



NATURAL FIBER-REINFORCED PLA COMPOSITES FOR FUSED DEPOSITION MODELING: A CRITICAL ASSESSMENT AND EXPERIMENTAL FEASIBILITY OF JUTE FIBER REINFORCEMENT

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ABSTRACT

Natural fiber-reinforced polymer composites for fused deposition modeling (FDM) are getting more attention due to growing need for ecofriendly materials in additive manufacturing. This study critically evaluates polymer filaments and natural fiber-reinforced polymer composite filaments, mainly focusing on FDM process parameters to evaluate the collective impact on mechanical, thermal, and microstructural performance. Existing literature on natural fiber reinforcement is systematically analyzed to identify key parameters governing to print feasibility, interlayer bonding, and part quality. The study led to the development of short jute fiber-reinforced PLA composite filaments and experimentally evaluated the performance of the developed materials. The results prove that fiber particle size and fiber volume fraction play a decisive role in interfacial adhesion and overall mechanical performance of FDM printed parts. Optimized processing parameters, low to moderate fiber content (1-5wt.%) and fine fiber particle sizes improve mechanical performance without compromising printability. Conversely, higher fibers content or bigger particle sizes induce agglomeration, weak interlayer bonding, and lead to reduced mechanical performance. This study emphasizes the crucial role of moisture control and filament conditioning in attaining stable extrusion of Jute natural fiber reinforced PLA filaments. This work carries a comprehensive understanding of the relationships between process, structure, and properties as well as practical guidance for developing high performance, natural composite filaments for advanced and sustainable FDM applications.



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1. INTRODUCTION

As Industry 4.0 grows, sustainability is becoming more and more important in engineering and industrial applications. This means using less material, streamlining production processes, and using less energy when designing and producing a product all without compromising the end product's functionality. Without giving sustainable material and energy use due consideration, humans have regularly used natural resources for their own interests since the start of the Industrial Revolution. Our world's future depends on our adopting more responsible behaviors [1]. Additive manufacturing (AM) has emerged as a transformative production technology capable of addressing several sustainability challenges associated with conventional manufacturing. Figure 1 shows the time evolution of

Additive manufacturing early technologies such as RP, SLA, SLS, and FFF in the 1980s and 1990s to commercialization in the 2000s and modernization with hybrid manufacturing and AI integration in the 2020s. Among the various AM techniques, fused filament fabrication (FFF) remains the most widely adopted due to its cost effectiveness, material versatility, and operational simplicity [2]. The growing integration of AM within sustainable manufacturing frameworks has accelerated research into environmentally friendly materials, particularly polymer based and composite filaments. In this context, the development and optimization of natural fiber-reinforced polymer composites for FFF offer significant potential for reducing environmental impact while achieving acceptable mechanical and functional performance. These aspects form the foundation for the present study.

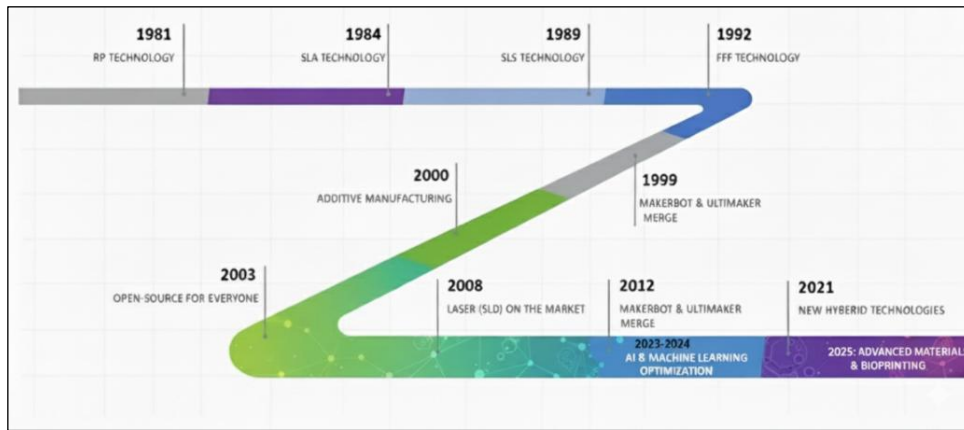


Figure 1: Time evolution of the AM machines.
Source: Authors, (2026).

II. FUSED DEPOSITION MODELING

Fused Deposition Modeling (FDM), introduced by Stratasys in 1992, is an additive manufacturing technique that fabricate a 3D prototype and products layer by layer using a computer aided process [3]. FDM is also known as Fused Filament Fabrication (FFF) one of the most widely adopted additive manufacturing methods due to its capability to fabricate complex parts with relatively low cost and high flexibility in material [4]. FDM is an additive manufacturing (AM) where material is deposited in successive layers by layer to produce a final part. The process primarily supports thermoplastic polymers and their composites in specialized systems, metal or fiber reinforced filaments. As illustrated in Figure 2, the FDM process begins with the create a 3D model using computer aided design software. The CAD model is converting into STL file and then transformed into machine readable G-code using various slicing software, which divides the geometry into discrete layers and generate the toolpath for material deposition. During printing, a thermoplastic filament is heated at glass transition temperature and extruded through a nozzle onto a build platform, where successive layers bond together to form the final component [5].

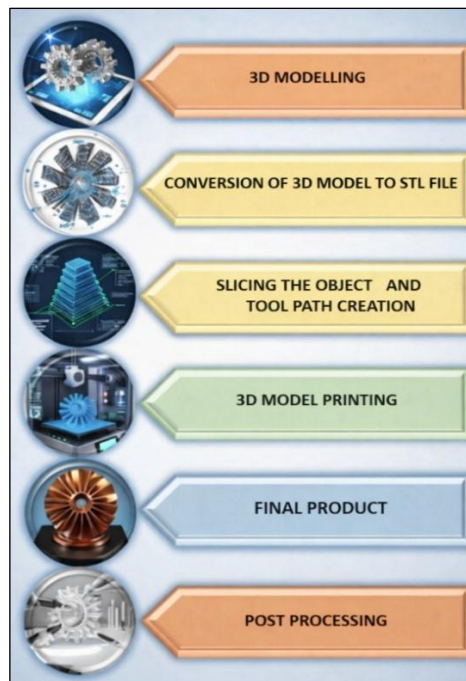


Figure 2: Process flow diagram of fused deposition modeling (FDM).
Source: Authors, (2026).

