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Layer-Paused FFF-Based Manufacturing of PLA-Hemp Composites: Mechanical Behavior and Failure Morphology

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Graphical/Tabular Abstract (Grafik Özet)

This study investigates the mechanical performance of hemp fiber-reinforced PLA composites fabricated via layer-paused FFF. The findings reveal that continuous natural reinforcement significantly improves load-bearing capacity while altering fracture behavior, offering a sustainable alternative for additive manufacturing without hardware modifications. / Bu çalışma, katman duraklatmalı FFF ile üretilen kenevir lifi takviyeli PLA kompozitlerin mekanik performansını incelemektedir. Bulgular, sürekli doğal takviyenin yük taşıma kapasitesini önemli ölçüde artırırken kırılma davranışını değiştirdiğini ve donanım modifikasyonu olmaksızın eklemeli imalat için sürdürülebilir bir alternatif sunduğunu ortaya koymaktadır.

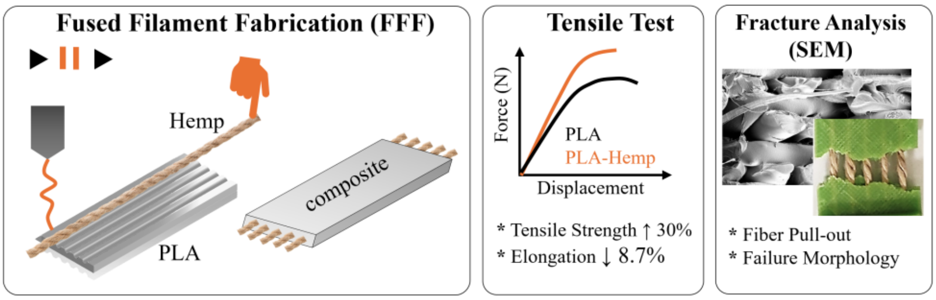

Figure A: *Production, mechanical performance, and failure morphology of PLA-hemp composites. /* ***Şekil A:*** *PLA-kenevir kompozitlerinin üretimi, mekanik performansı ve hasar morfolojisi.*

Highlights (Önemli noktalar)

- *Katman duraklatmalı FFF yöntemiyle sürekli kenevir takviyeli PLA kompozitler üretilmiştir. / Continuous hemp-reinforced PLA composites were fabricated via layer-paused FFF.*
- *Yöntem, filament modifikasyonu olmadan doğal liflerin doğrudan entegrasyonunu sağlar. / The method enables direct natural fiber integration without filament modification.*
- *Kenevir takviyesi çekme kuvvetini %30 artırırken uzamayı %8,7 azaltmıştır. / Hemp reinforcement increased tensile force by 30% while reducing elongation by 8.7%.*

Aim (Amaç): *The study aims to fabricate PLA-hemp composites via layer-paused FFF and investigate the effects of continuous reinforcement on mechanical behavior and failure morphology. / Bu çalışma, katman duraklatmalı FFF ile PLA-kenevir kompozitleri üretmeyi ve sürekli takviyenin mekanik davranış ile hasar morfolojisine etkilerini incelemeyi amaçlar.*

Originality (Özgünlük): *The originality lies in a practical manufacturing strategy enabling direct continuous fiber embedding into pre-designed channels without requiring hardware modifications or specialized filaments. / Özgünlük, donanım modifikasyonu veya özel filament gerektirmeksizin, sürekli liflerin önceden tasarlanmış kanallara doğrudan gömülmesini sağlayan pratik bir üretim stratejisidir.*

Results (Bulgular): *Hemp reinforcement increased tensile force by 30% but reduced elongation by 8.7%, while SEM confirmed fiber pull-out and interfacial separation as dominant failure mechanisms due to weak adhesion. / Kenevir takviyesi çekme kuvvetini %30 artırırken uzamayı %8,7 azalttı, SEM analizleri ise zayıf yapışmaya bağlı lif çekilmesini ve arayüz ayrılmasını baskın hasar mekanizmaları olarak doğrulamıştır.*

Conclusion (Sonuç): *This study confirms that continuous hemp fiber integration via layer-paused FFF significantly enhances PLA's strength, offering a sustainable composite manufacturing route despite reduced ductility. / Bu çalışma, katman duraklatmalı FFF ile sürekli kenevir lifi entegrasyonunun, azalan sünekliğe rağmen PLA'nın mukavemetini önemli ölçüde artırarak sürdürülebilir bir üretim yolu sunduğunu doğrulamaktadır.*

