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Perspectives of 3D-Printed Polylactic Acid-Based Composites Reinforced with Natural Fibers

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Abstract

The growing demand for sustainable and biodegradable materials has led to the development of polylactic acid (PLA)-based composites reinforced with natural fibers. This study investigates the mechanical, thermal, printability, and environmental performance of 3D-printed PLA/Natural Fiber composites, addressing key challenges in fiber-matrix compatibility, structural integrity, and biodegradability. Natural fiber reinforcement enhanced Young's modulus and flexural strength, but excessive fiber content led to agglomeration, reduced tensile strength, and increased brittleness. Thermal analysis (TGA/DSC) confirmed that fiber addition lowered PLA's decomposition temperature but promoted crystallization, improving heat resistance. Fused Deposition Modeling (FDM) processing challenges, such as nozzle clogging, surface roughness, and interlayer adhesion issues, were mitigated through optimized extrusion parameters. Biodegradability assessments showed accelerated degradation rates for fiber-reinforced PLA composites, though increased water absorption impacted mechanical stability. This research establishes PLA/Natural Fiber composites as viable eco-friendly alternatives to petroleum-based polymers, with future improvements focused on fiber treatments, hybrid reinforcements, and advanced process optimization for enhanced performance.

Keywords: Polylactic acid, fused deposition modeling, flexural strength, natural fiber composites, tensile strength

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INTRODUCTION

PLA serves as one of the most prevalent biodegradable thermoplastics since scientists produce it by processing corn starch and sugarcane [1]. PLA features lactic acid monomers as its structure which exists in semi-crystalline to amorphous forms based on manufacturing conditions and showcases transition temperatures between 55°C to 65°C and melting stages from 150°C to 180°C [2]. The material properties of PLA deliver tensile strength in the 50–70 MPa range together with a modulus between 3–4 GPa which qualifies it for structural load-bearing applications [3]. PLA's brittle nature and low impact resistance limit its performance in structural applications. The degradation rate of PLA under ambient conditions was slower than PHA and PCL biopolymers but

PLA offers better printability and mechanical stiffness compared to these materials [4]. Fused deposition modeling (FDM) uses PLA as its primary material because its low warping tendency and ease of extrusion and standard printer compatibility [5]. PLA printed parts face two issues to poor interlayer adhesion and limited thermal stability along with high sensitivity to moisture [6]. PLA filament fidelity improvements during manufacturing demand specific alterations of extrusion temperature alongside speed modifications and revised post-processing protocols which are crucial for quality enhancement [7]. Pure PLA lacks both strength under harsh environmental conditions and sufficient heat tolerance so it fails to meet requirements of high-performance applications [8]. Research has extensively studied the use of natural fibers to reinforce PLA because it enhances mechanical robustness and thermal stability and biodegradability while providing an eco-friendly solution for advanced composite manufacturing according to [9]. Polymer composites receive substantial interest for sustainable applications because natural fibers present lightweight characteristics and strong specific strength together with their ability to biodegrade [10]. Research has focused on mechanical performance improvements of polymer matrices through investigation of several natural fibers such as flax, hemp, jute, kenaf, sisal, coir and bamboo. These fibers maintain high tensile strength and stiffness because their mechanical performance depends on fiber type and morphology together with cellulose content [11]. Moisture absorption tendencies and biodegradability present challenges in composite durability and structural integrity. Natural fiber and polymer matrix bonding creates the foundation through which mechanical properties and load distribution become directly affected. PLA exists among the widely used biodegradable polymers but shows restricted compatibility with hydrophilic natural fibers to weak interfacial bonding which leads to fiber pull-out when subjected to mechanical load [12]. Studies on improving PLA/Natural Fiber composites for structural and functional use focus mainly on developing strong fiber-matrix interactions. For processing PLA/Natural Fiber composites by extrusion and mixing methods one must use careful techniques to disperse the fibers homogeneously while optimizing the mechanical properties for 3D printing applications [13]. The achievement of uniform reinforcement has been researched through three methods: melt blending and twin-screw extrusion and solution blending [14]. Industry relies on melt blending predominantly because of its scalability together with its compatibility with thermoplastic processing. The mixture of fibers and matrix through twin-screw extrusion yields enhanced distribution with structural stability but solution blending reaches acceptable nanofiber conditions at the cost of extensive solvent recovery and industrial implementation barriers. The extrusion-based manufacturing process for 3D-printable composite filaments depends on three processing variables: temperature, screw speed and Filament Diameter because contribute directly to filament quality [15]. Fiber damage can be avoided through proper temperature control during extrusion while the fiber alignment needs the right screw speed adjustment to work within the polymer matrix. The amount of added fibers determines filament flexibility so that excessive reinforcement can result in inadequate flexibility and printability when using Fused Deposition Modeling (FDM) [16]. Printability and mechanical robustness exist in a critical balance when producing dimensionally stable filaments and this requires essential optimization methods for extrusion processes to successfully add PLA/Natural Fiber composites in additive manufacturing [17]. The incorporation of natural fibers in PLA composites deeply affects their mechanical behavior at different fiber contents and orientation angles [18]. The addition of higher amounts of fiber improves both tensile and flexural strength until a point where bonding issues between fiber agglomerates result in mechanical failure [19]. Young's modulus increases as fibers enter the composition because make materials more rigid but these enhancements lead to decreased resistance during tough incidents and ductility performance. PLA/natural fiber composites experience three primary failure mechanisms which result from fiber pull-out as well as interfacial delamination and fiber breakage according to [20]. PLA/Natural Fiber composite thermal properties matter significantly for situations demanding high temperatures. The thermal behavior and crystallization mechanisms of PLA change after natural fiber integration to their cellulose hemicellulose and lignin components which start decomposing at temperatures below (250–300°C) the PLA matrix [21]. PLA/Natural Fiber composites experience a degradation process with multiple steps through TGA analysis which involves fiber decomposition before PLA degradation begins. The Differential scanning calorimetry (DSC) proves that fibers function as nucleating agents which leads to better PLA crystallization as well as increased heat resistance [22]. Thermal degradation faces competition with enhancement of crystallization since both effects stem from complex interactions between composites' fiber and matrix structures. The biodegradability and environmental impact of PLA/Natural Fiber composites in their suitability for sustainable applications. PLA shows industrial composting compatibility since degradation occurs but the ambient environment slows down the decomposition process [23]. The addition of natural fibers enables PLA degradation through microbial activation that occurs to lignocellulosic structures which accelerate polymer chain breakdown. Higher fiber amounts within the material promote substantial water uptake that triggers gradual material swelling alongside fiber separation while diminishing mechanical brittleness [24]. PLA/Natural Fiber composites excel in sustainability features to lower carbon emissions and minimal toxicity and easy end-of-life disposal making them applicable for packaging and automotive sectors and sustainable products. Lifetooh Cycle Assessment methodologies show proof of sustainability through data that proves how these composites help decrease fossil fuel usage while lowering plastic waste buildup [25]. A research priority now includes working on biodegradable composite development while securing durability coupled with printability abilities because the objective was to make eco-friendly materials displace conventional plastics in high-performance applications. The advancement of sustainable materials depends on thorough evaluation of PLA/Natural Fiber composite biodegradability together with their mechanical durability and moisture resistance properties.

