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Characterization of Bamboo Petung Fiber Reinforced Composites with Environmentally Friendly Enzymes

Rudianto Raharjo[1]*, Teguh Dwi Widodo[1], Redi Bintarto[1], Fikrul Akbar Alamsyah[2]

[1]Mechanical Engineering Department, Brawijaya University, Jl. MT Haryono167, Malang, 65145, Indonesia
[2]Department of Mechanical and Electro-Mechanical Engineering, National Sun Yat-Sen University, No. 70 Lien-hai Rd, Kaohsiung, 804, Taiwan
**Corresponding author:rudiantoraharjo@ub.ac.id*

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ABSTRACT

Natural fiber composites are a good choice for many businesses uses because of their better mechanical properties and are friendly environment. Researchers are currently looking into bamboo petung fiber (BPF) and epoxy composites as alternative to synthetic fibers and products made from petroleum. This study's goal is to improve the overall performance of these composites while reducing the need for non-organic materials. This study used the various concentration of bromelain enzyme in BPF to changes the mechanical and physical properties of epoxy composites made from BPF. Composites were characterized the mechanical properties including tensile strength using tensile tester, impact strength using Charpy impact test, bending strength using three point bending methods, and surface morphology observation using scanning electron microscope. This study indicates that BPF composites that have been treated with bromelain enzyme have better mechanical properties. After being treated with bromelain, the BPF composite's tensile strength increase up to 59% with maximum tensile strength of 138.230 MPa, flexural strength increases up to 42% with maximum flexural strength of 135.58 MPa, and impact strength increases up to 64% with maximum impact strength of 4.88 J/m. The bond between the epoxy resin and the BPF makes the composite stronger. These results suggest that combining natural fibers and enzymes can make composite materials that work well and are strong.

Keywords: *BPF, bromelain enzyme, strength, composite*

I. Introduction

Polymer composites face challenges like thermal stability, electrical conductivity, drilling flaws, and recycling issues. Eco-design, life cycle assessment, and circular economy strategies can address these issues by understanding the Carbon Fiber Reinforced Polymer (CFRP) microstructure [1]. Epoxy resin's strong adhesion, high compatibility, and design flexibility make it the material of choice for advanced polymer composite applications [2]. Because of their three-dimensional network structure, epoxy resins are brittle, which leads to low fault tolerance and fracture propagation [3]. Researchers are employing methods such as high-branched silicone epoxy resin synthesis, spatial mechanical property variation, polyurethane toughening, and hydroxyl-functionalized block co-polyimide to increase the toughness of epoxy resin [4].

In order to improve the mechanical, thermal, rheological, viscoelastic, and fire resistance properties of polymers, inorganic fillers like boron nitride, halloysite nanotubes, and nano clay are utilized. Degradation is influenced by variables such as filler type, loading,

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dispersibility, and surface functionalization [5]. Environmental problems caused by synthetic fibers include contamination, the release of hazardous chemicals, and the accumulation of microplastics. As a result, there is an increasing need for biodegradable alternatives to reduce waste and pollution [6],[7]. A sustainable, lightweight, and environmentally beneficial substitute for synthetic fibers are natural plant fibers such as curaua, kenaf, jute, hemp, flax, and bamboo [8]. Natural plant fibers are more cost-effective, renewable, and have a higher specific strength and modulus than synthetic fibers. Because of their properties, natural plant fibers are a good choice for a variety of applications, particularly when making sustainable and environmentally friendly composite materials [9],[10]. Modern developments in natural fiber composites are characterized by a greater emphasis on sustainability, performance optimization, and environmental impacts. Research and development in this area aims to fully utilize natural plant fibers to create innovative, reasonably priced, and ecologically friendly composite materials for a range of applications [11]. Bamboo fibers are superior to other natural fibers in a number of ways, including their mechanical properties, affordability, environmental sustainability, and versatility for a variety of uses. Bamboo fibers are among the natural fiber reinforcements that work particularly well in polymer composite materials. As evidenced by the extensive research and development in this field, bamboo fibers have the potential to be a significant reinforcement material for composite materials [12].

The study of bamboo fiber-modified polymer composites improves knowledge of preparation methods and possible applications by examining morphological, mechanical, flexural, and reinforcement properties, surface modification, rigid packaging applications, fiber treatment, and nano clay impacts [12],[13]. The results of studies on bamboo fibers in polymer composites are encouraging. It investigates mechanical, thermal, and morphological aspects in addition to thermoset and thermoplastic properties. Surface treatments influence the behavior and properties of crystallization, indicating improved mechanical qualities and heat tolerance [14]. Inorganic particles at the nanoscale enhance adhesion and compatibility by improving interface interaction with epoxy resin matrices. Epoxy resin can be used in many different applications because of its ability to transmit stress, strengthen structures, prevent cracks from spreading, and improve mechanical and thermal properties [15].

Enzymatic retting is an environmentally friendly process that effectively extracts fiber from bamboo plants by using enzymes to break down the pectin. This technique preserves the natural fiber structure while reducing wastewater and enhancing fiber quality [16]. Enzymatic treatments improve the ease of extraction by changing the chemical makeup of extracted fibers. In order to facilitate fiber isolation, they employ enzymes such as cellulases, hemicellulases, and pectinases to break down adhesive materials. This environmentally friendly process increases the amount of cellulose while reducing effluent and retting time. Understanding enzyme purification and evaluating the quality, consistency, and yield of fibers depend heavily on chemical characterization [17]. The mechanical characteristics of fiber-reinforced composites after enzymatic treatment have not been thoroughly studied.

