

Performance of strategically sandwiched continuous sisal fiber core 3D printed PLA composites for engineering applications

Mohit Kumar

mohit.dhiman349@gmail.com

King Mongkut's University of Technology North Bangkok <https://orcid.org/0000-0003-0462-450X>

Vinod Ayyapan

Ranvijay Kumar

Manoj Kumar Singh

Sanjay Mavinkere Rangappa

Suchart Siengchin

Research Article

Keywords: 3D printing, polylactic acid, natural fibers, sandwiched structure, biocomposites, NaOH treatment

Posted Date: October 1st, 2025

DOI: <https://doi.org/10.21203/rs.3.rs-7575389/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License. [Read Full License](#)

Version of Record: A version of this preprint was published at The International Journal of Advanced Manufacturing Technology on February 18th, 2026. See the published version at <https://doi.org/10.1007/s00170-026-17657-x>.

Abstract

The study presents an innovative method to enhance the structural performance of 3D-printed polylactic acid (PLA) composites by strategically incorporating continuous Agave sisalana fibers as a sandwiched core. This architecture aims to overcome existing limitations by enhancing fiber alignment, interfacial bonding, and mechanical performance, while maintaining the lightweight benefits of PLA. Alkaline treatment enhanced fiber/matrix interaction, confirmed via SEM analysis. Compared to neat 3D printed PLA, the treated fiber composite showed notable enhancement of 36.19% in tensile strength and 46.25% in interlaminar shear strength. The treated configuration showed tensile strength of 40.87 MPa and tensile modulus of 2420.88 MPa. While neat 3D printed PLA retained higher flexural strength and modulus, the treated fiber composite excelled in toughness (938.9 kJ/m³) and energy resilience (307 kJ/m³). Dynamic mechanical analysis revealed better thermal stability in the treated fiber composite (Tan δ = 0.53 vs. 1.49 for neat 3D printed PLA). Impact testing showed that untreated fiber layers absorbed more energy, evidenced by the highest puncture force (349.78 N) and maximum deformation. Overall, the study confirms the benefits of a continuous fiber core in optimizing 3D-printed PLA composites and suggests future work on fiber arrangement and volume fraction for enhanced performance.

1. Introduction

Surface treated continuous natural fibers integrated into PLA with the help of additive manufacturing offers sustainable composite structures for engineering applications. In engineering applications, lightweight and good mechanical properties of the manufactured parts are highly recommended, and can be accommodated by using continuous natural fibers into thermoplastics. The studies suggest that the fibers reinforced with polymers can greatly enhance the mechanical, thermal, chemical, surface, durability, and tribological properties [1, 2]. A number of studies have been reported in the recent past for the development of the natural fibers reinforced thermoplastics [3, 4]. PLA-based composites are known for good biocompatibility, degradability, good stiffness, and mechanical properties [5]. These excellent material properties make PLA as one of the acceptable thermoplastics for applications in tissue engineering, sensors, smart textiles, automobile, and aerospace applications [6]. The previous studies have explored the different materials performance of the natural fiber reinforced PLA composites. The studies conducted to investigate the effect of jute, sisal and elephant grass-based fibers in PLA matrix have suggested that impact strength was increased by 22.3%, 111.5% and 129.5% respectively as compared to plain PLA [7]. The addition of natural fibers is one of the ways to restore the material's properties, which can be ensured or established by mechanical recycling. However, the number of thermal cycles affects the mechanical properties of the composites. The study revealed that when basalt fibers and halloysite nanotubes were reinforced in PLA matrix by a combination of twin-screw extrusion and injection molding, the tensile strength was significantly affected after three recycling steps [8]. The reinforcement of pre-stressed natural fibers in PLA have ensured the 116% and 62% increase in tensile strength and stiffness respectively along with 14% and 10% increases in flexural strength and rigidity, respectively [9].

3D printing is becoming a promising tool for the manufacturing of natural fiber-based composite materials [10, 11]. The flour extract (90–250 μ m) from henequen fibers reinforced with PLA shows a potential for 3D printing of crack-resistant structures [12]. Fused deposition modeling (FDM) is a materials extrusion (MEX)

based 3D printing process that is largely reported for the manufacturing of natural fiber reinforced polymer composite structures [13, 14]. The study has reported for incorporation of different natural fibers of oil palm, pineapple leaf, coir, and bamboo (size: 250–500 μ m) into PLA for 3D printing. A higher tensile strength was observed for the combination of fibers (hybrid) as compared to pure biocomposites or pure PLA [15]. It was reported los decrease in mechanical properties of 3D printed natural fiber reinforced PLA composites after hydrolytic degradation, a potential candidate for furniture, decorations, and the automotive industry [16]. The manufacturing of micro-perforated panels is possible by 3D printing using cork fiber reinforced PLA for engineering noise control and the effectiveness of hearing conversation [17].

In 3D printing applications, PLA is often considered as a brittle and low impact-resistant material, which results in limited use. However, the addition of continuous fibers can improve the strength, load transfer efficiency, thermal stability, and crack resistance of PLA towards manufacturing lightweight components [18–20]. Cersoli et al. (2021) have outlined that continuous Kevlar fiber reinforcement has increased the tensile strength by two times and impact energy by a factor of four [21]. Similar observations have been reported in previous studies [14]. However, direct reinforcement of the fibers with PLA matrix is associated with many challenges, including poor fiber-matrix adhesion, non-uniform distribution, alignment, and formation of voids/porosity, which contributes to defects in the final manufactured parts [22, 23]. In some cases, reinforcement can create the problem of nozzle clogging in materials extrusion-based 3D printing [24, 25]. To solve these issues, the sandwiching of the continuous fibers within regular additive layers can be implemented. Sandwiching of the fibers is one of the alternative methods to incorporate the continuous fibers, especially for increasing the mechanical strength [26]. The process may also be named as the ‘interleaving’ process. A 44% higher elastic modulus and 119% higher strength were observed for a sandwich structure made by 3D printing of carbon fiber reinforced composites [27]. A higher stiffness (up to 4.1 times) could be ensured if 3D printing is performed for the manufacturing of a sandwich structure with a corrugated core [28]. Also, the bio-inspired sandwich structures prepared by 3D printing (of carbon fiber reinforced composites) can be used for energy absorption applications [29]. The surface treatment is one of the best approaches for tuning the properties. This can result in improved adhesion between the layers and mechanical strength. The study reveals that the 3D printed rice husk and rice straw (surface treated with NaOH) reinforced (5–20%) to PLA can be used for automotive and construction applications [30]. Along with this, the surface treatment can be helpful for controlling the hydrophobic behavior of the polymer composites [31]. The strength retention of surface treated sisal-polyester composites was observed higher as compared to untreated composites [32].

The reported literature is evident that reinforcement of the natural fibers as filler with PLA matrix has significantly improved the mechanical and physical properties [7, 9, 33]. Reinforcement of continuous fibers in the PLA matrix has also been reported for the improvement of the mechanical properties [14, 21]. 3D printing has become a crucial technology for the fabrication of PLA-natural fiber-based composite structures with suitable mechanical properties [13, 14, 16, 17]. In fact, surface treatment of the natural fibers can boost the mechanical properties by controlling the hydrophobic nature [30–32]. A very few studies have been reported on 3D printed sandwiched strcutures of continuous fibers configuration for tunable mechanical properties [27, 28]. Hitherto, fewer have reported on the manufacturing of sandwiched continuous fiber core structured composites using 3D printing. This study highlights a strategical approach for sandwiching the continuous fibers as a core in PLA composites using 3D printing technology. The manufactured 3D printed biocomposite

plate was further characterized for mechanical performance, thermal behaviour, morphological analysis, viscoelastic behavior and low velocity impact evaluation. This study seeks to address current challenges by improving fiber orientation, strengthening interfacial adhesion, and boosting mechanical properties, all while preserving the lightweight nature of PLA for engineering applications.

2. Materials and methods

2.1. Materials

In the present study, PLA 4043D grade was procured from NatureWorks LLC. This PLA grade is biodegradable and suitable for making 3D printed filaments. The density of the material is 1.25 g/cm³, glass transition temperature of 63°C and melting point of 155°C. The tensile strength and elongation at break of the material are 55–60 MPa and 2–4% respectively. Natural sisal fibers derived from *Agave sisalana* were utilized as reinforcement in this study. These fibers had an average diameter of approximately 0.18 mm, a tensile strength of 298 MPa, and a tensile modulus of 11.4 GPa. The fibers were sourced from Metro Composites, Chennai, India. To facilitate the application of PLA as an adhesive, chloroform was used as a solvent. The chloroform, with a stated purity of 99.98%, was procured from RCI Labscan Limited, located in Bangkok, Thailand.

2.2. Manufacturing process

2.2.1. Surface treatment of *Agave sisalana* (Sisal) fiber

The concentrated NaOH solution (5%) was prepared by dissolving 63.23 g of 98% NaOH pellets in 1200 mL distilled water and stirred till the pellets were completely dissolved. The actual density of NaOH pellets was 2.13 g/cc, and the final density for 1200 mL of 5% NaOH solution was 1.054 g/cc. The alkali surface treatment was done by soaking 200 g of derived fibers in 1200 mL of 5% NaOH solution using a magnetic stirrer at room temperature for 8 h. Later, the treated fibers were washed completely with distilled water until the pH was neutralized. Further, these treated fibers were dried in a hot oven at 65°C for 24 h. The chemical reaction of fiber with NaOH is given in Eq. (1).



The hydroxyl (OH) groups on the fiber surface were disintegrated, resulting in the removal of excess amorphous constituents like hemicellulose, wax, lignin, pectin, and impurities. NaOH treatment infiltrates the amorphous zones of cellulose, swelling the fibres and expanding their cell walls. The rougher surface and enlarged pores give the resin more room to penetrate, nurturing stronger fiber/matrix adhesion through mechanical interlocking. Meanwhile, NaOH cuts the original, moisture-prone hydroxyl linkages subsequent re-arrangement of the cellulose chains creates new hydroxyl bonds. With many of the moisture-prone hydroxyl groups removed, the treated fibres exhibit better resistance to moisture [34].