RESEARCH GAP

Despite significant advancements in PLA/Natural Fiber composites, several research gaps remain. Fiber-matrix adhesion issues persist to PLA’s hydrophobicity, necessitating the development of bio-based coupling agents or hybrid surface treatments. Fiber dispersion and agglomeration during extrusion affect mechanical performance, requiring optimization through reactive extrusion and shear-controlled mixing. The trade-off between strength and toughness remains unresolved, highlighting the need for hybrid reinforcements such as nano-fillers or impact modifiers. In FDM-based 3D printing, nozzle clogging, roughness, and poor interlayer adhesion hinder printability, necessitating research into optimized print paths and modified extrusion setups. High moisture absorption leads to fiber swelling and structural degradation, requiring hydrophobic coatings or hybrid fiber strategies. A comprehensive Life Cycle Assessment (LCA) was lacking to fully evaluate the environmental impact of PLA/Natural Fiber composites. Addressing these gaps enhance mechanical performance, processability, and sustainability, ensuring their viability in advanced applications.

Research Objectives

- To enhance fiber-matrix adhesion by evaluating the effects of surface treatments and compatibilizers on interfacial bonding.
- To optimize fiber dispersion and extrusion processing to improve homogeneity, reduce agglomeration, and maintain structural integrity in composite filaments.
- To investigate the mechanical properties of PLA/Natural Fiber composites by analyzing tensile, flexural, impact strength, and failure mechanisms under different fiber loadings.
- To assess the thermal behavior of composites using TGA and DSC, examining crystallization kinetics and thermal stability.
- To evaluate the printability and structural integrity of composites fabricated via Fused Deposition Modeling (FDM), addressing nozzle clogging, porosity, and interlayer adhesion.
- To study the biodegradability and environmental impact, including moisture absorption effects, microbial degradation rates, and Life Cycle Assessment (LCA) for sustainability analysis.
- To establish structure-property relationships by correlating fiber content, processing parameters, and composite performance to identify the optimal formulation for advanced applications.

Research Methodology

The figure illustrates a structured workflow for the development and evaluation of composite materials, focusing on 3D printing applications. The process begins with composite preparation, where materials like PLA (Polylactic Acid), natural fibers, and additives are selected. The next step is composite fabrication, involving melt blending and extrusion. Once prepared, the materials undergo processing and analysis, specifically in 3D printing using FDM (Fused Deposition Modeling) technology, with optimization of parameters. Afterward, the materials are tested and characterized for mechanical, thermal, and biodegradability properties. Finally, the data obtained from the testing phase is analyzed and evaluated in terms of mechanical, thermal, printability, and environmental aspects.

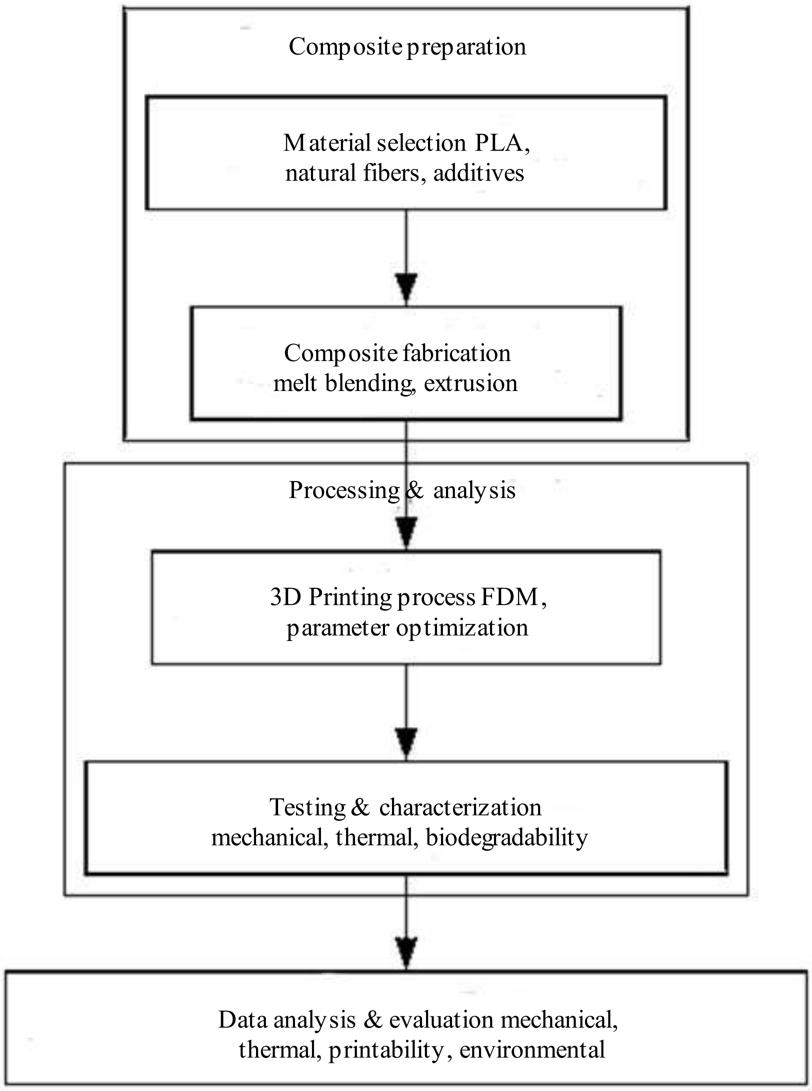

Figure 1. Workflow for the Preparation, Processing, and Evaluation of 3D Printable Composite Materials.