For manufacturing components using FDM, multiple CAD software applications are employed to generate a printable design in formats compatible with FDM machines. The designs are processed by slicing software and then they are exported into the printing machine [6]. Figure 3 Streamlined flows of FDM Process demonstrating the transformation of a CAD model into a file format compatible with RP Machine, subsequently followed by slicing through numerous software tools to create the toolpath. The parameters for polymer printing, such as nozzle temperature, are established to produce the final printed component.

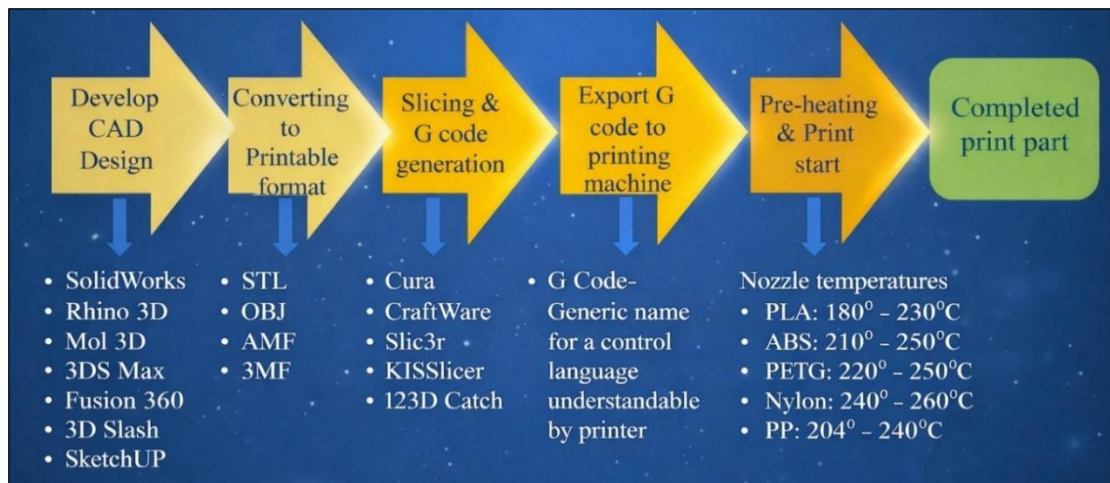


Figure 3: Streamlined flowcharts of the fused deposition modeling (FDM) process illustrating the use of different software applications and file formats in three-dimensional printing (STL-Stereolithography, AMF-Additive manufacturing file, OBJ-Wavefront 3D object, and 3MF-3D manufacturing format).

Source: Authors, (2026).

II. PROCESS PARAMETERS OF FDM AND THEIR IMPACT

Fused deposition modeling (FDM) is finding the application in many industries such as manufacturing, rapid prototyping, and the medical industry, particularly during emergency situations such as the COVID-19 pandemic for the production of personal protective equipment. To reduce production time and cost while improving part quality, the optimization of FDM process parameters is essential. Typically, thermoplastic filaments with diameters ranging from 1.75 to 3.0 mm are used. The FDM process can be broadly divided into three stages: pre-processing, production, and post-processing [5]. The quality of FDM-printed parts is depended on several process parameters, including extrusion temperature, layer height, printing speed, nozzle diameter, raster angle, build orientation, and infill characteristics. These factors have a direct impact on the quality of interlayer bonding, surface roughness, the accuracy of the dimensions, and the formation of defects [7]. To determine how effectively the printed part sticks to itself and to the layers next to it, it is needed to know the properties of each deposited layer. This affects how successfully the printed part works mechanically [8]. Figure 4 illustrates the cause-and-effect relationship between key FDM process parameters and part quality as well as mechanical properties.

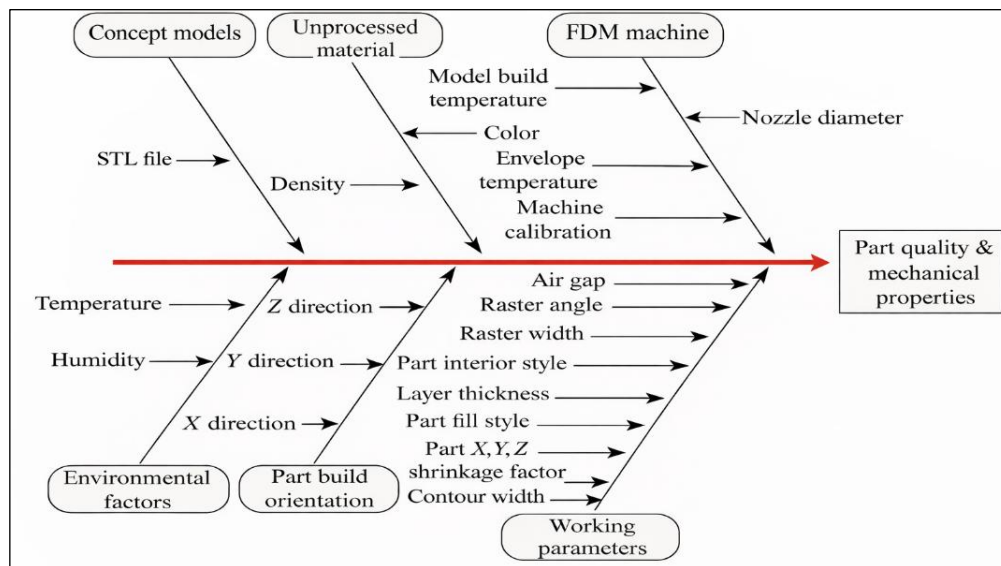


Figure 4: Cause-and-effect diagrams illustrating the influence of FDM process parameters on part quality and mechanical properties.

