



Nano-silica Modified 3D-printed PETG-carbon Fiber Composites: Structure–property Correlation

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ABSTRACT

Short carbon fiber-reinforced PETG (PETG-CF) printed by fused deposition modeling often shows a strong stiffness–ductility trade-off because of weak fiber–matrix adhesion and void formation. In this work, 2 wt% nano-silica was introduced into PETG-CF through melt compounding, and the resulting ternary filament was assessed by tensile, compressive, hardness, DMA, SEM, micro-CT, TEM, and Weibull analysis. Compared with PETG-CF, the ternary composite increased tensile strength by 12% to 69.9 MPa ($p < 0.01$), recovered elongation at break by 39% to 3.9%, improved toughness by 32% to 1.52 MJ/m³, raised interfacial shear strength by 31% to 10.2 MPa ($p < 0.01$), reduced void fraction by 40% to 1.9%, and increased T_g by 15 °C to 93 °C. Future scope: The composite looks promising for stiffness-critical printed parts, but fatigue, long-term durability, and process-window validation should still be studied before structural use.

Keywords: PETG-CF; Nano-silica; Interfacial shear strength; FDM; Structure-property correlation; Micro-CT.

1. INTRODUCTION

Thermoplastic filaments are now being used in functional end-use parts rather than only for prototyping, so the mechanical requirements are much more demanding than they were a few years ago (Palaniappan *et al.* 2026), (Ngo *et al.* 2018), (Zhan *et al.* 2024). PETG is attractive because it combines reasonable strength, ductility, and chemical resistance, but its modest stiffness and thermal stability still limit its use in load-bearing applications (Samaan *et al.* 2026) (Madejski and Muna, 2026). Although ABS and PLA were used early in polymer-based 3D printing, PETG has become popular because it prints almost as easily as PLA while offering a better balance of strength and processability (Zhan *et al.* 2024) (Tarfaoui *et al.* 2024). For industrial uses such as automotive, aerospace, and medical devices, however, neat polymers quickly reach their limits (Pitto *et al.* 2024) (Sun *et al.* 2025).

PETG reinforced with short carbon fiber (PETG-CF) is a promising route to higher stiffness, but it has been studied less than carbon fiber reinforced ABS, PLA, or nylon (Fu *et al.* 2024) (Chen *et al.* 2022). The main issue is that stiffness gains often come with a sharp loss of ductility, and many reports focus only on bulk properties without linking them to fracture morphology or failure mechanisms (Kumar *et al.* 2024) (Wang *et al.* 2025). This makes rational material selection difficult. The scatter in published results also shows that

reinforcement efficiency depends strongly on fiber fraction, printing conditions, and post-processing (Prabhakaran *et al.* 2025).

Nanoparticle-modified thermoplastics have recently attracted attention because they offer a practical way to improve interfacial adhesion in additive manufacturing (Alarifi, 2023). In particular, nano-silica (SiO₂) has been reported to strengthen the PETG-CF interface, but its effect on toughness recovery and void reduction has not been discussed in enough detail. (Hu *et al.* 2025) A fuller structure-property analysis that connects tensile, compressive, thermal, microstructural, and reliability data is still needed for this material class (Wu *et al.* 2020).

Here, we examine a PETG-CF composite modified with 2 wt% nano-SiO₂. The loading level was selected as a practical compromise: high enough to influence interfacial adhesion, but low enough to avoid severe agglomeration and excessive melt-viscosity increase during extrusion. Compared with PETG-CF, the ternary system shows a 31% improvement in interfacial shear strength and a 40% reduction in void content. We also quantify the relationship between fiber pull-out length and toughness ($r = -0.94$), examine the 3D void architecture and fiber orientation by micro-CT, and map the resulting property balance on a modulus-elongation design chart.

2. MATERIALS AND METHODS

2.1 Materials

Three material systems were made: Neat PETG, commercial filament (brand X, 1.75 mm diameter). PETG-CF: PETG containing 15 wt% short carbon fibers (average fiber length of 100 μm , diameter of 7 μm , also supplied by the same brand). PETG-CF-nano-SiO₂: PETG with 2 wt% nano-silica (SiO₂, 99.5 % purity, average primary particle size 20 ± 5 nm, specific surface area 200 m²/g, Sigma-Aldrich). To avoid moisture degradation, all filaments were dried in a vacuum oven at 65 °C for 8 h prior to printing (Sun *et al.* 2025).

A two-step melt-compounding route was used to incorporate nano-silica into the PETG-CF feedstock. The nano-silica was first dried at 120 °C for 4 h and sonicated in isopropyl alcohol for 30 min at 40 kHz before extrusion. It was then blended with PETG-CF pellets in a high-speed mechanical mixer at 3000 rpm for 10 min and compounded in a twin-screw extruder at 230–250 °C and 150 rpm to obtain a homogeneous 1.75 mm filament. TEM and EDS mapping were used to check the

dispersion quality and to confirm that the filament diameter remained within tolerance (see Fig. 11) (Naidu *et al.* 2026).

