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Fatigue Modeling and Mechanical Performance of Additively Manufactured and Commercial Polylactic Acid to Support Sustainable Development Goals (SDGs) Completed with Bibliometric Analysis

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ABSTRACT

This study evaluates the fatigue behavior and mechanical performance of polylactic acid (PLA) produced by fused deposition modeling (FDM) and compares it with commercially manufactured PLA to support Sustainable Development Goals (SDGs) related to sustainable manufacturing. Tensile, impact, and fatigue tests were conducted to evaluate the strength, toughness, and fatigue life under cyclic loading. A fatigue crack growth model based on linear elastic fracture mechanics and Paris' law was developed and solved numerically using MATLAB. In addition, a bibliometric analysis was conducted to identify recent research trends connecting additive manufacturing, fatigue performance, and sustainability. The results show that process-induced anisotropy and defects significantly reduce the fatigue resistance of FDM-printed PLA, while optimized infill density and raster orientation improve performance. The findings provide practical guidance for the reliable and sustainable application of additively manufactured polymer components.

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1. INTRODUCTION

Sustainable production has become a global priority in response to increasing concerns over material waste, energy consumption, and environmental degradation. In line with the United Nations Sustainable Development Goals (SDGs), particularly those addressing sustainable industrialization, responsible production, and climate action, modern engineering increasingly emphasizes material efficiency, durability, and lifecycle performance. Many reports regarding SDGs have been well-documented [1-3]. Specifically, additive manufacturing (AM), commonly referred to as 3D printing, offers a promising pathway toward sustainable manufacturing by enabling near-net-shape production, reduced material waste, and on-demand fabrication. These characteristics position AM as a key technology for supporting sustainable development through advanced materials processing.

Composite and polymer-based materials have played a crucial role in improving the performance of structural components due to their favorable strength-to-weight ratio, flexibility, and toughness [4]. From a sustainability perspective, polymers such as rubber, PET, and PLA are increasingly utilized because of their lightweight nature, durability, and recyclability, which contribute to reduced maintenance requirements and lower energy consumption throughout the product lifecycle. Such materials also support circular economy concepts through low-energy processing and potential closed-loop recycling routes [5-8]. However, the sustainability of these materials depends not only on their environmental credentials, but also on their long-term mechanical reliability under service conditions [9-13].

Among AM technologies, fused deposition modeling (FDM) is one of the most widely adopted methods in both academic and industrial contexts due to its cost-effectiveness, ease of operation, and compatibility with thermoplastic polymers. Polylactic acid (PLA) is the most commonly used filament material in FDM because it is derived from renewable resources, biodegradable, and suitable for low-temperature processing [14, 15]. These attributes make PLA a key material for sustainable materials processing and functional prototyping, with expanding applications in biomedical devices, consumer products, and lightweight structural components. Nevertheless, the use of FDM-printed PLA in load-bearing applications requires a thorough understanding of its mechanical integrity, particularly under cyclic loading conditions where fatigue failure governs service life.

In contrast to commercially manufactured polymers produced by injection molding or extrusion, FDM-printed PLA exhibits a heterogeneous and anisotropic microstructure. The layer-by-layer deposition process introduces interlayer voids, weak bonding between filaments, and residual stresses, which significantly influence elastic, plastic, and fatigue behavior [16]. Previous studies have shown that raster orientation strongly affects fatigue strength and crack propagation paths, with alignment parallel to the loading direction generally enhancing mechanical performance [17, 18]. Infill density and pattern further control stiffness, energy absorption, and stress distribution under cyclic loading [19, 20], while parameters such as layer height, printing temperature, and print speed influence interlayer adhesion, void formation, and tensile strength [21-23]. Additionally, geometric discontinuities such as notches significantly intensify stress concentrations and alter fatigue crack initiation sites [17, 24].

Modeling fatigue crack initiation and propagation in additively manufactured polymers remains challenging due to process-induced defects and anisotropic crack paths. Linear Elastic Fracture Mechanics (LEFM) has been widely applied to describe fatigue crack growth under proportional loading conditions [25, 26]. However, the relatively large plastic zone that can develop near crack tips in polymers such as PLA often violates strict LEFM assumptions. Consequently, alternative energy-based approaches that account for plastic dissipation have been proposed to improve fatigue life predictions [13]. Furthermore, fatigue behavior is strongly influenced by operating conditions such as non-zero mean stresses and environmental exposure, including moisture absorption, which can accelerate degradation of polymer properties [17, 27]. Post-processing techniques and protective coatings have therefore been explored to enhance the fatigue resistance and environmental durability of FDM-printed PLA components [28, 29].

Although the mechanical behavior of FDM-printed PLA has been extensively studied, several research gaps remain. First, many studies focus on individual printing parameters or isolated mechanical properties, lacking an integrated framework that links process-induced microstructure to tensile behavior, fatigue life, and crack propagation [30]. Second, while fracture and fatigue behavior of AM polymers have been investigated, experimental fatigue crack growth data coupled with predictive fracture-mechanics-based models for FDM-printed PLA remain limited [31]. Third, systematic benchmarking of fatigue performance between additively manufactured PLA and its commercially manufactured counterpart is still scarce, despite its importance for quantifying the mechanical performance penalty associated with AM processes. Advanced analytical and numerical techniques, such as homotopy perturbation methods and finite element modeling, have shown potential in related material systems [8, 10, 11, 32], but their application to fatigue modeling of AM polymers remains limited.

To address these gaps, based on our previous studies [8, 10, 11, 32], the present study investigates the mechanical performance and fatigue behavior of additively manufactured PLA specimens in direct comparison with commercially produced PLA. Tensile, impact, and fatigue tests are conducted to evaluate stiffness, strength, fracture energy, and fatigue life under cyclic loading. A fatigue crack growth model based on LEFM and Paris' law is developed and validated using experimental data. In addition, a bibliometric analysis is performed to examine recent research trends at the intersection of additive manufacturing, fatigue performance, and sustainability. The novelty of this work lies in the integrated framework that combines experimental characterization, fracture-mechanics-based fatigue modeling, and bibliometric analysis to quantitatively assess the mechanical reliability gap between additively manufactured and commercial PLA from a sustainability-oriented perspective aligned with the Sustainable Development Goals (SDGs). This comprehensive approach provides new insights into the role of process-induced anisotropy and defects in fatigue performance, while offering practical guidance for optimizing AM parameters to enable durable and sustainable deployment of PLA components in engineering applications.

