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# Investigation on Mechanical Performance of 3D Printed PLA-Kraft Lignin Composites

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***Abstract***

*Bio-based polymer composites are becoming more popular due to the growing need for sustainable and biodegradable materials in additive manufacturing. PLA-kraft lignin composites were created and their mechanical performance in fused deposition modeling (FDM) applications was assessed in this work. Polylactic acid (PLA) was mixed with Kraft lignin, a sustainable by-product of the paper industry, at weight percentages of 0%, 1%, 3%, 5%, and 7%. Melt blending was utilized to prepare the composites, which were then extruded into 1.75 mm diameter filaments that were used to create standard test specimens using an FDM 3D printer under ideal processing circumstances. Tensile, flexural, and impact tests were used to examine the mechanical characteristics of the printed specimens in compliance with ASTM guidelines. According to the findings, tensile strength increased with lignin addition up to 5 weight percent, suggesting improved load transmission and interfacial contact. However, additional increases in lignin content caused a minor decrease because to agglomeration effects. As the lignin content increased, the flexural strength and modulus gradually decreased, indicating the composites' increased stiffness and decreased flexibility. The brittle behavior of PLA–lignin composites was confirmed by the finding that impact strength decreased with increasing lignin content. In order to establish a balance between strength, stiffness, and toughness, an ideal lignin content of 3-5 weight percent was found. By proving that kraft lignin may be used as sustainable filler in PLA for 3D printing applications, this study advances the creation of environmentally friendly composite materials with enhanced performance attributes.*

**Keywords:** Polylactic acid (PLA), kraft lignin, fused deposition modeling (FDM), melt blending, biodegradable composites

## INTRODUCTION

Additive manufacturing (AM), a quickly developing manufacturing process, is widely used in electronics, soft robotics, nanodevices, and other industries. It can efficiently produce highly customized, tool-less complex parts and quick-develop solutions. Fused Deposition Modeling (FDM), the most widely used AM process, makes use of solid thermoplastic filaments. After being melted at high temperatures, the filament is cooled and solidified. Three-dimensional forms are formed from the bottom up by applying the polymer melt layer by layer. A great deal of effort has gone into creating a variety of filaments for various applications, ranging from costly filaments for technical applications to low-cost filaments for daily use or prototyping. Molten or semi-molten material is layered to make 3D objects in 3D printing, a form of additive manufacturing [1].

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Additional layers are added to continue generating the desired shape. This method uses a computer model within a machine to produce intricate shapes. Thanks to 3D printing, it is now simple to manufacture things that are difficult or impossible to construct using conventional manufacturing techniques. A new tool, mold, or jig is required each time a part design is changed, or a new component is made using traditional methods. However, once the item has been created in software, 3D printing removes the need for any physical machine or equipment adjustments [2].

Production processes that are slow and labor-intensive are being replaced by 3D printing techniques. Their material waste is lower than that of subtractive production methods. Along with other noteworthy advantages like personalization, customization, and the ability to create complex shapes with flexibility, additive manufacturing (AM) offers new opportunities in a variety of other fields, such as robotics, biomedicine, electronics, and electrical energy storage, in addition to the manufacturing industry [3].

**3D Printing Techniques**

The three main categories of 3D printing techniques are: stereolithography, melting, and sintering.

- *Stereolithography:* The additive manufacturing technique known as stereolithography (SLA) revolutionized the fields of 3D printing and fast prototyping. Currently in widespread use, it was among the first methods created to create intricate, high-resolution models and prototypes. Using a technique known as photopolymerization, SLA gradually transforms liquid photopolymer resins into solid three-dimensional objects by using ultraviolet (UV) light.
- *Melting:* 3D printing employs melting techniques such as direct energy deposition, powder bed fusion, and electron beam melting, which fuse materials at high temperatures utilizing lasers, electric arcs, or electron beams.
- *Sintering:* The additive manufacturing (AM) process known as selective laser sintering (SLS), which sinters powdered material typically, nylon or polyamide uses a laser as the heat source and power source. The material is bound together to form a solid structure by autonomously focusing the laser at certain locations in space using a three-dimensional (3D) model. Although technology's specifics differ, it is comparable to selective laser melting, which is an illustration of the same idea.

**Types of Materials Used in 3D Printing**

- *Plastics/Polymers:* Due to its ease of printing and biodegradability, polylactic acid, or PLA, is utilized in consumer goods and prototypes. Acrylonitrile Butadiene Styrene, or ABS, is a strong, heat-resistant material used in toys and vehicle parts. PETG, or polyethylene terephthalate glycol, is a robust and pliable substance that finds application in mechanical components and food containers [4].
- *Metals:* Aircraft and medical implants are made of stainless steel, which is robust and resistant to corrosion.
- *Titanium:* Sturdy and light, it is used in both medicine and aviation.
- *Aluminum:* Used in automotive and aeronautical parts, aluminum is conductive and lightweight.
- *Ceramics:* Dental and medical implants are made of alumina, a substance that can withstand high temperatures. Cutting tools and airplane parts are made of silicon carbide, a strong, resilient substance [5].

