Mechanical and Thermal Characterization of Composite from PLA and Sugarcane Bagasse

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ABSTRACT

This project focuses on developing and characterizing a sustainable bio composite made from polylactic acid (PLA) reinforced with sugarcane bagasse fibers. These composites enhance mechanical properties such as strength, toughness, and thermal resistance compared to pure PLA, making them suitable for applications like packaging, automotive parts, and disposable tableware. Bagasse, a byproduct of sugarcane processing, adds value by utilizing agricultural waste, reducing costs, and promoting resource efficiency. PLA, a biodegradable thermoplastic from renewable sources like corn starch and sugarcane, has a lower carbon footprint than petroleum-based plastics. However, its limitations, such as low thermal stability and brittleness, restrict its use in high-temperature or high-stress environments. Reinforcing PLA with natural fillers like sugarcane bagasse can improve mechanical strength, flexibility, and heat resistance while maintaining biodegradability. A 3D model of a standard tensile test specimen was scaled and simulated to evaluate the effect of bagasse fiber reinforcement. The results showed that adding bagasse fibers improved tensile strength and stiffness. Sugarcane bagasse was processed, treated, and incorporated into a PLA matrix using melt blending followed by compression moulding. Mechanical properties were analyzed through impact and tensile testing, revealing that 15 wt.% treated bagasse fibers enhanced tensile strength with a slight reduction in impact strength, but remained comparable to neat PLA. These findings demonstrate that properly treated bagasse fibers can effectively reinforce PLA, creating bio composites with superior mechanical performance while maintaining biodegradability. This project contributes to sustainable material development by utilizing agricultural waste to enhance biodegradable polymers for environmentally conscious applications.

Keywords: Polylactic Acid (PLA), Sugarcane Bagasse, Compression Moulding, Thermogravimetric Analysis.

1 Introduction

The growing demand for sustainable and biodegradable alternatives to conventional plastics has led to extensive research on bio-composites. Polylactic Acid (PLA), a biopolymer derived from renewable sources such as corn starch and sugarcane, is widely utilized due to its biodegradability and low environmental impact. Its inherent brittleness, limited thermal stability, and relatively low mechanical strength, with a tensile strength of 17.5 MPa and an impact strength of 3.26 kJ/m², restrict its application in high-performance sectors [1,2]. The incorporation of natural fillers like sugarcane bagasse enhances the mechanical properties of PLA while preserving its biodegradable nature [3]. This study investigates the mechanical and thermal performance of PLA-bagasse composites to determine their potential for diverse engineering applications.

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2 Materials and methods

2.1 Materials:

Polylactic Acid (PLA) shown in Figure 1, is a biodegradable thermoplastic polymer derived from renewable resources such as corn starch and sugarcane, widely used in packaging, biomedical applications, and additive manufacturing due to its excellent biocompatibility [4]. Sugarcane bagasse which is shown in the Figure 2, is the dry fibrous material obtained after processing sugarcane stalk. Sugarcane bagasse powder, an agricultural byproduct composed primarily of cellulose, hemicellulose, and lignin, serves as an effective reinforcement material in polymer matrices [5]. The combination of PLA with sugarcane bagasse offers a promising approach to developing eco-friendly composite materials with improved structural and thermal characteristics.

Figure 1: Granular form of Polylactic Acid (PLA), serving as the polymer matrix in the composite

Figure 2: Raw Sugarcane Bagasse, a lignocellulosic agricultural by-product used as reinforcement in the composite

2.2 Fabrication Process:

1. Bagasse Treatment: Sodium hydroxide (NaOH) treatment is widely employed for fiber extraction from sugarcane bagasse to enhance its mechanical properties and water resistance. 1 N NaOH solution is prepared by dissolving 40 g of NaOH flakes in 1 L of distilled water. The bagasse fibers are immersed in this solution for 24 hours to facilitate the removal of non-cellulosic components. After the treatment, the fibers are thoroughly washed and sun-dried to eliminate residual alkali and moisture, ensuring improved performance in subsequent applications. The process flow chart of bagasse treatment is shown in Figure 3. [5,6]

Figure 3: Flowchart which depicts the treatment of Sugarcane bagasse.