Few studies have included treated bamboo fibers, particularly to evaluate their mechanical properties, despite the fact that bamboo fiber-reinforced composites have been the subject of much research [18]. Previous studies have mostly looked at composites reinforced with only bamboo fibers treated with alkalizing, an environmentally unfriendly technique. Petung bamboo fiber composites also have potential, but there has been insufficient research on using bromelain enzyme to improve mechanical properties. The main objective of this study was to determine the mechanical properties of epoxy-based composites reinforced with bamboo petung fibers (BPF). This study aimed to determine how the concentration of bromelain enzyme affects the tensile strength, bending strength, and impact strength. In addition to mechanical testing, the fiber-matrix bond of the composites was assessed using a scanning electron microscope (SEM). The results of this study are expected to improve the existing knowledge on sustainable biocomposites by providing a better understanding of how natural fibers work synergistically with natural enzymes. The stringent requirements of the automotive, aerospace, and marine engineering industries, which often face high stress and wear conditions, can be met by successfully fabricating lightweight, high-performance composites using these materials.

II. Material and Methods

Material

The petung bamboo variety, which is a member of the Dendrocalamus asper species, was procured from Dalisodo Village in Wagir District, Malang, Indonesia. This town is about 715 meters above sea level and is located on a plateau. The fiber was taken from dry, fully grown bamboo stems that were six to seven years old. BPF were generated through the mechanical process of extracting the fibers by means of cutting tools, while simultaneously separating the sections using saws.

Polyester resin with a density of $1.2 \times 10{-}6$ kg/cm^3, a tensile strength of 8.8 kg/mm^2, and a viscosity of 6–8 P (at 25 °C) is supplied by Justus Kimia Raya (Surabaya, Indonesia). Methyl ethyl ketone peroxide is the catalyst utilized in this investigation. The treatment and its notation are displayed in Table 1.

Table 1. Study notation

No	Treatment	Notation
1	No Treatment	UBC
2	Bromelain 2g	2BC
3	Bromelain 5g	5BC
4	Bromelain 8g	8BC
5	Bromelain 11g	11BC

Bromelain Extraction and Treatment of BPF

The pretreatment process for BPF uses several tools, namely measuring cups and digital scales. If the equipment has been prepared, then make a bromelain enzyme solution with 1000 mL of distilled water as a bromelain enzyme solvent with a predetermined concentration, namely: 0, 2, 5, 8, and 11 g. Then, the bromelain enzyme solution and fiber are added to the ultrasonic cleaner according to the specified variations. After inserting, set the temperature on the ultrasonic cleaner to 60°C for 45 min. Once finished, lift the specimen, remove the fibers, and dry them in the oven for 15 min at a temperature of 110°C. The dried fibers are made into a composite for mechanical testing and SEM analysis.

Composite

The scheme of vacuum-assisted resin transfer molding can be seen in Figure 1, where the resin in the resin container is sucked in by a vacuum pump so that it can pass through or fill the mold cavity that has been given BPF and form a specimen.

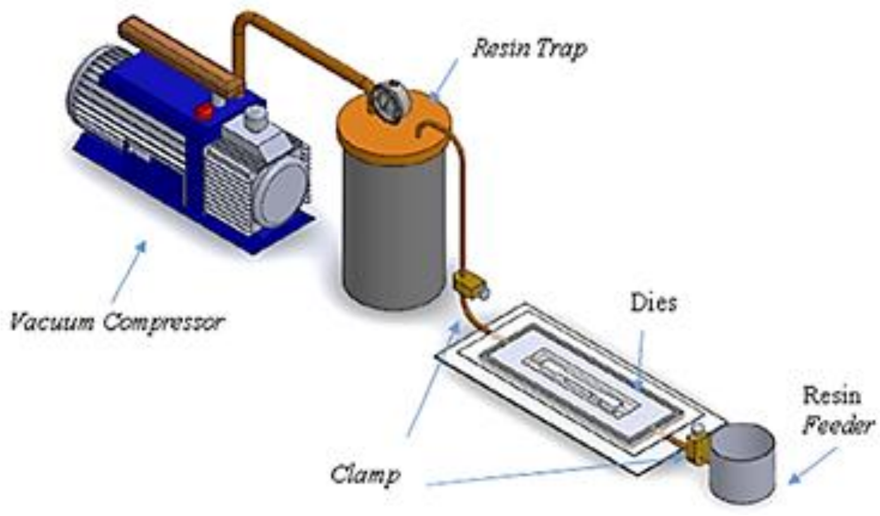

Fig. 1. Material preparation procedure

Tensile Testing

A Universal Testing Machine was used to perform the tensile test on the produced BPF-reinforced epoxy composite samples at room temperature (25 °C) in compliance with the ASTM D638-Type I standard[19]. Each composite was tested on five specimens. The standard deviation is provided along with the average values for tensile strength and tensile modulus.

SEM Analysis

SEM was used to examine the extracted specimens' surface morphology following bromelain treatment. The EDAX Model Inspect S-50 FEI, a SEM device that used thermal emission electron optics to provide high-resolution data, was utilized in these investigations.