2. MATERIALS AND METHODS

2.1. Materials

In this study, two categories of polymer materials were selected: Type 1: additively manufactured specimens (3D Printing) using PLA filament (1.75 mm) and a printing machine type. However, the printing parameters are: Layer height: 0.2 mm; Infill density: 50, 75, and 100%; Nozzle temperature: 200-220°C; Bed temperature: 60°C; and printing orientation: 0, 45, and 90°. The second type is a commercially manufactured polymer stock sheet/rod (injection-molded or extruded). Specimens machined according to ASTM standards using CNC machining.

2.2. Experimental Procedures

2.2.1. Tensile Testing

This test is used to measure the most important material properties include Young's Modulus (*E*), Yield Strength (σ_y), Ultimate Tensile Strength (UTS), and Fracture Strain (ε_f). This test is conducted per ASTM D638 using a universal testing machine (UTM) type Olison 250, with a testing speed of 5 mm/min. 3D printed samples with different angles and orientations, besides samples made of commercial PLA, are tested. However, for the fully linear assumption, the effective density (ρ_{eff}) compared to solid density (ρ_{solid}) is in Eq. (1):

$$\rho_{eff} = \rho_{solid} \cdot \left(\frac{100}{\text{infill}}\right) \quad (1)$$

2.2.2. Impact Testing

An impact test is a mechanical experiment to identify the tendency of a structural element to absorb energy under sudden impact loading and the resistance of materials to fracture. In terms of their importance, the acceptance by materials engineers and students of the contributions they make to safety and service adequacy is objective. The sample is struck by a released (pendulum, as in Izod or Charpy experiments. This allows us to calculate the breaking absorbed energy. These tests measure the stiffness of a material or its resistance to cracking, typically by subjecting it to high-velocity impacts (e.g., drop or impact testing). The critical test result is obtained by measuring the energy transferred during impact, as expressed by the following equation. However, Izod impact tests on the energy absorbed during the fracture process may be considered related to resistance to crack initiation and propagation. This test is conducted per ASTM D256. However, Impact strength is calculated from the following Eq. (2):

$$G_c = \frac{U_s}{A} \quad (2)$$

where *Gc* is the impact strength of the material (J/m^2), *Us* is the impact energy absorbed for the specimen rupture (J). Furthermore, it is in Eq. (3):

$$Us = Ei - Er \quad (3)$$

where *Ei* is the initial pendulum energy (J), *Er* is the remaining pendulum energy (J), and *A* is the cross-sectional area of the specimen (m^2).

Fracture toughness as *Kc* ((MPa.m$^{1/2}$), which describes the ability of a material containing a crack to resist fracture, can be expressed as Eq. (4):

$$K_c = \sqrt{G_c E} \quad (4)$$

2.2.3. Fatigue Testing

The alternating bending fatigue test is one of the most common methods for assessing fatigue resistance because it simulates the dynamic loading conditions many engineering components encounter in practical applications. This test relies on subjecting the specimen to a periodic bending moment whose direction alternates, so that the specimen's surface area is subjected to successive tensile and compressive stresses with each loading cycle. As the test column rotates or the load direction changes, the stress path reverses completely. This provides a good environment for studying fatigue crack initiation and growth, which is the main failure mechanism for most rotating parts. Due to the high stress sensitivity of material surfaces, there is a tendency for cracks to be formed at these surfaces. Furthermore, repeated bending causes the crack to gradually propagate according to fatigue fracture mechanisms until it reaches a critical size, leading to sudden failure.

This test allows for the determination of fatigue life, S–N cyclic curves, and endurance limit (if applicable), as well as the evaluation of the impact of manufacturing variables such as surface roughness, material quality, presence of voids or defects, and manufacturing orientation in the case of 3D printed parts. Thanks to its high sensitivity to minute structural variations, alternating bending testing is an essential tool for the design and evaluation of components used in engines, transmission systems, rotating shafts, and parts subject to vibration, helping engineers ensure long service life and reduce the likelihood of premature failure. In this study, the Fatigue Testing is conducted based on ASTM D7791. However, Basquin's equation is used to estimate Fatigue life (Eq. (5)):

$$\sigma_a = A.N_f^{\ -B} \tag{5}$$

where σ_a is the alternating stress (MPa), *A* and *B* are the constants, while *Nf* is the number of cycles to failure. Furthermore, a fracture mechanics approach is used to model fatigue life.

According to Paris' Law, we can apply Eq. (6):

$$\frac{da}{dN} = C(\Delta K)^m \tag{6}$$

where *a* = crack length, *N* = number of cycles, *C* and *m* are the material coefficients, and *ΔK* is the stress intensity range. Then, we can get Eq. (7):

$$\Delta K = Y\Delta\sigma\sqrt{\pi a} \tag{7}$$

and the number of cycles to failure can be estimated as equation (8):

$$N_f = \int_{a_0}^{a_c} \frac{1}{C(Y\Delta\sigma\sqrt{\pi a})^m} da \tag{8}$$

where a_0 is the initial crack length, and a_c is the critical crack length at failure.

Specimens undergo cyclic loading using a servo-hydraulic or electrodynamic test machine. The stress ratio ($R = \sigma_{min} / \sigma_{max}$) is -1, with a frequency of 2–5 Hz, and different values of bending load. The recoding data is the S–N curve and crack growth rate (*da*/*dN*).

