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الطباعة الثلاثية الأبعاد المستدامة بتقنية FDM على الأقمشة الطبيعية باستخدام مركبات حيوية مدعمة من PLA

Sustainable FDM 3D Printing on Natural Textiles Using Reinforced PLA Biocomposites

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الملخص

أصبحت تقنية النمذجة بالترسيب المنصهر (FDM) من أكثر تقنيات التصنيع الإضافي استخدامًا، لا سيما مع تزايد الاهتمام بتطبيقاتها في مجال هندسة النسيج لما توفره من إمكانيات واعدة لتصميم أقمشة وظيفية ومخصصة. غير أن الاعتماد الواسع على البوليمرات المشتقة من النفط يفرض تحديات بيئية متنامية، مما يعزز الحاجة إلى تطوير بدائل مادية أكثر استدامة. في هذا السياق، يبرز حمض البوليلاكتيك المدعَّم (PLA) كخيار حيوي وصديق للبيئة يتماشى مع مبادئ الاستهلاك والإنتاج المسؤولين.

تهدف هذه الدراسة إلى تقييم إمكانية دمج الطباعة ثلاثية الأبعاد المستدامة على ركائز نسيجية طبيعية، من خلال استخدام خيوط مركبة من PLA مدعّمة بحشوات من الخشب والكربون. تم تطبيق هذه الخيوط في تصنيع أنماط مطبوعة ثلاثيًا على أقمشة الصوف وألياف الجوت، وهما مادتان نسيجيتان متجدّدتان وقابلتان للتحلل الحيوي. وقد شمل التقييم الخصائص الفيزيائية والكيميائية للخيوط، بما في ذلك امتصاص الماء، والذوبانية، وأداء الالتصاق عند الواجهات البينية بين PLA وكل من الصوف وألياف الجوت.

أظهرت النتائج حساسية منخفضة تجاه الرطوبة واستقرارًا بينيًا مُرضيًا، مما يؤكد الجدوى التقنية لاستخدام مركبات PLA المدعّمة بمواد طبيعية في التطبيقات النسيجية الصديقة للبيئة. تسهم هذه النتائج في دعم الابتكار في تقنيات التصنيع المستدامة لقطاع النسيج، وتؤكد دور المواد الحيوية في الحد من الاعتماد على البوليمرات الأحفورية. كما تفتح هذه الدراسة آفاقًا بحثية مستقبلية لتطوير خيوط PLA مدعّمة بحشوات مشتقة من نفايات عضوية، بهدف تعزيز دائرية المواد وتحسين أدائها ضمن إطار الاقتصاد الدائري المستدام.

الكلمات المفتاحية

النمذجة بالترسيب المنصهر، مركبات PLA الحيوية، الطباعة ثلاثية الأبعاد على المنسوجات، أقمشة الألياف الطبيعية، الالتصاق البيني.

Abstract

Fused Deposition Modeling (FDM) is a widely adopted additive manufacturing technique with growing applications in textile engineering, offering new opportunities for functional and customized fabric design. However, the widespread use of petroleum-based polymers raises environmental concerns, highlighting the need for more sustainable material alternatives. In this context, bio-derived polymers such as reinforced polylactic acid (PLA) have attracted increasing attention as environmentally friendly solutions, contributing to Sustainable Development Goal. Despite these advances, the integration of 3D printing onto textile substrates remains limited by challenges related to material compatibility and interfacial adhesion. This study investigates the use of wood- and carbon-filled PLA composite filaments for the fabrication of sustainable 3D-printed patterns on wool and jute fabrics, two renewable, biodegradable textile materials. The selected approach supports innovation and infrastructure by advancing sustainable manufacturing technologies for the textile sector. The researchers evaluated biocomposite filaments for water absorption, solubility, and adhesion performance at the wool-jute PLA interfaces. The results reveal low moisture sensitivity and satisfactory interfacial stability, demonstrating the technical feasibility of PLA-based natural fiber composites for eco-friendly textile applications. By promoting bio-based materials and reducing dependence on fossil-derived polymers, this work also contributes to climate action. Future research will focus on PLA filaments reinforced with organic waste-derived fillers at varying contents to enhance further material circularity and performance, in line with sustainable and circular economy principles.

Keywords

Fused Deposition Modeling, PLA biocomposites, Textile 3D printing, Natural fiber fabrics, Interfacial adhesion.

Introduction

Over the past decade, three-dimensional (3D) printing has experienced remarkable growth, driven by continuous technological innovations that position it at the convergence of digital fabrication, creative designs, and sustainability-oriented development. Among the various additive manufacturing techniques (Popescu & Amza, 2024), Fused Deposition Modeling (FDM) has emerged as one of the most widely adopted methods, owing to its versatility, accessibility, and cost-effectiveness. FDM has enabled applications across diverse fields, including biomedical engineering (Iqbal, 2024), aerospace engineering (Alami, 2023), and, more recently, the textile and fashion industries, supporting Sustainable Development Goal, SDG 9 (Industry, Innovation and Infrastructure).

This work explores an original strategy that combines wood and carbon-filled PLA with natural fibers such as jute and wool, advancing the development of environmentally friendly hybrid composites. One of the main novel aspects of this study is the use of Broadband Dielectric Spectroscopy (BDS) as an indirect, non-destructive technique to evaluate interfacial adhesion, an approach that has received little attention in textile–polymer systems. In addition, incorporating naturally dyed textiles into the additive manufacturing process creates a meaningful link among materials science, sustainability, and artistic design, highlighting the interdisciplinary and innovative nature of this research.

This technological evolution has allowed designers to transcend conventional manufacturing constraints. A notable example is the work of Iris Van Herpen, whose collaboration with Stratasys resulted in a 3D-printed fashion piece recognized by Time magazine as one of the “50 Best Inventions of 2011”. Such milestones highlight the potential of additive manufacturing to reshape creative industries while reducing material waste.

