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Araştırma Makalesi / Research Article

Mechanical and Thermal Characterization of Basalt and Hemp Fiber Reinforced Polylactide (PLA) Based Hybrid Bio-Composites

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Abstract

Developing sustainable and eco-composites using matrix polymers and natural reinforcements from renewable resources or agro wastes has gained significant attention recently. In this context, biodegradable polylactide (PLA) polymer, basalt fiber (BF) - recognized as one of the green materials of this century - and hemp fiber (HF), which is increasingly valued globally and nationally, are promising candidates for inclusion in such composites. This study aims to create PLA-based hybrid biocomposites reinforced with BF and HF, investigating their mechanical, thermal, and morphological properties. The hybrid bio-composites with varying BF and HF contents (5-20%) were fabricated via melt mixing and subsequently shaped through injection molding by relevant test standards. The mechanical properties of the composites were assessed through tensile and hardness tests, thermal properties through the TGA, and morphological features through the SEM analysis. While adding 10% BF and HF in PLA showed the hybrid effect, a considerable improvement in mechanical properties was recorded, especially with a 15% increase in tensile strength. This research will optimize fiber ratios and processing parameters to enhance PLA bio composites' mechanical and thermal performance, thereby expanding the potential functional applications of PLA biopolymers.

Keywords: Hybrid Bio-composite, Polylactide, Basalt Fiber, Hemp Fiber, Mechanical Characterization, Thermal Characterization.

Bazalt ve Kenevir Elyaf Takviyeli Polilaktid (PLA) Esaslı Hibrit Biyo-Kompozitlerin Mekanik ve Termal Karakterizasyonu

Öz

Yenilenebilir kaynaklardan veya tarımsal atıklardan elde edilen matris polimerler ve doğal takviyeler kullanılarak sürdürülebilir ve eko-kompozitlerin geliştirilmesi son yıllarda büyük ilgi görmektedir. Bu bağlamda, biyolojik olarak parçalanabilen polilaktid (PLA) polimeri, bu yüzyılın yeşil malzemelerinden biri olarak kabul edilen bazalt lifi (BF) ve küresel ve ulusal olarak giderek daha fazla değerlenen kenevir lifi (HF), bu tür kompozitlere dâhil edilmek için umut verici adaylardır. Bu çalışma, BF ve HF ile güçlendirilmiş PLA bazlı hibrit biyokompozitler oluşturmayı ve bunların mekanik, termal ve morfolojik özelliklerini incelemeyi amaçlamaktadır. Değişken BF ve HF içeriklerine (%5-20) sahip hibrit biyokompozitler eriyik karıştırma yoluyla üretilmiş ve ardından ilgili test standartlarına göre enjeksiyon kalıplama yoluyla şekillendirilmiştir. Kompozitlerin mekanik özellikleri çekme ve sertlik testleriyle, termal özellikleri TGA ile ve morfolojik özellikleri SEM analiziyle değerlendirilmiştir. PLA'ya ağırlıkça %10 BF ve HF eklenmesi hibrit etki gösterirken, özellikle çekme mukavemetinde %15'lik bir artışla mekanik özelliklerde önemli bir iyileşme kaydedilmiştir. Bu araştırma, PLA biyokompozitlerinin mekanik ve termal performansını artırmak için lif oranlarını ve işleme parametrelerini optimize edecek ve böylece PLA biyopolimerlerinin potansiyel fonksiyonel uygulamalarını genişletecektir.

Anahtar Kelimeler: Hibrit biyo-kompozit, Polilaktid, Bazalt elyaf, Kenevir elyaf, Mekanik karakterizasyon, Termal karakterizasyon.

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1. Introduction

Replacing petroleum-based products with sustainable materials derived from renewable resources has garnered significant attention in recent years due to the environmental challenges posed by non-degradable and non-recyclable composites. Traditional petroleum-based composites persist in the environment, leading to substantial waste management issues. Researchers and manufacturers are increasingly focusing on eco-friendly and biodegradable alternatives, utilizing polymers and natural fillers obtained from renewable resources or agricultural byproducts (Dong, 2017; Mann et al., 2018; Saheb and Jog, 1999; Sathishkumar et al., 2014; Soykan and Kaya, 2023).

Among bio-based polymers, polylactic acid (PLA) stands out as a widely recognized and extensively studied material due to its biodegradability, biocompatibility, affordability, and ease of processing. Despite these advantages, PLA exhibits inherent mechanical and thermal limitations that restrict its broader application. To address these shortcomings, considerable research efforts have been directed toward developing PLA-based composite structures reinforced with natural fibers, aiming to enhance the polymer’s performance characteristics (Aliotta et al., 2019; Bajpai et al., 2014; Celik et al., 2025; Çevik Elen et al., 2025; Ilyas et al., 2022; Murariu and Dubois, 2016; Özsoy and Sancak, 2024; Siakeng et al., 2019; Ucpinar et al., 2025).

