

Development and Mechanical Characterization of Kenaf Fibre Reinforced PLA Filament for FDM 3D Printing Applications

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Abstract—Additive manufacturing has emerged as an important manufacturing technology for producing complex components with reduced material waste, shorter production time, and improved design flexibility. Fused Deposition Modeling (FDM) is one of the widely used additive manufacturing techniques because of its simplicity, cost effectiveness, and accessibility. Polylactic Acid (PLA) is commonly used in FDM owing to its biodegradability, low melting temperature, good printability, and environmental advantages. However, the relatively low mechanical strength, brittleness, and limited thermal resistance of PLA restrict its use in certain structural and load-bearing applications. Natural fibre reinforced polymer composites provide a potential solution to these limitations.

In the present study, kenaf fibre was selected as a natural reinforcement for PLA to develop a sustainable composite filament for FDM 3D printing. Kenaf fibres were subjected to alkaline treatment to remove surface impurities and improve fibre–matrix interaction. Composite materials containing different kenaf fibre weight percentages were prepared and processed through filament extrusion. Standard tensile and flexural specimens were subsequently designed using computer-aided design software and fabricated using FDM technology. The mechanical behaviour of the developed composite was evaluated through tensile and flexural testing. The experimental investigation demonstrates the potential of kenaf fibre reinforced PLA as a lightweight and environmentally friendly material for additive manufacturing applications.

Index Terms—Kenaf fibre, Polylactic Acid, PLA composite, FDM, additive manufacturing, 3D printing, natural fibre, filament extrusion.

I. INTRODUCTION

Additive manufacturing, commonly referred to as 3D printing, has significantly transformed modern manufacturing by enabling the fabrication of complex geometries with reduced material wastage and improved design flexibility. Unlike conventional manufacturing processes in which material is removed or shaped through several machining and forming operations, additive manufacturing produces components by depositing material layer by layer according to a digital model. This capability makes additive manufacturing attractive for rapid prototyping, customized products, lightweight structures, and low-volume production.

Among the different additive manufacturing technologies, Fused Deposition Modeling (FDM) is one of the most widely adopted processes because of its simple operation, relatively low equipment cost, ease of maintenance, and broad availability of thermoplastic materials. In FDM, a polymer filament is supplied to a heated extrusion nozzle, where it is melted and deposited layer by layer according to the tool path generated from a three-dimensional computer-aided design (CAD) model. The deposited material solidifies and gradually forms the required component.

Polylactic Acid (PLA) is one of the most commonly used materials in FDM 3D printing. PLA is a biodegradable and bio-based thermoplastic polymer derived from renewable resources such as corn starch and sugarcane. It offers several advantages, including

good printability, relatively low processing temperature, minimal warping, good surface finish, and environmental benefits. These characteristics make PLA particularly suitable for educational, prototyping, and general purpose additive manufacturing applications.

However, pure PLA also possesses certain limitations. Its relatively low mechanical strength for demanding structural applications, brittle behaviour, and limited thermal resistance can restrict its application in load-bearing components. Therefore, considerable research has been directed toward improving the mechanical performance of PLA by incorporating suitable reinforcement materials.

Natural fibres have gained increasing attention as reinforcement materials for polymer composites because of their low density, renewability, biodegradability, relatively low cost, and favourable strength-to-weight characteristics. Fibres such as kenaf, jute, flax, and hemp can provide additional stiffness and strength while maintaining the environmental advantages of biodegradable polymer matrices.

Kenaf fibre, obtained from the plant *Hibiscus cannabinus*, is considered a promising reinforcement for polymer composites. Its low density, good mechanical properties, renewability, and environmentally friendly characteristics make it suitable for lightweight composite applications. When incorporated into a PLA matrix, kenaf fibre has the potential to improve the mechanical performance of the polymer while retaining the sustainable characteristics of the base material.

In this work, kenaf fibre reinforced PLA composite filament was developed for FDM 3D printing applications. The kenaf fibres were treated and blended with PLA before filament extrusion. The developed material was subsequently used to fabricate test specimens through FDM, followed by mechanical characterization using tensile and flexural testing.

A. Research Gap

Although several studies have investigated natural fibre reinforced polymer composites, comparatively limited work has focused specifically on the development of natural fibre reinforced filament intended for FDM 3D printing. Conventional studies have often concentrated on composite fabrication

through processes such as injection moulding and compression moulding rather than filament extrusion and subsequent layer-by-layer deposition.

