

ORIGINAL RESEARCH ARTICLE

Mechanical degradation of bio-based FDM filaments under thermal ageing and moisture exposure: PLA, PETG, and PLA-Wood comparison

Md Ashequl Islam¹, Khairul Salleh Basaruddin^{1*}, Liyana Tajul¹, Nor Amalina Muhayudin¹, Hoang Tien-Dat², Hoang Tien Dung², and Giulio Mattera³

¹Mechanical Department, Faculty of Mechanical Engineering and Technology, Universiti Malaysia Perlis, Perlis, Malaysia

²School of Mechanical and Automotive Engineering, Ha Noi University of Industry, Hanoi, Vietnam

³Department of Chemical, Materials and Industrial Production Engineering, University of Naples Federico II, Napoli, Campania, Italy

Abstract

Thermoplastic filaments used in fused deposition modelling (FDM) are increasingly adopted for functional components, yet their durability under thermal and moisture-related service conditions remains incompletely characterised. This study presents a multi-modal investigation of the mechanical degradation of three commercial FDM filaments, namely polylactic acid (PLA), polyethylene terephthalate glycol (PETG), and wood-filled PLA (PLA-Wood), subjected to two independent degradation pathways: accelerated isothermal thermal ageing at material-relevant glass-transition temperatures for four and eight days, and immersion in distilled water for 24–720 h. Specimens were fabricated according to American Society for Testing and Materials (ASTM) D638, ASTM D790, and ASTM D695 standards using 70% concentric infill, then evaluated through tensile, flexural, and compressive testing, gravimetric mass and moisture analysis, and scanning electron microscopy (SEM). Under thermal ageing, PETG exhibited the highest tensile strength retention, maintaining 40.87 ± 1.18 MPa after eight days, with the smallest proportional tensile modulus reduction of $\leq 5.1\%$. PLA-Wood sustained the greatest compressive modulus loss of 15.6%, attributed to combined PLA matrix chain scission and hygroscopic wood-filler desorption. Under moisture exposure, PETG maintained stable wet-state tensile strengths of 24.38–25.60 MPa after initial conditioning, whereas PLA-Wood absorbed approximately 50% apparent moisture in compression specimens and suffered a 57% flexural strength reduction. PLA showed transient increases in stiffness associated with secondary crystallisation before degradation. SEM confirmed distinct material-stressor degradation pathways. These results establish the first integrated dual-stressor degradation profile for this filament triad, providing quantitative selection criteria for FDM applications involving thermal or humid service environments.

***Corresponding author:**
Khairul Salleh Basaruddin
(khsalleh@unimap.edu.my)

Citation: Islam MA, Basaruddin KS, Tajul L, *et al.* Mechanical degradation of bio-based FDM filaments under thermal ageing and moisture exposure: PLA, PETG, and PLA-Wood comparison. *Mater Sci Add Manuf.*
doi: 10.36922/MSAM026190041

Received: May 6, 2026

Revised: June 26, 2026

Accepted: June 29, 2026

Published online: July 24, 2026

Copyright: © 2026 Author(s). This is an Open-Access article distributed under the terms of the Creative Commons Attribution License, permitting distribution, and reproduction in any medium, provided the original work is properly cited.

Publisher's Note: AccScience Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Keywords: Fused deposition modelling; Polylactic acid; Polyethylene terephthalate glycol; Polylactic acid-Wood; Thermal ageing; Moisture absorption; Additive manufacturing

1. Introduction

Fused deposition modelling (FDM), the most widely deployed extrusion-based additive manufacturing process, has catalysed transformative advances in rapid prototyping, tooling, and end-use part production across biomedical, aerospace, and consumer-goods sectors.¹ Its adoption is driven by geometric freedom, low material waste, and compatibility with a broad palette of thermoplastic filaments. In parallel, intensifying regulatory and market pressures have accelerated interest in bio-based and biodegradable alternatives to conventional petroleum-derived plastics, motivating the development and characterisation of filaments derived from renewable feedstocks.^{2,3}

Poly(lactic acid) (PLA), derived from cornstarch or sugarcane fermentation, has emerged as the dominant bio-based FDM filament owing to its printability, low warpage, and biodegradability.⁴ Life cycle assessments have demonstrated that PLA consumes approximately one-tenth of the fossil fuel energy required to produce conventional synthetic polymers, making it a leading candidate for environmentally responsible manufacturing.⁵ Poly(ethylene terephthalate glycol) (PETG), a glycol-modified poly(ethylene terephthalate), occupies an intermediate position: while not fully bio-based, it offers superior toughness, chemical resistance, and moisture stability compared with PLA, making it popular for functional and structural parts.⁶ Recent biomedical studies have specifically identified PETG as a candidate material for bone implants and orthopaedic devices owing to its combination of mechanical stability and biocompatibility.^{7,8} Wood-filled PLA (PLA-Wood) composites, in which finely milled cellulosic wood particles are dispersed within a PLA matrix, offer renewable-resource aesthetics and enhanced rigidity, but introduce processing challenges related to nozzle abrasion and hygroscopic filler behaviour.^{9,10} Together, these three materials span a practical spectrum of bio-origin, mechanical character, and environmental durability that is representative of current FDM filament selection in sustainable manufacturing contexts.

Despite extensive characterisation of these materials under ambient, pristine conditions, their long-term mechanical reliability when subjected to real-world environmental stressors remains insufficiently understood. Two stressors are of particular practical concern: (i) thermal ageing near the glass-transition temperature (T_g), which can induce chain scission, plasticisation, crystallinity changes, and matrix–filler interfacial breakdown;^{11,12} and (ii) moisture absorption, which causes polymer chain disruption, hygroscopic swelling of natural-fibre fillers,

interfacial debonding, and microcrack nucleation.¹³ These mechanisms operate synergistically in many service environments, biomedical components, outdoor housings, and humid industrial settings, yet they have not been systematically co-examined for the PLA, PETG, and PLA-Wood filament triad.

Prior work has addressed components of this problem in isolation. Accelerated thermal ageing studies of FDM-printed PLA have reported significant reductions in fracture stress and stiffness without visible surface changes,¹⁴ and hydrolytic ageing of reinforced PLA biocomposites has been reported to reduce Young's modulus by 26–33% within months.¹⁵ Moisture-immersion studies on natural-fibre PLA composites have documented tensile strength reductions of up to 27% and flexural losses exceeding 13% under prolonged exposure.^{16,17} Bergaliyeva *et al.*¹⁸ demonstrated that combined thermal and hydrolytic ageing dramatically accelerates PLA degradation beyond what either stressor produces independently, a finding of direct relevance to the dual-pathway methodology employed here. Recent work by Krapež Tomec *et al.*¹⁹ further confirmed that wood-particle thermal modification substantially reduces moisture-induced swelling in PLA-Wood composites, pointing toward the critical role of filler surface chemistry in moisture resistance. However, a concurrent evaluation of all three filament types across both degradation mechanisms spanning tensile, compressive, and flexural test modes, supported by gravimetric and microstructural evidence, is absent from the literature. This represents a critical gap, given that real-world components are rarely subjected to only one environmental stressor.

The current study addresses the gap through two coordinated experimental workstreams. First, specimens of PLA, PETG, and PLA-Wood were subjected to isothermal thermal ageing at material-specific T_g values for four and eight days. Subsequently, their tensile, flexural, compressive properties, and mass loss were evaluated, and their microstructure was characterised by scanning electron microscopy (SEM). Second, specimens were immersed in distilled water for six durations from 24 to 720 h, and equivalent mechanical and gravimetric characterisation was performed. By integrating findings from both workstreams, this paper: (i) establishes baseline and post-degradation mechanical performance envelopes for all three materials; (ii) identifies and mechanistically interprets material-specific degradation responses, including a transient non-monotonic stiffness increase in PLA; (iii) quantifies a dual-degradation mechanism in PLA-Wood composites; and (iv) provides data-driven guidance for filament selection in thermally or hygroscopically demanding FDM applications.

2. Materials and methods

2.1. Materials

Three commercially available 1.75 mm diameter FDM filaments were investigated: (i) standard PLA (T_g = 55–60 °C; Flabbxible, Malaysia), a biopolymer derived from plant-based starch known for its excellent printability and biodegradability; (ii) PETG (T_g = 75–80 °C; Flabbxible, Malaysia), a glycol-modified thermoplastic offering improved chemical resistance and enhanced toughness; and (iii) PLA-Wood (Flabbxible, Malaysia), a composite material incorporating finely milled wood particles within a PLA matrix, providing a natural wood-like aesthetic while maintaining biodegradability. Prior to processing, all filaments were stored in sealed desiccated containers to minimise moisture uptake, in accordance with established handling protocols for hygroscopic materials.²⁰ The overall experimental workflow, encompassing filament selection, FDM fabrication, and subsequent environmental stress testing, is illustrated in Figure 1, providing a systematic overview of the study methodology.

2.2. Specimen design and fabrication

Test specimens were modelled in CATIA (V5, Dassault Systèmes, France) following three ASTM standard geometries: dog-bone tensile specimens (American Society for Testing and Materials [ASTM] D638 Type I; gauge length 50 mm), rectangular flexural bars (ASTM D790; 127 mm × 12.7 mm × 3.2 mm), and right-circular cylinders for compression (ASTM D695; 12.7 mm diameter × 25.4 mm height). The corresponding specimen geometries and

their structural configurations, including the concentric infill architecture adopted for compression samples, are illustrated in Figure 2A–C. All models were subsequently exported as STL files and processed using Ultimaker Cura (V5.10.0, Ultimaker, Netherlands) for toolpath generation prior to fabrication.

A concentric infill pattern at 70% density was adopted for all materials to provide consistent internal architecture and comparable porosity, in accordance with recommendations for biomedical FDM applications.²¹ Specimens were printed on an FDM printer (Creality Ender 5/Ender 5 Pro, Creality 3D Technology Co., Ltd., China). Material-specific printing parameters are summarised in Table 1.

Table 1. Fused deposition modelling printing parameters for each filament material

Parameter	PLA	PETG	PLA-Wood
Layer height	0.2 mm	0.2 mm	0.2 mm
Nozzle temperature	200 °C	220–240 °C	210–215 °C
Bed temperature	60 °C	60–70 °C	50–60 °C
Print speed	80 mm/s	80–85 mm/s	40–80 mm/s
Infill density	70%	70%	70%
Infill pattern	Concentric	Concentric	Concentric

Abbreviations: PETG: Polyethylene terephthalate glycol; PLA: Polylactic acid; PLA-Wood: Wood-filled polylactic acid.

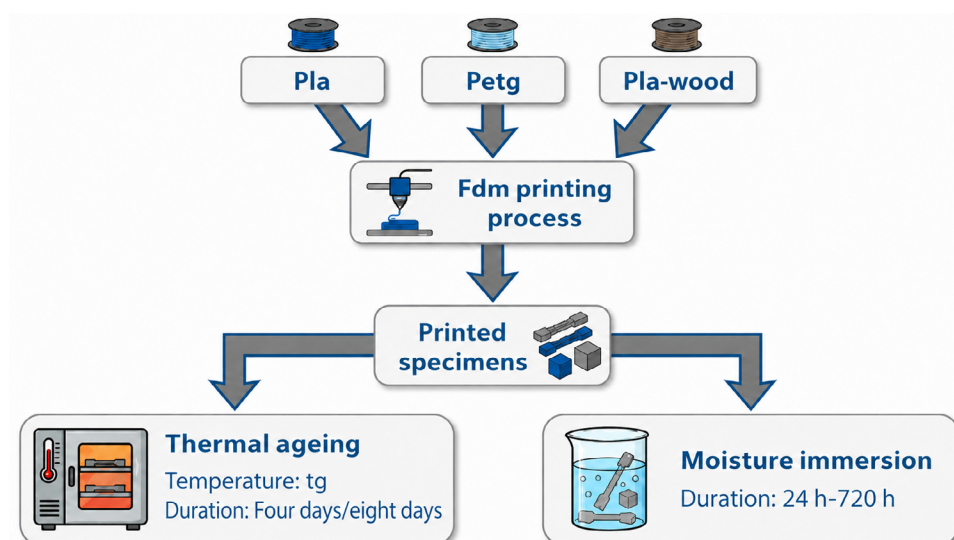


Figure 1. Workflow from filament selection through FDM processing to environmental stress testing

Abbreviations: FDM: Fused deposition modelling; PETG: Polyethylene terephthalate glycol; PLA: Polylactic acid; PLA-Wood: Wood-filled polylactic acid.

