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Development and Mechanical Characterization of Polylactic Acid (PLA) Composites Reinforced with Flax Fiber: Fabrication and Properties

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Abstract

Polylactic Acid (PLA) composites reinforced with flax fibers have emerged as a promising solution for sustainable, biodegradable materials. This research investigates the fabrication process and mechanical characterization of PLA composites reinforced with varying concentrations of flax fiber. The study assesses the effects of flax fiber loading on the composite's mechanical properties, including tensile strength, hardness, flexural strength, and interfacial bonding between the fibers and matrix. The composites were fabricated using a twin-screw extrusion process followed by injection molding. Mechanical testing, including tensile, hardness, and flexural tests, was performed to evaluate the composites' strength, stiffness, and resistance to deformation. Results indicated that the tensile strength of the composites increased with fiber content up to 35%, after which it decreased due to poor fiber-matrix bonding and fiber agglomeration. Additionally, the flexural strength followed a similar trend, with an optimal fiber content at 35%. The hardness of the composites also improved as flax fiber content increased. The study concludes that PLA-flax fiber composites have great potential as an eco- friendly alternative to traditional materials in various structural applications.

Major Findings: *The study revealed that incorporating flax fibers into PLA significantly improved the composite's tensile strength, flexural strength, and hardness up to an optimal fiber loading of 35%. Beyond this threshold, mechanical performance declined due to fiber agglomeration and weakened fiber-matrix interfacial bonding, highlighting the need for optimized processing and bonding techniques.*

Keywords: *Biodegradable Materials, Flexural Strength, Flax Fiber, Mechanical Characterization, Polylactic Acid (PLA), PLA Composites, Sustainability, Tensile Strength*

1.0 Introduction

In recent years, the pursuit of sustainable materials has intensified, driven by growing environmental concerns and the need to replace petroleum-based polymers with renewable alternatives. Among the biopolymers explored, polylactic acid (PLA) has emerged as a promising candidate due to its biodegradability, biocompatibility, and derivation from renewable resources[1]. However, the inherent brittleness and limited mechanical performance of PLA restrict its application in load-bearing and structural components[2].

To address these limitations, reinforcement with natural fibers particularly flax fiber has been widely

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investigated. Flax fiber offers advantages such as high specific strength, low density, and biodegradability, making it an ideal reinforcement for PLA-based composites[3,4]. These biocomposites have demonstrated enhanced mechanical properties and are increasingly considered for use in packaging, automotive, and structural applications[5,6].

Recent studies have focused on processing techniques such as melt blending[7], surface treatments like alkali modification[8], and the fiber–matrix interactions that influence composite performance[9]. Experimental analyses have also revealed that factors such as fiber treatment and dispersion significantly affect mechanical and wear behavior[10,11].

Numerous reviews have highlighted the importance of interfacial adhesion, fiber orientation, and fabrication methods in optimizing the mechanical, thermal, and tribological characteristics of PLA/flax fiber composites[12–14]. The integration of these materials in advanced manufacturing processes, such as 3D printing, further extends their applicability[15]. Additionally, environmental and performance assessments support their potential as sustainable alternatives in engineering and consumer product applications[16].

Despite significant progress, challenges remain in improving fiber–matrix bonding, achieving uniform dispersion, and enhancing scalability for industrial applications[17]. Continued research and innovation are essential to fully exploit the potential of PLA/flax fiber biocomposites as next-generation eco-friendly materials.

2.0 Materials and Fabrication of Specimen

The fabrication of PLA-flax fiber composites begins with the careful selection of raw materials. The PLA matrix used in this research was procured from ANHUI BBCA BIOCHEMICALS and FUTERRO PLA Corporation Limited, with the supplier being Total Solutions Enterprise, Bangalore. For the reinforcement, flax fibers were sourced from Vruksha Composites, Andhra Pradesh, which provided high-quality fibers suitable for composite manufacturing.

The fabrication process of PLA-flax fiber composites was carried out. The procedure involved several key stages to ensure uniform dispersion of flax fibers in the PLA matrix and to optimize the composite's properties.

