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Development and Mechanical Characterization of Polymer based Bio Composite Filaments for FDM Applications

Sathish Kumar Adapa[1,*], Kelli Durga Prasad[2], Suman Pandipati[3], Muddada Venkatesh[4], Venkata Maruti Prasad S[5], Satya Prasad Maddula[6], Rhoda Afriyie Mensah[7]

Abstract

Additive Manufacturing (AM) is an advanced fabrication process capable of producing complex and intricate components to meet diverse industrial and customer demands. For small-scale producers and researchers, FDM is the most straightforward, affordable, and easily accessible of the several AM processes. The majority of conventional polymer feedstocks used in FDM lack sufficient mechanical strength and thermal stability, which limits their use in load-bearing or structural components. This effort aims to design and characterize a bio composite filament for the FDM method that is sustainable and based on polymers. An NaOH solution was used to chemically treat coir fibers in order to eliminate surface deposition. This surface enhancement was thought to have improved the fiber's adherence to the matrix. To achieve uniform dispersion and high interfacial compatibility, treated fibers are next combined with PLA and a few additives via internal melt mixing. A controlled filament extrusion system was used to produce the filament, and FDM printing was used to create specimens for mechanical testing. The NaOH treatment successfully altered the coir fiber surface, enhancing mechanical interlocking and chemical bonding with the PLA matrix, according to mechanical characterization. The PLA-coir bio composite's improvement in tensile strength from virgin PLA (60.55 MPa) to 67.14 MPa validates the treated natural fiber's capacity to reinforce. On the other hand, because of the material's intrinsic porosity and the local stress concentration brought on by the fibers in the printed structures, several of the compressive strength values showed a minor drop when compared to pristine PLA. Additionally, their surface smoothness and dimensional accuracy were adequate for FDM applications. As a result, the generated PLA-coir bio composite filaments are environmentally benign, biodegradable, and compatible with any standard FDM equipment without necessitating any changes to the FDM processing settings. These results highlight natural fiber-supported PLA as a practical, environmentally friendly substitute for synthetic polymer filaments, enabling small-scale vendors and researchers to produce lightweight, sustainable parts with thousands of times greater tensile performance and environmental impact.

Keywords: FDM, coir fiber, PLA, filaments, tensile properties, compression properties

***Author for Correspondence**
Sathish Kumar Adapa

[1-4]Assistant Professor, Department of Mechanical Engineering, Aditya Institute of Technology and Management, Chakipalle, Andhra Pradesh, India
[5]Assistant Professor, Department of Chemistry, Aditya Institute of Technology and Management, Chakipalle, Andhra Pradesh, India
[6]Assistant Professor, Department of Aero Space Engineering, School of Technology, GITAM, Hyderabad, Telangana, India
[7]Assistant Professor, Department of Civil, Environmental and Natural Resources Engineering, Lulea University of Technology, Lulea, Sweden

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INTRODUCTION

In the current industrial landscape, most manufacturers are striving to reduce inventory, material wastage, tooling requirements, labor, and overall production costs. Such goals can be effectively addressed through advanced manufacturing (AM) processes. Among these, 3D printing, also known as additive manufacturing, has gained significant attention as it fabricates components by depositing material layer by layer, thereby fulfilling many industrial requirements. Several AM techniques are available, of which FDM is one of the most economical and versatile, particularly suitable for small- scale applications [1]. In FDM, metals, ceramics, and polymers can be used as feedstock materials. Polymers are especially popular due to their advantageous properties, including low weight, ease of shaping, wide availability, and good surface aesthetics. Among the various polymers, polylactic acid (PLA) is widely utilized because it is biodegradable and eco-friendly. However, PLA suffers from relatively poor mechanical and thermal properties compared to other polymers [2].