2.2.2. Manufacturing of PLA/Sisal fiber biocomposites laminate

The manufacturing procedure starts with preparing a PLA solution. For this, PLA pellets of 4043D grade are weighed and placed into a beaker, followed by the addition of chloroform as a solvent. A 1:10 weight-to-volume ratio is used specifically; 25 grams of PLA is dissolved in approximately 150 mL (around 222 grams) of chloroform. To facilitate complete dissolution, the mixture is stirred using a magnetic stirrer set to 60°C. Once a homogeneous PLA solution is obtained, it is uniformly spread over both untreated and chemically treated agave sisalana fibers that are aligned in a single direction. The coated fibers are then left undisturbed for about two hours, allowing the chloroform to evaporate completely. The dried composite is subsequently processed through compression molding at 150°C, under a pressure of 4000 kgf, for a duration of 15 minutes using a mold with a thickness of 0.4 mm. This step is essential for minimizing void content and ensuring a consistent final thickness in the fiber-sandwiched PLA composite. In this process, two types of biocomposite laminates were developed, one using untreated sisal fibers and the other incorporating treated sisal fibers.

2.2.3. Filament manufacturing and 3D printing of composites

To prepare the PLA filament, PLA pellets were initially dried in an oven at 45°C for 24 hours to eliminate any residual moisture. Following this drying step, the pellets were processed using a single-screw extruder (Noztek Xcalibur) to produce filaments with a target diameter of 1.75 ± 0.2 mm. The extruder featured three distinct heating zones: the nozzle (T1) was maintained at 200°C, the intermediate (T-2) at 190°C, and the feed zone near the hopper (T-3) at 185°C. The extrusion was conducted at a screw rotation speed ranging from 17 to 22 revolutions per minute (rpm). In the subsequent step, samples were prepared using a 3D printer, model BBC3040 manufactured by Bangkok Blue Ocean Co. Ltd, Bangkok, Thailand. The 3D printing parameter used in this work is presented in Table 1. The CAD design was created and saved in .stl format, further imported into the simply3D software for printing. The desired 3D printed composite specimen thickness was 3mm, which comprises of 3 stacks (stack 1- 1.3 mm, stack 2- 0.4 mm and stack 3- 1.3 mm) that were printed layer by layer. The composite sample descriptions were given in Table 2. Stack 2 is filled with PLA/sisal fiber laminate in case of untreated and treated samples.

Table 1
3D printing parameters

Parameters	Values (units)
Infill density	80%
Extruder temperature	210 °C
Bed temperature	55 °C
Printing speed	0.40 mm/s
Nozzle size	0.6 mm
Layer height	0.20 mm
Filling pattern	Rectilinear
Extrusion width	0.4 mm
Raster angle	45

Table 2
Description of composite samples

Composite samples	Designation
3D printed PLA biocomposite	Neat
3D printed PLA biocomposite sandwiched with untreated sisal fiber	Untreated
3D printed PLA biocomposite sandwiched with treated sisal fiber	Treated

To sandwich the biocomposites laminate, the 3D printing process was programmed to pause layer deposition at a height of 1.3 mm. After inserting the biocomposites laminate, the layer-by-layer deposition resumed from a height of 1.7 mm, ensuring a total sample thickness of 3 mm. To ensure proper adhesion of the biocomposites laminate after the stack 1, the prepared PLA solution was uniformly spread across the surface layer to bond with the deposited layers. Subsequently, the layer-by-layer deposition process was continued on top of the laminate, resulting in a final sample with a thickness of 3 mm. The complete schematic process for fabrication is shown in Fig. 1. Before conducting the experiments, all 3D-printed composite samples were placed in a hot air oven at 50°C to eliminate any moisture absorbed by the PLA materials.

2.3. Characterization techniques

2.3.1. Mechanical characterization – Tensile, Flexural, and Interlaminar shear strength (ILSS)

The mechanical characterization, such as tensile strength and modulus, flexural strength and modulus, and ILSS was measured via a Universal testing machine model, Comtech M1-type of 10 kN loadcell. The tensile test, flexural test, and ILSS test were performed using ASTM 3039D (100×10×3 mm³), ASTM D790 (90×10×3 mm³) and ASTM D2344 (60×10×3 mm³), respectively. Five samples for each 3D printed composite sample were tested with a test speed of 2 mm/min, and average values were reported in the results.

2.3.2. Scanning Electron Microscopy (SEM)

The surface morphology of tensile fractured samples was analyzed using Thermo Fisher Scientific-SEM, Ireland. Before SEM imaging, the fractured samples were gold-coated using an MP-19020NCTR Neocoater to ensure conductivity, as the materials were inherently non-conductive.

2.3.3. Dynamic Mechanical Analysis

The dynamic mechanical analysis (DMA) was done to evaluate the effect of sandwiched untreated and treated fibers in the 3D-printed composite samples on their viscoelastic behaviour. The loss modulus (E''), storage modulus (E') and $\tan \delta$ were evaluated as per ASTM D4065 standard, in dual cantilever mode with temperature range from 25°C to 125°C at heating rate of 5°C/min. The frequency mode and load were set at 1Hz and 0.8 N, respectively. The loss modulus signifies the energy dissipated during deformation, the storage modulus signifies the material's capacity to store energy under deformation, and $\tan \delta$ presents the material's damping properties.

2.3.4. Thermomechanical Analysis (TMA)

TMA was conducted to evaluate the temperature effect on the thermal expansion behavior and dimensional stability of the 3D printed composite samples. A thermomechanical analyzer, model TMA/SDTA 1+, Mettler Toledo, Switzerland, was used to study samples as per ASTM E831-03. The test was performed by putting the sample between flat silica plates under a quartz probe inside the furnace, at temperature ranges between 30–100°C, at a rate of 5°C/min in a nitrogen environment.

2.3.5. Low Velocity Impact

The low impact velocity was used to study the energy absorption behaviour, impact resistance, and damage tolerance of the 3D printed composite samples as per ASTM D7136 standard. The experiment was conducted on a 100×100 mm² plate using a Zwick Roell HIT 600F impact machine with an impact energy of 10J. The purpose of this study is to evaluate the real-time scenario where composites made from present materials get hit by any objects.

3. Results and Discussion

3.1. Tensile properties

The tensile results of neat, untreated, and treated fiber sandwiched 3D printed composite samples were investigated and shown in Fig. 2 and Table 3. It was observed that neat 3D printed PLA composite exhibited the lowest tensile performance among all tested samples, with a tensile strength of 30.01 MPa and a tensile modulus of 1750.91 MPa. Incorporating untreated fibers in a sandwiched structure improved the overall strength, resulting in a tensile strength of 33.17 MPa and a tensile modulus of 2316.55 MPa, reflecting a 10.20% increase in strength compared to the neat composite. Notably, the 3D printed composites sandwiched with treated fibers demonstrated the most significant enhancement, achieving a tensile strength of 40.87 MPa and a tensile modulus of 2420.88 MPa. This represents an overall improvement of 36.19% over the neat composite and 23.21% compared to the untreated fiber composite. It was attributed to the excellent stress transfer with the matrix and the fibers due to the increased surface area and improved interfacial adhesion resulting from the surface treatment [34].

Table 3
Tensile test results of 3D printed composite samples

Sample	Maximum tensile strength (MPa)	Tensile modulus (MPa)	Strain at break	Modulus of toughness (kJ/m ³)	Modulus of resilience (kJ/m ³)
Neat	30.01 ± 1.8	1750.91 ± 46.12	0.028 ± 0.003	530 ± 10	103 ± 9
Untreated	33.17 ± 3.4	2316.55 ± 58.95	0.030 ± 0.002	666.8 ± 15	230 ± 10
Treated	40.87 ± 2.3	2420.88 ± 50.02	0.035 ± 0.002	938.9 ± 10	307 ± 7

The strain at break for all the composites was shown in Fig. 2(a) and Table 3. It was observed that the 3D printed composites sandwiched with treated fibers exhibited a maximum strain at break of 0.035,

representing a 25% improvement compared to the neat composites. The observed increase in strain at break can be attributed to the improved interfacial bonding and enhanced tensile behavior. NaOH treatment of sisal fibers effectively eliminates considerable amorphous constituents such as lignin and hemicellulose, exposing a rougher and more reactive fiber surface [35]. This modification significantly strengthens the interaction between the fiber and the surrounding matrix, allowing for better mechanical interlocking and more efficient stress transfer [36]. As a result, the fiber sandwiched composite was able to endure greater deformation before fracturing. Moreover, the presence of continuous fibers acts as a mechanical bridge between cracks and redistributes localized stress, which helps to minimize stress concentrations. The stronger interface also contributes to improved energy absorption and dissipation during loading. Together, these mechanisms account for the increased strain at break observed in the treated fiber composites as compared to other composite sample configurations. The strain at break of composites significantly affects their modulus of toughness and resilience properties.

The modulus of toughness represents how much energy a material can absorb per unit area before it breaks, covering both its elastic and plastic deformation stages. In simpler terms, it reflects the material's capacity to endure stress and strain up to the point of fracture. On the other hand, resilience refers to a material's ability to absorb energy during elastic deformation and then recover its original shape once the applied stress is removed. This indicates the material's resistance to temporary deformation without undergoing lasting damage. Generally, materials that exhibit both high toughness and high resilience are better equipped to handle significant forces and impacts, making them ideal for use in structural and protective applications [37]. The results of all composite configurations in terms of modulus of toughness and resilience are shown in Fig. 2(c-d) and Table 3. The lowest modulus of toughness (530 kJ/m^3) and resilience (103 kJ/m^3) were observed in the neat 3D printed PLA composite. This is attributed to brittle behaviour with limited energy absorption during both elastic and plastic deformation [38]. The increase in both modulus of toughness (666.8 kJ/m^3) and resilience (230 kJ/m^3) was obtained for untreated composite corresponds to improved performance with fiber reinforcement. Although these values were less than treated values of modulus of toughness (938.9 kJ/m^3) and resilience (307 kJ/m^3), because of poor interfacial bonding in untreated composites. The higher toughness properties in treated composites attributes to superior energy dissipation, better stress transfer and plastic deformation making it more suitable for applications requiring improved toughness and ductility.

3.2. Flexural properties

The flexural results of neat, untreated, and treated fiber sandwiched 3D printed composite samples are shown in Fig. 3. It was noted that neat sample exhibited the highest flexural strength and flexural modulus of 61.73 MPa and 2560.11 MPa, respectively. Incorporating sandwiched core fiber layer between 3D printed PLA composite did not result in any notable enhancement in flexural strength and flexural modulus. For the untreated composite, the recorded flexural strength and modulus were 51.10 MPa and 2220.34 MPa, respectively. The reason was analysed from Fig. 3(a), where the strain values for sandwiched core fiber composites were significantly high (≈50%) as compared to neat composite sample. This increase is likely due to the enhanced deformability of the sandwiched structure, which results in lower stiffness and improved flexibility (include Core is restricting crack propagation) [39]. However, after NaOH treatment of fibers, these values increased to 55.79 MPa for flexural strength and 2413.37 MPa for flexural modulus, indicating

improvements of approximately 9.17% and 8.69%, respectively, as compared to untreated fiber core samples. This may be due to the increased surface roughness correspond to better interfacial bonding and better stress transfer between fibers and matrix [40]. This enables the material to absorb more energy and undergo greater deformation prior to failure.