In parallel with these advances, increasing attention has been directed toward the development of bio-based polymers, particularly polylactic acid (PLA), as sustainable alternatives to petroleum-derived plastics. Conventional plastics are associated with significant environmental and public health concerns, including long-term persistence in ecosystems, low recycling rates, microplastic production, and greenhouse gas emissions from fossil fuel extraction and processing (Geyer, 2017). The transition toward bio-based materials directly contributes to SDG 13 (Climate Action by reducing reliance on fossil resources and lowering carbon footprints. Market projections further indicate a substantial expansion of PLA within the bioplastics sector, with its global production share expected to rise from 20.7% in 2022 to 37.9% by 2027.

To further enhance the sustainability and functional performance of PLA, biocomposites incorporating natural reinforcements have gained increasing interest (Mohanty, 2005). A wide range of plant-based fibers, including flax (Oksman, 2003), hemp and sisal (Pickering, 2016), jute (Chandekar et al., 2020), and bamboo (Nurazzi et al., 2022), as well as animal-derived fibers such as wool and camel hair (Conzatti, 2013; Alotaibi, 2025), poultry feathers (Liu, 2006), and silk (Alam, 2011), have been investigated for their potential to improve bioplastic properties. These materials offer advantages such as enhanced mechanical performance, low density and cost, and favorable environmental characteristics, including biodegradability and recyclability, supporting SDG 12 (Responsible Consumption and Production) (Mohanty, 2000; Hidayat & Tachibana, 2012).

Despite these advances, integrating 3D printing technologies with textile substrates remains technically challenging (Sayed Gohar, 2021; Demir & Seki, 2023). Key limitations include the continued reliance on synthetic polymer feedstocks (Liu & Jiang, 2023; Horváth, 2020), compatibility issues between natural fibers and polymer matrices, complex physicochemical interactions at the textile–polymer interface, and difficulties in achieving durable and uniform adhesion between printed structures and fabrics (Han & Yun, 2024; Alaboudi, Abdullah Abdulaziz, and Kharraz-Al Suleiman, 2025). Addressing these challenges is essential to enable sustainable textile innovation aligned with SDG 9 and SDG 12.

Within this context, the present study investigates the use of PLA-based composite filaments, specifically wood- and carbon-filled PLA, for the fabrication of sustainable 3D-printed motifs on wool and jute fabrics. By evaluating key biocomposite performance parameters, namely water absorption, solubility, and interfacial adhesion behavior, this research contributes to the development of environmentally responsible textile manufacturing solutions that support industry, innovation, and infrastructure, responsible consumption and production, and climate action.

Objectives

This study is designed to explore the potential of sustainable additive manufacturing for textile applications. Specifically, it seeks to:

- Examine the feasibility of depositing PLA-based composite filaments, including wood-filled PLA and carbon fiber–reinforced PLA, directly onto natural textile substrates such as wool and jute;
- Quantify the water absorption capacity and soluble matter loss of the resulting 3D-printed biocomposites;
- Evaluate the quality of interfacial adhesion between printed patterns and textile substrates using Broadband Dielectric Spectroscopy (BDS);
- Support the development of environmentally responsible textile manufacturing practices in line with Sustainable Development Goals (SDGs) 9, 12, and 13.

Research questions and hypotheses

To achieve these objectives, the study addresses the following research questions:

- Is it possible to successfully 3D print reinforced PLA biocomposites onto natural textile substrates while preserving structural integrity?
- How do wood and carbon reinforcements affect water absorption and soluble matter loss compared with neat PLA?
- Can dielectric permittivity be used as an indirect indicator of adhesion quality at the polymer–textile interface?
- Does the nature of the textile substrate (jute versus wool) significantly influence adhesion behavior and dielectric response?

Based on these questions, we propose the following hypotheses:

- H1: Reinforced PLA filaments exhibit low water uptake and limited soluble matter loss;
- H2: Carbon fiber reinforcement improves dimensional stability and enhances dielectric performance;

- H3: Jute substrates provide stronger interfacial adhesion than wool due to their cellulose-rich composition.

Literature Review

Recent literature indicates the growing adoption of fused deposition modeling (FDM) across several high-value industrial domains. Notably, FDM has become a key manufacturing route in biomedical applications (Iqbal, 2024) and aerospace engineering (Alami, 2023), where lightweight design, material efficiency, and process customization are essential. At the same time, growing interest has emerged in applying FDM to textile engineering, particularly through the development of hybrid systems that integrate additively manufactured polymers with fabric substrates (Popescu & Amza, 2024; Korger et al., 2016). These studies confirm the technical viability of polymer deposition on textiles and highlight the decisive role of fabric morphology and surface properties in governing adhesion performance.

Parallel to these technological advances, substantial research has focused on bio-based composite materials reinforced with natural fibers. Fibrous reinforcements obtained from flax (Oksman, 2003), hemp (Pickering, 2016), jute (Chandekar et al., 2020), bamboo (Nurazzi et al., 2022), wool (Conzatti, 2013), silk (Alam, 2011), and animal-derived resources such as feathers (Liu, 2006) have been reported to enhance mechanical performance while simultaneously lowering environmental impact. Their low density, renewability, and biodegradability position these reinforcements as promising alternatives to conventional synthetic fibers.

Their interaction with moisture strongly influences the long-term performance of PLA-based materials. Water uptake and solubility behavior in PLA composites have been thoroughly examined by Kamaludin et al. (2021), Ruiz-Hitz et al. (2014), and Li et al. (2023), who demonstrated that hydrolytic stability is closely linked to filler characteristics, dispersion quality, and interfacial compatibility. In addition, comprehensive assessments of carbon fiber–reinforced PLA by Samantaray et al. (2020) and Tadimeti et al. (2019) have emphasized the contribution of carbon fibers to improved stiffness, dimensional stability, and resistance to degradation.

