natural fiber polymer composites in their widespread advanced applications [74]. Natural fibers contain a variety of material compositions which degrades at different temperatures. At higher temperatures, the

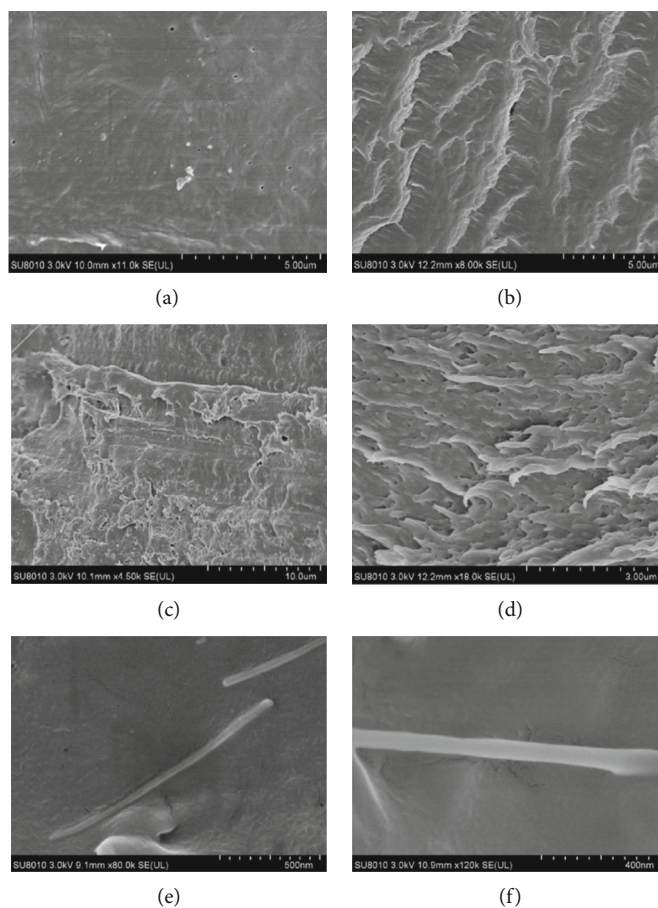


FIGURE 5: SEM images of PLA and PLA/2.5 wt% BCNW composites: (a) PLA surface, (b) PLA fractal surface, (c) PLA/BCNW composites surface, (d) PLA/BCNW composites fractal surface, and (e) and (f) morphology of BCNW in PLA matrix. (Reproduced with permission from Elsevier, license number: 5195441102270) [55].

significant properties of composite change immediately after the fiber constituents, such as cellulose, hemicellulose, and lignin, begin to degrade [75]. It is more important to increase the thermal effect and performance of the composite in high-temperature applications [76]. The three major testing methods and various parameters which can be found are shown in Figure 7.

The existence of volatile substances and moisture levels can induce degradation in natural fiber composites, which can be identified through thermal analysis [80, 81]. The thermal properties are influenced by the matrix material, type of fiber reinforcement, fiber-matrix bonding, fiber weight, and fiber percentage of the composite. When composites are exposed to heat, significant changes in their physical and chemical properties are likely to occur. The material will go through evaporation, sublimation, and water absorption, which are damaged by temperature and time [82]. In PLA-based polymer composites, the degradation of the natural fibers may be the foremost reason for reducing thermal stability [83]. The addition of additives/compatibilizers in the composites influenced the thermal properties. The esterification process in the polymer and fiber interphase will restrict chain mobility [84]. The existence of intermolecular hydrogen bonding further hampered polymer chain mobility.

The chain mobility restriction made the polymer composite with high crystallization temperature [85].

Concerning the T_g , T_c , and T_m for the composites reduces with the inclusion of ESO. Because of the ESO addition, the structure of PLA got damaged. Therefore, it is easier to melt the damaged PLA at higher temperature [41]. The NaOH treatment may introduce impurities in PLA composites. Therefore, T_g and T_c values reduced because of the increase in molecular motion and the effect of treated BPs on nucleation reduces the viscosity of the PLA [42]. The alkali treatment may be used to remove the part of lignin, cellulose materials, and other impurities from the fiber surfaces. Therefore, it does not significantly affect the T_g and T_c of the bamboo/PLA composite [42].