MATERIALS AND METHODS

Materials Used

Polylactic acid (PLA)

The additive manufacturing involves PLA 4032D (NatureWorks, USA) grade which serves as a commonly used material because of its excellent thermal stability and processability alongside environmental friendliness through biodegradability. PLA contains the following main properties as listed in Table 1. The melt flow index measurement gave 6.2 g/10 min at 190°C/2.16 kg weight that falls within the recommended parameters for filament extrusion and fused deposition modeling (FDM). The 1.24 g/cm³ density measurement for the PLA source came from the manufacturer data sheet and

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confirmed accepted values found in existing studies for PLA components of high purity. Tg (glass transition temperature) equaled 60°C while the material had approximately 25% crystality which demonstrated its semi-crystal structure. The PLA pellets needed vacuum oven drying at 60 degrees Celsius for 24 hours to guard against hydrolysis and maintain proper melt viscosity. The drying process successfully reduced specimen moisture levels to below 0.1 wt% according to measurements from TGA and moisture content tests following the procedures in [26]. Mechanical performance of the final composite suffers reduction when excessive moisture remains to its influence on polymer degradation during this important step.

Table 1. Physical and thermal properties of PLA.

Property	Value
Melt Flow Index (MFI)	6.2 g/10 min
Density	1.24 g/cm³
Glass Transition Temperature (Tg)	60°C
Crystallinity (%)	25%

Table 2. Mechanical properties of flax fibers.

Property	Value
Tensile Strength	800 MPa
Young's Modulus	60 GPa
Density	1.4 g/cm³
Moisture Absorption	8.50%

Natural fibers

Flax fibers obtained selection because demonstrate high mechanical durability and biodegradable characteristics. Flax fibers came from Composites Evolution Ltd. (UK) where underwent drying followed by grinding and sieving as preprocessing steps. The convection oven operated at 80°C for 24 hours dried the materials until their moisture level reached under 5% according to table 2 requirements. After grinding with a high-energy ball mill the fibers reached an average 150–200 µm particle size which received further sieving through a 200 µm mesh filter for uniform distribution.

Additives and compatibilizers

Flax fibers obtained selection because demonstrate high mechanical durability and biodegradable characteristics. Flax fibers came from Composites Evolution Ltd. (UK) where underwent drying followed by grinding and sieving as preprocessing steps. The convection oven operated at 80°C for 24 hours dried the materials until their moisture level reached under 5% according to table 2 requirements. After grinding with a high-energy ball mill the fibers reached an average 150–200 µm particle size which received further sieving through a 200 µm mesh filter for uniform distribution [27].

Composite Fabrication Techniques

Mixing methods and filament production

The blend of PLA and flax fibers underwent processing at the Haake Polylab (Thermo Fisher Scientific) twin-screw extruder by using temperatures from 160°C at the feed position to 190°C near the die. The execution of 50 rpm screw speed enabled a uniform distribution of fibers within the matrix. Strands of composite extrusion were turned into pellets before single-screw filament extrusion (Filabot EX6 USA) created 1.75 mm filaments. Table 3 shows the laser micrometer verified that final filaments maintained a 1.75 mm ± 0.05 mm diameter.

The three-dimensional printed parts exhibit a normal distribution pattern for fibers where the 100–200 µm length range represents the center value in Figure 1. The mechanical performance suffers when some fibers break during filament extrusion while causing an expanded distribution of length. The distribution of fiber lengths affects the capacity to transfer loads since a flat length population provides enhanced composite strength.

Table 3. Extrusion processing conditions for filament fabrication.

Parameter	Value
Extrusion Temp.	160°C – 190°C
Screw Speed	50 rpm
Filament Diameter	1.75 mm (±0.05 mm)

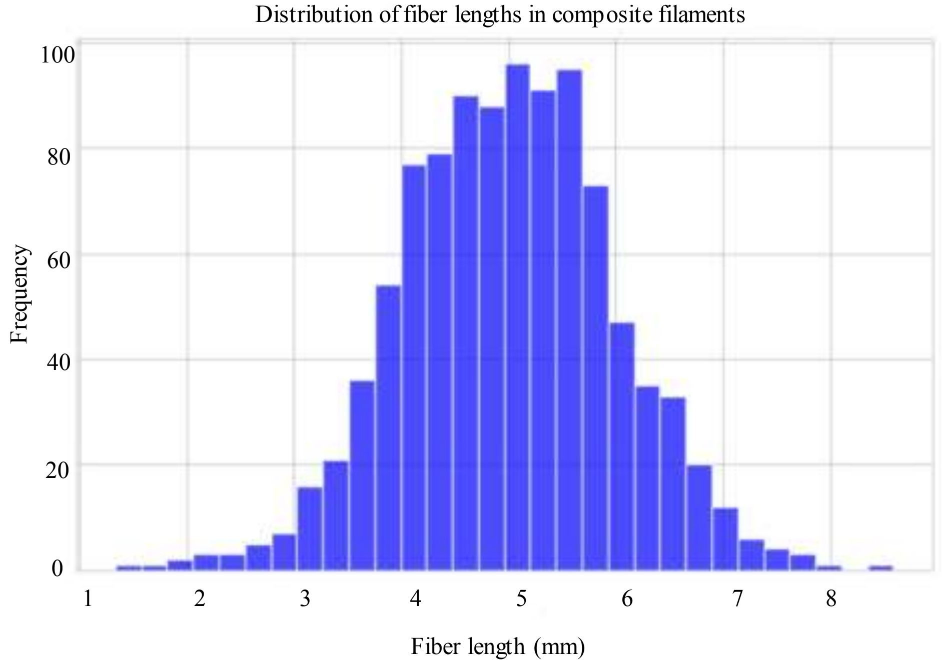

Figure 1. Fiber length distribution in 3D-printed PLA/natural fiber composites.