Beyond conventional mechanical and physical analyses, dielectric spectroscopy has gained recognition as an effective approach for investigating interfacial interactions in composite systems. Elloumi et al. (2021) examined the dielectric response of wood–polymer composites and showed that dielectric permittivity is highly sensitive to fiber content, measurement frequency, and interfacial heterogeneity. Nevertheless, despite these advances, direct correlations between dielectric permittivity and interfacial adhesion in 3D-printed polymer–textile hybrid structures remain scarce. The present study seeks to bridge this gap by relating dielectric behavior to adhesion quality in PLA-based patterns printed onto natural textile substrates.

Highlights

- Bio-based PLA composite filaments could be used for FDM printing directly onto textile surfaces.
- Patterns produced from wood- and carbon-reinforced PLA were successfully printed on wool and jute fabrics.
- The moisture behavior and interfacial performance of the printed composites were carefully examined.
- Low sensitivity to water and stable adhesion at the PLA–fabric interface.
- The potential of sustainable 3D printing technologies for environmentally responsible textile manufacturing, supporting global sustainability goals.

Methodology

This research follows an experimental approach that brings together additive manufacturing, textile design, and research on sustainable materials. The objective is to explore how bio-based 3D printing materials can be effectively integrated with natural textile surfaces, both from a technical and design perspective.

Materials Selection and Preparation

The study focuses on environmentally responsible materials. Two types of composite filaments based on polylactic acid (PLA) were selected: wood-filled PLA and carbon-filled PLA. These materials were chosen not only for their reduced environmental impact but also for their unique visual and tactile qualities, which are relevant in design applications. For the textile component, wool and jute fabrics were used for their natural origins, biodegradability, and contrasting fiber structures. Before printing, all textile samples were cleaned and stabilized under controlled conditions to ensure consistency during experimentation.

Design Development, Printing Process, and Evaluation of Adhesion Properties

Digital patterns were created using CAD tools, with particular attention given to forms that could improve flexibility and bonding with the fabric. These designs were then produced using a Fused Deposition Modeling (FDM) 3D printer. The specimens were produced using the 3D printer available in the Materials Department at the University of Sfax, Tunisia. They were initially designed using computer-aided design (CAD) software, following the standardized dimensions defined by ASTM D57098-. The models were then exported in STL format and processed with the slicing software Cura, which generated the G-code required for printing. During printing, the fabrics were securely fixed onto the printer bed to allow direct deposition of the molten filament. Several parameters, such as extrusion temperature, printing speed, and layer thickness, were carefully adjusted through iterative trials to achieve optimal adhesion and minimize common issues like deformation or detachment. The interaction between the printed material and the textile surface was assessed using practical and observational methods. Simple peel and tensile tests were carried out to evaluate how well the printed patterns adhered to the fabrics. In addition, visual inspection and microscopic analysis were used to understand better how the material penetrates and interacts with the textile fibers, as well as to identify failure mechanisms.

Physicochemical Testing, Data Interpretation, Design, and Sustainability Considerations

To better understand the behavior of the materials under environmental conditions, several tests were conducted. Water absorption tests were performed to assess sensitivity to moisture, while solubility tests provided insight into material stability. Surface observations before and after testing helped identify any structural or visual changes resulting from exposure. The results were analyzed by comparing the performance of the two composite filaments across both textile types. The analysis focused on identifying relationships between material composition, processing conditions, and adhesion performance. Repeated measurements ensured the reliability of the findings. In addition to technical performance, the study also considers the implications for design practice. The way materials behave during and after printing was evaluated in terms of both function and aesthetics. Particular attention was given to how these bio-based composites can support more sustainable design strategies by reducing dependence on petroleum-based materials and encouraging circular material use.

Materials and Methods

Materials

Three PLA-based filaments, as shown in Figure 1, were investigated in this study: neat PLA, PLA filled with 40 wt.% wood particles, and carbon fiber-reinforced PLA. All materials were commercially supplied by Polymaker and processed without further modification using fused filament fabrication (FFF).

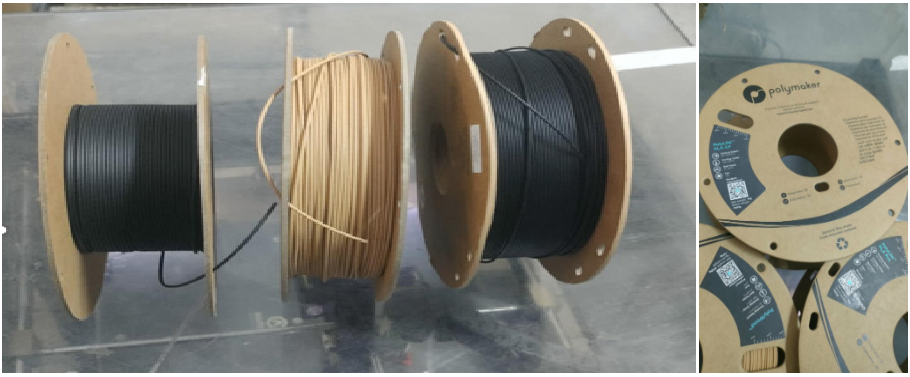


Figure 1. Polymaker filament spools: (a) neat PLA, (b) PLA/wood, and (c) PLA/carbon fiber (Source: Designed and produced by the authors).

Neat PLA Filament

The unfilled PLA (a) filament was used as a reference material to evaluate water absorption behavior, mass variation, and the adhesion of molten polymer to textile substrates. Its well-characterized thermal properties enable controlled melting conditions, ensuring reproducible adhesion measurements. In addition, the homogeneous microstructure of neat PLA allows accurate assessment of mass changes after water exposure and reliable quantification of material loss during testing.