The addition of MAH had an effect on the thermal behaviour of BP/PLA composite. This is due to the restriction of molecular movement by the reaction of esterification at the fiber/polymer interaction [44]. The inclusion of TA-ESO in PLA would enhance the molecular spacing between PLA polymer chains, increasing free volume, and promoting molecular movement at lower temperatures [50]. The thermal behaviour of A-1100-treated composites was significantly larger because of the strong hydro-carbons interaction among amino groups and PLA molecules. A-

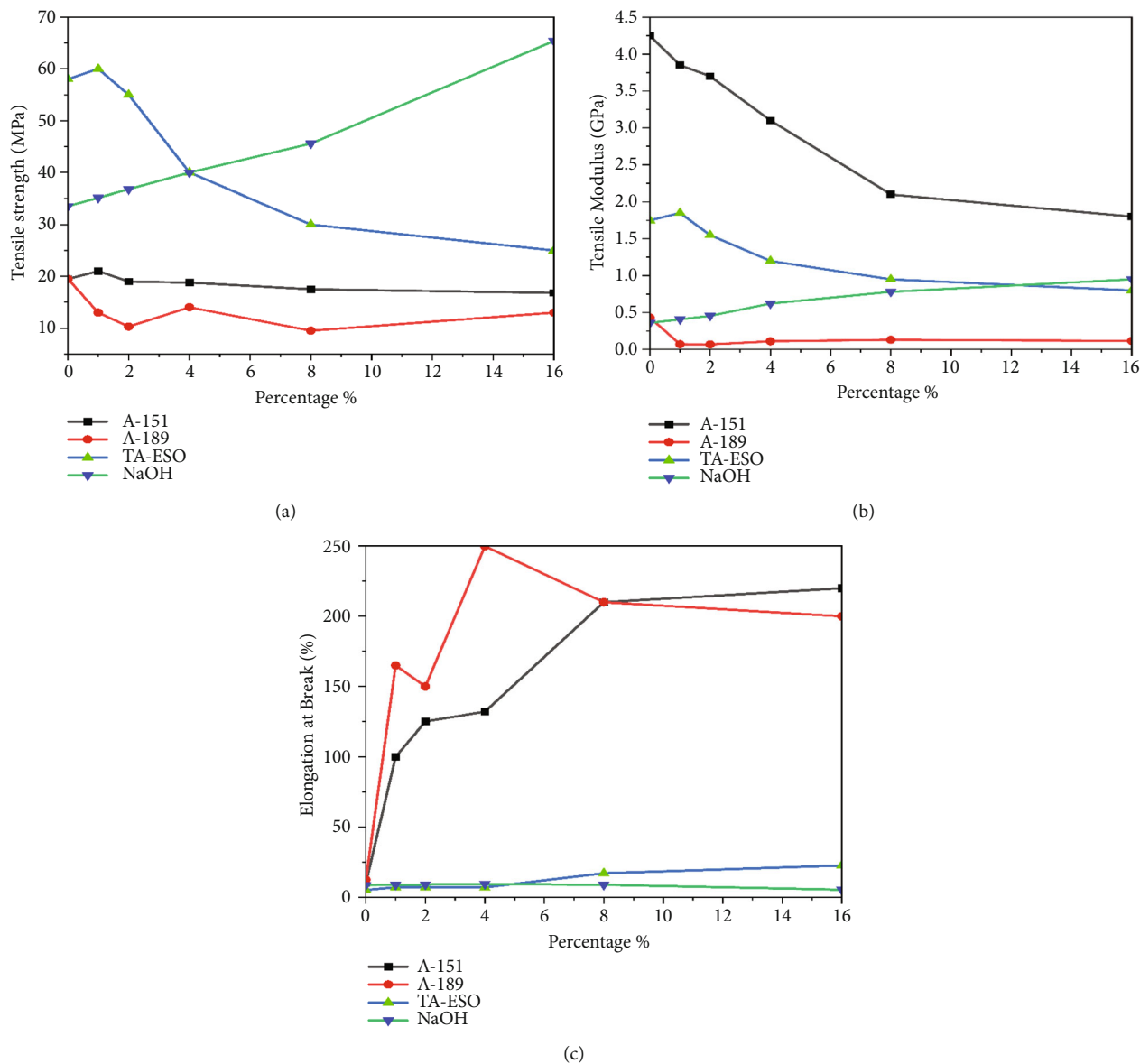


FIGURE 6: Mechanical properties of PLA composites pretreated at different concentrations: (a) tensile strength, (b) tensile modulus, and (c) elongation at break [49, 53, 56, 57].

