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Sisal Fiber Enhancement of PLA Biodegradable Composites: Synthesis and Characterization

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Abstract

Significant importance is placed on biodegradable polymers and biomaterials within the domain of tissue engineering and orthopedic applications, especially in the context of joint and replacement. Green composites offer several advantages, such as being lightweight, lowering production costs and energy consumption, having minimal environmental impact, and being recyclable. This study focuses on the mechanical properties of biocomposites made from biosourced polymers, specifically sisal fiber and Polylactic Acid (PLA). The biocomposites were extruded and injection molded with varying amounts of sisal fiber. Results indicate that increasing the reinforcement rate improves the mechanical properties of the biocomposites. Additionally, sisal fibers acted as a nucleating agent for the PLA, leading to an increase in the matrix's crystallinity from 47% to 61% as the sisal fiber content increases. The incorporation of inorganic fillers further contributes to the modification of their properties. This paper delves into the reinforcement of PLA through treated chopped sisal fiber, exploring the mechanical properties of PLA blended with 10% starch.

***Major findings:** The study emphasizes that increasing the amount of sisal fiber reinforcement in biocomposites improves their mechanical properties. The incorporation of inorganic fillers helps in further modifying the mechanical properties of the biocomposites. Sisal fibers act as a nucleating agent for PLA, which results in an increase in the crystallinity of the PLA matrix These findings demonstrate how bio-based materials can improve both the environmental and mechanical properties of biocomposites, making them suitable for advanced applications such as tissue engineering and orthopedics.*

Keywords: *Biodegradability, Biomaterial, Impact strength, PLA, Sisal*

1.0 Introduction

Conventional composite materials usually consist of synthetic fibers and non-biodegradable matrices. Researchers have found that natural fibers are cost-effective, biodegradable, and lightweight, positioning them as viable alternatives to synthetic fibers[1,2]. Composite reinforcements from natural fibers can be derived from plants, such as alfa[3], bamboo[4], or ramie[5], or from animals, like silk[6] or wool[7]. There has been extensive research on natural fiber-reinforced polymer composites combined with non-biodegradable matrices. A review by Mittal *et al.*,[8] highlights recent advancements in epoxy composites reinforced with natural fibers.

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The reviews findings indicate that various characteristics of natural fibers such as fiber content, geometry (including length and diameter), surface properties, compatibility, and aggregation enhance the mechanical, thermal, and water-absorption properties of epoxy composites reinforced with these fibers. Numerous studies have compared composites made from natural and synthetic fibers[9-11]. The advantages of natural fiber-based composites over their synthetic counterparts include lower cost, biodegradability, and reduced density, among others. Recent years have seen a significant focus on the study of biodegradable polymers[12,13]. Composites incorporating these polymers can decompose and are environmentally friendly. Additionally, many investigations have examined the impact of natural fiber content on the performance of biocomposites[14-16].

Research by Torres-Telloa *et al.*,[17] found that incorporating up to 30% additional agave fiber into polyhydroxybutyrate biocomposites can improve their tensile, bending, and impact properties. Similarly, Czigány *et al.*,[18] demonstrated that increasing the amount of basalt fiber in Polylactic Acid (PLA)-based composites enhances their tensile, flexural, and impact performance. According to a study by Bax *et al.*,[19] adding flax fiber to PLA-based composites at levels ranging from 5% to 20% also improves their tensile and impact characteristics. Many studies have investigated the impact of natural fiber content on the dynamic mechanical and thermal properties of biocomposites. Gamon *et al.*,[20] found that increasing the proportion of miscanthus fiber in PLA from 10% to 40% did not affect the polymer's melting point.

PLA is among the top biopolymers for balancing rheological and physical properties. To enhance its versatility and optimize biocomposites for specific applications, various additives have been incorporated. Commonly blended fibres include glass fibres and a limited selection of natural fibres, such as wood fibres and seasonally renewable plant fibres like flax and kenaf[21]. One of the most popular natural fibre sources is sisal, which is also quite easy to grow. It is taken from the agave (*Agavesisalana*) plant leaves[22].

Our research explored how sisal fibre influences the properties of PLA matrix biocomposites. The study aimed to determine the impact of varying sisal fibre content and incorporating maize starch as filler on the mechanical properties of PLA-based biocomposites. We also investigated the effect of sisal fibre on the degree of crystallization in the PLA polymer at different fibre concentrations. The results suggest that sisal fibre could potentially replace synthetic nucleating agents in PLA.

2.0 Materials

A decorticator machine was used to mechanically extract sisal fibres. After extraction, the fibres were rinsed with water for two hours and then oven-dried at 40°C for 24 hours. Various characterization techniques were applied to examine the properties of the dried sisal fibres. The composite matrix used was PLA (Nature Works In geo



Figure 1. PLA Pellet and Sisal plant.

3100HP), with a melt flow index of 24g/10min (at 210°C and 2.16kg).