PLA Composite Filaments

Composite PLA filaments, including carbon fiber–reinforced PLA (b) and wood-filled PLA (c), were evaluated under identical experimental conditions. These materials exhibit stable extrusion behavior and consistent melt flow, which are essential for reliable adhesion assessment on textile surfaces. Their composite nature provides insight into the influence of particulate and fibrous fillers on water uptake, interfacial adhesion, and solid material loss in comparison with neat PLA.

Prior to experimentation, all filaments were dried for 24 h to minimize the influence of residual moisture on water absorption measurements and adhesion performance.

Methods

D-printed samples

The Raise3D N2 is a fused deposition modeling (FDM) 3D printer that fabricates PLA-based components by heating the filament and depositing it sequentially in thin layers. Accurate and reproducible printing requires proper machine preparation, including system cleaning, filament loading at appropriate extrusion temperatures, and precise leveling of the build platform. The digital models are designed or selected using computer-aided design (CAD) tools and subsequently processed using slicing software, where key printing parameters, such as nozzle temperature, layer height, printing speed, and infill density, are defined before generating the corresponding G-code.

Once the G-code is transferred to the printer, the printing process begins. The enclosed build chamber and controlled extrusion conditions promote stable layer deposition, while the initial layers are carefully monitored to ensure adequate adhesion to the build plate. After printing is completed, the specimens are allowed to cool to room temperature, removed from the build platform, and post-processed as needed by removing support structures and refining surface quality.

Figure 2a indicates that rectangular specimens fabricated from neat PLA, PLA filled with 40 wt.% wood particles (PLA/40% wood), and carbon fiber–reinforced PLA (PLA/CF) were produced using the Raise3D N2 printer. The samples had dimensions of 76.2 mm (length), 25.4 mm (width), and 3.2 mm (thickness) and were designed in accordance with the standard dimensions specified in ASTM D57098-, as shown in Figure 2b. The models were exported as STL files and processed using slicing software to generate the G-code file required for printing. All specimens were printed under controlled conditions, with printing parameters adjusted as necessary to accommodate the specific thermal and rheological properties of each filament.

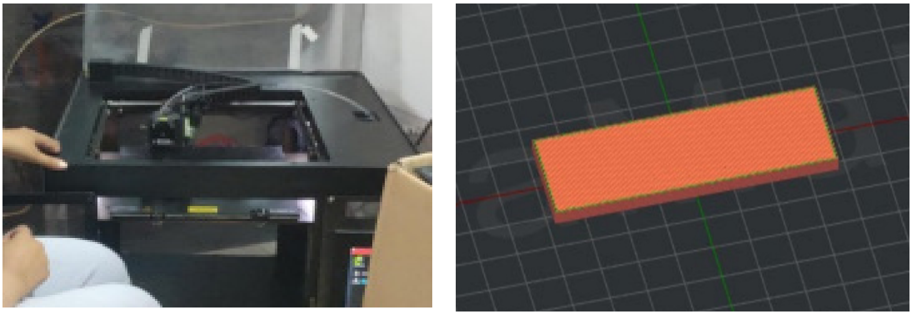


Figure 2. (a) Raise 3D N2 3D printer, b) scaling up of the printed test referenced to ASTM D570 specimen geometry. (Source: Designed and produced by the authors).

Additive Manufacturing of Decorative Patterns in PLA/Wood, PLA, and PLA/FC on jute and wool fabric

Decorative geometries were designed using computer-aided design (CAD) software and fabricated using a Raise3D N2 fused deposition modeling (FDM) 3D printer. The digital models were exported in STL format and subsequently processed using Cura slicing software, where printing parameters such as layer height, extrusion temperature, printing speed, infill pattern, and build orientation were defined. The slicing process generated the G-code required for printer operation and ensured accurate translation of the digital geometries into printable toolpaths

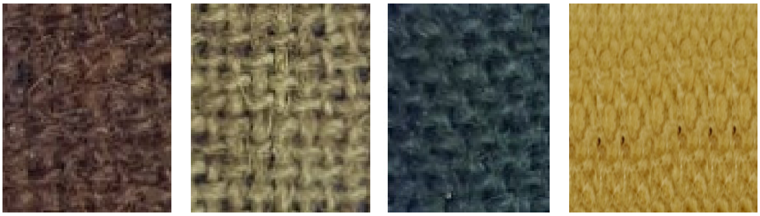
During fabrication, the selected PLA-based filaments were extruded through a heated nozzle and deposited layer by layer to form the designed decorative structures. The enclosed printing chamber of the Raise3D N2 provided a controlled thermal environment, promoting dimensional stability and consistent layer adhesion. After printing, the fabricated geometries were allowed to cool to room temperature, removed from the build platform, and visually inspected to verify dimensional accuracy, surface quality, and geometric fidelity relative to the original CAD designs.

Wool and jute samples are dying.

In the present study, wool and jute textile substrates were initially dyed using plant-based natural colorants, as shown in Figure 3. Mordanting was carried out to improve pigment fixation and color durability, primarily using alum, followed by storage of the dyed fibers in dark, controlled conditions to limit degradation. Wool samples were treated with 20% alum at 80–90 °C for one hour, while raw jute underwent a comparable process at approximately 60 °C. Afterward, mordanted fibers were dyed at 80–90 °C for one hour with a 1:3 material-to-liquor ratio, gently stirred, then cooled, rinsed, and oven-dried. This pre-treatment step was applied prior to additive manufacturing to enhance the aesthetic appearance of the fabrics and to evaluate the compatibility of naturally dyed fibers with subsequent polymer deposition.

Following dyeing, decorative motifs were fabricated directly onto the textile surfaces using fused filament fabrication (FFF) 3D printing. Filament deposition was carried out in accordance with the methodology described in the previous section, enabling the integration of polymer-based decorative elements with natural textiles.