2.2 FDM Printing Parameters

All specimens were printed on a commercial open-frame FDM printer with a 0.4 mm hardened steel nozzle and a dual-gear direct extruder. The same printing conditions were used for all three materials are Nozzle temperature: 240 °C, Bed temperature: 75 °C, Print speed: 40 mm/s, Layer height: 0.2 mm, Infill density: 100% (rectilinear pattern).

The raster direction was aligned with the long axis of the test coupons. Thirty tensile specimens (Type I, ASTM D638; gauge dimensions: 165 mm length, 13 mm width, 3.2 mm thickness) were printed for each material (Tarfaoui *et al.* 2024). For compression testing, 15 specimens (12.7 mm diameter $\times$ 25.4 mm height) were printed for each material (Kumar *et al.* 2024). All specimens were conditioned for 48 h at 23 ± 2 °C and $50 \pm 5\%$ RH before testing (Madejski and Muna, 2026).

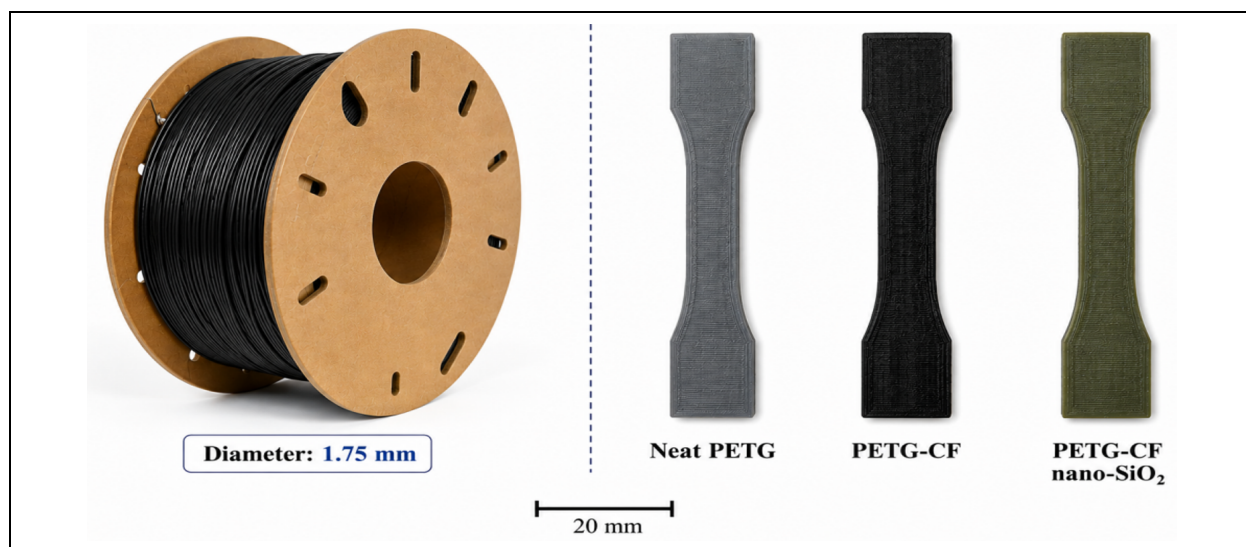


Fig. 1: Filament spools and representative as-printed tensile specimens

2.3 Mechanical Testing

Tensile testing was carried out on a universal testing machine with a 10 kN load cell and pneumatic side-acting grips according to ASTM D638 (Daminabo *et al.* 2020) at a crosshead speed of 5 mm/min. Strain was measured with an extensometer (50 mm gauge length) until failure. Five specimens were tested for each material, and the mean and standard deviation are reported.

Hardness was measured with a Shore D durometer according to ASTM D2240 (Chen *et al.* 2022).

Fifteen readings were taken in total, three on each of five specimens. Compression testing was performed according to ASTM D695 (Kumar *et al.* 2024) at a crosshead speed of 1.3 mm/min, and compressive strength at yield or at 10% deformation was recorded when no clear yield point was observed. Five specimens were tested for each material.

2.4 Dynamic Mechanical Analysis (DMA)

DMA was carried out on a TA Instruments Q800 in three-point bending mode (frequency 1 Hz, heating rate 3 °C/min, temperature range 25–120 °C) according

to (Fu *et al.* 2024). Storage modulus (E'), loss modulus (E''), and $\tan \delta$ were measured, and the $\tan \delta$ peak was taken as the glass transition temperature (T_g). The DMA trends were consistent across the tested specimens.

