

Effect of hemp filler on the mechanical and physical properties of PLA/PBAT composite films

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Advances in packaging materials and plastic waste management have recently been driven by the increasing use of bio-based biodegradable polymers such as polylactic acid (PLA) and poly (butylene adipate-co-terephthalate) (PBAT). Although these biopolymers are considered environmentally friendly due to their biodegradability, their limited mechanical performance restricts their broader application in flexible packaging systems.

In this study, industrial hemp (*Cannabis Sativa*) was incorporated as a natural filler into PLA/PBAT polymers to improve the mechanical properties of biodegradable films intended for sustainable packaging applications.

Polyethylene glycol (PEG200) was used as a plasticizer, and 20 µm thick films were fabricated *via* the solution casting method. Alkali treatment of hemp was applied to improve interfacial compatibility between hemp fibers and the polymer matrix. Structural, morphological, thermal, and mechanical characterizations of the hemp-incorporated composite films were performed using Fourier-transform infrared spectroscopy (FTIR), field-emission scanning electron microscopy (FE-SEM), differential scanning calorimetry (DSC), and mechanical testing

The results showed that the formulation with a PLA/PBAT ratio of 25/75 and 0.15% hemp exhibited the highest tensile strength of 12.18 MPa. Compared to the reference sample, the addition of 0.15% alkali-treated hemp increased tensile strength by up to 61%, whereas the incorporation of PEG200 negatively affected mechanical performance. These findings demonstrate the potential of hemp-reinforced PLA/PBAT composites as sustainable materials for flexible packaging applications.

Keywords: PLA (polylactic acid), PBAT (poly-butylene adipate-co-terephthalate), bio-based filler, mechanical properties.

INTRODUCTION

Plastic pollution, defined as the accumulation of plastics in the ecosystem in a manner that negatively impacts the environment, has become one of the most widespread global environmental challenges. Plastic products released into the environment are highly persistent; however, through processes such as photochemical oxidation and mechanical abrasion, they gradually fragment into microplastics (1 µm–5 mm) and nanoplastics (<1 µm) [1-3].

Due to their high mobility and resistance to natural degradation, these small particles enter aquatic food webs and accumulate in sediments. Furthermore, their high surface area-to-volume ratio enhances their capacity to adsorb heavy metals and persistent organic pollutants, posing significant ecological risks to aquatic organisms and water quality [4, 5].

Increasing concerns over the sustainability of petroleum-based feedstocks have intensified efforts to develop renewable bio-based polymer systems. Compared to fossil-derived materials, bio-based alternatives offer reduced environmental burden, lower carbon footprint, and decreased reliance on

finite fossil resources, aligning with sustainable material engineering principles [6, 7].

The extensive use of ecoplastic materials based on naturally derived polymers and fillers contributes to addressing ecological concerns through the utilization of renewable resources and components that are part of the natural environment [8-10]. Advancements in the processing technologies and property enhancement of biodegradable materials will enable the widespread utilization of products based on naturally derived components. This may lead to the partial or complete replacement of synthetic polymers with ecoplastics. Among these materials, polylactic acid (PLA) and poly(butylene adipate-co-terephthalate) (PBAT) have attracted significant attention for the development of sustainable products [11, 12].

The development of polymer composites with novel chemical compositions requires the investigation of their structure and properties as influenced by technological factors, thereby enabling the production of defect-free materials through consideration of phase transformation behavior under external physical fields.

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The high quality and durability of products and structures fabricated from the investigated environmentally friendly composite materials are almost always achieved through the proper selection of the material composition in combination with the most effective processing method. Therefore, it is possible to produce eco-friendly composites by incorporating hemp fibers, with varying compositions, morphologies, and particle sizes, as fillers into a renewable bioplastic blend composed of poly(butylene adipate-co-terephthalate) and poly(lactic acid) (PBAT/PLA composites) [13-16].

This study aims to fabricate biofilms with varying PLA and PBAT ratios by using alkali-treated hemp as a reinforcing filler in a matrix, employing the solution casting method. Biodegradable polymer formulations will be developed, and their morphological, physical, thermal, and mechanical properties will be characterized.

