Hindawi
International Journal of Polymer Science
Volume 2022, Article ID 1916877, 11 pages
https://doi.org/10.1155/2022/1916877

Research Article

Experimental Investigations on Static, Dynamic, and Morphological Characteristics of Bamboo Fiber-Reinforced Polyester Composites

N. Santhosh,[1] **B. A. Praveena**,[2] **H. V. Srikanth**,[3] **Santosh Angadi**,[2] **Amaresh Gunge**,[4] **M. Rudra Naik**,[5] **G. Shankar**,[1] **K. Ramesha**,[6] **and G. Ravichandran**[6]

[1]*Department of Mechanical Engineering, MVJ College of Engineering, Bengaluru 560067, India*
[2]*Department of Mechanical Engineering, Nitte Meenakshi Institute of Technology, Yelahanka, Bengaluru 560064, India*
[3]*Department of Aeronautical Engineering, Nitte Meenakshi Institute of Technology, Yelahanka, Bengaluru 560064, India*
[4]*Department of Mechanical Engineering, Nagarjuna College of Engineering & Technology, Bengaluru 562164, India*
[5]*Department of Electro-Mechanical Engineering, Arba Minch University, Sawla Campus, Ethiopia*
[6]*Department of Mechanical and Automobile Engineering, School of Engineering and Technology, CHRIST (Deemed to be University), Kengeri Campus, Bangalore, Karnataka, India*

Correspondence should be addressed to M. Rudra Naik; rudra.naik@amu.edu.et

Received 27 March 2022; Revised 19 May 2022; Accepted 23 May 2022; Published 9 June 2022

Academic Editor: Yiqi Yang

The use of natural fiber-reinforced polymer composites has increased over a period of time, majorly due to the ecosustainability and biodegradability of the composites. Among several grades of natural fibers, bamboo fibers offer numerous environmental and cost benefits and possess excellent mechanical characteristics. The superior properties of the bamboo fibers have triggered the research interests in the domain of bamboo fiber-reinforced polymer composites. Among the polymers, polyesters are long chain molecules made up of atoms arranged in various ways with other elements to form the basic building blocks of a polymeric chain. Polyester is being increasingly employed in today's industrial products due to its inherent advantages. As a result, based on the potential properties of bamboo fibers as reinforcing materials and polyester resin as matrix material, the biocomposites are synthesized by hand lay-up technique and the specimens cut as per the standard dimensions and subjected to mechanical investigations, vibration, and morphological characterization as per the ASTM test methods. The increase in fiber weight content has enhanced flexural, tensile, and impact characteristics and improved the damping characteristics of the composite specimens. The microstructural evaluations have revealed the uniform distribution of the bamboo fibers in the resin, and the morphological studies of the fractured specimens have revealed that the fracture is majorly due to the matrix cracks rather than the fiber debonding, which is a major attribute ascertaining the strong coherent strengthening mechanism brought about by the inclusion of bamboo fiber in the polyester resin.

1. Introduction

Natural fibers are finding major applications in composites, because of outstanding mechanical characteristics, low cost, biodegradability, durability, and sustainability [1, 2]. Demand for various forms of natural fiber composites is growing as the economy is constantly developing, and ecocompatibility is getting additional focus from the sustainability point of view. Among the natural fibers, bamboo fibers are a major type of reinforcement that can be considered for the synthesis of the natural composites. However, these bamboo fibers have certain intrinsic faults especially related to the processing technologies, including inadequate designs, characterization results, and market applicability [3, 4]. Bamboo fiber, in particular, exhibits high hygroscopicity as a typical plant fiber, resulting in a performance gap between bamboo fiber and other fiber composites. As a result, new technologies for the manufacturing of bamboo fiber composites must be explored in order to generate stable bamboo fiber composites [5, 6]. Many investigations have been conducted on elements of bamboo fiber morphology and size, bamboo fiber surface, and interfacial reactions of reinforcements and matrices, with plastic resin, types, and composite molding methods [7, 8]. Bamboo fibers provide a number of benefits, including light weight and high strength. They can replace glass fiber composites in various applications, demonstrating the benefits of regeneration and recycling, and can be used in automobile substructures, electrical shells, ornamentation, and packaging materials [9, 10].

Yang et al. have carried out research work on the functionalized modification of bamboo fibers for synthesis of composite materials. They have reported that the bamboo fibers possess a high degree of toughness, a low density, and acceptable specific strength. They also offer excellent thermal characteristics and improved energy recovery [11]. Yang et al. have reported the use of bamboo fibers as reinforcements in petroleum-based polymer matrices for the synthesis of bamboo composites. These composites can be used for structural applications [12]. Numerous studies have been conducted on various platforms to support the implementation of the same [13, 14]. New building materials for modern structures are being developed using bamboo and bamboo products [15, 16]. Sharma et al. have worked on the engineered bamboo for construction applications and have reported that the engineered bamboo offers greater strength and properties as compared to timber-based products [17]. Superior composite materials have been generated by altering the mechanical characteristics of the bamboo fibers through surface treatment and prestressing of the bamboo fibers for use as fiber reinforcements in the composites [18]. Chen et al. have studied the unpredictably structured framework of the bamboo plant consisting of two configurations of comparably structured vegetative axes one above ground and the other below which offers high strength to low weight characteristics [19].

Engineered bamboos are of keen interest for researchers, since they offer excellent static and dynamic load-bearing capability [20, 21]. Bamboo is commonly used as a component of construction and as a material for the manufacture of structural components like ladders and scaffoldings [22–24]. Construction with bamboo is consistent with the conception of sustainable development. Synthesis of natural fiber and fabrication of the composites have become a research hotspot in the context of sustainability [25, 26]. Bamboo fibers have a hollow cross-section that allows for great humidity absorption and air permeability, and their vascular bundle is dispersed along the radial route, making them easy to classify and use in the synthesis of natural fiber-reinforced polymer composites [27]. In this regard, Wang et al. have carried out extensive work on the synthesis and characterization of the bamboo fiber-reinforced polymer composites. From their studies, it is depicted that the inclusion of bamboo fibers in the polymer matrix has revealed mixed results with the mechanical characteristics of the composites exhibiting improvement for the volume fraction of reinforcement fibers of up to 60 wt.%, beyond which the inclusion of bamboo fibers has resulted in void formations [28]. Also, the works of Chen et al. on the microstructure and thermal stability of bamboo fibers have further reiterated the need for pretreatment and homogenous distribution of bamboo fibers in the matrix to enhance the thermal and mechanical characteristics of the composites [29].