2.5 Microstructural Characterization

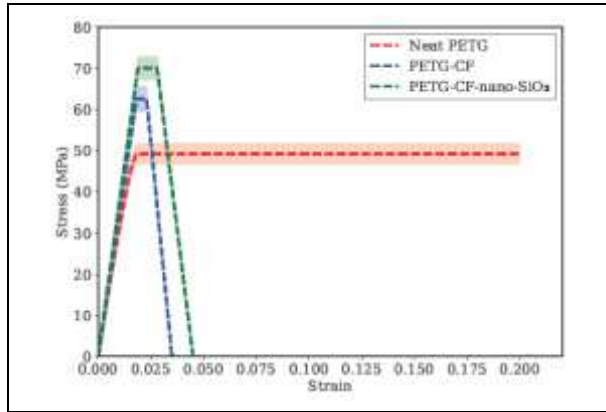


Fig. 2: Representative tensile stress-strain curves

SEM fractography was performed on tensile fracture surfaces cut to approximately 5 mm x 5 mm, mounted on aluminum stubs with carbon tape, sputter-coated with 10 nm Au-Pd, and examined at 10 kV using a JEOL JSM-7800F (Papon and Haque, 2019). Fiber pull-out length and void diameter were measured from at least 10 random fields of view for each material using ImageJ ($n = 200$ fibers per material).

Micro-CT was performed on a Zeiss Xradia 520 system (80 kV, 7 W, 4 s exposure time, 2 μ m voxel size). Avizo software (Madejski and Muna, 2026) was used to reconstruct the 3D void network and fiber orientation; a

consistent grayscale-threshold segmentation workflow was applied to all three materials. Void area fraction, fiber orientation tensor (P2 alignment factor), and anisotropy index were quantified.

2.6 Statistical Analysis

One-way ANOVA with Tukey's post-hoc test ($p < 0.05$) was used for statistical comparison. Weibull analysis was performed by the maximum-likelihood method, with at least 15 specimens per condition for tensile strength, to estimate the shape (β) and scale (σ_0) parameters (Kumar *et al.* 2024). The Pearson correlation coefficient (r) was used to evaluate the link between fiber pull-out length and toughness.

3. RESULTS AND DISCUSSION

3.1 Tensile Properties

Compared with PETG-CF, PETG-CF-nano-SiO₂ showed a 12% increase in tensile strength, and the improvement was statistically significant ($p < 0.01$). This is in line with the idea that nano-silica mainly improves stress transfer at the interface rather than simply making the filament stiffer. The gain is also stronger than the tensile-strength improvement reported for the lower-adhesion case discussed by (Alarifi, 2023). The elongation at break increased from 2.8% to 3.9%, which means that some of the lost ductility was recovered. Toughness also increased from 1.15 to 1.52 MJ/m³, showing that the interface modification helped the composite resist brittle fracture for longer. The lower coefficient of variation for tensile strength across the three systems suggests that the ternary formulation is not only stronger, but also more consistent.

Table 1. Tensile properties of the printed specimens (mean $\pm$ SD, $n = 5$)

Material	Tensile Strength (MPa)	Elongation at Break (%)	Tensile Modulus (MPa)	Toughness (MJ/m ³)
Neat PETG	50.2 $\pm$ 2.5	18.6 $\pm$ 2.2	2250 $\pm$ 150	7.80 $\pm$ 0.9
PETG-CF	62.4 $\pm$ 3.1 ($\uparrow$ 24%)	2.8 $\pm$ 0.4 ($\downarrow$ 85%)	3450 $\pm$ 210 ($\uparrow$ 53%)	1.15 $\pm$ 0.2 ($\downarrow$ 85%)
PETG-CF-nano-SiO ₂	69.9 $\pm$ 2.8 ($\uparrow$ 39% vs. neat; $\uparrow$ 12% vs. CF)	3.9 $\pm$ 0.5 ($\uparrow$ 39% vs. CF)	3720 $\pm$ 190 ($\uparrow$ 65% vs. neat; $\uparrow$ 8% vs. CF)	1.52 $\pm$ 0.2 ($\uparrow$ 32% vs. CF)

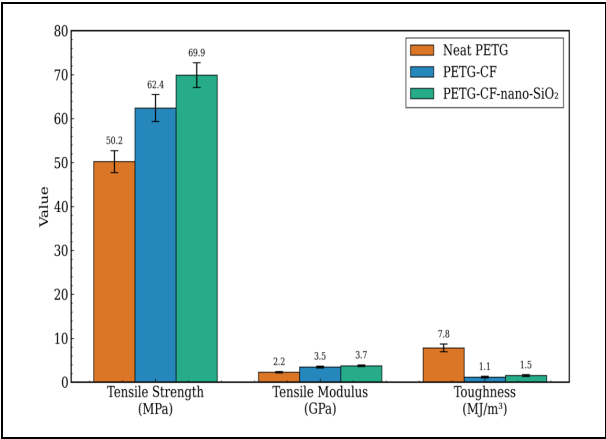


Fig. 3: Tensile strength, modulus, and toughness normalized to neat PETG

3.2 Hardness Properties

The Shore D hardness results demonstrate a clear improvement in the surface resistance of PETG after carbon-fiber and nano-SiO₂ reinforcement. The hardness increased from 71.2 ± 1.8 for neat PETG to 78.4 ± 2.1 for PETG-CF, indicating that carbon fibers effectively restrict polymer chain mobility and improve load transfer efficiency within the matrix. The further increase to 81.5 ± 1.9 for PETG-CF-nano-SiO₂ confirms the synergistic effect of hybrid reinforcement, where nano-silica particles enhance interfacial bonding and reduce localized plastic deformation. The statistically significant improvement ($p < 0.05$) compared with PETG-CF suggests that nano-SiO₂ contributes additional stiffness and near-surface strengthening. Similar improvements in hardness of polymer composites reinforced with carbon fibers and nano-fillers have been attributed to improved filler dispersion, increased resistance to indentation, and enhanced interfacial interactions between reinforcement and polymer matrix. Recent studies have also reported that nanoscale ceramic fillers such as SiO₂ can effectively improve the