Furthermore, the mechanical performance of an FDM printed composite is influenced not only by the material constituents but also by fibre distribution, fibre-matrix bonding, extrusion stability, filament diameter consistency, and printing conditions. Variations in fibre content can also influence filament flow behaviour and the quality of the printed specimens. Therefore, there is a need to investigate kenaf fibre reinforced PLA specifically as an FDM filament and to evaluate its mechanical performance under tensile and flexural loading. The present study addresses this requirement through composite preparation, filament extrusion, FDM specimen fabrication, and experimental mechanical testing.

B. Aim of the Project

The main aim of this research is to develop kenaf fibre reinforced PLA composite filament and evaluate its mechanical performance for FDM 3D printing applications.

C. Objectives

The objectives of the present study are:

- 1) To prepare kenaf fibre reinforced PLA composite material.
- 2) To develop composite filament suitable for FDM 3D printing.
- 3) To fabricate standard test specimens using the developed composite filament.
- 4) To perform tensile testing to evaluate the tensile strength of the composite.
- 5) To conduct flexural testing to determine the bending strength and stiffness of the composite.

II. LITERATURE REVIEW

The development of sustainable materials for additive manufacturing has received increasing attention because conventional polymer-based filaments can contribute to environmental pollution and may have limitations in mechanical performance. Recent research has therefore focused on polymer composites, natural fibre reinforcement, recycled polymers, and improved extrusion and printing techniques.

Zielinski *et al.* investigated the improvement of acoustic materials through controlled filament stringing in 3D printing. Their work demonstrated that controlled filament formation can influence the internal structure and functional performance of printed materials. The study highlights the importance of extrusion behaviour and filament formation in determining the final properties of FDM components.

Martinez-Sanchez *et al.* developed a sustainable desiccant wheel using a PLA–wood composite for HVAC energy recovery applications. The incorporation of a bio-based filler improved the functional performance of the polymer system and demonstrated the potential of combining PLA with renewable materials for sustainable engineering applications.

Han *et al.* introduced a fused powder extrusion process for direct 3D printing of polymer powders. The approach reduced the requirement for conventional filament preparation and demonstrated the potential of alternative extrusion routes for additive manufacturing. Such developments are relevant to future composite filament production because processing methods strongly influence material quality and printability.

Memis and Gok investigated Fe-reinforced PLA composite filaments fabricated through an extrusion process. Their results demonstrated that reinforcement can significantly influence the mechanical properties of PLA-based composite filaments. The study also emphasized the importance of controlling extrusion temperature and feed rate during composite filament fabrication.

Enarevba *et al.* conducted a life-cycle assessment comparing hemp–PLA composites with pure PLA. Their findings indicated that natural fibre reinforced PLA systems can provide environmental advantages, supporting the use of renewable fibres as alternatives to synthetic reinforcement materials.

Nayana and Manikandan investigated 3D-printed ABS honeycomb structures for beekeeping applications. Their work demonstrated the adaptability of additive manufacturing for lightweight and functional engineering structures. This supports the broader application of sustainable and customized 3D-printed materials.

Hosseinzadeh *et al.* presented a review of modified and composite ABS filaments for FDM printing.

Their study considered polymer blending, nanocomposite formation, and filler incorporation for improving mechanical and thermal properties. The findings demonstrate that suitable reinforcement and material combinations can be used to tailor the properties of FDM filaments.

Tadi and Mamilla investigated SS316L particle-filled PLA composite filaments produced using recycled PLA. The addition of stainless-steel particles improved tensile strength while maintaining printability. Microscopic and rheological investigations confirmed the importance of uniform particle dispersion within the polymer matrix. This observation is relevant to natural fibre reinforced PLA because uniform reinforcement distribution is similarly important for consistent mechanical performance.

Roveda *et al.* developed a fully 3D-printed electrochemical cell using commercial ABS and conductive CB–PLA filaments. Their study demonstrated the potential of additive manufacturing for producing functional, reusable, and sustainable components. The work further emphasizes the flexibility of FDM technology for engineering applications.

Ray *et al.* investigated Kevlar-reinforced ABS/PLA composites for improving strength and surface properties in FDM printing. The incorporation of reinforcement improved tensile strength and toughness, while microscopic analysis showed the importance of filler dispersion and surface integrity. These observations support the concept of reinforcing PLA with suitable fibres to improve its mechanical behaviour.