To overcome these limitations, researchers have investigated reinforcing PLA with other polymers such as polypropylene and acrylonitrile butadiene styrene (ABS), which improve its mechanical and thermal performance [3, 4]. Nevertheless, these materials are not biodegradable or environmentally friendly, which limits their sustainability. Consequently, research efforts have shifted toward reinforcing PLA with natural Fibers such as hemp, jute, flax, bamboo, yucca, rice husk, sugarcane, and wood Fibers [5–8]. While such reinforcements are eco-friendly, they often fail to significantly improve the mechanical properties of PLA due to challenges such as poor interfacial bonding between the polymer matrix and Fibers, as well as clogging and agglomeration issues during the printing process. The present study focuses on the development and mechanical characterization of PLA-based filaments reinforced with coir Fibers and coupling agents for FDM applications. Coir Fibers were first extracted and treated with NaOH solution to remove impurities and enhance surface roughness. The treated Fibers were then compounded with PLA in an internal melt mixer, and composite filaments were produced using a filament extrusion setup. Finally, the PLA composite samples were fabricated using FDM and evaluated through mechanical testing, with results compared against those of pure PLA [9].

MATERIALS AND METHODOLOGY

Materials

PLA granules (density: 1.24 g/cm³) were used as the matrix material, while coir fibres (density: 1.15 g/cm³; average length: 300 μm) served as the natural bio-reinforcement. Polyethylene glycol (PEG, density: 1.05 g/cm³) and maleic anhydride (MA, density: 1.48 g/cm³) were employed as coupling agents to enhance the interfacial bonding between the matrix and the reinforcement [10].

Coir Fiber Processing and Specimen Fabrication

Coconuts were collected and sun-dried for 30 days, after which coir fibres were extracted from the dried shells. A 5 wt% NaOH solution was prepared by dissolving NaOH pellets in 1000 ml of distilled water, and the coir fibres were immersed in the solution at 50 °C for 3 hours [11]. The treated fibres were then washed with acetone to remove any residual NaOH, followed by repeated washing with distilled water until the pH was reduced to below 7. Finally, the fibres were dried in a hot-air oven at 60 °C for 24 hours, milled into small fibres (~300 μm), and stored in airtight containers.

To prepare the PLA composite blend, the treated fibres were blended with PLA granules along with PEG and MA [12] additives using an internal melt mixer, which was subsequently chopped into small pieces. These composite pellets were then fed into the hopper of a filament extrusion unit to produce continuous PLA composite filaments of uniform diameter of 1.75 mm. The extruded filaments were carefully spooled and used as feedstock material in a FDM setup. Mechanical test specimens were fabricated through FDM under controlled processing parameters to ensure dimensional accuracy and consistency in the printed parts as shown in Figure 1.

Experimental Setup

The tensile specimens (ASTM D638) and compression specimens (ASTM D256) were tested using an INSTRON universal testing machine (Figure 2 (a-b)) with a load capacity of 30 N and a crosshead feed rate of 2 mm/min.

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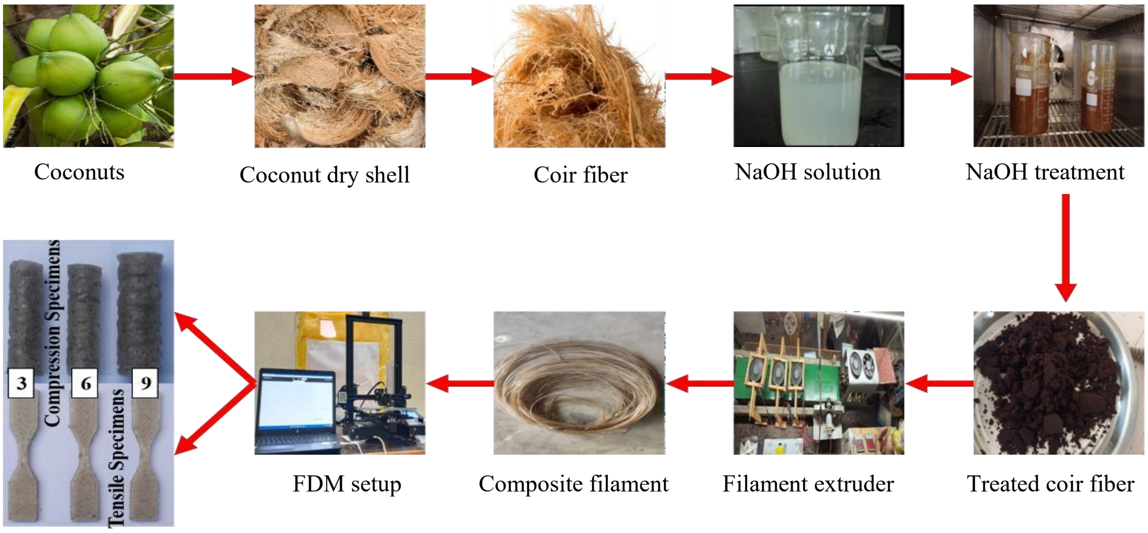