EXPERIMENTAL

Materials and methods

In this study, industrial hemp (*Cannabis Sativa*) stalks obtained from the Black Sea Agricultural Research Institute (Samsun, Türkiye) were used as the filler material. During the preparation phase, the outer bark layers of the stalks were peeled; after being soaked in water for 24 hours and cleaned, they were dried at ambient temperature for 2 days, followed by 48 h in an oven at 80°C. The dried samples were then ground to a particle size of less than 20 µm using a laboratory grinder. Since hemicellulose, lignin, and pectin contribute to the hydrophilic nature of natural fibers and may hinder adhesion to the polymer matrix, an alkaline treatment was applied using a 10% NaOH solution for 30 min. Following this, the samples were washed

with distilled water at 40°C, neutralized to pH 7 with acetic acid, and dried again at 80°C for 48 h.

To form the composite structure, PLA, PBAT, treated hemp, and PEG200 plasticizer were mixed in chloroform until complete dissolution was achieved. The resulting solution was cast onto Teflon-coated glass plates using an applicator to obtain films with a thickness of 20 µm. The samples were dried in a fume hood for 24 hours, followed by 6 hours of oven drying at 40°C to obtain the final films. In the final stage, the films were characterized using FTIR, DSC, and FE-SEM analyses, in addition to the evaluation of mechanical properties.

All biodegradable films were coded as shown in Table 1, and the preparation scheme of the hemp-incorporated films is presented in Figure 1.

RESULTS AND DISCUSSION

Structural analyses of biopolymer film samples were carried out in the 4000 – 400cm⁻¹ spectral range using a Spectrum Two Fourier transform infrared (FTIR) spectrometer (Perkin Elmer, USA). The measurements were performed in accordance with the ASTM E168 standard.

FTIR spectra of both the pure materials and hemp incorporated films are compared in Figure 2. The presence of similar characteristic peaks in the FTIR spectra of all samples indicates that they possess the same or highly similar chemical structures. The carbonyl (C=O) peak at 1711 cm⁻¹, together with the C–O stretching bands in the 1268–1101 cm⁻¹ range, confirms that the material is predominantly an ester-based polyester. The band observed at 727–728 cm⁻¹, attributed to CH₂ rocking vibrations, suggests the presence of long aliphatic chains, supporting a structure with ordered chain segments and a potentially semi-crystalline character.