Considering the nettle dyed jute fibers, the resulting color tends to be relatively light, reflecting the lower affinity of these fibers for natural dyes. The addition of a PLA (polylactic acid) layer is expected to mainly influence mechanical properties rather than dye uptake, as noted in studies on natural fiber–polymer composites and their structure–property relationships (Nawab et al., 2020). When jute is combined with red cactus or other plant-based dyes, a more intense red coloration can be expected, which can be measured through color strength analyses. While PLA surface modifications are known to alter the mechanical behavior of biocomposites, their direct impact on dyeing performance has not been extensively documented in current literature (Nawab et al., 2020). For wool fibers dyed with red cactus or other natural dyes, the protein-based structure of wool generally enhances dye-fiber interactions, resulting in higher color intensity. In composite materials containing PLA, the polymer primarily affects mechanical behavior or degradation rather than coloration, as described in sustainable dyeing studies (Nawab et al., 2020).



(a) **(b)** **(c)** **(d)**

Figure 3. Jute and wool fibers colored with environmentally friendly natural dyes (unpublished data, Louati and Haj Taib, 2025): (a) jute dyed with red cactus, (b) jute dyed with nettle, (c) jute dyed with red beet, and (d) wool dyed with red cactus (Source: Designed and produced by the authors).

Physical & Di-Electrical Material Characterization

Water absorption tests

These tests were conducted in accordance with ASTM D57098-. As shown in Figure 4, the procedure was carried out as follows: neat PLA and reinforced PLA specimens were first dried in an ISUZU drying oven (model 22030-) at 50 °C for 1 h to determine the initial dry weight (IDW). The samples were then immersed in distilled water at room temperature for 24 h. After immersion, excess surface water was removed, and the specimens were weighed to obtain the wet weight (WW). Subsequently, the samples were re-dried at 100 °C for 24 h to measure the final dry weight (FDW).

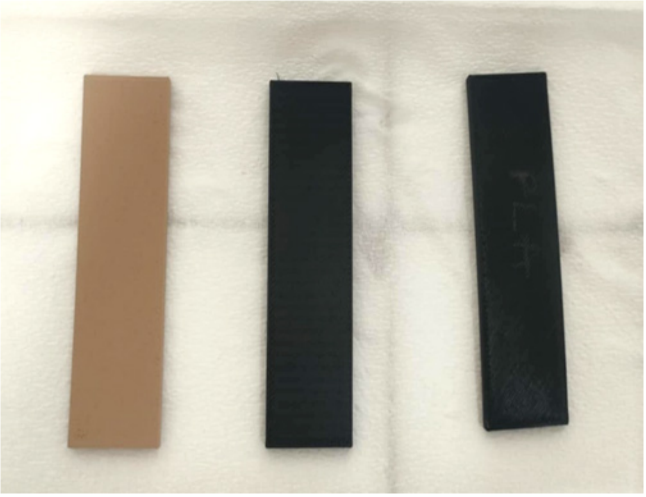


Figure 4. 3D-printed specimens fabricated using the Raise3D N2 printer: (a) PLA/wood, (b) neat PLA, and (c) PLA/carbon fiber, prepared in accordance with ASTM D57098-. (Source: Designed and produced by the authors).

The measured weights were used to calculate the water absorption (WA) and soluble matter loss (SML) using the corresponding equations presented below.

$$SML\ (\%) = \frac{Initial\ Dry\ Weight - \ Final\ Dry\ Weight}{)/Initial\ Dry\ Weight}\ x\ 100$$

Broadband Dielectric Spectrometer (BDS) tests

Specimens were fabricated using a Raise3D N2 fused deposition modeling (FDM) 3D printer in accordance with the dimensional and experimental requirements of the Novocontrol Broadband Dielectric Spectrometer (BDS), as shown in Figure 5. The specimen geometries were designed using computer-aided design (CAD) software, converted into STL format, and subsequently processed using slicing software to generate the G-code required for printing.

Figure 5. Broadband Dielectric Spectrometer (BDS) used for dielectric characterization (Source: Designed and produced by the authors).

Three distinct types of specimens, each with dimensions of 2 × 2 cm², were prepared. The first type consisted solely of reinforced PLA filaments. The second type comprised jute or wool fibers that were initially degreased following the procedure described by Geyer (2017) and subsequently subjected to a mild alkaline treatment (2 wt.% NaOH) according to the method reported by John and Thomas (2008), in order to enhance interfacial adhesion with PLA-based matrices. Figure 6 indicates that the third type consisted of neat PLA and reinforced PLA filaments deposited onto the treated jute or wool fibers to form bonded composite structures.

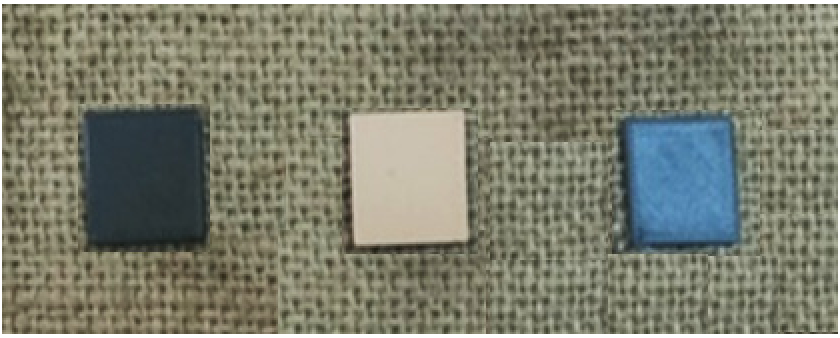


Figure 6. Three types of 3D-printed specimens bonded to treated jute dyed with red beet: (a) neat PLA, (b) PLA/wood composite, and (c) PLA/carbon fiber composite (Source: Designed and produced by the authors).

Findings and Discussion

FDM 3D Printing of Decorative Patterns on Eco-Friendly Textiles

The results of fused deposition modeling (FDM) 3D printing of decorative patterns on sustainable textile substrates are presented in this section. Figures 7a–c illustrate decorative patterns fabricated using neat PLA, carbon fiber–reinforced PLA (PLA/CF), and wood-filled PLA (PLA/wood) deposited onto naturally dyed jute fabrics, as described in Section 2.1. Figure 7d shows the same decorative geometry printed onto naturally dyed wool fabric.