Source: [9].

Mechanical strength, dimensional precision, and surface finish are particularly influence by nozzle diameter, layer thickness, build orientation, and infill density. In addition to machine and material settings, environmental conditions such as ambient temperature and humidity have also been reported that they significantly influence printing consistency and bonding quality [10]. Recent studies emphasize the significant of optimizing parameter combinations using methodologies such as design of experiments (DOE) and computational modeling to improve part performance for specific applications [11]. Adjustments in layer thickness, raster angle, and infill pattern have been shown to significantly enhance strength, durability, and microstructural integrity in FDM-printed parts [12]. A thorough examination of these interactions allows researchers and manufacturers to utilize structured models and multi objective optimization techniques for consistent and superior production. Figure 5 presents a fishbone (cause-and-effect) diagram show the importance of preprocessing parameters that significantly affect the mechanical properties of FDM-fabricated components.

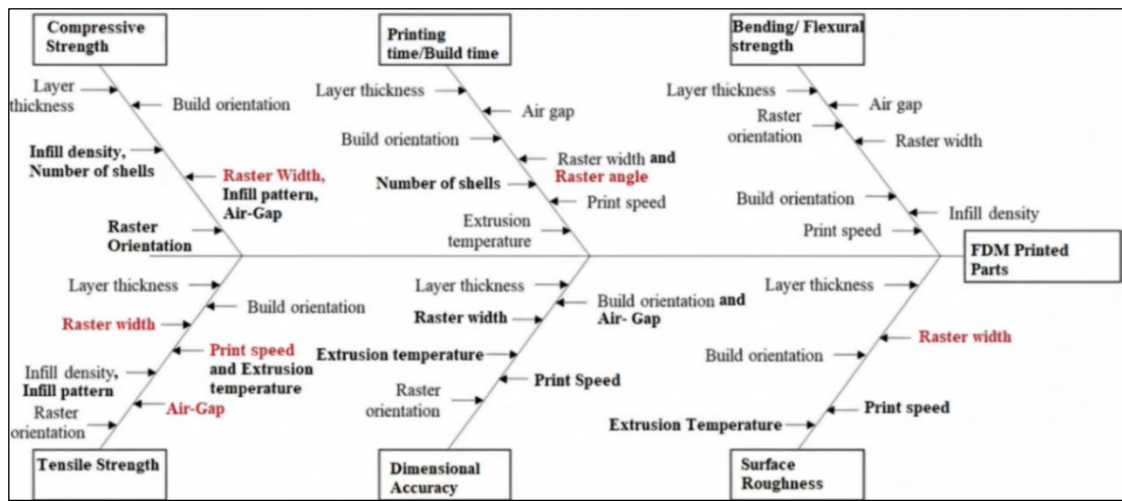


Figure 5: Fishbone diagram illustrating the effect of preprocessing parameters on the mechanical properties of FDM parts.
Source: [13].

Table 1: Extensive recent research on the parameters of the FDM process and their influences on the mechanical properties.

Effect of Process Parameter	Cause and Effect in Mechanical Properties
Extrusion Temperature [14][15], [16], [17]	High temperatures enhance tensile strength and modulus by increasing inter-layer fusion and filament bonding; excessively high temperatures destroy the material, making bonds weaker.
Layer Height[15], [16], [17], [18]	Lower layer heights increase tensile strength and flexural strength by increasing the number of layers and interface bonding area; higher layer heights decrease bonding quality.
Printing Speed[15], [16], [17], [18]	Moderate to low speeds enhance strength and elasticity because they provide increased heat transfer and material deposition to attain good bonding; high speeds yield weak bonds and voids.
Infill Density[16], [18], [19], [20]	Higher infill densities (up to 100%) significantly improve tensile and flexural strength due to increase in internal material volume, less voids and increased load bearing.
Infill Pattern[16], [18]	Rectilinear/linear infill patterns enhance the strength by aligning loading direction with filaments and optimising the stress distribution and minimising stress concentrations.
Nozzle Diameter[16], [20], [21]	A 0.4 mm nozzle balances detail and strength; smaller diameters enhance filament bonding and surface finish, but very small sizes risk clogging and inconsistent extrusion.
Raster Angle[17], [18], [21]	Raster angles near 45° distribute load evenly across layers, reducing anisotropy and stress concentration, thus improving tensile strength and modulus.
Build Orientation[15], [16], [17], [18], [21]	Flat XY Orientation improves mechanical strength because layers are aligned with the load direction, enhancing interlayer bonding; vertical orientation weakens bonds and promotes delamination.

Source: Authors, (2026).

Overall, mechanical performance in FDM is strongly governed by parameters that affect interlayer bonding and void formation. Table 1. summarizes recent research on key FDM process parameters and their influence on mechanical properties. Commonly used thermoplastic materials in FDM include PLA, ABS, PET-G, and PP. selecting the wrong parameter weakens interlayer adhesion, increases anisotropy, and results in reduction in mechanical performance [22]. Experimental study shows that infill density and pattern have major influence the mechanical strength. Infill densities of 20%, 50%, and 100% using infill patterns like line, rectilinear, and honeycomb indicated that a rectilinear infill with 100% density produced the highest tensile strength in desktop FFF systems [23].

Table 2: FDM Materials and Corresponding Process Parameters Investigated in Literature.

