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Sustainable 3D-Printing Filaments and their Applications

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The growing demand for sustainable materials has driven research into 3D printing technologies, particularly those focused on environmentally friendly filaments such as Polylactic Acid (PLA) and its composites. This study explores the mechanical performance and applications of four distinct PLA-based materials: conventional PLA, PLA Advanced PRO, Glass Reinforced PLA, and Foam PLA. Through a combination of tensile testing and Digital Image Correlation (DIC) analysis, the research highlights the displacement behavior and internal structural evolution of these materials under load-bearing conditions. Glass Reinforced PLA demonstrated the highest performance, showing a 10-15 % increase in displacement capacity compared to conventional PLA, while PLA Advanced PRO exhibited a 10 % improvement, and Foam PLA showed a modest 3-5 % enhancement. Infill density significantly impacted layer adhesion, especially for Glass Reinforced PLA, where an infill density above 30 % greatly enhanced structural integrity. This study not only underscores sustainable filaments' environmental and mechanical benefits but also emphasizes their potential as viable alternatives for complex, load-bearing applications in various industries. The findings contribute to the ongoing development of greener, high-performance 3D printing materials and suggest avenues for future research to optimize the balance between sustainability and material performance.

1. Introduction

By the latter half of the 20th century, industries saw the need for more cost-effective and resource-efficient ways to create precise spatial shapes, even in small production runs. This demand led to the rise of 3D printing, which began as rapid prototyping (RP) technology in the late 1980s, building on the foundations of additive manufacturing established in the 19th century (Szalai et al., 2023). Since then, 3D printing has shown significant potential to revolutionize industries by offering design flexibility, mass customization, and reduced waste. However, challenges remain in developing suitable materials, improving processing, and increasing production speed (Ngo et al., 2018).

Polylactic Acid (PLA), a biodegradable plastic derived from renewable resources like corn starch or sugarcane, is one of the most promising materials for 3D printing (Szalai et al., 2023). Despite its environmental advantages, PLA's brittleness, low heat resistance, and moisture sensitivity limit its use in some fields (Fratila et al., 2017). This highlights the need for ongoing research into sustainable filaments that provide high performance while reducing environmental impact. To address these limitations, recent advancements have focused on enhancing PLA's functional properties. For example, Verano-Naranjo et al. (2023) demonstrated that impregnation of PLA filaments with natural extracts using supercritical fluids can improve the material's performance, particularly in biomedical applications, highlighting the growing potential of PLA for specialized uses.

Research has increasingly focused on improving sustainable materials for 3D printing. Zhu et al. (2021) explored ionic liquids for recycling 3D-printed plastics, emphasizing circular economy principles. However, further optimization is needed to improve efficiency and scalability. Kumar et al. (2022) conducted a life cycle assessment comparing PLA, ABS, and PETG, noting that while PLA's biodegradability is beneficial, its high water consumption is an environmental drawback.

Efforts to develop sustainable materials continue, but research gaps remain in optimizing recycling methods and improving machine efficiency. Hasan et al. (2024) explored recycled PLA (rPLA), noting its environmental benefits but also its weaker mechanical properties compared to virgin PLA (vPLA). Blending rPLA with virgin

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materials or using additives could address these issues, but further research is needed to fully understand its environmental, social, and economic impacts.

Additionally, research on expanding 3D printing technologies has progressed. Shahrubudin et al. (2019) highlighted the need for better machine efficiency and material compatibility, while Sharma et al. (2023) developed a low-cost 3D printer using PLA and the Fused Deposition Method (FDM), showing how advancements in hardware can reduce costs and improve production speed.

In the medical field, PLA has shown potential in drug delivery. Hari et al. (2024) investigated 3D-printed PLA implants for sustained anti-HIV drug release, demonstrating the versatility of PLA in personalized medicine. However, its mechanical limitations may restrict its use in more demanding medical applications (Yu et al., 2023).