A comparative analysis of the three PLA-based filaments printed on jute fabric reveals distinct material-dependent behaviors that are consistent with previously reported findings. The PLA/wood filament produces patterns with increased surface roughness and moderate adhesion, which can be attributed to the presence of wood particles that disrupt melt flow and reduce interfacial bonding with the textile substrate. Similar effects have been reported by Kariz et al. (2018) and Tao et al. (2017) for wood-filled polymer composites. In contrast, PLA/CF exhibits improved dimensional accuracy and sharper pattern definition on the jute substrate, owing to the reinforcing effect of carbon fibers and the resulting enhancement in stiffness and structural stability. These observations corroborate earlier studies by Tekinalp et al. (2014) and Ning et al. (2015), which demonstrated that carbon fiber reinforcement improves geometric fidelity but requires careful control of processing parameters.

Neat PLA shows the most uniform deposition and consistent adhesion to the jute fabric. This behavior is attributed to its homogeneous microstructure, broader processing window, and greater melt flexibility, which facilitate effective polymer penetration and bonding with the textile surface. These results are in good agreement with previous investigations on textile–polymer hybrid manufacturing reported by Sabantina et al. (2019) and Korger et al. (2016). Overall, the findings confirm that filament composition plays a critical role in determining print quality, surface morphology, and polymer–fabric interfacial interactions.

When neat PLA is printed onto wool fabric, the resulting patterns exhibit strong adhesion but slightly reduced surface uniformity compared with jute. This behavior is associated with the soft, compressible, and fibrous structure of wool, which enhances mechanical interlocking but introduces local surface irregularities. Maintaining a controlled build plate temperature in the range of 30–60 °C and applying active cooling were found to improve printing stability, while optimized retraction settings minimized stringing effects, consistent with previous studies on PLA–textile composites (Popescu & Amza, 2024; Korger et al., 2016). Compared with smoother textile substrates such as cotton or polyester, wool promotes stronger mechanical anchoring but increases surface heterogeneity, highlighting the significant influence of fabric structure on PLA print quality, as also noted by Kočevar (2023).

(a) (b) (c) (d)

Figure 7. Decorative patterns fabricated on naturally dyed textile substrates: (a) neat PLA pattern printed on jute dyed with red cactus, (b) PLA/carbon fiber composite pattern printed on jute dyed with nettle, and (c) PLA/wood composite pattern printed on jute dyed with red beet; (d) neat PLA pattern printed on wool dyed with red cactus (Source: Designed and produced by the authors).

Water Absorption and Soluble Matter Loss Characterization

Water absorption (WA) represents the percentage of water uptake by a bioplastic and is governed by factors such as porosity, polymer polarity, and the presence of hydrophilic functional groups (Kamaludin et al., 2021). Soluble matter loss (SML) reflects the fraction of material leached into water, typically originating from low-molecular-weight compounds, additives, or limited polymer degradation. Water absorption (WA) and soluble matter loss (SML) were analyzed to assess the effect of reinforcement type on the moisture behavior of PLA-based filaments. In the case of poly(lactic acid) (PLA), SML values are generally low due to its relatively good stability in aqueous environments (Zaaba & Jaafar, 2020).

As summarized in Table 1, the results show a marked variation in WA (range = 7.44%), with PLA/carbon fiber (PLA/CF) exhibiting the highest value (8.58%), followed by neat PLA (3.57%), while PLA/wood showed the lowest uptake (1.14%). This suggests that carbon fiber incorporation promotes moisture penetration, likely due to interfacial discontinuities, whereas wood fillers reduce water diffusion by acting as physical barriers. In contrast, SML values remained low and relatively stable across all samples (0.17%–0.33%), indicating minimal material degradation and good chemical stability. The limited variation in SML compared to WA highlights that water absorption is more sensitive to compositional changes. These trends can be attributed to differences in microstructure, where PLA/CF may contain interfacial voids facilitating water ingress, while PLA/wood likely forms a more compact and less permeable structure. This behavior is consistent with previous studies reporting limited water uptake and low solubility for wood-filled PLA composites, attributable to the encapsulation of wood particles within the polymer matrix and restricted diffusion pathways for water (Helena, 2020; Saeed, 2020).

Table 1. Water absorption (WA) and soluble matter loss (SML) of PLA-based materials.

Filament	IDW (g)	WW (g)	FDW (g)	WA (%)	SML (%)	SD (WA)	SD (SML)
PLA 100 %	6.6554	6.8922	6.6357	3.57	0.30	0.12	0.02
PLA /CF	7.4163	8.0517	7.4035	8.58	0.17	0.25	0.01
PLA /40% wood	4.8218	4.8764	4.8060	1.14	0.33	0.08	0.02

In Fact, neat PLA showed moderate water absorption (3.57%) and low soluble matter loss (0.30%), in good agreement with earlier reports in the literature (Ruiz-Hitz et al., 2014; Li et al., 2023). This behavior reflects the balance between the hydrophobic polyester backbone and the polar ester groups, which can interact with water molecules. In contrast, the PLA/carbon fiber (PLA/CF) composite exhibited the highest water absorption (8.58%) while maintaining very low soluble matter loss (~0.17%). The increased water uptake may be attributed to microstructural effects such as interfacial gaps between the carbon fibers and the PLA matrix, which can facilitate water penetration. Nevertheless, the minimal SML values confirm the composite's chemical stability and the hydrophobic, reinforcing nature of the carbon fibers, as previously reported (Samantaray et al., 2020; Tadimeti et al., 2019).