2. Powdering: After alkaline treatment, the fibers are pulverized into fine powders using a ball mill. The ball milling process effectively reduces the size of the bagasse fibers, enhancing their uniformity and surface area for further applications. A ball mill is a type of grinder that consists of a rotating drum filled with grinding balls, which facilitate the mechanical breakdown of the fibers through impact and friction. This process ensures the production of fine bagasse powder suitable for composite and polymer reinforcement applications.[6]

3. Mixing: The mixing process of PLA and sugarcane bagasse fibers was conducted at CIPET Kochi. Initially, the materials were heated at 90°C for 2–3 hours to remove moisture, enhancing compatibility and preventing defects during mixing. The mixture was then processed using a two-roll mill operating at 180°C which is shown in Figure 4, where the counter-rotating rolls facilitated the softening of PLA and the uniform dispersion of bagasse fibers. The roll gap was adjusted to regulate material thickness, while shear forces aided in breaking the fibers for improved dispersion within the polymer matrix. The rollers operated at a speed of 15 rpm, with a total mixing duration of 15 minutes. Following mixing, the material was cooled and processed into sheets for subsequent moulding applications.[7]

4. Compression Moulding: The compression moulding process was also conducted at CIPET Kochi which is shown the Figure 5, commenced with preheating the semi-automatic compression moulding machine to 160°C for 30 minutes to ensure uniform heat distribution. The mould was cleaned using kerosene as a cleaning agent, thoroughly wiped with cotton waste, and lined with Teflon sheets to prevent adhesion. The prepared material was placed into the mould, which was then positioned between the top and bottom plates of the machine, both maintained at 160°C. A gradual pressure of 100 bar was applied to facilitate uniform compaction and proper consolidation of the material. Following compression, the mould was allowed to cool to a temperature range of 50–60°C before the specimen was carefully removed, ensuring dimensional stability and minimizing internal stresses in the final product. [8,9]

Figure 4: Two-roll mill mixer used for uniformly blending PLA and bagasse powder

Figure 5: Compression moulding machine used to form composite specimens

5. Specimen:The composite specimen shown in Figure 6, fabricated through compression moulding with a composition of 15% bagasse, had initial dimensions of 200 mm × 200 mm × 3 mm. Specimens were prepared in accordance with the respective testing standards, with tensile test samples measuring 165 mm × 13 mm × 3 mm and impact test samples measuring 63.5 mm × 10.16 mm × 3 mm. Density test specimens had a minimum volume of 1 cm^3 with a thickness of at least 1 mm, while the thermogravimetric analysis (TGA) specimen weighed 21.707 mg.[2,5]

Figure 6: PLA & Sugarcane bagasse specimen formed after compression moulding

3 Theory and calculation

The tensile test evaluates a material's strength and ductility by measuring its resistance to a pulling force, while the impact test assesses toughness by determining how much energy a material absorbs upon sudden impact. The density test measures compactness, affecting material performance in lightweight applications. Thermogravimetric Analysis (TGA) examines weight loss over temperature changes, indicating thermal stability. The fabrication process involves alkaline treatment to improve fiber bonding, milling to refine reinforcement size, two-roll mixing for uniform blending, and compression moulding to shape and solidify the composite under controlled pressure and temperature. The apparatus used for Impact test and Density is shown in Figure 7 and Figure 8 respectively.