3.3. Interlaminar shear strength (ILSS) properties

ILSS is one of the key properties to evaluate the delamination behavior of layered composites, particularly in sandwich structures. The ILSS of neat, untreated, and treated fiber sandwiched 3D printed composite samples were evaluated and presented in Fig. 4. The results showed that neat composite sample had interlaminar shear strength of 3.2 MPa, while untreated and treated fiber core composite samples had interlaminar shear strength of 4.13 MPa and 4.68 MPa, respectively. The lowest interlaminar shear strength was observed in neat composite sample, and the significant improvement of 29.70% was obtained for untreated composite sample. This was attributed to the presence of a continuous longitudinal sisal fiber core, where higher deformation limits crack propagation between the intermediate layers. Another phenomenon observed is that reduced thickness increases flexibility, with the sisal fibers in the core acting as a barrier across the overall thickness. As a result, the total thickness is effectively halved and supported by the sisal core, which restricts crack propagation and enhances flexibility and stress transfer [41]. Fibers in the sandwich layer hinder crack growth and sliding, enhancing shear resistance and boosting ILSS despite bonding issues [42]. The highest interlaminar shear strength was observed in the treated composite samples, exhibiting improvements of 46.25% and 13.31% compared to neat PLA and untreated composites, respectively. This enhancement is attributed to the increased stiffness of the fiber core resulting from the removal of amorphous constituents, thereby providing greater resistance to interlaminar shear loads. However, the overall shear strength was slightly compromised by the increased flexibility associated with the reduced laminate thickness. Thus, this type of composites can be used for vibrational damping panels where high interlaminar shear strength resist delamination under cyclic loads and can absorb vibrations.

3.4. SEM analysis

3.4.1. Surface morphology of sisal fibers

The SEM images showing the surface morphology of untreated and NaOH treated fibers are shown in Fig. 5(a-b). From Fig. 5(a-b), it can be seen that the surface texture of the sisal fiber changed from smooth to rough after the NaOH treatment. The diameter of the untreated and treated sisal fibers was measured using Image J (open-source software). The diameter of the untreated sisal fiber was 183.818 μm , but after NaOH treatment, the fiber diameter reduced to 164.047 μm . It was observed that NaOH treatment reduced the fiber diameter by 12.05%. The NaOH solution was strong enough to disintegrate more amorphous materials (Lignin/Hemicellulose), which led to a reduction in fiber diameter and an increase in surface roughness [43].

3.4.2. Morphology of fractured fiber sandwiched 3D printed composite samples.

The SEM images showing the morphology of tensile test fractured fiber sandwiched 3D printed composite samples are presented in Fig. 5(c-e). Figure 5(c) presents the SEM image of the neat PLA composite printed

with an 80% infill density, exhibiting a raster angle of 45° and a layer height of 0.20 mm. Figure 5 (d-e) reports the fractured morphology with fiber-matrix interaction and the stacking of sandwiched fiber layer in-between the 3D printed PLA layers. It was observed that the fracture morphology of the neat composite is different from sandwiched fiber composites, as fiber sandwiching increases the load-carrying capacity of the composites, as justified through tensile test results [44]. The fracture surface of the composite sandwiched with untreated fibers (Fig. 5(d)) exhibits evident fiber pull-outs, suggesting weak interfacial bonding. Conversely, the treated fiber sandwiched composite (Fig. 5(e)) demonstrates improved matrix-fiber adhesion, with minimal pull-out and enhanced fiber adhesion. As discussed in Section 3.4.1, this improvement is attributed to the NaOH surface treatment, which increased the fiber surface roughness and surface area, thereby introducing more active sites for matrix interaction. This enhanced interfacial adhesion was directly linked to the improved ultimate tensile strength of the treated fiber sandwiched composite. In contrast, the untreated samples exhibit lower tensile strength due to poor stress transfer resulting from inadequate fiber-matrix bonding and prevalent fiber pull-outs.

3.5. DMA analysis

The DMA was conducted on neat, untreated, and treated 3D printed composites samples, and the results were shown in Fig. 6. The following section discusses the results obtained through storage modulus and $\tan \delta$.

3.5.1. Storage Modulus

The storage modulus represents the amount of energy retained in a material as a function of temperature. Figure 6 (a) shows the storage modulus curves of the 3D printed composite samples. The results indicate that modulus values decreased slowly before the glass transition region, but after this region, samples exhibited a plastic behavior as the PLA matrix began to soften due to increase in temperature. This softening facilitated increased polymer chain mobility, leading to a noticeable decrease in the stiffness of the composites [45]. From storage modulus curves, it can be seen that the neat composite sample has a steep curve after the transition phase as compared to fiber sandwiched composite samples. This was due to more polymeric mobility in neat composite samples due to the absence of fibers. Sandwiching continuous fibers aids in carrying some of the mechanical load, preventing a sharp decline [46]. The storage modulus of all 3D printed composite samples lies between 1130 MPa and 785 MPa, with noticeable differences between neat and fiber-sandwiched composite samples. The neat composite samples showed a higher modulus of 1130 MPa, and the fiber sandwiched composite (untreated) showed the lowest modulus of 785 MPa. It is evident that the storage modulus exhibits a similar trend to the flexural modulus. The reduction in storage modulus is attributed to the composite architecture, wherein both the infill and overall composite thickness are effectively halved due to the incorporation of fibers as a sandwiched core, resulting in increased flexibility. However, composites with chemically treated fibers as the core demonstrated an enhanced storage modulus, owing to the increased stiffness imparted by the treatment. For the untreated fiber sandwiched composite, The decrease in modulus value may be due to the weak fiber/PLA interface that reduces the effective stress transfer especially under oscillatory loading. Another reason may be the local compliance due sandwiched structure, which means sandwiched fiber layer does not constraint deformation (as fiber layer is thin) and behave flexible (as reported in section 3.2), reducing apparent modulus. Although the treated composite,

having a storage modulus of 925 MPa, showed an increase in modulus by 17.83% compared to the untreated composite sample.

3.5.2. Damping factor (Tan δ)

The damping factor (Tan δ) represents a material's ability to dissipate mechanical energy as heat. Tan δ curves for the 3D-printed composites are presented in Fig. 6. The damping behavior of the fiber-sandwiched composites is influenced by several factors, including the composite architecture, fiber–matrix interaction, the chemical characteristics of the fibers, and the softening behavior of the matrix under thermal loading. Figure 6(b) shows that the glass transition temperatures (T_g), as indicated by the Tan δ peaks, exhibited minimal variation among all fiber-sandwiched 3D-printed composites. However, a notable difference in peak Tan δ values was observed across neat PLA, untreated fiber, and treated fiber sandwiched composites. The neat PLA 3D printed composite exhibited the highest Tan δ value (1.49), followed by the untreated fiber sandwiched composite (0.66) and the treated fiber sandwiched composite (0.53). The higher Tan δ value of neat 3D printed PLA reflects its greater molecular mobility and superior energy dissipation capacity at elevated temperatures [47]. In contrast, the treated and untreated fiber sandwiched composite demonstrated the lowest Tan δ value, indicating restricted molecular mobility due to the reinforcing effect of the fiber core. This was further supported by the E' curves, which revealed a gradual decline in storage modulus for the fiber-sandwiched composites. Although these composites entered the rubbery region, the presence of a stiff fiber core limited the softening behavior, enabling the composite to retain a significant level of stiffness (E') even at higher temperatures. This constraint reduced chain mobility, thereby lowering the damping capacity. Additionally, the steep drop in E' observed in the neat PLA sample suggests a quicker transition into the rubbery state compared to the fiber-reinforced composites. The inherent thermal response of neat PLA allows for greater stiffness at ambient conditions and enhanced energy dissipation near T_g . Therefore, the damping behavior, as reflected by the Tan δ profile, is governed by the composite's ability to balance stiffness retention and molecular mobility across the temperature range. Mostly, lower Tan δ values are desirable for structural applications, which means treated composite (PLA composite with NaOH-treated sisal fibers) are favorable for structural and automobile applications.

3.6. Thermomechanical analysis (TMA)

TMA of 3D-printed composites was performed to assess the material expands or contracts in response to varying temperatures. The Fig. 7 (a-b) shows the variation in thermal expansion and expansion coefficient of neat, untreated and treated 3D printed composites with change in temperature. The thermal shrinkage results in Fig. 7 (a) indicate that all composite samples maintained dimensional stability around 52°C. This stability could be attributed to the fact that fiber reinforcement does not significantly influence the glass transition temperature (T_g), which, as shown in Table 4, falls within the range of 50–55°C. Although after T_g region, a drastic change was noticed in thermal expansion. The addition of fibers reduces the thermal expansion % in untreated and treated fiber composites samples as compared to neat composite sample showing the steep curve (around 55–60°C) after the T_g . The neat composite shows the maximum thermal expansion (3.5%) whereas the treated composite sample shows the minimum thermal expansion (0.7%) during entire temperature range. This attributes that neat PLA composite was highly susceptible to dimensional instability near its T_g and NaOH treatment of sisal fibers likely improved fiber-matrix adhesion, limiting thermal deformation and enhancing dimensional stability.

It was noted that thermal expansion of the composite samples is directly linked with the results of thermal expansion coefficient as shown in Fig. 7 (b) and Table 4. At 40°C, no significant changes were observed in the thermal expansion coefficient for all the composites. Similar trends were observed in the thermal expansion coefficient till T_g . Beyond the glass transition temperature (T_g), the neat composite exhibits a sharp rise in thermal expansion coefficient, reaching up to 850 ppm/°C, which reflects its limited dimensional stability caused by increased polymer chain mobility. In contrast, the composite containing untreated fibers shows a reduced expansion coefficient of approximately 460 ppm/°C, indicating some restriction in thermal expansion. However, the treated fiber composite displays minimal variation in thermal expansion across the temperature range. This difference arises because untreated fibers offer limited resistance to thermal movement due to weak interfacial bonding, whereas the enhanced adhesion in treated fiber composites effectively suppresses thermal deformation, resulting in improved dimensional stability.