From the critical review of the latest research findings in the domain of the bamboo fibers, it is evident that the research on the use of bamboo fibers as reinforcements in the polyester resin for synthesis of composites is still in its incipient stage, and there is sufficient scope for carrying out research work on the synthesis of biocomposites by reinforcing the bamboo fibers and facilitating uniform distribution through hand lay-up and characterizing the composites for static, dynamic, and morphological studies. The findings of the present work shall provide scope for further utilization of polyester composites reinforced with bamboo fibers in potential engineering applications.

2. Materials and Methods

The bamboo fibers sourced from the Bindiganavile village of Mandya District, Karnataka state, India, were used as reinforcement in the present studies due to multifold advantages it offers. The unsaturated polyester resin was employed as a matrix to retain the fibers in this study. The bundles of bamboo fiber were extracted successfully from bamboo culms by water retting process, subsequently followed by enzymatic retting process, facilitated by the enzymes secreted by microorganisms in the retting medium. The effects of the lignolytic enzymes were monitored during the retting process. In totality, the manganese peroxidase–xylanase combined lignolytic enzyme-retting treatment has produced bamboo fibers processed from bamboo shoots which were subsequently sliced into various sizes and used as a reinforcement material. The hand lay-up technique was employed for synthesizing the composites. The process involved the laying of a release film on the mold, subsequently followed by the uniform dispersion of a predefined weight percent of chopped bamboo fibers in the 3 : 1 resin-hardener mixture. The resin-fiber mixture was then applied in layers in the mold and rolled to the shape of the mold to obtain the composite laminate of 6 mm thickness.

Table 1 gives the mechanical and physical properties of bamboo fiber and polyester resin, while Table 2 gives the weight fraction (W_f) of the resin, hardener, and bamboo fiber used in the present work for the synthesis of the composites.

The SEM images of the bamboo fiber and resin-hardener and the distribution of the bamboo fiber in the resin-hardener matrix were studied using a Hitachi make SU-3500 SEM at an accelerating voltage of 15 kV and a magnification of 250x. The studies have revealed uniform

Table 1: Mechanical and physical properties of bamboo fiber and polyester resin [30].

Properties	Bamboo fiber	Polyester resin
Compressive strength (MPa)	150	—
Tensile strength (MPa)	225	22.9
Modulus of elasticity (MPa)	1.72×10^4	580
Poison ratio	0.15	—
Density (g/cm^3)	0.76	1.159

Table 2: Composition of the resin, hardener, and fiber for synthesis of composites.

Sl. no.	Bamboo fiber (wt.%)	HP-P21 polyester resin (wt.%)	MEKP hardener (wt.%)
1	10	67.5	22.5
2	15	63.75	21.25
3	20	60	20
4	25	56.25	18.75

distribution of the bamboo fiber in the polyester resin matrix (Figures 1(a)–1(c)).

3. Experimental Procedure

The composite specimens synthesized from the hand lay-up technique were cut to the ASTM standard dimensions, viz., 250 mm length ∗ 25 mm width ∗ 3 mm thickness for tensile test, 120 mm length ∗ 13 mm width ∗ 3 mm thickness for flexural test, and 66 mm length ∗ 13 mm width ∗ 3 mm thickness with a 45° V notch of 2 mm depth at the mid length for impact test. The test coupons were subjected to a variety of mechanical strength tests, such as tensile and flexural test in the Instron make 3400 series UTM and impact strength test in the MCS make MIT30E Charpy impact testing machine, respectively. The repeatability of the experiments was validated by averaging the outcomes of three successive trials.

Further, the composite specimens were subjected to the vibration characterization using a Kistler make 9822A400 model FFT vibration analyzer test setup. The schematic of the test setup used in the present work is given in Figure 2(a), while the specimen fabricated for the vibration studies in accordance with the ASTM E756 standard is given in Figure 2(b). The specimens for vibration analysis were fabricated using hand lay-up and finished to the ASTM standard dimensions of 300 mm ∗ 300 mm ∗ 5 mm. The vibration studies were carried out using excitation mechanism. For the excitation of the fabricated composite, a sharp hardened impact hammer was used, while the displacement signals were obtained by an accelerometer connected by wax at the end of the composite and registered using a data acquisition device. For capturing the output signal, two different adaptors were used. One was attached to the impact hammer, and the other was fixed on the laminate composite's free end.

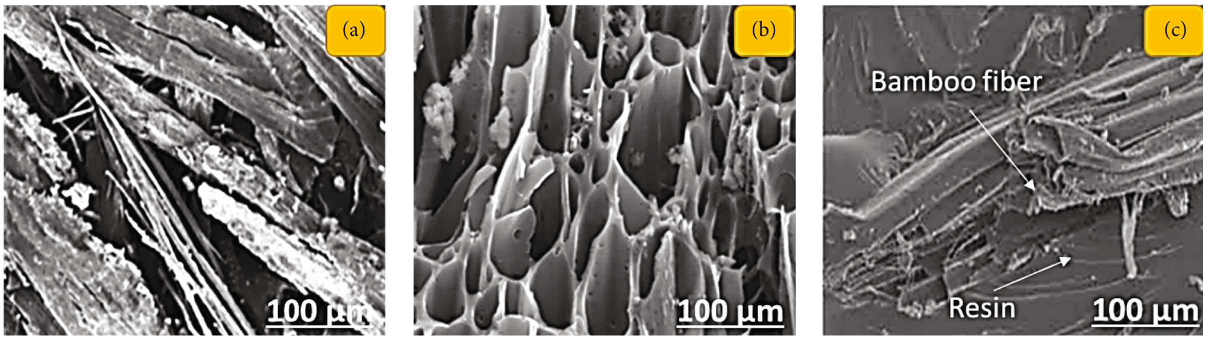
4. Results and Discussion

4.1. Tensile Test. From the results of the tensile test (Figures 3(a)–3(c)), it is evident that the tensile strength and young's modulus of the composite improve with the inclusion of bamboo fibers. This is due to the fiber matrix interfacial bond and the homogeneous distribution of the fibers in the matrix.

Furthermore, it was found that the tensile strength initially decreases for 15 wt.% of bamboo fiber, beyond which the tensile strength increases to 48 MPa for 20 wt.% and 52 MPa for 25 wt.%. However, Young's modulus increases for 15 wt.% of bamboo fiber reinforcements and depicts a steady increase in its values for further increment in bamboo fiber content. This sudden increase in Young's modulus for 15 wt.% is majorly due to the concentration of hemicellulose and lignin in bamboo fiber that affects the matrix and fiber bonding capabilities facilitated by hand lay-up in the mold and rolling the layers to remove the entrapped air. According to the literature survey, the interfacial bonding of natural fiber-reinforced polyester resin composites exhibits an improvement in Young's modulus of up to 40% when compared to neat polyester laminate [31–34]. Similarly, the low vacancy content of natural composites affects tensile characteristics due to improved interfacial bonding involving essential resources [35, 36]. The elongation at break was previously referred to as rupture strain, and it could be determined using a tensile test [37–41]. The graph in Figure 3(c) shows the stress-strain diagram for a different composition. It is evident from the graphs that the composite laminate with 25 wt.% bamboo reinforcements can withstand the tensile stress to the maximum extent possible (52 MPa), without failure. Thus, the increase in the bamboo fiber content and fabrication of the composite laminates without the voids leads to an increase in the stress withstanding capacities of the composites [42–45]. However, the elongation of the composite laminates decreases with the increase in the wt.% of bamboo reinforcements due to strengthening and embrittlement [46]. The elongation or the strain (%) is maximum for 10 wt.% bamboo fiber reinforcements and minimum for 15 and 20 wt.% bamboo fiber reinforcements due to the ductile to brittle transition brought about by embrittlement [47]. The photograph of the specimen before and after failure in Figure 3(d) depicts the prenecking and fiber rupture during the tensile failure.