1100-treated BCNW may have induced heterogeneous nucleation and improved PLA crystallinity [52]. The thermal properties of PLA composite with reinforcement of ultra-fine bamboo char (UFBC) increases with increases UFBC content. This could be ascribed to the presence of UFBC impeding the motion of PLA polymer molecules, requiring higher temperatures to break the chains and complete phase changes, as well as to a high elastic or viscous state [53]. Untreated BCNW had lower PLA compatibility than silylated BCNW, limiting PLA molecular motion due to steric hindrance. It also decelerated PLA crystallization, resulting in higher T_g and T_c values and reduced percentage elongation [54].

The T_g , T_c , and T_m of the various bamboo fiber-reinforced PLA polymer composite are reported in Table 6. The degradation of PLA starts at above 300°C [49]. Polymer degradation

often occurs after natural fiber degradation. As a result, determining the decomposition temperature of cellulose-based polymer composites is crucial. Adding bamboo cellulose fiber to PLA increases T_g , T_c , and T_m , enhancing its thermal properties. It was most likely due to the plasticizing effect enhancing the PLA molecular chain's mobility by adding bamboo cellulose fiber [49, 54]. The crystallization behaviour and thermal stability of polymer composite gradually increased with the addition of BC. Excessive BC restricts PLA composites' lateral rearrangements and crystallization [58].

4. Challenges

Compatibility is one of the most difficult aspects of fabricating polymer composite with natural fiber-reinforcement. The interaction of a hydrophobic polymer with natural

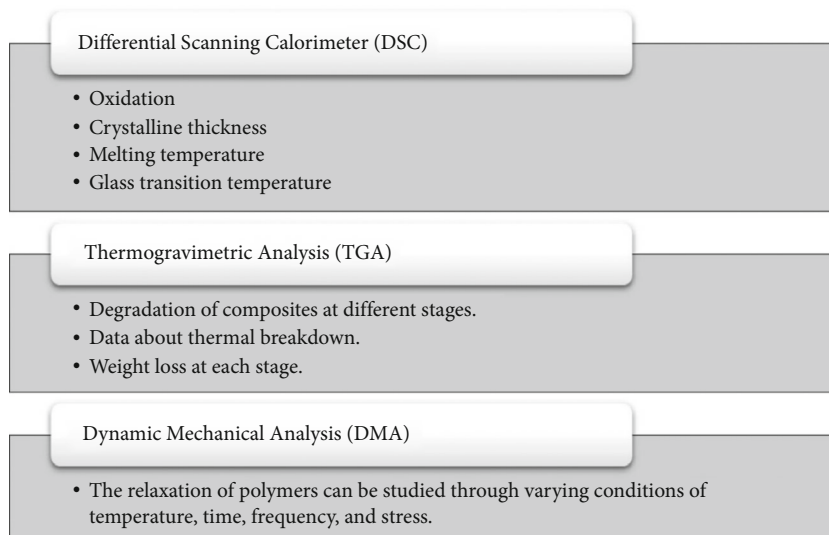


FIGURE 7: Major methods of thermal analysis [77–79].

TABLE 6: Temperature parameters of bamboo–reinforced polymer composites.

Fiber	Fiber addition (wt%)	Best combination (wt%)	Glass transition temperature (T_g)		Crystallization temperature (T_c)		Melting temperatures (T_m)		References
			Pure PLA (°C)	PLA composite (°C)	Pure PLA (°C)	PLA composite (°C)	Pure PLA (°C)	PLA composite (°C)	
Bamboo fiber	20	—	65.8	65.2	99.0	95.6	173.6	172.9	[41]
Bamboo particles	30	—	56.4	59.1	124.8	127.3	150.4	150.9	[42]
Bamboo particles	30	—	55.6	57.7	120.3	125.5	149.5	149.9	[44]
Bamboo fiber	40	—	58.78	61.52	97.42	108.5	166.0	168.89	[45]
Bamboo powder	5, 10	5	55.4	58.6	96.0	101.5	145.8	146	[47]
Bamboo particles	20	20	61	58.0	96.4	95.7	173.1	172	[50]
Bamboo cellulose nanowhiskers	2	—	40.9	45.9	96.8	103.7	156.1	168.1	[51]
Bamboo cellulose nanowhiskers	2.5	—	45.6	48.8	96.2	113.3	164.3	165.2	[52]
Bamboo char	0–4	4	31.3	39.3	90.2	100.4	154.6	159.3	[53]
Bamboo cellulose nanowhiskers	2.5	—	45.6	31.2	96.2	92.6	164.3	154.9	[54]
Bamboo cellulose nanowhiskers	0 – 4	—	40.9	45.9	96.8	103.7	156.1	168.1	[55]
Bamboo cellulose nanowhiskers	1–4	3	45.6	48.8	96.2	113.3	164.3	165.2	[58]
Ultrafine bamboo-char	5–40	30	54.6	51.2	126.3	102.7	149.7	150.0	[59]
Bamboo pulp	30–50	40	72.15	66.92	—	—	164.5	162.91	[65]