Impact Testing

The epoxy matrix BPF composite was tested with an ASTM D6110-compliant Charpy impact test [20]. In testing specimens, the specimen is placed on a support in a horizontal position, and the direction of loading is opposite to the direction of the notch. Each composite was tested on five specimens. Standard deviations and the average impact strength are provided.

Flexural/Bending Testing

A flexural test was performed on the composite material to ascertain its flexural strength. The maximum bending stress that can be applied as a result of external loading without causing damage is known as flexural strength. The type of material determines the amount of bending strength. The specimen undergoes tensile stress at the bottom and pressure at the top as a result of the bending test. The compressive strength of composite materials is greater than the tensile strength. The specimen will shatter as a result of its inability to sustain the tensile stress, failing the composite test. The bending strength on the top side is the same as the bending strength on the bottom side. Testing was carried out using the three-point bending method with the ASTM D790 standard [21]. The test is carried out on five samples each time it is run, and the average is used as the final result.

III. Results and Discussions

Morphology

Figure 2a shows an SEM image of the UBC composite. It can be observed on bamboo-enhanced composites without visible treatment of bamboo fibers, and the epoxy matrix cannot bind properly because there is still a natural substrate that BPF, so when the composite is given a pulling load, it cannot channel into the fiber properly, so the appearance of failure begins on the epoxy matrix because it cannot withstand high loads [22]. The failure resulted in the rupture of bamboo fiber-enhanced composites without treatment with long pull-out fibers.

A SEM image of the 2BC composite's fracture surface is displayed in Figure 2b. Because the adhesion between the fiber and the epoxy matrix is still insufficient, and because the addition of treatment concentrations is insufficient to maximize the mechanical properties of the natural fiber in the composite for the given load, visible fiber pull-out occurs [23]. In this case, a decrease in the pull-out fiber occurs as a result of the treatment given, which is capable of scratching the natural matrix of BPF, thus increasing the stiffness on the surface of the BPF and affecting its adhesive properties.

A SEM image of the 5BC composite's fracture surface is displayed in Figure 2c. It can be observed that there are still holes between the bamboo fiber and the epoxy matrix, represented by fibers that are visibly separated from the other fractures. The fiber is pulled out because the bonds formed between the bamboo fiber and the epoxy matrix are not at their maximum. But the fiber pull-out that happened at the 5BC break is a little bit. A reduction in the fiber pullout, in this case, occurs as a result of the given treatment, which is capable of scratching the natural matrix of the bamboo fiber of the cage, thus increasing the stiffness on the surface of the bamboo fibers of the cage, which affects its adhesive properties [24]. The fiber's excellent formation is evident from the contact between it and the epoxy matrix.

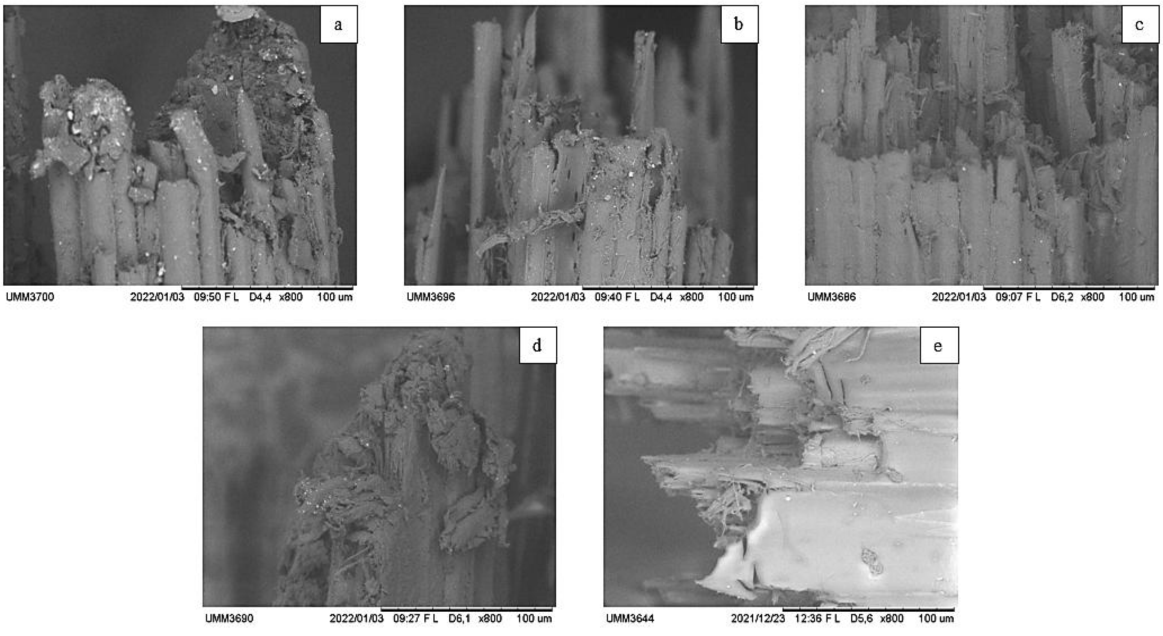

Fig. 2. Surface morphologies of the specimen: a. UBC; b. 2BC; c. 5BC; d. 8BC; e. 11BC

Figure 2d shows an SEM image of the fracture surface of the 8BC composite. It can be observed that there are still holes between the bamboo fiber and the epoxy matrix, represented by the fibers that are visible and separated from the other fractures. The fiber is pulled out because the bonds formed between the bamboo fiber and the epoxy matrix are not at their maximum. But the fiber pull-out that happens at the 8BC break is very little. A reduction in the fiber pullout, in this case, occurs as a result of the given treatment capable of scratching the natural matrix of the BPF, thereby increasing stiffness on the surface of the bamboo fibers of the container, which affects its adhesive properties. The rigidity increases the adhesive properties of the bamboo fiber so that the contact between the fiber and the epoxy resin is excellent because the addition of the treatment concentration is able to break the peptide bond faster and better [25], thereby reducing the lignin and other content in the fiber and thus producing better surface rigidities in the fibers.