FDM Material	Infill %	Raster angle	Layer thickness	Print Speed	Nozzle Temp.	Air Gap
PET-G, PLA[22]	Yes	Yes	Yes	-	Yes	-
ABS[23]	Yes	-	-	-	-	-
PETG[24]	-	-	Yes	-	Yes	-
Carbon fibre reinforced[25]	-	Yes	Yes	Yes	-	-
PLA[26]	Yes	-	Yes	-	-	-
PLA, PETG, and Carbon fiber reinforced PETG[27]	-	-	Yes	-	-	-
PLA+[28]	Yes	-	-	Yes	Yes	-
PLA[29]	Yes	Yes	Yes	-	-	-
ABS[30]	Yes	Yes	Yes	-	-	-
ABS[31]	-	-	Yes	-	-	-
ULTEM 9085[32]	-	Yes	-	-	-	Yes

Non-metallic material[33]	Yes	-	Yes	-	-	-
ABS, PETG, Multi-material[34]	Yes	-	-	-	Yes	-
PLA[35]	-	Yes	Yes	-	-	-
Metal/polymer composites[36]	-	Yes	Yes	-	Yes	-
PET-G[37]	-	Yes	-	-	-	-
PLA[38]	Yes	-	-	Yes	-	-
PLA[39]	Yes	Yes	Yes	Yes	-	-
ABS[39]	Yes	Yes	Yes	Yes	-	-
PEEK[39]	Yes	Yes	Yes	Yes	-	-
PETG[39]	Yes	Yes	Yes	Yes	-	-
PLA[40]	Yes	-	Yes	Yes	Yes	-
PLA[14]	-	Yes	-	-	-	-

Source: Authors, (2026).

Table 2 shows a summary of the FDM materials and process parameters that have been studied in the literature. These studies collectively suggest that parameter optimization strategies differ based on material type and application requirements. Recent progress includes improving the conditions for extruding PLA composite filaments without reinforcement and comparing their results to international standards for FFF [41]. Adding more heating units near the nozzle has also been shown to improve the quality of the parts by keeping the material that is deposited close to its glass transition temperature (T_g). This makes molecular surface diffusion faster, makes mechanical anisotropy less, and makes interlayer bonding stronger. These kinds of changes are especially promising for large-scale FDM applications, where better mechanical properties and dimensional accuracy are very important[42].

IV. FILAMENT MANUFACTURING OF NATURAL FIBER-REINFORCED POLYMERS: PROCESS EVOLUTION AND KEY PARAMETERS

The filament is the dominant element of the FDM method. The filament is usually made of pure polymer with a low melting point. There are instances in which pure polymer strength needs to be increased. As a result, numerous researchers have created polymer composites as materials for 3D printing filaments by fusing the matrix and improving the constituent parts to create systems with structural and functional advantages that cannot be obtained by using a pure polymer. Polymer composites are engineered materials composed of a polymer matrix reinforced with a secondary material, such as fiber, to enhance their mechanical, thermal, or functional properties. For decades, synthetic fiber like carbon fiber and glass fiber have been the industry standard for reinforcement due to their superior strength and stiffness [43]. ABS are mostly used in industry. Unfortunately, those materials are not environmentally friendly, and therefore the need to develop more biodegradable counterparts [44].

Acrylonitrile butadiene styrene (ABS) is extensively used in industrial applications; however, it is not environmentally friendly, leading to increasing interest in biodegradable alternatives [45]. PLA is biodegradable, but making it releases CO_2 into the air (about 1.3 kg CO_2 equivalent per kg of polymer). To make it better, bio-based fillers and reinforcements need to be used [46],[47]. However, because each reinforcement in a composite polymer will provide a different set of characteristics, the process of creating composite filaments needs to be approached carefully first. Filament production typically involves material preparation, extrusion, cooling, diameter regulation, and spool winding. Modern extrusion systems use real-time feedback control to maintain uniform diameter (usually 1.75 or 2.85 mm). Figure 6 shows the natural fiber reinforce filament development process. Melt-compounding techniques allow polymer blending with additives like nanofillers or fiber to enhance mechanical or thermal properties [48].

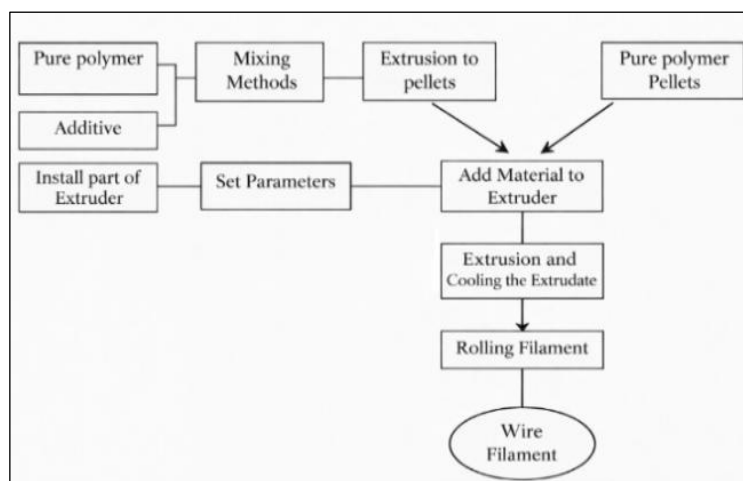


Figure 6: Schematic representation of the filament development process for natural fiber-reinforced composites.

Source: [48].

IV.1 EFFECT OF FIBER ORIENTATION

The mechanical properties of PLA matrix, including impact resistance, tensile strength, and flexural strength, can be greatly affected by modifying the orientation of fiber within it [49]. A certain mechanical property, such tensile strength, can be improved by suitable orientation along the printing direction. This study investigates the impact of fiber orientation on the durability of PLA reinforced with unidirectional continuous kenaf fibers at high temperatures. Composite samples were fabricated with fibers oriented at 0° , 45° , or 90° relative to the tensile force [50].

