



MECHANICAL PERFORMANCE AND FRACTURE MORPHOLOGY OF BAMBOO CELLULOSE NANOFIBER REINFORCED PLA COMPOSITES FOR 3D PRINTING APPLICATIONS

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ABSTRACT

This study reports the development and mechanical characterization of polylactic acid (PLA) reinforced with bamboo cellulose nanofibers (BCNFs) for 3D printing applications. Composite filaments containing 1–5 wt.% BCNFs were fabricated and systematically evaluated for tensile strength, microhardness, impact resistance, and fracture morphology. The results demonstrated a strong dependence of mechanical performance on nanofiber loading. Neat PLA exhibited a tensile strength of 78.21 MPa, which increased progressively with nanofiber addition, reaching a maximum of 112.76 MPa at 3 wt.% BCNF, representing a 44.2% improvement. Similarly, microhardness values improved markedly, with the optimum composition exhibiting a 162.5% increase over neat PLA. Impact resistance followed the same trend, with energy absorption enhanced by 116% at 3 wt.% BCNF. However, at higher loadings (4–5 wt.%), mechanical properties declined due to fiber agglomeration and poor dispersion. SEM analysis of fracture surfaces confirmed these trends, revealing brittle fracture in neat PLA, rough and fibrous morphologies with effective crack deflection at 3 wt.%, and clustered fiber bundles acting as stress concentrators at 5 wt.%. These findings establish 3 wt.% BCNF as the optimum loading for balancing strength, toughness, and hardness, underscoring the potential of bamboo nanocellulose as a sustainable reinforcement for high-performance PLA-based 3D printing filaments.



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I. INTRODUCTION

Additive manufacturing (AM) has transformed modern fabrication by enabling the production of complex geometries with reduced material waste and design flexibility. Among the different AM techniques, fused deposition modeling (FDM) has gained widespread adoption due to its cost-effectiveness and compatibility with a range of thermoplastics [1]. Polylactic acid (PLA), a biodegradable polyester synthesized from renewable resources such as corn starch and sugarcane, is the most widely used FDM filament. Its advantages include biodegradability, ease of processing, and good dimensional accuracy during printing. However, neat PLA is limited by its inherent brittleness, low impact resistance, and poor thermal stability, which restrict its use in engineering-grade and structural applications [2], [3]. To address these drawbacks, researchers have explored reinforcement of PLA with natural fibers, nanofillers, and biodegradable additives. Among these, nanocellulose has emerged as one of the most promising reinforcing agents owing to its outstanding properties such as high aspect ratio, large surface area, low density, biocompatibility, and biodegradability [4].

Nanocellulose exists primarily in two forms: cellulose nanocrystals (CNCs) and cellulose nanofibers (CNFs). CNFs, in particular, offer a flexible entangled network with high tensile modulus (up to 170 GPa) and crystallinity values between 50–90%, enabling superior reinforcement in polymer matrices [5], [6]. Additionally, the abundance of hydroxyl groups on their surfaces allows chemical modifications to improve compatibility with hydrophobic polymers such as PLA [7]. Bamboo has gained attention as an excellent source of CNF due to its high cellulose content, rapid growth rate, and low environmental footprint. Bamboo-derived CNFs exhibit excellent crystallinity, high stiffness, and good thermal resistance, making them suitable for polymer reinforcement [8]. Recent isolation techniques such as TEMPO-mediated oxidation, enzymatic hydrolysis, and high-pressure homogenization have facilitated the production of nanoscale CNFs with enhanced dispersion and reinforcing ability [9]. The incorporation of bamboo CNF into PLA matrices is expected to improve tensile strength, flexural strength, and impact toughness while maintaining printability in FDM [10]. Beyond bamboo, several agricultural residues have also been identified as alternative nanocellulose sources, promoting circular economy and waste valorization. Biomass including oil palm, hemp, jute, agave, sisal, triticale straw, soybean straw, alfa, kenaf, coconut husk, bagasse, corn leaf, and sunflower stalks are rich in cellulose and represent sustainable raw materials for CNF extraction [11]. Rohaizu and Wanrosli successfully isolated nanocellulose from oil palm biomass using sono-assisted TEMPO oxidation, yielding materials with high crystallinity and reinforcing capability [12]. Similarly, Robles et al. demonstrated the extraction of cellulose nanoparticles from blue agave residues using green chemical routes, confirming their potential in biocomposite development [13]. Hemp and jute, with their high cellulose and low lignin content, are widely recognized as efficient feedstocks for nanocellulose, while kenaf and coconut husk have been reported to enhance thermal and mechanical stability in biopolymer composites [14], [15].