The majority of the materials used in 3D printing today are derived from non-renewable resources, which is detrimental to the ideas of circular economy and sustainable development. For sustainable development, it is crucial to look for biodegradable materials that can take the place of petroleum-based ones. Sadly, there is very little utilization of wood and other forest-based materials for 3D printing as a substitute for petroleum-based polymers [8]. It's still difficult to create 3D printable polymeric materials that are mostly made from plant biomass [6].

**Introduction to Polylactic acid (PLA)**

A biodegradable and biobased thermoplastic polymer, polylactic acid (PLA) is made from renewable resources such sugarcane, cassava, maize starch, and other biomass high in carbohydrates. It is one of the most popular biopolymers because of its advantageous mechanical qualities, ease of production, and environmental friendliness. Lactic acid or lactide monomers, which are produced by fermenting carbohydrates, are polymerized to create PLA. In a number of sectors, including additive manufacturing, medicinal devices, packaging, and agriculture, PLA has drawn a lot of interest. PLA has emerged as the most popular material for fused deposition modeling (FDM) 3D printing in recent years because of its low melting temperature, low warping, high dimensional precision, and lack of harmful processing emissions [7, 8].

Due to its typical processing temperature of 180–210 °C, PLA can be used with both desktop and industrial extrusion devices. When compared to many traditional biodegradable polymers, PLA shows comparatively strong tensile strength and stiffness from a mechanical standpoint. It has a modulus of elasticity of roughly 2–3 GPa and a tensile strength of 50–70 MPa. PLA has intrinsic brittleness, poor impact resistance, and restricted thermal stability in spite of these benefits. PLA can only be used in high-temperature settings because of its glass transition temperature, which is between 55 and 65 °C, and the fact that it softens at fairly high temperatures. PLA is taken in the granules form as shown in Figure 1.

PLA's low toughness and small elongation at break—typically less than 10% are further drawbacks. Because of its brittleness, it is less appropriate for applications requiring load bearing and impact resistance.

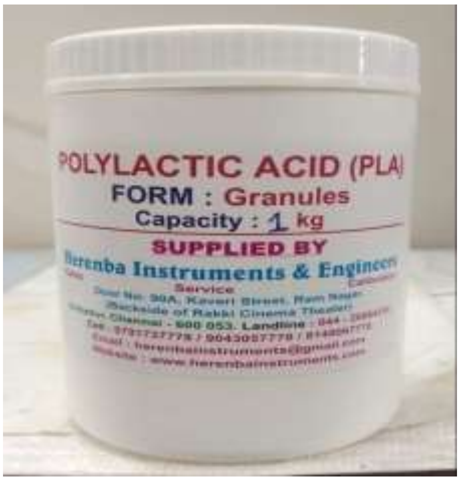


**Figure 1.** PLA granules.

**Table 1.** Properties of PLA.

| Property | Description |
|---|---|
| Chemical Formula | $(C_3H_4O_2)_n$ |
| Glass Transition Temp. | 60–65°C |
| Melting Point | 170–180°C |
| Density | 1.24 g/cm³ |
| Tensile Strength | 50–70 MPa (varies with processing) |
| Biodegradability | Yes, under industrial composting conditions |

| | |
|---|---|
| UV Resistance | Poor |
| Water Resistance | Moderate (can absorb moisture over time) |

Furthermore, PLA has comparatively sluggish crystallization rates, which may have an impact on mechanical performance and dimensional stability in additive manufacturing procedures. Plasticization, copolymerization, merging with other polymers, and reinforcing with fillers like natural fibers, nanoparticles, and bio-based additives are some of the ways that researchers have tried to modify PLA in order to get around these restrictions [9, 10]. The following Table -1 explains the properties of PLA.

The use of sustainable fillers has become more popular among these strategies as a result of cost-cutting demands and environmental concerns. By combining PLA with renewable resources, mechanical and thermal qualities can be adjusted while simultaneously improving sustainability. Material modification is a key factor in additive manufacturing since it enhances the functionality of printed parts. Repeated cycles of heating and cooling are a feature of the extrusion-based FDM process that can impact interlayer bonding and polymer crystalline [11].

**Introduction to Kraft Lignin**

Lignin makes up roughly 15–30% of lignocellulosic biomass and is the second most abundant natural polymer on Earth after cellulose. Plant cell walls include this amorphous, strongly cross-linked aromatic biopolymer, which gives them structural stiffness, water impermeability, and resistance to microbial attack. As a sustainable reinforcing material for polymer composites, lignin has gained more attention due to its high carbon content and phenolic structure. Of the various varieties of lignin, Kraft lignin is the most widely manufactured and economically accessible. In the paper and pulp industry, it is a by-product of the kraft pulping process.