Figure 1. Processing of coir fibres and fabrication of PLA composite samples by FDM.

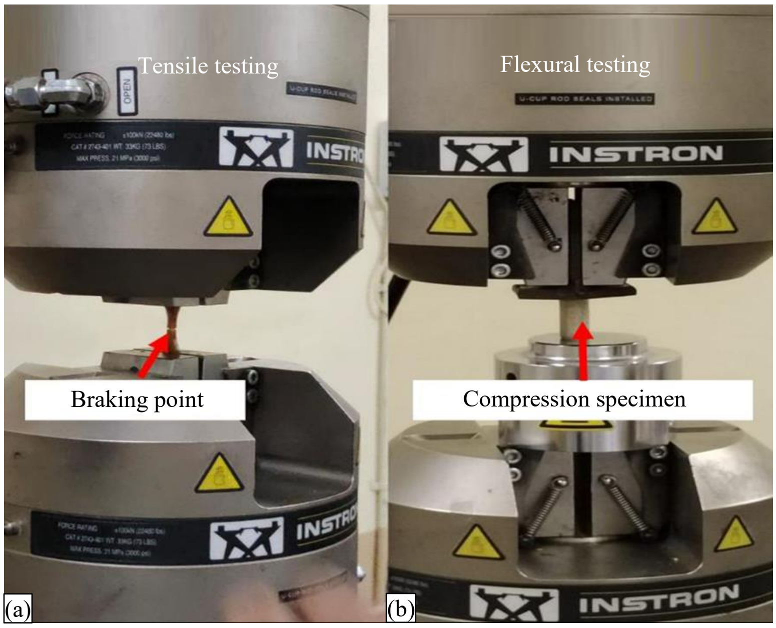

Figure 2. (a) Tensile testing (b) Compression testing.

Table 1. Tensile and Compression Test Results of PLA and PLA Composite Samples.

Mechanical Property	**Sample Type**							
	Pure PLA		***CF 03 wt%***		***CF 06 wt%***		***CF 09 wt%***	
	Mean	*Std. Dev*	*Mean*	*Std. Dev*	*Mean*	*Std. Dev*	*Mean*	*Std. Dev*
	Tensile Test (ASTM D638)							
UTS (MPa)	60.55	±2.79	67.14	±5.09	65.64	±2.35	54.03	±2.34
TM (MPa)	912.33	±2.13	986.77	±4.48	975.18	±7.17	799.97	±7.64
	Compression Test (ASTM D695)							
CS (MPa)	90.52	±2.31	51.970	±3.55	41.600	±2.00	55.620	±2.42
CM (MPa)	1320.01	±2.57	860.160	±5.53	730.280	±3.58	925.120	±8.48

The ultimate tensile strength (UTS), tensile modulus (TM), compressive strength (CS), and compressive modulus (CM) of FDM-printed PLA and PLA composite specimens were evaluated, and the results are summarized in Table 1. For each weight percentage, three specimens were tested to ensure repeatability and reliability of the data. The samples were fabricated using the following FDM process parameters: layer thickness of 0.2 mm, nozzle temperature of 205 °C, and infill density of 100%. To minimize variability, all specimens were conditioned under controlled laboratory conditions prior to testing.