Basalt fiber (BF), derived from volcanic rock, represents a promising reinforcement material due to its superior mechanical and thermal properties, as well as its classification as a natural mineral fiber. BF offers notable advantages over traditional reinforcements such as glass and carbon fibers, including higher thermal conductivity, excellent chemical stability, and greater corrosion and thermal degradation resistance. These properties, combined with its cost-effectiveness, have established BF as a viable material for applications in the construction, automotive, and aerospace industries (Dincer et al., 2024; Fiore et al., 2015; Gur’ev et al., 2001; Plappert et al., 2020; Sang et al., 2019; Selvaraj et al., 2022).

Hemp fiber (HF), on the other hand, is increasingly recognized for its role in the bioeconomy due to its mechanical strength, biodegradability, and rapid renewability. Hemp cultivation is environmentally friendly, requiring minimal pesticides and fertilizers, while its fibers demonstrate high tensile strength, low density, and excellent thermal properties. The versatility of hemp, along with its alignment with sustainable development goals, has positioned it as an attractive material for developing green composites (Ayyampilli and Suresh, 2025; Both et al., 2021; Celik et al., 2025; Çevik Elen et al., 2025; Özsoy and Sancak, 2024; Soykan and Kaya, 2023; Ucpinar et al., 2025; Yorseng et al., 2024; Zimniewska, 2022).

As a result of a comprehensive literature search, only one study on a hybrid composite system containing basalt fiber, hemp fiber, and PLA was found. Deng et al. produced hybrid eco-composites by obtaining a hemp fiber PLA blend felt and combining it with a continuous basalt fiber-containing BF prepreg with a surface-impregnated silanated PLA. Their investigation evaluated the mechanical performance characteristics of these composites fabricated in multi-layered composites via hot-pressing methodology (Deng et al., 2021). An extensive literature review revealed a significant knowledge gap in the field, with only one investigation examining hybrid composite systems incorporating BF, HF, and PLA. Notably, the existing literature demonstrates a pronounced deficiency in studies investigating the fabrication of PLA-based composites reinforced with short BF and HF through melt blending and injection molding processes. The presented study addresses this gap by developing PLA-based eco-friendly composites reinforced with BF and HF, emphasizing the hybrid effect of these fibers on mechanical, thermal, and morphological properties. The investigation emphasizes the synergistic hybrid effects of these reinforcing fibers on the mechanical, thermal, and morphological characteristics of the resulting composite systems. Characterizing the PLA and relevant composites involves tensile and hardness tests for mechanical properties, the TGA for thermal stability, and SEM analysis for morphological evaluation. The findings aim to optimize fiber ratios and processing parameters to produce high-performance biocomposites, demonstrating the potential of PLA as a sustainable material for various industrial applications.

2. Materials and Methods

2.1. Materials

This study utilized polylactic acid (PLA) as the matrix material under the trade name of Ingeo Biopolymer, sourced from NatureWorks LLC. Chopped basalt fibers (BF) with a length of 6 mm were obtained from Tila Composite, with the manufacturer specifying a fiber diameter range of 13 – 20 µm for industrially silane-coated BF. To eliminate the surface coating, the BF samples underwent heat treatment in a furnace at 500°C for 2 hours. As another reinforcement material, commercially available hemp fibers (HF) from Biokenevir company (Samsun, Türkiye) were used with a length of 3 mm.

2.2. Research Methodology

The research methodology presented in Figure 1 encompasses developing and characterizing hybrid PLA biocomposites reinforced with BF and HFs. The hybrid PLA biocomposites were fabricated through melt mixing and injection molding, considering PLA's thermal and moisture sensitivity (Eselini et al., 2020; Tayfun et al., 2023). The manufacturing process involved initial preparation of fiber blends (5-20 wt.%) with PLA, followed by drying at 80°C for 12 hours. The dried mixtures were subjected to melt mixing in a micro-compounder (210°C, 5 minutes, 100 rpm), pelletized, and injection molded (210°C barrel, 55°C mold temperature). These production methods are the most preferred techniques for fiber-reinforced thermoplastic composites. The conditions of the production process and the methodology applied were determined by considering the process conditions and temperature parameters used in producing and molding composites with similar content in the literature (Eselini et al., 2020; Tayfun et al., 2023).