In order to separate cellulose fibers from lignin, wood chips are treated with sodium hydroxide (NaOH) and sodium sulfide ($Na_2S$) at high temperatures and pressures. To recover the dissolved lignin, the resulting black liquor is filtered, dried, and acid precipitated. Millions of tons of kraft lignin are generated globally each year, but only a small percentage of this is valued for high-value material applications; the majority is burned as low-grade fuel. A significant contributing factor to the creation of composite materials with added value is underutilization.

The dark brown to black color, high aromatic content, and comparatively good thermal stability of kraft lignin are its distinguishing characteristics. It can be melted with thermoplastics like polylactic acid (PLA) due to its breakdown temperature, which is frequently higher than 200°C [12].

Aromatic rings and phenolic hydroxyl (-OH) groups are added to polymer matrices to boost their stiffness and rigidity. Lignin also contains antioxidant properties and the capacity to absorb UV rays, which may increase longevity in some applications. The use of kraft lignin in PLA and other biodegradable plastics supports international initiatives to produce sustainable materials. PLA is a thermoplastic that is biobased and biodegradable and is frequently used in Fused Deposition Modeling (FDM) and other additive manufacturing processes. On the other hand, PLA has limited thermal stability, low impact resistance, and inherent brittleness. Among the possible advantages of adding lignin are increased stiffness, reduced material costs, improved sustainability, and partial replacement of petroleum-based additives [13].

By using fewer polymers and an industrial by-product, kraft lignin significantly improves the composite's environmental profile. Although there are drawbacks to using kraft lignin as filler, there is potential. Particle aggregation, poor lignin-PLA interfacial adhesion, and decreased tensile strength with higher lignin loadings are a few of these. The lignin content and processing conditions must therefore be optimized in order to achieve balanced mechanical and processing performance. The below Figure 2 shows the structure of softwood kraft lignin.

 

Research on PLA-kraft lignin composites' filament extrusion and fused deposition modeling (FDM) applications is still scarce, especially when it comes to printability and mechanical characterization. The development of PLA–kraft lignin composite filament is thus examined in this paper, along with its

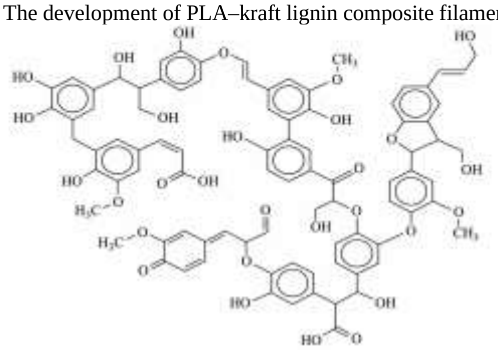

**Figure 2.** The model structure of softwood kraft lignin [11].

applicability to additive manufacturing applications. This effort intends to promote the development of sustainable polymer composites and increase the potential applications of lignin in advanced manufacturing technologies by using a plentiful and renewable industrial by-product [14, 15].

**EXPERIMENTAL SETUP**

Enhancing the mechanical performance and sustainability of materials used in additive manufacturing has been a major focus of recent research on biodegradable polymer composites. Because of its biodegradability, ease of processing, low melting temperature, and appropriateness for fused deposition modeling (FDM) 3D printing applications, polylactic acid (PLA) has drawn a lot of attention among the many biopolymers. However, PLA has significant drawbacks that limit its broader engineering uses, including as brittleness, limited impact resistance, and poor thermal stability. Researchers have looked into adding sustainable fillers, like lignin, to PLA matrices to improve material performance while preserving environmental sustainability in order to get around these problems [16].

The structure-property correlations of PLA composites reinforced with micro- and nano-kraft lignin were examined by Makri [17]. Their investigation showed that nano-lignin had a major impact on PLA composite's molecular mobility, crystallization behavior, and glass transition temperature. Additionally, the authors noted that reactive extrusion enhanced the overall behavior of the composite by improving filler dispersion and interfacial contact. Similar to this, Alshammari [18] created highly loaded PLA/lignin biocomposites for material extrusion additive manufacturing and found that PLA and lignin compatibility was enhanced by the inclusion of plasticizers and glycidyl methacrylate. The study also found that the composite filaments' tensile strength, elongation, and printability were improved under ideal processing conditions.