3. RESULTS AND DISCUSSION

3.1. Electronic Material Categories in Computer Engineering

Table 1 systematically presents the tensile properties (Elastic Modulus and Ultimate Tensile Strength (UTS)) of 3D-printed PLA specimens as functions of infill density (20-100%) and printing orientation (0, 45, and 90°). The data reveal a clear positive correlation between infill density and mechanical performance: both Elastic Modulus and UTS increase linearly with higher infill percentages. At 0° configuration, elastic modulus ranges from 3.2 GPa (20% infill) up to 3.392 GPa (100% infill), for example, and UTS increases from 60 MPa to 64.8 MPa. This could in turn be attributed to reduced void (and increasing continuum of the material), allowing to increase in load carrying capacity and stiffness. In this case, the raster orientation definitely reveals that additive manufacturing is an anisotropic process. After printing at 0° (filaments pointed to the direction of loading), the stiffness and strength of specimens printed at 90° (filaments perpendicular to the load) remain maximum and minimum. For example, at a 100% infill, the Elastic Modulus drops from 3.392 GPa (0°) to 2.544 GPa (45°) and to 1.696

GPa (90°). This is due to poor interlayer stickiness and increasing stresses at filament interfaces that are favorable sites for crack establishment and propagation. Based on the 45° orientation, it is regarded as having an intermediate behaviour, as the load is split between filament strength and interlayer bonding.

The tensile behaviour of AM PLA (additively manufactured PLA) and PLA (commercial) was compared in **Figure 1**. Overall, this commercial PLA has a higher yield strength, a higher ultimate tensile strength, and better ductility, having a longer section of plastic deformation preceding fracture. AM PLA, on the other hand, undergoes a brittle-like fracture but with minimal plastic strain. This discrepancy arises due to injection-molded commercial PLA having a homogeneous, void-free microstructure, which aids in distributing stress uniformly and thus delays necking. Conversely, AM specimens are filled with process-induced defects such as interlayer voids and incomplete fusion, leading to premature failure.

The data in **Table 1** are also confirmed in **Figure 2**. The 3D bar graphs also indicate that increasing the infill density enhances elastic modulus (**Figure 2(a)**) and UTS (**Figure 2(b)**), whereas changing the direction from 0 to 90° causes a decline of these coefficients. One physical explanation, on the other hand, is associated with the transfer mechanism of loading: stresses are transferred by the unbroken filaments at 0° effectively, whereas less effective transfer is achieved at 90° when weaker bonds between interlayer sections are required, causing early deboning and failure.