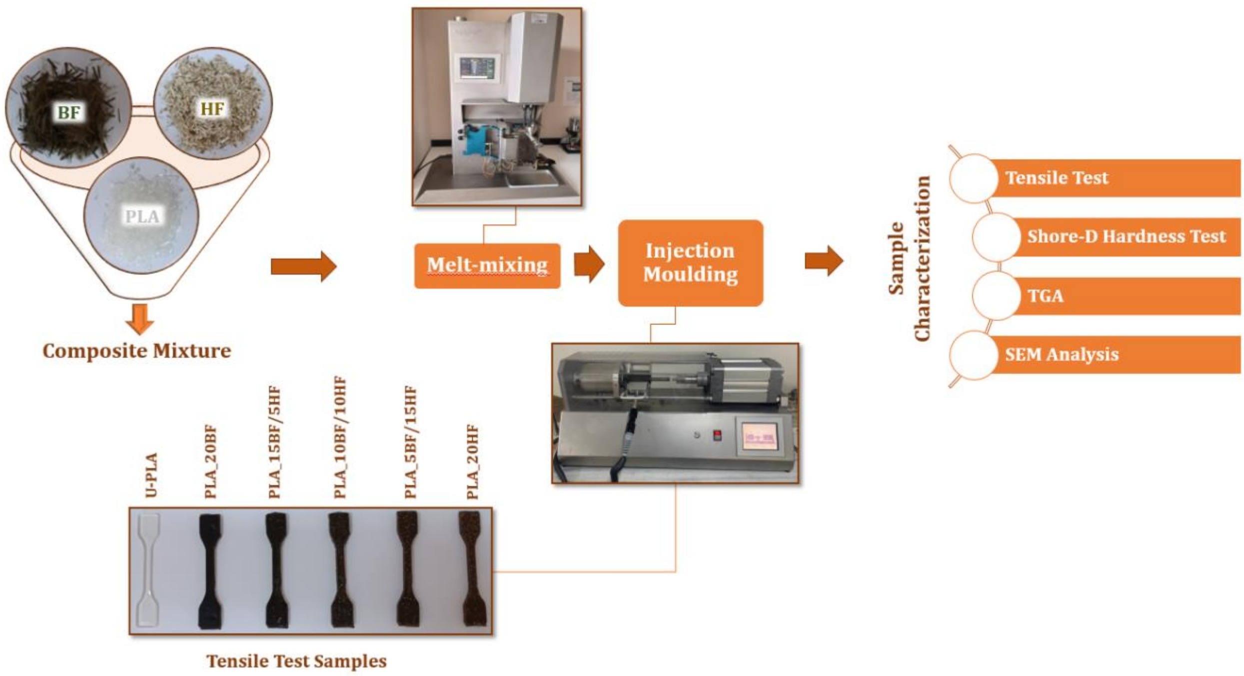

Figure 1. The methodology of the study.

2.3. Material Characterization

Material characterization involved mechanical and thermal analyses of unfilled PLA and the relevant composite specimens. Tensile tests were performed following ASTM D-638 using a mechanical testing machine, where five specimens of each mixture were tested to determine the average tensile strength, elongation, and tensile modulus (ASTM-D638, 1993). The load cell and crosshead speed were 5 kN and 5 cm/min, respectively. Shore hardness was measured using a digital Shore hardness tester following ISO 48-4, with ten measurements taken per mixture (ISO-48-4, 2018). The TGA (from 20 to 600°C, heating rate: 10°C/min, and flow rate: 50 ml/min) was conducted to assess the thermal stability of the PLA matrix and the relevant composite in a nitrogen atmosphere (Eselini et al., 2020). Finally, the SEM was used to analyze the fracture surfaces of the tensile-tested specimens, providing insights into the fiber-matrix interface and failure mechanisms (Deng et al., 2021; Eselini et al., 2020).

3. Findings and Discussion

3.1. Morphological Analysis

The SEM micrographs of tensile-fractured surfaces of the PLA-based composites at magnifications of 250x and 1000x are presented in Figure 2. As can be seen from the SEM images, it is observed that the fibers added into PLA show a homogeneous distribution, and these added fibers cause the PLA to undergo a brittle fracture. The PLA_20BF composite exhibits significant fiber pull-out phenomena, evidenced by numerous black holes and standing BFs, indicating moderate interfacial adhesion between the BFs and PLA matrix. Fiber pull-outs and the black holes left behind by them are seen in all composites, especially in composites containing BFs. The difference here is the number and length of fiber pull-outs. This ratio is lower in composites containing hemp fiber. The presence of hemp fibers modifies the fracture behavior, showing improved fiber-matrix adhesion compared to pure basalt fiber composites. In PLA_5BF/15HF and PLA_10BF/10HF composites, fewer fiber pull-out instances are observed, suggesting enhanced interfacial bonding. Notably, the PLA_20HF sample displays the most cohesive fracture surface among all compositions. Hemp fibers appear well-embedded within the PLA matrix, with minimal fiber pull-out and significant matrix deformation around the fibers, indicating better interfacial bonding (Li et al., 2007; Song et al., 2013). These morphological observations directly correlate with the mechanical performance, particularly the enhanced tensile properties in hemp fiber-rich compositions.