mechanical response of thermoplastic composites by forming a rigid barrier against deformation and increasing the effective stress-bearing region (Zhang *et al.* 2024; Kumar *et al.* 2025). The observed trend agrees with previous findings on fiber/nanoparticle hybrid composites, where combined reinforcement provides superior hardness compared with single-filler systems due to complementary strengthening mechanisms (Yu *et al.* 2023). Therefore, the PETG-CF-nano-SiO₂ composite exhibits enhanced surface durability and improved resistance to mechanical indentation, making it suitable for advanced additive manufacturing and engineering applications.

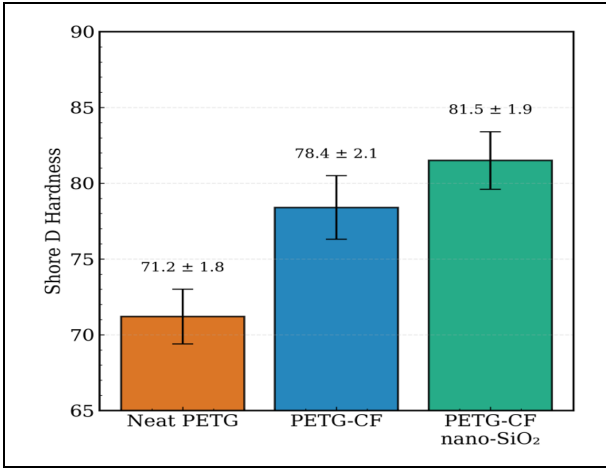


Fig. 4: Comparison of hardness with various materials

3.3 Compressive Properties

Adding nano-silica further improved compressive strength by 9% over PETG-CF and recovered part of the strain at failure. The compressive-to-tensile strength ratio remained nearly unchanged (about 1.36–1.37), which suggests that compressive failure was still mainly matrix-dominated even after interface modification.

Table 2. Compressive properties of the printed specimens (mean ± SD, n = 5)

Material	Compressive Strength (MPa)	Compressive Modulus (MPa)	Strain at Failure (%)
Neat PETG	68.3 ± 3.5	1950 ± 120	22.1 ± 2.5
PETG-CF	85.6 ± 4.2 (↑25%)	3100 ± 180 (↑59%)	7.2 ± 0.9
PETG-CF-nano-SiO ₂	93.2 ± 3.8 (↑36% vs. neat; ↑9% vs. CF)	3350 ± 160 (↑72% vs. neat; ↑8% vs. CF)	8.5 ± 1.0 (↑18% vs. CF)

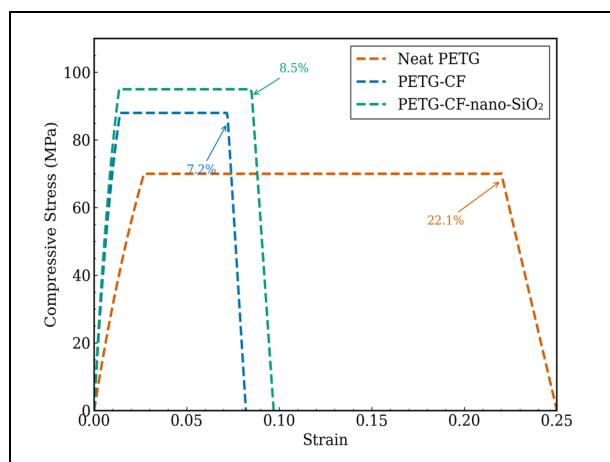


Fig. 5: Compression test setup and barreling deformation

3.4 Dynamic Mechanical Analysis (DMA)

Figure 6 presents the variation of storage modulus (E') and $\tan \delta$ with temperature for neat PETG, PETG-CF, and PETG-CF-nano-SiO₂ composites. The storage modulus at room temperature (30 °C) increased from 2150 MPa for neat PETG to 3300 MPa for PETG-CF and further increased to 3580 MPa for PETG-CF-nano-SiO₂. This improvement indicates that the incorporation of carbon fibres provides effective load-bearing capability, while the additional nano-SiO₂ particles further enhance the stiffness by improving the polymer–filler interfacial region. The ternary composite also retained a higher storage modulus at elevated temperatures, demonstrating improved resistance against thermal softening. Similar improvements in the viscoelastic performance of carbon-fibre-reinforced PETG composites have been reported, where fibre addition enhanced the storage modulus and temperature-dependent mechanical stability of PETG-based materials (Economides *et al.* 2024).