- Preparation of Flax Fiber: The flax fibers were cleaned, dried, and cut into the desired length of 5 mm. To enhance the fiber-matrix adhesion, the flax fibers underwent an alkali treatment, which helps to improve the bonding between the fibers and the PLA matrix.
- Preparation of PLA Resin: PLA pellets were heated to temperatures between 170°C and 200°C, allowing them to melt and form a resin suitable for blending.
- Blending of PLA and Flax Fibers: A twin-screw extruder was used to mix PLA with flax fibers at varying fiber loadings (ranging from 0 % to 50 % by weight). The extrusion process was conducted under controlled conditions with temperatures



Figure 1. PLA pellets and flax fibers.

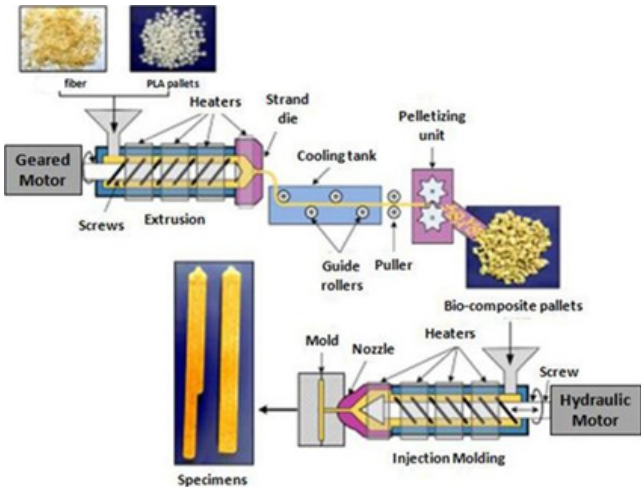


Figure 2. PLA composite fabrication process.

between 180°C and 210°C and screw speeds between 200 and 400 rpm to ensure uniform dispersion of the fibers in the matrix.

- Molding: The composite material was injected into molds using injection molding equipment. Molding conditions included a mold temperature of 30°C to 50°C, an injection temperature of 190°C to 220°C, and holding pressures between 500 and 1000 bar.
- Cooling and Solidification: After injection, the composite material was allowed to cool and solidify, ensuring that the molded specimens retained their shape and mechanical properties.

2.1 Testing

The mechanical properties of the PLA-flax fiber composites were evaluated through various tests, including tension, hardness, flexural strength, and microscopic analysis of the fiber-matrix interface.

2.2 Tension Test

Tensile testing is essential for assessing the strength and flexibility of the composite under stress. The specimens were prepared in accordance with ASTM D3039 standards, with dimensions of 250 mm × 25 mm × 4 mm. The specimens were then subjected to tensile forces using a Universal Testing Machine (UTM). The test measured the force and elongation, from which key properties like tensile strength, Young's modulus, and strain at fracture were calculated.

The results demonstrated an initial increase in tensile strength as the fiber volume fraction rose from 25 % to 35 %. The composite exhibited a peak tensile strength of 35



Figure 3. Tension test specimen – before and after testing.

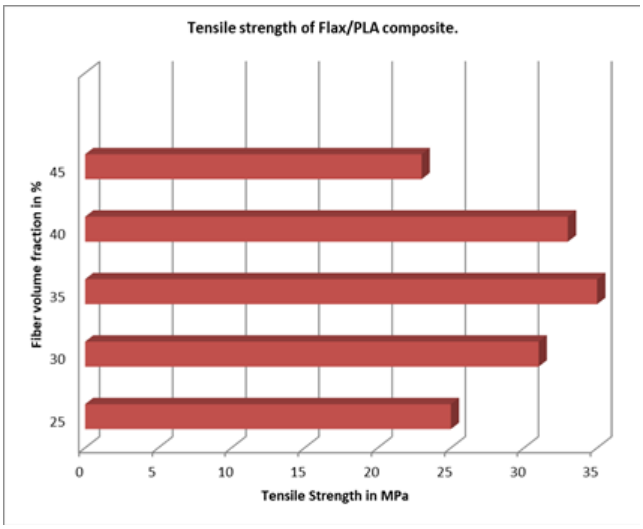


Figure 4. Tensile strength of Flax/PLA composite.