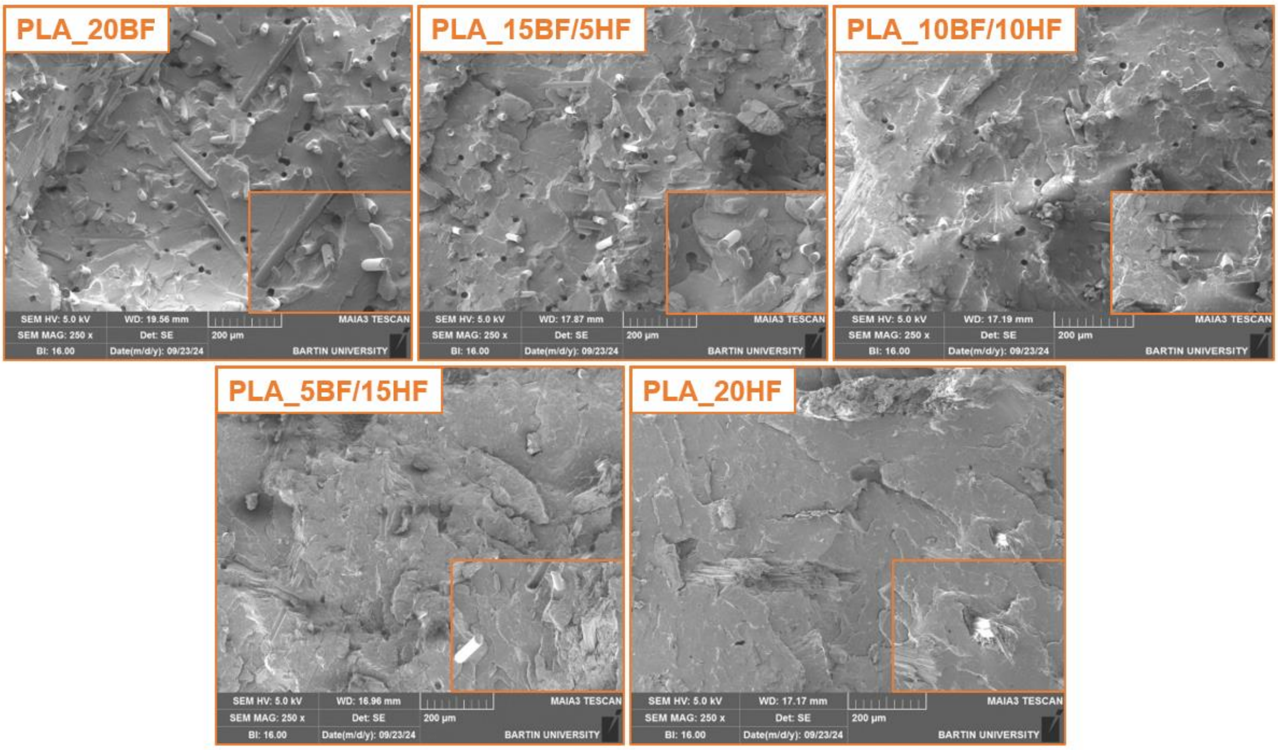

Figure 2. SEM images of the composites at the magnification of 250x and 1000x (bottom right corner).

3.2. Mechanical Characterization of the Composites

The mechanical properties of unfilled PLA and its composites, summarized in Table 1, demonstrate fiber type and content variations. Unfilled PLA exhibits a baseline tensile strength of 54.0 MPa with 12.5% elongation at break, characteristic of its semi-crystalline nature. Incorporating 20 wt.% basalt fiber (PLA_20BF) slightly improves the tensile strength to 55.9 MPa (4% increase) while substantially reducing elongation to 5.8%, reflecting the rigid nature of basalt fibers. In contrast, 20 wt.% hemp fiber addition (PLA_20HF) achieves a higher tensile strength of 58.2 MPa (8% increase) while maintaining better elongation (9.4%), suggesting more effective stress transfer. This is mainly due to the high strength and modulus, the uniform dispersion, and the good wetting of the hemp fibers (Song et al., 2013). The hybrid compositions exhibit synergistic effects, with PLA_10BF/10HF achieving optimal mechanical performance (61.9 MPa tensile strength, 15% increase). When three different basalt/hemp fiber blend ratios were examined, it was determined that the highest increase in tensile strength was obtained by adding 10% BF and HFs. However, a slight increase was observed in the other two blend ratios, so the hybridization effect was achieved significantly in this sample. The Young's modulus showed remarkable improvements, with PLA_20BF and PLA_20HF reaching 6.5 GPa (260% increase) and 4.2 GPa (68% increase) respectively. Such high increases are due to BF and HF inherently having a much higher modulus than pure PLA (Dixit et al., 2017; Lopresto et al., 2011; Öztürk, 2005). This effect is also evident in hybrid composites.

