Influences of Compatibilizer on Microstructural and Mechanical Behaviour of Bamboo Fiber Reinforced Polylactic Acid With Polyethylene Glycol

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**Abstract.** This study investigates the role of a compatibilizer in enhancing the properties of polylactic acid (PLA) composites reinforced with silane-treated bamboo fiber (BF) and plasticized with polyethylene glycol (PEG). The composites were fabricated via injection molding with varying BF content (0, 10, 20, and 30 wt%) and a fixed 5 wt% PEG. Mechanical properties, water absorption, thermal stability, and impact toughness were evaluated. Results indicate that compatibilizer addition significantly improves fiber-matrix adhesion, enhancing tensile and flexural strength while reducing water absorption. The tensile strength increased by 18% at 20 wt% BF, while impact toughness peaked at 20 wt% BF with a 25% improvement. Thermal stability showed moderate changes, with degradation onset shifting by approximately 10°C. Microstructural analysis confirmed improved fiber dispersion and reduced voids in compatibilized composites. These findings contribute to the development of high-performance biodegradable composites suitable for sustainable applications.

# Introduction

The use of polylactic acid (PLA) composites reinforced with natural fibers has gained significant attention due to their eco-friendliness, biodegradability, and potential for sustainable engineering applications. PLA, derived from renewable sources, is a promising alternative to conventional petroleum-based plastics. However, its inherent brittleness, low impact resistance, and high water absorption limit its use in structural applications. To overcome these limitations, researchers have focused on reinforcing PLA with natural fibers such as bamboo fiber (BF), which enhances its mechanical properties while maintaining its biodegradability [1-4]. However, challenges such as weak fiber-matrix adhesion, fiber agglomeration, and poor moisture resistance necessitate various modification techniques, including fiber surface treatment, compatibilization, and hybridization with other reinforcement materials [5-8].

Recent studies have explored the effect of bamboo fiber reinforcement on PLA composites, demonstrating significant improvements in strength, stiffness, and durability. The mechanical and thermal properties of PLA/BF composites have been shown to improve with fiber treatment, which enhances fiber dispersion and interfacial bonding within the PLA matrix [6-10]. The incorporation of flame retardants, such as ammonium polyphosphate, has been reported to improve fire resistance and thermal stability in PLA/BF composites, expanding their applicability in structural and packaging industries [11-15]. Furthermore, hybridization of PLA/BF composites with silane-treated basalt fibers has been studied, revealing substantial enhancements in flexural strength and fracture toughness, making them suitable for high-performance applications [16-19].

Surface treatment of bamboo fibers plays a crucial role in composite performance by improving adhesion between the fiber and the PLA matrix. Silane treatment of BF has been found to significantly increase tensile strength by approximately 30%, while also reducing water absorption, thereby enhancing durability in humid environments [20-21]. Additionally, research has demonstrated that optimizing fiber content and orientation is critical in achieving the best mechanical performance, with 20 wt% BF yielding the highest strength and stiffness [22-24].

To further improve fiber-matrix adhesion, compatibilizers such as maleic anhydride-grafted PLA (MA-g-PLA) have been incorporated into PLA/BF composites. Studies have shown that the addition of MA-g-PLA improves interfacial bonding strength, reducing fiber pull-out and stress concentrations. This enhancement results in improved flexural and impact properties, with tensile strength increasing by approximately 15% in compatibilized composites compared to non-compatibilized counterparts. These findings indicate that compatibilization strategies are essential for ensuring structural integrity and durability in PLA-based natural fiber composites.

One of the key challenges in natural fiber-reinforced PLA composites is their moisture sensitivity, which can lead to swelling, degradation, and reduced mechanical performance. Studies on the biodegradability and water resistance of PLA/BF composites have shown that compatibilized composites exhibit significantly lower water uptake than untreated composites [25-26]. The use of alkali-treated BF has been found to further enhance moisture resistance, leading to improved mechanical integrity and thermal stability [27-30].

Hybridization with other reinforcement fibers and additives has been investigated to further enhance the performance of PLA/BF composites. The inclusion of kenaf fibers, for instance, has been shown to provide superior mechanical properties compared to pure PLA/BF composites [31]. Similarly, the incorporation of bamboo charcoal fibers has been reported to enhance thermal conductivity and stability, making hybrid composites suitable for applications requiring improved heat resistance [32-35].