Table 4
Thermomechanical analysis and thermal expansion coefficient

Temperature (°C)	Thermal expansion coefficient (ppm/°C)		
	Neat	Untreated	Treated
40	20.07	36.14	38.96
50	51.64	78.34	63.65
60	856.91	363.16	104.78
70	860.2	430.89	142.6
Glass transition temperature, T_g (°C)	53.21	56.12	57.65

3.7. Low velocity impact evaluation

The peak force data obtained during the low velocity impact test was analyzed and is presented in the Table 5. The force vs. displacement and force vs. time graphs are shown in the Fig. 8 (a-b). The work done data was presented in Fig. 8 (c-d). These graphs were used to perform peak force analysis [48]. From the figures, it was observed that when the impact load was applied, initial deformation occurred, which progressed to a peak load as the energy was dissipated and absorbed [49]. After reaching the peak, crack initiation and fracture took place, extending the deformation. For the pure PLA composite, a total deformation of 12.20 mm was observed. A sudden drop in force at the peak indicated a sudden failure, as cracking initiated without further propagation, resulting in a large puncture hole. This implies higher energy dissipation, with a total work done of 4.19 J. In the case of the treated fiber-sandwiched composite, the peak force absorbed was 535.08 N, the lowest among the tested samples. This was attributed to the brittle nature of the sisal fiber after chemical treatment. The energy transferred from the matrix to the fiber layers, but the crack initiated and propagated gradually, as reflected by the smooth drop in force and increased deformation [50]. The presence of the intermediate sisal fiber layer helped reduce the damage area, leading to lower energy dissipation of 3.01 J. For the composite with untreated fiber reinforcement, a significantly higher force was required to cause damage, as the untreated fibers were less brittle and resisted deformation more effectively. Although crack propagation eventually led to failure, the lower brittleness of sisal allowed the composite to

absorb more energy before failing, compared to composites sandwiched with stiffer fibers. The peak deformation values were lower, indicating that the composite restricted deformation more effectively, while still reaching peak load, with a work done of 3.34 J.

Table 5
Peak force analysis

Composite Designation	Peak analysis		
	Force (N)	Deformation (mm)	Work done (J)
Neat	602.66	12.20	4.19
Untreated	699.57	8.11	3.34
Treated	535.08	9.56	3.01

The velocity and puncture analysis of the developed composites are presented in the Table 6 and Fig. 9. It was observed that the behavior of puncture force, displacement and the change in impactor velocity differ from that observed in the peak force analysis [51]. This difference is attributed to composite architecture and the force distribution characteristics during impact loading. From the Table 6, it was noted that the initial impact velocity for all composites was 2.15 m/s, but the end velocity decreased post-impact. The end velocity is a measure of how much the velocity was reduced during the interaction between the impactor and the composite [52]. The lower end velocity observed in both the Fig. 9 and the Table 6 indicates that a sudden failure occurred at the peak force, with no significant deformation beyond that point.

Table 6
Velocity and Puncture analysis

Composite Designation	Velocity (m/s)		Puncture	
	Begin	End	Displacement (mm)	Force (N)
Neat	2.15	1.64	11.59	267.54
Untreated	2.15	1.43	12.50	349.78
Treated	2.15	1.71	12.49	301.33

The puncture displacement for the neat PLA composite was 12.49 mm, which was comparable to the displacement observed in the composite sandwiched with untreated sisal fibers. However, the untreated fiber-sandwiched composite required a higher puncture force than neat PLA to allow the impactor to penetrate. This was due to effective stress distribution and the ability of the interlaid sisal fibers to resist puncture, owing to their non-brittle nature [53]. The puncture force for the untreated sisal fiber-sandwiched 3D-printed composite was 349.78 N, the highest among the tested samples. This composite also exhibited the highest energy dissipation, evident from the greater puncture deformation (12.50 mm) and the lower end velocity of the impactor (1.43 m/s), indicating effective energy absorption. In contrast, the treated sisal fiber-sandwiched composite displayed lower puncture displacement due to the higher stiffness and brittleness of the treated fibers. As a result, the composite was unable to significantly reduce the impactor's velocity, since cracking occurred rapidly [54]. Additionally, the treated composite required a lower puncture force, again due to the

brittle nature of the chemically treated fibers. However, good stress transfer from the matrix phase to the treated sisal fiber phase was observed during impact, which was evident in the work vs. displacement curves. These curves exhibited a smooth transition, indicating consistent energy transfer throughout the puncture event.

4. Conclusions

This study demonstrates the significant potential of 3D printing technology in fabricating continuous fiber-reinforced biocomposites using a strategically sandwiched architecture. The strategic placement of NaOH-treated continuous *Agave sisalana* sisal fibers within a PLA matrix resulted in significant improvements in mechanical and thermal performance, overcoming the common limitations of short or randomly oriented natural fiber composites. The mechanical performance of treated composite is impactful, showing the improvement of 36.19% in tensile strength and 46.25% in ILSS strength as compared to neat composite. In addition, the tensile modulus showed enhancements of 38.26% indicating a significant boost in stiffness and load-bearing capacity for automotive applications. Flexural strength and modulus of treated composites enhanced by 9.17% and 8.69%, respectively, as compared to untreated composites. SEM analysis confirmed improved fiber–matrix adhesion and a 12.05% reduction in fiber diameter post-treatment, contributing to better stress transfer. DMA analysis revealed a lower damping factor ($\tan \delta = 0.53$) in treated composites, highlighting their suitability for semi-structural and vibration-damping applications. TMA results indicated a low thermal expansion of 0.7% and a coefficient of thermal expansion of 142.6 ppm/°C at 70°C, pointing to enhanced dimensional stability. Low-velocity impact tests provided additional insights into energy absorption mechanisms. The untreated fiber composite exhibited the highest puncture force (349.78 N), greatest deformation (12.50 mm), and lowest end velocity (1.43 m/s), indicating superior energy dissipation. In contrast, the treated fiber composite showed reduced puncture displacement and lower energy absorption (3.01 J), attributed to increased brittleness but also exhibited smoother force-displacement behavior, reflecting consistent stress transfer. The findings validate the effectiveness of the strategically sandwiched continuous fiber approach in producing lightweight, high-performance 3D-printed composites. Future work should explore optimizing stacking sequences and fiber volume fractions to further tailor the mechanical and thermal properties for specific end-use applications.

5. Future scope

The present work offers the strong technique for producing sustainable, high performance biocomposites through strategic sandwiching of treated sisal fibers through 3D printing. This work opens up the possibilities for developing next generation sustainable composites to meet diverse engineering applications. Based on this future work can be done in following areas:

- Use of hybrid natural fibers and natural filler loaded biopolymers for manufacturing of composite with similar technique.
- Incorporation of nano-reinforcements such as nanoclay, graphene, or cellulose nanocrystals alongside the sisal fibers could offer multifunctionality including improved barrier, thermal, or electrical properties.
- Exploration of shape memory or self-healing functionalities in manufactured biocomposites using 4D printing for intelligent material systems.

Declarations

Acknowledgement

The authors are highly thankful to Natural Composites Research Group Lab, Department of Materials and Production Engineering, The Sirindhorn International Thai-German Graduate School of Engineering (TGGS) and the COIDEM-STRI, King Mongkut's University of Technology Thonburi, Thailand for their instruments and continuous support.

Author Contributions

Mohit Kumar: Conceptualization; methodology; visualization; software; validation; writing—original draft; writing—review and editing. **Ranvijay Kumar:** Conceptualization; visualization; writing—review and editing. **Manoj Kumar Singh:** Conceptualization; visualization; writing—review and editing. **Vinod Ayyapan:** Conceptualization; validation; visualization; writing—review and editing. **Sanjay Mavinkere Rangappa:** Supervision; conceptualization; methodology; visualization; writing—review and editing. **Suchart Siengchin:** Supervision; conceptualization; methodology; visualization; writing—review and editing.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors used ChatGPT-4o to assist with proofreading and refining certain sections of the manuscript. After using this tool, the author carefully reviewed and revised the manuscript to ensure accuracy and clarity. The authors accept full responsibility for the final content presented in this publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

Data will be made available on request.

References

1. S. Prashanth, K. Subbaya, K. Nithin, S. Sachhidananda, Fiber reinforced composites-a review, J. Mater. Sci. Eng 6(03) (2017) 2-6.
2. D.K. Rajak, D.D. Pagar, P.L. Menezes, E. Linul, Fiber-reinforced polymer composites: Manufacturing, properties, and applications, Polymers 11(10) (2019) 1667.
3. J. Proy, F. Massa, D. Notta-Cuvier, F. Lauro, T. Tison, G. Spingler, Integrating fibers and injection molding process variability in short-natural-fiber-reinforced thermoplastics behavior: A review, Materials Today Communications 29 (2021) 102785.
4. J.L. Thomason, J.L. Rudeiros-Fernández, A review of the impact performance of natural fiber thermoplastic composites, Frontiers in Materials 5 (2018) 60.