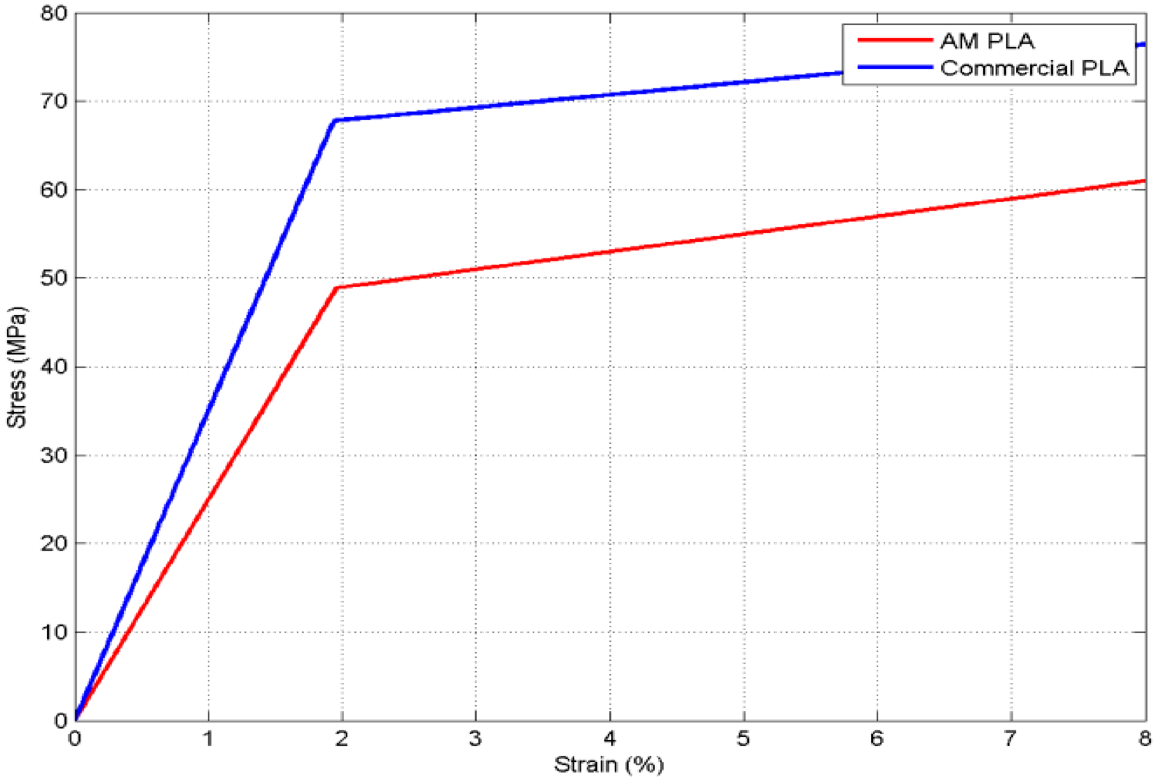


Figure 1. Tensile stress–strain: AM versus commercial PLA

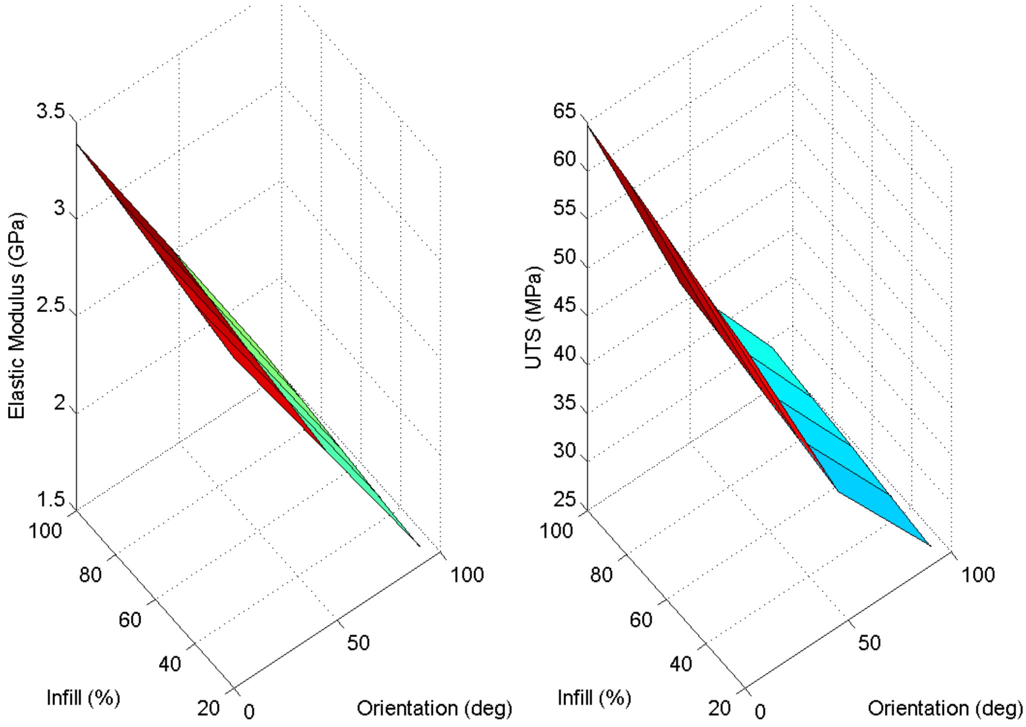
Table 1. The results of the tensile test for 3D printed PLA samples

INFILL	ORIENTATION	ELASTIC MODULUS (GPA)	UTS (MPA)
20	0	3.2	60
40	0	3.248	61.2
60	0	3.296	62.4
80	0	3.344	63.6
100	0	3.392	64.8
20	45	2.4	39
40	45	2.436	39.78
60	45	2.472	40.56
80	45	2.508	41.34
100	45	2.544	42.12
20	90	1.6	27
40	90	1.624	27.54
60	90	1.648	28.08
80	90	1.672	28.62
100	90	1.696	29.16

3.2. Impact Energy

The impact energy of commercial specimens and 3D printed samples was established. Findings showed that the measured sample type 1 absorbs more energy related to reduced notch sensitivity, and the printed samples in type 2 fail due to interlayer delamination under impact loading. Impact test results reveal that commercially fabricated PLA specimens have large energy absorption before fracture compared to 3D printed PLAs. This can be explained by the isotropic and homogeneous microstructure of commercial PLA, allowing for higher efficiency of dissipation through plastic deformation. AM specimens, in comparison, generally fail via interlayer delamination, a brittle fracture path due to the weak bond between deposited layers. The presence of voids and raster boundaries reduces the crack initiation resistance and consequently the impact toughness (see **Figure 3**).

With increasing infill density, impact energy and fracture toughness (KIC) increase and are found to be highest for 0° orientations (see **Figures 4-6**). Thus, higher infill allows for less porosity with more continuity and resistance to crack propagation in the material. The directionality effect is also observed: the specimen printed at 0° will have optimal toughness as cracks have to propagate through the filaments, and at 45 and 90°, cracks will easily propagate along layer interfaces. KIC of fracture toughness is confirmed in the analysis, where anisotropic printing compromises both strength and toughness using combined impact energy and Elastic Modulus. The direction-dependent fracture toughness is shown in **Figure 5**, and the near-linear correlation of effective density to infill percent is shown in **Figure 6**. The density model (equation (1)) is a physical representation of the material's volumetric integrity. Increased infill would reflect greater density and enhanced mechanical properties caused by the lower stress concentrations and greater load distribution.



(a) (b)

Figure 2. The effect of infill and orientation on elastic modulus (a) and UTS (b)