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Abstract

In this study, polylactic acid (PLA)-hemp composite samples were fabricated using a layer-paused fused filament fabrication (FFF) method, in which natural hemp fibers were manually inserted into pre-designed internal channels generated via computer-aided design (CAD). The novelty of this work lies in the introduction of a simple yet effective manufacturing approach that enables the direct integration of continuous natural fibers into the FFF process without requiring filament modification. This approach allows controlled fiber alignment and improved structural performance while maintaining the accessibility and sustainability of the FFF technique. Mechanical testing revealed that hemp fiber reinforcement increased the maximum tensile force from 1545 N to 1999 N (30%), while the displacement at maximum force decreased from 7.8 mm to 7.2 mm (8.7%), indicating a moderate reduction in ductility. Scanning electron microscopy (SEM) further confirmed the presence of fiber pull-out and interfacial separation as dominant fracture mechanisms. These results highlight the potential of the proposed method for advancing sustainable natural fiber-reinforced composites produced via additive manufacturing.

Katman Duraklamalı FFF Tabanlı PLA-Kenevir Kompozit Üretimi: Mekanik Davranış ve Hasar Morfolojisi

Makale Bilgisi

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Anahtar Kelimeler

Katmanlı İmalat
Eritilmiş Filament İmalatı
FFF
PLA-Kenevir Kompoziti
Sürekli Takviye

Öz

Bu çalışmada, bilgisayar destekli tasarım (CAD) ile oluşturulan önceden tasarlanmış iç kanallara doğal kenevir liflerinin elle yerleştirilmesiyle, katman duraklatmalı ergitilmiş filament imalatı (FFF) yöntemi kullanılarak polilaktik asit (PLA)-kenevir kompozit numuneleri üretilmiştir. Bu çalışmanın yeniliği, filament modifikasyonu gerektirmeksizin sürekli doğal liflerin doğrudan FFF sürecine entegre edilmesine olanak tanıyan basit ancak etkili bir üretim yaklaşımının sunulmasıdır. Bu yaklaşım, lif yönelimini kontrol edilebilir kılmakta ve yapısal performansı iyileştirirken FFF tekniğinin erişilebilirliğini ve sürdürülebilirliğini korumaktadır. Mekanik testler, kenevir lifi takviyesinin maksimum çekme kuvvetini 1545 N'den 1999 N'ye (%30) artırdığını, maksimum kuvvette yer değiştirme değerini ise 7.8 mm'den 7.2 mm'ye (%8,7) düşürdüğünü ortaya koymuş, bu durum süneklilikte orta düzeyde bir azalmaya işaret etmiştir. Taramalı elektron mikroskobu (SEM) analizleri, baskın kırılma mekanizmaları olarak lif çekilmesi ve ara yüzey ayrılmasının varlığını doğrulamıştır. Elde edilen sonuçlar, önerilen yöntemin eklemeli imalat ile sürdürülebilir doğal lif takviyeli kompozitlerin geliştirilmesi açısından potansiyelini vurgulamaktadır.

1. INTRODUCTION (GİRİŞ)

Additive manufacturing technologies are gaining increasing attention in the engineering and design world because they enable the production of complex geometries faster, more customizable, and with material savings compared to traditional manufacturing methods. Among these technologies, the FFF (Fused Filament Fabrication) method stands out for its low equipment costs, ease of access, and user-friendly interface [1, 2]. Polylactic acid (PLA), which is widely preferred in the FFF process, contributes significantly to sustainable production approaches owing to its biodegradable structure, environmentally friendly character, and thermoplastic processability [3, 4]. However, PLA is a fragile polymer by nature and has performance limitations, especially in structural load-bearing applications, due to its low toughness and limited elongation properties [5-7]. To address these drawbacks and expand the application potential of PLA, natural fibers have been increasingly

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employed as reinforcements, providing improvements in stiffness, strength, and cost-effectiveness while preserving the environmental advantages of PLA-based materials [8, 9]. In order to overcome these limitations, numerous reinforcements have been incorporated into PLA through different fabrication routes, including twin-screw extrusion, compression molding, solution casting, and FFF.