RESULTS AND DISCUSSIONS

NaOH Effect on Coir Fibers

Coir fiber is composed of approximately 50% cellulose, 34% lignin, 12% hemicellulose, and 4% pectin along with other soluble compounds. When coir Fibers are treated with a NaOH solution, hemicellulose, lignin, pectin, and surface impurities are effectively removed [13]. This treatment produces a rougher Fiber surface, as shown in Figure 3 (a–b), which enhances interfacial adhesion between the matrix and reinforcement, thereby improving the mechanical properties of the composite. Energy-dispersive X-ray spectroscopy (EDX) analysis revealed that both untreated and NaOH-treated Fiber consist mainly of carbon (C) and oxygen (O), originating from cellulose. However, the treated Fibers exhibited a decrease in C and O content compared to the untreated fibres as shown in Figure 3(b, d). This reduction confirms the removal of hemicellulose, pectin, and lignin, leaving cellulose as the dominant constituent in the treated Fibers [14].

Tensile Properties

The Figure 4 presents the tensile stress–strain responses of pure PLA and PLA reinforced with varying coir fiber contents (3, 6, and 9 wt%). The curve of pure PLA exhibits a maximum tensile stress of 54.03 MPa at a strain of ~0.06 mm/mm, beyond which the material undergoes brittle failure with limited elongation. This characteristic sharp drop reflects the inherently brittle nature of PLA, restricting its load-bearing capacity in structural applications [11].

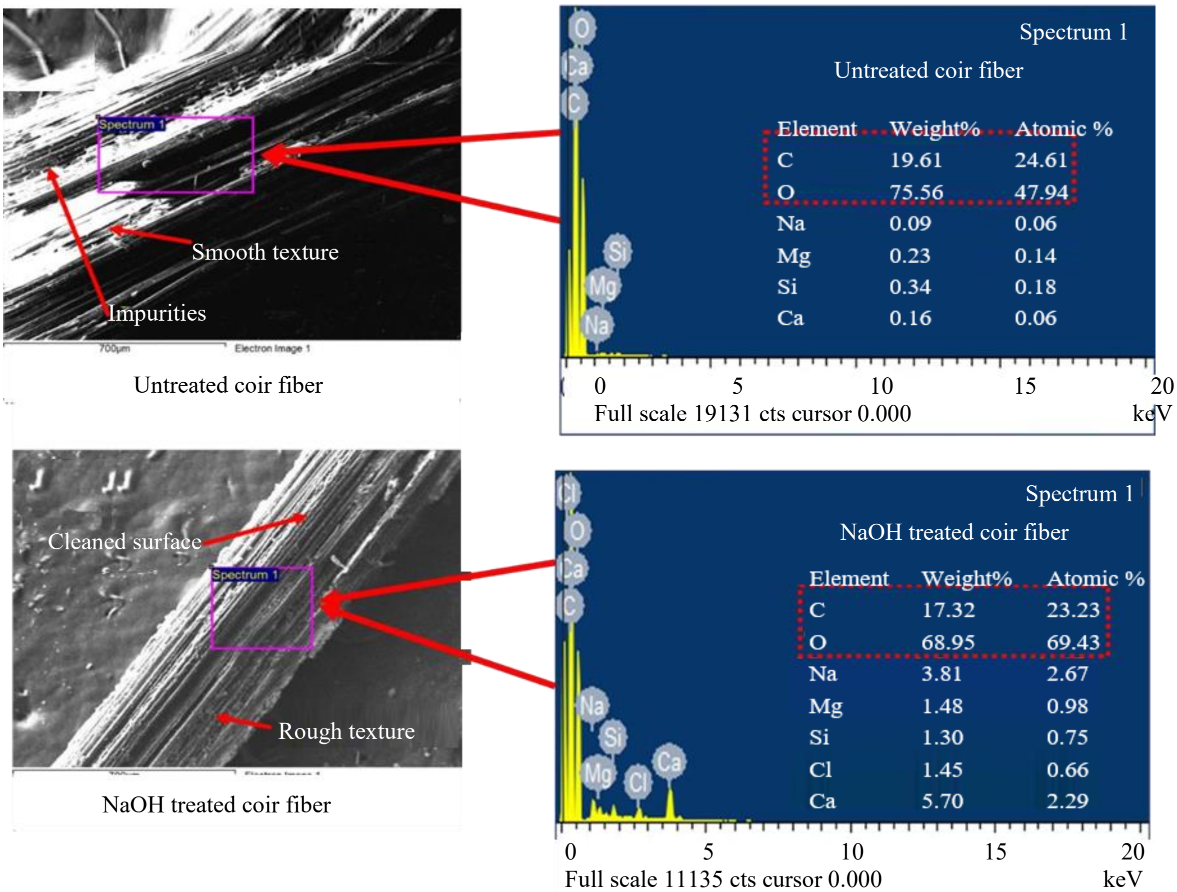

Figure 3. Coir fiber SEM and EDX images of (a-b) Untreated (c-d) NaOH treated.