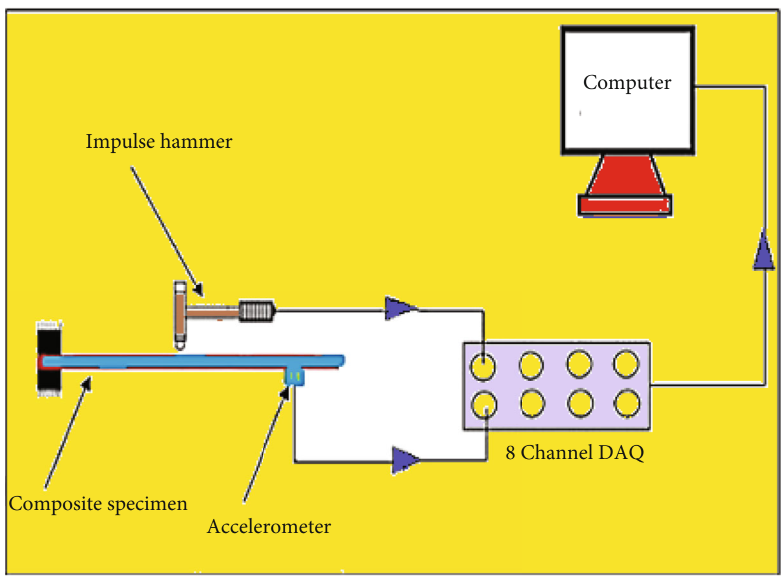
4.2. Flexural Test. From the results of flexural test (Figures 4(a) and 4(b)), it is evident that the bamboo fiber improves the composite specimens' flexural strength. The optimum flexural strength of the bamboo fiber composite was 75 MPa for a load of 10.25 N, and the average deflection without breaking was 2.25 mm.

The flexural test results showed that bamboo fiber composite specimens improved their flexural strength by 18 percent for 25% wt. fraction of bamboo fibers when compared to 20% wt. fraction of bamboo fibers in the composites. As a result of the reinforcement of the bamboo fibers in the matrix phase, the flexural characteristics are improved. Thus, the natural composites made from bamboo fiber-

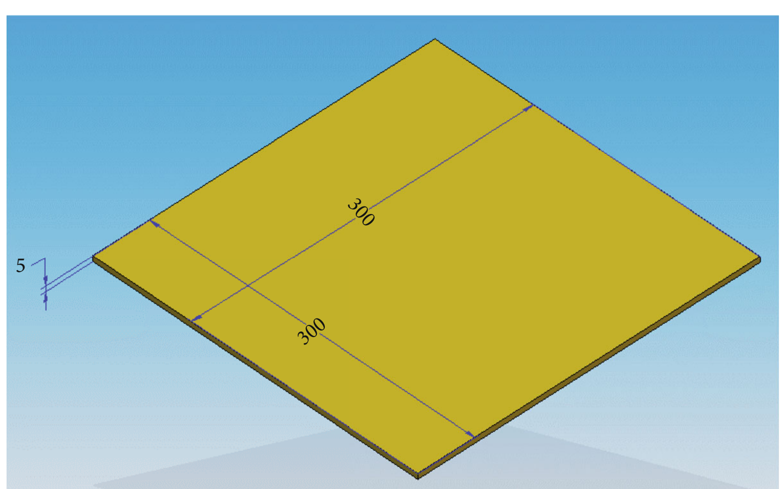


(a) (b) (c)

Figure 1: SEM image of (a) bamboo fiber and (b) resin-hardener and (c) distribution of the bamboo fiber in the matrix.



(a)



(b)

Figure 2: (a) Schematic of the free vibration test setup used in the present work. (b) 3D model of the vibration test specimen.