In a typical continuous fiber FDM system, as illustrated in Figure 7(a), PLA filament is fed into a heated nozzle where it melts, while a continuous fiber bundle is simultaneously guided into the heating zone. Within the nozzle, the molten polymer impregnates the fiber, forming a fiber–matrix composite that is deposited layer by layer. Figure 7(b) shows the corresponding printing process. Experimental studies using custom dual-feed FDM systems have confirmed that fiber orientation strongly affects mechanical properties, with 0° alignment providing the highest strength. This approach offers a scalable and cost-effective alternative to conventional composite manufacturing techniques [51].

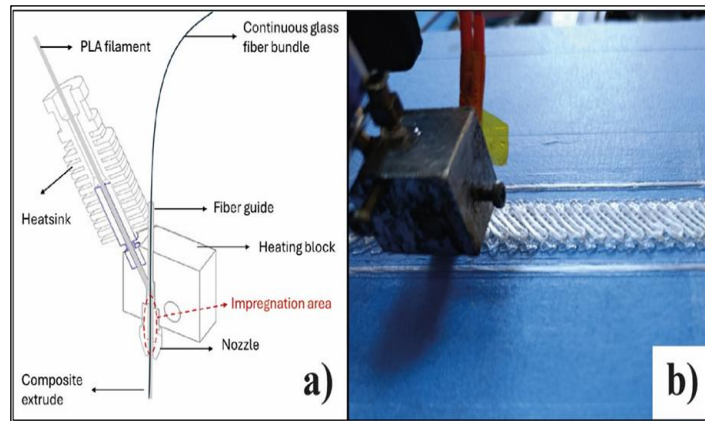


Figure 7: Continuous fiber–reinforced FDM process: (a) schematic of the extruder system and (b) photograph of the 3D printing process.

Source: [51].

IV.2 NATURAL FIBER–REINFORCED FDM SPECIMENS FOR TENSILE TESTING

Tensile properties of natural fiber–reinforced FDM parts are commonly evaluated using standardized dumbbell-shaped specimens ASTM D638 Type-I or ISO 527-1:2012 [52],[53]. In this study, ASTM D638 Type-I specimen is used to find the tensile properties of natural fiber filament, as illustrated in Figure 8 [54],[55].

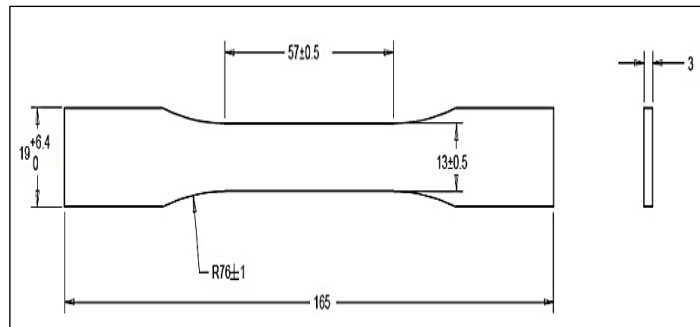


Figure.8 Tensile specimen according to ASTM D638 Type-I.

Source: [52],[53].

IV.3 FIBER PARTICLE SIZE AND VOLUME FRACTION

Extensive studies indicate that successful FDM printing of natural fiber–reinforced composites strongly depend on fiber particle size, volume fraction, and processing parameters. Lower fiber contents (typically 2.5 to 5 wt.%) combined with larger nozzle diameters (≥ 0.6 mm) improve printability and reduce nozzle clogging.

Table 3: Summarizes the relationship between nozzle size and fiber particle size stated in the literature.

Nozzle Size (mm)	Fibre Partial Size
0.4	75 μm
0.5	100 μm
0.75	125 μm
1.0	1mm

Source: [56].

PLA-based composites generally require lower nozzle diameter and bed temperatures compared to ABS-based composites. High infill densities normally 100% and optimized raster orientations are frequently adopted to improve mechanical performance. While increasing fiber volume fraction can enhance stiffness and strength, excessive fiber loading often leads to agglomeration, reduced interfacial bonding, print defects, and diminished impact resistance. Agricultural waste-derived fillers, including hemp, weed, tomato, carob, and pruned biomass, have been explored to reduce material costs and environmental impact [57].

Table 4: Key attributes of agricultural waste-derived particles used as filler phase.

Filler Material	Particle Size (µm)	Percentage	Particle Shape
Hemp	130	6%	Spherical
Weed	150	4%	Spherical
Tomato	100	4%	Spherical
Carob	130	4%	Spherical
Pruned	100	4%	Spherical

Source: [57].

Table 5: Summarizes comparative process parameters used for various natural fiber-reinforced polymer composites.

Sr. No.	Materials	Process Parameters								
		Fiber wt %	Layer Hight (mm)	Nozzl e Dia. (mm)	Nozzle Temp. (°C)	Infill %	Infill Patterns	Bed Temp. (°C)	Print Speed (mm/s)	Raster Angle
1	PLA Bamboo[58]	-	0.2	0.6	230	100	Lines	50	60	0°,90° 0°/90° ±45°
2	PLA Kenaf[59]	2.5	-	0.8	210	100	Lines	60	-	-
3	PLA Henequen [60]	1-5	0.15	0.8	215	100	Lines	60	30	0°, ±45°, 90°
4	PLA Hemp[61]	10-30	1	1	-	-	-	110	-	-
5	PLA Harakeke [61]	10-30	1	1	-	-	-	110	-	-
6	PLA Teak wood [62]	-	0.2	0.4	200	-	-	-	-	-
7	PLA Bamboo [63]	0,3,6, 9,12	0.4	0.8	215	100	Rectilinear	60	90	45°
8	PLA Jute [63]	0,3,6,9	0.4	0.8	215	100	Rectilinear	60	90	45°
9	PLA Wood Flour[64]	5	-	0.4	210	-	-	-	-	-
10	PLA Rice Husk[65]	0,0.5,1, 2	0.2	-	200	-	-	60	60	-
11	PLA Banana [66]	0,1,3,5	0.1-0.4	0.4-1.0	190-205	-	Grid, Gyroid Cubic, Zig-zag	-	-	-
12	ABS Kenaf [67]	0-5	0.8		230	100	Lines	105	40	-

Source: Authors, (2026).