The impact of various lignin sources on the mechanical and thermal characteristics of PLA composites has also been investigated by a number of researchers. PLA biocomposites with organosolv lignin from various biomass sources were compared by Obielodan [19] for use in 3D printing. According to their findings, oak-based composites showed greater stiffness and impact stability, whereas maple-derived lignin composites showed superior tensile strength. In a different study, Obielodan and colleagues described PLA/lignin biocomposites with up to 40 weight percent lignin and verified that lignin could be effectively added to PLA for environmentally friendly 3D printing applications without appreciably compromising process ability. These investigations demonstrated how crucial lignin type and concentration are in defining PLA composites' ultimate characteristics [19].

The impact of various lignin sources on the mechanical and thermal characteristics of PLA

 

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The compatibility of PLA with various types of lignin has also been thoroughly studied. The compatibility of kraft lignin, organosolv lignin, and lignosulfonate with PLA in 3D printing applications was investigated by Mimini et al. According to their findings, lignosulfonate mixes showed encouraging printability, while organosolv lignin was more compatible with PLA than kraft lignin. The study also highlighted that at greater lignin loadings, poor interfacial bonding and filler agglomeration may have a detrimental effect on mechanical characteristics. Similarly, Ryu examined how extrusion temperature and lignin content affected the characteristics of PLA filaments and found that while lignin enhanced nucleation behavior at lower extrusion temperatures, it became a weak point at higher temperatures due to increased crystallinity and decreased interfacial bonding [20].

Additional research has focused on improving PLA-lignin composites' functionality via chemical modification and efficient manufacturing. In their evaluation of the effects of kraft lignin and oxypropylated lignin in PLA composites, Esakkimuthu[21] found improvements in mechanical characteristics, antioxidant activity, and thermal stability at low lignin concentrations. Hydrogen bonding between lignin and PLA enhanced dispersion and preserved mechanical performance at reduced filler loadings, according to Terzopoulou's [22] synthesis of PLA composites using organosolv lignin. Furthermore, a number of review studies highlighted the potential for improving compatibility and mechanical behavior in biodegradable composites using lignin modification techniques such acetylation, grafting, and surface treatment [21, 22].

The literature shows that there are still a few research gaps concerning the optimization of lignin loading, processing parameters, interfacial compatibility, and printability for FDM applications, despite the notable advancements in the creation of PLA–lignin composites. The majority of research concentrated on either very high lignin loadings with chemical alterations or low lignin concentrations to preserve strength. The mechanical performance of PLA-kraft lignin composites made using controlled melt extrusion and FDM printing methods has not been thoroughly studied. In order to identify the ideal composition that offers balanced strength, stiffness, toughness, and sustainability for additive manufacturing applications, the current study focuses on examining the mechanical behavior of 3D printed PLA-kraft lignin composites with different lignin contents.

**Problem Definition**

Using different lignin types, loadings, and processing techniques, PLA–lignin composites have advanced significantly, according to the reviewed literature; nevertheless, a number of crucial gaps still exist. For FDM-based additive manufacturing, there is little systematic comparison of lignin type, particle size, surface chemistry, and processing route under controlled conditions. Most studies either concentrate on low lignin contents (≤10 wt%) to maintain mechanical performance or investigate very high loadings (up to 40 wt%) with modifications like plasticizers or grafting. There are still differences in mechanical performance, interfacial interaction, and molecular mobility behavior, especially under various extrusion temperatures and printing parameters, despite the extensive reporting of thermodynamic behavior, antioxidant functionality, and crystallization effects. Furthermore, nothing is known about how lignin biomass supply, nucleation mechanisms, and dynamical heterogeneities affect print lifetime and quality. For PLA-lignin composites to have suitable mechanical, thermal, and printability efficiency for scalable and environmentally friendly 3D printing applications, lignin type, concentration, and processing technique must be thoroughly investigated.

 

**Objectives**

The current research indicates that for FDM-based 3D printing applications, controlled lignin incorporation into PLA under ideal processing conditions can increase sustainability while preserving or improving mechanical and thermal performance. Melt extrusion will be used to create PLA–lignin composite filaments for this project. Printability will be assessed under different processing conditions, and the mechanical, thermal, and morphological characteristics of the filaments will be assessed as well as the interfacial interactions and crystallization behavior. Finding the best lignin type and concentration that provides balanced strength, thermal stability, and process ability is one of the expected outcomes, along with a deeper comprehension of structure–property relationships to support the development of scalable and reasonably priced bio-based feedstock materials for additive manufacturing.

Producing and characterizing PLA-Kraft lignin biocomposites appropriate for fused deposition modeling (FDM) 3D printing applications is the primary goal of this project. The goal of the work is to assess how various Kraft lignin loadings affect the mechanical characteristics, interfacial compatibility, and crystallization behavior of PLA composites. In addition to evaluating the produced composites' extrusion process capability, filament quality, and printability, the study aims to identify the ideal Kraft lignin content that strikes a compromise between mechanical performance, thermal stability, cost effectiveness, and sustainability.