Table 1. Tensile strength values of Flax/PLA composite

Fiber Volume Fraction (wt. %)	25	30	35	40	45
Tensile Strength (MPa)	25	31	35	33	23

Table 2. Flexural strength values of Flax/PLA composite

Fiber Volume Fraction (wt. %)	25	30	35	40	45
Flexural Strength (MPa)	39	43	45	41	38

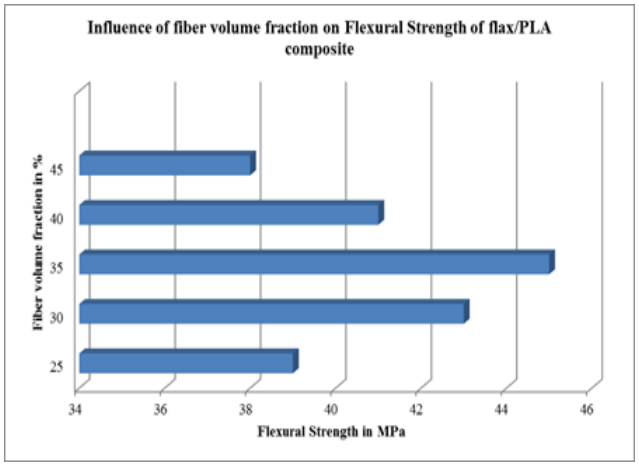


Figure 5. Flexural strength of Flax/PLA composite.

MPa at 35 % fiber content. However, beyond this point (40 % and 45 %), the tensile strength decreased, likely due to poor fiber-matrix bonding and potential fiber aggregation.

2.3 Flexural Strength Test

The influence of fiber volume fraction on the flexural strength of PLA-flax composites was also studied. Flexural strength is critical for applications that involve bending or flexing of the material, such as in structural components and packaging. The flexural strength values were measured at varying fiber volume fractions (25 %, 30 %, 35 %, 40 % and 45 %).

The flexural strength increased with fiber content up to 35 %, peaking at 45 MPa. However, beyond this point (at 40 % and 45 %), the strength dropped. This decline is due to poor fiber-matrix bonding and fiber agglomeration, which result in uneven fiber distribution and a weaker structure, especially under bending stress.

2.4 Hardness Test

Hardness testing, conducted using the Shore D durometer, assessed the composite's resistance to surface indentation. Higher hardness values indicate better durability and wear resistance, crucial for applications in automotive and packaging.

The hardness increased with the flax fiber content, reaching the highest value of 82.65 at the 60/40 PLA-flax composite. This indicates that the incorporation of flax fibers enhances the rigidity and toughness of the PLA matrix.

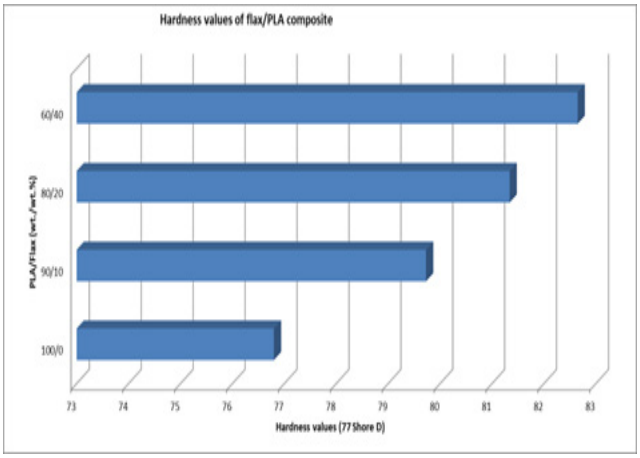


Figure 6. Hardness values of flax/PLA composite.