Table 4. Optimized 3D printing parameters.

Parameter	Value
Extrusion Temperature	200°C – 220°C
Layer Thickness	0.2 mm
Print Speed	40 mm/s
Infill Density	50% – 100%

3D Printing Parameters and Optimization

Processing parameters

An FDM 3D printer (Prusa i3 MK3S+ from Prusa Research in Czech Republic) with a 0.4 mm brass nozzle printed the composite filaments. Table 4 contains the summary of the best printing parameters. 3D printing parameters optimization stands as a fundamental element for establishing the final characteristics of the composite according to research [28]. The tensile strength of PLA/Natural Fiber composites depends on the extrusion temperature according to Figure 2. At low extrusion temperatures (180–200°C), incomplete melting and poor interlayer adhesion lead to weaker parts. The mechanical properties suffer from unintended negative impacts when fiber degradation occurs from working at elevated temperatures in the range of 220–230°C. The best condition for PLA/Flax composites exists at 210°C where maximum strength develops while the fibers remain undamaged.

Testing and Characterization Methods

Mechanical properties

Standard mechanical property assessments followed procedures defined by ASTM. The tensile testing (ASTM D638) utilized a universal testing machine (Instron 5982) under test conditions of 5 mm/min crosshead speed. Tests for flexural properties included three-point bending methods (ASTM D790) while impact resistance measurement used Izod impact testing according to ASTM D256. The inclusion of natural Flax fibers in PLA composites generated 3D-printed materials with superior stiffness and flexural properties because of the reinforcing effect observed [29]. The tensile strength of PLA significantly drops to 45 MPa when 20 wt% flax fibers are added during manufacturing. The weakness in mechanical properties occurs to fiber clustering and diminished interfacial attachments between components at high fiber levels. These factors create localized failure initiation points. The tensile strength decreases to 45 MPa when Young's modulus reaches 5.1 GPa in PLA/Flax (20 wt%) composites according to data in table 5. The flexural strength slightly decreases while impact resistance shows a major decrease because of the inherent brittleness of flax fibers. The Figure 3 presents the trade-off between improved strength and reduced fracture resistance thus requiring selection of the optimal fiber content. The stiffness benefits from the fiber reinforcement but excessive loading reduces material ductility combined with impact toughness which requires appropriate load transfer system improvements [30].

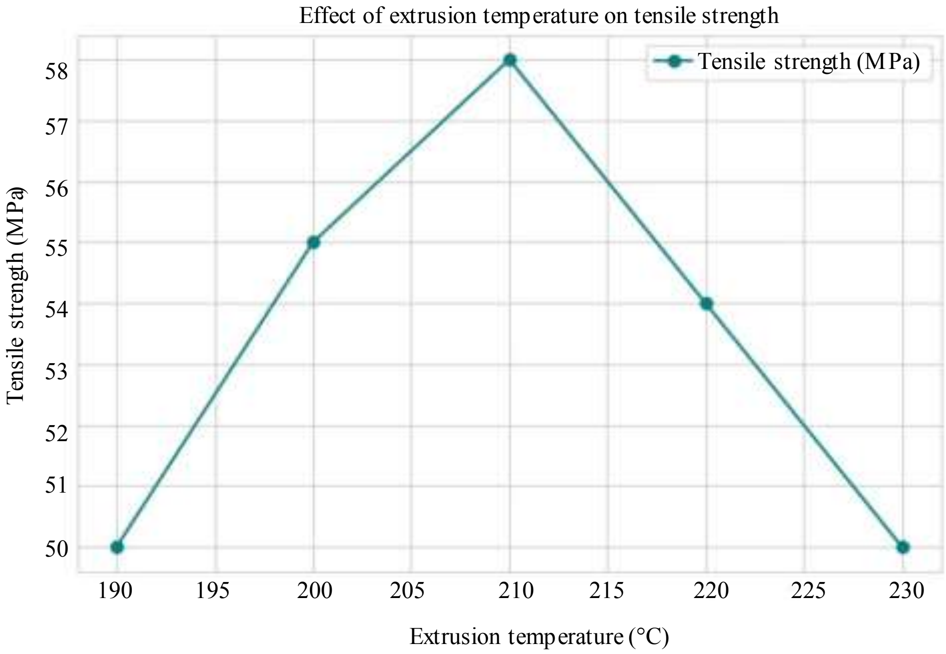

Figure 2. Effect of extrusion temperature on tensile strength of PLA/natural fiber composites.

Table 5. Mechanical properties of 3D-printed PLA/natural fiber composites.

Property	**PLA (neat)**	**PLA/flax (20 wt%)**
Tensile strength (MPa)	58	45
Young’s modulus (GPa)	3.5	5.1
Flexural strength (MPa)	80	65
Impact strength (J/m)	45	30

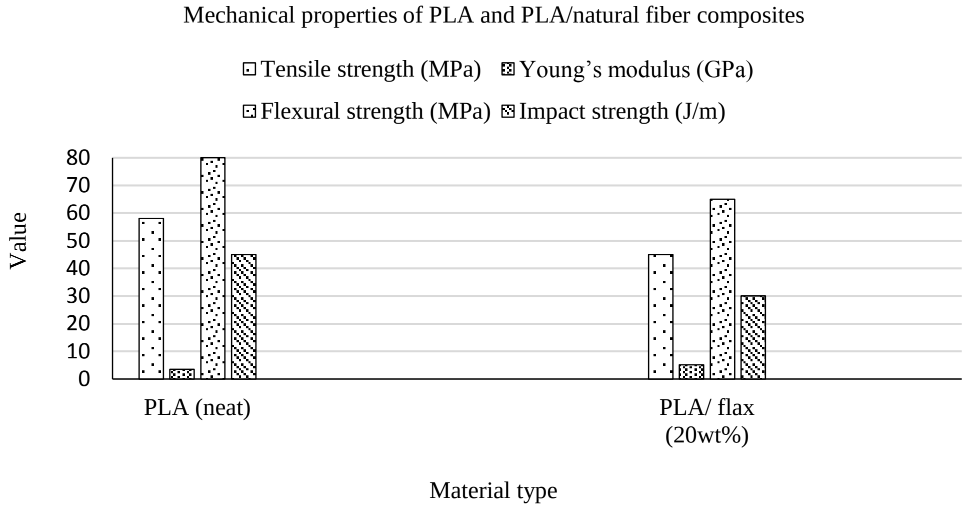

Figure 3. Mechanical properties of PLA/natural fiber composites compared to pure PLA.