Wei and Bahr compared virgin and recycled PLA filaments for sustainable additive manufacturing. Although recycled PLA required different processing conditions, the material retained useful tensile and flexural characteristics. Their study demonstrates the possibility of recycling polymer feedstock while maintaining functional performance.

Devra *et al.* investigated the production of sustainable 3D printing filament from recycled LDPE waste. The study emphasized the optimization of extrusion parameters such as nozzle temperature and screw speed to obtain consistent filament dimensions. This is particularly relevant to composite filament fabrication, where dimensional stability and continuous extrusion are essential for reliable FDM

printing.

Elessawy *et al.* developed eco-friendly 3D printing filaments using recycled PET blended with date palm frond nanoparticles. The incorporation of natural reinforcement improved tensile and thermal performance without significantly affecting printability. The study demonstrates the potential of bio-based reinforcement for developing sustainable polymer composite filaments.

Divakaran *et al.* investigated material-extrusion-based 3D printed capacitors using ABS reinforced with ZnO and CuCNT nanofillers. The results emphasized the influence of filler–matrix interaction and uniform filler dispersion on the resulting properties. Similar principles are applicable to fibre-reinforced PLA systems, where effective interaction between the reinforcement and polymer matrix is necessary for improved performance.

Thota *et al.* investigated the influence of infill pattern and printing parameters on the mechanical properties of PLA based FDM components. Honeycomb, grid, and triangular infill configurations were evaluated for tensile and flexural performance. Their results indicated that infill configuration and density can significantly influence the strength-to-weight characteristics of printed components.

Ahmad *et al.* investigated oil-palm-fibre-reinforced thermoplastic composites for FDM applications. Their mechanical and thermal characterization showed that fibre reinforcement can improve tensile strength, modulus, and dimensional stability. However, excessive fibre loading was associated with a reduction in flexural performance. This highlights the importance of selecting an appropriate fibre content for composite filament development.

Gultekin *et al.* developed ABS filaments containing rare earth oxide nanoparticles for gamma-ray shielding applications. Their work demonstrated the importance of uniform reinforcement distribution in achieving consistent material properties. The same principle is applicable to kenaf fibre reinforced PLA, where non-uniform fibre distribution can affect filament quality and printed-part performance.

Vallejos Baier and Vega investigated porous structures produced using low-cost open-source FDM equipment. Their results demonstrated that cost-effective FDM systems can produce components with useful mechanical performance and dimensional precision. This supports the feasibility of using

conventional FDM systems for the fabrication of sustainable polymer composite specimens.

A. Summary of Literature Findings

The reviewed studies indicate that the mechanical and functional performance of FDM components depends on several interacting factors, including reinforcement type, reinforcement concentration, fibre or particle distribution, polymer–reinforcement bonding, extrusion conditions, filament dimensional stability, and printing parameters.

Natural fibre reinforcement provides an attractive route for reducing the environmental impact of polymer-based additive manufacturing while potentially improving mechanical performance. However, the incorporation of natural fibres introduces additional challenges related to fibre dispersion, extrusion stability, filament formation, and printability.

The literature also indicates that increasing reinforcement content does not necessarily produce a continuous improvement in mechanical properties. Excessive reinforcement can affect material flow, interfacial bonding, and print quality. Therefore, optimization of reinforcement content and processing conditions is essential.

B. Research Motivation

Based on the reviewed studies, there remains a need for further experimental investigation of kenaf fibre reinforced PLA filament specifically developed through filament extrusion for FDM applications. In particular, the relationship between fibre content, filament quality, printability, and mechanical performance requires further investigation.

The present study therefore focuses on the preparation of kenaf fibre reinforced PLA filament, fabrication of FDM test specimens, and evaluation of their tensile and flexural behaviour. The study also considers the practical challenges associated with producing stable natural-fibre reinforced filament.

III. MATERIALS AND COMPOSITE PREPARATION

A. Materials Used

Poly(lactic Acid) (PLA) was selected as the matrix material for the development of the composite filament. PLA is a biodegradable thermoplastic

polymer commonly used in FDM 3D printing because of its good printability, relatively low processing temperature, and environmental advantages. The PLA used in the study was supplied in granule form for subsequent composite preparation.