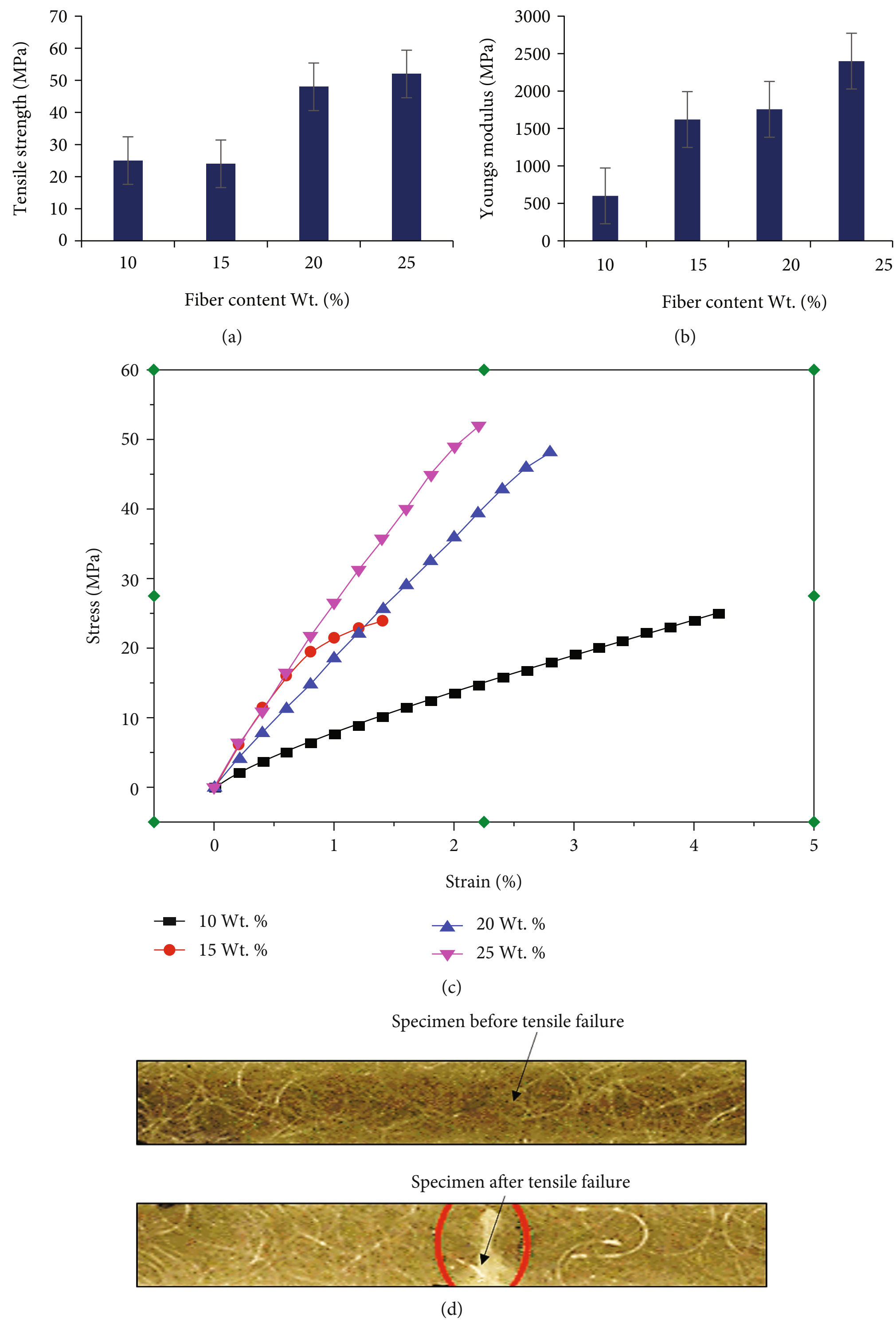


Figure 3: (a) Tensile strength vs. fiber content and (b) Young's modulus vs. fiber content. (c) Stress vs. strain diagram for composite specimens with different wt.% of bamboo fiber reinforcements. (d) Specimen before and after tensile failure.

reinforced polyester matrix exhibit better tensile and flexural properties. Furthermore, this emphasized the bamboo fibers' ability to slow down the degradation process.

Ngo et al. have carried out extensive work on the flexural characteristics of the natural fiber-reinforced polymer composites. It is herewith evident that the flexural strength of the composites increases with the increase in the natural fiber content in the composites up to an optimum level, beyond which it starts decreasing owing to agglomeration and microcoring [48]. The outcomes of the flexural tests in the present work are in close correlation with the findings reported in research work of similar kind.

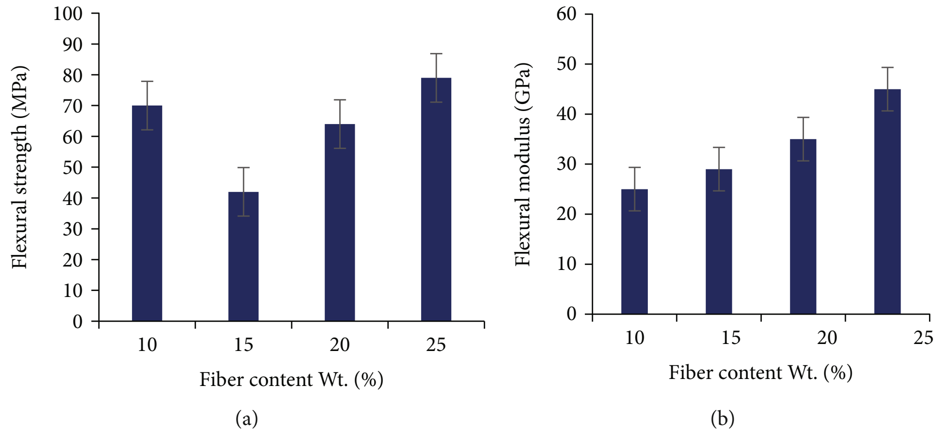


Figure 4: (a) Flexural strength vs. fiber content and (b) flexural modulus vs. fiber content.

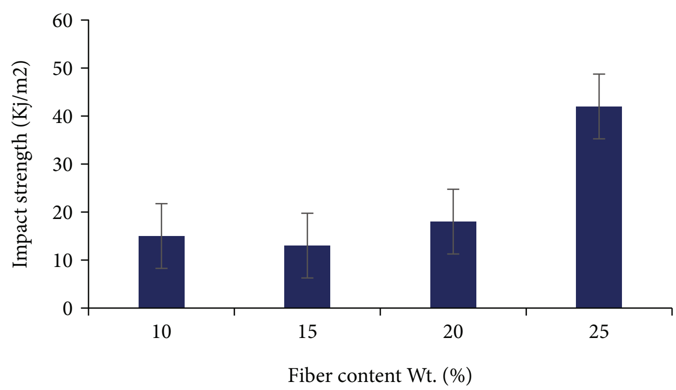


Figure 5: Impact strength vs. fiber content.

Table 3: Variation of natural frequency and modal damping factor with varying bamboo fiber weight percentage in polyester resin composites.

Sl. no.	Fiber wt.%	Natural frequency (Hz)		Damping factor	
		Mode 1	Mode 2	Mode 1	Mode 2
1	Neat laminate	34.21	197.12	0.0712	0.0512
2	10	38.12	300.13	0.0753	0.0546
3	15	43.45	284.32	0.0621	0.0325
4	20	31.21	234.14	0.0628	0.0569
5	25	30.21	243.52	0.0865	0.0636

4.3. Impact Test. The variation of the impact strength with the wt.% of bamboo fiber is graphically observed in Figure 5. The results reveal that the impact strength of the bamboo fiber-reinforced composite specimens initially decreases from 15 kJ/m^2 to 13 kJ/m^2 for the increase in the wt.% of bamboo fibers from 10 wt.% to 15 wt.% and then gradually increases from 15 kJ/m^2 to 42 kJ/m^2 for the composition of bamboo fibers in the composite increasing from 15 wt.% to 25 wt.%, respectively.

The improvement in the impact strength with the increase in the bamboo fiber wt.% is attributed to the fact that the fiber reinforcement acts as a load-bearing component and the bamboo fiber has an inherent adhesive characteristic that facilitates a strong bonding between the matrix and fiber, resulting in improved impact characteristics. Combining natural fibers in a resin will result in composite structures with better impact characteristics.

4.4. Vibration Studies. The results of the free vibration test are tabulated in Table 3, and the variation of the natural frequency and damping factor with varying wt.% of bamboo fiber for modes 1 and 2 are depicted in Figures 6 and 7, respectively.

From the graph in Figure 6, for mode 1, it is evident that the natural frequency for neat polyester laminate is 34.21 Hz, while the natural frequency is 38.12 Hz for 10 wt.% bamboo fiber-reinforced polyester composite laminate. The natural frequency of the composite laminates increases from 38.12 to 43.45 Hz for increase in bamboo fiber content from 10 to 15 wt.%. However, it decreases from 43.45 to 31.21 Hz for 15 to 20 wt.% of fiber, and it becomes approximately constant for 25 wt.% fiber decreasing slightly from 31.21 Hz to 30.21 Hz.