Studies have demonstrated that ceramic fillers such as hydroxyapatite and TiO_2, and boron nitride enhance thermal stability, wear resistance, and bioactivity of PLA-based composites [10, 11]. Natural fibers like flax, jute, and kenaf, as well as agro-industrial residues such as rice husk ash and wood flour, have also been introduced to reduce density while improving stiffness and biodegradation rates [12, 13]. Furthermore, the development of PLA composites via additive manufacturing has highlighted the influence of processing conditions and filler dispersion on mechanical and morphological performance [13-15]. Collectively, these investigations confirm that PLA composites can achieve superior functional properties, extending their use to biomedical devices, packaging, and lightweight structural applications [13, 16].

Within this context, hemp fibers have gained significant attention as a sustainable reinforcement for PLA due to their high cellulose content, low density, and availability as an agricultural by-product [17, 18]. Research has focused on enhancing fiber-matrix adhesion through alkali treatment, the incorporation of Poly(butylene adipate-co-terephthalate) (PBAT) and ethylene-methyl acrylate-glycidyl methacrylate (EGMA) terpolymer, optimizing fiber loading, and producing extrudable filaments for 3D printing [19-21]. Mechanical studies have reported that hemp addition improves tensile modulus and stiffness, although excessive fiber content may reduce elongation at break due to interfacial debonding [21]. Thermal analyses indicate improved stability and crystallinity, while morphological observations reveal the critical role of fiber dispersion and orientation. Recent works manufactured PLA-hemp composites through twin-screw extrusion, compression molding and additive manufacturing, confirming their versatility in both conventional and advanced processing techniques [19, 22, 23].

However, standard FFF printers have limited capacity to directly integrate continuous or long filaments, which has stimulated the development of alternative reinforcement strategies. Among existing approaches, co-extrusion has been widely employed to simultaneously feed matrix and fiber materials, producing continuous reinforcement and significantly higher tensile properties in flax/PLA composites [24]. Nevertheless, this technique requires complex hardware modification and still suffers from weak fiber-matrix interfacial bonding. Similarly, in-situ fiber placement, such as the in-nozzle impregnation of jute yarns [25], allows accurate alignment of fibers during deposition, but it is prone to interfacial defects when the process is interrupted and restarted, which restricts its flexibility. In contrast, the “layer-paused method” offers a simpler and more adaptable route, in which the printer is manually paused at a designated layer and natural fibers are inserted into pre-designed channels. Therefore, the layer-paused method may be considered a complementary and accessible approach within the current state of the art, offering a balance between simplicity and adaptability while addressing some of the limitations of co-extrusion and in-situ fiber placement techniques [26, 27].

In this study, a new approach for the fabrication of natural fiber-reinforced PLA composites was presented. Composite samples were produced using a layer-paused FFF method, in which the printing process was temporarily paused at predetermined layers and hemp fibers were manually inserted into pre-designed internal channels before resuming printing. The key novelty of this work is the implementation of a layer-paused fiber placement strategy, which provides a practical route for incorporating continuous natural fibers into the FFF process without the need for filament modification. By enabling controlled fiber orientation and direct fiber placement, this method addresses the inherent limitations of PLA in load-bearing applications and offers a sustainable pathway for improving the mechanical performance of additively manufactured composites. The mechanical properties were characterized through tensile testing, while morphological features and fracture mechanisms were examined using SEM analysis.

2. MATERIALS AND METHODS (MATERYAL VE METOD)

2.1. Materials (Malzemeler)

The materials utilized in this study were polylactic acid (PLA) filament and natural hemp fibers. The PLA filament was supplied by Flashforge (China), with a diameter of 1.75 mm and natural green color, commonly used in FFF due to its biodegradable nature and thermoplastic behavior [28]. The hemp fibers were uncoated and untreated, exhibiting a coarse surface texture and an average diameter of approximately 1 mm. Each fiber was cut slightly longer than the specimen length to ensure extension beyond both ends during testing. The use of hemp as a reinforcement material in PLA matrices has been reported to improve tensile and interfacial properties due to the natural fiber's high aspect ratio and mechanical interlocking capabilities [29]. The properties of the materials used were provided in Table 1.

2.2. Specimen Preparation (Numune Hazırlama)

Specimens were fabricated using a CCH X30 FFF 3D printer, which has a build volume of 300 × 200 × 250 mm. The geometry followed the guidelines of ASTM D3039 [33], which defines the shape and dimensions for uniaxial tensile testing of polymer composites. The geometry of the ASTM standard sample is shown in Figure 1.