Kenaf fibre was selected as the reinforcement material because of its low density, good mechanical properties, renewability, and biodegradable nature. Kenaf fibre is obtained from

TABLE I
PROPERTIES OF PLA AND KENAF FIBRE

Property	PLA	Kenaf Fibre
Density	1.24 g/cm ³	1.2–1.4 g/cm ³
Tensile Strength	60–70 MPa	295–930 MPa
Young's Modulus	–	11–60 GPa
Melting Temperature	160–180°C	–
Biodegradability	Yes	Excellent



Fig. 1. Experimental kenaf fibre samples prepared for composite fabrication.

the plant *Hibiscus cannabinus* and is considered a suitable natural reinforcement for polymer-based composite materials. The properties reported for the materials are summarized in

Table I.

The combination of PLA and kenaf fibre provides a biodegradable polymer composite in which PLA acts as the matrix and kenaf fibre provides reinforcement. The matrix binds the reinforcement and transfers the applied load, while the fibre contributes to the mechanical performance of the composite.

B. Kenaf Fibre Processing

Before incorporation into the PLA matrix, the kenaf fibre underwent processing to obtain a suitable particle form. The chemically treated and dried kenaf fibres were ground using a spice milling

machine. The ground material was subsequently sieved to obtain fine particles suitable for blending with PLA. The report specifies an average particle size of approximately 90 μm . Fine particle size was selected to promote better dispersion of the reinforcement within the polymer matrix and to support smooth filament fabrication.

The experimental kenaf samples corresponding to different reinforcement quantities are shown in Fig. 1. The four measured quantities were used to prepare the different composite formulations.

C. Alkaline Treatment of Kenaf Fibre

Natural fibres contain surface constituents such as lignin, hemicellulose, waxes, and other impurities that can interfere with bonding between the reinforcement and polymer matrix. Therefore, an alkaline treatment was carried out before composite preparation.

In the reported procedure, kenaf fibres were soaked in sodium hydroxide (NaOH) solution for a specified period. The

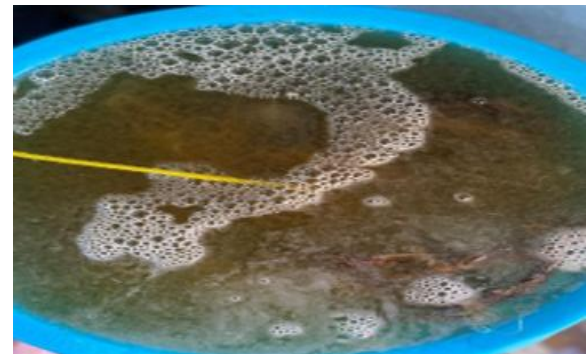


Fig. 2. Alkaline treatment process used for kenaf fibre preparation.



Fig. 3. Spice milling machine used to reduce the treated kenaf fibre to fine particles.

alkaline treatment removes surface impurities and increases the surface roughness of the fibre. This treatment is intended to improve the interaction between the kenaf fibre and PLA matrix.

After treatment, the fibres were thoroughly washed using distilled water to remove residual chemicals. The treated fibres were then dried before further processing.

D. Grinding and Sieving

The treated and dried kenaf fibres were ground into fine particles using a spice milling machine. The machine reduces the fibre size through high-speed rotating blades. The resulting material was sieved to obtain particles with an average size of approximately 90 μm .

The reduction of fibre size is important for the subsequent

mixing process because smaller particles can be distributed more uniformly within the PLA matrix. The source report also states that fine particles help to prevent clogging during FDM printing.

E. Material Drying

Moisture removal was carried out before composite fabrication. The source report states that 1 kg of PLA granules and 100 g of kenaf fibre powder with an average particle size of 90 μm were placed inside a laboratory oven.

The materials were dried at a constant temperature of 60°C for a duration of 6 hours. This controlled drying process was performed to eliminate absorbed moisture from the raw materials before filament fabrication.

F. Composite Formulation

Four different PLA–Kenaf formulations were prepared by varying the amount of kenaf fibre while maintaining the



Fig. 4. Convection oven used for controlled drying of the raw materials.

TABLE II
PLA–KENAF COMPOSITE FORMULATIONS

Sample	PLA (g)	Kenaf Fibre (g)	Fibre Content
Sample 1	198	2	1 wt%
Sample 2	194	6	3 wt%
Sample 3	190	10	5 wt%
Sample 4	186	14	7 wt%

required total material quantity. The compositions used in the experimental work are presented in Table II.