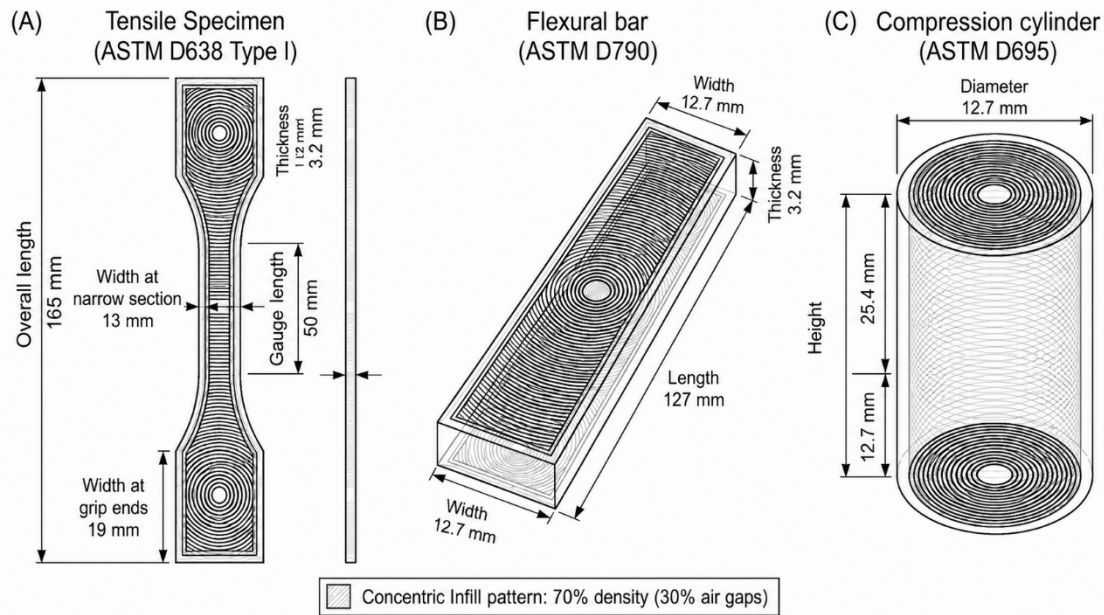


Figure 2. Multi-panel schematic showing (A) tensile dog-bone, (B) flexural bar, and (C) compressive cylinder with concentric infill architecture

2.3. Thermal ageing protocol

After printing, specimens for the thermal ageing workstream were divided into three groups: a non-aged control group, a four-day-aged group, and an eight-day-aged group. Ageing was performed in a laboratory oven at temperatures corresponding to each material's glass-transition onset: PLA and PLA-Wood at 55 °C; PETG at 70 °C. These temperatures were selected to simulate accelerated in-service thermal stress without inducing gross dimensional distortion, following protocols established in prior FDM ageing studies.^{5,8} Specimen mass was recorded before and after ageing on an analytical balance (± 0.01 g), and percentage weight loss was calculated per **Equation 1**:

$$\text{Weight loss (\%)} = \frac{W_0 - W_i}{W_0} \times 100 \quad (1)$$

where W_0 is the initial pre-ageing mass, and W_i is the mass after ageing.

2.4. Moisture absorption protocol

Specimens for the moisture workstream were stored under desiccated conditions prior to testing to establish dry baseline masses (W_{dry}). They were subsequently fully submerged in distilled water at room temperature (~ 25 °C) for six immersion durations: 24, 72, 120, 168, 336, and 720 h. Upon retrieval, surface water was removed with a lint-free microfibre cloth and wet weight (W_{wet}) was recorded immediately. Moisture absorption was calculated per

Equation 2:

$$\text{Moisture Absorption (\%)} = \frac{W_{wet} - W_{dry}}{W_{dry}} \times 100 \quad (2)$$

2.5. Mechanical testing

All mechanical tests were performed using a Universal Testing Machine (3367, Instron, USA) equipped with a 30 kN load cell and standardised testing fixtures. The machine was calibrated in 2025, ensuring the reliability and reproducibility of the measured mechanical responses. All tests were conducted under controlled laboratory conditions at 23 ± 2 °C and $50 \pm 5\%$ relative humidity. Prior to testing, specimens were conditioned according to their assigned environmental exposure duration and then tested under the same laboratory conditions. Tensile tests were conducted according to ASTM D638 at a crosshead speed of 5 mm/min; tensile strength was calculated as the peak force divided by the original cross-sectional area of the specimen, as shown in **Equation 3**. Three-point flexural tests were performed according to ASTM D790 using a support span of 64–125 mm, selected based on specimen thickness and the recommended span-to-depth ratio; flexural strength was derived using **Equation 4**. Compression tests were conducted according to ASTM D695 at a crosshead speed of 1.3 mm/min, and compressive strength was obtained from **Equation 5**. Young's modulus was extracted from the linear region of each stress–strain curve. A minimum of three independent specimens were

tested for each material-condition combination. The reported values correspond to the arithmetic mean $\pm$ standard deviation (SD) of the replicate measurements. SD was used to quantify experimental variability and assess the repeatability of the measurements. The relatively small SD values obtained across repeated tests indicate good repeatability and reliability of the experimental procedure.

$$\sigma = \frac{F}{A} \quad (3)$$

$$\sigma^f = \frac{3FL}{2bd^2} \quad (4)$$

$$\sigma_c = \frac{F}{A} \quad (5)$$

where F = applied force (N), A = cross-sectional area (mm²), L = support span (mm), b = specimen width (mm), d = specimen thickness (mm).

2.6. Scanning electron microscopy

Representative fractures and free surfaces from control and eight-day thermally aged specimens were examined by SEM at multiple magnifications. Specimens were sputter-coated with a thin gold layer prior to imaging. Analysis focused on identifying surface defects, voids, interlayer delamination, and evidence of matrix or filler degradation.

2.7. Theoretical framework for environmental degradation of fused deposition modelling polymers

The long-term mechanical performance of FDM polymers is strongly governed by environmental exposure, particularly thermal ageing and moisture absorption. The degradation behaviour of thermoplastic materials, including PLA, PETG, and PLA-Wood composites, is interpreted within established theoretical frameworks encompassing polymer thermal degradation, moisture diffusion, and thermo-hygro-mechanical coupling.

2.7.1. Thermal degradation mechanisms

Thermal ageing promotes molecular mobility within polymer chains, particularly when exposure temperature approaches the material's T_g. Elevated thermal energy drives chain scission, the rupture of covalent bonds within the polymer backbone, reducing molecular weight and consequently diminishing mechanical strength. The degradation kinetics are described by an Arrhenius-type relationship (Equation 6):

$$k = A \cdot \exp\left(\frac{-E_a}{RT}\right) \quad (6)$$

where k is the degradation rate constant, A is the pre-exponential frequency factor, E_a is the activation energy, R is the universal gas constant, and T is the absolute temperature.

In PLA-based polymers, degradation primarily occurs through ester bond cleavage, generating low-molecular-weight fragments and reducing tensile strength and modulus. This back-biting ester-interchange reaction is well documented in thermogravimetric and gel-permeation chromatography studies of PLA above 55 °C.^{14,22} PETG, with its higher T_g and more stable amorphous structure, exhibits comparatively greater resistance to thermally induced degradation.⁶ In semi-crystalline PLA, thermal exposure may also induce secondary crystallisation, a transient reorganisation of molecular chains into ordered structures which can temporarily increase stiffness prior to embrittlement. This competing crystallisation-chain-scission dynamic is a defining feature of PLA thermal ageing and has practical implications for short-duration characterisation studies.²³

2.7.2. Moisture diffusion and hygroscopic effects

Moisture uptake in polymeric materials is governed by Fickian diffusion, in which water molecules progressively penetrate the polymer matrix. The transient moisture absorption behaviour is expressed as Equation 7:

$$\frac{M_t}{M_\infty} = 1 - \left(\frac{8}{\pi^2}\right) \sum \frac{1}{(2n+1)^2} \cdot \exp\left(\frac{-(2n+1)^2 \pi^2 D t}{4h^2}\right) \quad (7)$$

where M_t is the moisture content at time t , M_∞ is the equilibrium moisture content, D is the diffusion coefficient, and h is the specimen thickness. Microstructure-based modelling of water diffusion in FDM-printed PETG has confirmed Fickian behaviour in the early stages, with deviations observed at extended timescales attributed to structural heterogeneities introduced by layer-by-layer deposition.²⁴

Absorbed water molecules function as plasticising agents, increasing chain mobility and weakening intermolecular interactions, thereby reducing stiffness and strength. In composite filaments such as PLA-Wood, hygroscopic effects are amplified by the inherently hydrophilic nature of cellulose fibres: water absorption induces fibre swelling, promotes interfacial debonding, and initiates microcrack formation.^{25,26}

2.7.3. Thermo-hygro-mechanical coupling

In practical service environments, polymers are exposed simultaneously to elevated temperature and humidity, producing coupled degradation effects that cannot be

adequately described by either mechanism in isolation. The combined influence of thermal ageing and moisture absorption on a mechanical property P is approximated by Equation 8:

$$P(t, M) = P_0 \cdot \exp(-kt) \cdot (1 - \alpha M) \quad (8)$$

where P_0 is the initial mechanical property, k is the thermal degradation rate constant, M is the moisture content, and α is the moisture sensitivity coefficient. This formulation reflects two concurrent and interacting processes: molecular deterioration driven by thermal activation and structural weakening from moisture plasticisation.²⁷

2.7.4. Influence of fused deposition modelling microstructure on degradation

Beyond intrinsic polymer chemistry, the layer-by-layer deposition process in FDM introduces microstructural heterogeneities, including interlayer boundaries, residual voids, and incompletely fused filament interfaces. These features act as stress concentration sites and provide pathways for accelerated moisture ingress, thereby promoting premature crack initiation and propagation. As a result, additively manufactured polymers typically exhibit more pronounced environmental degradation than equivalent bulk-processed materials.²¹ Recent parametric studies have further shown that infill density and layer height significantly modulate moisture absorption in both PLA and PLA-Wood components, establishing that FDM process variables are not decoupled from environmental durability.^{28,29}

2.8. Statistical analysis

All experimental measurements were performed using at least three independent specimens per test condition. Results are reported as mean $\pm$ standard deviation (SD). Statistical significance between control and conditioned groups was evaluated using Student's t -test with a significance level of $p < 0.05$. Coefficients of variation (CV) were calculated to assess experimental repeatability. The relatively small SD and CV values observed across replicate measurements indicate good consistency and reliability of the experimental data.

3. Results

All mechanical and gravimetric measurements were obtained from at least three replicate specimens per condition and are reported as mean $\pm$ SD. The observed SDs were generally small relative to the mean values, indicating good experimental repeatability and limited random variation. This supports the reliability of the reported trends and comparisons among materials and

degradation conditions.

3.1. Thermal ageing: Tensile properties and mass loss

Under control, non-aged conditions, PLA exhibited the highest tensile Young's modulus ($1,797 \pm 89$ MPa), followed by PLA-Wood ($1,335 \pm 72$ MPa) and PETG ($1,201 \pm 54$ MPa). This confirms the higher stiffness of PLA, consistent with baseline mechanical comparisons reported by Hsueh *et al.*³⁰ and Ramírez-Revilla *et al.*³¹ After eight days of thermal ageing, all materials showed a reduction in tensile stiffness. PLA declined to $1,567 \pm 93$ MPa, corresponding to a 12.8% reduction, while PLA-Wood decreased to $1,185 \pm 68$ MPa, representing an 11.2% loss. PETG showed the smallest reduction, decreasing only to approximately $1,140 \pm 51$ MPa, equivalent to less than 5.1% loss. These results indicate that PETG retained its tensile stiffness more effectively than PLA and PLA-Wood under the ageing condition used in this study.