A CAD model of the specimen was created in SolidWorks, and the fiber channels were embedded into the model prior to slicing. Specifically, five cylindrical channels with a diameter of approximately 1.3 mm were positioned symmetrically along the specimen width, located precisely at the mid-plane of the specimen thickness. These channels were spaced uniformly to ensure fiber distribution and were intended to allow precise manual fiber insertion during the paused printing process. This approach of designing embedded voids for fiber placement has been shown to facilitate improved positional control during hybrid 3D printing of continuous or short fibers [34].

The slicing process was conducted using Ultimaker Cura 5.4. A 0.4 mm brass nozzle and a layer height of 0.2 mm were used. The extrusion temperature was set to 210 °C, while the bed temperature was maintained at 60 °C [35]. The infill density was configured as 100%, using a linear pattern to maximize material continuity and mechanical stiffness. A print speed of 50 mm/s was applied uniformly. No adhesives, surface treatments, or support structures were used.

To insert hemp fibers into the PLA matrix, the print was programmed to pause at a layer height slightly above the mid-plane of the specimen thickness, approximately 1.5 mm from the bottom surface. This timing ensured that the pre-designed fiber channels were fully formed but not yet closed, allowing easy manual access for fiber insertion. At the paused layer, the print head was retracted to a safe position. Five hemp fibers were then manually placed into the cylindrical cavities, aligned in the longitudinal direction and spanning the entire gauge length with both ends protruding. Once the fibers were positioned, the printing process was resumed, depositing molten PLA on top of the inserted fibers to complete the embedding.

Table 1. Mechanical properties of used materials (Kullanılan malzemelerin mekanik özellikleri)

Property	**PLA** [30, 31]	**Hemp fiber** [32]
Density (g/cm3)	1.21-1.25	1.47-1.48
Melting temperature (°C)	150	-
Tensile strength (MPa)	21-60	550-900
Young's modulus (GPa)	0.35-3.5	70
Failure strain (%)	2.5-6	1.6-4.0

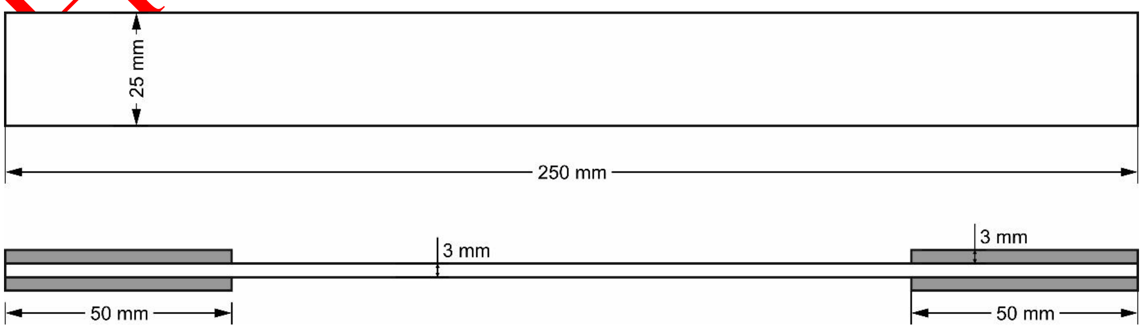

Figure 1. ASTM D3039 standard (ASTM D3039 standardı)

A visual representation of the CAD model, including both the top view and cross-sectional view, is shown in Figure 2. The cross-section further illustrates the rationale behind selecting a pause height just beyond the midpoint of the thickness, enabling access to the fiber cavities without damaging the print integrity. Such geometry-driven fiber embedding strategies have been used to achieve controlled reinforcement alignment in recent hybrid AM studies [34]. Figure 3 shows the printed test specimens, test specimens with tabs joined to them, and a cross-sectional view of the specimen.