The prepared PLA and kenaf fibre quantities were mixed to obtain a uniform distribution of the reinforcement within the polymer matrix before filament fabrication. The different formulations allowed the effect of increasing kenaf fibre content on filament formation and subsequent FDM processing to be investigated.

G. Composite Mixing

The required quantity of dried PLA granules was combined with the corresponding quantity of processed kenaf fibre powder. The materials were mixed properly before extrusion with the objective of obtaining a uniform distribution of kenaf particles throughout the PLA matrix.

Uniform reinforcement distribution is particularly important for FDM filament because localized accumulation of fibre can influence material flow through the extrusion nozzle and can also affect the mechanical properties of the final printed component.

H. Preparation for Filament Extrusion

After drying and mixing, the composite material was prepared for filament extrusion. The material was subsequently introduced into the RP filament extruder, where the polymer was heated and forced through a heated nozzle to form a continuous filament.

The extrusion stage is described in detail in the following section, including the operating principle of the RP extruder and the fabrication of the final FDM filament

IV. FILAMENT EXTRUSION AND CAD MODEL DEVELOPMENT

A. RP Filament Extruder

The prepared PLA–Kenaf composite mixture was

processed using an RP filament extruder to produce continuous thermoplastic filament. The RP extruder is used to convert polymer

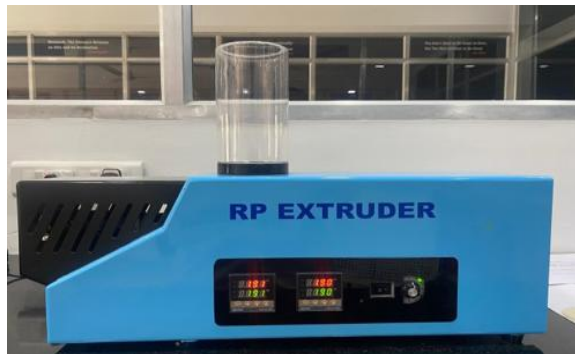


Fig. 5. RP filament extruder used for fabrication of PLA-Kenaf composite filament.

granules or composite blends into filament of suitable geometry for subsequent FDM printing.

The extrusion process is based on the thermoplastic extrusion principle. The composite material is introduced into the extruder and heated above the processing temperature of the polymer. A rotating screw conveys the heated material toward the nozzle, where the molten composite is forced through a die to form a continuous filament. After exiting the nozzle, the material cools and solidifies.

The quality of the extruded filament is an important factor in FDM printing. A stable filament must maintain sufficient structural integrity and consistent dimensions so that it can be continuously fed through the printer without interruption.

B. Filament Fabrication Process

The dried PLA granules and processed kenaf fibre were supplied to the RP extruder according to the selected composite formulation. Inside the extruder, the polymer matrix was heated and mixed with the reinforcement while being transported toward the nozzle.

The molten composite was subsequently forced through the extrusion die to form continuous filament. The extruded filament was allowed to cool and solidify before being collected for further processing.

The general sequence adopted for filament fabrication can be represented as:

The extrusion process was carried out for the

different material compositions prepared in the study. The resulting filaments were visually examined for continuous formation, dimensional stability, and suitability for FDM printing.

C. Filament Quality and Printability

The experimental investigation demonstrated that the quality of the composite filament was strongly dependent on the material formulation and processing conditions. Among the four fabricated samples, only the first sample demonstrated proper filament formation and consistent diameter suitable for subsequent printing.

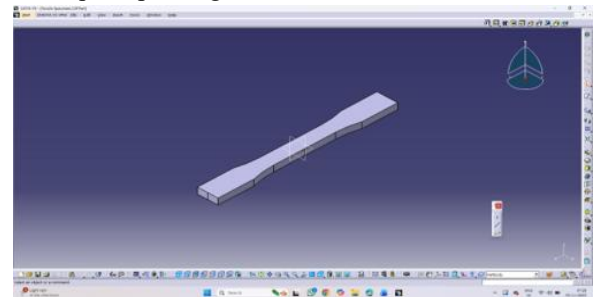


Fig. 6. CAD model of tensile test specimen based on ASTM D638.

The second and third samples experienced improper filament flow and poor layer adhesion during printing. These issues may be associated with non-uniform reinforcement distribution or instability during extrusion. The fourth sample did not maintain sufficient structural integrity and continuous extrusion and was therefore unsuitable for printing.

These observations demonstrate that increasing the amount of natural fibre in the polymer matrix can introduce processing challenges. Fibre dispersion, polymer flow, extrusion stability, and filament dimensional consistency must therefore be controlled to obtain a filament suitable for FDM fabrication.