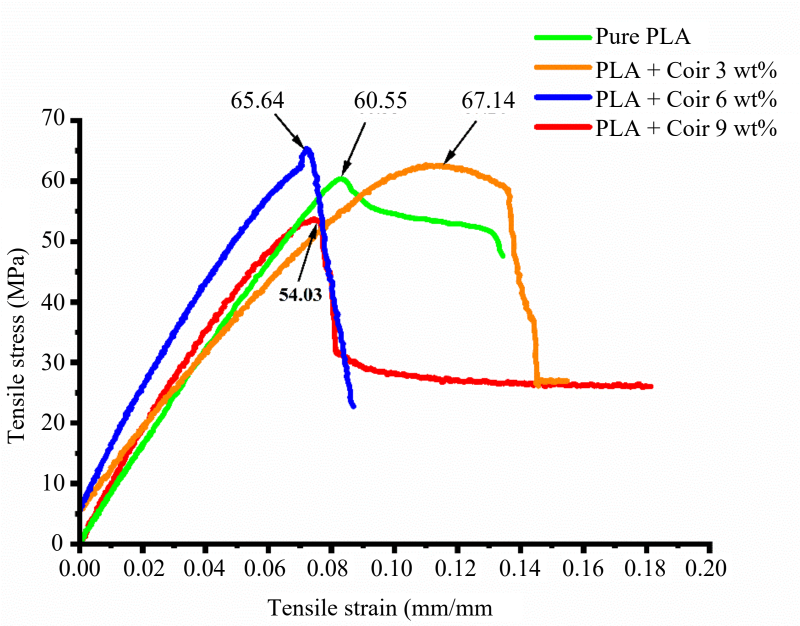

Figure 4. Stress vs strain curve of PLA and PLA composite samples.

In contrast, the incorporation of coir fibers significantly alters the stress–strain profile. At 3 wt% coir reinforcement, the composite shows a higher ultimate tensile stress of 60.55 MPa, combined with an increased strain at break (~0.14 mm/mm). This improvement indicates better load transfer from matrix to fiber, while the extended ductility suggests fiber–matrix interaction contributes to energy absorption before failure.

The 6 wt% coir composite demonstrates further enhancement, achieving a peak tensile stress of 65.64 MPa, which is ~21% higher than pure PLA. However, the corresponding strain at break (~0.08 mm/mm) is lower compared to the 3 wt% composite, implying that increased fiber loading improves strength but reduces elongation due to fiber agglomeration and stress concentration effects. Interestingly, at 9 wt% coir, the composite reaches the highest tensile strength of 67.14 MPa, but the strain at break (~0.07 mm/mm) decreases further. This trend suggests that while additional fiber loading maximizes strength through improved stress transfer, it simultaneously reduces ductility as excessive fiber content may cause poor dispersion, weak interfacial bonding, and micro void formation [12].

This improvement can be attributed to the uniform dispersion of the reinforcement and the presence of coupling agents, which enhance interfacial adhesion between the polymer matrix and the fibres, thereby resulting in improved ultimate tensile strength (UTS) of the composites [15]. Furthermore, the tensile modulus of the PLA composites was also higher than that of the pure PLA samples.

Whereas, the pure PLA samples extension is more as compared to PLA composite samples as shown in Figure 5. This is due to fact that, PLA is a ductile polymer matrix capable of undergoing significant deformation before failure. When coir Fibers are incorporated, the rigid and brittle nature of the Fibers restricts the mobility of the PLA polymer chains, reducing the overall elongation capability of the composite [8]. Additionally, the Fiber–matrix interface acts as a stress concentration region, where micro-cracks can initiate under tensile loading. As a result, the composite fails at lower extension compared to pure PLA, even though the reinforcement improves stiffness and load-bearing capacity [16].