Figure 2e shows an SEM image of the rupture surface of the 11BC composite. It can be observed that the holes found at 11BC have decreased considerably and are almost nonexistent. The very low presence of pull-out fiber on this composite occurs as a result of the treatment given, which scrapes the natural matrix of bamboo fibers from the covers, thus increasing the roughness on the surface of the BPF, which affects its adhesive properties [26]. It can be seen from the contact between the fiber and the epoxy matrix that it formed very well.

The fibers and matrix are shown to have strong bonds in Figure 2. It is known that the hydrogen bonding between BPFs and the polymer matrix interface improves the composite's tensile strength[27]. The lack of this interaction is known and explained by the hydrophobic epoxy properties combined with the hydrophilic properties of bamboo fibers. Bromelain adhesion enhancement process: When water and the bromelain enzyme produce negative and positive ions. As anions, positive ions break hydrogen bonds between the hydroxyl functional groups (OH) in BPF by releasing two hydrogens, creating dipole forces. As cations, negative ions emit oxygen (O), which breaks the hydroxyl functional group and produces H_2O. The petung bamboo fiber's surface changes due to this reaction. Bromelain modification is known to make the stain surface rougher because the stain is firmly embedded in the epoxy matrix and evenly distributed in the epoxy matrix, so mechanical interlocking occurs. The modification of bromelain is known to make the stain surface rougher because the stains are strongly embedded in the epoxy matrix and are evenly dispersed within the epoxy matrix. Thus, this composite shows fiber damage compared to withdrawal, which indicates a better tensile strength transfer between the bamboo fiber cushion and the epoxy matrix [28]. In addition, there are several connections and splinters on the composite surfaces, which indicate improved compatibility between epoxy and modified fibers [29]. Therefore, when such a composite is pressed, the fiber will not be easily drawn out of the matrix [30]. Thus, the attractive properties of the epoxy fiber composite petung bamboo modified with bromelain can be enhanced.

Tensile Strengths of BPF-Reinforced Composites

The composite with bamboo fiber fittings as reinforcement exhibits a tendency to increase in tensile strength, as seen in Figure 3. The increase started with the untreated fiber-enhancing composite and then continued with the fiber-enhanced composite with the immersion treatment at an enzyme concentration of bromelain of 11 gr/L (11BC). Of the five samples of each composite, the highest tensile strength value obtained in each composite starts from UBC with the highest value of 87.4 MPa and an average tensile strength value of 77.981 MPa, 2BC with the highest value of 96.93 MPa, 5BC of 100.838 MPa, 8BC of

123.537 MPa, and 11BC of 138.23 MPa, with an average tensile strength value of 92.186 MPa, 99.919 MPa, 113.785 MPa, and 131.006 MPa.