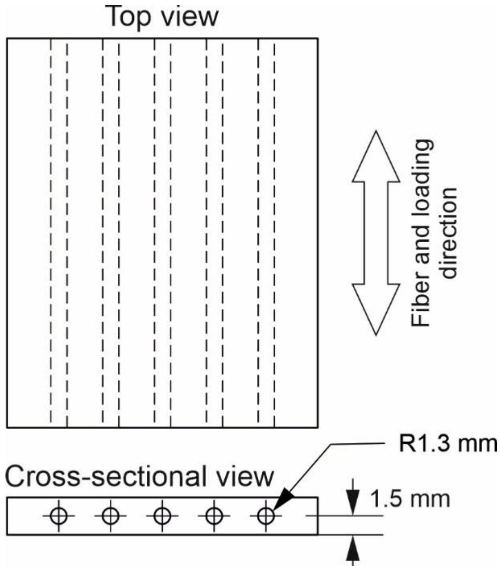

Figure 2. Top view and cross-sectional view of the fiber placed across the width of the specimen
(Numunenin genişliği boyunca yerleştirilen fiberin üstten görünümü ve kesit görünümü)

2.3. Experimental Methods (Deneysel Yöntemler)

Tensile tests were conducted according to ASTM D3039 using a Shimadzu AGS-X (50 kN) universal testing machine equipped (Figure 4). PLA end-tabs were bonded to both ends of each specimen to minimize grip-induced damage and ensure uniform load transfer. Tests were performed at room temperature. The crosshead speed was set to 2 mm/min. For each configuration, at least three specimens were tested to ensure statistical reliability. Load-displacement data were recorded and analyzed to evaluate the influence of fiber addition on tensile strength and stiffness.

Post-failure analysis was carried out using SEM analysis in order to investigate the fiber-matrix interface, failure mechanisms, and internal damage morphology at higher resolution. Fracture surfaces were coated with a thin layer of gold using a sputter coater to ensure conductivity and then imaged using a Carl Zeiss Ultra Plus Gemini Fesem.

Figure 4. Tensile test (Çekme testi)

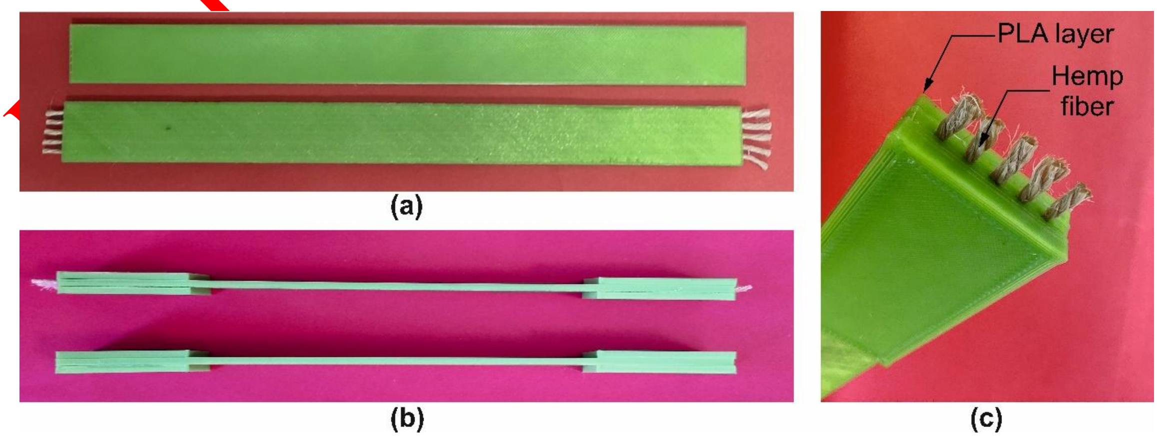

Figure 3. PLA and PLA-hemp composite specimens: (a) top view, (b) side view, (c) cross-sectional view
(PLA ve PLA-kenevir kompozit numuneler: (a) üstten görünüm, (b) yandan görünüm, (c) kesit görünümü)