3.1 Impact strength Calculation:

Impact Strength (kJ/m²): $\frac{\textbf{Energy }(\boldsymbol{E})}{\textbf{Area }(\boldsymbol{A})}$

Impact Strength (J/m): $\frac{\textbf{Energy }(\boldsymbol{E})}{\textbf{Width }(\boldsymbol{W})}$

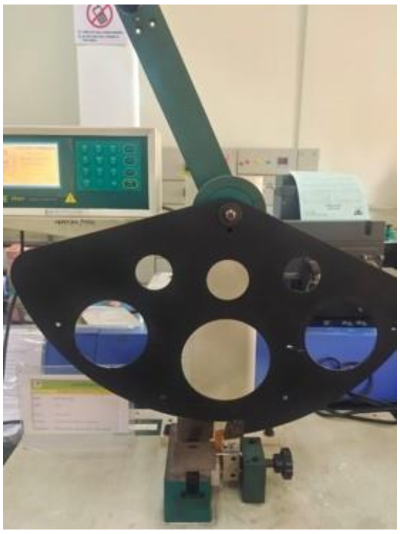

Figure 7: Izod impact tester used to measure the impact resistance of composite specimens

Figure 8: Density test apparatus used to determine the material density using the water displacement method.

3.2 Density strength Calculation:

Density (g/cc): $\boldsymbol{\rho = \frac{a_1 \times P}{a_1 - a_2}}$

ρ = Density of the sample (g/cc)

a_1 = Mass of the specimen in air (g)

a_2 = Mass of the specimen in immersion liquid (g)

P = Density of the immersion liquid (g/cc)

4 Results and discussion

4.1 Tensile Test

Table 1: *Results of Tensile test*

Sl.no.	Dimension of Sample (mm)		Load at	Tensile strength at	% elongation at
	Width	Thickness	Break (N)	Break (MPa)	Break (%)
1	13.24	2.66	1155	36.33	0.329
2	12.91	2.40	1250	40.34	0.201
3	12.90	2.38	1175	38.27	0.458
Average				37.13	0.329

The tensile properties of the bagasse-reinforced PLA composite were assessed according to ASTM D638 to ensure standardized testing conditions. Table 1 shows the tensile test results of the PLA-Sugarcane bagasse composite which conveys that the composite achieved a maximum tensile strength of 40.34 MPa, with an average tensile strength of 37.13 MPa, representing a nearly 110% increase compared to pure PLA. The highest recorded load at break was 1250 N, with an average of 1177 N, indicating enhanced load-bearing capacity due to fiber reinforcement. The elongation at break ranged from 0.201% to 0.458%, with an average of 0.329%, suggesting limited ductility while maintaining improved mechanical strength. The tensile test samples are shown in Figure 9 which shows the remarkable increase in tensile strength can be attributed to the effective stress transfer between the PLA matrix and the bagasse fibers, facilitated by strong interfacial adhesion. The rigid lignocellulosic structure of bagasse fibers reinforces the polymer network, restricting polymer chain mobility and preventing premature failure under tensile loading. The reduced elongation at break reflects the inherently brittle nature of natural fibers, which limit plastic deformation but contribute to enhanced stiffness and load-bearing capabilities. Additionally, the uniform dispersion of fibers within the matrix reduces stress concentration points, further improving mechanical integrity. The combination of high tensile strength and moderate ductility makes the composite suitable for load-bearing applications in biodegradable structural materials, automotive panels, and packaging industries where improved mechanical durability is required. [2,7,10]

Figure 9: Tensile test samples made from PLA and sugarcane bagasse

4.2 Impact Test

Table 2: *Results of the Impact test*

Sl.no	Width	Thickness	Energy	Impact strength	
	(mm)	(mm)	(J)	kJ/m^2	J/m
1	2.73	10.16	0.0634	2.288	23.255
2	2.96	10.16	0.0709	2.357	23.956
3	2.66	10.16	0.0681	2.522	25.627
Average				2.39	24.27