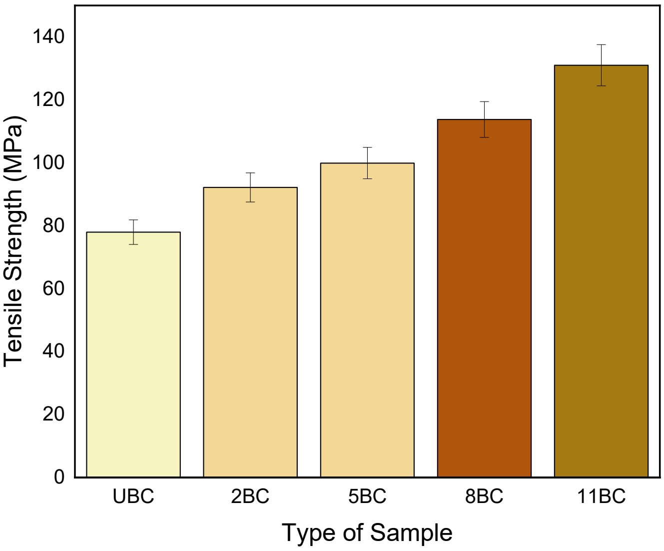

Fig. 3. Tensile strength of BPF-reinforced composite

Fiber delivery as a reinforcement serves to repair the structure and properties of a previously non-existent matrix so that it can withstand a larger force [31]. The epoxy matrix has a low drawing strength value, which results in a low resistance value even in cracking and breaking [32]. Composites made with treated bamboo fiber can make the substrate less hydrophobic, increase the surface stiffness, permeability, and spreading rate, and decrease the fiber's contact angle [33]. The tensile strength of untreated bamboo fiber composite and bamboo fiber composite that performs immersion with variations in bromelain enzyme concentration using an ultrasonic cleaner also shows an increase in tensile force value. The tendency present on the graph is due to the treatment received by the reinforcement; in this case, the amplifier is a BPF. Figure 3 shows that composites reinforced with untreated fibers exhibit the lowest tensile strength compared to those with treated fibers. The substance in the bamboo fiber that hasn't yet broken down is causing it. Substances such as lignin, hemicellulose, candles, and so on cover and block the fiber's surface. This will eventually result in the fiber being unable to bind properly to the epoxy matrix because the surface still contains its natural resin. The tensile strength values increase when bamboo fiber-rich composites are treated with bromelain enzymes for enzymatic delignification. This makes the fiber's surface rougher so that the bond between the epoxy matrix and the bamboo fiber is better. Increased tensile strength of bamboo fiber composites immersed in bromelain enzyme treatment. This happened because some of the natural substances on the fiber's surface were reduced, which led to an increase in the tensile force and a higher ratio of cellulose to the substrate [34]. The increase in enzyme concentration accelerates the enzyme-substrate reaction, making it easier to break down the substances adhering to the fiber surface [35]. However, at the time of application to the composite, the bamboo-matrix fiber bonding interaction improved.

Stress-Strain Test Results of BPF Reinforced Composite

Figure 4 displays the stress and strain levels of the bamboo fiber-rich composite test that had not been treated and had been treated with bromelain enzymes using ultrasonic cleaners. The maximum stress at 11BC is 138.230 MPa, and the lowest at UBC is 87.40

MPa. Furthermore, the maximum stress at 2BC is 96.93 MPa, at 5BC is 100.838 MPa, and at 8BC is 123.537 MPa._The maximum stress for the UBC is 87.40 MPa, with a strain of 15.707%. The elasticity modulus value is 0.556 GPa. The maximum stress for the 2BC is 96.93 MPa, and the strain is 17.164%. The elasticity modulus value is 0.564 GPa. The maximum strain for the 5BC is 100.84 MPa, with a strain of 18.613%. The elasticity modulus value is 0.06 GPa, and the maximum stress is 138.23 MPa for the 11BC, with a strain of 19.57.

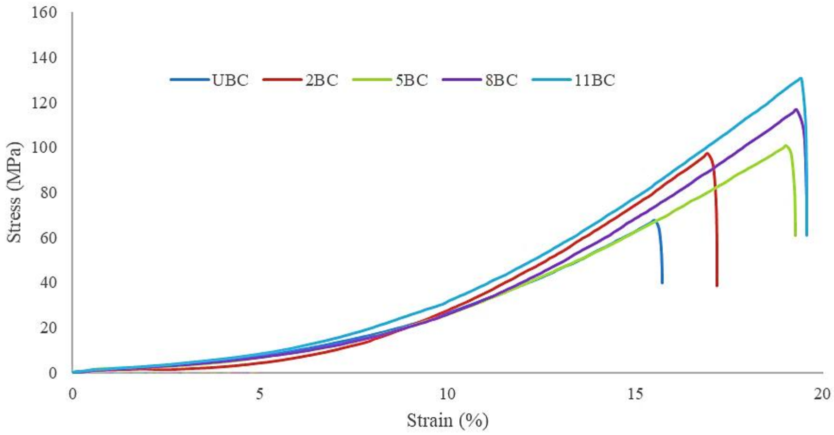

Fig. 4. Tensile test stress and strain of BPF-reinforced composite

The cellulose fibers' elasticity modulus within the bamboo's fibrous structure is a major factor in determining the tensile capacity of the bamboo composite. When bamboo fibers were exposed to different amounts of the bromelain enzyme, it was seen that higher enzyme amounts increased the cellulose fiber to lignin ratio. This increase is believed to occur because bamboo fibers are more rigid than epoxy fibers, thereby altering the micro-composite structure developed [36]. Furthermore, another cause of the increased composite rigidity of bamboo epoxy fibers is the reduced mobility of the polymer chain in the presence of BPFs. Other researchers also found similar increases in Young's modulus for epoxy composites, where natural fibers were used as reinforcement [37],[38].

Bending and Impact Strength

Figure 5a displays a flat plot of the bending strength of bamboo fiber composites made with an epoxy matrix, where the fiber variation was considered. It can be seen that the composite with the bromelain enzyme 0 g in bamboo fiber has a bending strength value of 58.49 MPa. However, there is a significant increase as the concentration of bromelain enzymes increases in the 2, 5, 8, and 11 g enzyme variations. The bending strength increased successively from 73.38 to 135.58 MPa

Figure 5b illustrates the impact strength of bamboo fiber composites with an epoxy matrix under applied force. Initially, the UBC showed a bending strength of about 3.15 J/m. However, there was a striking increase in the strength of the composite with increased concentrations of the enzyme bromelain. At 2BC, the composite’s impact strength was 3.61 J/m. At 5BC, it reached 3.668 J/m, increasing to 4.438 J/m at 8BC and 4.88 J/m at 11BC.

Researchers tested bamboo fibers for bending and impact and found that adding more of the bromelain enzyme made them much stronger [39]. This means that the composite is more resistant. This is due to a decrease in the amorphous phase of lignin, which increases its mechanical properties. From the graph, it can be seen that the more bromelain enzymes are given to the fiber, the composite has an increase than those without the bromelain enzyme. This is due to the presence of an enzymatic delignification treatment of the fiber. It is one of the proteolytic enzymes that contains proteases that can break down the peptide bond in a protein into a simpler substrate [40]. So, higher lignin levels lead to greater weight loss in the fiber [41].