5. X. Li, Y. Lin, M. Liu, L. Meng, C. Li, A review of research and application of polylactic acid composites, *Journal of Applied Polymer Science* 140(7) (2023) e53477.
6. E.H. Tümer, H.Y. Erbil, Extrusion-based 3D printing applications of PLA composites: a review, *Coatings* 11(4) (2021) 390.
7. R. Gunti, A. Ratna Prasad, A. Gupta, Mechanical and degradation properties of natural fiber-reinforced PLA composites: Jute, sisal, and elephant grass, *Polymer Composites* 39(4) (2018) 1125-1136.
8. J. Finnerty, S. Rowe, T. Howard, S. Connolly, C. Doran, D.M. Devine, N.M. Gately, V. Chyzna, A. Portela, G.S.N. Bezerra, Effect of mechanical recycling on the mechanical properties of PLA-based natural fiber-reinforced composites, *Journal of Composites Science* 7(4) (2023) 141.
9. S.A. Hinchcliffe, K.M. Hess, W.V. Srubar III, Experimental and theoretical investigation of prestressed natural fiber-reinforced polylactic acid (PLA) composite materials, *Composites Part B: Engineering* 95 (2016) 346-354.
10. V.K. Balla, K.H. Kate, J. Satyavolu, P. Singh, J.G.D. Tadimeti, Additive manufacturing of natural fiber reinforced polymer composites: Processing and prospects, *Composites Part B: Engineering* 174 (2019) 106956.
11. I.A. Khilji, C.R. Chilakamarthy, A.N. Surendran, K. Kate, J. Satyavolu, Natural fiber composite filaments for additive manufacturing: a comprehensive review, *Sustainability* 15(23) (2023) 16171.
12. E.M. Agaliotis, B.D. Ake-Concha, A. May-Pat, J.P. Morales-Arias, C. Bernal, A. Valadez-Gonzalez, P.J. Herrera-Franco, G. Proust, J.F. Koh-Dzul, J.G. Carrillo, Tensile behavior of 3D printed polylactic acid (PLA) based composites reinforced with natural fiber, *Polymers* 14(19) (2022) 3976.
13. D. Deb, J. Jafferson, Natural fibers reinforced FDM 3D printing filaments, *Materials Today: Proceedings* 46 (2021) 1308-1318.
14. C.H. Lee, F.N.B.M. Padzil, S.H. Lee, Z.M.A.a. Ainun, L.C. Abdullah, Potential for natural fiber reinforcement in PLA polymer filaments for fused deposition modeling (FDM) additive manufacturing: A review, *Polymers* 13(9) (2021) 1407.
15. S. Awad, R. Siakeng, E.M. Khalaf, M.H. Mahmoud, H. Fouad, M. Jawaid, M. Sain, Evaluation of characterisation efficiency of natural fibre-reinforced polylactic acid biocomposites for 3D printing applications, *Sustainable Materials and Technologies* 36 (2023) e00620.
16. K.E. Mazur, A. Borucka, P. Kaczor, S. Gądek, R. Bogucki, D. Mirzawiński, S. Kuciel, Mechanical, thermal and microstructural characteristic of 3D printed polylactide composites with natural fibers: wood, bamboo and cork, *Journal of Polymers and the Environment* 30(6) (2022) 2341-2354.
17. E. Rezaieyan, E. Taban, U. Berardi, S.B. Mortazavi, M. Faridan, E. Mahmoudi, Acoustic properties of natural fiber reinforced composite micro-perforated panel (NFRC-MPP) made from cork fiber and polylactic acid (PLA) using 3D printing, *Journal of Building Engineering* 84 (2024) 108491.
18. S. Valvez, P. Santos, J. Parente, M. Silva, P. Reis, 3D printed continuous carbon fiber reinforced PLA composites: A short review, *Procedia Structural Integrity* 25 (2020) 394-399.
19. H. Zhao, X. Liu, W. Zhao, G. Wang, B. Liu, An overview of research on FDM 3D printing process of continuous fiber reinforced composites, *Journal of Physics: Conference Series*, IOP Publishing, 2019, p. 052037.

20. H. Zhang, T. Huang, Q. Jiang, L. He, A. Bismarck, Q. Hu, Recent progress of 3D printed continuous fiber reinforced polymer composites based on fused deposition modeling: a review, *Journal of Materials Science* 56(23) (2021) 12999-13022.
21. T. Cersoli, B. Yelamanchi, E. MacDonald, J.G. Carrillo, P. Cortes, 3D printing of a continuous fiber-reinforced composite based on a coaxial Kevlar/PLA filament, *Composites and Advanced Materials* 30 (2021) 26349833211000058.
22. P. Cheng, Y. Peng, K. Wang, A. Le Duigou, S. Ahzi, 3D printing continuous natural fiber reinforced polymer composites: a review, *Polymers for Advanced Technologies* 35(1) (2024) e6242.
23. X. Tian, T. Liu, C. Yang, Q. Wang, D. Li, Interface and performance of 3D printed continuous carbon fiber reinforced PLA composites, *Composites Part A: Applied Science and Manufacturing* 88 (2016) 198-205.
24. H. Zhang, L. Zhang, H. Zhang, J. Wu, X. An, D. Yang, Fibre bridging and nozzle clogging in 3D printing of discontinuous carbon fibre-reinforced polymer composites: Coupled CFD-DEM modelling, *The International Journal of Advanced Manufacturing Technology* 117(11) (2021) 3549-3562.
25. T. Beran, T. Mulholland, F. Henning, N. Rudolph, T.A. Osswald, Nozzle clogging factors during fused filament fabrication of spherical particle filled polymers, *Additive Manufacturing* 23 (2018) 206-214.
26. M. Kumar, R. Kumar, R. Kumar, Material extrusion-based additive manufacturing of sandwiched acrylonitrile butadiene styrene/glass fibers composites: machine learning approach to model tensile stress, *Polymer Composites* 45(16) (2024) 15100-15112.
27. J. Feng, L. Yao, Z. Lyu, Z. Wu, G. Zhang, H. Zhao, Mechanical properties and damage failure of 3D-printed continuous carbon fiber-reinforced composite honeycomb sandwich structures with fiber-interleaved core, *Polymer Composites* 44(3) (2023) 1980-1992.
28. H.-J. Um, J.-S. Lee, J.-H. Shin, H.-S. Kim, 3D printed continuous carbon fiber reinforced thermoplastic composite sandwich structure with corrugated core for high stiffness/load capability, *Composite Structures* 291 (2022) 115590.
29. Y. Chen, Z. Jin, W. Kang, Z. Liu, W. Yang, Y. Li, 3D printed bio-inspired self-similar carbon fiber reinforced composite sandwich structures for energy absorption, *Composites Science and Technology* 248 (2024) 110453.
30. N. Somsuk, S. Pramoonmak, B. Chongkolnee, P. Tipboonsri, A. Memon, Enhancing Mechanical Properties of 3D-Printed PLA Composites Reinforced with Natural Fibers: A Comparative Study, *Journal of Composites Science* 9(4) (2025) 180.
31. M. Mohammed, R. Rahman, A.M. Mohammed, T. Adam, B.O. Betar, A.F. Osman, O.S. Dahham, Surface treatment to improve water repellence and compatibility of natural fiber with polymer matrix: Recent advancement, *Polymer Testing* 115 (2022) 107707.
32. B. Singh, M. Gupta, A. Verma, Influence of fiber surface treatment on the properties of sisal-polyester composites, *Polymer Composites* 17(6) (1996) 910-918.
33. P.K. Bajpai, I. Singh, J. Madaan, Tribological behavior of natural fiber reinforced PLA composites, *Wear* 297(1-2) (2013) 829-840.
34. A. Vinod, S.M. Rangappa, R. Srisuk, J. Tengsuthiwat, S. Siengchin, Agro-waste Capsicum Annum stem: an alternative raw material for lightweight composites, *Industrial Crops and Products* 193 (2023) 116141.

35. A.D. Gudayu, L. Steuernagel, D. Meiners, R. Gideon, Effect of surface treatment on moisture absorption, thermal, and mechanical properties of sisal fiber, *Journal of Industrial Textiles* 51(2_suppl) (2022) 2853S-2873S.
36. M. Kumar, J. Saini, H. Bhunia, Investigations on the strength of mechanical joints prepared from carbon fiber laminates with addition of carbon nanotubes, *Journal of Mechanical Science and Technology* 34(3) (2020) 1059-1070.
37. S.M. Husainie, S.U. Khattak, J. Robinson, H.E. Naguib, A comparative study on the mechanical properties of different natural fiber reinforced free-rise polyurethane foam composites, *Industrial & Engineering Chemistry Research* 59(50) (2020) 21745-21755.
38. L. Marşavina, C. Vălean, M. Mărghiţaş, E. Linul, N. Razavi, F. Berto, R. Brighenti, Effect of the manufacturing parameters on the tensile and fracture properties of FDM 3D-printed PLA specimens, *Engineering Fracture Mechanics* 274 (2022) 108766.
39. H. Bharath, D. Bonthu, S. Gururaja, P. Prabhakar, M. Doddamani, Flexural response of 3D printed sandwich composite, *Composite Structures* 263 (2021) 113732.
40. E. Kassegn, B. Sirhabizu, T. Berhanu, B. Buffel, F. Desplentere, Influence of fiber surface treatment on the mechanical properties of sisal fiber reinforced polylactic acid bio-composites, *Composites and Advanced Materials* 33 (2024) 26349833241275700.
41. E.M. Agaliotis, J.P. Morales-Arias, C.R. Bernal, Morphological, mechanical and thermal characterization of Intralayer hybrid composites based on Polylactic acid (PLA) and sisal fiber, *Journal of Natural Fibers* 19(14) (2022) 7852-7863.
42. M.K. Singh, G. Arora, R. Tewari, S. Zafar, H. Pathak, A.K. Sehgal, Effect of pine cone filler particle size and treatment on the performance of recycled thermoplastics reinforced wood composites, *Materials Today: Proceedings* 62 (2022) 7358-7363.
43. G. Albornoz-Palma, D. Ching, O. Valerio, R.T. Mendonça, M. Pereira, Effect of lignin and hemicellulose on the properties of lignocellulose nanofibril suspensions, *Cellulose* 27 (2020) 10631-10647.
44. S.W. Supit, T. Nishiwaki, F.U. Shaikh, K. Boonserm, S.A. Rahman, Influences of hybrid fiber-reinforcement using wollastonite and cellulose nanofibers on strength and microstructure characterization of ultra-high-performance mortar, *Construction and Building Materials* 423 (2024) 135802.
45. W. Nie, Y. Liao, S. Ghazanfari, Y. Wang, X. Wang, Y. Huang, W. Xia, Insights into the thermomechanical and interfacial behaviors of polymer-clay nanocomposites via coarse-grained molecular dynamics simulations, *Polymer Composites* 45(9) (2024) 8508-8526.
46. S.S. Kumar, P. Shyamala, P.R. Pati, J. Giri, E. Makki, T. Sathish, Mechanical (static and dynamic) characterization and thermal stability of hybrid green composites for engineering applications, *Journal of Materials Research and Technology* 30 (2024) 7214-7227.
47. K. Litauszki, Á. Kmetty, Investigation of the damping properties of polylactic acid-based syntactic foam structures, *Polymer Testing* 103 (2021) 107347.
48. V. Ayyappan, J. Tengsuthiwat, V. Raghunathan, M.R. Sanjay, S. Siengchin, Quasi-static–cyclic and fatigue properties of carbon-innegra/pineapple multi-material laminates, *Industrial Crops and Products* 222 (2024) 119894.