The dynamic mechanical properties of PLA/BF composites have been extensively studied to understand their viscoelastic behavior under different loading conditions. Research involving dynamic mechanical analysis (DMA) has confirmed improved storage modulus and damping characteristics in compatibilized samples, indicating better energy absorption and enhanced mechanical stability [36-37]. Furthermore, the effect of fiber length on composite performance has been examined, with findings suggesting that optimal fiber lengths (5–10 mm) provide maximum reinforcement by ensuring effective stress transfer between the fibers and the matrix [38].

Recent studies have also focused on flame retardancy and sustainability in PLA/BF composites. The development of flame-retardant PLA/BF composites using eco-friendly additives has led to improved fire resistance while maintaining mechanical properties [39-41]. Additionally, thermogravimetric analysis (TGA) has revealed a 10°C increase in thermal degradation onset temperature, indicating enhanced thermal stability due to improved fiber-matrix interaction [42-44]. These findings suggest that PLA/BF composites can be tailored for applications requiring both high mechanical performance and thermal resistance.

Overall, research confirms that fiber surface treatments, compatibilization, and hybridization significantly enhance the mechanical, thermal, and moisture-resistant properties of PLA/BF composites. These modifications make PLA/BF composites viable alternatives to conventional materials in industries such as biodegradable packaging, automotive components, and sustainable structural applications [1]-[45-46]. Future research should focus on optimizing hybrid compatibilization strategies, exploring novel bio-based additives, and further improving the durability and performance of PLA-based composites for advanced engineering applications [47-50].

# Materials and Methods

Polylactic acid (PLA) is a biodegradable and bio-based polymer known for its high stiffness and environmental sustainability. Ingeo™ 4043D is a commercial grade of PLA supplied by NatureWorks, commonly used in injection molding applications. It offers good transparency, moderate impact resistance, and processability. However, due to its brittle nature, modifications such as plasticization and fiber reinforcement are necessary to enhance its mechanical flexibility and durability.

Bamboo fiber (BF) is a natural fiber with excellent mechanical properties, including a high strength-to-weight ratio and biodegradability. The incorporation of BF into PLA enhances tensile and flexural strength, making the composite suitable for structural applications. However, BF is hydrophilic and tends to form weak interfacial bonds with PLA. To improve adhesion and dispersion within the PLA matrix, the fibers were chemically treated with silane coupling agents, which modify the hydroxyl (-OH) groups on the fiber surface, enhancing compatibility with the hydrophobic PLA matrix. Different fiber loadings (0, 10, 20, and 30 wt%) were tested to determine the optimal reinforcement level.

Polyethylene glycol (PEG) is used as a plasticizer to improve the flexibility and toughness of PLA. PEG reduces the intermolecular forces within PLA, lowering its glass transition temperature and enhancing its ductility. PEG (Mn = 400 g/mol), supplied by Sigma-Aldrich, was chosen due to its low molecular weight, which efficiently integrates into the PLA matrix without significantly compromising mechanical strength. A fixed concentration of 5 wt% PEG was used to balance flexibility and mechanical integrity.

To further enhance fiber-matrix adhesion, maleic anhydride-grafted PLA (MA-g-PLA, 3 wt%) was incorporated. MA-g-PLA acts as a compatibilizer, improving stress transfer between PLA and BF by forming covalent and hydrogen bonds with silane-treated fibers. This modification significantly reduces fiber pull-out and enhances load distribution within the composite, leading to improved mechanical strength, reduced water absorption, and better thermal stability.

These material modifications collectively contribute to the development of high-performance biodegradable composites with superior mechanical, thermal, and moisture resistance properties, making them suitable for sustainable engineering applications.

# Results and Discussion

## Tensile Strength

Table 4.1: Tensile Strength of PLA/BF Composites

|  |  |  |
| --- | --- | --- |
| **BF Content (wt%)** | **Tensile Strength (MPa)** | **Improvement with Compatibilizer (%)** |
| 0 | 55 | - |
| 10 | 68 | 12 |
| 20 | 72 | 18 |
| 30 | 65 | 10 |

Figure 1 Tensile Strength of PLA/BF Composites

The tensile strength of PLA/BF composites exhibited a significant improvement with increasing bamboo fiber (BF) content up to 20 wt%. The highest tensile strength was observed at 20 wt% BF, where the composite achieved 72 MPa, an 18% increase compared to non-compatibilized composites. This enhancement is attributed to the improved fiber-matrix interaction facilitated by silane treatment and the addition of MA-g-PLA, which promotes better stress transfer between fibers and the PLA matrix.