Tensile strength followed a similar degradation trend, as shown in Figure 3A. PLA decreased from 28.64 ± 1.43 MPa under control conditions to 23.89 ± 1.27 MPa after eight days of ageing, representing a 16.6% reduction. PLA-Wood showed a more pronounced strength loss, decreasing from 18.00 ± 1.52 MPa to 14.00 ± 1.38 MPa, corresponding to a 22.2% reduction. In contrast, PETG exhibited only a marginal decrease from 41.53 ± 1.21 MPa to 40.87 ± 1.18 MPa, equivalent to a 1.6% reduction. The strength degradation observed in PLA is likely associated with chain scission and thermal degradation of the polymer backbone, which agrees with the degradation mechanisms reported by Korkut *et al.*¹⁴ under comparable thermal exposure conditions. However, the lower magnitude of degradation in the present study may be attributed to the moderate ageing temperature of 55 °C, compared to the higher ageing temperatures of 60–70 °C commonly used in accelerated ageing studies.¹⁸

The superior retention of tensile properties in PETG can be attributed to the glycol-modified polymer structure, which improves thermal stability and reduces susceptibility to ester hydrolysis, as also reported by Li *et al.*³² Although PLA showed the highest initial stiffness, its greater reduction in modulus and tensile strength after ageing indicates higher sensitivity to thermal exposure. PLA-Wood also showed considerable degradation, which may be influenced by the presence of wood particulates, interfacial weakening, and moisture-related effects during heating.

Mass loss behaviour after thermal ageing is presented in Figure 3B and further summarised in Table 2. Among the tensile specimens, PLA exhibited the highest mass loss

Table 2. Tensile strength and gravimetric data: control vs. eight-day thermally aged specimens

Material	Condition	Tensile strength (MPa)	Initial mass (g)	Final mass (g)	Mass loss (%)	Failure mode	CV (%)
PLA	Control	28.64 ± 1.43	10.09 ± 0.04	10.09 ± 0.04	0.00	Brittle	5.0
PLA	Eight-day aged	23.89 ± 1.27	10.09 ± 0.04	9.84 ± 0.05	2.48 ± 0.21	Brittle (embrittled)	5.3
PLA-Wood	Control	18.00 ± 1.52	9.76 ± 0.05	9.76 ± 0.05	0.00	Brittle	8.4
PLA-Wood	Eight-day aged	14.00 ± 1.38	9.76 ± 0.05	9.58 ± 0.06	1.84 ± 0.18	Brittle + delamination	9.9
PETG	Control	41.53 ± 1.21	10.37 ± 0.04	10.37 ± 0.04	0.00	Ductile (necking)	2.9
PETG	Eight-day aged	40.87 ± 1.18	10.37 ± 0.04	10.19 ± 0.05	1.74 ± 0.14	Ductile	2.9

Abbreviations: CV: Coefficient of variation; PETG: Polyethylene terephthalate glycol; PLA: Polylactic acid; PLA-Wood: Wood-filled polylactic acid.

of 2.48%, which may be attributed to the volatilisation of low-molecular-weight oligomers and chain-scission by-products, particularly lactide monomer. This behaviour is consistent with reported thermogravimetric observations of PLA degradation above 55 °C.^{11,22} PLA-Wood and PETG showed lower mass losses of 1.84% and 1.74%, respectively. In PLA-Wood, part of the observed mass loss may also be associated with moisture desorption from hygroscopic wood particulates rather than polymer matrix degradation alone. PETG showed comparatively limited mass loss, with the compression specimens recording only 0.53% mass loss, as shown in Table 3. This further supports PETG's lower chemical reactivity and greater thermal stability under the ageing conditions applied in this study.

Tensile and mass loss results demonstrate that thermal ageing had the greatest effect on PLA and PLA-Wood, while PETG maintained the highest tensile strength retention and the lowest sensitivity to thermal degradation. These findings suggest that PETG is more suitable for applications requiring improved mechanical stability under moderate thermal ageing, whereas PLA and PLA-Wood may require careful consideration when used in environments involving prolonged heat exposure.

3.2. Thermal ageing: Compressive properties and mass loss

Under control, non-aged conditions, PETG exhibited the highest compressive Young's modulus (775 ± 31 MPa), followed by PLA (750 ± 38 MPa) and PLA-Wood (327 ± 29 MPa). This indicates that PETG and PLA possessed relatively comparable initial compressive stiffness, whereas PLA-Wood showed substantially lower stiffness due to the presence of wood particulates and weaker polymer–filler interfacial bonding.

A notable non-monotonic ageing response was observed in PLA, as shown in Figure 4. The compressive modulus increased transiently to approximately 800 ± 41 MPa after four days of thermal ageing, then decreased to 710 ± 36 MPa after eight days, corresponding to a net reduction of 5.3% compared with the control condition. This temporary increase in stiffness may be attributed to thermally induced secondary crystallisation, which can enhance molecular packing and matrix rigidity during the early stage of ageing. However, prolonged exposure appears to promote chain scission and thermal degradation, leading to a subsequent reduction in compressive stiffness.

The PLA-Wood exhibited the greatest proportional reduction in compressive modulus, decreasing from 327 ± 29 MPa to 276 MPa after eight days, equivalent to a 15.6% loss. This larger reduction suggests accelerated weakening of the wood–polymer interface during thermal exposure. The hygroscopic nature of the wood particles may also contribute to moisture desorption and microstructural instability, thereby reducing load-bearing capacity under compression. In contrast, PETG maintained comparatively stable compressive behaviour, showing only a moderate reduction in stiffness after ageing. This confirms its greater resistance to thermally induced degradation compared with PLA and PLA-Wood.

The failure modes further supported the observed mechanical trends. PLA specimens showed brittle buckling with spiral-like collapse, indicating reduced deformation tolerance after ageing. PLA-Wood exhibited irregular crumbling and interfacial delamination, which may be associated with poor stress transfer between the polymer matrix and wood filler. PETG, in contrast, demonstrated uniform plastic deformation and progressive flattening, reflecting its greater ductility and superior structural

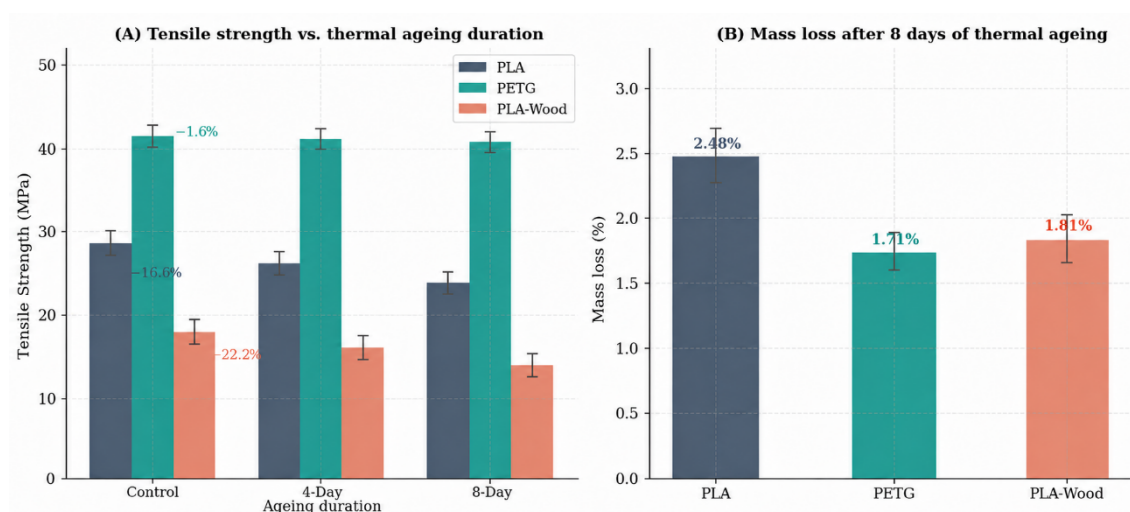


Figure 3. Effect of thermal ageing on the mechanical and physical degradation of PLA, PETG, and PLA-Wood after eight days of exposure. (A) Tensile strength reduction after eight days of thermal ageing for each material, annotated with percentage loss. (B) Gravimetric mass loss after eight days. PLA shows the highest mass loss (2.48%), consistent with volatilisation of chain-scission by-products.

Abbreviations: PETG: Polyethene terephthalate glycol; PLA: Polylactic acid; PLA-Wood: Wood-filled polylactic acid.

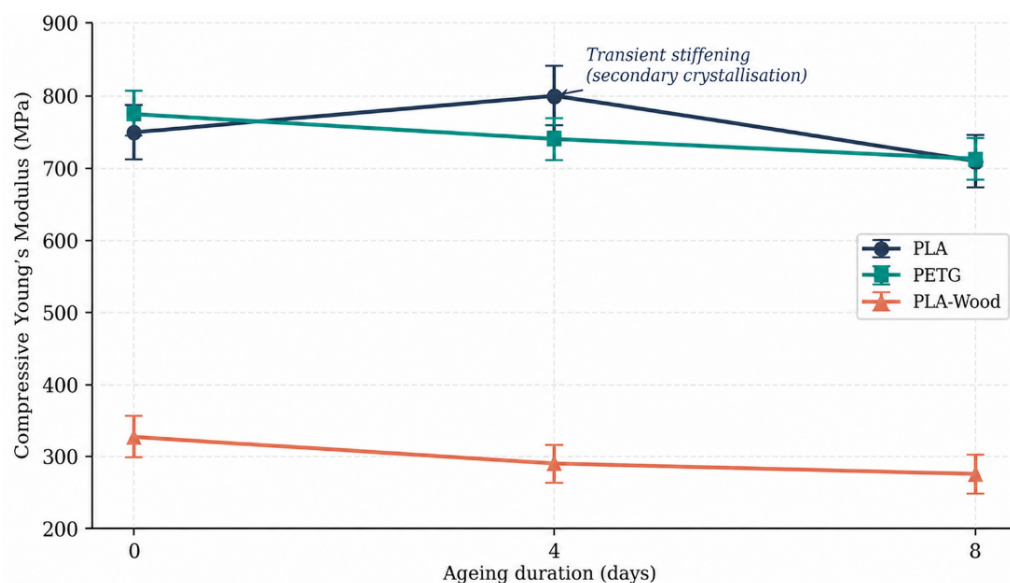


Figure 4. Non-monotonic evolution of compressive Young's modulus indicating transient secondary crystallisation

Abbreviations: PETG: Polyethene terephthalate glycol; PLA: Polylactic acid; PLA-Wood: Wood-filled polylactic acid.

stability under compressive loading.

The compressive properties and corresponding gravimetric mass loss data are summarised in Table 3. Overall, the results show that thermal ageing had the most detrimental effect on PLA-Wood, while PETG retained the most stable compressive response. PLA showed intermediate behaviour, with an initial stiffness enhancement due to secondary crystallisation, followed by degradation after prolonged thermal exposure.

3.3. Thermal ageing: Flexural properties

Under control, non-aged conditions, PLA and PETG exhibited almost identical initial flexural moduli of $1,926 \pm 82$ MPa and $1,929 \pm 78$ MPa, respectively. Both materials showed substantially higher flexural stiffness than PLA-Wood, which recorded an initial modulus of approximately $1,400 \pm 91$ MPa. This indicates that neat PLA and PETG provided greater resistance to bending deformation, while the lower modulus of PLA-Wood may be associated with

Table 3. Compressive modulus and gravimetric changes after eight days of thermal ageing

Material	Control modulus (MPa)	Eight-day modulus (MPa)	Reduction (%)	Initial mass (g)	Final mass (g)	Mass loss (%)
PLA	750 ± 38	710 ± 36	5.3	3.53 ± 0.02	3.48 ± 0.02	1.40 ± 0.12
PLA-Wood	327 ± 29	276 ± 27	15.6	3.18 ± 0.03	3.09 ± 0.03	2.83 ± 0.22
PETG	775 ± 31	713 ± 29	8.0	3.78 ± 0.02	3.76 ± 0.02	0.53 ± 0.06

Abbreviations: PETG: Polyethylene terephthalate glycol; PLA: Polylactic acid; PLA-Wood: Wood-filled polylactic acid.

the heterogeneous distribution of wood particulates and weaker interfacial bonding between the polymer matrix and natural filler.

After eight days of thermal ageing, all materials showed a reduction in flexural modulus. PLA decreased to $1,724 \pm 88$ MPa, corresponding to a 10.5% reduction, while PETG decreased to $1,728 \pm 81$ MPa, representing a 10.4% reduction. Although PETG demonstrated stronger retention in tensile and compressive properties, its flexural stiffness reduction was comparable to that of PLA, suggesting that bending performance may be more sensitive to surface and interlayer degradation effects.