Process parameter optimization using statistical methods such as the Taguchi approach has demonstrated that natural fiber-reinforced PLA and ABS composites can be efficiently produced with minor adjustments to conventional FDM settings. Studies employing L9 orthogonal arrays report significant improvements in tensile strength, impact resistance, and dimensional accuracy [68]. Most studies suggest that in order to achieve a consistent flow of material and consistent mechanical performance, the nozzle diameter between 0.6 to 1.0 mm, the nozzle temperature between 190 °C to 230 °C, and the print speed should be between 30 to 90 mm/s. Bed temperatures vary with the polymer matrix, typically around 50°C to 60°C for PLA and approximately 105°C for ABS.

IV.4 PRINTING FEASIBILITY OF SHORT JUTE FIBER-REINFORCED PLA FILAMENTS

During the initial printing trials, PLA filament reinforced with 2.5wt.% short jute fibers exhibited nozzle clogging, which restricted continuous material flow and interrupted the FDM process. This printing defect, shown in Fig. 9 (a) caused uneven material deposition and under-extrusion. The observed behaviour was primarily attributed due to moisture retained by the jute fibers, as natural fibers are inherently hydrophilic and readily absorb water from the surrounding environment. The presence of moisture reduced melt stability within the nozzle, resulting in uneven extrusion.

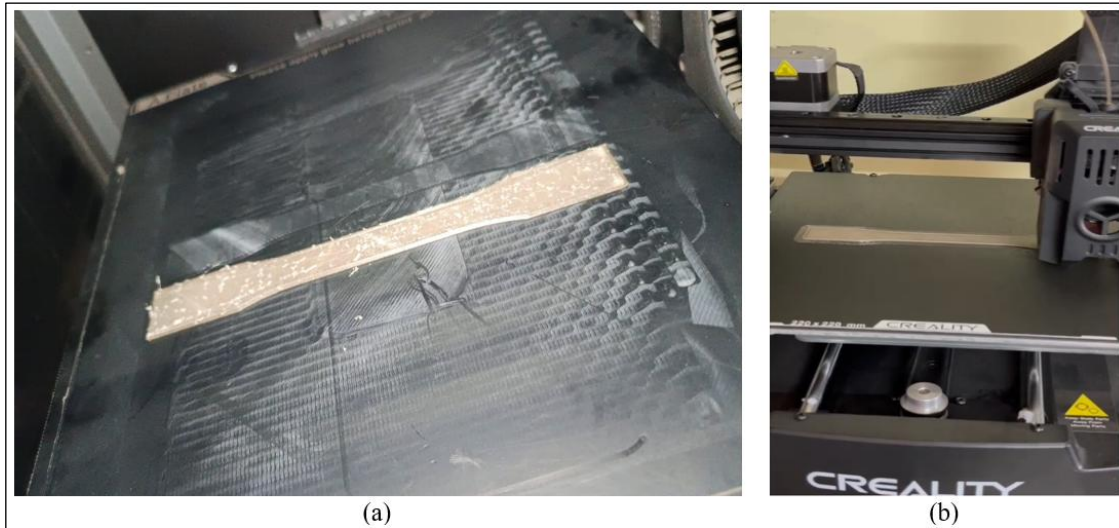


Figure 9: (a) Nozzle clogging and irregular extrusion observed during initial FDM printing of short jute fiber– reinforced PLA filament. (b) Tensile specimen geometry for natural fiber–reinforced PLA composites ASTM D638 Type-I.

Source: Authors, (2026).

To overcome this issue, the composite filaments were dried and annealed in a controlled filament dryer prior to subsequent printing trials. In addition to moisture removal, the extrusion temperature was set carefully to ensure proper polymer melt flow and improved fiber matrix mobility during deposition. After implementing these measures, extrusion stability improved significantly, enabling continuous and uniform layer deposition. Based on the post-treatment trials, Figure 9 (b) shows that PLA reinforced with 2.5 wt.% jute fiber and PLA reinforced with 5 wt.% jute fiber were found to be feasible for FDM printing without noticeable nozzle clogging or extrusion interruptions. These findings highlight the critical role of moisture control and proper extrusion temperature in achieving stable printing of short jute fiber–reinforced PLA composites.

IV.5 MECHANICAL, THERMAL, AND MORPHOLOGICAL CHARACTERIZATION

Mechanical Properties of natural fiber reinforcement of composite is mostly determined by the mechanical nature of bonding between the fiber and the polymer matrix. While moderate fiber contents enhance mechanical properties, excessive reinforcement leads to agglomeration and weak interfacial adhesion, resulting in reduced strength [69].

Table 6: Comprehensive study of Fiber Particle size and volume fraction on Mechanical Performance Outcomes in Natural Fiber-Reinforced FDM Composites.

Sr. No	Base Material	Fiber Name	Fiber Particle Size	Fiber Volume Fraction %	Research Finding
1	PLA [58]	Bamboo	5 to 35 μm	11.80%	A 0° raster angle yields the best mechanical strength in flexure, compression, impact, and shear for bamboo-filled PLA. Print orientation has little effect on ultimate tensile strength but a significant effect on ductility.
2	PLA[59]	Kenaf	$\leq 100 \mu\text{m}$	2.5%	Smaller fiber size $\leq 100 \mu\text{m}$ fiber gives highest tensile & flexural strength; larger fibers reduce bonding and increase defects; surface finish improves with smaller size.
3	PLA[60]	Henequen flour	90 to 250 μm	1 - 5%	1% improves tensile strength; >2% causes porosity and agglomeration, reducing mechanical properties; degree of crystallinity slightly increases.
4	PLA[61]	Hemp	12.3 μm	10%, 20%, 30%	Tensile strength generally decreases; voids and poor inter-layer fusion reduce strength; modulus increases with fiber content.
5	PLA[61]	Harakeke	28.3 μm	10%, 20%, 30%	20% shows highest improvement in tensile strength and modulus; fewer defects compared to hemp due to finer fiber morphology.