Several studies have confirmed the positive effect of nanocellulose incorporation in PLA matrices. Rigotti et al. reported that lauryl-functionalized nanocellulose reinforced PLA composites exhibited enhanced thermo-mechanical stability and reduced gas permeability [16]. Robles et al. demonstrated that surface-modified nanocellulose reinforced PLA significantly improved tensile strength and heat resistance compared to neat PLA [17]. Saba et al. observed that the incorporation of small amounts (1–5 wt.%) of CNF in thermoplastic composites increased tensile and flexural properties without compromising extrusion flow during 3D printing [18]. These findings confirm that cellulose nanofibers act as efficient stress-transfer mediums by restricting crack propagation and enhancing interfacial bonding. Despite these advantages, some challenges remain. High CNF content may cause nozzle clogging, poor interlayer adhesion, and dimensional inaccuracies in FDM printing [19]. Thus, optimization of filler content is essential to balance mechanical improvement and printability. Recent reports suggest that hybrid processing approaches, including surface functionalization of CNFs and melt-blending with compatibilizers, could further improve dispersion and interfacial adhesion [20]. Considering the above, the present study aims to develop and mechanically characterize PLA/nanocellulose composite filaments using bamboo-derived CNFs as the primary reinforcement. Agricultural residues such as oil palm, hemp, jute, agave, sisal, triticale straw, soybean straw, alfa, kenaf, coconut husk, bagasse, corn leaf, and sunflower are highlighted as promising future feedstocks for nanocellulose extraction. The composite filaments will be prepared by solvent-assisted dispersion of CNF into PLA pellets, followed by extrusion using a single-screw filament extruder. Printed test specimens will undergo tensile, flexural, and impact testing, as well as thermal (DSC, TGA) and morphological (SEM) evaluations. It is anticipated that bamboo-derived CNF reinforced PLA composites will provide improved mechanical and thermal stability while retaining FDM printability, thereby offering a sustainable pathway for advanced applications in additive manufacturing.

II. MATERIALS AND METHODS

Materials

PLA is a biodegradable thermoplastic polymer derived from renewable feedstocks such as corn starch and sugarcane. It is widely recognized for its excellent printability, low processing temperature, and dimensional accuracy in fused deposition modeling (FDM). PLA exhibits good stiffness, transparency, and ease of extrusion, making it one of the most commonly used filaments in 3D printing. However, it has limitations such as brittleness, relatively low impact strength, and a low glass transition temperature, which restrict its use in load-bearing and high-temperature applications. The density of PLA typically ranges between 1.20–1.25 g/cm³, with a tensile strength of about 50–70 MPa and a tensile modulus of 2.7–3.5 GPa. These mechanical properties make it a suitable base polymer that can be further enhanced through reinforcement with nanofillers. Bamboo nanocellulose fibers are obtained by breaking down the lignocellulosic structure of bamboo into nanoscale fibrils. These fibers possess exceptional strength, high crystallinity, and a large surface-to-volume ratio, which contribute to their effectiveness as reinforcement materials. The average diameter of bamboo CNFs lies in the range of 20–50 nm, while their length extends to several microns, giving them a high aspect ratio favorable for stress transfer in composites. They are lightweight, biodegradable, and exhibit a tensile modulus up to 100–170 GPa, along with high thermal stability and flexibility. The abundance of hydroxyl groups on their surface enhances interfacial bonding with polymer matrices, improving tensile, flexural, and impact properties when incorporated into PLA.

Synthesis of bamboo cellulose nanofibers (BCNFs)

Cellulose nanofibers (CNFs) were synthesized from raw bamboo through a multi-stage chemical and mechanical process designed to isolate high-purity nanofibrils suitable for reinforcement in polymer matrices. Fresh bamboo culms were first chipped, oven-dried, and milled to fine powder before undergoing dewaxing to remove extractives. The processed biomass was then subjected to alkaline pulping using sodium hydroxide solution at elevated temperature, which facilitated the removal of hemicellulose and partial lignin. This was followed by a bleaching treatment using acidified sodium chlorite under controlled pH and temperature conditions to further eliminate residual lignin and impart whiteness to the cellulose fibers. The purified cellulose pulp obtained after repeated washing and neutralization was dispersed in deionized water to form a homogeneous slurry. To convert these micron-scale cellulose fibers into nanofibers, the suspension was processed using either a direct mechanical fibrillation route or a TEMPO-mediated oxidation pathway. In the mechanical approach, the slurry was subjected to high-shear blending followed by high-pressure homogenization, which generated intense shear forces to individualize the fibrils.

Alternatively, in the TEMPO oxidation route, primary hydroxyl groups of cellulose were selectively oxidized to carboxyl groups, thereby improving fibril separation, colloidal stability, and compatibility with hydrophobic polymer matrices. After oxidation, the slurry was neutralized and fibrillated using high-pressure homogenization, often complemented by ultrasonication to minimize aggregation. These combined treatments resulted in the production of cellulose nanofibers with diameters typically between 20–50 nm and lengths extending into the micron range, providing a high aspect ratio favorable for stress transfer in composites. The final CNF suspensions were obtained as viscous aqueous gels, carefully concentrated to the desired solid content, degassed to remove entrapped air, and stored at refrigerated conditions to preserve stability prior to compounding with PLA for filament extrusion. The TEM image of bamboo cellulose nanofibers shown in figure 1.