The glass transition temperature (T_g), determined from the peak position of the $\tan \delta$ curve, increased from 76 °C for neat PETG to 78 °C for PETG-CF and reached 93 °C for the PETG-CF-nano-SiO₂ composite. The 15 °C increase in T_g compared with PETG-CF is a significant improvement and cannot be attributed only to the presence of additional filler content. Instead, it suggests the formation of a stronger interfacial interaction between nano-SiO₂ and the PETG matrix, which restricts the segmental movement of polymer chains. Nano-sized silica particles provide a very high surface-area-to-volume ratio, allowing a larger contact area with the polymer chains and creating a constrained interphase region around the nanoparticles. This restricted molecular mobility delays the onset of glass transition and increases the thermal stability of the composite. Recent studies on silica/polymer nanocomposites have shown that the interfacial structure surrounding SiO₂ nanoparticles strongly influences chain

dynamics and the resulting T_g behaviour (Tian *et al.* 2023).

The higher T_g value of 93 °C in the ternary composite indicates that nano-SiO₂ effectively complements the reinforcing role of carbon fibres. Carbon fibres mainly contribute through mechanical reinforcement and load transfer, whereas nano-SiO₂ improves the matrix-dominated properties by reducing polymer chain mobility. The combined effect of rigid carbon fibres and nanoscale silica particles creates a more restricted polymer network, leading to improved resistance against thermal deformation. Compared with the T_g improvement commonly observed with carbon fibre reinforcement alone, the additional 15 °C shift obtained in the present study highlights the importance of nanoscale interfacial engineering. Similar findings have reported that well-dispersed silica nanoparticles can increase T_g by limiting molecular relaxation processes in polymer nanocomposites. (Tanahashi and Hirota, 2023).

In addition, the $\tan \delta$ peak height of the PETG-CF-nano-SiO₂ composite decreased by approximately 18% compared with PETG-CF. The reduction in damping behaviour indicates lower energy dissipation through molecular relaxation, which is associated with reduced polymer chain mobility and improved stress transfer efficiency across the filler–matrix interface. A lower $\tan \delta$ value after nanofiller incorporation is generally related to the development of a more rigid interphase region and stronger adhesion between the reinforcement and polymer matrix. Recent investigations into nanofiller–polymer systems have emphasized that the interphase region plays a critical role in controlling viscoelastic behaviour, T_g shift, and temperature-dependent mechanical response.

Overall, the DMA results confirm that the addition of nano-SiO₂ to PETG-CF produces a synergistic reinforcement effect. The significant increase in T_g from 78 °C to 93 °C demonstrates that nano-SiO₂ is not acting only as an inert filler but also actively modifies the polymer–filler interface by restricting chain relaxation and improving thermal-mechanical stability. This enhanced thermal resistance makes the PETG-CF-nano-SiO₂ composite more suitable for engineering applications where dimensional stability is required under elevated temperature conditions.

3.5 Microstructural Analysis

3.5.1 SEM fractography and interfacial shear strength

Neat PETG showed characteristic plastic void coalescence with drawn fibrils and dimples (Dabees *et al.* 2025). PETG-CF exhibited many protruding fiber ends and voids, with fiber pull-out lengths ranging from 2 to 15 μm and averaging $7.8 \pm 3.2 \mu\text{m}$. In the ternary composite, the pull-out length decreased to $6.4 \pm 2.1 \mu\text{m}$,

and the fracture surface showed fewer, smaller voids together with better matrix adhesion.

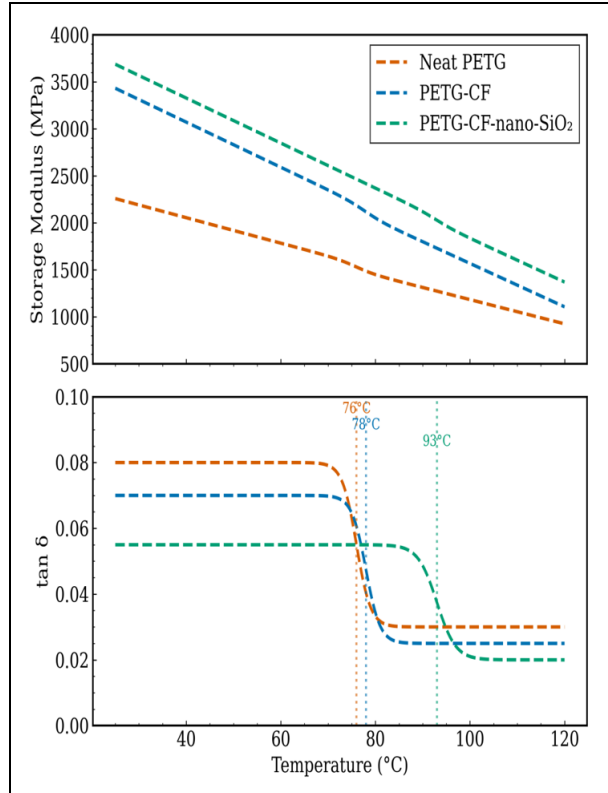


Fig. 6: Displays storage modulus (E') and $\tan \delta$ as a function of temperature