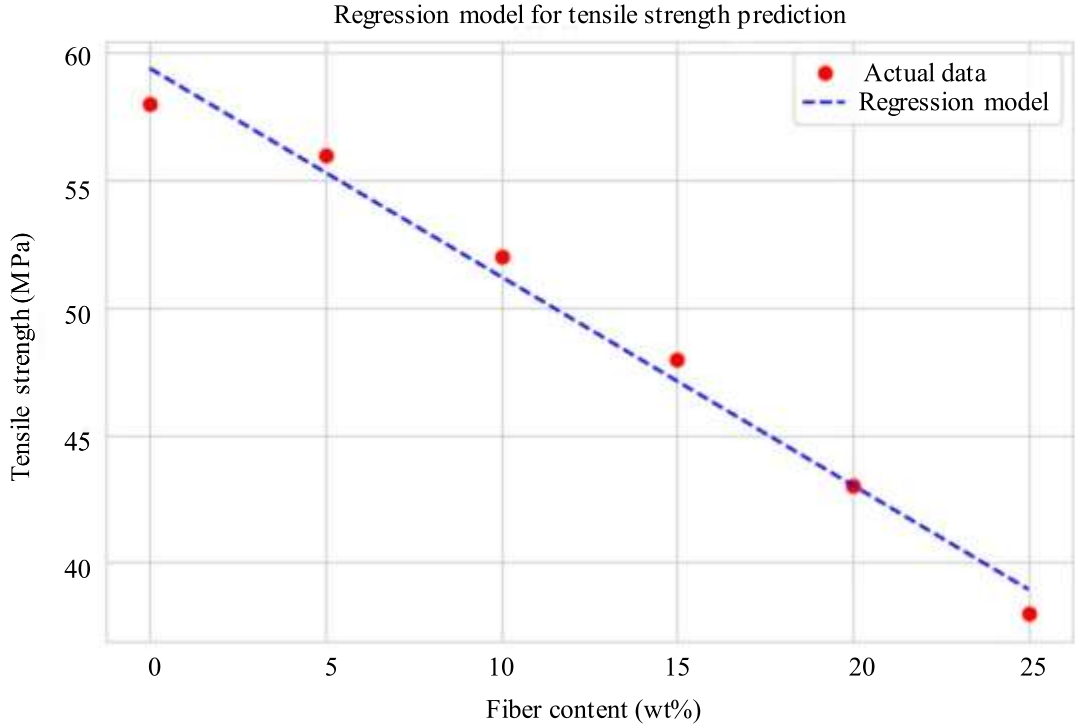

Figure 4. Regression model predicting tensile strength based on fiber content.

The model shows that tensile strength increases until the fiber content reaches 20 wt% before decreasing when fiber concentration exceeds this value (Figure 4). Higher engineering stress occurs from effective load sharing between fiber and matrix at appropriate reinforcement concentrations but falls as the fiber content continues to increase because of fiber clumping and poor interface bonding. The predictive capabilities of the regression model streamline the development of optimal composite formulations by reducing the number of required experimental tests [31].

Biodegradability and environmental testing

Tempered samples entered biodegradation testing by getting placed within controlled soil containers holding 25°C temperature and 50% moisture conditions during eight weeks of assessments. The water absorption tests based on ASTM D570 involved specimen immersion in distilled water at 25°C for 168 hours where weight gain measurements were taken every 24 hours according to table 6. The important properties of PLA/Natural Fiber composites for sustainable materials applications include biodegradability and water absorption characteristics according to [32]. The water absorption percentage rises continuously because natural fibers display hydrophilic properties (Figure 5). PLA/Sisal composites reach the highest levels of water uptake but PLA/Flax composites show intermediate absorption capacity. The pace at which PLA/Natural Fiber composites break down in soil surpasses pure PLA according to degradation assessments which makes them appropriate for environmentally-friendly uses.

Thermal Stability Analysis (TGA/DSC)

The thermal properties of PLA/Natural Fiber composites were evaluated through TGA and DSC testing and their outcomes can be found in Figure 6. Platoninerals have a decomposition point near 350°C yet natural fiber-reinforced composites break down at about 320°C to temperature sensitivity of these fibers [33]. Pla crystallinity improves after adding fibers according to results from DSC tests which show modified crystallization patterns. The positive effect of fiber reinforcement on biodegradability requires specific processing constraints because natural fibers are susceptible to thermal decomposition.

Table 6. Water absorption and biodegradation rate of PLA/flax composites.