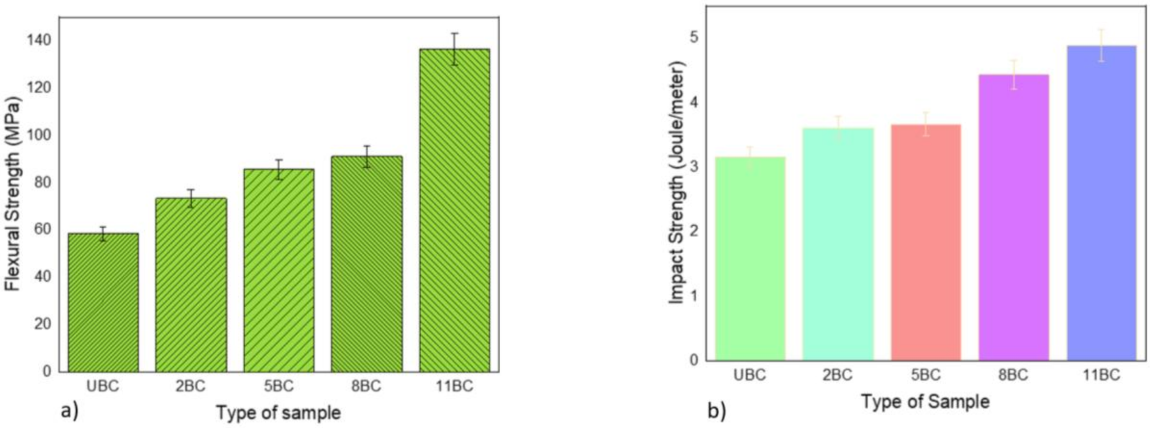

Fig. 5. (a) Flexural/bending strength, (b) Impact strength

IV. Conclusions

This study used BPF treated with bromelain enzyme as a reinforced composite. The mechanical properties of the epoxy resin matrix and BPF composite demonstrate how the mechanical properties of the matrix are greatly enhanced by BPF treated with bromelain. There is a large strengthening effect associated with this. The concentration of bromelain enzyme 11% has the highest mechanical properties in this bamboo petung fiber composite, with a tensile strength reaching 131 MPa, a bending strength of 135.58 MPa, and an impact strength of 4.88 J/m. After applying bromelain treatment, the tensile strength of the BPF composite increased significantly by 59%, the flexural strength by 42%, and the impact strength by 64%. The bond between the epoxy resin and BPF increases the composite's strength. The bond that occurs is mechanical interlocking and is strengthened by hydrogen and Van der Waals forces. According to this study, bromelain can be added to BPF to increase the strength of polymer composites effectively. The biocomposite made can be used for dashboards and other automotive parts. Future research may consider new approaches, including processing different types of natural enzymes. Plant cellulose fibers can be improved through chemical and physical modifications to improve their mechanical properties. However, further research is still needed to understand biocomposites fully.

References

[1] A. La Rosa, “Grand challenges in resource recovery from polymer composites,” *Journal of Resource Recovery*, vol. 1, no. 1, pp. 0–0, 2023, doi: 10.52547/jrr.2211.1005.

[2] J. Parameswaranpillai, J.A. Gopi, M. Chavali, C.D.M. Dominic, S. Radoor, A. Jayakumar *et al.*, “Advances in epoxy/synthetic/natural fiber composites BT - Handbook of epoxy/fiber composites,” Singapore: Springer Nature Singapore, 2022, pp. 1093–1120. doi: 10.1007/978-981-19-3603-6_52.

[3] A. Shundo, M. Aoki, P. Wang, T. Hoshino, S. Yamamoto, S. Yamada *et al.*, “Effect of a heterogeneous network on the fracture behavior of epoxy resins,”

Macromolecules, vol. 56, no. 11, pp. 3884–3890, Jun. 2023, doi: 10.1021/acs.macromol.3c00341.

[4] R. Zhang, “Research development on the toughness and performance of epoxy resin-based composites in low-temperature environments,” *Applied and Computational Engineering*, vol. 7, pp. 208–213, 2023, doi: 10.54254/2755-2721/7/20230453.

[5] F. Deeba, K. Shrivastava, M. Bafna, and A. Jain, “Tuning of dielectric properties of polymers by composite formation: The effect of inorganic fillers addition,” *Journal of Composites Science*, vol. 6, no. 12, 2022, doi: 10.3390/jcs6120355.

[6] D.S. Stefan, M. Bosomoiu, and M. Stefan, “Methods for natural and synthetic polymers recovery from textile waste,” *Polymers (Basel)*, vol. 14, no. 19, 2022, doi: 10.3390/polym14193939.

[7] Z. Samouh, K. Molnár, S. Hajba, F. Boussu, O. Cherkaoui, and R. El Moznine, “Elaboration and characterization of biocomposite based on polylactic acid and Moroccan sisal fiber as reinforcement,” *Polymer Composite*, vol. 42, no. 8, pp. 3812–3826, Aug. 2021, doi: https://doi.org/10.1002/pc.26095.

[8] J. De Prez, A.W. Van Vuure, J. Ivens, G. Aerts, and I. Van de Voorde, “Effect of enzymatic treatment of flax on fineness of fibers and mechanical performance of composites,” *Composites Part A: Applied Science and Manufacturing*, vol. 123, pp. 190–199, 2019, doi: https://doi.org/10.1016/j.compositesa.2019.05.007.