Based on the literature review executed, it can be stated that 3D printing, emerging from rapid prototyping in the 1980s, offers design flexibility, customization, and waste reduction but faces challenges in materials and processing. PLA, a biodegradable plastic from renewable sources, shows promise but is limited by brittleness and low heat resistance. Research is enhancing PLA’s properties for specialized uses, especially in medicine while exploring recycling methods and sustainable alternatives. Despite progress, optimizing machine efficiency and addressing material limitations remain key areas for future development. This study aims to contribute by investigating the development and performance of sustainable PLA-based filaments in load-bearing 3D printing applications. The structure of the current paper is the following: Section 2 is about the applied materials and methods, Section 3 contains the results and discussion, and Section 4 summarizes the drawn conclusions.

2. Materials and methods

This section describes the materials, instruments, measurement procedures, and processes used in the research. Only the PLA raw material will be investigated in this research. The raw materials used are typically natural-based materials from renewable resources. The raw material for PLA is maize, and the additives used for the individual filaments, e.g., gypsum, carbon fiber, and carbon powder, are also natural materials. The filaments contain additives (additives) to give the filament suitable mechanical, physical, and chemical properties for the application. These materials positively affect printability, modifying the surface structure of the printed objects. PLA with additives can be a recyclable alternative to other non-recyclable materials.

2.1 Filaments

Based on the literature data, 4 different PLA-based materials were used for this research due to their favorable printing properties. The materials were selected to cover a wide range of applications.

Filaticum PLA is a conventional PLA with favorable printability at temperatures as low as 190-205 °C.

PLA Advanced PRO is the base material specifically designed for filaments used in 3D printing, which can be used as an alternative to PETG and ABS with additional additives. Objects printed from PRO filament are more flexible and impact-resistant. It adheres easily to the table, and its excellent layer adhesion ensures a smooth surface and more precise printing. Higher printing temperatures (225 °C) are required for better mechanical properties.

Filaticum Glass-Reinforced filament has strength, hardness, and heat resistance far beyond standard PLA. It can withstand temperatures up to 100 °C. Objects printed with Glass Reinforced filament have very low warpage. Recommended initial printing parameters: 215 °C nozzle, 60 °C bed.

Objects printed from Filaticum Foam (lightweight) have a foamy, spongy texture. The foam has an open-cell structure and is rigid. Due to the foam structure, the layers are barely visible, and the surface has a rough, sandy texture. However, it can be easily sanded, cut, painted, and shaped as required. The foam's structure, the surface's quality, and the texture can be mainly influenced by changing the print settings. Objects with the density and texture to meet technical requirements can be produced by adjusting the parameters accordingly. The main properties of all filaments used are summarized in the following table (Table 1).

Table 1: Properties of used filaments

Specific	Basic (PLA)	Advanced Pro PLA (AdvPro)	Glass Reinforced PLA (GR)	Foam PLA (Foam)
Nozzle [°C]	195-215	190-210	210-250	215-250
Bed [°C]	55-70	55-70	60-75	55-70
Layer height [mm]	0.2-0.8	0.2-1.2	0.2-1.2	0.4-0.8
Max speed [mm/s]	120	160	200	100
Color	white	white	transparent	black

2.2 3D printers and printing setups

The research used FDM printers with a conventional design (Cartesian machines). It was essential to use various PLA materials in the research and affordable and easily accessible printers to produce test pieces so that the results could be used more widely. The printers used are presented in the following table (Table 2).

Table 2: Properties of used 3D Printers

Specific	Creality Ender S1	FlashForge Creator Pro 2	Creality Ender 3 V2
Nozzle [mm]	0.4	0.4	0.4
Extruder system	Direct Drive	Direct Drive	Direct Drive
Filament diam.	1.75 mm	1.75 mm	1.75 mm
Hotend	normal	all metal	normal
Bed leveling	automatic	manual	manual