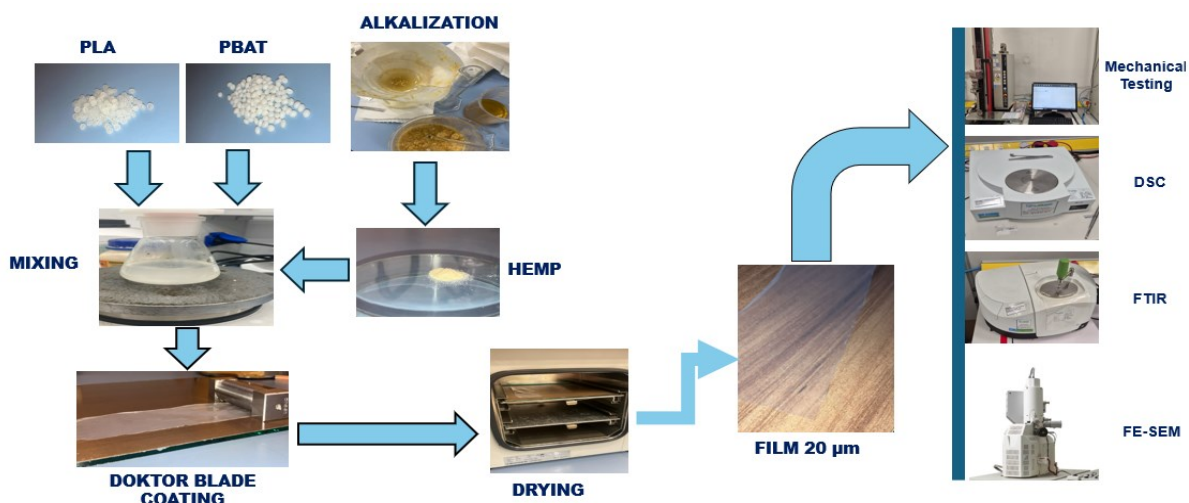


Figure 1. Schematic representation of composite films

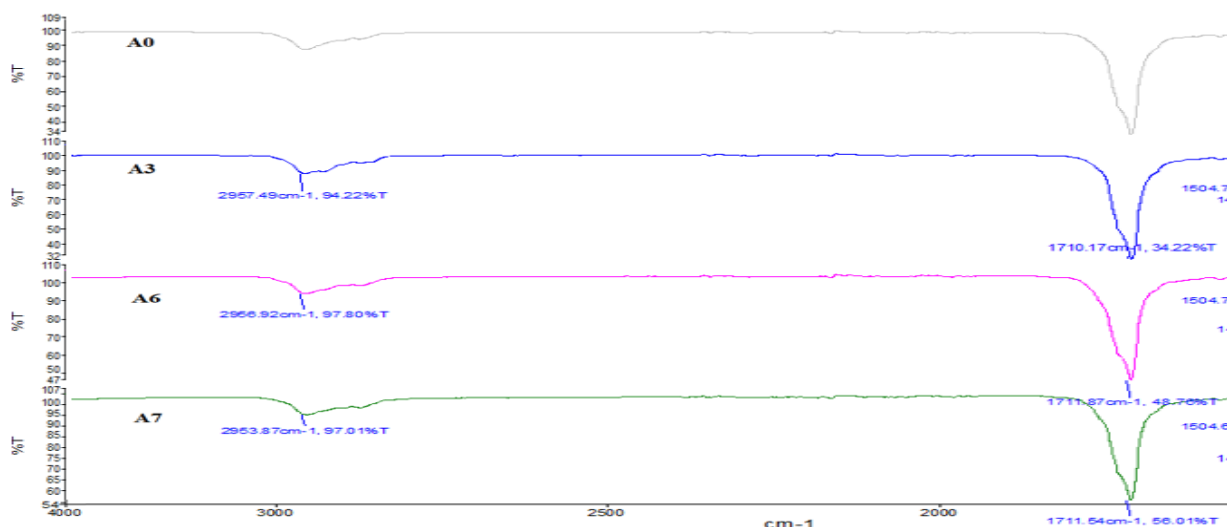


Figure 2. FTIR spectra of PLA/PBAT-based composite films

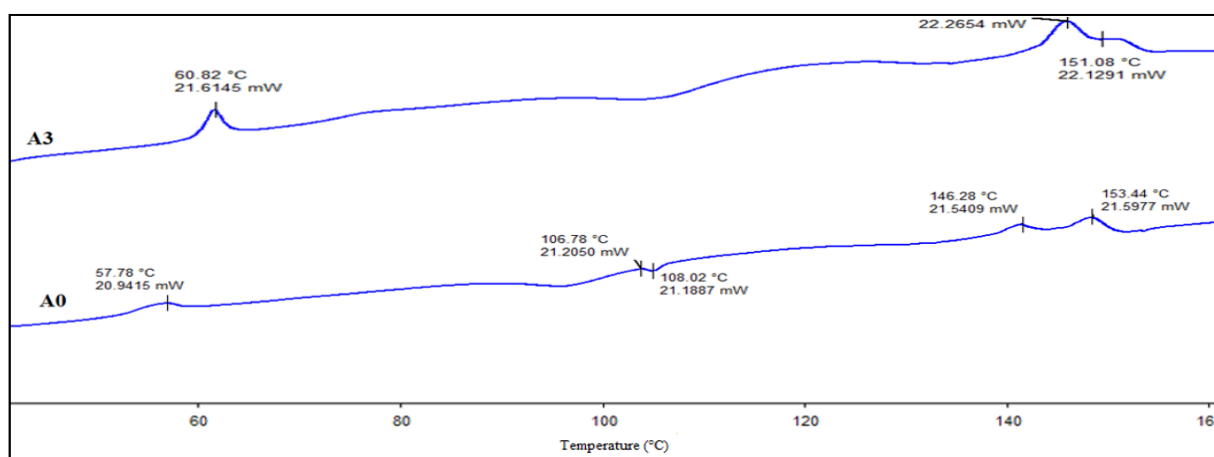


Figure 3. DSC curves of PLA/PBAT films: control (A0) and hemp-incorporated (A3)