**Work Methodology**

- *Material selection and design:* PLA and kraft lignin were chosen because of their biodegradability, thermal stability, and suitability for melt processing. To investigate the impact of different lignin weight percentages on mechanical and thermal performance, composite formulations were created.
- *Filament extrusion:* Using regulated temperature and screw speed settings, the dried PLA and kraft lignin were melted and extruded into a filament with a diameter of 1.75 mm. The filament's surface quality and dimensional accuracy were regularly assessed to make sure it was appropriate for FDM printing.
- *3D printing:* A fused deposition modeling (FDM) 3D printer was utilized to create standardized test specimens with ideal printing parameters. To achieve good surface smoothness and interlayer bonding, printing parameters like infill density, layer height, and nozzle temperature were changed.
- *Post-processing:* After being allowed to cool at room temperature, the printed specimens were conditioned to eliminate any remaining tension. Before mechanical testing, a surface inspection was performed to check for any obvious flaws.

The complete flow chart of the work is given in the below Figure 3.

- *Testing and evaluation:* A Universal Testing Machine was used to assess mechanical characteristics such modulus, elongation at break, and tensile strength. In order to ascertain how Kraft lignin loading affected composite performance and overall viability for 3D printing applications, the data were evaluated.

 

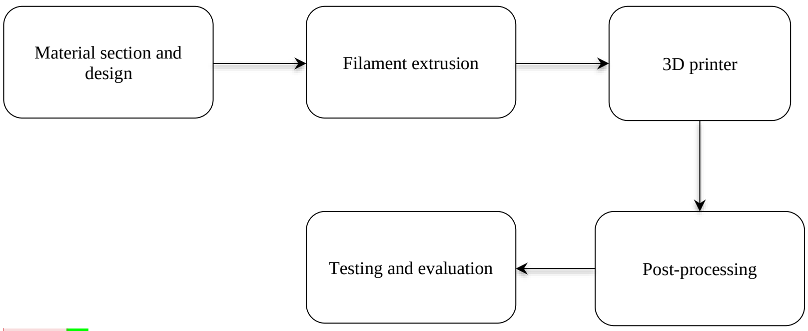


**Figure 3.** Work methodology.

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**Tools**

- *Oven:* Before melt processing, the kraft lignin powder and PLA pellets were dried in a hot air oven. Moisture is eliminated and PLA is kept from hydrolyzing during extrusion by drying at a regulated temperature.
- *Mechanical mixer:* PLA pellets and Kraft lignin powder were initially dry combined using a mechanical mixer. This made sure that before melt compounding, the lignin was dispersed evenly.
- *Extruder:* At specific temperature ranges, mixed PLA and kraft lignin were melted using the extruder. It made the process of making composite pellets easier and guaranteed that the lignin was dispersed uniformly throughout the polymer matrix.
- *Filament extruder unit:* This device produced a 1.75 mm-diameter composite filament that was appropriate for FDM printing. To maintain dimensional tolerance and guarantee consistent print quality, diameter monitoring was done.
- *FDM 3D printer:* The composite filament was used to manufacture standardized test specimens using an FDM 3D printer. Layer height, bed temperature, and nozzle temperature were among the printing parameters that were changed for the best interlayer bonding.
- *Computer:* In accordance with ASTM rules, CAD software was used to build test specimens. Software that could be printed by a machine was used to slice the 3D models into G-code.
- *Universal testing machine:* Tensile properties such as modulus, strength, and elongation at break were evaluated by the use of the Universal Testing Machine. It offered numerical data for evaluating the composites' mechanical performance.

**Geometry**

Tensile specimen was prepared according as per ASTM D638 standards, which are one of the common standards widely, used to test polymer and composites. As the type I dog-bone has defined fillet radii and grip lengths, it is optimum. It's 13 x 50 x 3.2mm. This shape helps minimize stress concentrations in the gauge section, as well as eliminate failure in the vicinity of the grips, and ensures uniform stress distribution in the gauge section, leading to accurate readings of mechanical properties. For an FEA model and a 3D print, the model was implemented once it was produced in CAD. The dog-bone profile of the specimen was drawn using ASTM measurements and CAD software. Fillets were incorporated at the shoulders to guarantee a smooth transition from the gauge to the grip area. Datum planes were created and the profile was formed to the required thickness in order to monitor the gauge region during simulation. In this instance, full coupon geometry was used to match the conditions of the experiment however symmetry might be applied for numerical efficiency. The Figure 4 below shows the ASTM D638 standard specimen design for Tensile test.