The research used Cura's slicing software, a top-rated and easy-to-use software that allows many adjustments. The software offers a wide range of settings, but only the settings used in the research are described: infill density, infill pattern, and layer height. The infill density controls how dense or hollow the model should be. It is a percentage value that indicates how much of the internal structure of the print is occupied by solid infill. For infill, a value between 15 % and 50 % is set with steps of 5 %. (Figure 1) The infill pattern indicates the printer used to build the infill structure of the printed product. The most common infill pattern is Cubic, which is the default in most software. Since the primary purpose of this research was to investigate the default pattern, only the Cubic pattern was used. A Cubic pattern is filled with print paths that cross within a layer. It creates 3-dimensional cubes with one corner facing downwards. It has the advantage of having approximately the same strength in all directions, including the vertical direction. In addition, this infill has the lowest incidence of the so-called pillowing effect, as no elongated hot air pockets are created during printing. The pillowing effect occurs when the printing process causes the hot air to rise upwards and push the top layer out, creating pillow-like bumps on the surface.

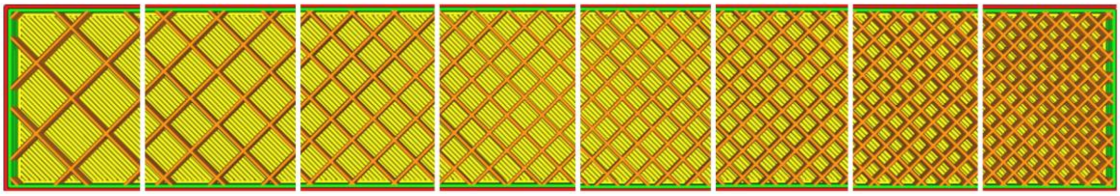

Figure 1: The Grid infill setup in Cura, Infill values from left to right: 15 % - 20 % - 25 % - 30 % - 35 % - 40 % - 45 % - 50 %.

2.3 GOM Aramis DIC system

The GOM ARAMIS 5M measuring system was used for the tests during the research. ARAMIS systems perform non-contact and material-independent measurements based on the principle of digital image correlation. These systems offer a reliable solution for entire surface and point-based inspections, from a few millimeters to several meters. The ARAMIS 5M has a maximum image acquisition rate of 25 fps at full resolution. During the measurement, the system is responsible for comparing image sequences of a specimen coated with a unique pattern, searching for and tracking identical points on the entire image sequence. Searching for individual pixels between two images is not always successful, as the pixel's color and/or intensity value may be the same as several pixels in the reference image. To solve this problem, a small area (facet, sub-frame – called the evaluation window) is selected in the environment of a pixel and identified among the images. The evaluation window is usually square and can be identified on the whole image sequence due to the sample's unique pattern taken during the test specimen's preparation. There are several methods for finding the area around a pixel in another image, the two most common being normalized cross-correlation and normalized least squares. In order to achieve sufficient accuracy, the deformation of the evaluation windows must be taken into account, for which some form of iteration is usually used. Most DIC (digital image correlation) software uses some variation of the Levenberg-Marquardt algorithm for nonlinear optimization. The research setup of the Aramis 5M system is as follows (Szalai et al., 2023): Caliber Panel: CP90; measuring area: 110×120 mm; camera distance from the 3D-printed frame: 836 mm; resolution: full resolution; measuring frames: 25 Hz; camera slider distance: 316; camera angle: 25 ° (Szalai et al., 2023a).

2.4 Specimen preparation and speckle pattern

Using the correct pattern in DIC tests is essential to reduce measurement noise and improve the accuracy of measurement results. When preparing the test specimens, care should be taken to ensure that the painted pattern is as similar as possible to the reference pattern required for the range of measurements. A good quality sample is necessary because during DIC, a small area of the image, the evaluation window, is monitored as the sample is deformed and compared with the reference image. The aim is to get the best possible fit of the evaluation window until the end of the measurement. As described above and based on previous preliminary experiments, test specimens with the appropriate pattern were used for the measurements. For all samples, tests were completed between 3 and 12 h after painting.

In all cases, DupliColor matt white and black (RAL9001, RAL9005) water-based spray paint suitable for indoor use was used for the tests. The paints are readily available in white and black and can be used for primer coats and staining (Figure 2).