3. RESULTS AND DISCUSSION (SONUÇLAR VE TARTIŞMA)

3.1. Mechanical Test Results (Mekanik Test Sonuçları)

The tensile test results revealed significant differences between pure PLA samples and hemp fiber-reinforced PLA composite samples. As shown in Figure 5, the force-displacement curves indicate that PLA-hemp composite samples can withstand higher tensile loads compared to pure PLA. This can be attributed to the high aspect ratio and mechanical interlocking properties of hemp fibers, which enable effective transfer of stress from the matrix to the fiber [36, 37]. The maximum tensile force of PLA-hemp composite samples increased by approximately 30% compared to pure PLA (1545 N to 1999 N), whereas the displacement at maximum force decreased by 8.7% (7.8 mm to 7.2 mm). These results indicate that the composite structure has improved in terms of strength and stiffness, however, ductility has decreased to some extent. Since an extensometer was not employed, the tensile modulus could not be directly calculated however, the initial slopes of the force-displacement curves provide comparative insights into stiffness. The PLA-hemp composites exhibit a steeper initial slope than neat PLA, which reflects enhanced rigidity due to fiber reinforcement. From a molecular perspective, neat PLA samples demonstrate localized necking prior to fracture, a phenomenon related to polymer chain alignment under tensile stress. By contrast, the addition of hemp fibers constrains chain mobility, thereby suppressing pronounced necking and resulting in a stiffer but less ductile response. Similar findings have been reported in the literature, where insufficient fiber-matrix adhesion led to increased necking, whereas surface treatments and optimized bonding reduced necking and improved stability [38, 39]. Furthermore, it has been shown that reinforcement with natural fibers or nanofillers can effectively suppress necking by limiting molecular chain slippage, enhancing modulus, and promoting more uniform stress distribution [40, 41].

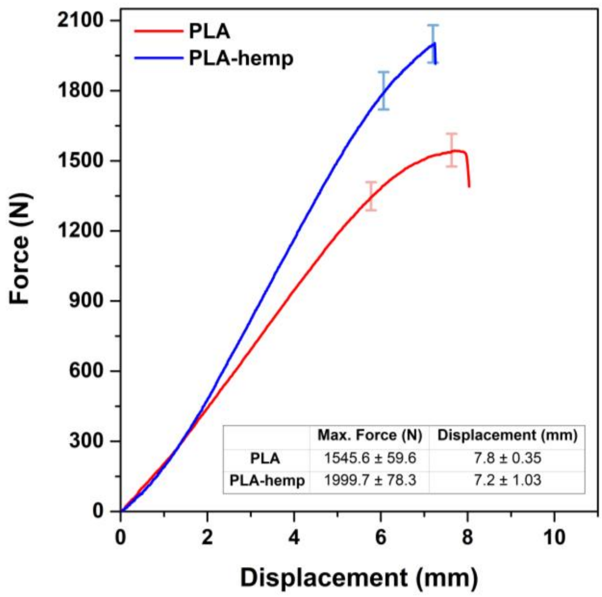

Figure 5. Tensile force-deformation curves of pure PLA and PLA-hemp composite specimens (Saf PLA ve PLA-kenevir kompozit numunelerinin çekme kuvveti-deformasyon eğrileri)

Figure 6 shows a comparison of the fracture surfaces obtained after the tensile test. The fracture surface of the pure PLA sample at the top is smooth, shiny, and seamless. This indicates that PLA fractures suddenly and brittly. In the PLA-hemp composite sample at the bottom, a rougher and fibrous fracture surface is noticeable. On these surfaces, it is clearly observed that the fibers are not broken in the middle but are pulled out from the matrix. This indicates that the fibers contribute to the load-bearing capacity but separate without breaking due to insufficient adhesion at the interface [42, 43]. However, the contribution of this type of pull-out mechanism to the composite structure is not negative. The literature reports that the pull-out mechanism contributes to energy absorption during fracture, thereby delaying crack propagation and increasing the toughness of the composite [44]. In conclusion, the fiber reinforcement observed in this study not only increased mechanical strength but also transformed the fracture behavior into a more complex and energy-absorbing structure.

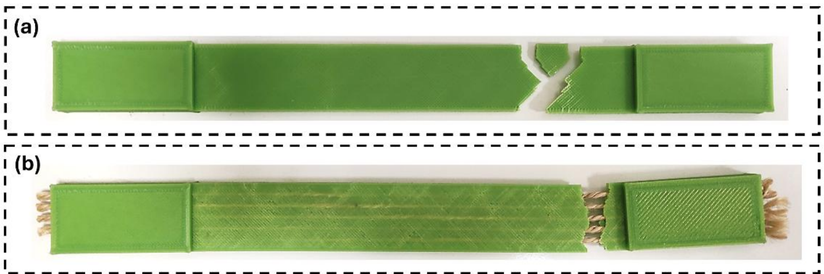

Figure 6. Fracture surfaces of tensile specimens: pure PLA (top) and PLA-hemp composite (bottom) (Çekme numunelerinin kırılma yüzeyleri: saf PLA (üstte) ve PLA-kenevir kompoziti (altta))

However, if the adhesion force at the fiber-matrix interface is too high, fiber movement may be restricted and the pull-out effect may decrease, which can reduce ductility and increase brittleness [45, 46].