[9] M. Akter, M.H. Uddin, and I.S. Tania, “Biocomposites based on natural fibers and polymers: A review on properties and potential applications,” *Journal of Reinforced Plastics and Composites*, vol. 41, no. 17–18, pp. 705–742, Feb. 2022, doi: 10.1177/07316844211070609.

[10] V. Ordonez, H. Baykara, A. Riofrio, M. Cornejo, and R. Rodríguez, “Preparation and Characterization of Ecuadorian Bamboo Fiber-Low-Density Polyethylene (LDPE) Biocomposites,” *Evergreen*, vol. 10, no. 1, pp. 43–54, 2023, doi: 10.5109/6781037.

[11] S.I. Hossain, M. Hasan, Md. N. Hasan, and A. Hassan, “Effect of chemical treatment on physical, mechanical and thermal properties of ladies finger natural fiber,” *Advances in Materials Science and Engineering*, vol. 2013, p. 824274, 2013, doi: 10.1155/2013/824274.

[12] L. Osorio, E. Trujillo, A.W. van Vuure, and I. Verpoest, “Morphological aspects and mechanical properties of single bamboo fibers and flexural characterization of bamboo/ epoxy composites,” *Journal of Reinforced Plastics and Composites*, vol. 30, pp. 396–408, 2011.

[13] S. Chattopadhyay, R. Khandal, R. Uppaluri, and A. Ghoshal, “Bamboo fiber reinforced polypropylene composites and their mechanical, thermal, and morphological properties,” *Journal of Applied Polymer Science*, vol. 119, pp. 1619–1626, Feb. 2011, doi: 10.1002/app.32826.

[14] Ş. Yildizhan, A. Çalik, M. Özcanli, and H. Serin, “Bio-composite materials: a short review of recent trends, mechanical and chemical properties, and applications,” *European Mechanical Science*, vol. 2, no. 3, pp. 83–91, 2018, doi: 10.26701/ems.369005.

[15] A. Gharieh, M. Moghadas, and M. Pourghasem, “Synergistic effects of acrylic/silica armored structured nanoparticles on the toughness and physicomechanical properties of epoxy polymers,” *ACS Applied Polymer Materials*, vol. 3, Jul. 2021, doi: 10.1021/acsapm.1c00530.

[16] C.H. Lee, A. Khalina, S.H. Lee, and M. Liu, “A comprehensive review on bast fibre retting process for optimal performance in fibre-reinforced polymer composites,”

Advances in Materials Science and Engineering, vol. 2020, p. 6074063, 2020, doi: 10.1155/2020/6074063.

[17] M. Khlif, R. Chaari, and C. Bradai, "Physico-mechanical characterization of poly (butylene succinate) and date palm fiber-based biodegradable composites," *Polymers and Polymer Composites*, vol. 30, p. 096739112210801, Mar. 2022, doi: 10.1177/09673911221080157.

[18] S. Han, X. Chen, F. Chen, Z. Lou, X. Ren, H. Ye, and G. Wang, "Sustainable high-strength and dimensionally stable composites through in situ regulation and reconstitution of bamboo-derived lignin and hemicellulose contents," *International Journal of Biological Macromolecules*, vol. 267, p. 131595, May 2024, doi: 10.1016/j.ijbiomac.2024.131595.

[19] S.S. Raj, A. Kuzmin, K. Subramanian, and S. Sathiamoorthyi, "Philosophy of selecting ASTM standards for mechanical characterization of polymers and polymer composites," *Materiale Plastice*, vol. 58, no. 3, pp. 247–256, October 2021, doi: 10.37358/MP.21.3.5523.

[20] ASTM, "Standard test method for determining the charpy impact resistance of notched specimens of plastics 1," no. April, 2010, doi: 10.1520/D6110-10.1.

[21] Annual book of ASTM Standard, "ASTM D882-88: Standard methods for tensile properties of thin plastic sheeting," 1989.

[22] L. Karthikeyan, M. Pan, N. Wanders, D.N. Kumar, and E.F. Wood, "Four decades of microwave satellite soil moisture observations: Part 1. A review of retrieval algorithms," *Advances in water resources*, vol. 109, pp. 106–120, 2017, doi: https://doi.org/10.1016/j.advwatres.2017.09.006.

[23] M. Jacob, S. Thomas, and K.T. Varughese, "Mechanical properties of sisal/oil palm hybrid fiber reinforced natural rubber composites," *Composites Science and Technology*, vol. 64, no. 7, pp. 955–965, 2004, doi: https://doi.org/10.1016/S0266-3538(03)00261-6.

[24] I. Mohammed, A.R.A. Talib, M.T. Sultan, M. Jawaid, A.H. Ariffin, and S. Saadon, "Mechanical properties of fibre-metal laminates made of natural/synthetic fibre composites," *Bioresources*, vol. 13, no. 1, pp. 2022–2034, 2018, doi: 10.15376/biores.13.1.2022-2034.

[25] A. Pelletier, K. Li, Y. Zhao, G. Court, J. Luo, and M. Frith, "Improvement of enzyme transport in wood chips for thermomechanical pulp refining," *Carbohydrate Polymer*, vol. 95, no. 1, pp. 25–31, Jun. 2013, doi: 10.1016/J.CARBPOL.2013.02.025.