RESULTS AND DISCUSSION

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Thermal behavior of the biofilms was characterized using a DSC 4000 (PerkinElmer) instrument under a nitrogen atmosphere, in accordance with ASTM D3417. The sample masses used for the analyses ranged from 1.7 to 2.5 mg. During the measurements, the samples were first heated from 30 °C to 200 °C at a heating rate of 10 °C/min and held at 200 °C for 5 min, followed by cooling to the initial temperature at a cooling rate of 20 °C/min.

The thermal behavior of the samples is presented in the DSC thermograms (Figure 3). Based on the DSC thermograms, differences in the thermal response of the films were observed depending on the presence of alkali-treated hemp. The composite containing alkali-treated hemp exhibited higher heat flow intensities compared to the hemp-free sample, suggesting changes in the thermal transitions and possible variations in the degree of molecular ordering within the polymer matrix. The thermal events observed in the range of 106–108 °C may be associated with alterations in the crystallization or

relaxation behavior of the polymer chains induced by the presence of hemp fibers.

Mechanical properties of the film specimens were measured at room temperature (25 °C) using a Zwick Roell universal testing machine at a crosshead speed of 500 mm/min in accordance with ASTM D882. The film dimensions were prepared for uniaxial tensile testing with dimensions of 50 × 25.4 × 0.02 (mm), corresponding to the specimen length, width, and thickness, respectively. For the mechanical tests, three specimens were prepared for each formulation. Differences among the formulations were discussed based on the magnitude of the observed changes and the non-overlapping nature of the standard deviation values.

Analysis of the mechanical test results indicated that both the hemp filler and PEG200 plastizer had a significant influence on the mechanical performance of the composite structure. For the 20-micrometer-thick films prepared via the solution casting method, the PLA/PBAT ratio and hemp content were found to be key parameters governing the overall performance, as summarized in Table 1.

The highest tensile strength of 12.18 MPa was obtained for the formulation containing 25% PLA,

75% PBAT, and 0.15% hemp. This improvement is attributed to enhanced fiber–matrix interactions and a more uniform dispersion of hemp fibers within the polymer matrix, as evidenced by FE-SEM analyses (Figure 4).

Overall, these results suggest that a small amount of alkali-treated hemp can contribute to mechanical reinforcement in PLA/PBAT-based biodegradable films.

In contrast, the lowest mechanical strength was observed for the film containing 20% PLA, 80% PBAT, 5% PEG200, and 0.25% hemp, and was determined to be 2.45 MPa. The presence of PEG200 was found to exert a negative effect on the mechanical strength. Although PEG200 was incorporated into the matrix as a plasticizer, its use beyond certain concentrations reduced the stiffness of the matrix, resulting in a decrease in tensile strength.

Furthermore, increasing the hemp ratio to 0.25% may have prevented the fibers from being fully wetted by the matrix at lower polymer ratios and created stress concentration points within the structure, leading to premature failure

Table 1. Compositions and mechanical properties of PLA/PBAT/hemp composite films

	PLA(w%)	PBAT% (w%)	PEG200 (V%)	Hemp (W%)	Tensile Strength N (Newton)	Tensile Strength MPa
A0	25	75			3,84	7,56
A1	25	75		0,25	3,23	6,36
A2	25	75		0,2	3,68	7,25
A3	25	75		0,15	6,19	12,18
A4	25	75		0,1	4,25	8,86
A5	25	75		0,05	5,86	11,53
A6	25	75	5		2,41	4,75
A7	25	75	5	0,25	5,48	4,31
B0	20	80			14,52	9,68
B1	20	80		0,25	45,43	9,49
B2	20	80		0,2	9,27	7,32
B3	20	80		0,15	3,97	7,81
B4	20	80		0,1	4,78	9,42
B5	20	80		0,05	5,04	9,92
B6	20	80	5		2,45	4,82
B7	20	80	5	0,25	3,11	2,45