3.2. SEM Analysis (SEM Analizi)

To investigate the fracture behavior of the materials and the fiber-matrix interface interaction in greater detail, SEM analyses were performed on the samples before and after the tensile test. Figure 8 presents the surface of the untested PLA-hemp sample (a-b), the fracture surface of the pure PLA sample after the tensile test (c-d), and the fracture surface of the PLA-hemp composite sample (e-f). In the untested composite (Figure 8a), hemp fibers appear evenly distributed on the PLA surface, indicating that the layer pause method applied during production was effective. A closer view (Figure 8b) shows the characteristic layer lines of the PLA matrix, where uniform deposition and strong interlayer bonding confirm that the printing parameters were appropriately selected. In contrast, the fracture surfaces of pure PLA (Figures 8c-d) exhibit smooth morphology with distinct and sharp crack lines, characteristic of brittle fracture behavior.

The fracture surfaces of the PLA-hemp composites (Figures 8e-f) reveal fiber ends separated from the matrix, pull-out marks, and interfacial voids. Because the fibers did not completely fracture during tensile testing, they were cut prior to SEM analysis; nevertheless, clear evidence of fiber pull-out indicates that interfacial adhesion was the primary site of failure. This observation is consistent with Xu et al. [42], who noted that weak fiber-matrix adhesion promotes pull-out and interfacial debonding before fiber rupture. Although pull-out reflects limited bonding, it can contribute positively to fracture resistance by dissipating energy and delaying crack propagation, thereby enhancing toughness [44]. Conversely, excessively strong interfacial bonds restrict fiber mobility, reducing ductility and leading to brittle failure, as reported by Ketata et al. [43] and Liu et al. [46].

SEM findings in this study therefore suggest that PLA and hemp fibers form a limited interfacial bond. During tensile testing, fibers predominantly slid out of the matrix rather than fractured, highlighting weak adhesion at the interface. While some voids may have resulted from cutting during sample preparation, the presence of fiber pull-out strongly supports this interpretation. A plausible explanation is the incompatibility between the hydrophilic nature of hemp fibers and the hydrophobic character of PLA, which restricts chemical bonding and promotes interfacial separation [47, 48]. At the same time, the rough surface morphology of hemp fibers enables partial mechanical interlocking and stress transfer, in agreement with studies emphasizing the importance of fiber orientation and surface topography in interfacial adhesion [49]. Consequently, the limited bonding observed here explains the increase in strength and stiffness coupled with a reduction in ductility.