 

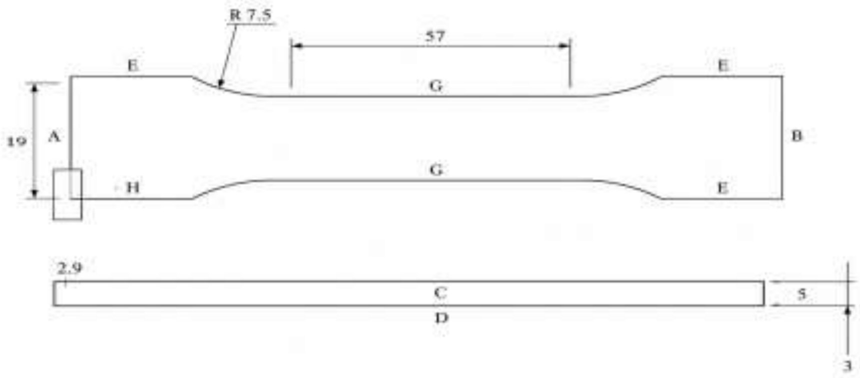


**Figure 4.** ASTM D638 standard specimen design.

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**Figure 5.** Filament Extruder.

**Filament Extrusion**

PLA pellets and kraft lignin powder were dried for 6–8 hours at 60–70°C in a hot air oven to eliminate any potential moisture absorption before processing. Moisture removal was crucial to preventing hydrolytic breakdown during melt blending, which could have decreased PLA's molecular weight and mechanical strength because to its hygroscopic nature. Before building the composite, the dry ingredients were kept in airtight containers to prevent moisture reabsorption. To examine the impact of filler loading on material performance, PLA-Kraft lignin composites were made with lignin concentrations ranging from 1% to 7%. A precision electronic balance was used to measure the necessary amounts of PLA and lignin, which were then dry mixed to guarantee uniform distribution. At controlled temperatures, melting mixing was then carried out to produce homogeneous composite pellets free from severe agglomeration or thermal deterioration [23, 24].

The composite pellets were heated to 180–210°C, which is suitable for PLA melting, using a filament extrusion apparatus. To preserve dimensional accuracy (±0.05 mm), the molten composite was continually monitored while it was extruded through a die to create a 1.75 mm diameter filament. To avoid internal tensions and guarantee constant roundness, the filament was chilled evenly using either ambient air or a controlled cooling system prior to being spooled [25]. The equipment for the extruding filament is shown in below Figure 5.

**3D Printing of Specimen**

Using a FDM 3D printer, standardized mechanical test specimens were created using PLA-kraft lignin composite filament. CAD software was used to develop the ASTM D638 tensile specimen geometry, which was then exported in STL format before printing. The STL file was processed using slicing software, which was also utilized to modify printing parameters such as temperature, infill density, print speed, and layer height. The temperature of the nozzle was maintained between 190 and 210°C to ensure proper melting of the composite filament [26, 27]. A temperature range of 50 to 60°C was chosen for the bed in order to prevent warping and promote adequate adherence of the first layer. For mechanical testing, a 100% infill density was chosen to remove internal cavities and offer consistent load distribution. To ensure a steady extrusion flow while balancing surface finish and printing time, the layer height was chosen and the print speed was adjusted [28]. To prevent flaws like under-extrusion, clogging, or layer separation, the filament feeding, extruded flow, and layer deposition were constantly observed during the printing process. After production, the printed specimens were allowed to cool at ambient temperature to release any remaining tensions. The specimens were examined for surface homogeneity, dimensional accuracy, and obvious flaws before mechanical testing. The accuracy and reproducibility of the testing results were guaranteed by this closely monitored printing procedure [29].

The experiment's goal was to evaluate the mechanical performance of the 3D printed composite specimens under varied loading conditions. Standardized testing procedures were used to ensure the accuracy and reliability of the results. The fabricated specimens underwent a variety of mechanical testing to evaluate their strength, stiffness, and toughness, including tensile, flexural, and impact tests.

Tensile Testing: The tensile test was used to evaluate the strength and deformation behavior of the 3D printed composite specimens under uniaxial loading conditions. The test produces critical mechanical properties such tensile strength, Young's modulus, and elongation at break that are essential for assessing the material's structural performance.

Flexural Testing: The flexural test was used to evaluate the 3D printed composite specimens' stiffness and bending behavior under transverse loading conditions. This test evaluates the material's resistance to deformation when bent and yields important mechanical properties like flexural strength and flexural modulus.

Impact Testing: The impact test evaluated the 3D printed composite specimen's toughness, or its ability to absorb energy under sudden loading conditions. Because it provides insight into the material's resistance to fracture under high strain-rate loading, this test is particularly important for assessing brittle materials like PLA-based composites.

## RESULTS AND DISCUSSIONS

### Tensile Test

The maximum force and displacement from the tensile test are shown in Table 2 below.