Figure 2: Speckle pattern on the specimen

2.5 Testing equipment and 3d printed specimen fixture

There is extensive literature and research on tensile testing of 3D printed materials, and this research focuses on composite forming. The tests were conducted on a 10 t force Erichsen hydraulic testing machine, where the specimens were subjected to bending and tensile loading. This allowed a complex deformation, different from the literature, to be investigated. The test and tooling used conform to ISO 20482:2013 Metallic materials – Sheet and strip – Erichsen cupping test standard (International Organization for Standardization, 2013). The test lasts until the first crack appears; at the end of the process, the die movement at the crack is recorded. During the measurement, the GOM ARAMIS 5M DIC system, placed above the test area, records the deformation of the specimen. When evaluating the results, the displacements of the cracked specimen are extracted. The device used on the machine is a 3D-printed gripping device used for the test, which allows the specimen to move during deformation. The advantage is that the brittle material can give a lower displacement value (Aydin et al., 2018), while the tougher, more flexible material can give a higher displacement value (Szalai et al., 2023b).

3. Results and discussion

This section presents the observations made during the measurement, the stamp displacement, and the results of the DIC measurement.

3.1 Measurement experience, die displacement results

During the measurements, it was observed that at lower infill levels, the adhesion of the layers was insufficient for both normal and Advanced Pro PLA filaments, leading to separation during forming (Figure 3, left side). This result is consistent with findings from previous research where the mechanical performance of PLA is highly dependent on infill density and bonding between layers. The separation issue was resolved for both materials at infill levels above 30 %, indicating that higher infill percentages are crucial for maintaining structural integrity under load.

In contrast, the Foam and Glass-Reinforced filaments did not exhibit layer separation at any infill percentage, even under complex loading conditions. This observation can be compared to the results of Hasan et al. (2024), who found that adding reinforcing materials, such as glass fibers, significantly enhances the interlayer adhesion and overall strength of printed parts. The current results support the conclusions of Fratila et al. (2017), who suggested that materials reinforced with fibers exhibit better mechanical performance than conventional plastics under similar conditions.

When considering the die displacement results, it was evident that Glass-Reinforced filament outperformed the other materials by a margin of 10-15 %, making it ideal for applications that require higher durability and strength. The performance of Advanced Pro PLA also showed an improvement of approximately 10 % compared to normal PLA, while the Foam filament demonstrated a slight increase of 3-5 % over PLA (Figure 4). These findings are consistent with Kumar et al. (2022), who noted that Glass-Reinforced PLA tends to offer higher tensile and flexural strengths due to the incorporation of reinforcing fibers. The comparative advantage of Glass-Reinforced and Advanced Pro materials underscores their suitability for applications involving complex geometries and dynamic loads, which demand higher mechar

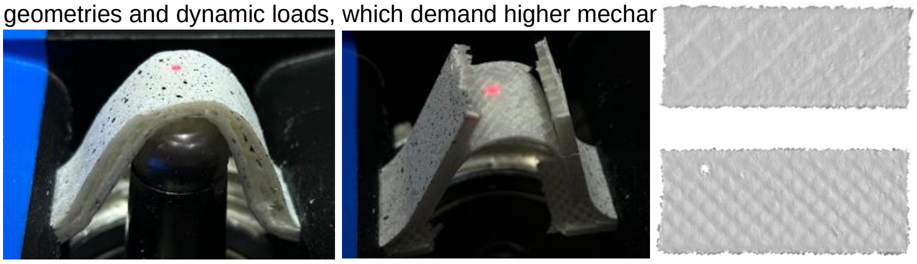

Figure 3: Results of the visual inspection (left: AdvPro, middle: GR, right: speckle pattern recognition)