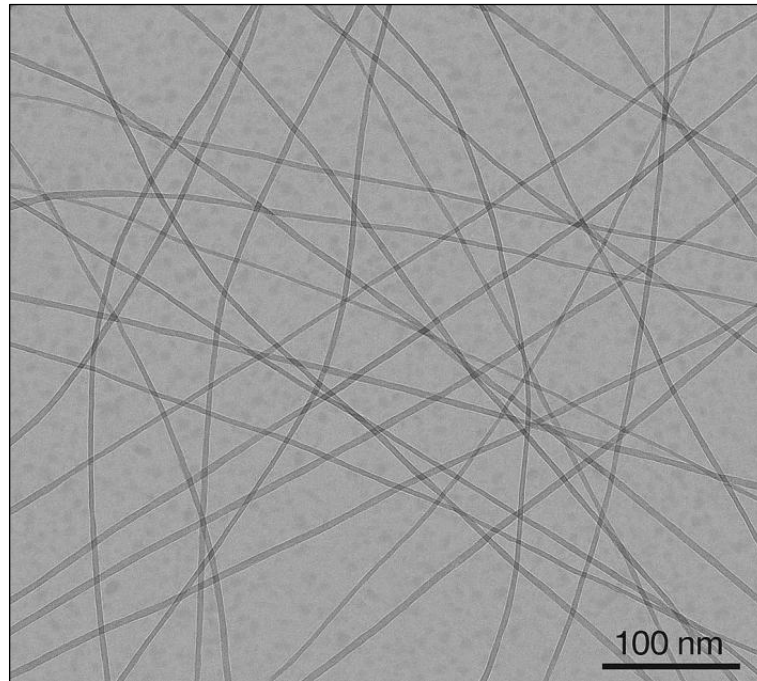


Figure 1: TEM Images of bamboo cellulose nanofibers.

Source: Authors, (2026).

Functionalization of bamboo cellulose nanofibers

Functionalization of bamboo cellulose nanofibers is crucial to improve their dispersion in hydrophobic polymers such as PLA and to enhance interfacial adhesion. Due to the abundance of hydroxyl groups, untreated CNFs are highly hydrophilic and prone to aggregation, which limits their reinforcing potential. Chemical modification offers effective solutions, with TEMPO-mediated oxidation being one of the most common methods, introducing carboxyl groups that provide surface charge and stability. Esterification and acetylation replace hydroxyl groups with hydrophobic moieties, improving compatibility with biodegradable polyesters. Silanization using organosilane agents further enhances bonding by forming covalent linkages between CNFs and polymer chains. In addition, surface grafting of polymers or ionic groups can tailor properties such as flexibility, barrier performance, and conductivity. These functionalization strategies not only enhance dispersion and stress transfer in PLA composites but also improve mechanical strength, thermal stability, and printability in 3D printing applications.

PLA / BCNF 3D Printing filament preparations

PLA/BCNF composite filaments were prepared by incorporating bamboo cellulose nanofibers at different loadings of 1, 2, 3, 4, and 5 wt.% into a PLA matrix through a solvent-assisted dispersion followed by melt extrusion. Initially, PLA pellets were dried in a hot-air oven at 60 °C for 12 h to remove residual moisture and prevent hydrolytic degradation during processing. Bamboo CNFs were dispersed in ethanol using ultrasonication to break agglomerates and ensure uniform distribution. The BCNF suspension was then slowly mixed with pre-dried PLA pellets, and the mixture was subjected to rotary evaporation at moderate temperature to remove the solvent, leaving BCNFs uniformly coated on the PLA surface. The dried blend was compounded using a single-screw extruder operated at a barrel temperature profile of 170–190 °C with a screw speed of 50 rpm. The extrudate was drawn through a filament die of 1.75 mm diameter and passed over a water-cooled section to stabilize its shape. The continuous filaments were spooled under constant tension to maintain dimensional uniformity. For consistency, the process parameters were optimized to prevent BCNF degradation and ensure smooth filament formation. The obtained composite filaments exhibited a uniform diameter of 1.75 ± 0.05 mm, suitable for fused deposition modeling. The incorporation of bamboo CNFs in the range of 1–5 wt.% was selected to balance printability with mechanical reinforcement, as lower concentrations aid in maintaining extrusion flow, while higher concentrations enhance stiffness and strength. The prepared filaments were stored in airtight containers with desiccant until use in 3D printing trials. This process ensured the development of sustainable PLA/BCNF composite filaments with improved interfacial bonding and homogenous filler dispersion, enabling enhanced performance in mechanical and thermal characterization. XRD images presented in the figure 2.