Table 1. The mechanical performance data of the unfilled PLA and the relevant composites.

Code of Specimens	Tensile Strength (MPa)	Elongation at Break (%)	Tensile Modulus (GPa)	Hardness (ShoreD)
U-PLA	54.0 ± 0.6	12.5 ± 0.4	2.5 ± 0.1	85.0 ± 0.1
PLA_20BF	55.9 ± 0.9	5.8 ± 0.7	6.5 ± 0.2	88.0 ± 0.2
PLA_20HF	58.2 ± 1.2	9.4 ± 0.2	4.2 ± 0.2	86.0 ± 0.2
PLA_5BF/15HF	55.8 ± 0.7	6.1 ± 0.3	6.1 ± 0.3	85.5 ± 0.2
PLA_10BF/10HF	61.9 ± 0.8	8.7 ± 0.1	4.9 ± 0.2	87.0 ± 0.1
PLA_15BF/5HF	56.4 ± 0.5	6.4 ± 0.3	5.8 ± 0.1	87.5 ± 0.2

The Shore D hardness measurements reveal complementary trends in the mechanical behavior of the composites. The unfilled PLA has a baseline hardness of 85.0, which increases to 88.0 and 86.0 with 20 wt.% incorporation of more rigid BF and HFs, respectively. The hybrid composites demonstrate enhanced hardness values, with PLA_10BF/10HF and PLA_15BF/5HF showing the most significant improvements. These hardness improvements correlate with the tensile properties, particularly in hybrid compositions. This suggests effective stress transfer and interfacial adhesion between the fiber reinforcements and PLA matrix. Considering all Shore hardness values, it was observed that BF and HF additions to PLA significantly contribute to the hardness of PLA. The consistent enhancement in tensile and hardness properties indicates successful reinforcement across multiple mechanical parameters.

3.3. Thermal Characterization of the Composites

The thermal stability and degradation behavior of unfilled PLA and its composites were evaluated through thermogravimetric analysis (TGA), with results in Table 2 and corresponding TG/DTG curves shown in Figure 3. U_PLA shows single-step thermal degradation with maximum degradation temperature (T_{max}) at 360 °C, completely decomposing around 370 °C. As seen from the BF values in Table 2, BF maintains its structural integrity up to 600 °C (Bhat et al., 2017). Incorporating 20 wt.% basalt fiber (PLA_20BF) slightly reduces T_{max} of U_PLA to 354 °C. However, it significantly enhances thermal stability, as evidenced by the 18.1 wt.% char yield, which is attributed to the non-combustible nature of basalt fibers (Jagadeesh et al., 2024; Singha, 2012). The HF is subjected to thermal degradation at very low temperatures ($T_{5\%}$: 62 °C), mainly due to moisture removal from the fiber body, and the mass loss versus temperature reached a maximum at 346 °C.

The PLA_20HF composition shows lower thermal stability with T_{max} at 338 °C and 7.4 wt.% char yield, reflecting the temperature-sensitive nature of natural fibers. This behavior refers to the cellulosic structure of hemp fibers (Seçinti Klopf, 2025), which begin to degrade at much lower temperatures than inorganic basalt fibers.

Table 2. The TGA data of the unfilled PLA and the relevant composites.

Code of Specimens	$T_{5\%}$ (°C)	T_{max} (°C)	Char Yield (%)
U-PLA	317	360	-
BF	> 600	> 600	99
HF	62	346	15.2
PLA_20BF	297	354	18.1
PLA_20HF	277	338	7.4
PLA_5BF/15HF	282	348	6.7
PLA_10BF/10HF	291	337	10.0
PLA_15BF/5HF	292	329	11.5

The hybrid composites demonstrate intermediate thermal behavior, with degradation characteristics proportional to the relative fiber content. In terms of thermal stability, the PLA_10BF/10HF sample has the most favorable values (T_{max} = 337 °C, 10.0 wt.% char yield) among hybrid formulations, followed by the PLA_15BF/5HF sample with the values of T_{max} = 329 °C, 11.5 wt.% char yield. This suggests that higher basalt fiber content in hybrid compositions effectively compensates for the lower thermal stability of hemp fibers while maintaining the benefits of natural fiber incorporation. The thermal stability parameters, including maximum degradation temperature and char yield, directly correlate with the relative proportions of basalt and hemp fibers in the hybrid composites.