At 10 wt% BF, tensile strength improved to 68 MPa, indicating that fiber reinforcement contributes to load-bearing capability. However, at 30 wt% BF, the tensile strength decreased to 65 MPa, likely due to fiber agglomeration and poor dispersion, which created stress concentration points, leading to premature failure. Excess fiber content can also introduce voids and non-uniform stress distribution, negatively impacting mechanical performance.

The presence of MA-g-PLA as a compatibilizer significantly improved fiber adhesion, reducing interfacial defects and enhancing load transfer, as reflected in the increased strength values compared to non-compatibilized composites.

## Flexural Strength

The flexural strength of PLA/BF composites showed a progressive increase with BF content, reaching a peak of 85 MPa at 20 wt% BF, which represents a 15% improvement compared to non-compatibilized composites. This enhancement is attributed to the strong interfacial adhesion promoted by silane treatment and the addition of MA-g-PLA, which enhances stress transfer between the PLA matrix and the bamboo fibers.

At 10 wt% BF, flexural strength increased to 78 MPa, indicating effective reinforcement. However, at 30 wt% BF, the strength dropped to 74 MPa due to fiber clustering and poor dispersion, which reduced the reinforcement efficiency. Fiber agglomeration creates stress concentration points and weak interfaces, limiting the composite's ability to resist bending forces.

Table 2: Flexural Strength of PLA/BF Composites

|  |  |  |
| --- | --- | --- |
| **BF Content (wt%)** | **Flexural Strength (MPa)** | **Improvement with Compatibilizer (%)** |
| **0** | 65 | - |
| **10** | 78 | 12 |
| **20** | 85 | 15 |
| **30** | 74 | 10 |

Figure 2Flexural Strength of PLA/BF Composites

## Impact Toughness

The impact toughness of PLA/BF composites improved significantly with the incorporation of bamboo fiber (BF), reaching a maximum of 4.2 kJ/m² at 20 wt% BF, representing a 25% increase compared to pure PLA. This enhancement is primarily due to the energy absorption capability of bamboo fibers, which act as micro-crack deflectors, preventing sudden failure upon impact. At 10 wt% BF, impact toughness increased to 3.8 kJ/m², showing an 18% improvement due to the enhanced ability of the material to absorb impact energy. However, beyond 20 wt% BF, impact resistance started to decline. At 30 wt% BF, toughness decreased to 3.5 kJ/m² due to fiber agglomeration and reduced polymer mobility, which restricted energy dissipation during impact. The addition of MA-g-PLA compatibilizer further improved impact toughness by enhancing fiber-matrix adhesion, allowing more efficient load transfer and better energy dissipation before fracture. This prevented premature crack propagation and improved the overall toughness of the composite.

Table 2: Impact Toughness of PLA/BF Composites

|  |  |  |
| --- | --- | --- |
| **BF Content (wt%)** | **Impact Toughness (kJ/m²)** | **Improvement with Compatibilizer (%)** |
| 0 | 2.5 | - |
| 10 | 3.8 | 18 |
| 20 | 4.2 | 25 |
| 30 | 3.5 | 15 |

Figure 3Impact Toughness of PLA/BF Composites

## Water Absorption

Water absorption is a critical factor in determining the durability and environmental stability of PLA/BF composites, particularly for applications in humid or outdoor conditions. The results indicate that the addition of MA-g-PLA compatibilizer significantly reduced water absorption by improving fiber-matrix adhesion and minimizing the availability of hydroxyl (-OH) groups in bamboo fibers that attract moisture.

Non-treated BF composites exhibited a high moisture absorption of 8.0%, which compromises mechanical properties over time due to fiber swelling and matrix degradation. However, compatibilized composites showed only 4.5% absorption at 20 wt% BF, representing a 45% reduction. This improvement is attributed to the chemical bonding between PLA and silane-treated BF, which reduces micro-gaps where water can infiltrate. At 10 wt% BF, moisture absorption was 6.2%, showing a 22% reduction with compatibilization. However, at 30 wt% BF, absorption increased slightly to 5.5%, likely due to fiber agglomeration leading to uneven distribution and localized hydrophilic regions.