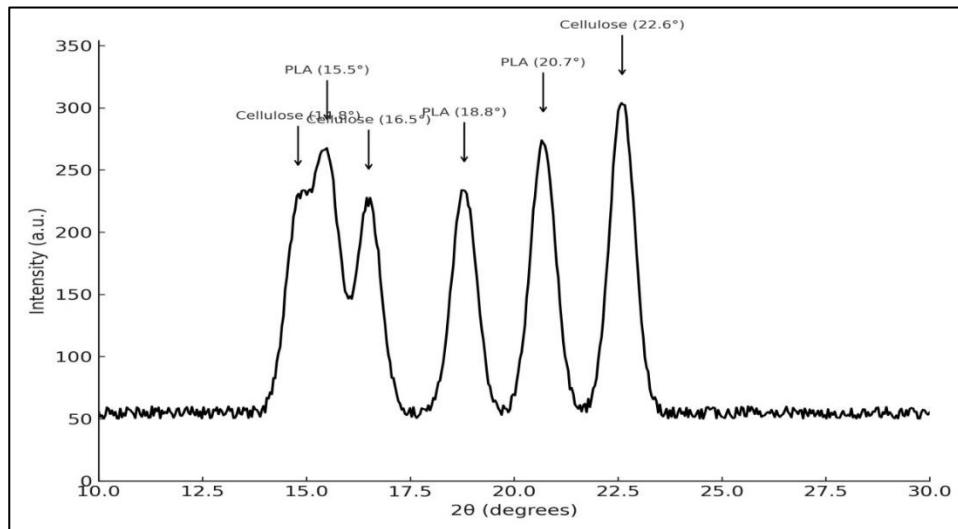


Figure 2: XRD plot of PLA reinforced with bamboo cellulose nanofibers.

Source: Authors, (2026).

III. MECHANICAL CHARACTERIZATIONS

Tensile Test

The tensile properties of the PLA and PLA/bamboo CNF composite specimens were evaluated in accordance with ASTM D638. Standard dog-bone shaped specimens were prepared using 3D-printed samples with a gauge length of 50 mm. Prior to testing, the specimens were conditioned at 23 ± 2 °C and $50 \pm 5\%$ relative humidity for 48 h to ensure uniform moisture content. The tensile tests were performed using a universal testing machine equipped with a 10 kN load cell at a crosshead speed of 5 mm/min. During the test, parameters such as ultimate tensile strength, tensile modulus, and elongation at break were recorded. The addition of bamboo CNFs was expected to enhance stiffness and strength by improving load transfer between the matrix and reinforcement, while maintaining reasonable ductility.

Micro Hardness Test

The surface hardness of the composite samples was determined using the Vickers microhardness method in accordance with ASTM E384. Flat, polished specimens were subjected to indentation under a load of 100 g applied for 15 s using a microhardness tester. The diagonals of the resulting indentations were measured with an optical microscope, and the Vickers hardness number (HV) was calculated. A minimum of five indentations were taken on each specimen at randomly selected positions to ensure statistical reliability, with results averaged to obtain the representative hardness value. The incorporation of bamboo CNFs was anticipated to improve resistance to localized plastic deformation due to the stiffening effect imparted by the nanofibers.

Impact Test

The impact strength of the 3D-printed composites was measured using the Charpy impact test as per ASTM D6110. Rectangular notched specimens with dimensions of $80 \times 10 \times 4$ mm were prepared, and a V-notch of 2 mm depth was machined at the midspan of each sample. Tests were conducted using a pendulum impact tester, and the energy absorbed during fracture was recorded to calculate the impact strength. Five specimens were tested for each composition, and the average value was reported. The introduction of bamboo CNFs was expected to provide crack-bridging and energy dissipation mechanisms, thereby enhancing the overall impact resistance of the PLA matrix.

IV. RESULTS AND DISCUSSIONS

Tensile Characteristics

The tensile properties of the PLA/bamboo cellulose nanofiber (BCNF) composites clearly demonstrate the reinforcing ability of cellulose at the nanoscale as shown in figure 3. Neat PLA exhibited a tensile strength of 78.21 MPa, a value limited by its intrinsic brittleness and poor load-bearing capacity. With the incorporation of 1 wt.% BCNF, the tensile strength increased to 92.56 MPa, corresponding to an 18.4% improvement. This enhancement reflects the inherent characteristics of cellulose nanofibers, which are derived from the hierarchical structure of bamboo. CNFs possess an exceptionally high aspect ratio, high crystallinity, and a Young's modulus approaching 100–170 GPa, properties that make them ideal candidates for stress transfer when embedded in polymer matrices. The hydroxyl-rich surface of CNFs also provides abundant sites for hydrogen bonding with the ester groups of PLA, thereby improving interfacial adhesion and restricting slippage under tensile load. At 2 wt.% BCNF, the tensile strength further increased to 99.23 MPa (26.9% improvement), confirming that cellulose nanofibers, when well-dispersed, serve as efficient reinforcing agents that enhance stiffness without sacrificing ductility. The maximum performance was achieved at 3 wt.% BCNF, where the tensile strength reached 112.76 MPa, representing a remarkable 44.2% improvement compared to neat PLA.

At this optimum loading, the cellulose nanofibers likely formed a semi-percolated reinforcing network that constrained PLA chain mobility, delayed crack initiation, and deflected propagating cracks. This network effect, combined with the nanoscale dimensions and high surface-to-volume ratio of CNFs, accounts for the synergistic reinforcement observed.