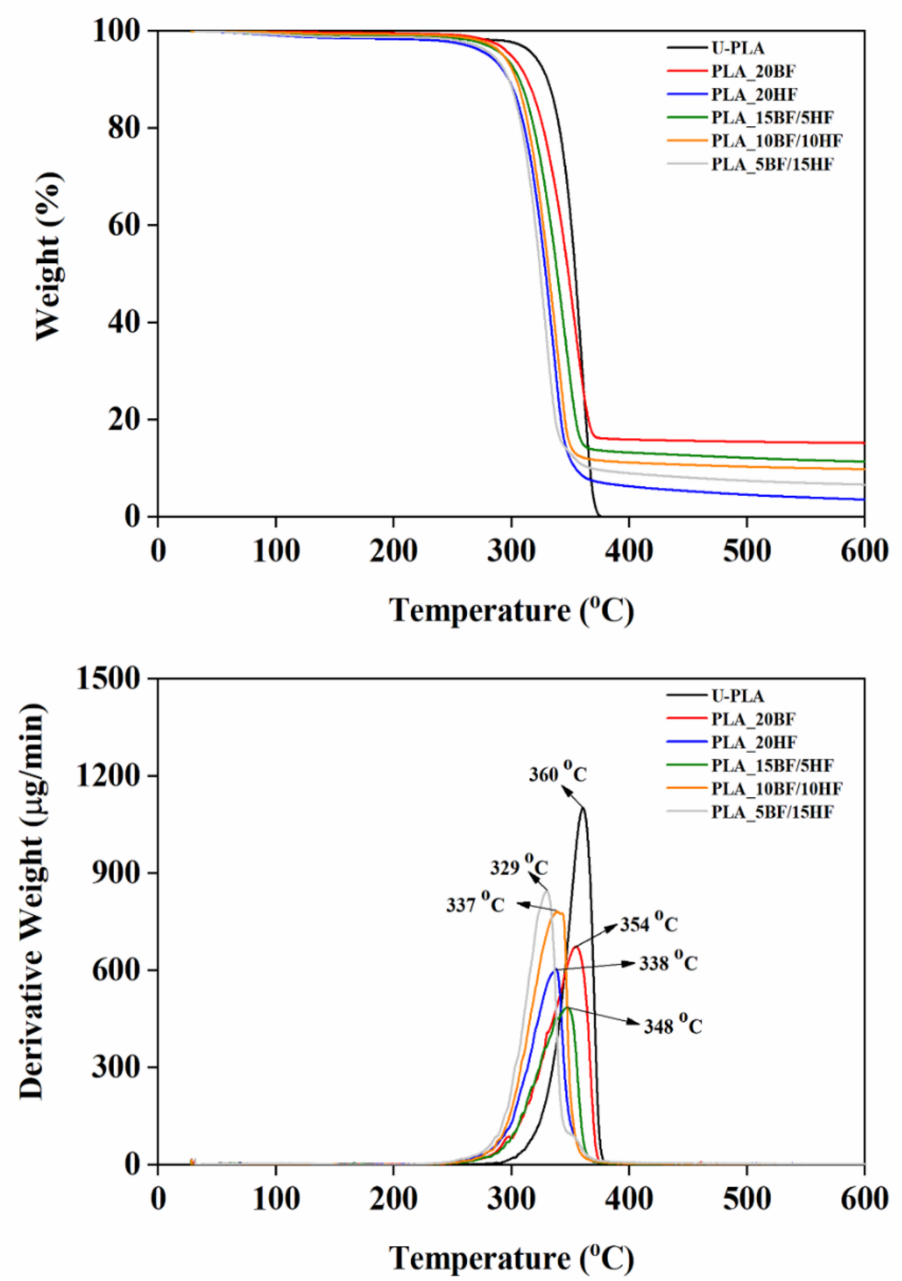

Figure 3. TG/DTG curves of the U-PLA matrix and the relevant composites.

4. Conclusions and Recommendations

This study proposed the development and characterization via mechanical, thermal, and morphological approaches of environmentally friendly PLA-based hybrid composites reinforced with basalt and hemp fibers. The hybrid effect of basalt and hemp fiber reinforcements on the mechanical and thermal performance of PLA-based hybrid eco-composites is studied. Tensile and Shore D hardness tests, thermogravimetric analysis (TGA), and scanning electron microscopy (SEM) analysis are reported. The incorporation of fibers significantly enhances the mechanical performance of PLA composites (from ↑%4 to ↑%15). Most notably, PLA_20BF exhibits a remarkable 260% increase in