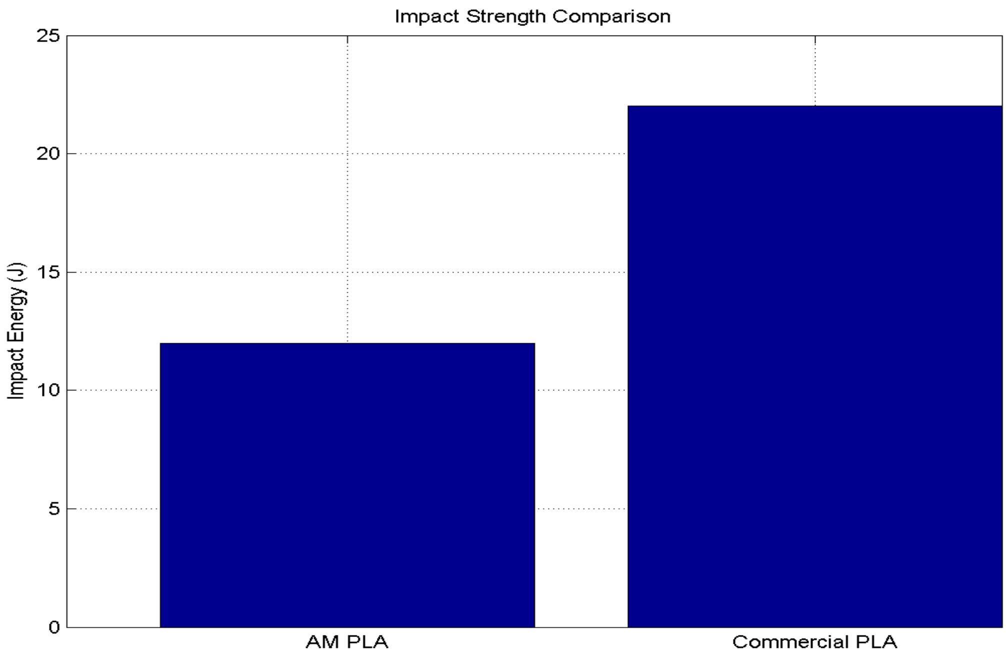


Figure 3. Impact strength comparison results

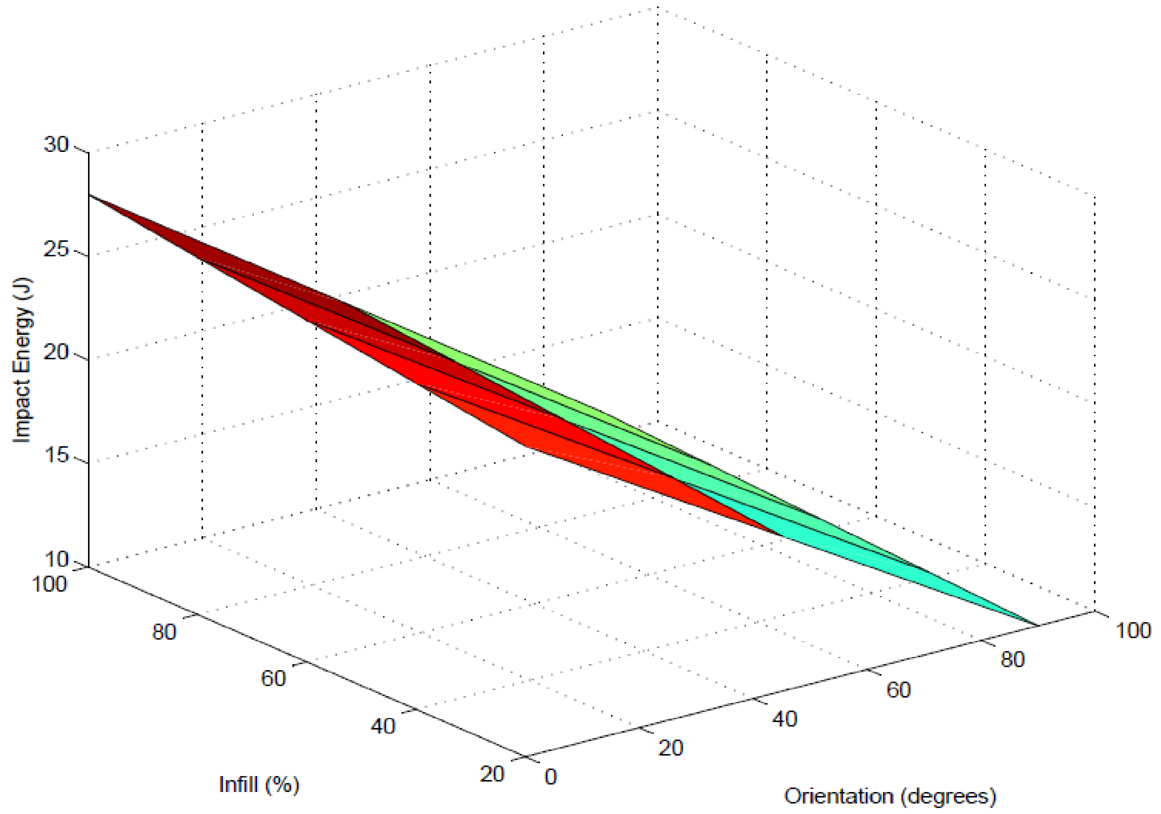


Figure 4. The Effect of infill and orientation on impact energy.

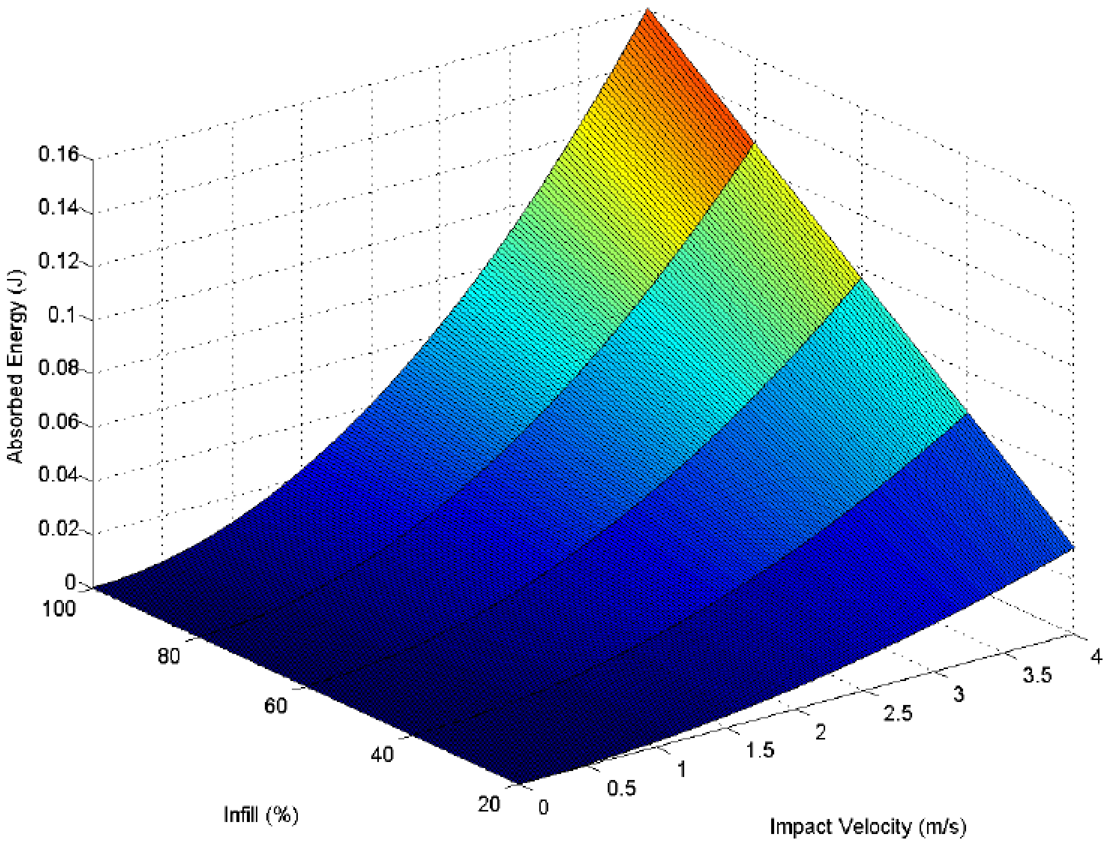


Figure 5. Effect of infill and orientation on fracture toughness (K_{IC}).