49. A.M. Al-Areqi, B. Aloyaydi, S. Subbarayan, F.A. Al-Mufadi, Low-velocity impact performance of 3D-printed PLA/Epoxy/Glass fibers of composite structures and latches, *Materials Today Communications* 39 (2024) 109264.
50. N.D. Muralidharan, J. Subramanian, J.J. Mary, H. Ramakrishnan, B.R. Jayamaruthi, An Experimental Study on the Low-Velocity Impact Behavior of Biopolymer-Coated Kenaf Fiber Reinforced Epoxy Nanocomposites: A Route to Sustainability, *Materials Circular Economy* 6(1) (2024) 20.
51. Y. Yang, Z. Miao, Y. Liu, H. Tu, Y. Wei, A comprehensive review of fiber-reinforced polymer-matrix composites under low-velocity impact, *Mechanics of Advanced Materials and Structures* (2025) 1-39.
52. S. Karami, M. Haghighi-Yazdi, M. Safarabadi, Low-Velocity Impact Behavior of 3D-Printed Sandwich Panels with Integrated Composite Face Sheets, *Advanced Engineering Materials* 27(4) (2025) 2401923.
53. J.H. Kumar, R. Ramakrishnan, A. Elkaseer, G. Venkatachalam, P.S. Velu, Low-Velocity Impact Behavior of 3D Printed Sandwich Composite with Polylactic Acid–Micro-crystalline Cellulose Bio-inspired Xylotus Lattice Core: Energy Absorption and Crashworthiness, *Journal of Materials Engineering and Performance* (2025) 1-20.
54. S. Kalaimagal, M. Vasumathi, S. Rashia Begum, M. Saravana Kumar, V. Romanovski, B. Salah, Evaluation of impact resistance of sustainable sandwich structures with optimized FDM core geometries using low-velocity drop impact tests, *Polymer Composites* (2025).

Figures

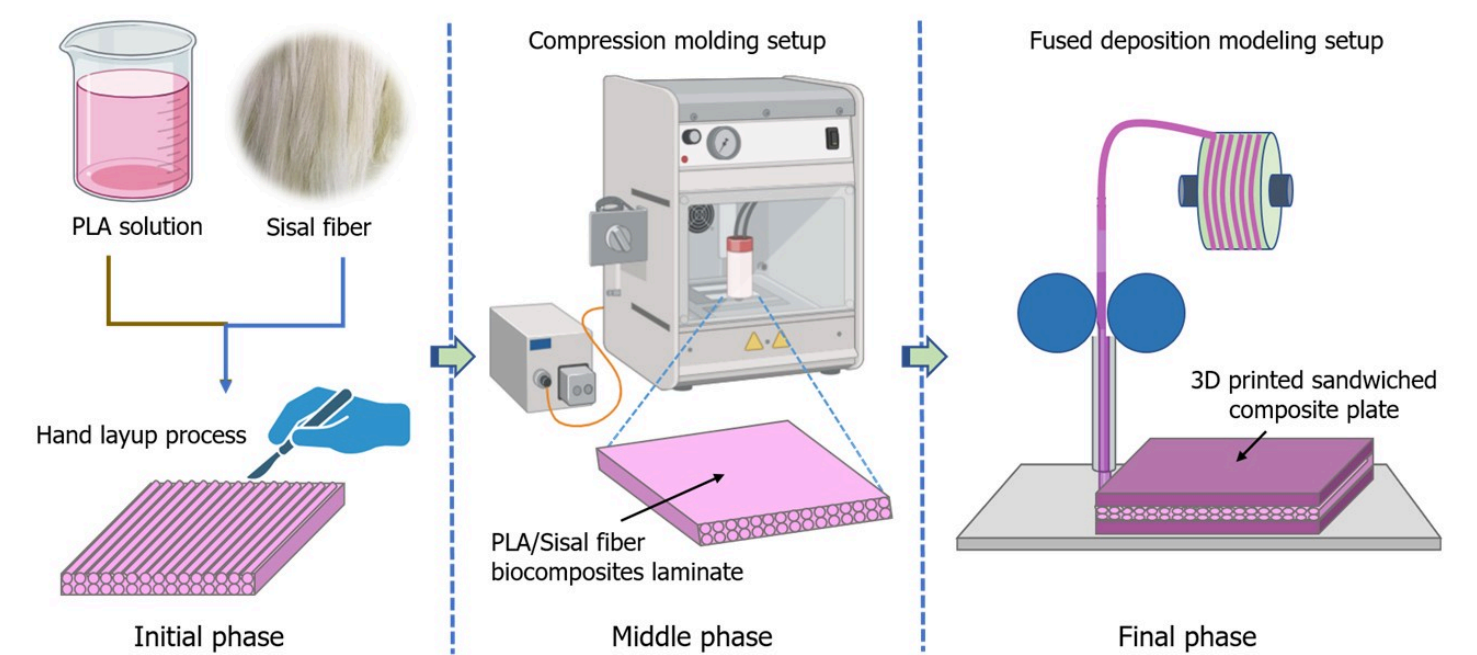


Figure 1

Schematics of the manufacturing of 3D printed sandwiched composite plate

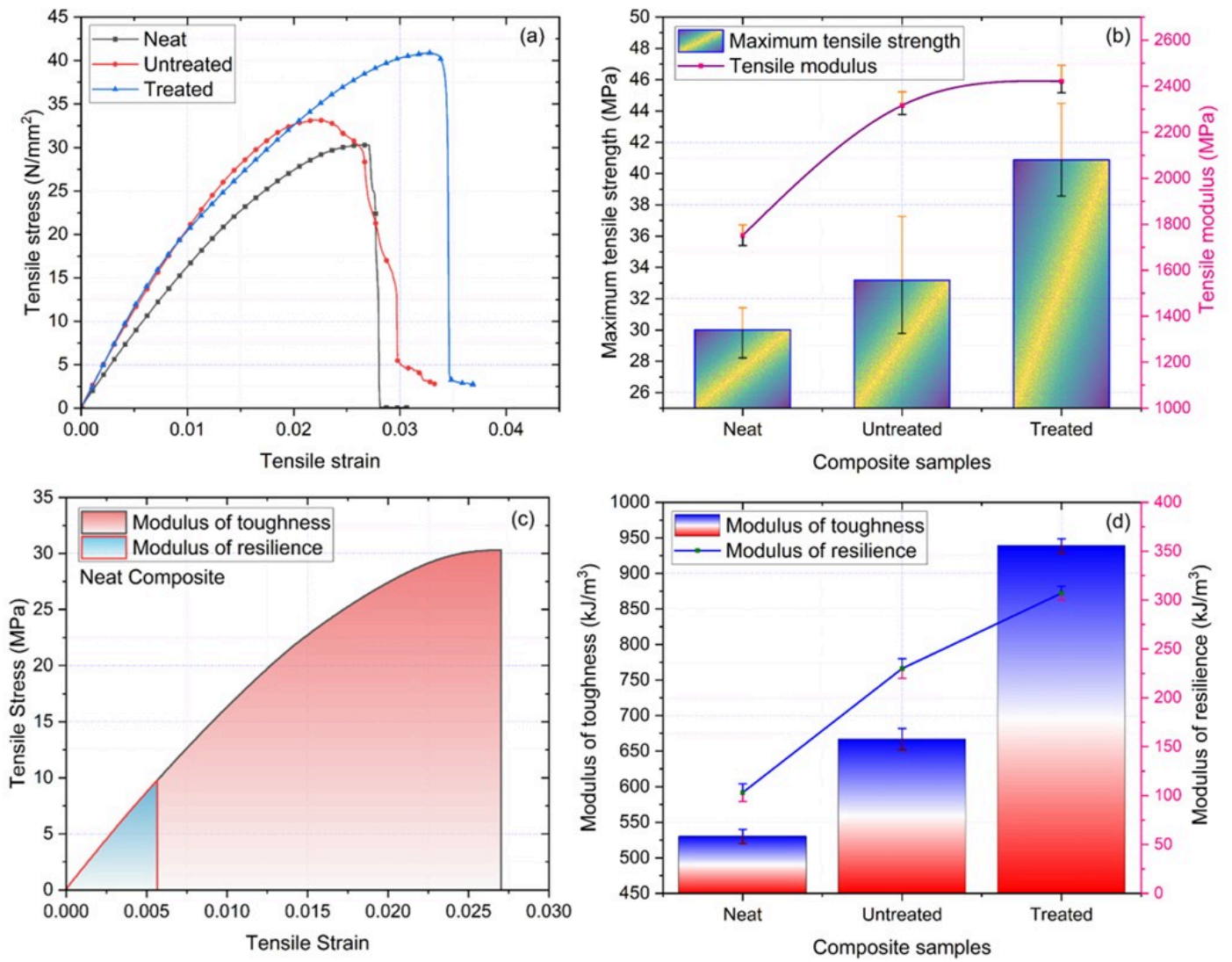


Figure 2

Tensile test results of 3D printed composite samples of neat, untreated and treated configuration (a) Tensile stress vs strain plots, (b) Maximum tensile strength and modulus, (c) representation of modulus of resilience and toughness and (d) Modulus of toughness and resilience plots.

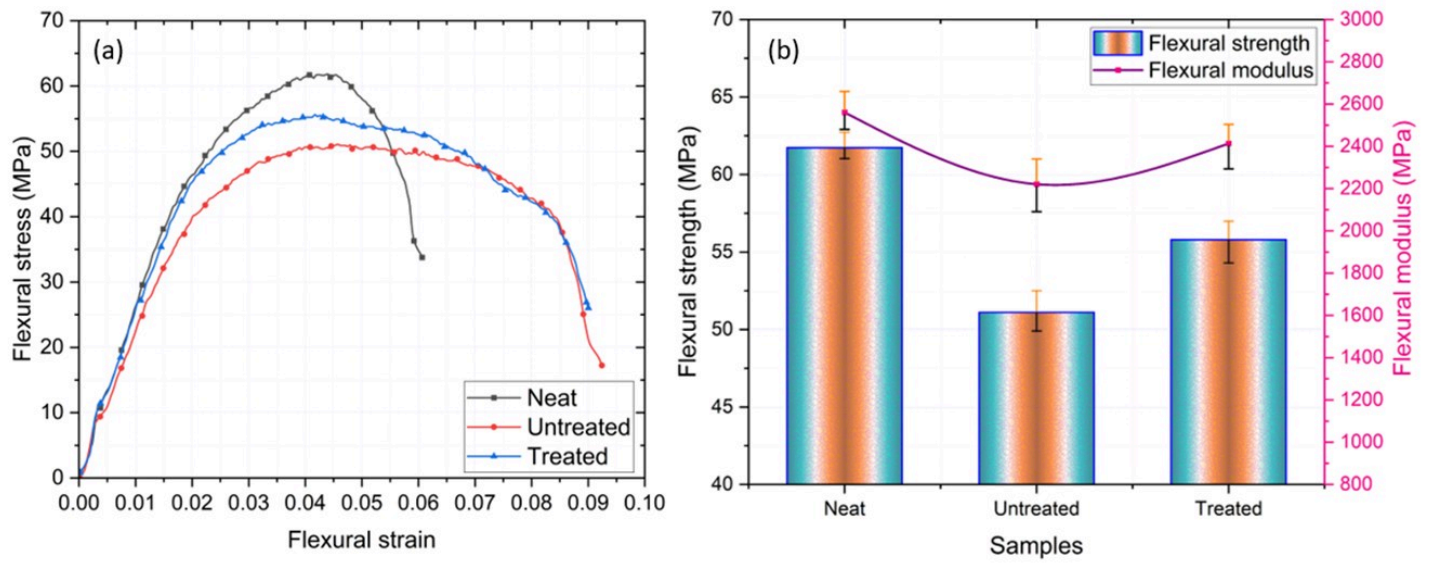


Figure 3

Flexural test results of 3D printed composite samples of neat, untreated and treated configurations (a) Flexural stress vs strain plots and (b) Maximum flexural strength and modulus