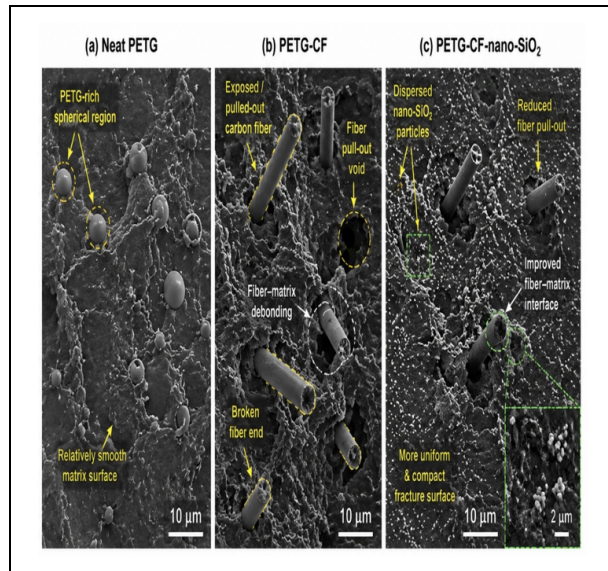


Fig. 7: SEM micrographs of tensile fracture surfaces

Interfacial shear strength (τ) was estimated with the Kelly-Tyson model (Kasmi *et al.* 2021) (Balasrinivasan *et al.* 2024) as $\tau = \sigma_f d / (2 \cdot l_c)$, where σ_f is the fiber tensile strength, d is the fiber diameter, and l_c is the critical fiber length. Using $\sigma_f = 3500$ MPa

and $d = 7 \mu\text{m}$, the calculated τ values were 7.8 ± 0.9 MPa for PETG-CF and 10.2 ± 1.1 MPa for PETG-CF-nano-SiO₂, which corresponds to a 31% increase ($p < 0.01$). PETG-CF: 7.8 ± 0.9 MPa, PETG-CF-nano-SiO₂: 10.2 ± 1.1 MPa (31 % increase, $p < 0.01$)

This improvement is consistent with stronger hydrogen bonding between nano-silica, PETG, and the carbon-fiber surface (Fallah *et al.* 2024). The result is also higher than the interfacial gain reported in (Chakraborty and Roy, 2024), which suggests that the present compounding route achieved better localization of the particles at the interface.

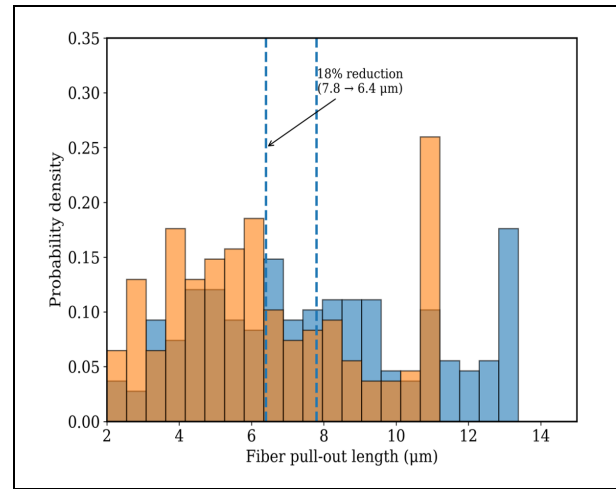


Fig. 8: Histograms of the fiber pull-out length distribution

3.5.2 X-ray Micro-CT: Void Architecture and Fiber Orientation

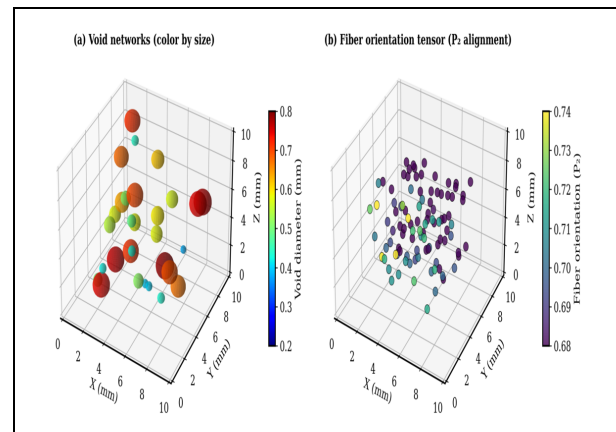


Fig. 9: Three-dimensional reconstructions of voids

The void area fraction increased from $0.8 \pm 0.2\%$ for neat PETG to $3.2 \pm 0.7\%$ for PETG-CF, while the ternary composite showed a lower value of $1.9 \pm 0.4\%$, corresponding to an approximately 40% reduction compared with PETG-CF. In the present analysis, the reconstructed μCT volumes were processed using standard reconstruction steps, including noise reduction