Even the damping factor increases from 0.0712 for neat polyester laminate to 0.0753 for 10 wt.% fiber content, subsequently followed by a reduction in the damping factor from 0.0753 to 0.0621 for the fiber content increasing from 10 to 15 wt.%; however, the damping factor again increases from 0.0621 to 0.0865 with the increase in fiber wt. fraction from

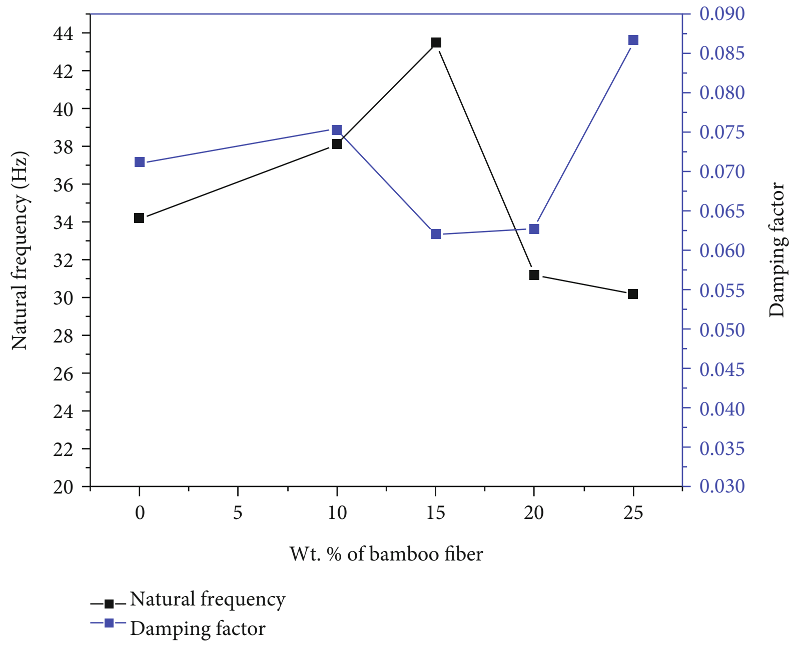


Figure 6: Natural frequency and damping factor with varying bamboo fiber wt.% (mode 1)

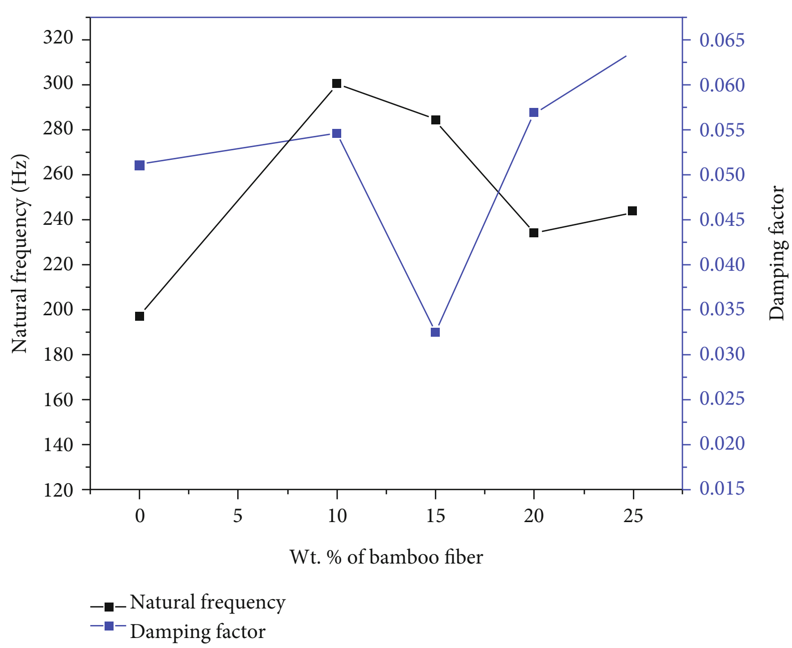
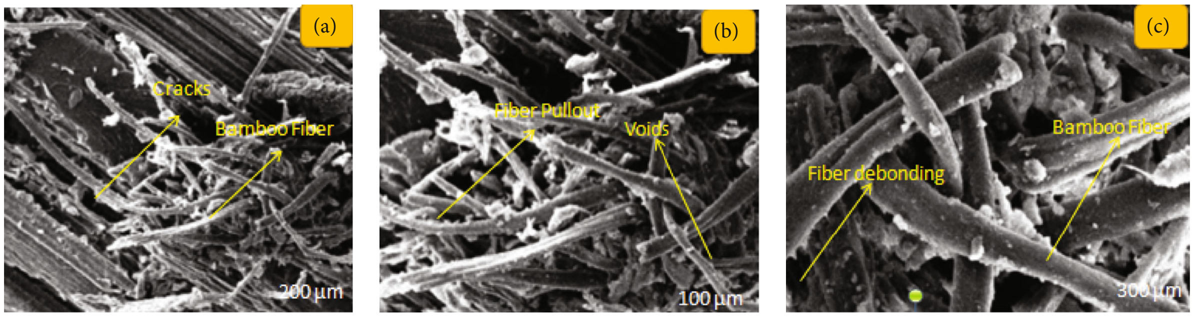


Figure 7: Natural frequency and damping factor with varying bamboo fiber wt.% (mode 2)

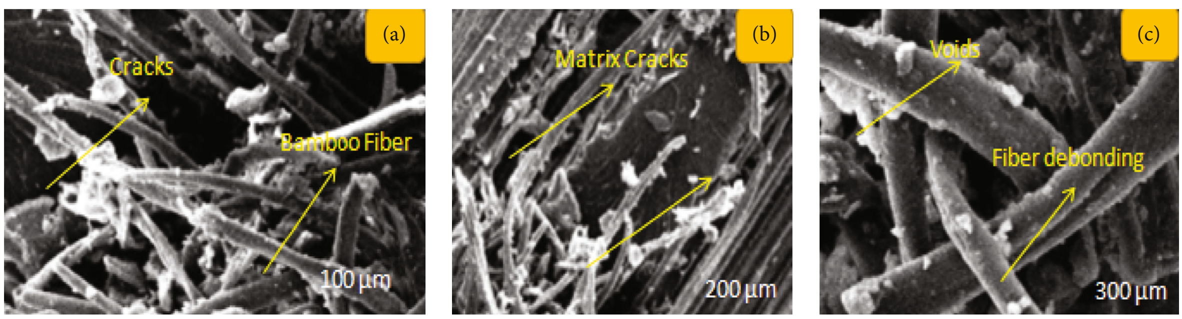
15 to 25%, respectively. This is attributed to the strong bonding brought about by the reinforcement of natural fibers in the matrix phase [30, 49].