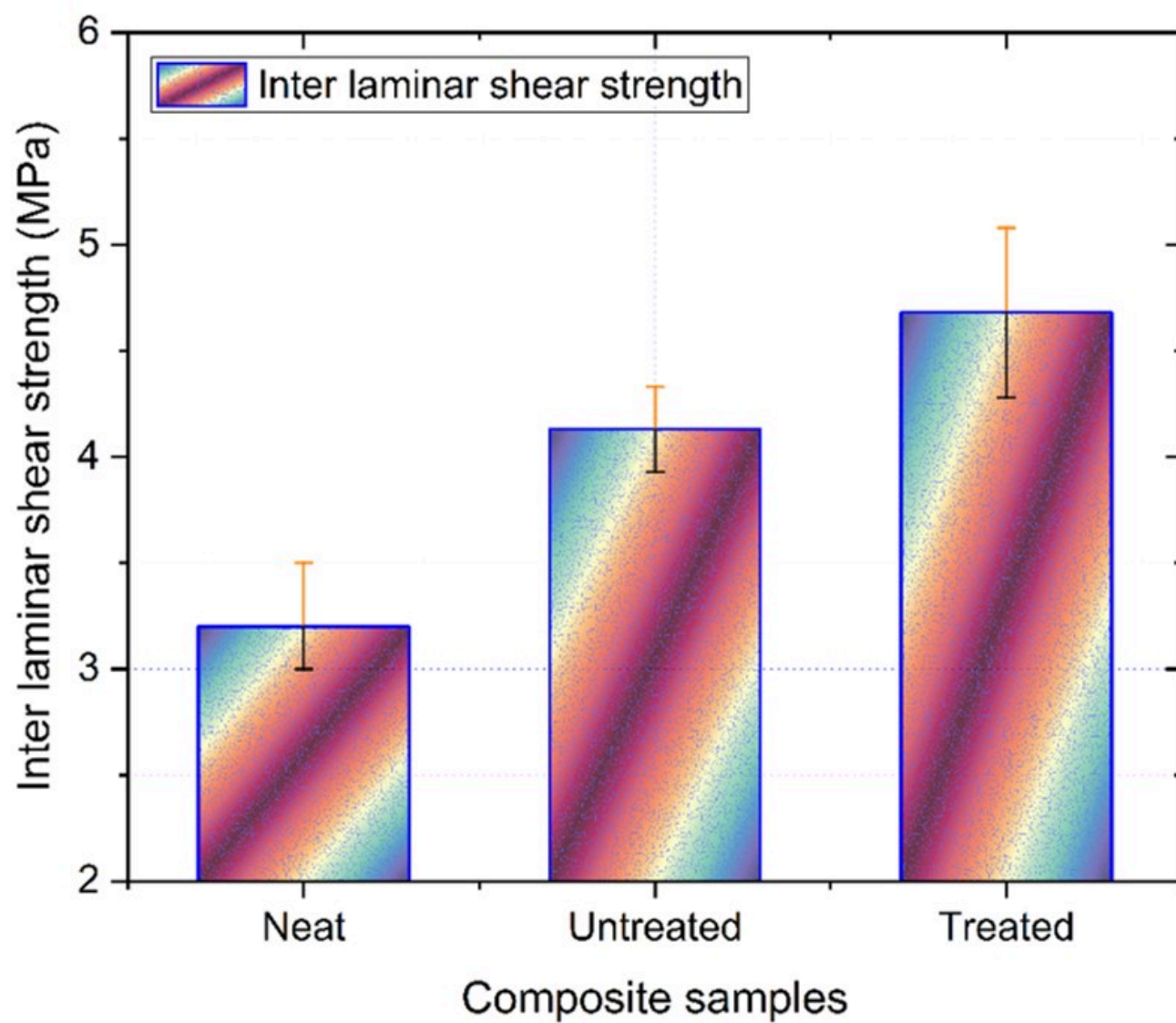


Figure 4

Interlaminar shear strength of 3D printed composite samples of neat, untreated and treated configurations

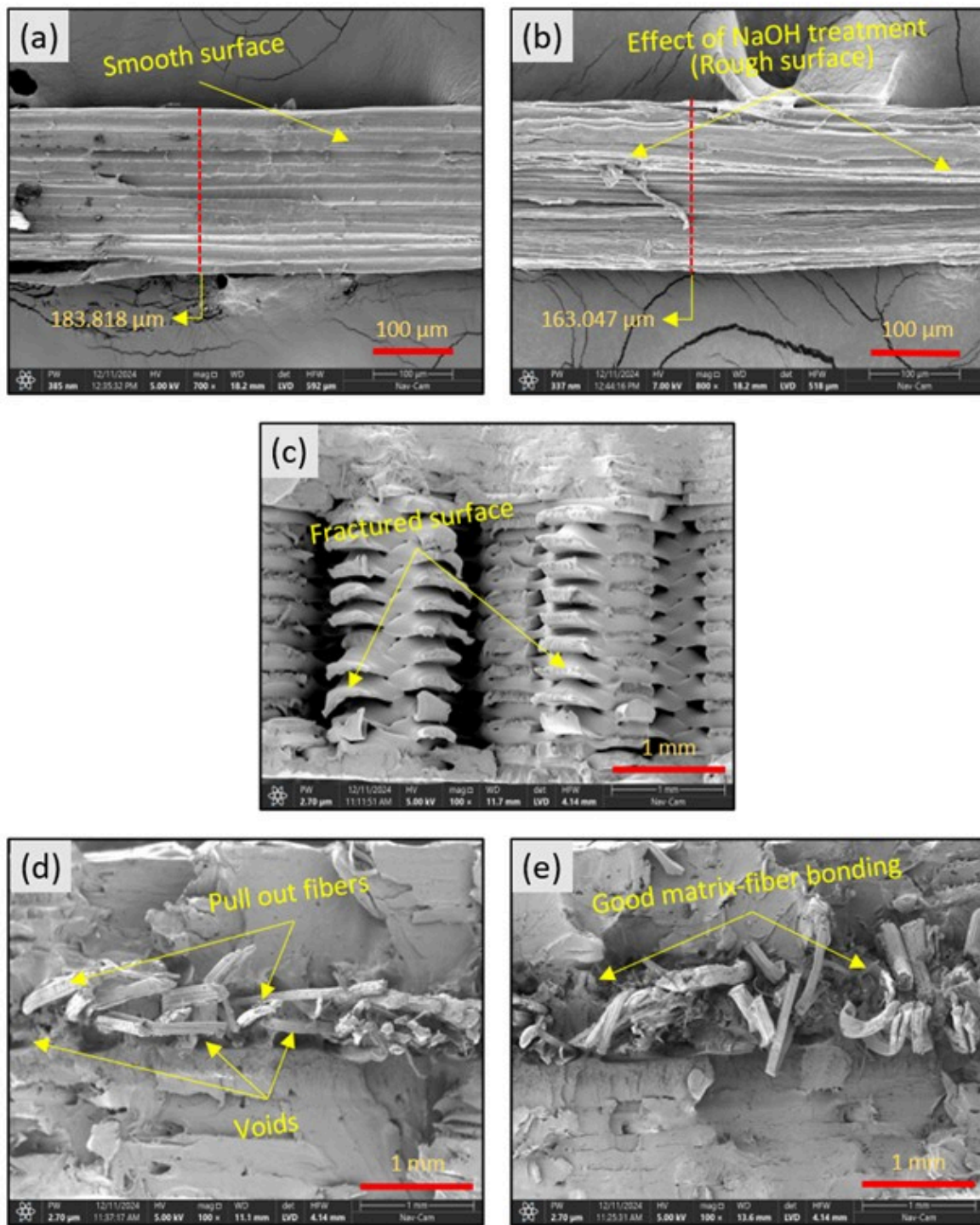


Figure 5

Surface Morphology of the (a) untreated sisal fiber, (b) NaOH treated sisal fiber and fractured samples from tensile test for (c) Neat 3D printed composite sample, (d) 3D printed sandwiched with untreated fibers composite and (e) 3D printed sandwiched with untreated fibers composite samples

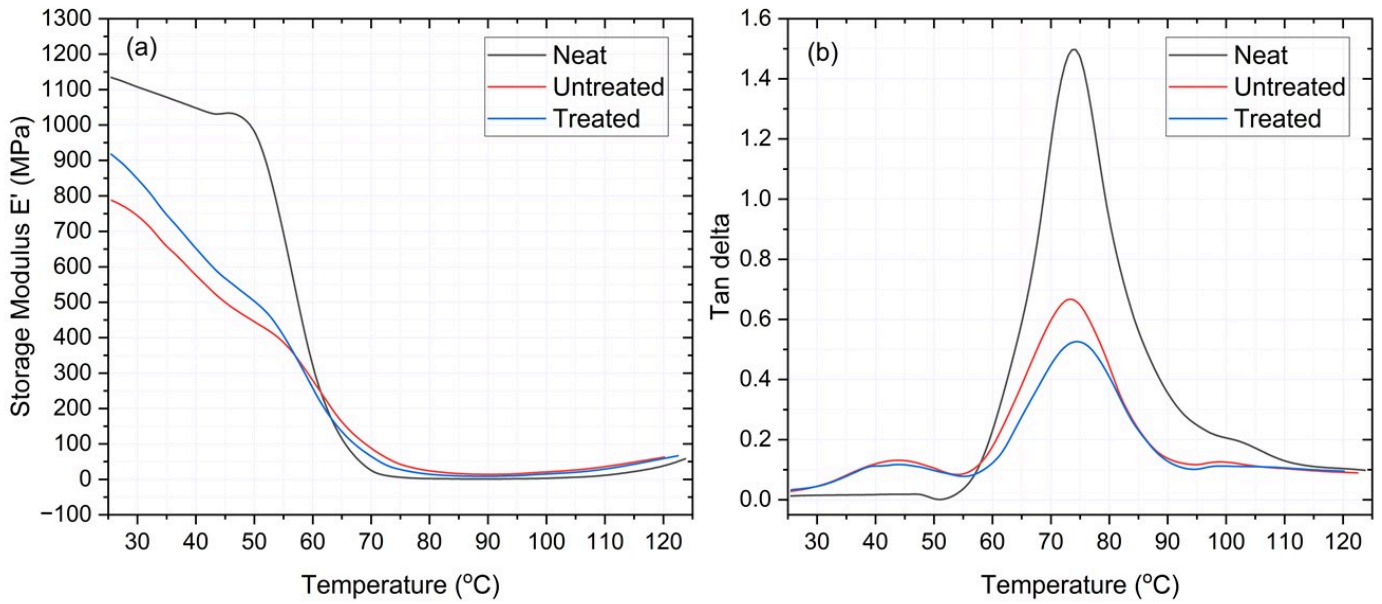


Figure 6

DMA test results in terms of viscoelastic properties as (a) Storage modulus (E') and (b) Damping factor (Tan delta (δ))