2.5 Interfacial Bonding and Fiber Behavior

Scanning Electron Microscopy (SEM) was used to investigate the bonding between the PLA matrix and flax fibers. The quality of the fiber-matrix interface is critical for the composite's mechanical properties. Strong bonding ensures efficient load transfer, while weak bonding results in poor performance. SEM images revealed well-bonded

Table 3. Hardness values of Flax/PLA composite

PLA/Flax (wt./wt. %)	100/0	90/10	80/20	60/40
Hardness (Shore D)	76.8	79.73	81.34	82.65

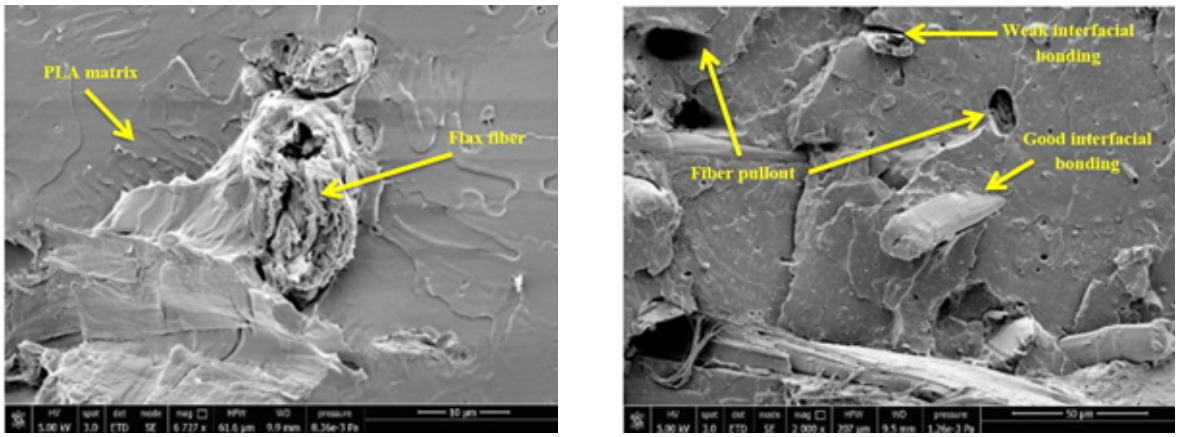


Figure 7. SEM image showing bonding between matrix and fiber.

fibers with minimal gaps in the matrix, signifying effective load transfer. However, in areas with weak bonding, fiber pullout was observed, indicating reduced strength.

3.0 Results and Discussion

The experimental data obtained from the tensile and hardness tests provided critical insights into the mechanical properties of PLA-flax fiber composites. The results showed that the incorporation of flax fibers significantly improved the mechanical strength and stiffness of PLA, but the effects varied depending on the fiber content.

3.1 Tensile Strength

The tensile strength of PLA-flax composites showed a clear dependence on the fiber content. As the fiber volume fraction increased from 25% to 35%, the tensile strength increased from 25 MPa to 35 MPa, demonstrating the reinforcing effect of the flax fibers. This improvement is likely due to the efficient transfer of stress from the PLA matrix to the flax fibers, which have higher tensile strength compared to PLA.

However, beyond 35% fiber content, the tensile strength began to decrease. The composite with 45% fiber content exhibited the lowest tensile strength (23 MPa). This reduction can be attributed to several factors. At higher fiber contents, the fibers tend to agglomerate, leading to uneven fiber dispersion within the PLA matrix. Agglomeration weakens the overall structure, as the fibers are not uniformly distributed, which disrupts the stress transfer mechanisms. Additionally, excessive fiber loading can lead to poor fiber-matrix adhesion, where the fibers do not effectively bond with the PLA matrix, resulting in reduced load-bearing capacity and mechanical strength.

The optimal fiber content for maximizing tensile strength was found to be 35%. This result aligns with previous studies on natural fiber-reinforced composites, where an optimal fiber loading threshold is typically observed, beyond which further increases in fiber content can negatively impact the composite's performance due to poor bonding or excessive fiber clustering.