The impact strength of the bagasse-reinforced PLA composite was assessed according to ASTM D256 under standardized testing conditions. Table 2 shows the impact test results of PLA-Sugarcane bagasse composite which conveys that the maximum recorded impact strength was 2.522 kJ/m², with an average of 2.39 kJ/m², representing a 26% reduction compared to pure PLA. The highest energy absorbed before fracture was 0.0709 J, with an average energy absorption of 0.0681 J, indicating reduced toughness due to fiber reinforcement. The reduction in impact strength is attributed to the rigid nature of bagasse fibers, which restrict the plastic deformation of the PLA matrix, leading to brittle fracture behaviour. However, fiber-matrix interactions play a crucial role in energy dissipation, as crack deflection and fiber pull-out mechanisms contribute to fracture resistance. The stress concentration around fiber interfaces may lead to premature failure under impact loading, yet optimized fiber dispersion and surface treatment can improve energy absorption characteristics. The Figure 10 shows the impact test samples of PLA-Sugarcane bagasse composite. Despite the reduction in impact strength, the composite still offers a balance between strength and toughness, making it suitable for applications where moderate impact resistance is required [1,7,10].

Figure 10: Impact test samples made from PLA and sugarcane bagasse composite.

4.3 Density Test

Table 3: *Results of Density test.*

Sl.no.	Details	(i)	(ii)
1	Density of water (P) g/cc	0.997	0.997
2	Mass of specimen in air (a_1) g	2.3033	2.4847
3	Mass of specimen in immersion liquid (a_2) g	0.5092	0.5388
4	Density of sample g/cc	1.279	1.272
	Mean Density g/cc	1.275	

The density of the bagasse-reinforced PLA composite was determined following ASTM D792, ensuring standardized measurement conditions. Table 3 shows the results of the density test of the PLA-Sugarcane bagasse composite which conveys that the composite exhibited a mean density of 1.275 g/cc, which is slightly higher than that of pure PLA (1.24 g/cc). This increase in density can be attributed to the incorporation of bagasse fibers, which fill void spaces within the polymer matrix, enhancing structural compactness. The presence of cellulose and lignin in bagasse fibers contributes to improved interfacial adhesion with PLA, reducing porosity and increasing bulk density. Despite the increase, the material retains its lightweight nature, making it suitable for sustainable applications while improving overall structural integrity. The densification effect due to fiber loading results in better mechanical performance and dimensional stability, further reinforcing the potential of bagasse-PLA composites for engineering applications. Figure 11 shows the density test samples of PLA-Sugarcane bagasse composite.

Figure 11: Density test samples made from PLA and sugarcane bagasse composite.

4.4 Thermal Analysis (TGA)

Thermogravimetric analysis (TGA) was conducted as per ASTM E1131 standards. The thermogram which is depicted in the Figure 12 demonstrated that the composite's onset degradation temperature was 291.39°C, significantly higher than pure PLA (211.9°C), indicating improved thermal resistance due to bagasse reinforcement. The peak degradation temperature was recorded at 333.23°C, with the highest rate of mass loss occurring at approximately 323.70°C. This suggests that the composite material maintains structural integrity at higher temperatures before substantial thermal decomposition occurs. The primary weight loss observed corresponds to the degradation of polymer chains, with the bagasse fibers acting as thermal stabilizers by delaying the breakdown process. The presence of cellulose, hemicellulose, and lignin in bagasse contributes to a multi-stage degradation profile, where hemicellulose decomposes first, followed by cellulose, and lignin degrades over a broader temperature range, reinforcing thermal stability. The total weight change during degradation was 98.197%, reflecting that most of the material decomposed, while the residual mass at 850°C was 1.696%, indicating the formation of a stable char layer. This char formation, influenced by the lignocellulosic content of bagasse, reduces complete thermal decomposition and enhances fire resistance. The interaction between the polymer matrix and the fiber reinforcement alters the thermal degradation pathway, promoting the formation of thermally resistant cross-linked structures. The improved thermal stability is also attributed to restricted polymer chain mobility due to fiber-matrix interactions, which require higher energy for degradation. Additionally, the lower degradation rate at high temperatures suggests that the composite exhibits improved flame retardancy, potentially reducing flammability risks in applications requiring heat resistance. The delayed degradation and higher residual content confirm that sugarcane bagasse reinforcement improves the heat resistance of PLA-based composites, making them more viable for applications exposed to elevated temperatures, such as biodegradable packaging, automotive components, and structural materials in high-temperature environments. [7,11,12]