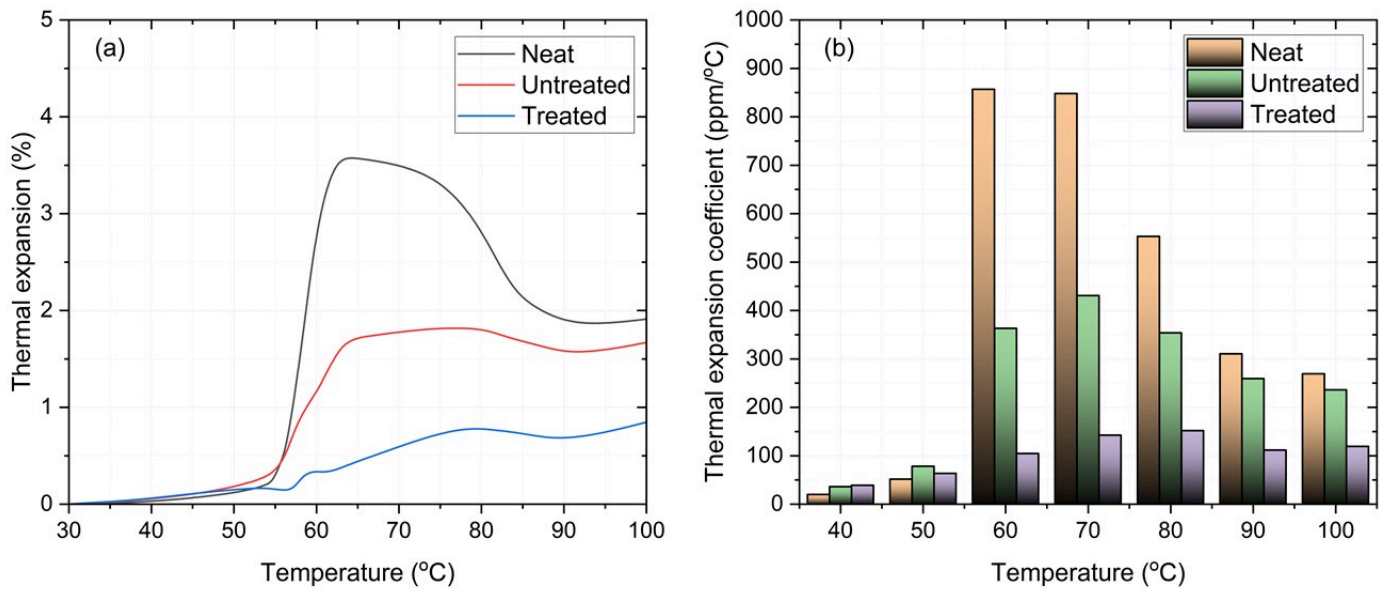


Figure 7

TMA of neat, untreated and treated 3D printed composites via (a) thermal shrinkage and (b) thermal expansion coefficient with temperature

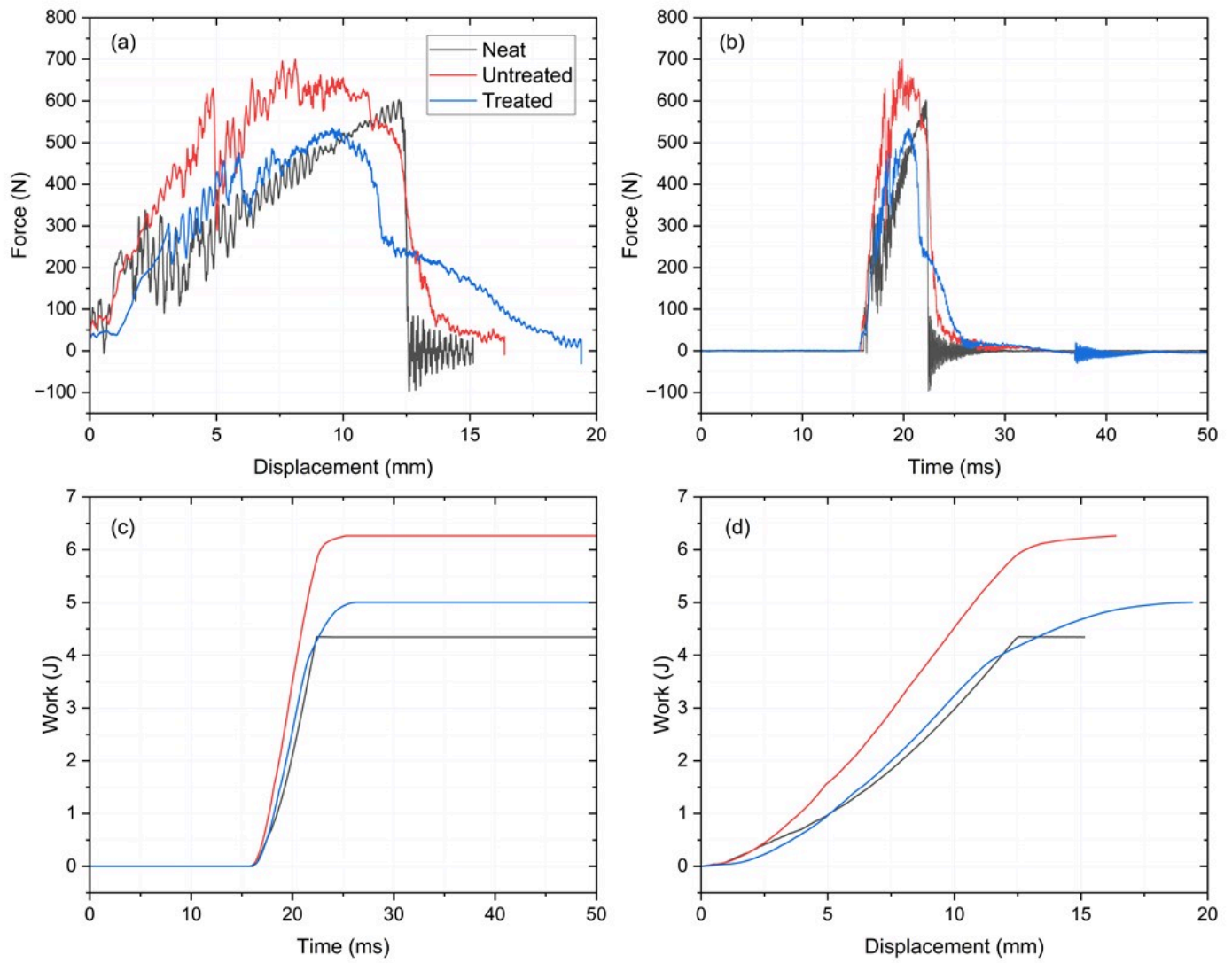


Figure 8

Peak force results (a) force vs displacement, (b) force vs time, and work done (c) work vs displacement, (d) work vs time during low velocity impact

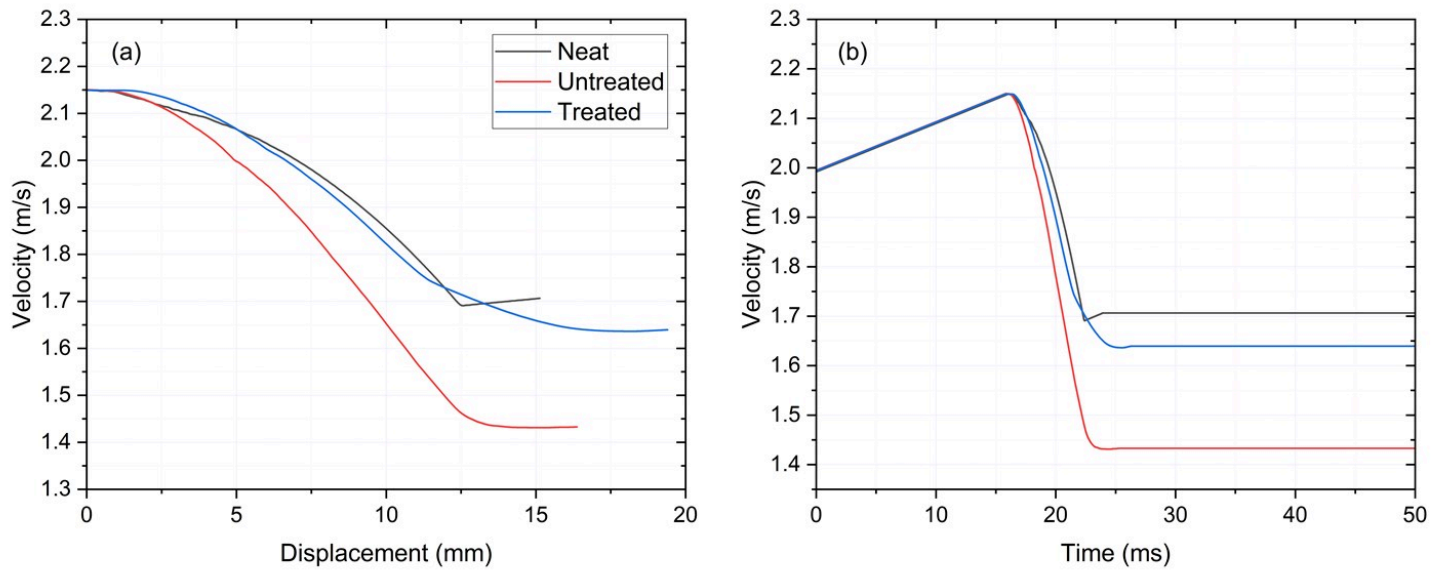


Figure 9

Velocity and puncture results (a) velocity vs displacement and (b) velocity vs time during low velocity impact