3.2 Flexural Strength

The flexural strength of the PLA-flax composites also showed a clear dependence on the fiber volume fraction. At 25% fiber content, the flexural strength was 39 MPa, and as the fiber content increased to 30%, the flexural strength improved to 43 MPa. This increase continued at 35% fiber content, where the flexural strength peaked at 45 MPa. This demonstrates the significant reinforcing effect of the flax fibers on the composite, as they contribute to better load-bearing capacity and resistance to bending.

However, as the fiber content increased beyond 35%, a decrease in flexural strength was observed. At 40 % fiber content, the flexural strength dropped to 41 MPa. The composite with 45 % flax fiber exhibited the lowest flexural strength of 38 MPa. This decline at higher fiber contents can be attributed to several issues, including fiber agglomeration and poor fiber-matrix adhesion, as discussed in the tensile strength section. At higher fiber

volumes, the fibers tend to cluster together, leading to uneven distribution within the matrix, which weakens the composite's overall performance. The results suggest that a fiber content of 35% provides the best balance between reinforcement and the material's structural integrity.

3.3 Hardness

The Shore D hardness test showed a progressive increase in hardness values as the flax fiber content increased. The pure PLA exhibited a hardness value of 76.8, while the composite with 60% flax fiber had the highest hardness of 82.65. This increase in hardness can be attributed to the stiffening effect of the flax fibers. The fibers, acting as reinforcing agents, enhance the rigidity of the PLA matrix, making the composite more resistant to surface deformation.

The trend in hardness was consistent with the tensile strength results, confirming that as the fiber content increases, the material becomes stiffer and more resistant to indentation and deformation. This makes the PLA-flax composites more suitable for applications where durability and surface resistance to wear are critical, such as in automotive parts, packaging materials, and construction components.

3.4 Interfacial Bonding and Fiber Behavior

Scanning Electron Microscopy (SEM) images of the fractured surfaces of the composites provided additional insights into the behavior of the flax fibers within the PLA matrix. At lower fiber contents (up to 35%), the SEM images revealed good interfacial bonding between the flax fibers and the PLA matrix. The fibers appeared to be well-embedded in the matrix with minimal gaps, suggesting efficient load transfer.

However, at higher fiber contents (40% and 45%), SEM images revealed signs of poor fiber-matrix adhesion, such as fiber pullout and fiber agglomeration. In these composites, the fibers were not as well-bonded to the PLA, leading to regions where the fibers were detached from the matrix. This weak bonding resulted in reduced mechanical strength, as the fibers could not effectively contribute to the load-bearing capacity of the composite. Fiber pullout is a common issue in fiber-reinforced composites, especially at higher fiber loadings, and is a key factor in determining the overall mechanical performance.

4.0 Conclusion

In this study, the mechanical properties of PLA-flax fiber composites were analyzed, revealing key trends in strength, hardness, and fiber-matrix interactions. The findings are summarized below:

- Tensile strength increased with flax fiber content up to 35% (35 MPa), indicating a reinforcing effect. It declined beyond 35% fiber loading due to fiber agglomeration and poor fiber-matrix bonding.
- Flexural strength improved with fiber content up to 35% (45 MPa), showing better resistance to bending. It decreased beyond 35% fiber loading because of uneven fiber distribution and weak bonding.
- Hardness increased progressively with fiber content, reaching the highest value of 82.65 Shore D at 40% flax fiber. This indicates improved surface durability and resistance to wear with higher fiber content.
- The best performance in tensile and flexural strength was observed at 35% flax fiber. Beyond this threshold, fiber agglomeration and poor bonding reduced the composite's overall mechanical integrity.
- SEM analysis showed strong interfacial bonding at lower fiber contents (up to 35%). At higher fiber contents, fiber pullout and weak bonding were observed, negatively impacting the mechanical properties.
- PLA-flax composites offer a renewable, biodegradable alternative to synthetic materials. The findings suggest potential for automotive, packaging, and construction applications due to improved mechanical performance and eco-friendly nature.
- Future studies should focus on enhancing fiber-matrix bonding and optimizing processing conditions to prevent fiber agglomeration and improve the overall performance of the composite.

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