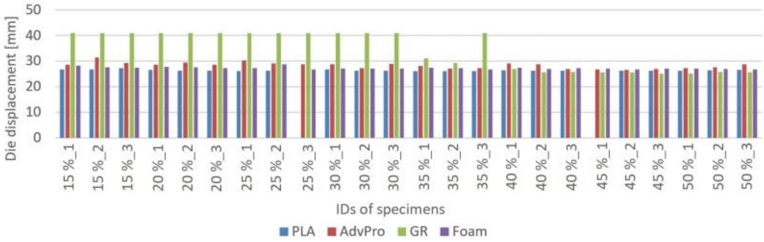

Figure 4: Die displacement results of (normal) PLA, AdvPro PLA, GR PLA and Foam PLA specimens

3.2 DIC results

The DIC measurements provided further insight into the displacement patterns for different materials (Figure 5). As shown, the displacement trends across all materials were consistent with those observed in the die displacement results, although the absolute values differed slightly due to the positioning of the DIC system relative to the test specimen. GR showed the least displacement, followed by Advanced Pro, Foam, and normal PLA, confirming the superior performance of reinforced materials regarding stiffness and structural stability.

The Cubic infill pattern, widely used in FDM printing, was found to have minimal impact on displacement for most materials, except GR, where a slight increase in stiffness was noted as the infill percentage increased. This observation aligns with the findings of Aydin et al. (2018), who reported that fiber-reinforced materials tend to exhibit higher mechanical performance even with lower infill densities. The minimal impact of infill density on displacement for non-reinforced materials, such as normal and AdvPro, suggests that material composition plays a more significant role in mechanical performance than infill structure alone, a conclusion also supported by the research of Zhu et al. (2021).

The ability of the DIC system to capture fine details of internal structural changes highlights its potential for optimizing material performance in 3D-printed applications.

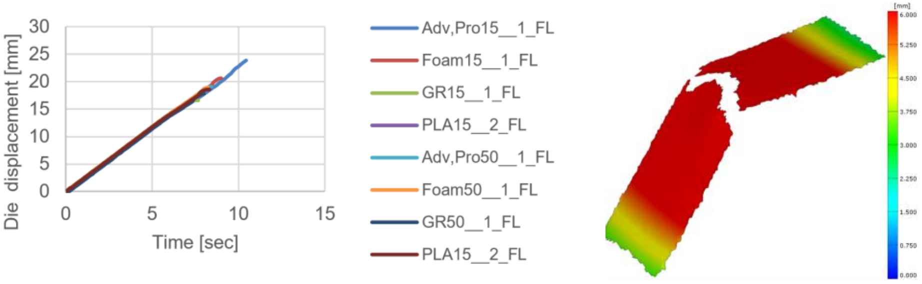

Figure 5: Result of DIC measurements. Left: die displacement vs. time graphs; right: a typical DIC image

4. Conclusions

In conclusion, this study demonstrates the promising mechanical properties of various PLA-based filaments for sustainable 3D printing applications, particularly in load-bearing scenarios. Glass-Reinforced PLA stood out with its 10-15 % improvement in displacement capacity over conventional PLA, underscoring its suitability for more demanding applications. PLA Advanced PRO followed with a 10 % improvement, while Foam PLA exhibited a modest 3-5 % increase. These materials showed varying responses to infill density, with Glass-Reinforced PLA benefiting significantly from an infill density above 30 %, which enhanced its layer adhesion and overall structural integrity. However, the other materials, such as PLA Advanced PRO and Foam PLA, were less sensitive to changes in infill density under the same conditions.

Despite these positive results, several limitations were identified. The study focused on a small selection of PLA materials and primarily considered tensile and bending stresses, leaving out essential conditions like shear and impact stresses that are relevant in real-world applications. Additionally, while this research provides a foundation for sustainable 3D printing materials, it did not account for the entire lifecycle impact, particularly recycling and material reuse.

Future research should expand to cover a broader range of materials, stress conditions, and environmental factors. Investigating dynamic stresses, diverse infill patterns, and the long-term environmental impact of these materials would offer more comprehensive insights. These findings will be essential for optimizing the balance between sustainability and performance in industrial-scale 3D printing applications, pushing the boundaries of what can be achieved with eco-friendly materials.

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