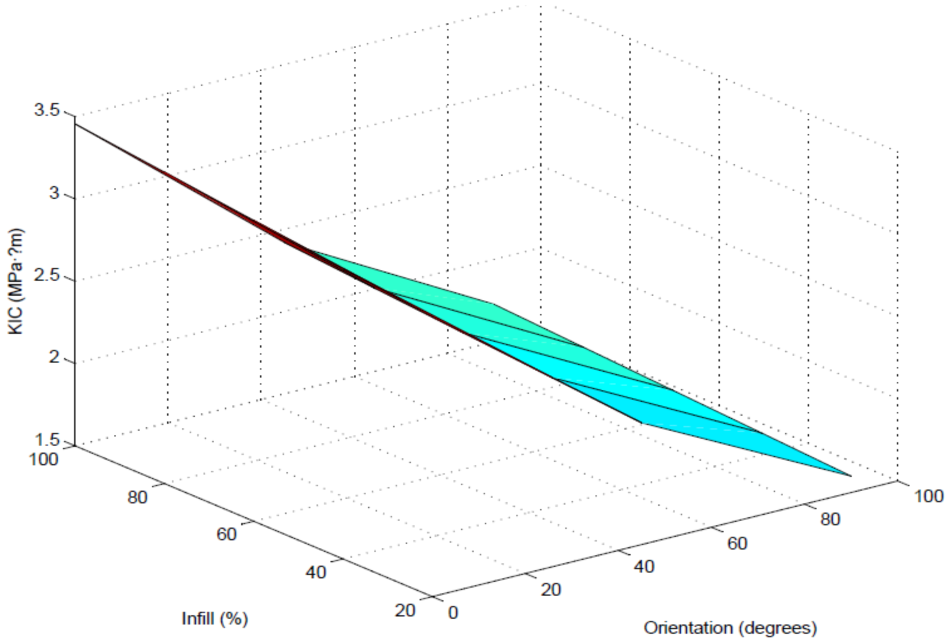


Figure 6. Effect of infill and orientation on fracture toughness (K_{IC})

3.3. Fatigue Behavior

Figure 7 compares fatigue crack growth rates between AM and commercial PLA. AM specimens exhibit faster crack propagation and lower fatigue limits due to inherent defects such as voids, poor interlayer adhesion, and surface irregularities. These defects act as stress concentrators and facilitate early crack initiation. In contrast, commercial PLA shows slower crack growth and higher fatigue resistance, owing to its uniform microstructure. The fatigue life data (N_f) in the accompanying **Figure 8** demonstrate that fatigue strength increases with infill density and is highest at 0° orientations. For example, at 100% infill and 0° orientations, the fatigue limit is 60 MPa with $N_f \approx 2.4 \times 10^{14}$ cycles, whereas at 90° orientations, it drops to 30 MPa with $N_f \approx 2.21 \times 10^{13}$ cycles. This reduction is attributed to the anisotropic fatigue crack path, which preferentially follows layer boundaries in off-axis orientations.

3.4. Discussion of Modelling Results

The fatigue life prediction model, based on Paris' law (Eq. (8)), was implemented in MATLAB and validated against experimental data. The model accurately captures the accelerated crack growth in AM specimens, particularly at higher stress intensities (ΔK). The parameters C and m, derived from regression analysis, reflect the material's resistance to fatigue crack propagation. AM PLA exhibits higher C values, indicating greater susceptibility to crack growth due to microstructural defects (see **Figure 9**).

The developed model confirms that fatigue life is highly sensitive to initial defect size (a_o), stress range ($\Delta\sigma$), and material constants (C and m). AM specimens, with larger inherent flaws, consistently show lower predicted fatigue lives. The integration of Linear Elastic Fracture Mechanics (LEFM) with Paris' law provides a robust framework for fatigue life prediction, though it is noted that significant plastic zone formation at crack tips in PLA may challenge strict LEFM assumptions. Future work could incorporate energy-based methods to account for plastic dissipation. The comparative analysis underscores the "performance penalty" of AM due to process-induced anisotropies and defects. However, the model also offers a pathway for optimization: by controlling printing parameters (e.g., increasing infill, optimizing raster angle), fatigue performance can be significantly improved, bridging the gap between AM and conventional manufacturing.