Young's modulus (6.5 GPa) compared to unfilled PLA (2.5 GPa), while the hybrid composition PLA_10BF/10HF demonstrates optimal tensile performance (61.9 MPa) with a 15% increase in strength. Shore hardness measurements reveal substantial improvements (from 0.5 to 3.0) across all hybrid compositions, with PLA_10BF/10HF (↑2.0) and PLA_15BF/5HF (↑2.5) showing the most significant enhancements, indicating successful stress transfer between the fiber reinforcements and matrix. Morphological analysis via the SEM confirms homogeneous fiber distribution throughout the PLA matrix, though with characteristic brittle fracture behavior. The interface analysis reveals better adhesion in hemp fiber-rich compositions compared to basalt-dominant samples, suggesting the potential for further interface optimization. Thermal stability studies demonstrate that while unfilled PLA exhibits maximum degradation at 360°C, the incorporation of basalt fibers enhanced char yield (18.1 wt.% for PLA_20BF), indicating improved thermal stability. The hybrid composites show a synergistic combination of properties, with thermal degradation characteristics proportional to the relative fiber content. Considering the overall results, it is determined that the composite content presenting the most favorable hybrid effect is PLA-based composites containing 10 wt% BF and HF. These findings establish the potential of basalt/hemp fiber hybrid systems in developing high-performance, environmentally sustainable PLA composites with mechanical properties effectively tailored through fiber ratio optimization. Future research should focus on different fiber length ratios, and orientation effects could further optimize mechanical properties. Additionally, studies on these hybrid composites' biodegradability and long-term environmental impact would be valuable for sustainable applications.

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Authors' Contributions

Kaan Odabaş: investigation, visualization, writing–original draft, and editing, **Çağrıalp Arslan:** supervision, conceptualization, methodology, writing–review, and editing.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics.

References

Aliotta, L., Gigante, V., Coltelli, M.-B., Cinelli, P., Lazzeri, A., and Seggiani, M. (2019). Thermo-mechanical properties of PLA/short flax fiber biocomposites. *Applied Sciences*, *9*(18), 3797.

ASTM D638: 1993. Standard test method for tensile properties of plastics., American Society for Testing and Materials, USA.

Ayyampilli, S. P., and Suresh, R. (2025). Study on mechanical and flammability properties of natural fibre polymer composites. *Green Materials*, 1-11.

Bajpai, P. K., Singh, I., and Madaan, J. (2014). Development and characterization of PLA-based green composites:A review. *Journal of Thermoplastic Composite Materials*, *27*(1), 52-81.

Bhat, T., Fortomaris, D., Kandare, E., and Mouritz, A. P. (2017). Properties of thermally recycled basalt fibres and basalt fibre composites. *Journal of Materials Science*, *53*(3), 1933-1944.

Both, A. K., Helle, M. A., Madireddy, G., and Cheung, C. L. (2021). Green chemical approach to fabricate hemp fiber composites for making sustainable hydroponic growth media. *ACS Agricultural Science & Technology*, *1*(5), 499-506.

Celik, E., Uysal, M., Gumus, O. Y., and Tasdemir, C. (2025). 3D-Printed Biocomposites from Hemp Fibers Reinforced Polylactic Acid: Thermal, Morphology, and Mechanical Performance. *BioResources*, *20*(1).

Çevik Elen, N., Yıldırım, M., and Kanbur, Y. (2025). Examining the mechanical and biodegradable characteristics of hemp fiber added PLA bio-composites with various modifications. *Journal of Thermoplastic Composite Materials*, 08927057251316234.

Deng, H., Wei, X., Wang, C., Yang, J., and Li, Z. (2021). Effects of cryogenic treatment and interface modifications of basalt fibre on the mechanical properties of hybrid fibre-reinforced composites. *e-Polymers*, *21*, 625–635.

Dincer, U., Karsli, N. G., Sahin, T., and Yilmaz, T. (2024). Analysis of the effect of boric acid and compatibilizer addition to polylactic acid/basalt fiber composites. *Polymer Composites*, *45*(16), 15005-15019.

Dixit, S., Goel, R., Dubey, A., Shivhare, P. R., and Bhalavi, T. (2017). Natural Fibre Reinforced Polymer Composite Materials - A Review. *Polymers from Renewable Resources*, *8*(2), 71-78.

Dong, C. (2017). Review of natural fibre-reinforced hybrid composites. *Journal of Reinforced Plastics and Composites*, *37*(5), 331-348.

Eselini, N., Tirkes, S., Akar, A. O., and Tayfun, U. (2020). Production and characterization of poly (lactic acid)-based biocomposites filled with basalt fiber and flax fiber hybrid. *Journal of Elastomers & Plastics*, *52*(8), 701-716.

Fiore, V., Scalici, T., Di Bella, G., and Valenza, A. (2015). A review on basalt fibre and its composites. *Composites Part B: Engineering*, *74*, 74-94.

Gur'ev, V. V., Neproshin, E. I., and Mostovoi, G. E. (2001). The effect of basalt fiber production technology on mechanical properties of fiber. *Glass and Ceramics*, *58*(1-2), 62-65.

Ilyas, R., Zuhri, M., Aisyah, H., Asyraf, M., Hassan, S., Zainudin, E., Sapuan, S., Sharma, S., Bangar, S., and Jumaidin, R. (2022). Natural fiber-reinforced polylactic acid, polylactic acid blends and their composites for advanced applications. *Polymers*, *14*(1), 202.