The tensile test was carried out in accordance with ASTM D638, which describes the specimen shape, testing conditions, and procedure for determining the tensile properties of polymer materials. To verify reproducibility and accuracy of results, three specimens (Sample-1, Sample-2, and Sample-3) were evaluated for each of the five weight percentages of kraft lignin (0%, 1%, 3%, 5%, and 7%). The specimen's dimensions width of 13 mm and thickness of 3.2 mm were used to compute the gauge section's cross-sectional area, which came out to be 41.6 mm². The following relation was used to determine the tensile strength: $\sigma = F/A$, where A is the cross-sectional area (mm2), F is the maximum applied load (N), and $\sigma$ is the tensile strength (MPa). The Table 3 explains the tensile strength of samples with different composition of kraft lignin.

### Flexural Test

The test was carried out in accordance with ASTM D790, which describes the specimen size, loading conditions, and testing procedure for three-point bending tests. The flexural test was conducted using a Universal Testing Machine (UTM) equipped with a three-point bending fixture. The fixture consists of two supports and a loading nose positioned in the center.

**Table 2.** Force and displacements obtained from tensile test.

 

| Kraft Lignin weight % | Sample-1 | | Sample-2 | | Sample-3 | |
|---|---|---|---|---|---|---|
| | ***Force (kN)*** | ***Displacement (mm)*** | ***Force (kN)*** | ***Displacement (mm)*** | ***Force (kN)*** | ***Displacement (mm)*** |
| 0 | 2.253 | 0.451 | 2.202 | 0.395 | 2.231 | 0.413 |
| 1 | 2.331 | 0.473 | 2.325 | 0.460 | 2.287 | 0.435 |
| 3 | 2.359 | 0.501 | 2.335 | 0.442 | 2.315 | 0.443 |
| 5 | 2.364 | 0.446 | 2.373 | 0.446 | 2.356 | 0.468 |
| 7 | 2.311 | 0.414 | 2.337 | 0.467 | 2.277 | 0.438 |

**Table 3.** Tensile strength of samples with different composition.

| Kraft lignin weight % | Tensile Strength (MPa) | | |
|---|---|---|---|
| | ***Sample-1*** | ***Sample-2*** | ***Sample-3*** |
| 0 | 54.158 | 52.933 | 53.629 |
| 1 | 56.034 | 55.889 | 54.976 |
| 3 | 56.707 | 56.129 | 55.649 |
| 5 | 56.827 | 57.043 | 56.635 |
| 7 | 55.553 | 56.178 | 54.736 |

**Table 4.** Results from flexural test on different composition of kraft lignin.

| Kraft Lignin Weight % | Maximum Force (N) | | |
|---|---|---|---|
| | ***Sample-1*** | ***Sample-2*** | ***Sample-3*** |
| 0 | 157.323 | 159.537 | 159.446 |
| 1 | 155.433 | 155.152 | 157.370 |
| 3 | 152.813 | 154.900 | 156.012 |
| 5 | 150.981 | 151.998 | 152.675 |
| 7 | 150.094 | 152.641 | 149.840 |

**Table 5.** Flexural strength and modulus for different compositions.

| Kraft Lignin weight % | Flexural Strength (MPa) | | | Flexural Modulus (MPa) | | |
|---|---|---|---|---|---|---|
| | ***Sample-1*** | ***Sample-2*** | ***Sample-3*** | ***Sample-1*** | ***Sample-2*** | ***Sample-3*** |
| 0 | 92.544 | 93.847 | 93.793 | 2984.969 | 3026.976 | 3025.250 |
| 1 | 91.433 | 91.267 | 92.572 | 2949.109 | 2943.777 | 2985.861 |
| 3 | 89.891 | 91.119 | 91.773 | 2899.398 | 2938.996 | 2960.095 |
| 5 | 88.814 | 89.412 | 89.810 | 2864.639 | 2883.935 | 2896.780 |
| 7 | 88.292 | 89.790 | 88.143 | 2847.809 | 2896.135 | 2842.990 |

The specimen was placed horizontally on two supports. A load was applied to the centroid of the specimen. The weight was gradually increased at a constant crosshead speed. The load and deflection were recorded until the specimen broke or experienced the most distortion. The flexural test results are listed in Table 4, which includes the maximum force.

According to ASTM D790 guidelines, a three-point bending test was used to assess the flexural characteristics of the 3D printed PLA–kraft lignin composite specimens. The following formula was used to determine the specimens' flexural strength:

$$\sigma_f = \frac{3FL}{2bd^2}\text{-}$$

and the flexural modulus were calculated from the load-deflection curve's slope using the following formula:

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$$E_f = \frac{L^3 m}{4bd^3}\text{-}$$

where F is the maximum load (N), L is the support span (mm), b is the specimen width (mm), d is the specimen thickness (mm), and m is the slope of the load-deflection curve's initial linear phase. The findings show that while an excessive filler content reduces efficiency because of poor dispersion and increased brittleness, an ideal lignin content produces superior flexural performance. Flexural strength and modulus are calculated and recorded in the Table 5.