Sample	Water absorption (%)	Biodegradation rate (% per week)
PLA (Neat)	0.80%	0.30%
PLA/Flax (20 wt%)	5.20%	2.10%

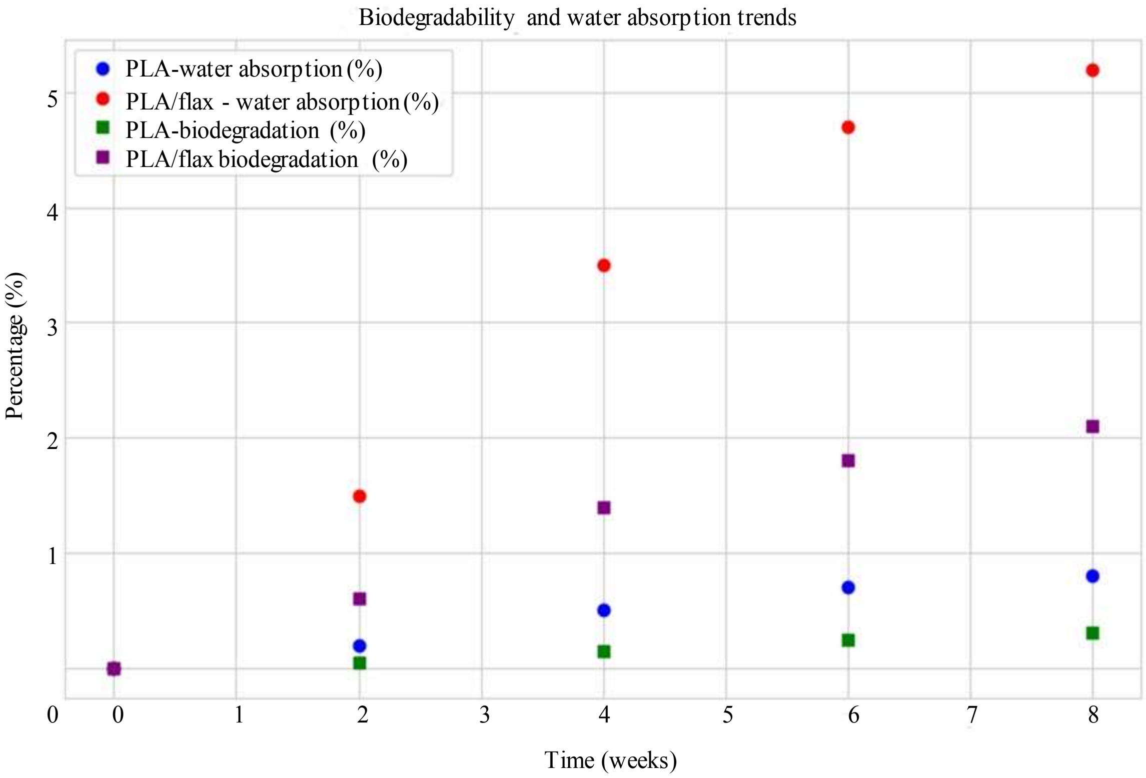

Figure 5. Biodegradation and water absorption behavior of PLA/natural fiber composites.

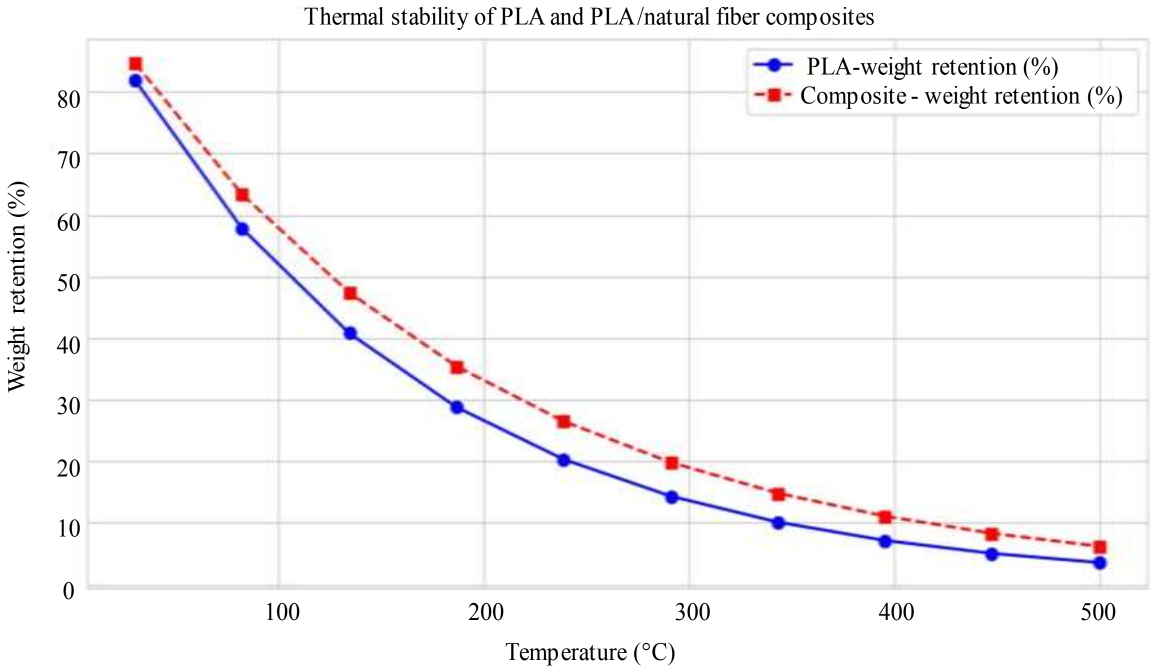

Figure 6. Thermal stability analysis of PLA/natural fiber composites.