In contrast, PLA-Wood exhibited the most pronounced degradation, with its flexural modulus decreasing to approximately $1,120 \pm 84$ MPa after eight days of ageing, corresponding to a 20.0% reduction. This larger decline further confirms the reduced thermal stability of the natural fibre reinforced composite system. The degradation may be attributed to thermal weakening of the wood-polymer interface, moisture desorption from hygroscopic wood particles, and reduced stress-transfer efficiency during bending.

As illustrated in Figure 5, PLA showed a reduction in flexural stiffness after eight days of thermal ageing compared with the control sample. The flexural modulus decreased by approximately 10.5%, indicating that prolonged thermal exposure weakened the PLA matrix. This reduction may be attributed to progressive chain scission, thermal degradation, and reduced molecular integrity during ageing. A similar decline was observed for PETG, while PLA-Wood exhibited the largest reduction, suggesting that wood-filler interfacial weakening further contributed to stiffness loss. This behaviour is consistent with degradation-related reductions in polymer stiffness reported in the literature.³³

The complete flexural modulus results, together with modulus data from tensile and compressive testing across all ageing durations, are summarised in Table 4. Overall, the flexural results show that PLA-Wood was the most

sensitive to thermal ageing, whereas PLA and PETG maintained comparatively higher bending stiffness after exposure.

3.4. Thermal ageing: Scanning electron microscopy

The SEM analysis of control and eight-day-aged specimens revealed distinct morphological progressions across the three materials, as presented in Figure 6. PLA specimens under control conditions (Figure 6A) displayed a relatively homogeneous surface with minor FDM-induced voids, typical of layer-wise deposition. After eight days of thermal ageing, PLA exhibited a marked increase in surface defects, including visible fractures, enlarged voids, and localised regions of polymer breakdown, consistent with molecular-level chain scission and hydrolytic degradation. This deterioration in surface integrity correlates strongly with the observed reductions in tensile strength and Young's modulus.

The PLA-Wood specimens in the control state (Figure 6C) showed moderate void content with reasonably uniform wood-particle dispersion and acceptable matrix-filler adhesion. However, following thermal exposure, pronounced morphological degradation was observed, including deeper voids, matrix cracking, phase separation between the PLA matrix and wood particles, and microcrack propagation along interfacial regions. These features indicate a combined thermal degradation of the polymer matrix and moisture loss from hygroscopic wood fibres, a dual degradation mechanism unique to this composite system. The observed interfacial debonding is consistent with the filler-matrix separation mechanisms reported by Krapež Tomec *et al.*,¹⁹ confirming that interfacial integrity is a critical limitation in natural fibre-reinforced composites under thermal stress.

In contrast, PETG specimens (Figure 6E and 6F) exhibited the most stable morphology. Control samples showed dense, well-bonded layers with smooth surface characteristics, while aged specimens retained consistent layer alignment with only minor increases in void

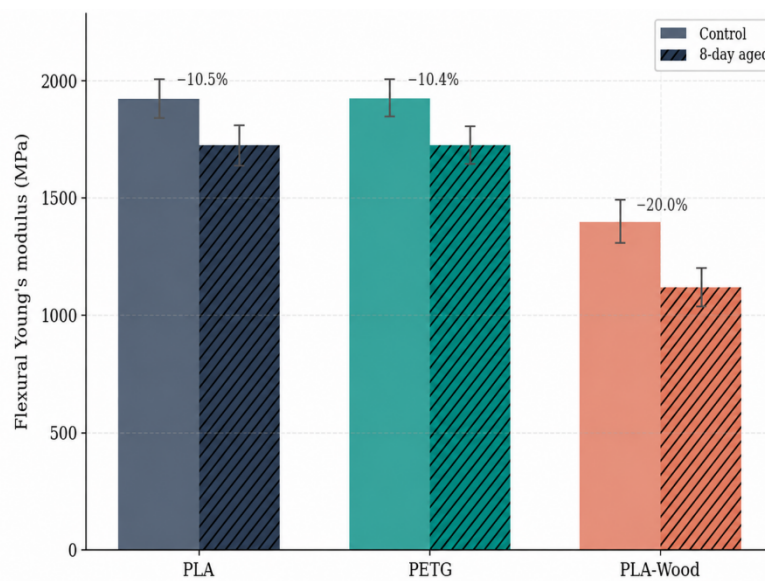


Figure 5. Flexural Young's modulus before (control) and after eight days of thermal ageing. PLA-Wood shows the largest proportional decline (~20%), reflecting combined PLA matrix degradation and wood-filler interfacial weakening.

Abbreviations: PETG: Polyethylene terephthalate glycol; PLA: Polylactic acid; PLA-Wood: Wood-filled polylactic acid.

Table 4. Summary of Young's modulus across all test types and thermal ageing conditions

Material	Test mode	Control (MPa)	Four days (MPa)	Eight days (MPa)	Reduction (%)	<i>p</i> -value
PLA	Tensile	1,797 ± 89	~1,680 ± 85	1,567 ± 93	12.8	<0.05
PLA-Wood	Tensile	1,335 ± 72	~1,250 ± 69	1,185 ± 68	11.2	<0.05
PETG	Tensile	1,201 ± 54	~1,170 ± 52	~1,140 ± 51	<5.1	<0.05
PLA	Compression	750 ± 38	~800 ± 41 ^a	~710 ± 36	5.3	<0.05
PLA-Wood	Compression	327 ± 29	~290 ± 26	276 ± 27	15.6	<0.05
PETG	Compression	775 ± 31	~740 ± 29	713 ± 29	8.0	<0.05
PLA	Flexural	1,926 ± 82	~1,900 ± 79	1,724 ± 88	10.5	<0.05
PLA-Wood	Flexural	~1,400 ± 91	~1,250 ± 84	~1,120 ± 84	20.0	<0.05
PETG	Flexural	1,929 ± 78	~1,850 ± 75	1,728 ± 81	10.4	<0.05

Note: ^aTransient increase attributed to secondary crystallisation (Section 4.2).

Abbreviations: PETG: Polyethylene terephthalate glycol; PLA: Polylactic acid; PLA-Wood: Wood-filled polylactic acid.

content. This structural stability corroborates the minimal degradation observed in mechanical properties and confirms that PETG's molecular architecture provides superior resistance to thermally induced microstructural damage, consistent with prior findings in biomechanical applications.^{7,8}

3.5. Moisture absorption behaviour

Moisture absorption profiles varied substantially among the materials and specimen geometries, as illustrated in

Figure 7. For tensile specimens, the absorption behaviour is summarised in **Table 5**. PLA exhibited rapid initial moisture uptake, reaching approximately 9–10% by 72 h, followed by a stabilisation phase that continued up to 720 h. This behaviour suggests near-saturation of the amorphous interlaminar regions, which are likely the primary moisture uptake sites in FDM-printed PLA. The observed profile is broadly consistent with Fickian-type diffusion, although the plateau between 168 and 720 h indicates that moisture transport became increasingly limited once the accessible

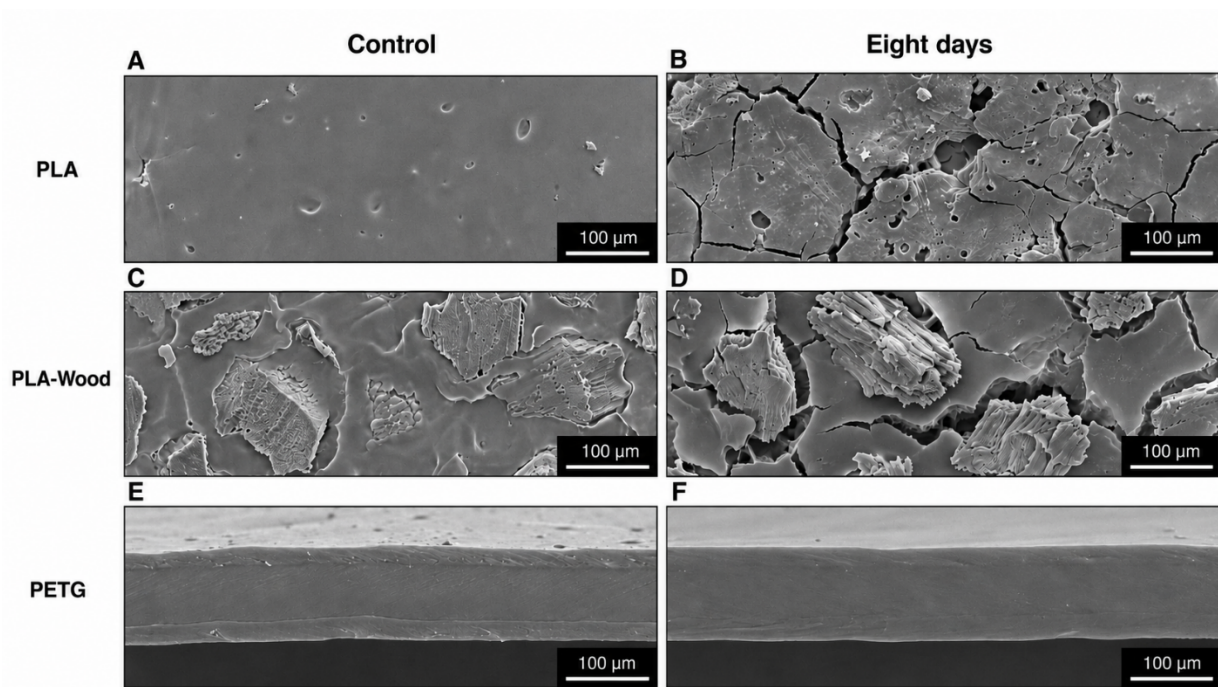


Figure 6. Scanning electron micrographs showing morphological evolution after eight days of thermal ageing. (A, B) PLA void enlargement and fracture formation. (C, D) PLA-Wood matrix cracking and filler–matrix debonding. (E, F) PETG stable layer structure with minimal defect growth. Scale bar: 100 μm; Magnification: 500×.

Abbreviations: PETG: Polyethene terephthalate glycol; PLA: Polylactic acid; PLA-Wood: Wood-filled polylactic acid.

Table 5. Moisture absorption (%) for tensile specimens across all immersion durations

Material	24 h	72 h	120 h	168 h	336 h	720 h	CV, 720 h (%)
PLA	0.00 ± 0.00	9.09 ± 0.82	10.00 ± 0.91	9.09 ± 0.84	7.27 ± 0.73	10.00 ± 0.91	9.1
PETG	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	10.00 ± 0.88	10.00 ± 0.89	8.9
PLA-Wood	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	11.11 ± 1.02	11.11 ± 1.04	10.00 ± 0.93	9.3

Abbreviations: CV: Coefficient of variation; PETG: Polyethene terephthalate glycol; PLA: Polylactic acid; PLA-Wood: Wood-filled polylactic acid.

interlayer regions approached saturation.^{13,20}

The PETG showed negligible moisture absorption up to 168 h, after which the uptake increased to approximately 10%. This delayed absorption response confirms PETG's superior short- to medium-term moisture resistance compared with PLA and PLA-Wood. The delayed onset of water uptake is mechanistically significant and may be attributed to PETG's relatively hydrophobic ester-based backbone and denser interlayer structure, both of which restrict early water ingress through interlaminar pathways. A similar delayed absorption behaviour has been reported by Li *et al.*³² in carbon-fibre-reinforced PETG systems, where moisture penetration initially occurred only at surface-accessible defects before progressing into the bulk.

In contrast, PLA-Wood tensile specimens showed higher moisture sensitivity, reaching approximately 11.11% absorption at 168 h before stabilising at around 10% by 720 h. This behaviour may be associated with the initial filling of surface voids and interfacial gaps, followed by slower diffusion into the composite matrix. The presence of wood particulates increases the number of hydrophilic sites within the material, thereby enhancing moisture uptake compared with neat polymer systems.