hydrophilic fibers results in poor fiber dispersion and mechanical properties. Additives, such as compatibilizers, surface treatments, and chemical treatments on natural fibers, have been carried out to enhance the interfacial bonding. Understanding polymer–fiber interaction and the relationship between structure and properties of polymer composite would be the major challenge.

The search for real polymers with high mechanical characteristics for use as matrix material is another challenge due to their large particle size, biopolymers with a low water resistance, and inadequate tensile strength. They are very brittle, which demands the incorporation of plasticizers in the presence of heat and pressure. Modifiers have traditionally been utilized to enhance tensile modulus, minimize the

costs, and enhance the degradation rate. PLA is perhaps the most attractive biodegradable polymer today, requiring more attention.

5. Application of PLA-Reinforced Bamboo Composites

PLA polymer and natural fibers are used globally in various applications. The industry has responded strongly to using different natural fibers since they are cheaper and lighter [84]. The lightweight nature of bamboo fiber composites is a significant consideration in their application. PLA becomes increasingly capable when plasticized with its monomers, producing a series of products replicating synthetic polymers [85]. These bamboo fiber-reinforced PLA polymer composites have various applications, such as packaging, medical, upholstery, textile, and automotive interiors [86, 87]. The mechanical characteristics of PLA bamboo fiber polymer composites were comparable with conventional polymer composites. They could be used in interior and exterior automobile parts like door panels, door handles, dashboards, seat cushions, timing belt covers, and bumpers [88, 89]. Despite all efforts by researchers to enhance the properties of PLA, there are still some complicated problems to be fixed. The biggest impediment to PLA's usage in the automotive industry is its brittleness and low thermal stability [90]. Using suitable additives and modifiers could make a difference in the composite [91–93]. This study details the interactions between the matrix and various additives and the effect of modifiers.

6. Potential Concerns of Bamboo Fiber Polymer Composite

In addition to the benefits of incorporating bamboo fibers in PLA polymer matrix composites, there are certain limitations, including their mechanical and thermal properties and adherence to the polymer matrix. The bamboo fibers are not consistent in producing above mentioned properties because of different growing conditions. Because of these factors, there will be significant changes in the properties. The mixing of fibers provides protection against variations in any single fiber. More specifically, it is necessary to identify the suitable processing techniques that result in fine and even fibers before composite manufacturing.

Another significant disadvantage of bamboo fibers is their inability to interact with common polymer matrices. The uniform distribution of fibers leads to inadequate stress transfer between the hydrophobic polymer matrix and hydrophilic BF. BFs are moisture sensitive, which causes a reduction in their mechanical properties. Using chemical coupling agents and compatibilizer is an often-proposed solution to this problem, with the intent of enhancing surface compatibility by boosting the bonding between PLA polymer and fiber.

The next disadvantage of employing BFs is their low thermal stability. The maximum processing temperature is roughly 250°C–300°C, over which the fibers break down considerably and affect the mechanical characteristics of

the composites. Thermal treatment temperature and treatment duration should be tightly monitored based on fiber durability to avoid flaws induced by processing techniques.

7. Conclusion

The utilization of bamboo in PLA-based polymer composite offers useful results for new development in the material field. PLA is a biodegradable polymer, and bamboo trees are natural resources that grow fast with a shorter duration, leading to a constant supply of bamboo fibers with very low manufacturing costs than the other traditional fibers. The mechanical properties of bamboo fibers are excellent, and they can replace traditional fibers. A suitable fiber extraction method and pretreatment of fibers can improve the molecular interaction within the matrix and fiber. The distribution of fibers in the matrix depends on the optimum amount of fiber loading. These parameters can increase the mechanical characteristics of the PLA polymer composite. The use of bamboo fibers in PLA develops environment-friendly products. Furthermore, research must be carried out to use the PLA polymer instead of conventional polymers to improve the thermal properties for the wide range of applications in automobile interiors, food containers, furniture, and structural objects.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The author(s) declare(s) that they have no conflicts of interest.

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