2.1 Specimen Preparation

A Lab Tech LTE 26-44 twin-screw extruder was used to process the PLA biodegradable polymer, which was blended with varying weight percentages of sisal fibre. The extruder's temperature profile was set at 190°C across all zones. The PLA was fed into the extruder using a screw feeder operating at 20 rpm, with sisal fibres carefully incorporated. The maximum fibre content, limited by manual feeding, was 10%. The resulting strands were cut into 2 mm granules using a strand pelletiser (LZ-120).

The composite specimens were molded using an Arburg Allrounder injection molding machine with a cycle time of 270 seconds. The injection pressure was set at 1200 bar, and the injection speed was 50 cm^3/s. Each specimen had an overall length of 170 mm and a nominal cross-section of 4 × 10 mm. The barrel temperature of the injection unit was maintained at 190°C, while the mould temperature was set to 25°C.

2.2 Alkaline Treatment of Fiber

The dry fiber undergoes alkali treatment, a process also recognized as Mercerization. This technique proves effective in eliminating both natural and synthetic impurities, thereby ensuring the creation of high-quality fibers that strengthen the bond between the fiber and matrix. The elimination of impurities leads to a reduction in diameter, resulting in an increased aspect ratio. This treatment contributes to enhanced mechanical properties by improving surface roughness[23-25].

The chemical reaction is

$$Fiber–OH+NaOH→Fiber\text{-}o\text{-}Na+H_2O \quad (1)$$

To remove synthetic and natural contaminants from the fiber, including dust, cellulose, hemicellulose, pectin, lignin, and dirt, the dry fibers are soaked in a 5% NaOH solution for two hours, maintaining a constant weight ratio of 1:25 between the fiber and the solution. After two hours, the fiber is thoroughly rinsed with distilled water to eliminate the solution, then air-dried for a full day. Once treated, the fibers are cut to a length of two to four millimeters.



Figure 2. Sisal fiber in NaOH solutions.

2.3 Corn Starch

Most green plants produce starch, a polymeric carbohydrate composed of multiple glucose units linked by glycosidic bonds, which serves as their primary energy storage source. Starch is a common carbohydrate in human diets, found in substantial quantities in staple foods like cassava, wheat, potatoes, and maize (corn)[26-28]. Two effective methods for creating biodegradable polymer products involve integrating Poly (Lactic Acid) (PLA) with starch or reinforcing it with cellulose. This is particularly significant because both cellulose and starch are readily available commercially and derived from renewable resources. However, despite their potential, the thermodynamic immiscibility of hydrophilic starches and hydrophobic aliphatic polyester PLA often leads to inadequate adhesion between the two[29,30].

2.4 Compounding of Specimen

Below are various proportions of mixing PLA [Matrix] with treated chopped natural fibers and filler.

A thermoplastic injection moulding equipment and moulds are used to inject the polylactic acid composite. The following are the specific prerequisites for the injection moulding of the polylactic acid composite:

- Pre-drying at +75°C for 8 hours using a dehumidifying dryer
- Temperature profile: +200/185/185/180°C
- Injection pressure maintained below 1000 bar
- Mold temperature set between +5 to +20°C

Table 1. Percentage composition of Specimen

Sample	Percentage of Sisal	Percentage of PLA	Percentage of Starch
Virgin	0	100	0
A	10	90	0
B	10	80	10



Figure 3. Injection molding equipment.

- Recommended nozzle diameter exceeding 2mm (although not mandatory)

2.5 Specimen Preparation

Specimens are prepared in accordance with ASTM standards



Figure 4. Prepared test specimen

Specimen dimensions:-ASTMD638 of tensile test

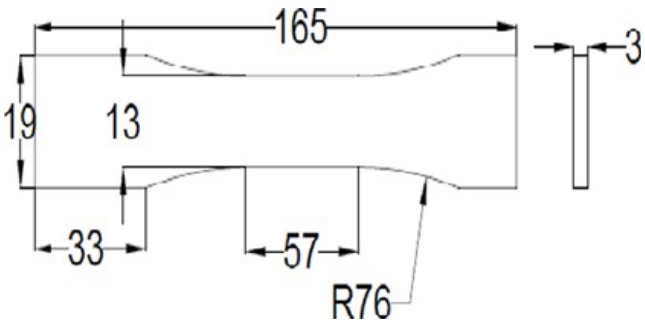


Figure 5. Tensile test specimen.

Specimen dimensions:-ASTMD790 of flexural test

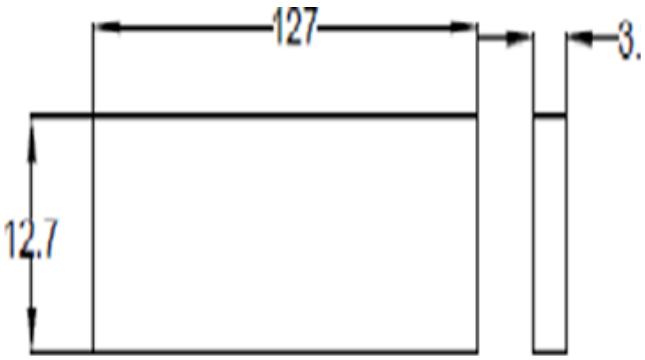


Figure 6. Flexural test specimen.