[26] M. Mohammed, R. Rahman, A. Mohammed, A. Osman, T. Adam, O. Dahham *et al.*, "ZnO NP composites," *Bioresources*, vol. 13, no. 3, pp. 6480–6496, 2018.

[27] R. Liu, Y. Peng, and J. Cao, "Thermal stability of organo-montmorillonite-modified wood flour/poly(lactic acid) composites," *Polymer Composite*, vol. 37, no. 7, pp. 1971–1977, Jul. 2016, doi: https://doi.org/10.1002/pc.23375.

[28] R. Gunti, A.V. Ratna Prasad, and A.V.S.S.K.S. Gupta, "Mechanical and degradation properties of natural fiber-reinforced PLA composites: Jute, sisal, and elephant grass," *Polymer Composite*, vol. 39, no. 4, pp. 1125–1136, Apr. 2018, doi: https://doi.org/10.1002/pc.24041.

[29] H. Wang, E.A.M. Hassan, H. Memon, T.H.H. Elagib, and F.A. AllaIdris, "Characterization of natural composites fabricated from abutilon-fiber-reinforced poly (lactic acid)," *Processes*, vol. 7, no. 9, 2019, doi: 10.3390/pr7090583.

[30] M. Zahedi, T. Tabarsa, A. Ashori, M. Madhoushi, and A. Shakeri, "A comparative study on some properties of wood plastic composites using canola stalk, Paulownia,

and nanoclay," *Journal of Applied Polymer Science*, vol. 129, no. 3, pp. 1491–1498, Aug. 2013, doi: https://doi.org/10.1002/app.38849.

[31] L.Y. Mwaikambo and M.P. Ansell, "Chemical modification of hemp, sisal, jute, and kapok fibers by alkalization," *Journal of Applied Polymer Science*, vol. 84, no. 12, pp. 2222–2234, Jun. 2002, doi: https://doi.org/10.1002/app.10460.

[32] F.M. Zhao and N. Takeda, "Effect of interfacial adhesion and statistical fiber strength on tensile strength of unidirectional glass fiber/epoxy composites. Part I: experiment results," *Composites Part A: Applied Science and Manufacturing*, vol. 31, no. 11, pp. 1203–1214, Nov. 2000, doi: 10.1016/S1359-835X(00)00085-3.

[33] A.A. Salih, R. Zulkifli, and C.H. Azhari, "Tensile properties and microstructure of single-cellulosic bamboo fiber strips after alkali treatment," *Fibers*, vol. 8, no. 5, p. 26, 2020. doi: 10.3390/fib8050026.

[34] E. Jayamani, S. Hamdan, K.H. Soon, M.R. Rahman, M.K.B. Bakri, and A. Kakar, "The effect of natural fibres mercerization on natural fibres/polypropylene composites: A study of thermal stability, morphology and infrared spectrum," *Australian Journal of Basic and Applied Sciences*, vol. 8, no. 15, pp. 332–340, 2014.

[35] K. Dome, E. Podgorbunskikh, A. Bychkov, and O. Lomovsky, "Influence of mechanical treatment on the crystalline structure of pea starch", *AIP Conference Proceeding*, vol. 2390, No. 030013, 2022. doi: 10.1063/5.0069197.

[36] A. Orue, A. Jauregi, U. Unsuain, J. Labidi, A. Eceiza, and A. Arbelaiz, "The effect of alkaline and silane treatments on mechanical properties and breakage of sisal fibers and poly(lactic acid)/sisal fiber composites," *Composites Part A: Applied Science and Manufacturing*, vol. 84, pp. 186–195, 2016, doi: https://doi.org/10.1016/j.compositesa.2016.01.021.

[37] M.Z. Hassan, S.M. Sapuan, S.A. Roslan, S.A. Aziz, and S. Sarip, "Optimization of tensile behavior of banana pseudo-stem (Musa acuminate) fiber reinforced epoxy composites using response surface methodology," *Journal of Materials Research and Technology*, vol. 8, no. 4, pp. 3517–3528, 2019, doi: https://doi.org/10.1016/j.jmrt.2019.06.026.

[38] H.A. Aisyah, M. Paridah, S. Sapuan, A. Khalina, O. Berkalp, S. Lee *et al.*, "Thermal properties of woven Kenaf/Carbon fibre-reinforced epoxy hybrid composite panels," *International Journal of Polymer Science*, vol. 2019, p. 5258621, 2019, doi: 10.1155/2019/5258621.

[39] S. Mouhoubi, M. Bourahli, H. Osmani, and S. Abdeslam, "Effect of alkali treatment on alfa fibers behavior," *Journal of Natural Fibers*, pp. 1–11, Oct. 2016, doi: 10.1080/15440478.2016.1193088.

[40] L.C. de L. Novaes, A.F. Jozala, A.M. Lopes, V. de C. Santos-Ebinuma, P.G. Mazzola, and A.P. Junior, "Stability, purification, and applications of bromelain: A review," *Biotechnology Progress*, vol. 32, no. 1, pp. 5–13, 2016, doi: 10.1002/btpr.2190.

[41] S.L. Sun, J.L. Wen, M.G. Ma, R.C. Sun, and G.L. Jones, "Structural features and antioxidant activities of degraded lignins from steam exploded bamboo stem," *Industrial Crops and Products,* vol. 56, pp. 128–136, May 2014, doi: 10.1016/J.INDCROP.2014.02.031.