Similarly for the mode 2, the graph in Figure 7 shows the variation of natural frequency and damping factor with the wt.% of bamboo fiber. The natural frequency for the neat polyester laminate is 197.12 Hz; as 10 wt.% of bamboo fiber is added to the matrix, the natural frequency increases to 300.13 Hz. However, it decreases to 284.32 Hz for 15 wt.% of fiber and again it decreases to 234.14 for 20 wt.% of bamboo fiber; further, it increases to 243.52 Hz for 25 wt.% of bamboo fiber. Even the damping factor increases initially from 0.0512 for neat polyester laminate to 0.0546 for composite laminates with 10 wt.% of bamboo fiber in the matrix phase. However, it decreases to 0.0325 for 15 wt.% of fiber attributed majorly to the voids formed during the postcuring process. The damping factor increases to 0.0569 for 20 wt.% bamboo fiber, and again, it increases to 0.0636 for 25 wt.% of bamboo fiber. Thus, the inclusion of the bamboo fiber enhances the vibration characteristics of the composites due to microcoring and strong bonding of the reinforcements in the matrix phase [50, 51].



(a) (b) (c)

Figure 8: Micrographic images for tensile fractured surfaces of samples (a) 10% (b) 15%, and (c) 20%.



(a) (b) (c)

Figure 9: Micrographic images for flexural fractured surfaces of samples (a) 10% (b) 15%, and (c) 20%.

4.5. Microstructural Analysis. The ruptured surfaces of bamboo fiber composite specimens were analyzed by observation of micrographs captured in a Bruker make contour elite 3D microscope as in Figures 8 and 9. The fracture due to the pull out of the fiber in the matrix phase is observed in Figures 8(a)–8(c). The rupture surface morphology of reinforced fiber composite samples due to tensile failure revealed a significant void formation among bamboo fiber and resin that was not fit-lined and fabricated in the mold cavity. In addition to providing strength for bamboo fiber composite materials, the bamboo fiber has shown strong bonding in matrix.

The flexural breakage shell of samples of bamboo composite was micrographed. The mixture of fiber and matrix is to the maximum extent homogenized, according to microstructural investigation. However, there are some localized regions with cracks and void contents in the majority of the fault exterior region. Also, the bamboo fiber has formed grooves as well as a fiber pullout, resulting in a damaged fiber matrix boundary [52–55].

Figures 9(a)–9(c) provide information about the sample's surface topography and composition of bamboo fiber-reinforced polyester composite subjected to flexural failure. Through the critical observations of the micrographs, the information of the prepared composite specimens and the topographical properties of the fabricated composite surfaces indicate variance in mechanical properties. Figure 9(a) depicts the bamboo fiber composite phase subjected to flexural failure due to the ductile to brittle transition. It can be seen from the topography that the composite has a low binding capacity. As a result, mechanical characteristics are decreased. Figure 9(b) displays bamboo fiber bundles, indicating that the polyester resin did not properly wet these fibers, resulting in low stress. Figure 9(c) illustrates a considerable number of bamboo fibers in the matrix thereby depicting that the composites have excellent cohesive qualities. In comparison to composites with 15% wt. fraction specimens, the composite specimens with 20 wt.% of reinforcements as seen in Figure 9(c) depict the presence of bamboo fibers, indicating better interfacial bonding, resulting in good mechanical characteristics.

5. Conclusions

From the critical observation of the results, the following conclusions are drawn based on the inferences.

(i) The results of tensile test reveal that the composites reinforced with 25% weight fraction of bamboo fiber possess maximum tensile strength of 52 MPa with an improvement of 27 MPa in comparison with the composites reinforced with 10% wt. fraction of the bamboo fiber reinforcements

(ii) Young's modulus for composite specimens reinforced with 25 wt.% bamboo fibers is 2500 MPa, which is the maximum among all the composites

(iii) Composite with 20% wt. fraction of bamboo fiber has a flexural strength of 80 MPa, which is three times that of composites reinforced with 10% wt. fraction of bamboo fibers

(iv) The flexural modulus of the composite with 25% wt. fraction of bamboo fiber is 45 GPa, which is practically superior to the composite reinforced with 10% wt. fraction of bamboo fibers

(v) The greatest impact strength attained in impact test is 47 kJ/m^2 for the composite specimens reinforced with 25% wt. fraction of bamboo fibers

(vi) The micrographic images of the synthesized composite with bamboo fibers demonstrate that composite specimens reinforced with 20% wt. fraction of bamboo fibers have less fiber pullouts and debonding. It reveals that composite with 20% wt. fraction of bamboo fibers has superior bonding and dispersion than composites 10%, 15%, and 25% wt. specimen

(vii) The vibration analysis has depicted an improvement in the damping factor for the composites with the increase in the bamboo fiber content in the matrix phase. The damping factor for the composite specimens with 25 wt.% bamboo fibers is 0.0865 for mode 1 and 0.0636 for model 2

Further, the experimentations to study the static and dynamic mechanical characteristics by modifying the fiber content have proved that the characteristics of the composite laminates subjected to static and dynamic loading can be improved by strong bonding and microcoring between the matrix and the bamboo fibers and fabrication of the composite laminates with minimum voids.

Data Availability

The authors declare that the major data are already embedded in the manuscript, and further datasets are readily available and will be furnished upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Acknowledgments

The authors appreciate the supports from the Arba Minch University, Sawla Campus, Ethiopia, during the research and preparation of the manuscript. The authors thank Nitte Meenakshi Institute of Technology, MVJ College of Engineering, for providing assistance to complete this work. This work is a self-financed research work.

References

[1] H. Li, B. J. Wang, L. Wang, P. Wei, Y. Wei, and P. Wang, "Characterizing engineering performance of bamboo-wood composite cross- laminated timber made from bamboo mat-curtain panel and hem-fir lumber," *Composite Structures*, vol. 266, p. 113785, 2021.

[2] X. Wang, Y. Wu, H. Chen, X. Zhou, Z. Zhang, and W. Xu, "Effect of surface carbonization on mechanical properties of LVL," *Bio Resources*, vol. 14, no. 1, pp. 453–463, 2019.

[3] Y. Wu, Y. Zheng, F. Yang, and L. Yang, "Preparation process and characterization of mechanical properties of twisted bamboo spun fiber bundles," *Journal of Materials Research and Technology*, vol. 14, pp. 2131–2139, 2021.

[4] X. Wang, L. Fang, H. Chen, Z. Wu, and B. Fei, "Effect of cladding materials on the mechanical properties of structural insulation panels," *Journal of Forestry Engineering*, vol. 2, no. 3, pp. 16–21, 2017.