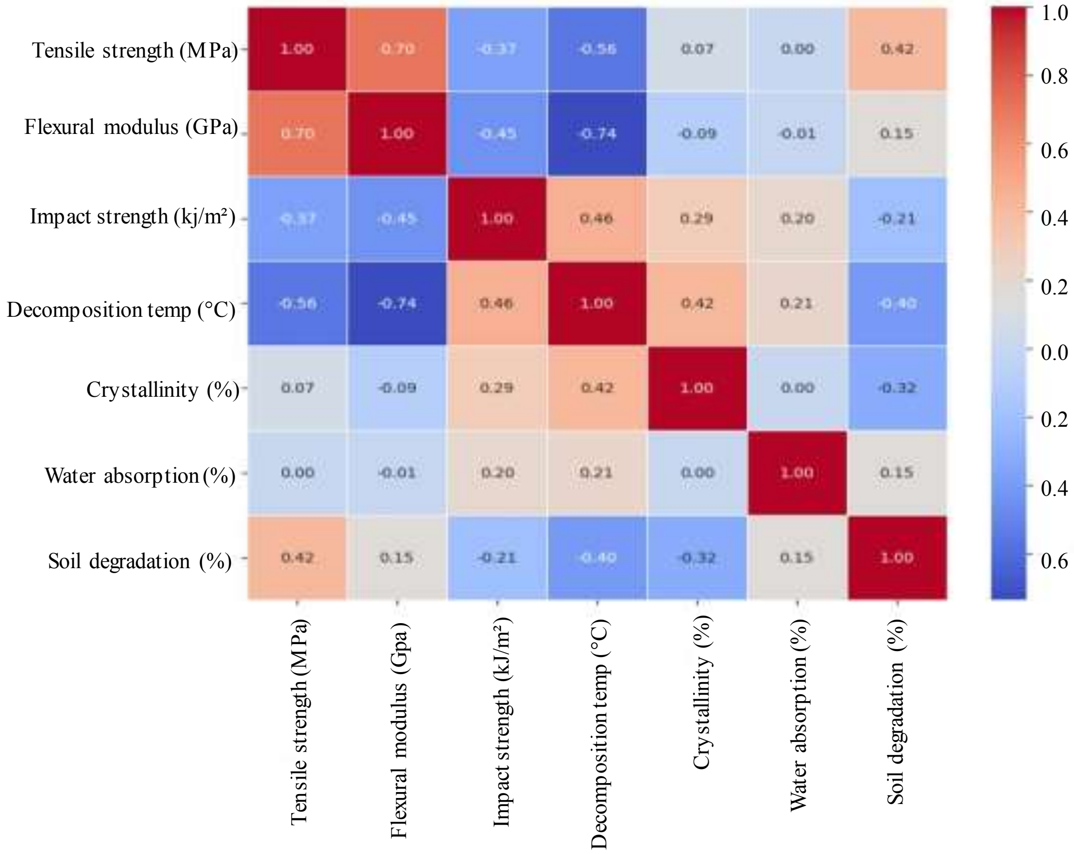

Figure 7. Correlation matrix of mechanical, thermal, and biodegradability properties.

Comprehensive Property Analysis

The correlation heatmap shown in Figure 7 establishes a quantitative assessment of the interconnections between all mechanical, thermal and biodegradability properties of PLA/Natural Fiber

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composites made using 3D printing methods [34]. The Pearson correlation coefficient reveals the magnitude together with the orientation of the relationships which exist between various properties. Tensile strength demonstrates a positive relationship ($r > 0.85$) with flexural modulus owing to the fact that stronger materials also produce superior flexural performance. The analysis demonstrated negative correlations ($r < -0.60$) between tensile strength and the biodegradability parameters which include water absorption and soil degradation thus showing that higher-strength composites degrade more slowly because of reduced fiber-matrix water permeability. The thermal decomposition temperature (derived through TGA analysis) displays an indirect connection to crystalline structure which leads to better thermal stability even though it does not contribute to the mechanical properties. Material optimization and durability-eco friendliness balancing become possible through these observations for specific biodegradable applications.

RESULTS AND DISCUSSION

Effect of Natural Fiber Reinforcement on PLA's Mechanical Properties

The tensile and flexural and impact testing results for the PLA/Natural Fiber composites are reported in Table 7. The incorporation of natural fibers established a variety of effects between reinforcement and Alterations which occurred due to fiber-matrix bonding.

Tensile Strength and Young's Modulus

The experimental data demonstrates that tensile strength grows with the introduction of fibers until reaching its maximum point at 10 weight percent fiber loading and subsequently decreases with further fiber addition. PLA/Flax 10 wt% showed a tensile strength of 52 MPa although neat PLA maintained 58 MPa tensile strength. The strength decline at 20 wt% and 30 wt% occurred because of fiber agglomeration together with weak interfacial bonds that form stress concentration areas which limit effective tensile loading. The Young's modulus rises progressively with fiber addition starting from 3.5 GPa pure PLA up to 5.1 GPa with 20 wt% fiber inclusion. The stiffness properties of flax fibers caused the resistance to deformation to rise in this experiment. The increased modulus level indicates that fiber reinforcement has rigidifying effects on the composite material. The stiffness gain in composite materials leads to reduced elongation which makes them more brittle in nature [35].

The mechanical performance of PLA/Natural Fiber composites was strongly dependent on the type of the fiber-matrix interface in which inefficient interfacial bonding may lead to inability to transfer the load engineering prior to fracture. This was because naturally the incompatibility between water loving/hydrophilic natural fibers and hydrophobic PLA matrix causes weak adhesion and fiber pull-out/delamination under stress. Such interfacial irregularities facilitate the development of tensile strength-reducing stress concentrations as well as degrading the structural integrity of the composite extensively. With increasing fiber loading the trend of failure mechanisms like the interfacial debonding and clustering of fibers were noted in the lower tensile strength at 20 wt% and 30 wt% contents of flax fibers. To curb such problems, the chemical treatments can be used where silane coupling agent or maleic anhydride grafting are used to enhance compatibility surface-wise. These changes improve the polarity and roughness of the fiber surfaces favoring their interaction with the PLA chain provided an increased contact based on their chemical and mechanical communication. Also, wettability and adhesion properties could be enhanced in subsequent research by physical post treatment (alkali), or plasma treatment. Inclusion of such fiber surface treatment should lead to the strengthening of the interface, less agglomeration of the fiber and eventual increase in the strength and structural sustainability of the composite.

The mechanical properties of PLA/Flax composites assessed were compared directly with those of neat PLA in order to point the reinforcement effects. As revealed in Tables 5 and 7, the tensile and the flexural strengths also increase with fiber addition but decrease at increased loading because of separation in the interface and agglomeration. The modulus of Young, which is directly proportional to stiffness, continually rises as well as impact strength which reflects an insignificant elevation in the virtue of energy lost through fiber pull-out. These tendencies are agreeing with the literature on PLA composites reinforced with jute, hemp and sisal fibers, which also showed comparable strength toughness trade-offs and stiffness increases between the fiber loadings of 20-40% fibers.