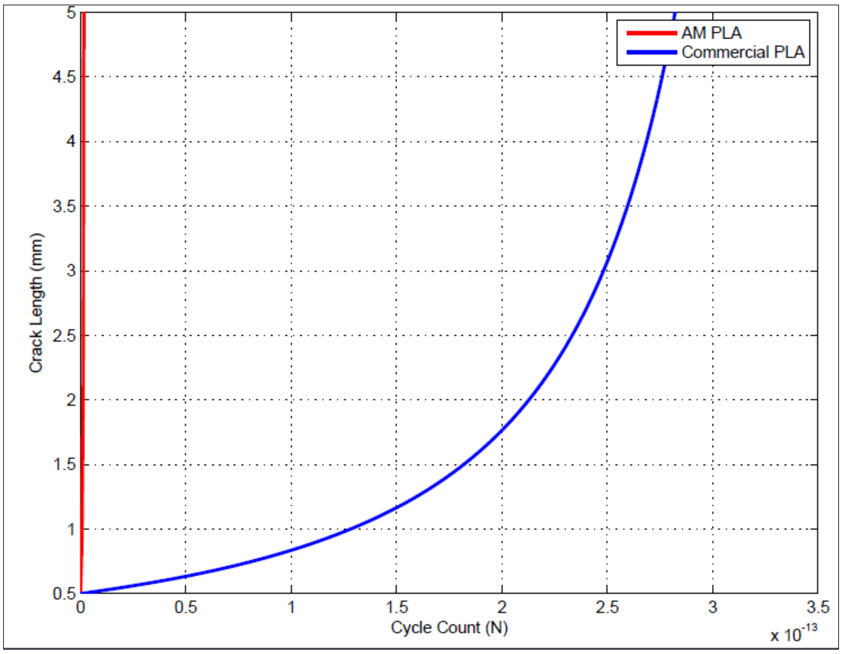


Figure 7. Results of fatigue crack growth: AM versus commercial PLA

Table 2 shows that the fatigue life of 3D-printed PLA is predominantly governed by two process-induced factors: infill density and raster orientation. Higher infill density reduces internal voids and stress concentrations, thereby delaying crack initiation and extending fatigue life. Raster orientation critically controls anisotropy; alignment at 0° maximizes performance by loading filaments axially, while 90° orientation leads to premature failure through weak interlayer bonds. This anisotropy represents the primary mechanical trade-off in additive manufacturing, necessitating optimized printing strategies for load-bearing applications to balance sustainability benefits with structural reliability.

Table 2. Fatigue limit and cycles to failure (Nf) of 3D-printed PLA specimens as a function of infill density and raster orientation

INFILL	ORIENTATION	FATIGUE LIMIT (MPA)	NF
20	0	50.4	4.19×10^{-14}
40	0	52.8	3.61×10^{-14}
60	0	55.2	3.13×10^{-14}
80	0	57.6	2.74×10^{-14}
100	0	60	2.40×10^{-14}
20	45	35.28	1.31×10^{-13}
40	45	36.96	1.13×10^{-13}
60	45	38.64	9.81×10^{-14}
80	45	40.32	8.56×10^{-14}
100	45	42	7.51×10^{-14}
20	90	25.2	3.85×10^{-13}
40	90	26.4	3.32×10^{-13}
60	90	27.6	2.88×10^{-13}
80	90	28.8	2.51×10^{-13}
100	90	30	2.21×10^{-13}