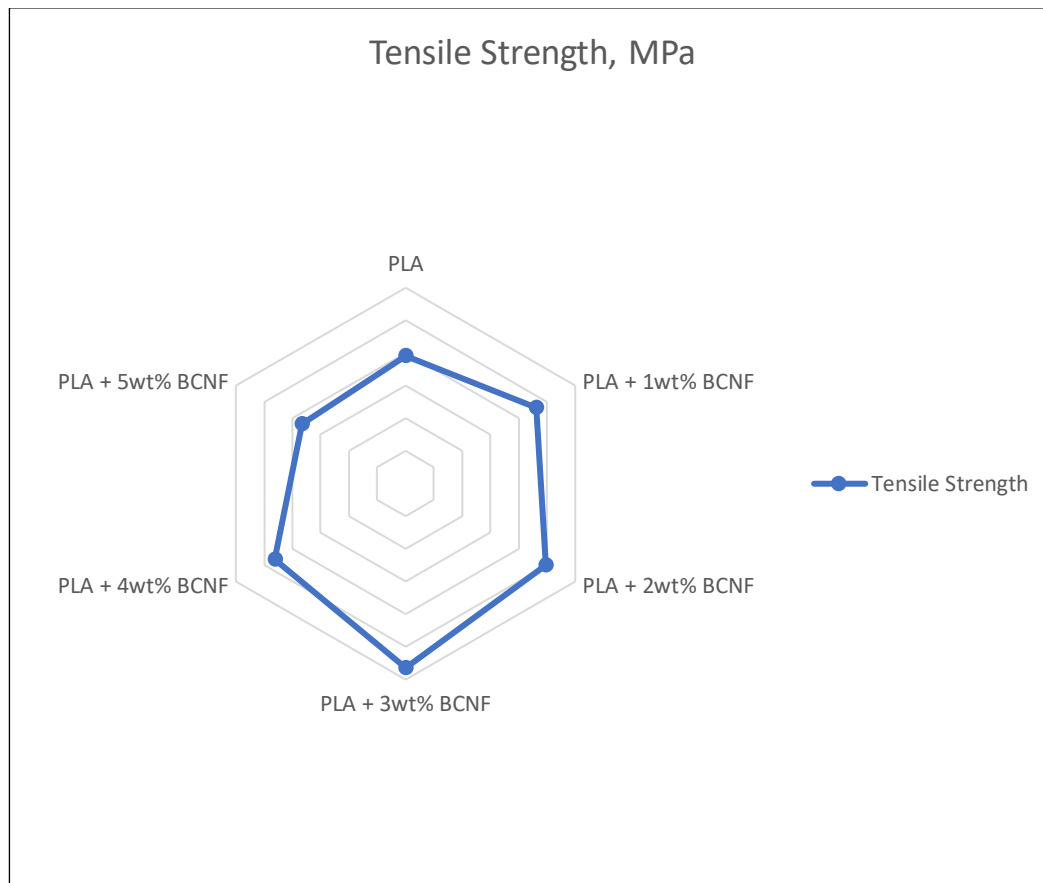


Figure 3: Tensile strength of PLA and its bamboo cellulose nanofiber reinforced composites.
Source: Authors, (2026).

Beyond the optimum, tensile strength declined; at 4 wt.% BCNF, the value fell to 92.54 MPa, while at 5 wt.% it dropped further to 73.41 MPa, which is 6.1% lower than neat PLA. The reduction is explained by the tendency of cellulose nanofibers to agglomerate at higher concentrations due to strong hydrogen bonding and van der Waals forces, leading to stress concentration zones and poor dispersion. Moreover, excess CNF content increases melt viscosity during extrusion, hindering proper filament formation and generating voids that reduce structural integrity. The results demonstrate that cellulose nanofibers are not merely fillers but active nanoscale reinforcements with unique structural features that can dramatically enhance the tensile performance of PLA at relatively low loadings. Their renewable origin, biodegradability, high crystallinity, and surface reactivity make them superior candidates compared to conventional fillers. The optimal 3 wt.% BCNF loading highlights the balance between effective dispersion, strong interfacial bonding, and the intrinsic mechanical advantages of cellulose, thereby offering a sustainable route to engineer high-performance PLA-based filaments for additive manufacturing.