The effect of specimen geometry was particularly evident in compression specimens. PLA-Wood compression specimens reached substantially higher apparent absorption levels of approximately 50% after 720 h, greatly exceeding the approximately 17% observed

for neat PLA compression specimens. This pronounced increase is attributed to the dominant contribution of hygroscopic wood fibres, pore-retained water, and the cylindrical specimen geometry, which may promote moisture retention within internal voids and interfacial regions. Therefore, the high apparent absorption in PLA-Wood compression specimens should not be interpreted solely as matrix diffusion, but rather as a combined effect of fibre hygroscopicity, internal porosity, and geometry-dependent water retention.

The moisture absorption results demonstrate that PLA-Wood was the most moisture-sensitive material, particularly in compression geometry, while PETG exhibited the greatest resistance to early-stage water ingress. These findings highlight the importance of both material composition and specimen geometry in determining moisture transport behaviour in FDM-printed polymer systems.

3.6. Moisture exposure: Tensile properties

In the dry state, PETG demonstrated the highest tensile strength (43.98 ± 1.09 MPa), followed by PLA (28.64 ± 1.43 MPa) and PLA-Wood (18.00 ± 1.52 MPa). These results confirm the superior baseline tensile performance of PETG, while PLA-Wood showed the lowest strength due to the presence of wood particulates and weaker polymer-filler interfacial bonding. It is important to note that these dry-state values differ from the post-printing aged data reported in Table 2, highlighting the importance of clearly defining baseline conditions, such as freshly dried, unaged specimens versus specimens stored under ambient conditions prior to testing.

Upon moisture exposure, PLA exhibited a progressive reduction in tensile strength, decreasing from 21.92 ± 1.31 MPa at 24 h to 15.99 ± 1.14 MPa at 168 h. This corresponds to an approximate 27% reduction and is primarily attributed to moisture-induced plasticisation and disruption of intermolecular hydrogen bonding within the PLA matrix.^{13,16} The degradation trend is illustrated in Figure 8A and summarised in Table 6. Similar moisture-related reductions in PLA tensile performance have been reported by Islam *et al.*¹³ and Banjo *et al.*,¹⁶ who observed strength losses of approximately 25–30% in moisture-conditioned PLA systems.

Interestingly, PLA showed a partial recovery in tensile strength to 20.88 ± 1.24 MPa after 720 h of moisture exposure. This apparent recovery is unlikely to represent complete restoration of mechanical integrity. Instead, it may be associated with moisture-mediated secondary crystallisation of amorphous PLA regions, which can temporarily increase matrix rigidity. This interpretation is supported by the concurrent increase in Young's modulus from 1,154.97 MPa at 24 h to 2,214.88 MPa at 168 h, as shown in Table 6. Therefore, the observed strength recovery may reflect structural rearrangement and crystallisation effects rather than reversal of hydrolytic or plasticisation-related damage.

The PETG exhibited the most stable tensile behaviour after initial wet conditioning, with tensile strength varying only between 24.38 and 25.60 MPa over the 720-h exposure period. This represents less than 5% variation during moisture exposure, confirming PETG's comparatively stable post-conditioning response. However, the large reduction from its dry-state tensile strength of 43.98 ± 1.09

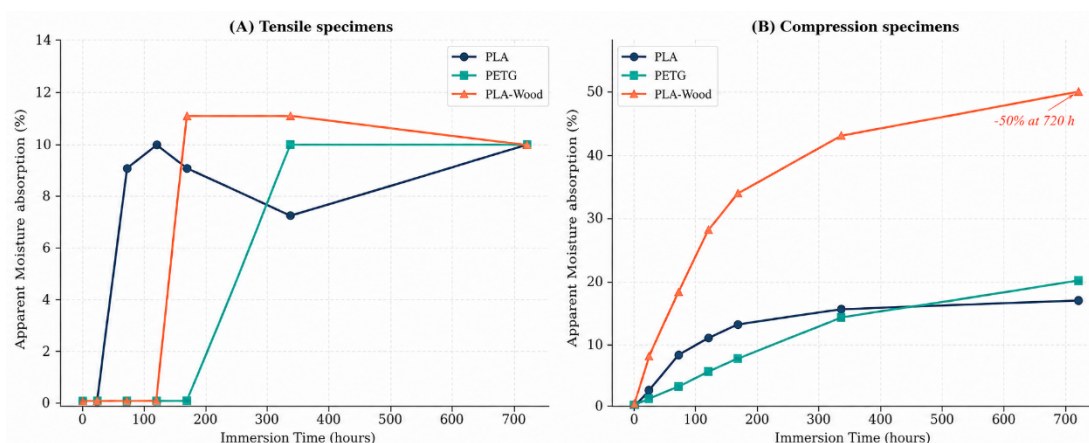


Figure 7. Apparent moisture absorption kinetics for (A) tensile and (B) compression specimens over 720 h. PLA-Wood compression specimens reach approximately 50% apparent absorption, substantially exceeding neat PLA (~17%), confirming the dominant roles of hygroscopic wood fibres and internal pore water retention.

Abbreviations: PETG: Polyethylene terephthalate glycol; PLA: Polylactic acid; PLA-Wood: Wood-filled polylactic acid.

Table 6. Selected tensile strength and Young's modulus data under moisture exposure

Material	Duration (h)	Tensile strength (MPa)	Young's modulus (MPa)	Strain at break (%)	CV (%)	<i>p</i> -value vs. dry
PLA	Dry	28.64 ± 1.43	1,297.82 ± 71	1.37 ± 0.12	5.0	—
PLA	24	21.92 ± 1.31	1,154.97 ± 83	1.90 ± 0.15	6.0	<0.05
PLA	168	15.99 ± 1.14	2,214.88 ± 142	1.20 ± 0.10	7.1	<0.05
PLA	720	20.88 ± 1.24	2,022.41 ± 131	1.57 ± 0.13	5.9	<0.05
PETG	Dry	43.98 ± 1.09	1,182.12 ± 58	1.37 ± 0.11	2.5	—
PETG	24	24.38 ± 0.71	1,451.33 ± 79	2.80 ± 0.18	2.9	<0.05
PETG	720	25.60 ± 0.74	892.61 ± 52	2.87 ± 0.19	2.9	<0.05
PLA-Wood	Dry	18.00 ± 1.52	610.25 ± 44	1.84 ± 0.16	8.4	—
PLA-Wood	24	7.94 ± 0.82	324.28 ± 31	2.45 ± 0.21	10.3	<0.05
PLA-Wood	720	7.63 ± 0.76	168.33 ± 19	4.53 ± 0.41	10.0	<0.05

Abbreviations: CV: Coefficient of variation; PETG: Polyethylene terephthalate glycol; PLA: Polylactic acid; PLA-Wood: Wood-filled polylactic acid.

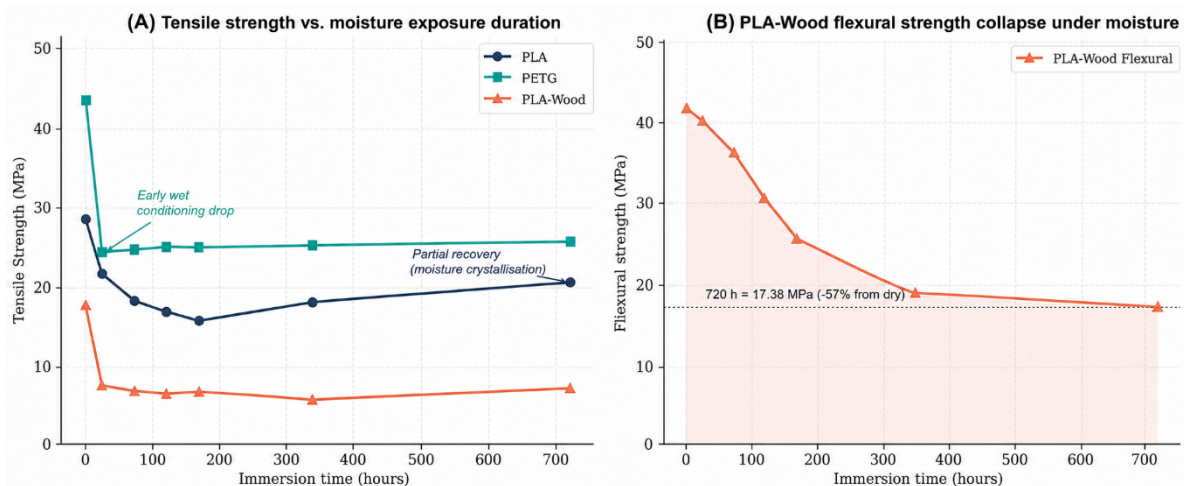


Figure 8. Effect of moisture exposure duration on the mechanical performance of FDM-printed PLA, PETG, and PLA-Wood specimens. (A) Tensile strength evolution under moisture exposure showing stable post-conditioning behaviour of PETG, progressive degradation of PLA with partial recovery at 720 h, and consistently poor performance of PLA-Wood. (B) Catastrophic flexural strength collapse of PLA-Wood (57% reduction at 720 h) driven by wood-fibre swelling and interfacial debonding.

Abbreviations: PETG: Polyethylene terephthalate glycol; PLA: Polylactic acid; PLA-Wood: Wood-filled polylactic acid.

MPa to the first wet measurement of 24.38 MPa must be emphasised. Therefore, PETG should be considered stable after initial moisture conditioning rather than completely unaffected by moisture. Its relatively stable wet-state performance may be linked to its hydrophobic molecular structure and dense interlayer morphology, which reduce progressive moisture-induced degradation.

In contrast, PLA-Wood showed the lowest tensile strength and the highest susceptibility to moisture-related

degradation. Its tensile strength decreased from 7.94 MPa at 24 h to 6.12 MPa at 336 h, corresponding to an approximate 23% reduction. This degradation is mainly attributed to fibre swelling, interfacial debonding, and reduced load-transfer efficiency between the PLA matrix and wood particulates. The hydrophilic nature of the wood phase promotes moisture uptake, weakening the interface and accelerating mechanical deterioration under tensile loading.

In addition to tensile degradation, PLA-Wood also exhibited severe deterioration under flexural loading, with an approximate 57% reduction in flexural strength after prolonged moisture exposure, as highlighted in Figure 8B. This pronounced loss further confirms that natural fibre-reinforced FDM composites are highly vulnerable to combined moisture ingress, fibre swelling, and interfacial weakening. Tensile results demonstrate that PETG maintained the most stable wet-state performance, PLA showed moisture-sensitive but partially recoverable behaviour, and PLA-Wood displayed the poorest resistance to humid environments.

3.7. Moisture exposure: Flexural and compressive properties

In dry conditions, PLA achieved the highest flexural strength (96.15 ± 3.84 MPa), followed by PETG (85.14 ± 3.07 MPa) and PLA-Wood (41.52 ± 4.23 MPa). Under moisture exposure, PLA exhibited a non-monotonic flexural response, reaching 94.91 MPa at 72 h before progressively declining to 72.13 ± 3.33 MPa at 720 h. This corresponds to an overall reduction of approximately 25% relative to the dry condition. The temporary retention of flexural strength at the early exposure stage may be associated with plasticisation-enhanced ductility, whereas the subsequent decline indicates progressive moisture-induced weakening of the polymer matrix and interlayer bonding.

The PETG maintained comparatively superior flexural stability during moisture exposure. Its flexural strength increased slightly to a peak value of 89.59 MPa before decreasing to 75.47 ± 2.94 MPa at 720 h. This represents an approximate 15.8% reduction from the peak value, or about 11.4% relative to the dry baseline. The relatively moderate reduction confirms PETG's better resistance to moisture-assisted degradation compared with PLA and PLA-Wood, although the reduction at prolonged exposure indicates that PETG is not completely unaffected by water ingress.

In contrast, PLA-Wood experienced the most severe flexural degradation, with strength decreasing from 40.21 MPa at 24 h to 17.38 ± 2.52 MPa at 720 h, corresponding to an approximate 57% reduction. This catastrophic loss is primarily attributed to wood-fibre swelling, moisture retention within the filler phase, and extensive interfacial debonding between the wood particulates and PLA matrix. The degradation is more pronounced than the 13% flexural strength reduction reported by Ecker *et al.*¹⁷ for injection-moulded PLA-Wood composites, suggesting that FDM layer architecture introduces additional crack initiation sites and moisture ingress pathways compared

with conventionally processed materials.