Specimen dimensions:-ASTMD256 of impact test

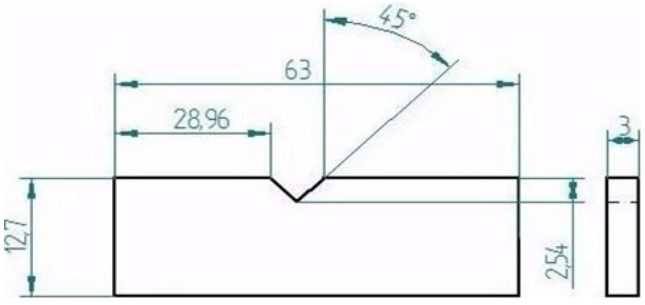


Figure 4. Prepared test specimen

3.0 Results and Discussion

3.1 Tensile Test

The tensile properties of the composites were tested using a Zwick Z050 universal load machine in accordance with ISO 638 standards. The tensile tests were conducted at room temperature with a crosshead speed of 5 mm/min. For each composite type, reinforced with different sisal fibre weight fractions (0%, 5%, 10%), five injection-molded samples were tested. The average values of the tensile characteristics were then calculated based on the results.

3.2 Flexural Test

The flexural test was performed in accordance with ISO 790 standards using the Zwick Z050 universal load machine and a three-point bending method. Composite specimens were tested at room temperature with a crosshead speed of 2 mm/min. For each composite type (5%, 10%) sisal fibre content), five injection-molded samples were tested, along with five reference specimens containing 0% fibre. After testing the samples, the average flexural values were calculated.

3.3 Charpy Impact Test

The Charpy impact test was conducted using a Ceast Resil Impactor Junior machine, with composite specimens measuring 60 × 10 × 4 mm, in accordance with ISO 256. The impact speed was set at 2.9 m/s. For each composite type, reinforced with different sisal fibre weight fractions (5%, 10%), five injection-molded samples were tested, along with a clean PLA sample. The Charpy impact strength of the composite specimens was measured, and the average value was calculated.

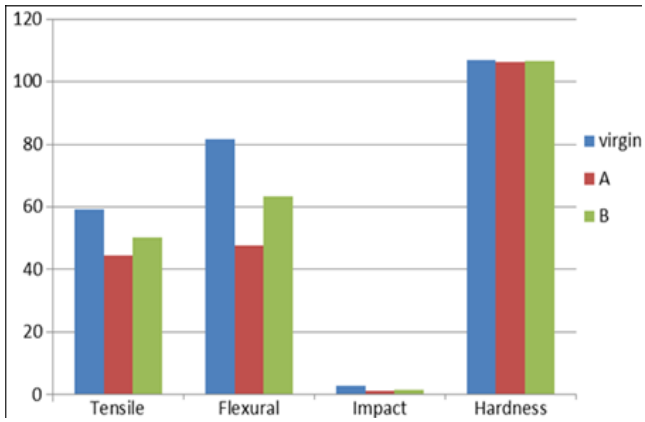


Figure 8. Mechanical properties of virgin PLA with 10% sisal fiber and 10% filler.

This study investigated the impact of sisal fibre content on the properties of PLA composites reinforced with sisal fibre. The compounding process was carried out using twin-screw extrusion, followed by injection molding to produce composite samples.

The tensile properties of PLA composites reinforced with different sisal fibre contents (5%, 10%) showed a progressive improvement in tensile strength, flexural strength, and impact resistance as the fibre content increased. Notably, PLA is naturally rigid, so the addition of sisal fibre and Maize starch significantly enhanced the Charpy impact properties, providing the material with both greater strength and impact resistance.

The investigation focuses on how the polylactic acid polymer matrix is affected by filler and sisal fibre reinforcement.

Table 2. Results obtained after test

Sample code	Tensile strength as per ASTMD638 [MPa]	Flexural strength as per ASTMD790 [MPa]	Impact Strength as per ASTMD 256 [MPa]	Rockwell Hardness as per ASTMD785 [Scale R]
Virgin	59.18	81.6	2.68	106.88
A	50.75	70.3	2.69	101.16
B	48.33	70.9	2.75	107.62

It has been observed that adding 10% sisal fibre reinforcement lowers the mechanical qualities, such as tensile and flexural strength. However, it is noteworthy to emphasize that the artificial specimen's impact strength shows a minor improvement. Comparing specimens with filler material alone to those with only sisal fibre, the tensile strength has increased by 6MPa. In addition, the specimen's impact strength has increased by 4% once the filler material was added in comparison to the PLA composition.

4.0 Conclusion

- Biodegradable Sisal/PLA composites were prepared by Injection moulding technique.
- The introduction of 10% sisal fiber has led to a minor enhancement in impact strength, paving the way for potential specimens with higher sisal fiber percentages.
- Ongoing exploration includes assessing impact strength with heightened sisal fiber percentages, such as 20%, 30%, and 40%.
- The impact of increased fiber percentages on tensile and flexural strength is a focal point for further investigation.
- In addition, 10% starch added as a filler material along with 10% sisal fibre has resulted in a 4% increase in impact strength over pure PLA. Additional research is required in order to fully assess the impact of starch on mechanical strength, with a particular focus on impact strength.

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