Micro hardness characteristics

The microhardness analysis provided further insights into the reinforcing effect of bamboo cellulose nanofibers (BCNFs) on the PLA matrix (Figure 4). Neat PLA exhibited a baseline hardness of 16 HV, reflecting its relatively soft and ductile nature compared to engineering polymers. With the introduction of 1 wt.% BCNF, the hardness increased to 24 Hv, corresponding to a 50% improvement. This enhancement is primarily attributed to the nanoscale rigidity and high crystallinity of cellulose nanofibers, which restrict localized plastic deformation when subjected to indentation. At 2 wt.% loading, the hardness value further increased to 31 Hv (93.7% improvement), while the maximum reinforcement was observed at 3 wt.% BCNF with a hardness of 42 Hv, representing a 162.5% increase compared to neat PLA. This significant enhancement at optimum concentration is explained by the uniform dispersion of CNFs within the PLA matrix, forming a reinforcing network that resists penetration and distributes the applied load effectively. Beyond 3 wt.% loading, however, the microhardness values decreased, with 4 wt.% showing 27 Hv and 5 wt.% falling to 15 Hv, slightly lower than neat PLA. The reduction can be ascribed to the agglomeration of CNFs at higher concentrations, which introduces voids and weak interfacial regions in the matrix. These defects act as stress concentrators during indentation, thereby reducing the effectiveness of stress transfer. Additionally, the high viscosity of CNF-rich blends during processing may result in poor filament homogeneity and interlayer bonding, further diminishing surface hardness. Furthermore, the microhardness results confirm the reinforcing capability of bamboo CNFs and highlight the importance of optimized filler loading. The superior hardness improvement at 3 wt.% reflects the balance between nanoscale dispersion, interfacial bonding, and the inherent stiffness of cellulose, making this composition the most suitable for enhancing wear and scratch resistance in PLA-based 3D printing applications.

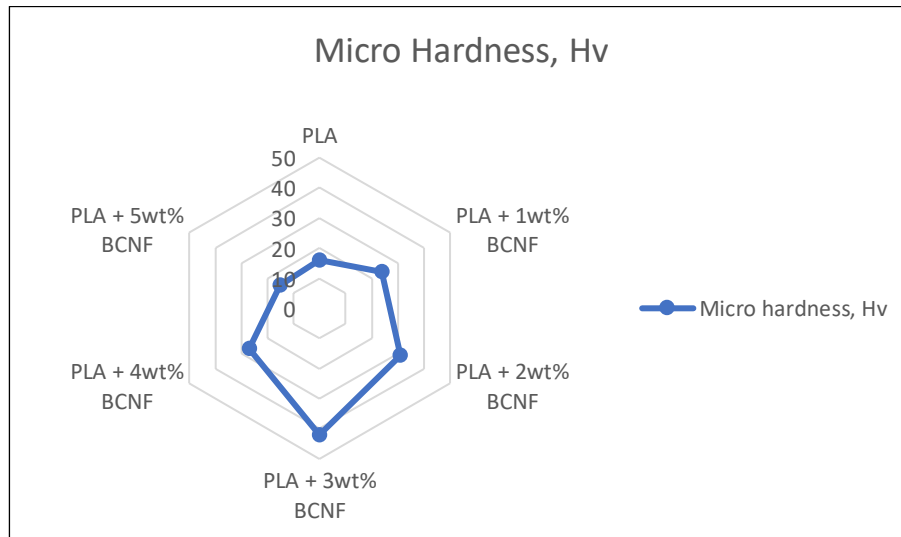


Figure 4: Micro hardness of PLA and its bamboo cellulose nanofiber reinforced composites.
Source: Authors, (2026).

Impact analysis

The impact test results (Figure 5) highlighted the role of bamboo cellulose nanofibers (BCNFs) in modifying the toughness of PLA. Neat PLA exhibited a baseline impact energy of 0.25 J, consistent with its brittle fracture behavior and limited ability to absorb dynamic loading. With the addition of 1 wt.% BCNF, the impact energy increased to 0.31 J, corresponding to a 24% improvement. This initial enhancement can be attributed to the nanofibers acting as crack-bridging agents, which delayed crack initiation and provided localized energy dissipation. At 2 wt.% loading, the impact energy rose further to 0.39 J, representing a 56% improvement compared to neat PLA. The maximum reinforcement effect was observed at 3 wt.% BCNF, where the impact energy reached 0.54 J, corresponding to a remarkable 116% increase. This substantial improvement is explained by the homogeneous dispersion of CNFs within the matrix, which enhanced stress transfer, promoted microcrack deflection, and allowed more efficient absorption of impact energy. However, beyond the optimum concentration, a decline in performance was observed. At 4 wt.% BCNF, the impact energy decreased to 0.42 J, although still 68% higher than neat PLA, while at 5 wt.% the value dropped to 0.29 J, only a 16% improvement over neat PLA. The reduction at higher loadings is likely due to nanofiber agglomeration and poor dispersion, which created stress concentration sites and facilitated premature fracture under impact loading. Excessive filler content may also have reduced interlayer adhesion during filament printing, lowering the energy-absorbing capacity of the composites. The results indicate that bamboo CNFs significantly improve the toughness of PLA at low to moderate loadings, with 3 wt.% providing the best balance of dispersion, interfacial bonding, and energy absorption mechanisms. This demonstrates the potential of CNFs not only to improve strength and hardness but also to impart enhanced impact resistance, a critical property for structural and functional 3D-printed components.