**Table 6.** Impact test readings of energy absorption.

| **Kraft lignin weight %** | **Maximum energy absorbed (J)** | | |
|---|---|---|---|
| | ***Sample-1*** | ***Sample-2*** | ***Sample-3*** |
| 0 | 0.487 | 0.479 | 0.456 |
| 1 | 0.515 | 0.491 | 0.463 |
| 3 | 0.478 | 0.467 | 0.489 |
| 5 | 0.429 | 0.418 | 0.421 |
| 7 | 0.398 | 0.367 | 0.394 |

**Table 7.** Impact strength calculated from test results.

| **Kraft lignin weight %** | **Impact strength (J/mm$^2$)** | | |
|---|---|---|---|
| | ***Sample-1*** | ***Sample-2*** | ***Sample-3*** |
| 0 | 14.979 | 14.733 | 14.026 |
| 1 | 15.840 | 15.102 | 14.241 |
| 3 | 14.702 | 14.364 | 15.041 |
| 5 | 13.195 | 12.857 | 12.949 |
| 7 | 12.242 | 11.288 | 12.119 |

**Impact Test**

The test was conducted using ASTM D256 (Izod test). The test was carried out using an impact testing instrument (Izod) that includes of a pendulum that strikes the specimen and tracks the energy absorbed during fracture. The specimen was placed vertically in the apparatus (Izod). A traditional notch was inserted to create a focus of emphasis for tension. The pendulum was released at a predetermined height. It was noted how much energy was required to break the specimen. The highest energy absorbed data from the impact test are listed in Table 6.

The Izod impact test was utilized to evaluate the impact parameters of the 3D printed PLA-kraft lignin composite specimens, in accordance with ASTM D256 standards. The specimens' impact strength was calculated using the formula Impact strength = E/A, where A is the cross-sectional area at the notch (mm² or m²) and E is the energy absorbed during fracture (J).

Even very little lignin additions would not have a significant effect on toughness, the data clearly demonstrate that increasing filler content reduces energy absorption capacity, confirming the brittle nature of PLA-lignin composites. Table 7 below lists the calculated impact strength values for several samples.

**Discussions**

The mechanical characteristics of the 3D printed PLA-kraft lignin composites was clearly correlated with the lignin content. The tensile test findings showed that the tensile strength increased from pure PLA (0 weight percent) to 5 weight percent lignin, indicating improved load transmission and interfacial interaction between the PLA matrix and lignin particles. Due to possible lignin particle aggregation and insufficient dispersion, a slight drop was observed at 7 weight percent after the maximum tensile strength was obtained at 5 weight percent. In a similar vein, the flexural test results demonstrated a decreasing trend in flexural strength and modulus with increasing lignin content, suggesting that although lignin increases stiffness, the material's resistance to bending loads is reduced.

The brittle nature of PLA–lignin composites was further confirmed by the impact test findings, which demonstrated that the energy absorption capacity decreased with increasing lignin content. Because of poor interfacial bonding and stress concentration caused by lignin agglomeration, higher lignin content (5–7 weight percent) significantly reduced impact strength, while lower lignin percentages (around 1 weight percent) showed a slight improvement or no change. Overall, the results demonstrate that a moderate lignin level (about 3–5 weight percent) provides a compromise between strength and stiffness, whereas greater filler content adversely affects toughness and ductility. These findings highlight how important it is to maximize filler loading in environmentally friendly PLA-based composites for FDM applications in order to increase mechanical performance.

## CONCLUSION

In this study, fused deposition modeling (FDM) was successfully used to manufacture PLA-kraft lignin composite filaments that were used to produce 3D printed specimens. By varying the kraft lignin percentage from 0% to 7%, the mechanical performance of the composites was evaluated by tensile, flexural, and impact testing. The results demonstrated that adding lignin significantly alters the mechanical properties of PLA-based composites. The tensile test findings showed that adding kraft lignin enhanced PLA's tensile strength up to an optimal value of 5% weight, after which weak interfacial bonding and particle aggregation caused a slight drop. Conversely, the flexural properties gradually declined as the lignin content rose, exhibiting increasing stiffness but decreasing resistance to bending deformation. The impact test results, which demonstrated a decrease in hardness with increasing lignin content, particularly at higher filler concentrations, validated the fragile nature of PLA-lignin composites. Overall, the study concludes that a moderate addition of kraft lignin (about 3–5 weight percent) in FDM applications provides a balanced enhancement of mechanical performance while maintaining printability and processability. Higher lignin content deteriorates mechanical properties due to poor dispersion and increased brittleness. The findings show kraft lignin's potential as an affordable and sustainable filler for PLA-based composites, promoting the development of eco-friendly materials for applications in additive manufacturing.

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