Compression Properties

The compression strength of pure PLA samples printed by FDM possess higher than that of PLA reinforced coir Fibers and additives as shown in Figure 6. This due to fact that, the incorporation of natural Fibers introduces discontinuities and weak interfaces within the polymer matrix [17]. Under compressive loading, these Fiber–matrix interfaces are more prone to debonding and micro-crack initiation, which reduces the ability of the composite to withstand compressive stress. In addition, coir Fibers possess lower stiffness and strength in compression compared to PLA, and their hollow, porous structure can act as stress concentrators. As a result, instead of reinforcing the matrix, the Fibers reduce the overall compressive strength of the composite despite improving tensile properties [15].

From the Figure 6, pure PLA exhibits the highest compressive strength of 90.52 MPa, reflecting its relatively high stiffness and load-bearing capacity. The stress–strain curve shows a steep initial slope and a pronounced peak, typical of a brittle thermoplastic polymer that undergoes limited plastic deformation before failure. Upon introducing coir fibers into the PLA matrix, a progressive reduction in compressive strength is observed.

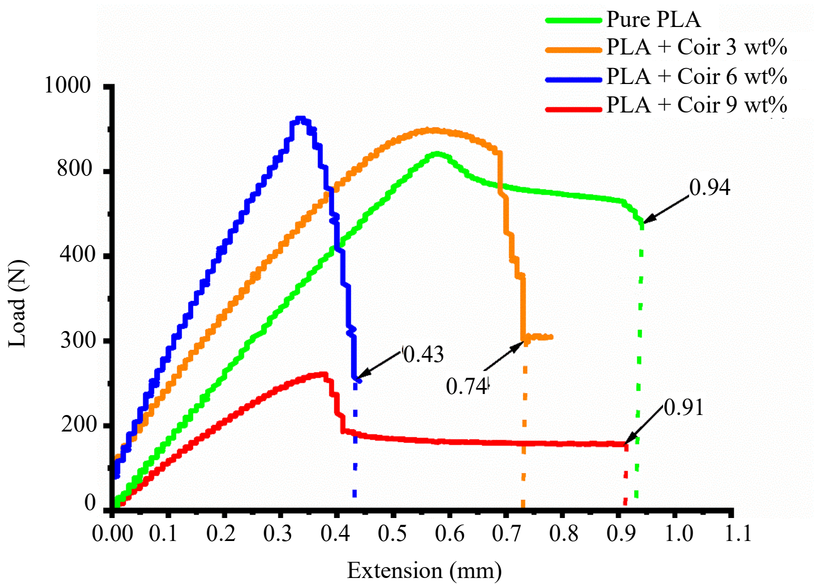

Figure 5. Load vs extension plot for PLA and PLA composite samples.