For compressive properties, PETG maintained the highest dry compressive strength (6.16 ± 0.24 MPa), followed by PLA and PLA-Wood. Upon moisture exposure, PLA reached 3.51 ± 0.18 MPa at 720 h, while PETG decreased to 3.68 ± 0.14 MPa. PLA-Wood showed the weakest compressive response, collapsing to only 0.85 ± 0.14 MPa at 720 h, as illustrated in Figure 9. The reduction in PETG compressive strength was more pronounced than its tensile reduction, which may be associated with the geometry-specific sensitivity of cylindrical compression specimens. These specimens can retain more water within surface defects, pores, and interlayer regions, increasing the effective moisture exposure per unit gauge volume. The flexural and compressive results confirm that PLA-Wood is the most vulnerable material under moisture exposure, particularly under bending and compression. PLA showed moderate degradation with some early-stage non-monotonic behaviour, while PETG retained the most stable mechanical performance across both loading modes. These findings indicate that PETG is the most suitable of the three materials for moisture-exposed applications, whereas PLA-Wood has limited structural reliability in humid or water-rich environments.

4. Discussion

4.1. Thermal degradation mechanisms

The differential thermal stability observed among PLA, PLA-Wood, and PETG can be attributed to their distinct molecular architectures and degradation pathways. PLA is known to be susceptible to thermal degradation when exposed near or above its T_g , where chain scission may occur via back-biting ester-interchange reactions. This process reduces molecular weight, increases brittleness, and weakens mechanical performance.^{11,14} In the present study, PLA exhibited the highest mass loss among the tensile specimens, reaching 2.48% after ageing. This mass reduction is likely associated with the volatilisation of chain-scission fragments, mainly lactide monomers and low-molecular-weight oligomers. This observation is consistent with thermogravimetric studies showing that PLA can undergo measurable degradation above 55 °C under prolonged exposure.²² The 12.8% reduction in tensile Young's modulus, together with SEM-observed void formation after eight days, provides direct mechanical and morphological evidence of thermally induced chain scission.

An important finding of this study is the quantitative divergence in PLA degradation response across different mechanical loading modes. PLA's tensile modulus decreased by 12.8%, whereas its compressive modulus

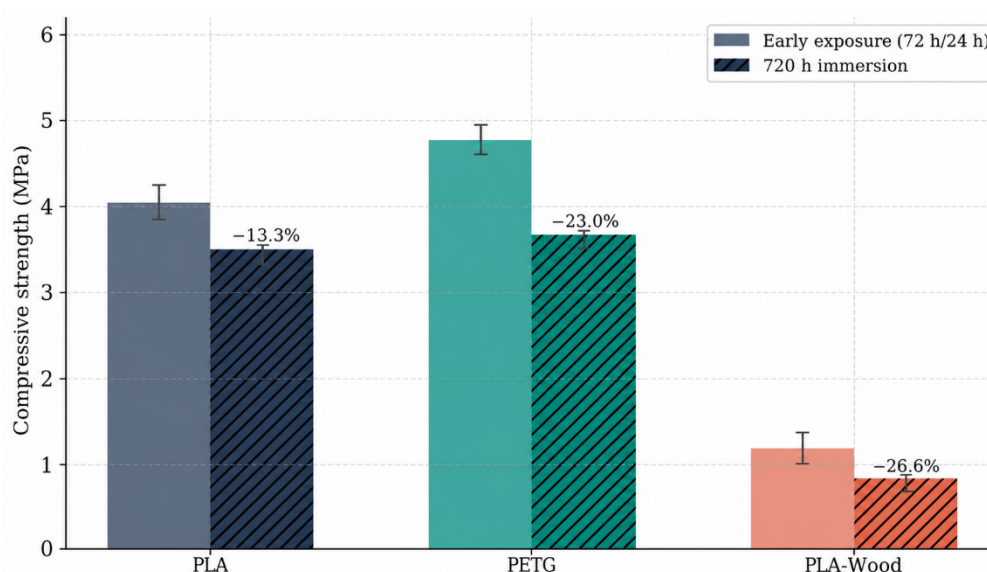


Figure 9. Compressive strength comparison at 24 h and 720 h immersion

Abbreviations: PETG: Polyethylene terephthalate glycol; PLA: Polylactic acid; PLA-Wood: Wood-filled polylactic acid.

decreased by only 5.3% over the same ageing period. This anisotropic degradation behaviour is mechanistically significant. Under tensile loading, the amorphous regions and interlayer bonding zones are more critically engaged, making the material more sensitive to chain scission and molecular mobility. In contrast, compressive loading may recruit crystalline domains and bulk matrix regions more effectively, thereby partially resisting chain-scission-induced softening. This interpretation is consistent with the stress relaxation behaviour reported by Tüfekci *et al.*,²³ who showed that amorphous-phase mobility strongly governs the time-dependent mechanical response of FDM-printed PLA near its T_g . Therefore, the present study extends previous findings by providing multi-modal evidence of anisotropic thermal degradation across tensile, compressive, and flexural loading conditions.

The degradation of PLA-Wood is governed by a compounded dual mechanism involving both PLA matrix degradation and wood-fibre-related instability. In addition to chain scission within the PLA matrix, the hydrophilic wood particles may undergo moisture desorption during thermal exposure, leading to volumetric shrinkage, fibre-matrix interfacial cracking, and phase separation. This explains why PLA-Wood showed the largest proportional reduction in compressive modulus, decreasing by 15.6%, despite having lower absolute stiffness than PLA and PETG. The wood filler acts as both a stress concentrator and a preferential site for crack initiation under thermal stress. SEM observations confirmed interfacial gap formation and particle pull-out, which are consistent

with debonding-driven property loss reported in previous wood–PLA ageing studies.^{9,19}

The behaviour of PLA-Wood also highlights an important material-design limitation of commercial wood-filled filaments. Krapež Tomec *et al.*¹⁹ demonstrated that thermal pre-modification of wood particles at approximately 180–200 °C can substantially reduce moisture-induced swelling by lowering the hygroscopicity of the wood filler. This suggests a potential mitigation strategy to improve the thermal and moisture stability of PLA-Wood composites. However, this strategy was not applied to the commercial filaments used in the present study. Future formulations using thermally modified wood particles may therefore offer improved resistance to combined thermal and moisture exposure.

Overall, PETG exhibited the greatest thermal stability among the three materials. This behaviour can be attributed to its higher T_g (typically around 75–80 °C), its predominantly amorphous molecular structure, and its lower susceptibility to hydrolysis compared with ester-bonded PLA.^{6,30,31} PETG showed minimal mass loss, with compression specimens recording only 0.53%, and SEM analysis revealed comparatively intact morphology after eight days of ageing. These results indicate that PETG underwent limited chain scission or morphological damage under the ageing conditions used in this study. The superior thermal resistance of PETG supports its suitability for functional FDM applications that require dimensional and mechanical stability under moderate thermal exposure, including biomedical models, orthotic

devices, and other service components where long-term stability is necessary.^{7,8,25}

4.2. Non-monotonic stiffness response in polylactic acid

The temporary increase in PLA's modulus after four days of ageing observed across both compressive and flexural test modes, followed by a decline at eight days, is one of the most practically significant findings of this study and requires careful mechanistic interpretation. This behaviour is characteristic of thermally induced secondary crystallisation: when PLA is held near its T_g , residual amorphous domains can partially reorganise into ordered crystalline structures, transiently increasing stiffness.²³ As exposure continues, chain degradation overwhelms the crystallisation benefit, and properties decline.

This non-monotonic response has direct and underappreciated implications for engineering design. If a structural component is characterised only at the four-day interval, or if a test protocol captures the crystallisation peak without the subsequent degradation, the material's long-term performance will be overestimated. Similarly, if short-term thermal annealing is used as a post-processing step to improve stiffness, a practice employed in FDM component optimization,³⁴⁻³⁶ the resulting improvement may be transient rather than permanent if the component is subsequently exposed to elevated temperatures in service. The present study provides the first multi-modal, multi-duration evidence of this effect across both compressive and flexural test modes, adding specificity to the single-mode reports in the prior literature.²³

Mechanistically, the parallel appearance of non-monotonic behaviour under early moisture exposure (Section 3.7) confirms that the stiffening process is not exclusively temperature-dependent: plasticisation of amorphous domains by water molecules also increases chain mobility, facilitating crystallisation reorganisation at room temperature, a process sometimes termed moisture-induced crystallisation. This convergence of thermal and moisture-induced crystallisation as competing mechanisms is a novel integrative finding that enriches understanding of PLA degradation kinetics beyond the classical chain-scission model.

4.3. Moisture degradation mechanisms

The moisture-induced degradation mechanisms observed in this study are distinct from thermal ageing pathways, although both ultimately reduce mechanical performance through matrix weakening, interfacial damage, and microstructural instability. In PLA, water molecules primarily act as plasticisers, disrupting inter-chain

hydrogen bonding within amorphous regions and reducing intermolecular cohesion.^{13,20} This weakens the polymer matrix and lowers tensile performance, as illustrated in Figure 10. The 27% reduction in tensile strength observed between 24 and 168 h of immersion aligns closely with the degradation ranges reported by Banjo *et al.*¹⁶ and Islam *et al.*,¹³ providing independent validation of the present experimental methodology.

The increase in PLA Young's modulus from 1,154.97 MPa at 24 h to 2,214.88 MPa at 168 h appears counterintuitive and requires careful interpretation. Rather than indicating genuine structural improvement, this behaviour is most likely associated with moisture-mediated secondary crystallisation in amorphous PLA domains. Water-assisted molecular mobility may allow polymer chains to reorganise into more ordered crystalline regions, thereby increasing stiffness despite a simultaneous reduction in tensile strength. This interpretation is consistent with the hygrothermal study by Aguado *et al.*,³³ who reported modulus increases associated with crystallisation at intermediate immersion durations in PLA-based composites.

However, increased stiffness occurring alongside reduced strength indicates that the material is becoming more brittle rather than mechanically stronger. This behaviour is generally undesirable for structural applications, because a stiffer but weaker material is less able to tolerate deformation, stress concentration, and impact loading. The non-monotonic response also highlights a limitation of simple linear degradation models, such as Equation 8, when applied to semi-crystalline polymers. A more accurate thermo-hygro-mechanical framework for PLA should include a crystallisation term, potentially based on Avrami-type crystallisation kinetics, to capture the competing effects of plasticisation, hydrolysis, and moisture-mediated crystallisation.

For PLA-Wood, the dominant moisture-degradation mechanism is fibre-mediated. The hydrophilic wood particles preferentially absorb water, causing fibre swelling, volumetric expansion within the PLA matrix, and progressive fibre-matrix interfacial debonding, as shown schematically in Figure 10. The approximately 50% apparent moisture absorption observed in PLA-Wood compression specimens after 720 h, compared with approximately 17% for neat PLA, quantitatively confirms the dominant role of wood fibres in governing moisture transport and retention. This behaviour is consistent with published observations for natural-fibre PLA composites^{16,17} and FDM-printed PLA-Wood components, where increasing wood content has been associated with higher moisture adsorption capacity.³⁷⁻³⁹