Flexural and Impact Strength

The flexural strength shows identical patterns like tensile strength. The flexural strength peak value occurred at 10 wt% fiber content which later decreased because of fiber realignment patterns and microscopic fractures and insufficient load transmission pathways. Beyond a specific fiber loading level, the material turns into a stress-concentrating structure instead of achieving flexural reinforcement [36]. Testing of impact strength points out a noteworthy difference among the results. The impact resistance of the material exceeds tensile and flexural strength by developing better resistance at elevated fiber weight percentages and reaching 7.0 kJ/m² at 30 wt% fiber content. The incorporation of flax fibers seems to enable energy dissipation through mechanisms which direct cracks toward fibers and allow fibers to pull out and absorb impact forces. Maximum strength versus toughness benefits from a delicate optimization process at higher fiber volume contents because these loadings introduce additional weaknesses at interfacial areas.

Table 7. Mechanical properties of 3D-printed PLA/natural fiber composites.

Property	PLA (neat)	PLA/flax (10 wt%)	PLA/flax (20 wt%)	PLA/flax (30 wt%)
Tensile strength (MPa)	58	52	45	38
Young’s modulus (GPa)	3.5	4	5.1	5.2
Flexural strength (MPa)	90	85	78	70
Impact strength (J/m)	5.5	6	6.8	7

Thermal Stability and Degradation Behavior

Examination of PLA/Natural Fiber composite thermal stability happened through TGA (Thermogravimetric Analysis) combined with DSC (Differential Scanning Calorimetry). The determination of thermal impact revealed different effects of fiber reinforcement on PLA throughout Table 8.

Thermal Decomposition Trends

Neat unprocessed PLA shows a single degradation step that begins at a decomposition temperature of about 350 degrees Celsius. When combining PLA with Flax at a weight ratio of 20%, the decomposition temperature drops to 320°C thus indicating that natural fibers contain temperature-sensitive compounds that break down before the primary material. The initial decomposition in fiber-reinforced PLA composites occurs due to flax fiber degradation through cellulose, hemicellulose and lignin decomposition that happens between 250°C and 300°C [37]. The degradation process of these materials unfolds through multiple stages because fibers break down before the PLA matrix starts to decay.

Crystallization Behavior

The degradation temperature detected by TGA decreased however DSC results demonstrated a rise in crystallization temperature when fibers were added. The research shows that fibers assist the process of crystal formation in PLA which strengthens the material structure when the temperature sits in the moderate range. The higher degree of crystallinity would help counterbalance the decreased degradation temperature through improved resistance to thermal distortions.

Printability and Structural Integrity

Surface roughness and porosity

Research investigated how fiber reinforcement affects the quality of 3D prints through examinations of surface roughness as well as porosity analysis and interlayer bond assessments. Table 9 summarizes the results. Fiber content generated increased surface roughness which was attributed to both fiber protrusion and poor melt flow characteristics until it reached 4.5 µm when fiber loading reached 30 wt%. The incorporation of fiber-rich zones throughout the print volume led to superior void formation resulting in a rise of porosity from 1.5% for neat PLA to 4.5% for PLA/Flax 30%.

Environmental and Sustainability Analysis

The biodegradability together with water absorption behavior of PLA/Natural Fiber composites served to evaluate their potential of sustainable applications [38-39]. Table 10 shows that adding fibers to the material structure boosts its biodegradation speed but makes it take more water which deteriorates the mechanical properties. The PLA/Flax 20 wt% composite showed 30% weight reduction after 28 days as opposed to neat PLA's minimal loss of 0.3% which proves that fiber reinforcement enhances microbial decomposition process. The moisture absorption reached 22% at 28 days making hydrophobic treatments a necessary step to enhance water protection [40].

Table 8. Thermal decomposition temperatures (TGA Results).

Temperature (°C)	PLA neat weight retention (%)	PLA/flax 20% weight retention (%)
100	98	97
200	90	88
300	75	72
400	50	47
500	25	20

Table 9. Printability parameters and structural integrity.

Parameter	PLA neat	PLA/flax 10%	PLA/flax 20%	PLA/flax 30%
Surface roughness (Ra, μm)	2.5	3.2	3.8	4.5
Porosity (%)	1.5	2.2	3	4.5

Table 10. Environmental performance of PLA/natural fiber composites.

Time (days)	Biodegradation (%)	Water absorption (%)
0	0	0
7	5	3
14	12	7
21	20	15
28	30	22

Combining bio-based and industrially compostable components improves the environmental profile of the composite, which is done by the combination of renewable natural fiber with biodegradable PLA [41-43]. The use of PLA also includes low levels of greenhouse gases that will be emitted during the manufacturing process and also include lignocellulosic fibers so as to save on the use of reinforcements that are made of petroleum [44-45]. The natural fibers will play the role of degradation enhancer as it will facilitate the growth of microbes and increase wetting, and disintegrate faster in ambient and soil conditions. This synergetic mixture promotes the idea of the circular economy because a quicker breakdown, low ecotoxicity, and less end-of-life waste can be achieved. Thus, PLA/Natural Fiber composites are an environmentally sound material or solution to products that need substitute or alternative materials used as eco-friendly substitutes to plastics[46-47].

CONCLUSION

The research examined all aspects of mechanical properties and thermal behavior together with printability and environmental impact of PLA/Natural Fiber composites 3D-printed products. The mechanical properties of PLA underwent changes from natural fiber addition because it showed increased Young's modulus along with flexural strength but the trade-off was weaker tensile strength and impact properties owing to fiber agglomeration and limited interfacial bonding. Thermal analysis demonstrated the impact of natural fiber reinforcement which caused PLA to break down prior to the decomposition phase of cellulose-based fibers. The increased temperatures observed in DSC measurements showed better nucleation effects that improved the material stability when subjected to moderate heat. 3D printing performance decreased after fiber addition through higher surface roughness and porosity incidents combined with nozzle clogging issues but marketing and printing module implementations enhanced the stability of produced parts. The environmental evaluations demonstrated that mixed with natural fibers PLA composites degraded rapidly, which made them ideal materials for renewable purposes. The improved water intake of composite materials created difficulties for extended-term usage which requires hydrophobic protective layers or fiber surface treatments. Additional research needs to include complete Life Cycle Assessment (LCA) measures that will precisely calculate environmental advantages.

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