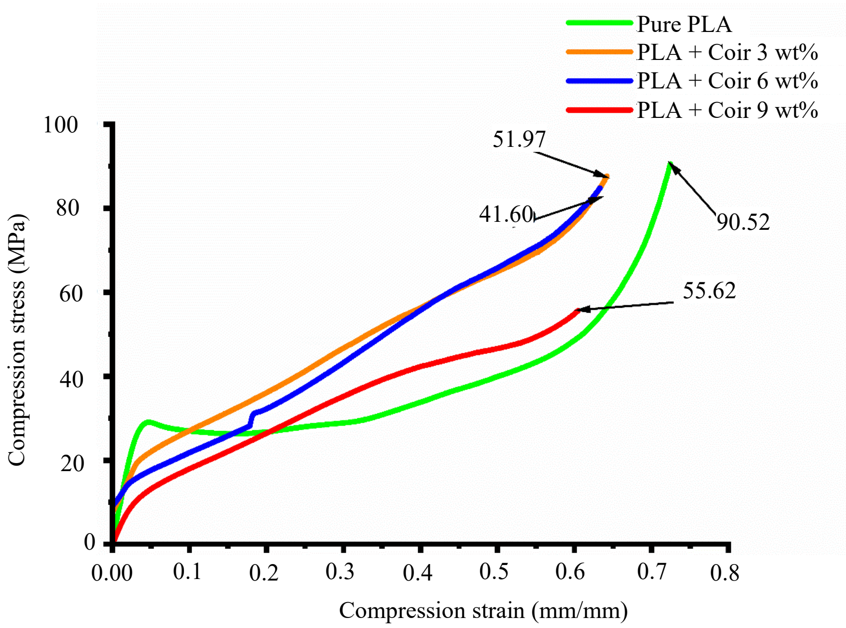

Figure 6. Compression stress vs compression strain graph of PLA and PLA composite.

The composite with 3 wt% coir achieves a peak compressive stress of 51.97 MPa, representing a decrease of approximately 43% compared to pure PLA [18]. The addition of natural fibers disrupts the continuity of the PLA matrix and introduces fiber–matrix interfaces that may act as stress concentrators during compression. The reduction in strength at low fiber loadings suggests that the interfacial bonding between the hydrophobic PLA and hydrophilic coir fibers is insufficient to enable effective stress transfer [15].

Further increasing the coir content to 6 wt% results in a further decrease in compressive strength to 41.60 MPa, the lowest among all compositions tested. This pronounced reduction can be attributed to fiber agglomeration and increased void content, which are common at higher fiber loadings. These structural imperfections weaken the interfacial adhesion and hinder homogeneous stress distribution within the composite. Additionally, the mismatch in stiffness between the PLA matrix and the coir fibers can lead to micro-crack formation at the fiber–matrix interface under compressive loading [17]. Interestingly, a slight recovery in compressive strength is observed at 9 wt% coir, where the material exhibits a peak strength of 55.62 MPa. This improvement compared to the 6 wt% composite may result from enhanced fiber–fiber interactions and a more interconnected reinforcement network at higher fiber concentrations, which can partially compensate for the poor matrix–fiber adhesion. The stress–strain curve for this composition shows a smoother deformation profile, indicating some energy absorption through fiber pull-out and matrix deformation mechanisms [14].

Despite the marginal improvement at higher fiber loading, all coir-reinforced composites demonstrate lower compressive strength than neat PLA. This trend contrasts with many synthetic fiber-reinforced composites, where reinforcement generally enhances strength. In this case, the reduction in performance can be attributed to the incompatibility between the PLA matrix and untreated coir fibers, as well as the absence of chemical coupling agents to promote adhesion. The hydrophilic nature of coir fibers leads to poor wettability by the hydrophobic PLA, resulting in weak interfacial bonding and premature failure under compressive stress [7, 10].

CONCLUSIONS

This study successfully developed and characterized PLA-based bio-composite filaments reinforced with NaOH-treated coir fibers for FDM applications. The alkali treatment of the coir fibers effectively removed impurities and improved surface roughness, resulting in enhanced interfacial bonding between the fibers and the PLA matrix. The composites containing 3 wt% and 6 wt% coir fibers exhibited higher ultimate tensile strength compared to pure PLA, demonstrating the reinforcing potential of treated natural fibers. However, a reduction in compressive strength was observed across all fiber-reinforced samples, indicating the need for optimization in fiber content and dispersion to achieve balanced mechanical properties. Overall, the developed polymer-based bio-filaments are eco-friendly, biodegradable, and hold significant potential for use in FDM applications, particularly for researchers and small-scale vendors.

Further research can focus on optimizing fiber treatment methods, fiber loading, and processing parameters to achieve superior mechanical and thermal properties. The development of hybrid composites using coir fibers in combination with other natural or nano-fillers could lead to enhanced performance suitable for a wider range of engineering applications. Additionally, exploring the biodegradability, recyclability, and long-term stability of these materials will strengthen their position as eco-friendly alternatives in the 3D printing industry. With continued innovation, PLA/coir fiber composites have the potential to replace conventional plastics in research, prototyping, and small-scale production, contributing significantly to a more sustainable manufacturing ecosystem.

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