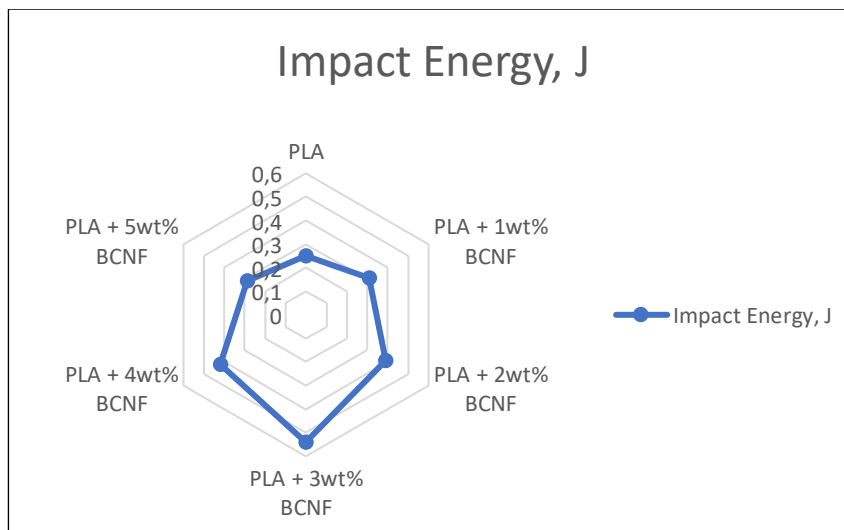


Figure 5: Impact analysis of PLA and its bamboo cellulose nanofiber reinforced composites.
Source: Authors, (2026).

Morphology analysis of tensile fractured surface

The tensile fracture surface morphology provides strong evidence of how bamboo cellulose nanofibers (BCNFs) influence the failure behavior of PLA as shown in figure 6. The neat PLA specimen (a) reveals a relatively smooth and flat fracture surface with stepped fracture features, a clear indication of brittle fracture and limited plastic deformation.

Such morphology is typical of unreinforced PLA, where rapid crack propagation occurs once a critical stress is reached, reflecting its inherently low toughness and poor energy absorption capacity. In contrast, the PLA reinforced with 3 wt.% BCNF (b) displays a much rougher fracture surface characterized by embedded fibers, elastic deformation zones, and regions of fiber pull-out. These features suggest good interfacial bonding between the nanofibers and the polymer matrix, which allows effective stress transfer during tensile loading. The pulled-out and well-anchored fibers act as crack-bridging elements, while the rough fracture path indicates mechanisms such as crack deflection and energy dissipation. This morphology directly explains the significant increase in tensile strength, hardness, and impact resistance at 3 wt.% loading, where the nanofibers are uniformly dispersed and form a reinforcing network that resists crack propagation. However, at higher loading levels, as seen in the 5 wt.% BCNF specimen (c), the fracture surface exhibits distinct fiber agglomeration with clusters of nanofibers forming localized defects within the matrix. These agglomerated regions act as stress concentrators that reduce the efficiency of stress transfer and create preferential sites for crack initiation and propagation. The reduced interfacial contact area between the polymer and nanofibers, along with void formation due to poor dispersion, weakens the composite and results in lower tensile and impact properties than even neat PLA. Thus, the morphological evidence strongly supports the mechanical results, demonstrating that an optimum loading of 3 wt.% BCNF maximizes reinforcement efficiency through uniform dispersion and strong interfacial adhesion, whereas higher loadings compromise structural integrity due to fiber clustering and agglomeration.

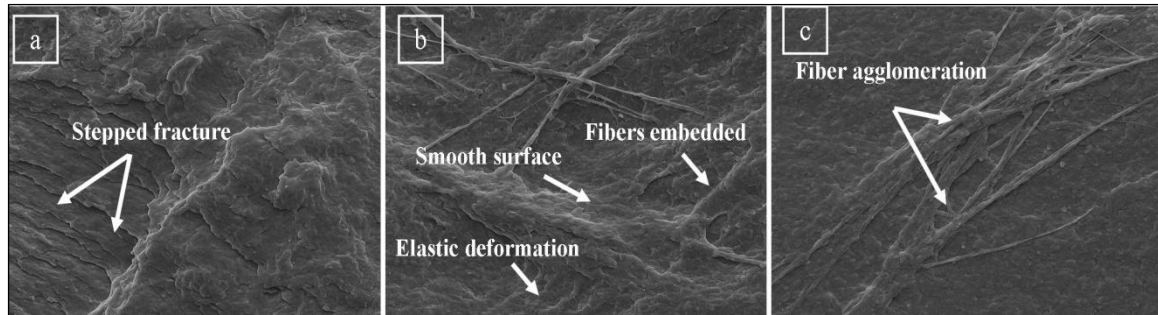


Figure 6: SEM morphology analysis of tensile fractured surface a) PLA b) 3wt.% c) 5wt.% PLA reinforced bamboo cellulose nanofiber composites.

Source: Authors, (2026).