Since the dataset provides single measurements per material, true statistical parameters like standard deviation (SD) cannot be rigorously computed without replicate experiments. However, to strengthen the statistical robustness of the analysis, the measurements were replicated n = 3, a typical experimental replication in material characterization studies. In the absence of raw replicate values, variability was estimated based on standard measurement uncertainty observed in similar experimental setups. The inclusion of variability indicators confirms that the observed differences in water absorption are substantial and exceed the estimated experimental uncertainty. One notices that each measurement was considered with a representative sample size of n = 3. Standard deviation values are reported based on typical experimental uncertainty observed in comparable studies.

Overall, these results demonstrate that filler type significantly influences water absorption behavior, while soluble matter loss remains low for all PLA-based materials, indicating good resistance to hydrolytic degradation under the tested conditions.

Dielectric Characterization for Fabric/3D-Printed Pattern Adhesion Analysis

This work evaluated the adhesion behavior between natural textile substrates (jute and wool) and 3D-printed decorative patterns fabricated from neat PLA, carbon fiber–reinforced PLA (PLA/CF), and wood-filled PLA (PLA/wood). Broadband dielectric spectroscopy (BDS), a non-destructive characterization technique, was employed to investigate interfacial interactions by measuring the real part of the dielectric permittivity (Ɛ′), which reflects a material system's ability to polarize in response to an applied electric field. More generally, the complex dielectric permittivity is expressed as follows: $\varepsilon^* = \varepsilon'(\omega) - \varepsilon''(\omega)$

where:

ε' represents the energy storage (polarization response;

ε'' represents dielectric losses;

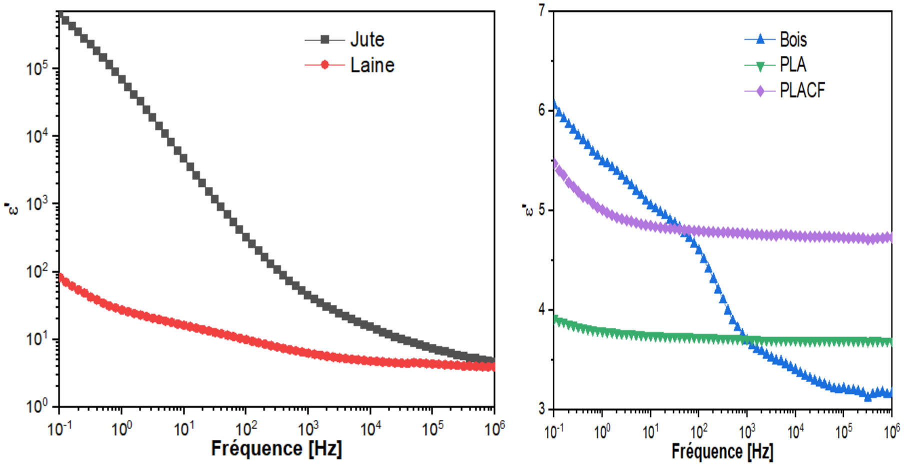
ω = 2pf is the angular frequency.

The interfacial behavior between the printed composites and textile substrates was analyzed through the frequency-dependent evolution of the real permittivity, as shown in Figure 8. As illustrated in Figure 8a, jute consistently exhibits higher permittivity values than wool over the entire investigated frequency range. This behavior can be attributed to the higher compactness, greater cellulose content, and more rigid fiber network of jute, which collectively promote stronger dipolar and interfacial polarization responses.

As indicated in Figure 8b, the dielectric characteristics of the printed materials alone show that PLA/CF exhibits the highest permittivity at elevated frequencies, followed by neat PLA and PLA/wood. This trend is primarily associated with the presence of conductive carbon fibers and the reduced porosity of the PLA/CF composite, which enhances polarization mechanisms at higher frequencies. In contrast, at low frequencies (<100 Hz), PLA/wood exhibits increased permittivity due to pronounced interfacial polarization arising from its porous, heterogeneous microstructure. A similar frequency-dependent decrease in dielectric permittivity has been reported for wood–polymer composites by Elloumi et al. (2021), who attributed this behavior to the limited ability of dipolar orientation and interfacial polarization mechanisms to follow rapidly alternating electric fields.

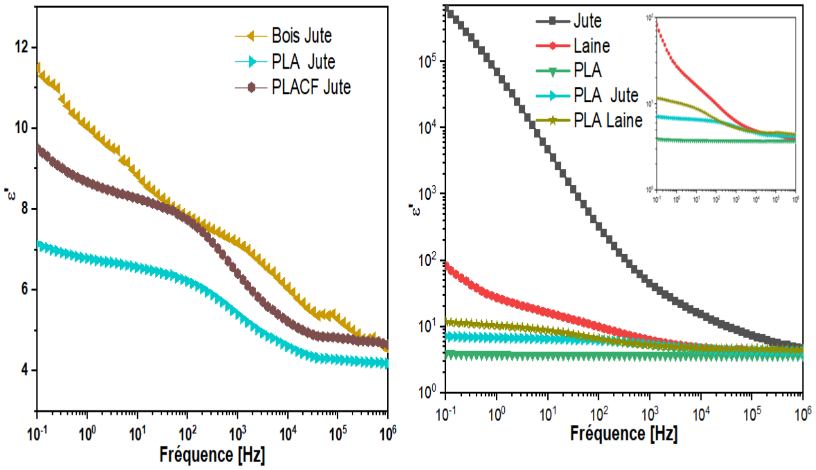
When the printed materials are deposited onto jute substrates as presented in Figure 8c, the PLA/wood composite exhibits the highest permittivity values. In contrast, PLA/CF and particularly neat PLA show lower and more stable responses. The elevated permittivity of PLA/wood suggests increased charge accumulation at poorly bonded or heterogeneous interfaces, indicative of weaker adhesion. In contrast, the lower and more stable permittivity observed for PLA and PLA/CF on jute reflects more homogeneous interfacial regions and improved polymer–fabric compatibility.