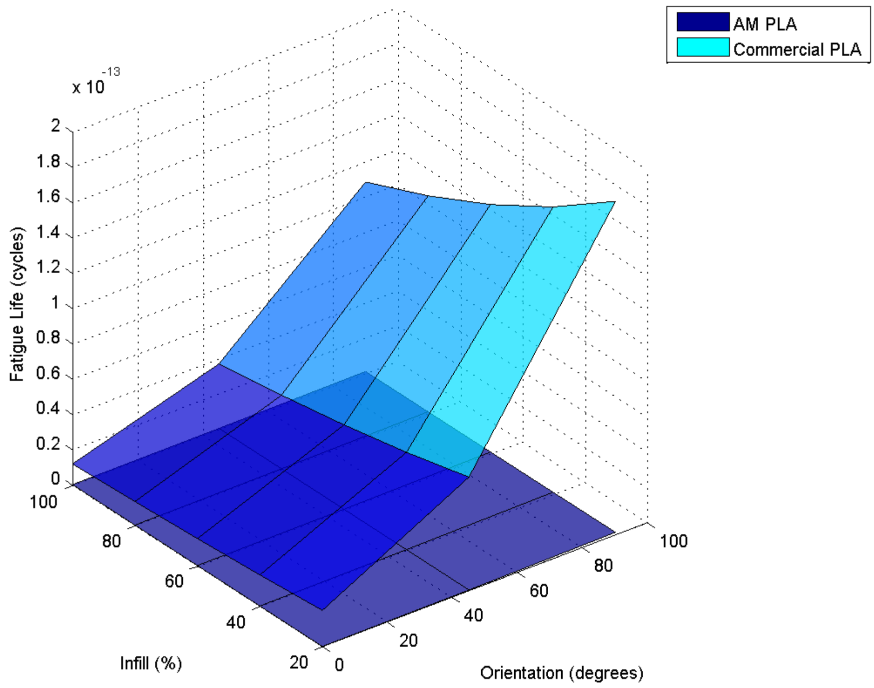


Figure 8. Results of fatigue crack growth: AM versus commercial PLA

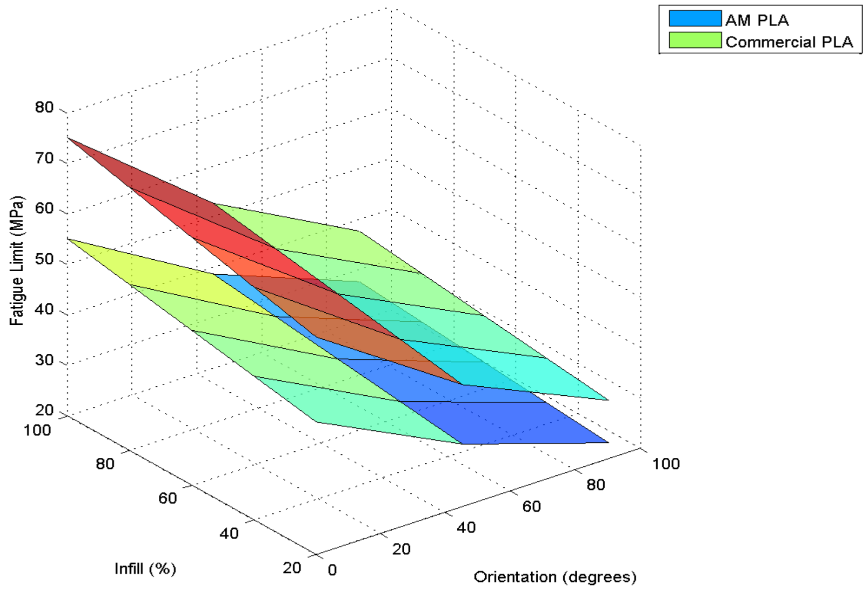


Figure 9. Results of fatigue crack growth: AM versus commercial PLA

3.5. Contribution to Sustainable Development Goals (SDGs)

Additive manufacturing and sustainable material selection play an increasingly important role in achieving several United Nations SDGs, particularly those related to sustainable industrial development and responsible resource utilization. This study directly contributes to SDG 9 (Industry, Innovation and Infrastructure) by advancing the understanding of fatigue behavior and mechanical reliability of additively manufactured PLA, which is essential for enabling safe and durable implementation of innovative manufacturing technologies in engineering applications. By providing experimentally validated fatigue models, the work supports the development of reliable design methodologies for load-bearing polymer components.

In addition, the findings align with SDG 12 (Responsible Consumption and Production) by addressing material efficiency and waste reduction through optimized printing parameters such as infill density and raster orientation. Improving fatigue life and structural reliability reduces premature failure and material replacement, thereby minimizing resource consumption over the product lifecycle. Furthermore, the use of PLA, a bio-based and biodegradable polymer, combined with additive manufacturing's near-net-shape capability, contributes indirectly to SDG 13 (Climate Action) by lowering energy demand and material waste compared to conventional manufacturing routes. Overall, this work demonstrates how integrating mechanical performance assessment, fatigue modeling, and sustainability considerations can support the practical realization of SDGs within advanced manufacturing systems.

3.6. Bibliometric Analysis

A bibliometric analysis was performed to identify global research trends. Many reports regarding this analysis have been reported [33-36]. **Figure 10** presents the annual publication output related to fatigue modeling research. We focused on fatigue modeling and positioned the present study within the broader scientific landscape. The analysis was conducted using the Scopus database with the query TITLE-ABS-KEY (fatigue AND modeling) covering the period 1959–2024, yielding a total of 26,580 documents. The results show a relatively low number of publications before the 1990s, followed by a steady increase and a pronounced growth after 2005. In recent years, the publication rate has exceeded 2,000 articles per year, reaching 2,144 documents in 2024, which reflects the increasing importance of fatigue modeling in engineering design, advanced materials, and sustainability-oriented manufacturing. Despite this growth, studies focusing on fatigue modeling of additively manufactured polymers, particularly PLA, and direct comparisons with commercially manufactured materials remain limited, highlighting the research gap addressed in this work.

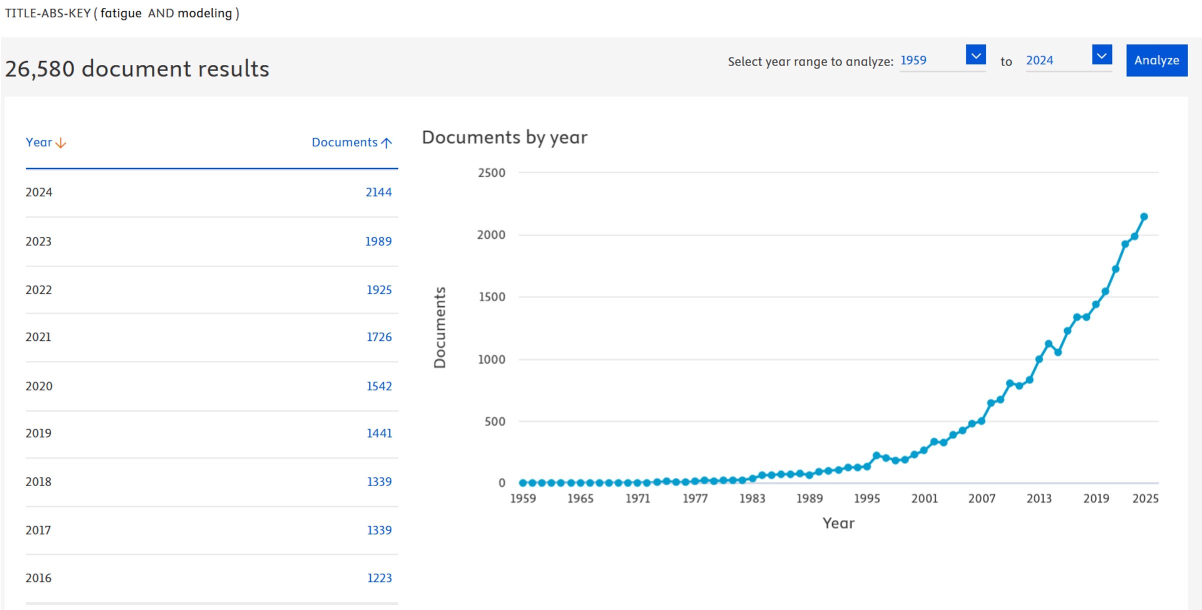


Figure 10. Annual number of publications on fatigue modeling indexed in the Scopus database (TITLE-ABS-KEY: *fatigue AND modeling*) from 1959 to 2024

4. CONCLUSION

This study investigated the mechanical performance of FDM PLA in comparison with commercially produced PLA, in the context of SDGs. Experimental results showed that commercial PLA exhibits superior strength, ductility, impact resistance, and fatigue life due to its homogeneous microstructure, while FDM-printed PLA is adversely affected by process-induced anisotropy and interlayer defects. Increasing infill density and aligning raster orientation with the loading direction significantly improved the mechanical and fatigue performance of AM PLA. A fatigue crack growth model based on Linear Elastic Fracture Mechanics and Paris' law successfully captured experimental trends. The integrated experimental, modeling, and bibliometric framework provides practical guidance for the reliable and sustainable application of additively manufactured PLA components.

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6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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