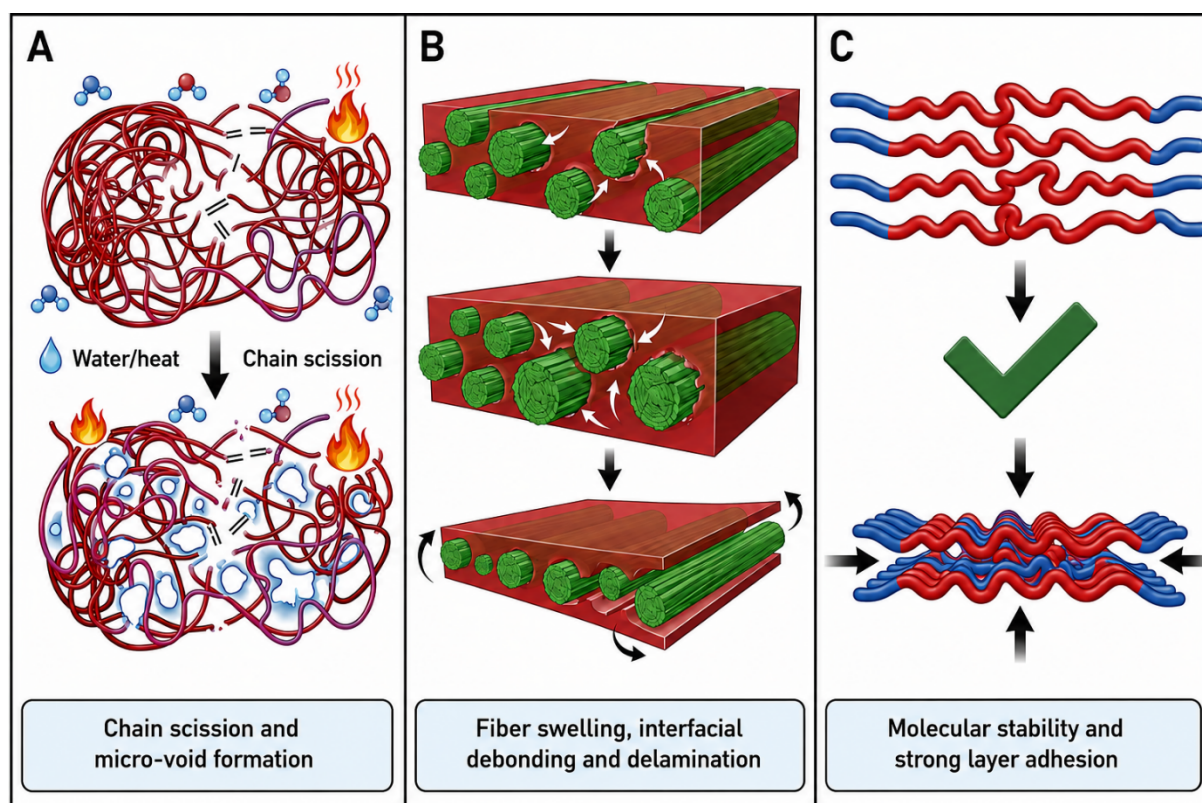


Figure 10. Schematic representation of molecular degradation pathways. (A) Polylactic acid (PLA). (B) Wood-filled PLA. (C) Poly(ethylene terephthalate) glycol (PETG).

The mechanical consequences of this fibre-mediated degradation were most severe under flexural loading. PLA-Wood exhibited a 57% reduction in flexural strength after prolonged moisture exposure, substantially exceeding the 13% reduction reported by Ecker *et al.*¹⁷ for injection-moulded PLA-Wood composites. This divergence is mechanistically coherent because FDM-printed components contain interlayer voids, raster boundaries, and layer interfaces that provide additional pathways for moisture ingress and crack initiation sites. Under bending, these defects become particularly critical because tensile stress develops on one side of the specimen, promoting crack opening and interfacial separation.

This finding has important methodological and practical implications. Mechanical degradation data obtained from injection-moulded or compression-moulded natural-fibre composites cannot be directly transferred to FDM-printed equivalents without considering process-induced porosity, anisotropy, and interlayer bonding quality. Therefore, component qualification for humid or water-exposed environments must be based on tests performed using the actual manufacturing process and specimen architecture. For regulated or safety-critical applications,

this distinction is essential because FDM layer architecture can significantly amplify moisture-induced degradation beyond that predicted from conventionally processed composite data.

4.4. Integrated comparison: Thermal ageing vs. moisture exposure

When the two degradation pathways are compared directly, moisture exposure generally produces more severe absolute strength losses than equivalent-duration thermal ageing, particularly for PLA-Wood. This behaviour is consistent with the expectation that, once sufficient water molecules penetrate the printed structure, moisture diffusion can cause more pervasive molecular and interfacial disruption than dry thermal exposure at sub-decomposition temperatures. In practical terms, this indicates that moisture-exposed PLA-Wood components are likely to fail mechanically earlier than thermally aged equivalents, especially in outdoor, humid, or water-contact environments.

The PETG demonstrated the highest resistance to both environmental stressors. Under thermal ageing, it maintained tensile strength above 40 MPa, while under

moisture exposure, its tensile strength remained within approximately 24–26 MPa after initial wet conditioning. Although the reduction from the dry state under moisture exposure should not be overlooked, PETG showed the most stable post-conditioning response among the three materials. Its ductile failure behaviour under both thermal and moisture exposure is a particularly important advantage. Unlike brittle failure, ductile deformation provides a visible warning before catastrophic fracture, which is valuable for safety-critical applications such as medical devices, load-bearing supports, and dynamic mechanical assemblies.^{40–42}

For PLA, it exhibited moderate degradation under both ageing conditions. Under moisture exposure, PLA showed a partial tensile strength recovery at 720 h, suggesting that moisture-induced crystallisation may partly compensate for plasticisation over extended immersion periods. However, this recovery should not be interpreted as a full restoration of structural integrity. Any crystallisation-induced stiffness gain occurs alongside progressive molecular damage, meaning that the material may become stiffer but more brittle. This combination is generally undesirable in structural applications because it reduces deformation tolerance and increases sensitivity to crack initiation.

In contrast, PLA-Wood showed the poorest

environmental durability across both degradation pathways. Its severe strength loss under moisture exposure was mainly driven by wood-fibre swelling, water retention, and interfacial debonding. These effects were further intensified by FDM-related features, such as interlayer voids and raster boundaries, which provide additional pathways for moisture ingress and crack initiation sites. Therefore, PLA-Wood should not be considered suitable for load-bearing or moisture-exposed applications unless significant material modification, surface protection, or post-processing is applied.

The ranking PETG > PLA > PLA-Wood was consistent across thermal ageing, moisture exposure, and all three mechanical test modes, as summarised in Figure 11. This ranking provides a clear framework for filament selection in degradation-prone environments and is consistent with the comparative degradability hierarchy reported by Ramírez-Revilla *et al.*³¹ for FDM-printed PLA, PETG, and related thermoplastics. Based on these findings, PETG is recommended for functional FDM applications requiring long-term thermal or moisture stability. PLA is more appropriate for short-term, dry applications where biodegradability and stiffness are prioritised over environmental durability. If moisture contact is expected, hydrophobic surface coatings or protective post-treatments are strongly recommended. PLA-Wood should

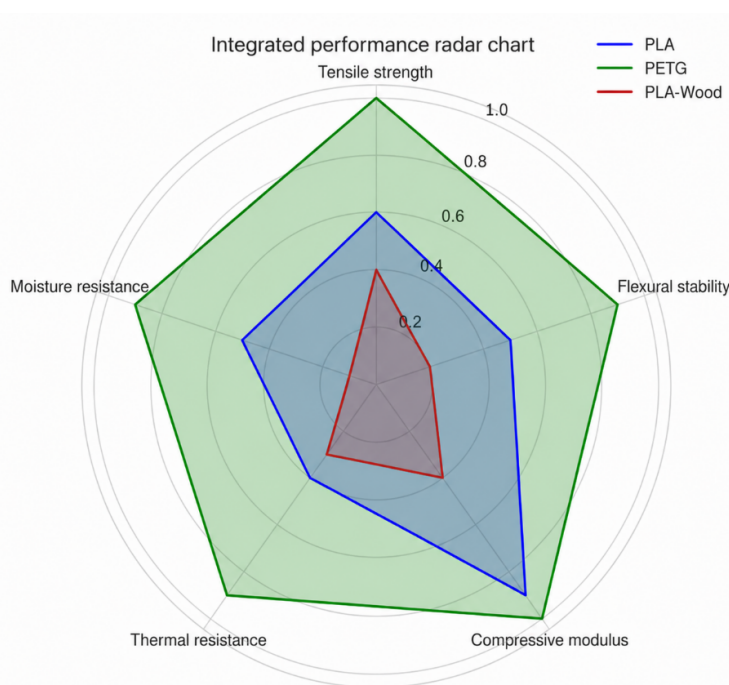


Figure 11. Spider chart summarising performance across five critical axes

Abbreviations: PETG: Polyethylene terephthalate glycol; PLA: Polylactic acid; PLA-Wood: Wood-filled polylactic acid.

be reserved mainly for decorative, aesthetic, or non-load-bearing applications where environmental exposure and mechanical demand are limited.

4.5. Implications for material selection

The results yield clear, empirically grounded guidance on material selection. PETG is recommended for functional FDM applications requiring long-term thermal or moisture stability, including biomedical braces, prosthetic sockets, outdoor housings, and mechanical fixtures, owing to its consistently high strength, stable modulus, ductile failure mode, and minimal degradation under both stressors. The ductile failure behaviour of PETG is particularly advantageous in safety-critical applications, as it provides warning deformation prior to catastrophic failure, contrasting sharply with the brittle sudden fracture observed in PLA and PLA-Wood.

In addition, PLA is appropriate for short-term, non-thermally stressed or dry applications such as educational prototypes, conceptual models, and biodegradable packaging, where its superior biodegradability and ease of processing outweigh the mechanical limitations under environmental ageing. If used in moisture-present environments, protective hydrophobic surface coatings are strongly recommended. PLA-Wood is best reserved for decorative, aesthetic, or non-load-bearing applications where its natural-Wood appearance adds value; its consistently inferior performance under both compressive loading and environmental ageing renders it unsuitable for any structurally or environmentally demanding FDM application.

4.6. Limitations and future directions

Several limitations should be acknowledged. First, $n = 3$ specimens per condition is acceptable for initial comparison but should be increased to $n \geq 5$ in future studies. Second, maximum exposure durations (eight days thermal; 720 h moisture) should be extended to capture saturation behaviour and multi-stage kinetics. Third, independent application of thermal and moisture stressors does not replicate combined hygrothermal service conditions. Fourth, apparent moisture absorption values include pore-retained water; micro-computed tomography or controlled desorption would separate these contributions. Fifth, no direct molecular characterisation (differential scanning calorimetry, Fourier transform infrared spectroscopy, gel permeation chromatography, dynamic mechanical analysis, thermogravimetric analysis) was performed, and mechanistic interpretations remain plausible rather than definitively proven. Future studies should address all five limitations and additionally investigate infill patterns and density effects, cyclic thermal fatigue, and alternative

sustainable filament formulations.

5. Conclusion

This study provides a quantitative baseline for the environmental durability of bio-based FDM filaments. The experimental results are consistent with the thermo-hygro-mechanical degradation framework described earlier. PETG emerges as the most robust material, while PLA-Wood is highly susceptible to moisture-induced failure. These findings enable informed material selection for additive manufacturing in diverse service environments. The following conclusions are drawn:

- (i) PETG demonstrated the highest baseline tensile strength (41.53 ± 1.21 MPa thermal control; 43.98 ± 1.09 MPa dry moisture baseline), the smallest proportional modulus reductions across all test modes, and stable wet-conditioned tensile strength (24.38–25.60 MPa) over 720 h. PETG is the most thermally and hygroscopically stable filament of the three examined and is recommended for functional and structural FDM applications in environmentally demanding service conditions.
- (ii) PLA exhibited moderate progressive sensitivity to thermal ageing (–12.8% tensile modulus over eight days) and moisture exposure (–27% tensile strength from 24 to 168 h). A transient non-monotonic stiffness increase under both short-term thermal ageing and early moisture exposure is mechanistically attributed to secondary crystallisation of amorphous domains, subsequently overwhelmed by chain-scission or plasticisation-driven degradation. This non-monotonic behaviour has direct implications for design characterisation protocols and post-processing annealing strategies.
- (iii) PLA-Wood demonstrated the poorest overall environmental durability. The largest proportional compressive modulus reduction under thermal ageing (15.6%), approximately 50% apparent moisture absorption in compression specimens at 720 h, and 57% flexural strength loss confirm a dual-degradation mechanism combining PLA matrix chain scission with hygroscopic wood-fibre desorption and swelling-induced interfacial debonding. PLA-Wood should be limited to decorative or non-load-bearing applications.
- (iv) SEM analysis provided mechanistic corroboration for all macroscopic mechanical results: PLA and PLA-Wood developed progressive voids, interlayer fractures, and phase separation under thermal ageing, while PETG retained near-intact surface morphology, reinforcing its suitability for prolonged environmental service.

(v) A consistent performance hierarchy (PETG > PLA > PLA-Wood) is established across all test modes and both degradation pathways, providing a robust empirical foundation for filament selection in thermally or hygroscopically demanding FDM applications.