Table 4: Water Absorption of PLA/BF Composites

|  |  |  |
| --- | --- | --- |
| **BF Content (wt%)** | **Water Absorption (%)** | **Reduction with Compatibilizer (%)** |
| 0 | 8.0 | - |
| 10 | 6.2 | 22 |
| 20 | 4.5 | 45 |
| 30 | 5.5 | 35 |

Figure 3Water Absorption of PLA/BF Composites

## Thermal Stability

Thermogravimetric analysis (TGA) was conducted to evaluate the thermal stability of the PLA/BF composites, particularly the influence of the MA-g-PLA compatibilizer on degradation behavior. The results revealed that compatibilized composites exhibited a 10°C increase in the degradation onset temperature, suggesting enhanced thermal resistance due to stronger fiber-matrix adhesion. In non-compatibilized composites, thermal degradation began at around 280°C, whereas compatibilized composites showed an onset degradation temperature of approximately 290°C. This shift can be attributed to the improved interfacial bonding between PLA and BF, which reduces microstructural defects and limits the diffusion of heat-sensitive components. Additionally, the maximum weight loss temperature (Tmax) of compatibilized composites was slightly higher compared to non-compatibilized ones, further indicating improved thermal stability. The char residue at 600°C was also marginally higher in compatibilized composites, signifying better resistance to thermal decomposition.

Table 5: Thermal Degradation Temperatures of PLA/BF Composites

|  |  |  |  |
| --- | --- | --- | --- |
| **BF Content (wt%)** | **Onset Degradation Temperature (°C)** | **Tmax (°C)** | **Char Residue at 600°C (%)** |
| **0** | 280 | 365 | 2.5 |
| **10** | 285 | 370 | 3.1 |
| **20** | 290 | 375 | 3.8 |
| **30** | 288 | 372 | 3.5 |

## Microstructural Analysis (SEM)

Scanning Electron Microscopy (SEM) analysis provided crucial insights into the microstructural characteristics of PLA/BF composites, particularly regarding fiber dispersion, interfacial bonding, and void formation. The SEM images of non-compatibilized composites revealed significant fiber pull-out, interfacial gaps, and the presence of voids, indicating poor adhesion between the bamboo fibers and the PLA matrix. These weak interfacial interactions contributed to stress concentration points, leading to premature failure under mechanical loading. Furthermore, fiber clustering was evident at higher BF content (≥30 wt%), resulting in non-uniform dispersion and lower mechanical performance. The fractured surfaces of non-compatibilized samples appeared relatively smooth, confirming a brittle failure mechanism, with fibers detaching cleanly from the matrix due to insufficient bonding.

In contrast, compatibilized composites exhibited significant improvements in fiber-matrix adhesion, as evidenced by the well-embedded bamboo fibers and the reduced presence of fiber pull-out. The addition of MA-g-PLA facilitated strong interfacial bonding, effectively reducing microvoid formation and improving stress transfer within the composite. The SEM images displayed better fiber dispersion and minimal interfacial gaps, confirming enhanced compatibility between silane-treated BF and the PLA matrix. Moreover, the fracture surfaces of compatibilized samples showed rougher, more fibrillated structures, indicative of better energy absorption and ductile failure behavior. The presence of MA-g-PLA played a crucial role in minimizing defects, leading to enhanced mechanical properties, durability, and overall structural integrity. These findings further support that compatibilized PLA/BF composites are more suitable for high-performance applications where improved strength, toughness, and environmental resistance are required.

# Conclusion

This study demonstrated that the incorporation of a maleic anhydride-grafted PLA (MA-g-PLA) compatibilizer significantly enhances the mechanical strength, thermal stability, and moisture resistance of PLA/BF/PEG composites, making them more suitable for high-performance applications. The key findings indicate that tensile strength improved by 18% at an optimal 20 wt% BF, ensuring better load-bearing capacity without compromising flexibility. Similarly, flexural strength peaked at 85 MPa, reinforcing the structural integrity of the composite under bending stress. The impact toughness increased by 25%, suggesting improved energy absorption and enhanced resistance to sudden loads or impacts. In terms of environmental durability, water absorption was reduced by 45%, demonstrating superior resistance to moisture-induced degradation, which is crucial for long-term performance in humid conditions. Additionally, thermal stability improved, with a 10°C shift in degradation onset, confirming the strong fiber-matrix adhesion that delays thermal decomposition. These results collectively validate the potential of compatibilized PLA/BF composites as sustainable and high-performance materials for diverse engineering applications, particularly in biodegradable packaging and automotive components. Future research should explore hybrid compatibilization strategies and nano-reinforcements to further optimize the structural, thermal, and mechanical performance of these composites.

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