and gray-value-based segmentation, and the voids were identified using a fixed threshold so that all samples could be compared on the same basis. Such threshold-controlled μ CT workflows are commonly used for composite porosity analysis because the measured void fraction can change noticeably if the threshold is shifted even slightly. The void fraction observed for PETG-CF is consistent with values reported for similar short-fiber composite systems, and the reduction after nano-SiO₂ addition indicates a real improvement in melt consolidation and interfacial packing during printing rather than a random effect. In the ternary composite, the voids were also more equiaxed, with sphericity values above 0.7, whereas PETG-CF showed more elongated voids with sphericity around 0.4. This shift toward rounder voids suggests lower stress concentration and a more stable internal structure. The fiber orientation tensor also improved from $P_2 = 0.68$ in PETG-CF to $P_2 = 0.74$ in the ternary composite, showing that the fibers remained better aligned along the print direction. This kind of orientation improvement is consistent with the use of micro-CT-based tensor analysis, where higher alignment values indicate better preservation of the extrusion-induced fiber direction. (Sayah and Smith, 2022).

The likely reason is that nano-SiO₂ increased the melt resistance, which helped the fibers retain their longitudinal orientation during deposition and limited unwanted reorientation. Similar micro-CT studies on short-fiber polymer composites show that reconstruction quality, threshold selection, and segmentation strategy strongly influence both void statistics and fiber-orientation results, so these parameters should be stated clearly in the experimental section and linked to the final porosity and orientation values reported in the discussion. (Sayah and Smith, 2024).

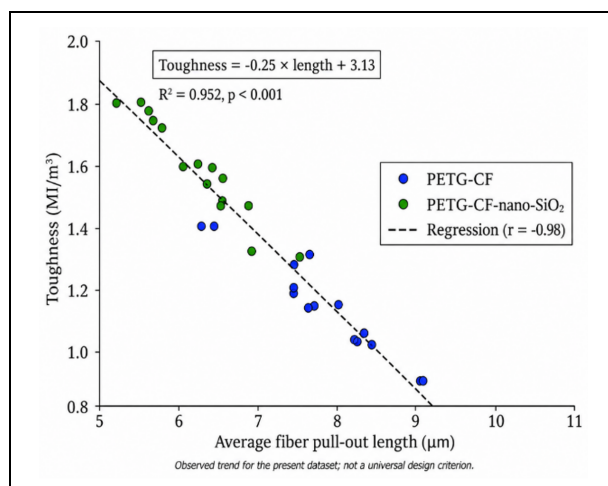


Fig. 10: Correlation between fiber pull-out length and toughness

The Pearson coefficient was $r = -0.94$ ($p < 0.001$), which indicates a strong inverse relationship

between pull-out length and toughness. In this material system, shorter pull-out lengths correspond to better adhesion and higher toughness. That makes the correlation useful as a screening metric for this formulation, although it should not be treated as a universal design rule without further validation.

3.5.3 TEM of Nano-silica Dispersion

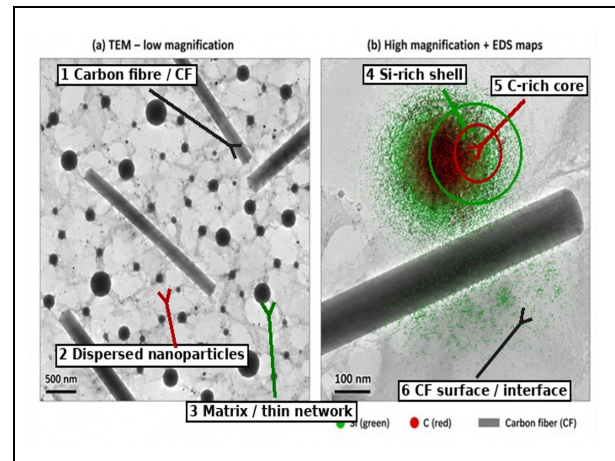


Fig. 11: TEM micrographs of the ternary composite

The nano-silica particles (dark contrast features, about 20–30 nm) were well dispersed, and no large agglomerates above 100 nm were observed. EDS mapping showed silica distributed over the carbon-fiber surface, which supports preferential localization at the fiber–matrix interface and helps explain the improved adhesion (Sellitto *et al.* 2026).