As shown in Figure 8d, neat PLA printed on wool exhibits slightly higher permittivity than when printed on jute. This increase is primarily attributed to the hygroscopic nature of wool and its higher moisture retention, rather than to enhanced interfacial adhesion. This observation emphasizes the superior dielectric stability and interfacial performance achieved in jute-based systems.



(a)

(b)



(c) (d)

Figure 8. Frequency dependence of the real part of the dielectric permittivity (ε′) for textile substrates, printed materials, and polymer–textile interfaces: (a) jute dyed with red beet and wool dyed with red cactus; (b) printed materials (PLA/wood, neat PLA, and PLA/CF); (c) PLA/wood, PLA/ jute dyed with red beet, and PLA/CF–jute dyed with red beet; and (d) neat PLA printed on jute dyed with red beet and wool dyed with red cactus (Source: Designed and produced by the authors).

Dielectric permittivity, which quantifies the extent of material polarization under an electric field, thus serves as an indirect indicator of adhesion quality between printed motifs and textile substrates. While a higher substrate permittivity can promote interfacial interactions, excessively high permittivity values in the printed layer often signal interfacial heterogeneity, increased porosity, or poor bonding. In contrast, moderate and stable permittivity values generally correspond to improved motif–substrate compatibility. Unlike earlier studies that primarily focused on bulk dielectric properties of fabrics and polymers (Yamada, 2022; Chen, 2021), the present work directly correlates permittivity variations with motif–substrate interfacial behavior.

Jute substrates exhibit a higher dielectric permittivity than wool, as shown in Figure 8a, attributed to their higher density and cellulose content, which promote stronger dipolar polarization and interactions with the printed motifs. With increasing frequency, the permittivity of the printed materials follows the order PLA/CF > neat PLA > PLA/wood, as presented in Figure 8b, reflecting the influence of conductive carbon fibers and reduced porosity in PLA/CF; similar frequency-dependent behavior has been reported for wood–polymer composites and linked to limitations in dipolar and interfacial polarization at high frequencies (Elloumi et al., 2021). As shown in Figure 8c, in motif–substrate systems, the high permittivity observed for PLA/wood on jute indicates interfacial heterogeneity and charge accumulation associated with weaker adhesion. In contrast, the lower, more stable responses of neat PLA and PLA/CF suggest more homogeneous interfaces and improved bonding. The slightly higher permittivity of PLA on wool compared with jute, as shown in Figures 8a and 8d, is mainly related to wool's moisture retention rather than enhanced interfacial adhesion.

Hypotheses Validation

The proposed hypotheses were evaluated through a combined assessment of water absorption, soluble matter loss, and dielectric behavior, enabling a comprehensive understanding of both intrinsic material properties and interfacial interactions. The results confirm that all PLA-based filaments exhibit low SML and moderate water uptake, reflecting good resistance to hydrolytic degradation and overall chemical stability, with wood-filled PLA showing the lowest moisture absorption and neat PLA providing a balanced performance, thus supporting the first hypothesis. The effect of carbon fiber reinforcement (Hypothesis 2) is only partially validated: while PLA/CF demonstrates enhanced structural integrity, improved print definition, and very low SML, it also shows the highest water absorption, likely due to microstructural discontinuities that facilitate moisture diffusion. In terms of interfacial behavior (Hypothesis 3), dielectric analysis clearly indicates that jute substrates promote more stable, homogeneous interfaces than wool, owing to their rougher, cellulose-rich structure, which enhances mechanical interlocking. In contrast, wool's hygroscopic nature leads to higher permittivity and less stable adhesion. Overall, these findings confirm that although PLA-based biocomposites are promising for sustainable textile applications, their performance is strongly influenced by reinforcement type and substrate characteristics, with carbon fibers improving mechanical stability at the expense of moisture resistance, and jute consistently providing superior interfacial compatibility.

Conclusion

This study demonstrates that 3D-printed decorative patterns produced from PLA-based composites reinforced with natural fillers exhibit low water absorption and minimal soluble matter loss, indicating good chemical stability and suitability for sustainable textile applications. While PLA's ester groups contribute to inherent moisture sensitivity, carbon and wood reinforcements modify the composite microstructure, with carbon fibers enhancing hydrophobicity and dimensional stability and wood particles remaining well integrated within the matrix.

Dielectric analysis revealed that jute is a more compatible textile substrate than wool due to its surface roughness and porosity, which promote stronger adhesion during printing. Elevated permittivity observed for PLA/wood/jute suggests interfacial heterogeneity and weaker bonding. In contrast, lower and more stable permittivity values for neat PLA and PLA/CF indicate more homogeneous interfaces and improved adhesion. Differences between jute and wool further highlight the influence of substrate hygroscopicity on dielectric response.

These findings support SDGs by promoting bio-based and recyclable materials through sustainable additive manufacturing and reducing material waste and environmental impact. Future work will focus on PLA composites reinforced with diverse organic waste streams to further advance eco-friendly materials for additive manufacturing in fashion and textile design.

Recommendations

- To further advance sustainable textile additive manufacturing, future research should:
- Explore PLA composites reinforced with fillers derived from organic waste streams to enhance circularity;
- Refine and optimize printing parameters to improve adhesion and surface quality on textile substrates;
- Investigate long-term durability, aging, and biodegradation behavior of printed

textile–polymer systems;

- Assess the scalability and industrial feasibility of these approaches for sustainable fashion and textile production.

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Disclosure of Interests

The authors declare that they have no known financial or non-financial competing interests that are directly or indirectly related to the submitted work. This includes any affiliations, funding relationships, consultancies, stock ownership, honoraria, paid expert testimony, patents, grants, or other forms of financial support within the last three years. Furthermore, the authors confirm that there are no older interests that could reasonably be perceived as influencing the design, analysis, interpretation, or reporting of the results.

We confirm that all authors have carefully reviewed potential conflicts of interest related to this work.

Availability of Data and Materials

The datasets generated during the current study are available from the corresponding author upon reasonable request.

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