[5] Y. M. Zeng, *Development of Bamboo Fiber Products*, Tianjin University of Technology, 2017.

[6] J. X. He, W. Zhang, and S. Y. Wang, "Structural analysis of bamboo fibers," *Journal of Textiles*, vol. 29, no. 2, p. 24, 2008.

[7] C. Jia, C. Chen, Y. Kuang et al., "From wood to textiles: top-down assembly of aligned cellulose nanofibers," *Advanced Materials*, vol. 30, no. 30, article e1801347, 2018.

[8] H. Chen, Y. Yu, T. Zhong et al., "Effect of alkali treatment on microstructure and mechanical properties of individual bamboo fibers," *Cellulose*, vol. 24, no. 1, pp. 333–347, 2017.

[9] Y. Wu, Y. Bian, F. Yang, Y. Ding, and K. Chen, "Preparation and properties of chitosan/graphene modified bamboo fiber fabrics," *Polymers*, vol. 11, no. 10, p. 1540, 2019.

[10] L. Fang, X. Lu, J. Zeng, Y. Chen, and Q. Tang, "Investigation of the flame-retardant and mechanical properties of bamboo fiber-reinforced polypropylene composites with melamine pyrophosphate and aluminum hypophosphite addition," *Materials*, vol. 13, no. 2, pp. 479–491, 2020.

[11] F. Yang, Z. L. Zhao, L. J. Fu et al., "Functionalized modification of bamboo recycled textiles with antibacterial properties," *Dyeing and Finishing Technology*, vol. 41, no. 8, pp. 1–24, 2019.

[12] S. Yang, X. E. Liu, L. L. Shang et al., "Advances in lignin properties and characterization methods of bamboo wood," *Materials Direct*, vol. 34, no. 7, pp. 7177–7182, 2020.

[13] H. Chen, W. Zhang, X. Wang et al., "Effect of alkali treatment on wettability and thermal stability of individual bamboo fibers," *Journal of Wood Science*, vol. 64, no. 4, pp. 398–405, 2018.

[14] R. Li, W. Xu, C. Wang, S. Zhang, and W. Song, "Optimization for the liquefaction of moso bamboo in phenol using response surface methodology," *Wood and Fiber Science*, vol. 50, no. 2, pp. 220–227, 2018.

[15] A. U. Md Shah, M. T. H. Sultan, M. Jawaid, F. Cardona, and A. R. Abu Talib, "A review on the tensile properties of bamboo fiber reinforced polymer composites," *BioResources*, vol. 11, no. 4, pp. 10654–10676, 2016.

[16] M. Ramachandran, S. Bansal, V. Fegade, and P. Raichurkar, "Analysis of bamboo fibre composite with polyester and epoxy resin," *International Journal on Textile Engineering and Processes*, vol. 1, no. 4, pp. 18–21, 2015.

[17] B. Sharma, A. Gatóo, M. Bock, and M. Ramage, "Engineered bamboo for structural applications," *Construction and Building Materials*, vol. 81, pp. 66–73, 2015.

[18] Y. X. Zhu, M. G. Guan, and Y. K. Fan, "Pre-stress effect of twisted bamboo bundles in bamboo-wood composite veneer laminated timber," *Journal of Materials Research and Technology*, vol. 31, no. 6, pp. 16–20, 2007.

[19] H. Chen, Y. Zhang, X. Yang, H. Ji, T. Zhong, and G. Wang, "A comparative study of the microstructure and water permeability between flattened bamboo and bamboo culm," *Journal of Wood Science*, vol. 65, no. 1, p. 64, 2019.

[20] C. Wang, X. J. Li, W. Yan et al., "A preliminary investigation on the dyeing process of bamboo with reactive dyes," *Journal of Central South University of Forestry Science and Technology*, vol. 35, no. 3, pp. 117–119, 2015.

[21] J. M. Wu, Y. Wu, Q. T. Huang, J. C. Zhou, and Y. Han, "Effect of silane coupling agent modification on transparent wood properties," *Forest Industry*, vol. 46, no. 8, pp. 22–25, 2019.

[22] H. Sun, X. Li, H. Li, D. Hui, M. Gaff, and R. Lorenzo, "Nanotechnology application on bamboo materials: A review," *Nanotechnology Reviews*, vol. 11, no. 1, pp. 1670–1695, 2022.

[23] Y. Huang, Y. Ji, and W. Yu, "Development of bamboo scrimber: a literature review," *Journal of Wood Science*, vol. 65, no. 1, pp. 1–10, 2019.

[24] Y. Wu, J. Zhou, Q. Huang, F. Yang, Y. Wang, and J. Wang, "Study on the properties of partially transparent wood under different delignification processes," *Polymers*, vol. 12, no. 3, pp. 661–675, 2020.

[25] Q. Lin, Y. Huang, and W. Yu, "Effects of extraction methods on morphology, structure and properties of bamboo cellulose," *Industrial Crops and Products*, vol. 169, article 113640, 2021.

[26] C. Y. Tang, Y. Wu, J. M. Wu et al., "Study of transparent wood-based composites - optimization of delignification process," *Furniture*, vol. 39, no. 227, pp. 22–27, 2018.

[27] Y. Yu, Y. Huang, Y. Zhang, R. Liu, F. Meng, and W. Yu, "The reinforcing mechanism of mechanical properties of bamboo fiber bundle-reinforced composites," *Polymer Composites*, vol. 40, no. 4, pp. 1463–1472, 2019.

[28] C. H. Wang, S. K. Liu, and Z. L. Ye, "Surface energy analysis of bamboo fibers and their mechanical properties of reinforced PP composites," *Engineering Plastics Applications*, vol. 12, pp. 23–28, 2014.

[29] H. Chen, J. Wu, J. Shi, W. Zhang, and H. Wang, "Effect of alkali treatment on microstructure and thermal stability of parenchyma cell compared with bamboo fiber," *Industrial Crops and Products*, vol. 164, no. 1, p. 113380, 2021.

[30] W. Zhang, C. Wang, S. Gu, H. Yu, H. Cheng, and G. Wang, "Physical-mechanical properties of bamboo fiber composites using filament winding," *Polymers*, vol. 13, no. 17, p. 2913, 2021.

[31] B. A. Praveena, B. P. Shetty, N. Vinayaka, H. V. Srikanth, S. P. S. Yadav, and L. Avinash, "Mechanical properties and water absorption behaviour of pineapple leaf fibre reinforced polymer composites," *Advances in Materials and Processing Technologies*, vol. 6, no. 4, pp. 1–16, 2020.

[32] B. A. Praveena, B. P. Shetty, B. Sachin, S. P. S. Yadav, and L. Avinash, "Physical and mechanical properties, morphological behaviour of pineapple leaf fibre reinforced polyester resin composites," *Advances in Materials and Processing Technologies*, vol. 6, no. 4, pp. 1–13, 2020.