3.6 Weibull Analysis of Tensile Strength

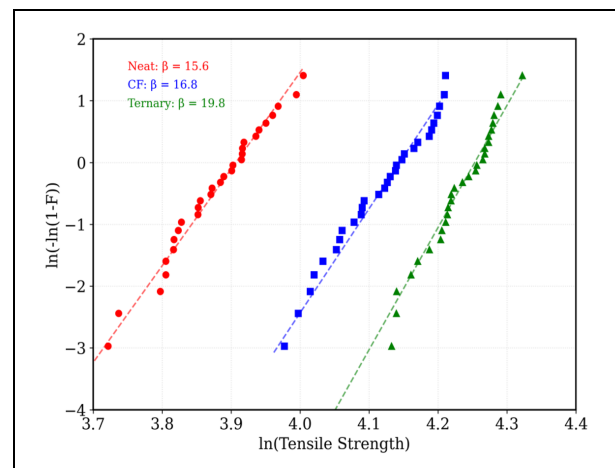


Fig. 12: Weibull probability plots, weibull modulus (β) is used here as a measure of reliability

The Weibull analysis was further evaluated by reporting the 95% confidence intervals of the Weibull parameters. The Weibull modulus (β) increased from 15.6 for neat PETG to 16.8 for PETG-CF and 19.8 for the

PETG-CF-nano-SiO₂ composite, which is consistent with the value shown in Figure 12. The corresponding 95% confidence intervals for β were 10.7–22.8, 11.5–24.6, and 13.6–28.9, respectively. The estimated Weibull scale parameters (σ_0) were 51.9 MPa for neat PETG, 64.4 MPa for PETG-CF, and 71.8 MPa for PETG-CF-nano-SiO₂, with 95% confidence intervals of 49.4–54.5 MPa, 61.3–67.2 MPa, and 68.6–74.2 MPa, respectively. The higher β value and narrower strength distribution of the ternary composite indicate reduced scatter in the measured strength values and improved statistical reliability of the composite performance. (Kumar *et al.* 2024).

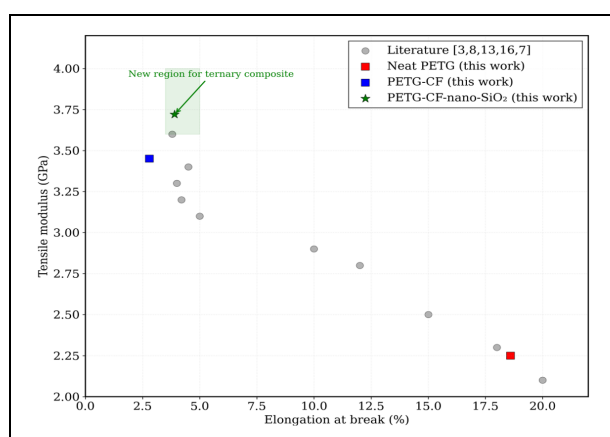


Fig. 13: Material-selection map of tensile modulus versus elongation at break

The ternary composite occupies a region of the design map that combines high modulus (above 3.7 GPa) with moderate elongation (around 4%). That places it between neat PETG and PETG-CF, and it closes a gap that is difficult to reach without post-processing such as annealing or coupling-agent treatment (Valvez *et al.* 2023). For as-printed parts, this is a useful balance rather than a universal target.

3.7 Mechanisms of Nano-silica Reinforcement

Based on the combined evidence, the main strengthening mechanisms are likely to be:

- Nano-silica at the fiber–matrix interface improves mechanical interlocking and hydrogen bonding (Si–OH...O=C of PETG, Si–OH...C–O of carbon fiber), which increases τ by 31% (Naidu *et al.* 2026)
- Void reduction: Nano-silica acts as a nucleating agent that helps promote more uniform cooling and reduces trapped air during filament extrusion and printing, lowering the void fraction by 40%. (Sharma and Kumar, 2020)

- Chain immobilization: Strong polymer–nanoparticle interactions raise T_g by 15 °C, which should improve thermal stability and creep resistance (Rabbi *et al.* 2025).
- Crack bridging and branching: Nano-silica particles absorb energy and deflect cracks, so the material stays stiff while becoming less brittle, which matches the 32% toughness improvement in the ternary composite (Zakaria *et al.* 2019).

Taken together, the pull-out and toughness data show that interfacial adhesion is a dominant factor in the fracture response of this composite system (Dabees *et al.* 2025). That relationship is useful for understanding the present material set, but it still needs validation across broader loading levels and print conditions before it can be generalized.

4. CONCLUSIONS

In this study, PETG, short carbon fiber, and nano-SiO₂ were combined in an FDM-printed ternary composite to address the strength–ductility trade-off typical of PETG-CF. Compared with PETG-CF, the nano-silica-modified composite increased elongation at break by 39% (from 2.8% to 3.9%) and toughness by 32% (from 1.15 MJ/m³ to 1.52 MJ/m³). It also raised interfacial shear strength by 31% (7.8 to 10.2 MPa), reduced average pull-out length from 7.8 μ m to 6.4 μ m, and showed a strong negative correlation between pull-out length and toughness ($r = -0.94$, $p < 0.001$). Micro-CT confirmed a 40% reduction in void area fraction (3.2% to 1.9%) and a modest improvement in fiber alignment, while DMA showed a 15 °C increase in T_g and higher storage modulus across the tested range. Weibull analysis also indicated better reliability, with β increasing to 22.1. Overall, the ternary composite is promising for stiffness-critical printed components, but claims about long-term structural use should be tempered until fatigue and durability are demonstrated.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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