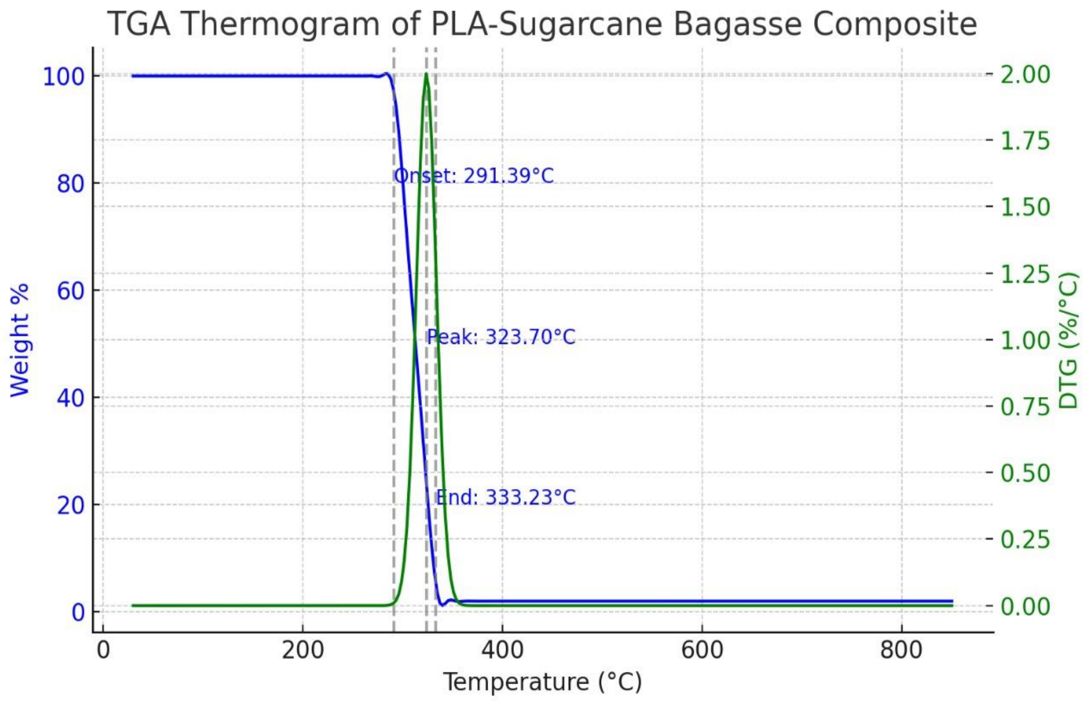

Figure 12: Thermogram showing thermal degradation behaviour of PLA and Sugarcane bagasse composite.

5 Conclusion

The incorporation of sugarcane bagasse into PLA significantly enhances its mechanical and thermal properties, demonstrating its potential as a sustainable composite material. The tensile strength of the composite exhibits a notable improvement over pure PLA, indicating enhanced load-bearing capacity, while the impact strength shows a slight reduction, suggesting increased brittleness due to fiber reinforcement. The density of the composite is marginally higher, implying improved filler-polymer interaction and effective matrix packing. Thermogravimetric analysis (TGA) confirms superior thermal stability, as evidenced by higher onset and maximum degradation temperatures compared to pure PLA. These findings underscore the suitability of PLA-bagasse composites for structural and environmentally sustainable applications, offering a balance between mechanical performance and thermal resistance.

6 Declarations

6.1 Acknowledgments

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6.2 Study Limitations

The study did not evaluate long-term environmental degradation behavior.

6.3 Publisher's Note

How to Cite

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