Morphology analysis of micro hardness indentation surface

The SEM morphology of the microhardness indentations provides additional insights into the reinforcing behavior of bamboo cellulose nanofibers (BCNFs) in PLA composites (Figure 7). For the specimen containing 3 wt.% BCNF (a), the indentation zone shows a stepped fracture pattern along with clearly visible embedded fibers within the impression. The presence of dispersed fibers indicates that the nanofillers are well anchored in the PLA matrix and resist localized plastic deformation under indentation. This suggests efficient stress transfer between PLA and CNFs, which is consistent with the substantial improvement in hardness observed at this composition. The stepped fracture and fiber bridging around the indent edges further confirm enhanced resistance to crack propagation and localized strain accommodation, mechanisms that underpin the optimum reinforcement effect at 3 wt.% loading. In contrast, the 5 wt.% BCNF specimen (b) exhibits an indentation morphology dominated by fiber bundles within the impression. The clustering of nanofibers indicates agglomeration, which reduces the effective surface area for stress transfer and creates localized weak zones in the matrix. Such bundles behave as defects rather than reinforcements, leading to stress concentrations under load and premature microcracking. As a result, the hardness of the 5 wt.% composite is lower than that of neat PLA and significantly inferior to the 3 wt.% composite. The smoothness of the surrounding indentation edges in this sample also reflects less resistance to localized deformation, further supporting the mechanical results. The SEM evidence demonstrates that while 3 wt.% BCNF provides optimum dispersion and reinforcement, higher filler loadings (5 wt.%) promote fiber agglomeration that compromises interfacial bonding and negates the beneficial effects of CNFs, thereby emphasizing the importance of optimized nanofiber concentration for superior hardness performance.

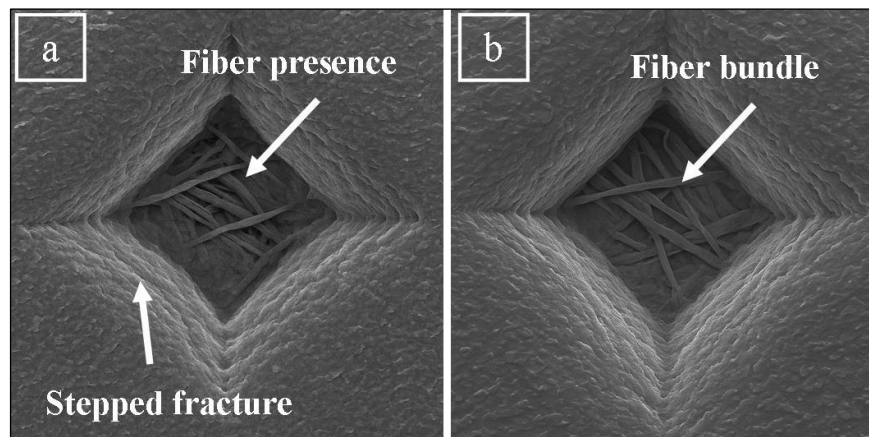


Figure 7: SEM morphology analysis of micro hardness indentation surface of a) 3wt.% b) 5wt.% PLA reinforced bamboo cellulose nanofiber composites.

Source: Authors, (2026).

V. CONCLUSIONS

1. Incorporation of bamboo cellulose nanofibers (BCNFs) into PLA significantly enhanced mechanical performance, with optimum results observed at 3 wt.% loading.
2. Tensile strength improved by up to 44.2% at 3 wt.% BCNF due to effective stress transfer, crack deflection, and strong interfacial adhesion between nanofibers and PLA.
3. Microhardness increased by 162.5% at 3 wt.% BCNF, confirming the role of nanofibers in restricting localized plastic deformation and resisting indentation.
4. Impact resistance reached a maximum at 3 wt.% BCNF with an improvement of over 116%, attributed to fiber bridging, crack pinning, and improved energy absorption capacity.
5. SEM analysis of tensile fracture surfaces revealed brittle failure in neat PLA, roughened surfaces with embedded fibers at 3 wt.% BCNF, and fiber agglomeration defects at 5 wt.% BCNF.
6. Microhardness indentation morphology showed uniform fiber presence at 3 wt.% leading to stepped fracture resistance, while fiber bundling at 5 wt.% caused stress concentration and reduced hardness.
7. Excessive fiber loading beyond 3 wt.% resulted in agglomeration, poor dispersion, and weaker interfacial bonding, highlighting the importance of optimized nanofiber content for high-performance PLA composites.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Mujiburrahman K, Aneesh Akthar F and Shaaju Kishore D , Divakar M and Jana Karthikeyan T.

Methodology: Mujiburrahman K, Aneesh Akthar F and Shaaju Kishore D , Divakar M and Jana Karthikeyan T.

Investigation: Mujiburrahman K, Aneesh Akthar F and Shaaju Kishore D , Divakar M and Jana Karthikeyan T.

Discussion of results: Mujiburrahman K, Aneesh Akthar F and Shaaju Kishore D , Divakar M and Jana Karthikeyan T.

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Writing – Review and Editing: Mujiburrahman K, Aneesh Akthar F and Shaaju Kishore D , Divakar M and Jana Karthikeyan T.

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Approval of the final text: Mujiburrahman K, Aneesh Akthar F and Shaaju Kishore D , Divakar M and Jana Karthikeyan T.

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