[33] B. A. Praveena, B. P. Shetty, A. S. Akshay, and B. Kalyan, "Experimental study on mechanical properties of pineapple and banana leaf fiber reinforced hybrid composites," in *AIP Conference Proceedings*, vol. 2274, Bangalore, India, 2020.

[34] G. Ravichandran, G. Rathnakar, and N. Santhosh, "Effect of heat treated HNT on physico-mechanical properties of epoxy nanocomposites," *Composites Communications*, vol. 13, no. 2, pp. 42–46, 2019.

[35] G. Ravichandran, G. Rathnakar, N. Santhosh, R. Chennakeshava, and M. A. Hashmi, "Enhancement of mechanical properties of epoxy/halloysite nanotube (HNT) nanocomposites," *SN Applied Sciences*, vol. 1, no. 4, p. 296, 2019.

[36] H. G. Anilthota and B. A. Praveena, "Processing and characterization of green composites using sisal and palm fibers," *International Journal of Engineering Science and Computing IJESC*, vol. 7, no. 1, pp. 4262–4265, 2017.

[37] M. Korisidda, C. Prasad, B. C. Mahantesh, S. S. Sheregar, and B. Praveena, "Study on mechanical properties of bio-composites," *International Journal for Scientific Research & Development*, vol. 6, no. 2, pp. 1–5, 2018.

[38] B. A. Praveena, S. V. Kumar, H. N. Manjunath et al., "Investigation of moisture absorption and mechanical properties of natural fibre reinforced polymer hybrid composite," *Materials Today Proceedings*, vol. 45, part 9, pp. 8219–8223, 2021.

[39] S. G. Aftab, A. Faisal, H. Hussain, B. Sreedhara, N. R. Babu, and B. A. Praveen, "Structural analysis of human femur bone to select an alternative composite material," *Materials Today Proceedings*, vol. 54, pp. 141–146, 2022.

[40] S. P. S. Yadav, V. K. Shankar, L. Avinash et al., "Development of 3D printed electromyography controlled bionic arm, sustainable machining strategies for better performance," in *Lecture Notes in Mechanical Engineering*, Springer, Singapore, 2021.

[41] Z. Zhang, Y. Li, and C. Chen, "Synergic effects of cellulose nanocrystals and alkali on the mechanical properties of sisal fibers and their bonding properties with epoxy," *Composites Part A: Applied Science and Manufacturing*, vol. 101, pp. 480–489, 2017.

[42] C. C. Wang, H. T. Cheng, Y. Xian, G. Wang, and S. B. Zhang, "Improving dynamic mechanical property of bamboo pulp fiber reinforced epoxy resin composite treated by nano calcium carbonate," *Transactions of the Chinese Society of Agricultural Engineering*, vol. 33, pp. 281–287, 2017.

[43] N. Saba, M. Jawaid, O. Y. Alothman, M. Paridah, and A. Hassan, "Recent advances in epoxy resin, natural fiber-reinforced epoxy composites and their applications," *Journal of Reinforced Plastics and Composites*, vol. 35, pp. 447–470, 2015.

[44] V. Mittal, R. Saini, and S. Sinha, "Natural fiber-mediated epoxy composites - a review," *Composites. Part B, Engineering*, vol. 99, pp. 425–435, 2016.

[45] G. Wang, H. T. Cheng, S. H. Gu, C. C. Wang, and W. F. Zhang, "Classification and application status of bamboo profile," *China For. Prod. Ind.*, vol. 45, pp. 1–5, 2018.

[46] X. Gao, D. Zhu, S. Fan, Md. Z. Rahman, S. Guo, and F. Chen, "Structural and mechanical properties of bamboo fiber bundle and fiber/bundle reinforced composites: a review," *Journal of Materials Research and Technology*, vol. 19, pp. 1162–1190, 2022.

[47] Z. X. Yu, Z. H. Jiang, G. Wang, W. F. Zhang, and F. M. Chen, "Mechanical properties of laminated bamboo scrimber in hygrothermal environment," *Journal of Central South University of Technology*, vol. 32, pp. 127–130, 2012.

[48] W. L. Ngo, M. M. Pang, L. C. Yong, and K. Y. Tshai, "Mechanical properties of natural fibre (Kenaf, oil palm empty fruit bunch) reinforced polymer composites," *Advances in Environmental Biology*, vol. 8, no. 8, pp. 2742–2747, 2014.

[49] D. S. Santosh Kumar, B. A. Praveen, S. Kiran Aithal, and K. Un, "Development of pineapple leaf fiber reinforced epoxy

resin composites," *International Research Journal of Engineering and Technology*, vol. 2, no. 3, pp. 2190–2193, 2015.

[50] B. A. Praveena, B. Abdulrajak, N. Santhosh, V. V. Kedambadi, H. Jaibheem, and D. Huliya, "Study on characterization of mechanical, thermal properties, machinability and biodegerability of natural fiber reinforced polymer composites and its applications, recent developments and future potentials: a comprehensive review," *Material today proceedings*, vol. 52, Part 3, pp. 1255–1259, 2021.

[51] C. Wang, L. M. Smith, G. Wang, S. Q. Shi, H. Cheng, and S. Zhang, "Characterization of interfacial interactions in bamboo pulp fiber/high-density polyethylene composites treated by nano $CaCO_3$ impregnation modification using fractal theory and dynamic mechanical analysis," *Industrial Crops and Products*, vol. 141, p. 111712, 2019.

[52] B. Praveen, S. U. Abhishek, P. B. Shetty, J. Sudheer Reddy, and B. A. Praveena, "Industry 4.0 researchers computer numerical control machine tool to manufacture calligraphy board," in *Emerging Research in Computing, Information, Communication and Applications. Lecture Notes in Electrical Engineering*, N. R. Shetty, L. M. Patnaik, H. C. Nagaraj, P. N. Hamsavath, and N. Nalini, Eds., vol. 790, Springer, Singapore, 2022.

[53] S. Nagaraja, P. Bindiganavile Anand, R. N. Mahadeva Naik, and S. Gunashekaran, "Effect of aging on the biopolymer composites: mechanisms, modes and characterization," *Polymer Composites*, vol. 43, no. 5, pp. 1–11, 2022.

[54] X. Wang, Z. Yuan, X. Zhan et al., "Multi-scale characterization of the thermal - mechanically isolated bamboo fiber bundles and its potential application on engineered composites," *Construction and Building Materials*, vol. 262, no. 10, p. 120866, 2020.

[55] F. Yang, S. Q. Zhang, Y. M. Cui et al., "Durability issues in promoting the application of bamboo winding composites," *Wood Processing Machinery*, vol. 29, no. 5, pp. 34–37, 2018.