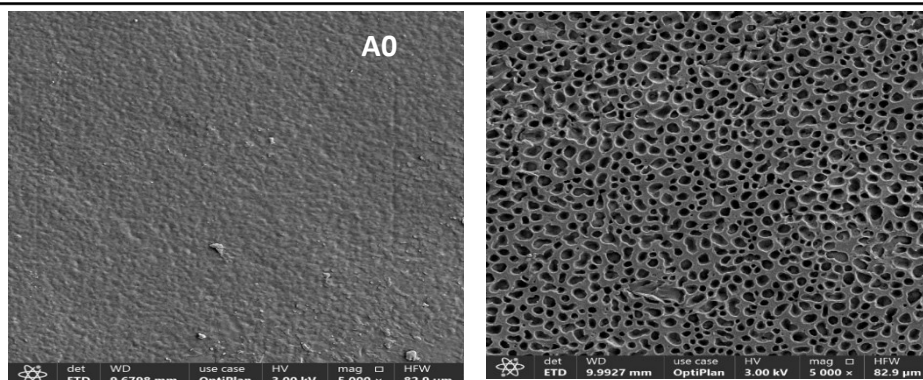


Figure 4. FE-SEM images of PLA/PBAT films: control (A0) and hemp-incorporated (A3)

The field-emission scanning electron microscopy (FESEM) images clearly reveal the significant morphological influence of hemp incorporation on the PLA/PBAT matrix structure. The observed morphology of A0 corresponds to a neat polymer matrix without reinforcing additives, characterized by a smooth surface.

In image A3, corresponding to the 0.15% hemp content (where the highest tensile strength of 12.18 MPa was obtained), a marked change in the matrix morphology is observed. The structure exhibits a more heterogeneous and porous, honeycomb-like network compared to the neat sample. This morphological change suggests improved fiber dispersion within the polymer matrix following alkali treatment, which removes surface impurities such as lignin and hemicellulose from the fibers.

The relatively uniform porous structure observed in the FE-SEM micrographs indicates better filler distribution within the matrix. The presence of finely ground hemp fibers (<20 µm) may contribute to improved stress transfer efficiency, which is consistent with the higher tensile strength observed for this formulation.

The 10% NaOH alkali treatment applied to the hemp fibers constitutes an important preliminary step in this study. The removal of components such as hemicellulose, lignin, and pectin, which are present in natural fibers and may limit interaction with the polymer matrix, modified the hydrophilic nature of the fibers and is expected to improve interfacial adhesion with the matrix. This process, also known as mercerization in the literature, helps to clean the fiber surface by removing waxes and oils and may enhance stress transfer by affecting the structural organization of cellulose.

The results indicate that incorporating hemp fibers into PLA/PBAT improved the tensile strength and elastic modulus. These findings suggest that hemp can act as a sustainable, lightweight, and promising filler material, offering potential for use as an alternative reinforcing agent in biodegradable plastic systems for flexible packaging applications.

CONCLUSION

Reinforcing biodegradable polymers (PLA/PBAT) with industrial hemp fibers may offer a promising approach to addressing plastic pollution in sustainable packaging applications. In this study, hemp fibers were used as a filler material in the development of eco-friendly biocomposite films as an alternative to fossil-fuel-based plastics.

The 10% NaOH alkali treatment purified the hemp fibers and may improve their interaction with the polymer matrix, contributing to enhanced

mechanical performance. Among the films prepared via the solution casting method, the formulation containing 25% PLA, 75% PBAT, and 0.15% hemp exhibited the highest tensile strength of 12.18 MPa. In contrast, the addition of PEG200 negatively influenced the tensile strength, while certain hemp contents supported the structural integrity of the composites.