Acknowledgments

The authors would like to acknowledge the technical support provided by the laboratory staff during specimen fabrication, environmental conditioning, and mechanical testing. The authors also appreciate the institutional facilities and research environment that supported the completion of this work. Special thanks are extended to colleagues and collaborators who provided constructive feedback during manuscript preparation and data interpretation.

Funding

The authors would like to acknowledge financial support from UniMAP and HaUI under the International Research Fund (INTERES) matching grant with the grant number 9008-00104.

Conflict of interest

The authors declare no conflict of interest.

Author contributions

Conceptualization: Khairul Salleh Basaruddin, Hoang Tien Dung

Investigation: Md Ashequl Islam, Liyana Tajul, Hoang Tien-Dat

Methodology: Md Ashequl Islam, Nor Amalina Muhayudin

Supervision: Khairul Salleh Basaruddin

Writing—original draft: Md Ashequl Islam

Writing—review & editing: All authors

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

References

1. Kristiawan RB, Imaduddin F, Ariawan D, Ubaidillah, Arifin Z. A review on the fused deposition modeling (FDM) 3D printing: Filament processing, materials, and printing parameters. *Open Eng.* 2021;11(1):639-649. doi: 10.1515/eng-2021-0063
2. Mendenhall R, Eslami B. Experimental investigation on effect of temperature on FDM 3D printing polymers: ABS, PETG, and PLA. *Appl Sci.* 2023;13(20):11503. doi: 10.3390/app132011503
3. Saqib MA, Abbas MS, Tanaka H. Sustainability and innovation in 3D printing: Outlook and trends. *Clean Technol Recycl.* 2024;4(1):1-21. doi: 10.3934/ctr.2024001
4. Bhagia S, Bornani K, Agrawal R, *et al.* Critical review of FDM 3D printing of PLA biocomposites filled with biomass resources, characterization, biodegradability, upcycling and opportunities for biorefineries. *Appl Mater Today.* 2021;24:101078. doi: 10.1016/j.apmt.2021.101078
5. Farah S, Anderson DG, Langer R. Physical and mechanical properties of PLA, and their functions in widespread applications: A comprehensive review. *Adv Drug Deliv Rev.* 2016;107:367-392. doi: 10.1016/j.addr.2016.06.012
6. Patel KS, Shah DB, Joshi SJ, Aldawood FK, Kchaou M. Effect of process parameters on the mechanical performance of FDM printed carbon fiber reinforced PETG. *J Mater Res Technol.* 2024;30:8006-8018. doi: 10.1016/j.jmrt.2024.05.184
7. Martins RF, Branco R, Martins M, *et al.* Mechanical properties of additively manufactured polymeric materials—PLA and PETG—for biomechanical applications. *Polymers (Basel).* 2024;16(13):1868. doi: 10.3390/polym16131868
8. Sultan MM, Aized T, Farooq M, *et al.* Optimization of PETG 3D printing parameters for the design and development of biocompatible bone implants. *Front Bioeng Biotechnol.* 2025;13:1549191. doi: 10.3389/fbioe.2025.1549191
9. Ulkir O, Karadağ A. Sustainable additive manufacturing with FDM: Taguchi-based parameter optimization and AI-driven prediction of mechanical and environmental metrics. *J Thermoplast Compos Mater.* Published online 2026. doi: 10.1177/08927057261415795
10. Sultana J, Rahman MM, Wang Y, Ahmed A, Xiaohu C. Influences of 3D printing parameters on the mechanical properties of wood PLA filament: An experimental analysis by Taguchi method. *Prog Addit Manuf.* 2024;9(4):1239-1251. doi: 10.1007/s40964-023-00516-6

11. Barbaz-Isfahani R, Saber-Samandari S, Salehi M. Multi-scale modeling and experimental study on electrosprayed multicore microcapsule-based self-healing polymers. *Mech Adv Mater Struct.* 2024;31(12):2581-2594.
doi: 10.1080/15376494.2022.2162638
12. Jha S, Akula B, Enyioma H, Novak M, Amin V, Liang H. Biodegradable biobased polymers: A review of the state of the art, challenges, and future directions. *Polymers (Basel).* 2024;16(16):2262.
doi: 10.3390/polym16162262
13. Islam MA, Basaruddin KS, Hassan M, Kamarrudin NS, Rashid AHA, Hoang TD. Influence of infill pattern on tensile strength and material efficiency of fused deposition modelling (FDM)-printed polylactic acid (PLA) parts. *Int J Nanoelectron Mater.* 2026;19(2):213-222.
doi: 10.58915/ijneam.v19i2.3093
14. Korkut V, Daricik F, Aktitiz I, Aydin K. Failure of surface modification 3D printed polymer materials by UV/ozone irradiation. *Eng Fail Anal.* 2023;152:107466.
doi: 10.1016/j.engfailanal.2023.107466
15. Fijol N, Mathew AP. Accelerated ageing of 3D printed water purification filters based on PLA reinforced with green nanofibers. *Polym Test.* 2023;129:108303.
doi: 10.1016/j.polymertesting.2023.108270
16. Banjo AD, Agrawal V, Auad ML, Celestine ADN. Moisture-induced changes in the mechanical behavior of 3D printed polymers. *Compos Part C Open Access.* 2022;7:100243.
doi: 10.1016/j.jcomc.2022.100243
17. Ecker JV, Haider A, Burzic I, Huber A, Eder G, Hild S. Mechanical properties and water absorption behaviour of PLA and PLA/wood composites prepared by 3D printing and injection moulding. *Rapid Prototyp J.* 2019;25(4):672-678.
doi: 10.1108/RPJ-06-2018-0149
18. Bergaliyeva S, Sales DL. Effect of thermal and hydrothermal accelerated aging on 3D printed polylactic acid. *Polymers (Basel).* 2022;14(23):5256.
doi: 10.3390/polym14235256
19. Krapež Tomec D, Schöflinger M, Lefšlumer J, Žigon J, Humar M, Kariž M. Effect of thermal modification of wood on the rheology, mechanical properties and dimensional stability of wood composite filaments and 3D-printed parts. *Wood Mater Sci Eng.* 2024;19(6):1251-1265.
doi: 10.1080/17480272.2024.2316740
20. Quader R, Dramko E, Grewell D, Randall J, Narayanan LK. Characterizing the effect of filament moisture on tensile properties and morphology of fused deposition modeled polylactic acid/polybutylene succinate parts. *3D Print Addit Manuf.* 2024;11(3):e1151-e1161.
doi: 10.1089/3dp.2022.0222
21. Triawan F, Syefira D, Rismalia M, *et al.* The influence of infill density and pattern on the mechanical and fracture behavior of 3D printed structure subjected to uniaxial tensile load. *J Eng Sci Technol.* 2022;17(5):3254-3266.
22. Orellana-Barrasa J, Ferrández-Montero A, Ferrari B, Pastor JY. Natural ageing of PLA filaments: Can it be frozen? *Polymers (Basel).* 2022;14(16):3361.
doi: 10.3390/polym14163361
23. Tüfekci K, Cakan BG, Kucukakarsu VM. Stress relaxation of 3D printed PLA of various infill orientations under tensile and bending loadings. *J Appl Polym Sci.* 2023;140(39):e54456.
doi: 10.1002/app.54463
24. Li B, Baxevanakis KP, Silberschmidt VV. Water diffusion in additively manufactured PETG: Microstructure-based modelling. *Mech Mach Sci.* 2024;152:793-801.
doi: 10.1007/978-3-031-49421-5_82
25. Kannan G, Kurien RA, Khoklang K, Sriamornsak P, Suttirungwong S. Biodegradable polymers and biocomposites in sustainable additive manufacturing: A review. *Int J Biol Macromol.* 2025;333(1):148611.
doi: 10.1016/j.ijbiomac.2025.148611
26. Martínez-Sánchez JA, Romero PE, Comino F, Molero E, Ruiz de Adana M. Effect of material extrusion process parameters to enhance water vapour adsorption capacity of PLA/wood composite printed parts. *Polymers (Basel).* 2024;16(20):2934.
doi: 10.3390/polym16202934
27. Joseph A, Mahesh V, Mahesh V, Harursampath D, Loja MAR. Effects of hygrothermal aging on the mechanical properties of the biocomposites. In: *Aging Effects on Natural Fiber-Reinforced Polymer Composites*. Composites Science and Technology. Singapore: Springer; 2022.
doi: 10.1007/978-981-16-8360-2_5
28. Kariž M, Sernek M, Obućina M, Kuzman MK. Effect of printing layer thickness on water absorption and mechanical properties of 3D-printed wood/PLA composite materials. *Int J Adv Manuf Technol.* 2019;102(5-8):2195-2200.
doi: 10.1007/s00170-019-03299-9
29. Trivedi AK, Gupta MK. PLA based biocomposites for sustainable products: A review. *Adv Ind Eng Polym Res.* 2023;6(4):382-395.
doi: 10.1016/j.aiepr.2023.02.002
30. Hsueh MH, Lai CJ, Wang SH, *et al.* Effect of printing parameters on the thermal and mechanical properties of 3D-printed PLA and PETG, using fused deposition modeling. *Polymers (Basel).* 2021;13(11):1758.
doi: 10.3390/polym13111758
31. Ramírez-Revilla S, Camacho-Valencia D, Gonzales-

- Condori EG, Márquez G. Evaluation and comparison of the degradability and compressive and tensile properties of 3D printing polymeric materials: PLA, PETG, PC, and ASA. *MRS Commun.* 2023;13(1):55-62.
doi: 10.1557/s43579-022-00311-4
32. Li W, Zhao X, Liu Y, Ouyang Y, Chen D, Ye D. Hygrothermal aging behavior and flexural property of carbon fiber-reinforced polyethylene terephthalate glycol composites. *Text Res J.* 2023;93(5-6):1005-1018.
doi: 10.1177/00405175221126005
33. Aguado RJ, Bastida GA, Espinach FX, *et al.* Comparative study on the stiffness of poly (lactic acid) reinforced with untreated and bleached hemp fibers. *Polymers (Basel).* 2023;15(13):2960.
doi: 10.3390/polym15132960
34. Stojković JR, Turudija R, Vitković N, *et al.* An experimental study on the impact of layer height and annealing parameters on the tensile strength and dimensional accuracy of FDM 3D printed parts. *Materials (Basel).* 2023;16(13):4574.
doi: 10.3390/ma16134574
35. Eryildiz M, Kosa E, Akgun IC, Yavuzer B. Enhancing the mechanical performance of fused deposition modeling-printed recycled polypropylene through annealing temperature, duration, and cooling method. *J Mater Eng Perform.* 2025;34(15):16032-16048.
doi: 10.1007/s11665-025-11539-1
36. Dallal S, Eslami B, Tiari S. Recent advances in PEEK for biomedical applications: A comprehensive review of material properties, processing, and additive manufacturing. *Polymers (Basel).* 2025;17(14):1968.
doi: 10.3390/polym17141968
37. Xu W, Li M, Xu Y, Entezari A, Fang J. Mechanical characterization of fused deposition modeling-printed wood-poly(lactic acid) composites under water conditioning. *Polym Compos.* 2026;47(6):5205-5221.
doi: 10.1002/pc.70484
38. Magalhães FDC, Rubio CVC, Rubio JCC. Enhancing mechanical and structural properties of PLA/wood composites through annealing. *Mater Res.* 2025;28:e20250640.
doi: 10.1590/1980-5373-MR-2025-0640
39. Ulkir O, Karadağ A. Effect of infill geometry on the structural performance and fracture morphology of FDM-printed PLA composites. *Multidiscip Model Mater Struct.* 2026;22(5):1218-1231.
doi: 10.1108/MMMS-02-2026-0047
40. Wang C, Xue H, Wan Q, *et al.* TPMS-based PLA/PETG interpenetrating composites: The synergistic enhancement of mechanical properties for bone implant. *Compos Struct.* 2025;373:119644.
doi: 10.1016/j.compstruct.2025.119644
41. Tyagi B, Velu R, Raj A. Failure analysis and statistical validation of fused filament fabricated PETG composite for transtibial prosthetics. *Prog Addit Manuf.* 2025;10(10):8239-8264.
doi: 10.1007/s40964-025-01113-5
42. Daskalakis E, Hassan M, Omar A, *et al.* 3D-printed PETG/BC scaffolds for bone tissue repair. *Int J Bioprint.* 2025;12(1):413-431.
doi: 10.36922/IJB025210212