6	ABS [67]	Kenaf fiber	Avg. 120 μm	0%, 2.5%, 5%, 7.5%, 10%	2.5% gives best tensile and flexural performance; higher contents worsen strength due to porosity and poor fiber–matrix bonding.
7	PLA[62]	Teak Wood Flour	74 μm	1%, 3%, 5%, 5% (with 5% silane)	Filaments with a 74 μm wood flour size successfully printed, but those with 125 μm clogged the nozzle. Adding a silane coupling agent improved interfacial adhesion, increasing both tensile strength and elongation.
8	PLA[63]	Bamboo	Finer Powder	3%, 6%, 9%, 12%	Bamboo powder slightly improves impact and flexural stiffness at low content but overall weakens PLA due to poor bonding and pore formation.
9	PLA[63]	Jute	Powder	3%, 6%, 9%,	Jute powder causes a steady drop in mechanical strength because of large particles and voids, with only a small impact improvement at 3%.
10	PLA[64]	Wood Flour	Mean Size 14 μm	5%	Thermal stability decreased slightly, while melting temperature remained unaffected.
11	PLA[65]	Rice Husk	1–50 μm	0%, 0.5%, 1%, & 2%	PLA rice husk filament up to 2% printable; tensile strength ≥ 25 MPa; elongation decreases $>50\%$.
12	PLA[66]	Banana Fiber	-	0%, 1%, 3%, & 5%	3% banana fiber gives highest impact strength.
13	PLA[70]	Hemp Fiber	400–600 μm	5%	5% untreated hemp reduced tensile strength by 87.8% and strain due to poor interfacial adhesion.
14	PLA[71]	Jute fibers	10-400 μm	5%	Pulverized PLA improved fiber–matrix bonding, giving higher tensile strength and better homogeneity compared to pure PLA and pellet-based composite.
15	PLA[71]	Jute fibers	10-400 μm	5%	Pellet-based PLA + Jute showed lower mechanical performance due to non-uniform mixing and weaker interfacial bonding.
16	PC[72]	Hemp	-	10%,	Alkali-treated hemp fibers improved tensile strength, thermal stability, and matrix bonding; only $\sim 2\%$ strength reduction vs pure PC.
17	PLA[73]	cotton, flax, jute, woven fabrics	Continuous fibre	-	Alkali pretreatment improved adhesion strength due to better surface roughness and removal of impurities.
18	PLA[74]	Ramie fibers	Continuous fibre	-	Continuous ramie yarn greatly improved tensile & flexural strength.

Source: Authors, (2026).

Table 6 show that fine fibers and continuous reinforcements generally improve tensile and flexural properties, whereas coarse fibers and high loadings degrade performance.

Table 7: Mechanical and Material Characterization of Natural Fiber–Reinforced FDM Materials.

Sr. No	Base Material	Fiber Name	Mechanical Properties				
			Tensile Test	Impact Strength	Compression strength	Flexural Strength	Shear Strength
1	PLA[58]	Bamboo	Yes	Yes	Yes	Yes	Yes
2	PLA[59]	Kenaf	Yes	-	-	Yes	-
3	PLA[60]	Henequen Flour	Yes	-	-	-	-
4	PLA[61]	Hemp	Yes	-	-	-	-
5	PLA[61]	Harakeke	Yes	-	-	-	-
6	ABS[67]	Kenaf	Yes	-	-	Yes	-
7	PLA[62]	Teak Wood Flour	Yes	-	-	-	-

8	PLA[63]	Bamboo Powder	Yes	Yes	Yes	-	-
9	PLA[63]	Jute Powder	Yes	Yes	Yes	-	-
10	PLA[64]	Wood Flour	Yes	-	-	-	-
11	PLA[65]	Rice Husk	Yes	Yes	-	-	-
12	PLA[66]	Banana Fiber	Yes	Yes	Yes	-	-
13	PLA [70]	Hemp Fiber	Yes	-	-	-	-
14	PLA [71]	Jute fibers	Yes	-	-	-	-
15	PLA[75]	Kenaf	Yes	-	-	Yes	-

Source: Authors, (2026).

Table 8: Thermal structural and Morphological Characterization of Natural Fiber-Reinforced FDM Materials.

Sr. No	Base Material	Fiber Name	Thermal Properties		Structural / Crystallinity Analysis	Morphological / Chemical Properties	
			TGA	DSC		SEM	EDS / EDX
1	PLA[59]	Kenaf	-	-	-	Yes	-
2	PLA[60]	Henequen Flour	-	Yes	-	Yes	-
3	PLA[61]	Hemp	-	-	-	Yes	-
4	PLA[61]	Harakeke	-	-	-	Yes	-
5	ABS[67]	Kenaf	-	-	-	Yes	-
6	PLA[62]	Teak Wood Flour	Yes	Yes	-	Yes	-
7	PLA[63]	Bamboo Powder	Yes	Yes	-	Yes	-
8	PLA[63]	Jute Powder	Yes	Yes	-	Yes	-
9	PLA[64]	Wood Flour	Yes	Yes	Yes	Yes	-
10	PLA[65]	Rice Husk	-	-	-	Yes	Yes
11	PLA[70]	Hemp Fiber	-	-	-	Yes	Yes
12	PLA[71]	Jute fibers	Yes	Yes	-	-	-
13	PLA[75]	Kenaf	Yes	-	-	Yes	-

Source: Authors, (2026).