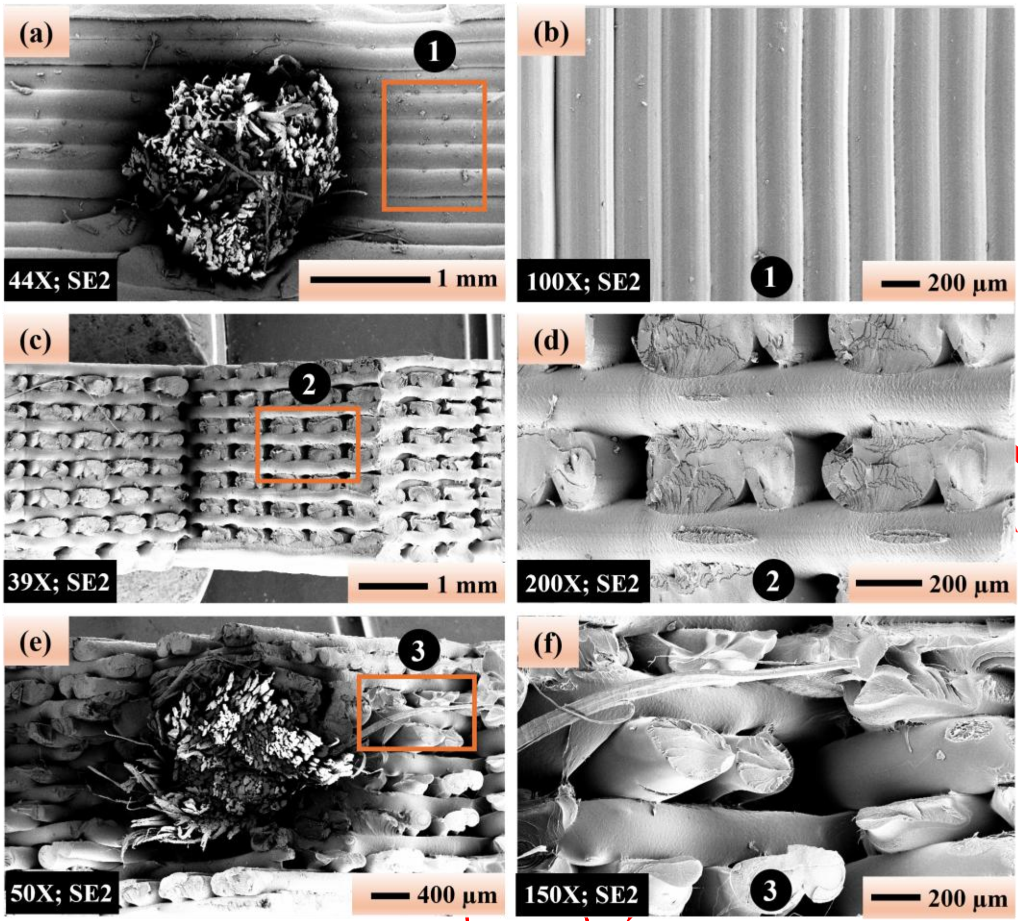

Figure 7. SEM images of PLA and PLA-hemp specimens: (a-b) Untested PLA-hemp surface and its magnified view; (c-d) Fracture surface of pure PLA after tensile test and magnified view; (e-f) Fracture surface of PLA-hemp composite after tensile test and magnified view (PLA ve PLA-kenevir numunelerinin SEM görüntüleri: (a-b) Test edilmemiş PLA-kenevir yüzeyi ve büyütülmüş görünümü; (c-d) Çekme testi ve büyütülmüş görünümden sonra saf PLA'nın kırılma yüzeyi; (e-f) Çekme testi ve büyütülmüş görünümden sonra PLA-kenevir kompozitinin kırılma yüzeyi)

4. CONCLUSIONS (SONUÇLAR)

In this study, PLA-hemp composites were produced through a layer-paused FFF technique, in which natural fibers were manually inserted into pre-designed internal channels during the printing process. This method demonstrated that fiber reinforcement can be integrated into polymer matrices without additional hardware modifications, offering a practical route for the development of sustainable composites.

Mechanical characterization indicated that the incorporation of hemp fibers increased the maximum tensile force from 1545 N to 1999 N, corresponding to an improvement of approximately 30%. In contrast, the displacement at maximum force decreased from 7.8 mm to 7.2 mm, representing a reduction of about 7.7%. These findings demonstrate that natural fiber addition enhances the load-bearing capacity of PLA while slightly limiting its deformability, thereby adjusting the overall balance between strength and ductility.

Fractographic examinations revealed distinct failure behaviors between the materials. Pure PLA fractured abruptly and brittlely, whereas PLA-hemp composites exhibited more complex mechanisms, including fiber pull-out and interfacial separation. SEM observations confirmed that fibers tended to slide out of the matrix without significant breakage, evidencing weak adhesion at the interface but also contributing to energy dissipation during fracture.

Collectively, these findings indicate that PLA-hemp composites hold potential for applications in areas where moderate mechanical properties and environmental compatibility are required. Nevertheless, limitations such as fiber-matrix adhesion, moisture sensitivity, and fiber distribution remain critical challenges. Future studies should therefore focus on improving interfacial bonding through surface treatments, assessing long-term durability, and refining printing strategies for consistent fiber placement. With such advancements, layer-paused FFF composites may contribute more broadly to the utilization of natural fiber-reinforced PLA in biomedical, packaging, and lightweight structural applications.

DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Muhammet Mevlüt KARACA*:** He conducted the experiments, analyzed the results and performed the writing process.

Deneyleri yapmış, sonuçlarını analiz etmiş ve maklenin yazım işlemini gerçekleştirmiştir.

***Fatih Huzeyfe ÖZTÜRK*:** He conducted the experiments, analyzed the results and performed the writing process.

Deneyleri yapmış, sonuçlarını analiz etmiş ve maklenin yazım işlemini gerçekleştirmiştir.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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