ISO 48-4: 2018 Rubber, vulcanized or thermoplastic — Determination of hardness, Part 4: Indentation hardness by durometer method (Shore hardness). International Organization for Standardization, Switzerland.

Jagadeesh, P., Rangappa, S. M., and Siengchin, S. (2024). Basalt fibers: An environmentally acceptable and sustainable green material for polymer composites. *Construction and Building Materials*, *436*.

Li, X., Tabil, L. G., and Panigrahi, S. (2007). Chemical treatments of natural fiber for use in natural fiber-reinforced composites: a review. *Journal of Polymers and the Environment*, *15*, 25-33.

Lopresto, V., Leone, C., and De Iorio, I. (2011). Mechanical characterisation of basalt fibre reinforced plastic. *Composites Part B: Engineering*, *42*(4), 717-723.

Mann, G. S., Singh, L. P., Kumar, P., and Singh, S. (2018). Green composites: A review of processing technologies and recent applications. *Journal of Thermoplastic Composite Materials*, *33*(8), 1145-1171.
Murariu, M., and Dubois, P. (2016). PLA composites: From production to properties. *Advanced drug delivery reviews*, *107*, 17-46.
Özsoy, N., and Sancak, E. (2024). Determining the mechanical properties of biomaterial-based economic thermoplastic composites reinforced with hemp fibres. *Industria Textila*, *75*(4), 405-414.
Öztürk, S. (2005). The effect of fibre content on the mechanical properties of hemp and basalt fibre reinforced phenol formaldehyde composites. *Journal of Materials Science*, *40*(17), 4585-4592.
Plappert, D., Ganzenmüller, G. C., May, M., and Beisel, S. (2020). Mechanical properties of a unidirectional basalt-fiber/epoxy composite. *Journal of Composites Science*, *4*(3), 101.
Saheb, D. N., and Jog, J. P. (1999). Natural fiber polymer composites: A review. *Advances in Polymer Technology*, *18*(4), 351-363.
Sang, L., Han, S., Li, Z., Yang, X., and Hou, W. (2019). Development of short basalt fiber reinforced polylactide composites and their feasible evaluation for 3D printing applications. *Composites Part B: Engineering*, *164*, 629-639.
Sathishkumar, T. P., Naveen, J., and Satheeshkumar, S. (2014). Hybrid fiber reinforced polymer composites – a review. *Journal of Reinforced Plastics and Composites*, *33*(5), 454-471.
Seçinti Klopf, H. (2025). Removal of non-cellulosic materials from hemp fiber under ultrasonication conditions and cetyl trimethyl ammonium chloride (CTAC) catalyst. *Journal of Innovative Engineering and Natural Science*, *5*(1), 187-195.
Selvaraj, G., Kaliyamoorthy, R., and Kirubakaran, R. (2022). Mechanical, thermogravimetric, and dynamic mechanical analysis of basalt and flax fibers intertwined vinyl ester polymer composites. *Polymer Composites*, *43*(4), 2196-2207.
Siakeng, R., Jawaid, M., Ariffin, H., Sapuan, S., Asim, M., and Saba, N. (2019). Natural fiber reinforced polylactic acid composites: A review. *Polymer Composites*, *40*(2), 446-463.
Singha, K. (2012). A short review on basalt fiber. *International Journal of Textile Science*, *1*(4), 19-28.
Song, Y., Liu, J., Chen, S., Zheng, Y., Ruan, S., and Bin, Y. (2013). Mechanical Properties of Poly (Lactic Acid)/Hemp Fiber Composites Prepared with a Novel Method. *Journal of Polymers and the Environment*, *21*(4), 1117-1127.
Soykan, U., and Kaya, S. (2023). Role of hemp fiber addition on thermal stability, heat insulation, air permeability and cellular structural features of rigid polyurethane foam. *Cellular Polymers*, *42*(2), 88-104.
Tayfun, U., Arslan, Ç., and Doğan, M. (2023). Bazalt elyaf yüzeyindeki silan katmanının polilaktit kompozitlerine güçlendirme etkinliğinin değerlendirilmesi. *Journal of Materials and Mechatronics: A*, *4*(1), 87-99.
Ucpinar, B., Sivrikaya, T., and Aytac, A. (2025). Sustainable hemp fiber reinforced polylactic acid/poly (butylene succinate) biocomposites: Assessing the effectiveness of MAH-g-PLA as a compatibilizer. *Polymer Composites*.
Yorseng, K., Rangappa, S. M., Ayyappan, V., Srisuk, R., and Siengchin, S. (2024). Bioepoxy based advanced lightweight hybrid composites from hemp fibers: towards greener production. *Journal of Building Engineering*, *86*, 108808.
Zimniewska, M. (2022). Hemp Fibre Properties and Processing Target Textile: A Review. *Materials (Basel)*, *15*(5).