Tables 7 and 8 give an extensive overview of the mechanical, thermal, structural, and morphological characterization that has been written about in previous decades. Most studies emphasize morphological analysis using SEM to evaluate fiber dispersion and interfacial bonding. However, thermal characterization using Thermogravimetric analysis (TGA), Differential scanning calorimetry (DSC), and Crystallinity assessment via X-Ray diffraction (XRD) remain limited. Chemical analysis employing energy-dispersive spectroscopy (EDS/EDX) is rarely documented, thereby limiting thorough structure–property correlations. This study overcomes these limitations by integrating tensile testing with TGA, DSC, XRD, SEM, and EDS analyses to deliver a comprehensive assessment of natural fiber-reinforced PLA composites.

V. OBSERVATION

This section critically discusses the influence of FDM process parameters and natural fiber reinforcement on the mechanical, thermal, and morphological behaviour of polymer composites. The discussion integrates trends identified in the literature with experimental observations obtained from the development and printing of short jute fiber reinforced PLA filaments in this study, thereby establishing clear process, structure and property relationships relevant to sustainable additive manufacturing process.

V.1 PROCESS–STRUCTURE–PROPERTY RELATIONSHIPS IN FDM COMPOSITES

The mechanical performance of FDM printed parts is fundamentally governed by interlayer bonding, which is controlled by key processing parameters including layer height, raster angle, nozzle temperature, print speed infill density, and printing speed. Adequate thermal input during printing promotes polymer chain diffusion across adjacent layers which improving interlayer fusion and reducing void formation. Research shows that by lower layer heights and using proper extrusion temperatures, tensile and flexural strength are improved. This is due to the effective bonding area is increased and interfacial flaws are minimized. Raster orientations about 45° and higher infill densities further contribute to improved load distribution capacity and reduced anisotropy. also, insufficient thermal energy or excessive printing speeds restrict molecular mobility, resulting in poor interlayer interfaces and premature mechanical failure. This process induced microstructural features form the basis for understanding the behaviour of both pure polymers and Natural fiber reinforced FDM composites.

V.2 EFFECT OF NATURAL FIBER CONTENT AND PARTICLE SIZE

The combination of natural fibers into thermoplastic matrices introduces competing effects related to reinforcement efficiency and printability. At low to moderate fiber content (1–5 wt.%) with fine natural fibers particle enhances stiffness in some cases, strength by facilitating stress transfer within the polymer matrix. Fiber particle size is important in this context because smaller particles scatter more uniformly and increase fiber matrix wetting during extrusion.

However, increasing fiber content or using coarse particles promotes agglomeration, interfacial void formation, and melt flow instability. These defects adversely affect interlayer bonding and reduce mechanical performance. The observed literature constantly shows that optimal fiber content and particle size are crucial for striking a compromise between mechanical enhancement and process stability in FDM based natural fiber composites.

V.3 PRINTABILITY AND MOISTURE SENSITIVITY OF PLA-JUTE FILAMENTS (PRESENT STUDY)

The experimental results from this study directly confirm the trends observed in this literature. Initial FDM printing attempts using PLA reinforced with 2.5wt.% short jute fibers caused nozzle clogging and uneven extrusion, indicating a key challenge with natural fiber reinforced filaments. This is due to moisture retained within the hydrophilic jute fibers, which destabilized melt flow within the nozzle. Following controlled filament drying and annealing along with optimization of extrusion temperature and extrusion stability improved markedly. Both 2.5wt.% and 5wt.% jute fiber reinforced PLA filaments were successfully printed without noticeable nozzle clogging or under extrusion. These results show that controlling moisture is an important part of developing natural fiber reinforced PLA filaments that can be printed successfully. It should be taken into account along with fiber content and particle size when designing filaments.

V.4 IMPLICATIONS FOR SUSTAINABLE NATURAL FIBER FDM FILAMENT DESIGN

The combined analysis of literature and experimental study indicates that sustainable, high performance FDM composites cannot be accomplished by material selection or parameter optimization alone. A comprehensive approach is needed that includes optimizing processing conditions, controlling moisture, and developing the filament. The present research illustrates that short jute fiber reinforced PLA filaments, when adequately conditioned, can be effectively processed with standard FDM systems while conserving satisfactory mechanical and thermal properties. These insights are helpful for making bio based composite filaments that have potential for sustainable additive manufacturing, especially for non-structural and semi structural parts where reducing the impact on the environment is very essential.

VI. CONCLUSION AND FUTURE SCOPE

VI.1 Conclusion

This study integrates a systematic analysis of FDM process parameters with the experimental development and validation of jute fiber reinforced PLA materials. The results confirm that interlayer bonding is the dominant factor in governing mechanical performance of FDM printed parts and is strongly influenced by extrusion temperature, layer height, raster angel, and infill density. Natural fiber reinforcement was found to be successful when fiber particle size, volume fraction, and filament conditioning were precisely regulated. Low to moderate fiber contents (1–5 wt.%) in PLA with fine particles enhance mechanical performance without compromising printability, whereas excessive fiber content led to agglomeration, extrusion instability, and reduced strength. Experimental printing trials shows that moisture control is essential for achieving stable extrusion of PLA–jute composite filaments. The results provide a detailed process-structure-property model that may be used to create sustainable FDM filaments reinforced with natural fibers.

VI.2 Future Scope

Future work should focus on long-term performance evaluation of natural fiber-reinforced PLA composites, including fatigue, creep, and environmental durability. Further improvements in fiber–matrix adhesion may be achieved through surface treatments and bio-based compatibilizers, while controlled fiber alignment or continuous reinforcement strategies offer potential for enhanced mechanical efficiency.

In addition, statistical optimization approaches that combine material composition and processing parameters, as well as scale-up studies and life cycle assessments, are suggested to promote the industrial adoption of sustainable FDM composite filaments.

VII. AUTHOR'S CONTRIBUTION

Conceptualization: Divyeshkumar Morabiya and Hiren Joshi.

Methodology: Hiren Joshi.

Investigation: Divyeshkumar Morabiya and Hiren Joshi.

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