Overall, industrial hemp fibers have shown potential as a cost-effective and sustainable reinforcing component for biopolymer matrices. These biocomposites may contribute to reducing packaging waste and increasing the value of locally available renewable resources. The developed formulations provide a basis for future studies on sustainable packaging materials.

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REFERENCES

1. C.-G. Miriam, R. Marci, C. Lanna, *Biol. Lett.* **8**, 817 (2012). <https://doi.org/10.1098/rsbl.2012.0298>
2. R.-G. Lisa, D.-O. Mark, L.-D. Miriam, W. Watson, *CalCOFI Rep.* **50**, 123 (2009)
3. H.-R. Valeria, G. Lars, C.-T. Richard, T. Martin, *Environ. Sci. Technol.* **46**, 3060 (2012). <https://doi.org/10.1021/es2031505>
4. M. Rebecca M, M.-R. Saymur, *J. Hazard. Mater. Adv.* **18**, 100663 (2025). DOI: <https://doi.org/10.1016/j.hazadv.2025.100663>
5. C. Klára, V. Martina, M. Tomáš, Z. Lukáš, B. Lucia, *Life* **11**, 1349 (2021). DOI: <https://doi.org/10.3390/life11121349>
6. K.-A. Syed, A.-A. Abdullah, A. Faris, M.-A. Hassien, P. Humaira, M. Sayeed, Shaily, A.-K. Liyaqat, W. Mohd, S. Adnan, *J. Environ. Chem. Eng.* **14**, 121722 (2026), <https://doi.org/10.1016/j.jece.2026.121722>
7. M. Olczyk, M. Kuc-Czarneck, *J. Clean. Prod.* **495**, 145077 (2025). <https://doi.org/10.1016/j.jclepro.2025.145077>
8. M.-D. Banea, *Polymers* **15**, 1185 (2023). <https://doi.org/10.3390/polym15051185>
9. A.-L. Pereira, M.-D. Banea, J.-S. Neto, D.K.-K. Cavalcanti, *Polymers* **12**, 866 (2020). <https://doi.org/10.1016/j.jclepro.2025.145077>
10. J.S.-S. Neto, H.F.-M. de Queiroz, R. A.-A. Aguiar, M.D. Banea, *Polymers* **13**, 4425 (2021). <https://doi.org/10.3390/polym13244425>
11. J.-B. Mu'azu, S.-D. Adamu, S.-B. Mamudu, A. Dalhatu, H. Ataitiya, M.-Y. Abubakar, A.-B. Adam, *J. Chem. Technol.* **2**, 48 (2026). <https://doi.org/10.22034/jchemtech.2025.556439.1030>
12. N.-A. Asri, N.A.-A. Sezali, H.-L. Ong, M.-H. M. Pital, Y.-H. Lim, J. Fang, *Macromol. Res.*, **45**, 202400475 (2024). <https://doi.org/10.1002/marc.202400475>

13. A. Kariev, V. Lebedev, D. Miroshnichenko, Y. Sokol, M. Gasanov, A. Cherkashina, Y. Lutsenko, S. Pyshyev *Tech Sci. Press.* **13**, (2025). <https://doi.org/10.32604/jrm.2025.02025-0049>
14. O. Boughanmi, L. Allegue, H. Marouani, A. Koubaa, Y. Fouad, *Polym. Eng. Sci.* **64**, 5613 (2024). <https://doi.org/10.1002/pen.26938>
15. V. Lebedev, D. Miroshnichenko, N. Vytrykush, S. Pyshyev, A. Masikevych, O. Filenko, O. Tsereniuk, L. Lysenko, *Mater. Chem. Phys.* **313**, 128778 (2024). <https://doi.org/10.1016/j.matchemphys.2023.128778>
16. Y.G.-T. Girijappa, R.-S. Mavinkere, J. Parameswaranpillai, S. Siengchin, *Front. Mater.* **6**, 226 (2019). <https://doi.org/10.3389/fmats.2019.00226>