D. CAD Model Creation

After fabrication of the composite filament, standard test specimens were designed using Computer-Aided Design (CAD) software. CATIA V5 was used for creating the three dimensional models of the tensile and flexural specimens.

The use of CAD provides accurate control over specimen geometry and dimensions before fabrication. The digital models were subsequently converted into STL format for use in the FDM

printing workflow.

E. Tensile Test Specimen

The tensile specimen was designed according to the dimensions identified in the study for ASTM D638 testing. The geometry was created in CATIA V5 using the Part Design environment.

The CAD model provides the required specimen profile and dimensions necessary for evaluating the tensile behaviour of the developed composite filament.

F. Flexural Test Specimen

A separate specimen was designed for evaluating the bending behaviour of the composite. The flexural specimen was developed according to the dimensions identified for ASTM D790 testing.

The specimen geometry was created using CATIA V5 and subsequently prepared for additive manufacturing. The flexural specimen was intended to evaluate the bending strength and stiffness of the developed PLA–Kenaf composite.

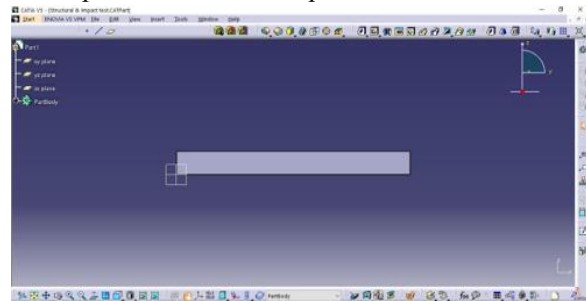


Fig. 7. CAD model of flexural test specimen based on ASTM D790.

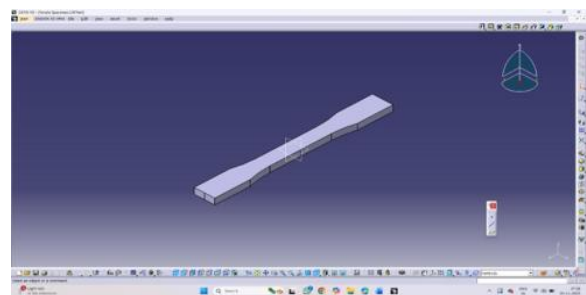


Fig. 8. STL conversion and slicing preparation of the test specimen.

G. STL Conversion

After completion of the CAD modelling process, the tensile and flexural specimens were converted into STL (Stereolithography) format. STL represents the

surface geometry of a three-dimensional model using triangular facets and is commonly used as an input format for additive manufacturing.

The STL files were imported into slicing software to prepare the models for FDM printing. The required printing parameters, including layer height, printing speed, infill density, and temperature, were defined during the slicing stage.

The slicing software generated the corresponding G-code required by the FDM printer. The G-code contains the movement and extrusion instructions required to fabricate the specimen layer by layer.

H. FDM Fabrication Workflow

The complete fabrication sequence followed in the study can be summarized as:

Raw PLA + Kenaf → Fibre Treatment

→ Grinding and Sieving

→ Drying

→ Mixing

→ Filament Extrusion (2)

→ CAD Model

→ STL Conversion

→ Slicing

→ FDM Printing

This workflow connects material preparation and filament fabrication with the subsequent digital manufacturing

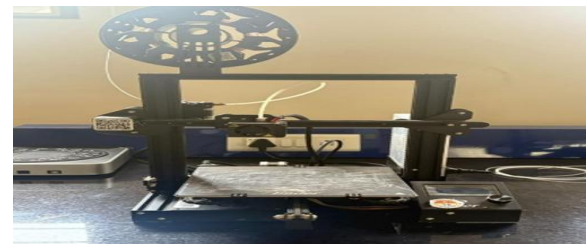


Fig. 9. FDM 3D printer used for fabrication of the mechanical test specimens.

process. The resulting printed specimens were then subjected to tensile and flexural testing to determine their mechanical performance.

V. FDM PRINTING AND EXPERIMENTAL TESTING

A. FDM Printing of Test Specimens

The successfully fabricated composite filament was

used as feedstock for Fused Deposition Modeling (FDM) 3D printing. The tensile and flexural specimens developed using CATIA V5 were first converted into STL format and subsequently processed using slicing software.

During the slicing stage, the digital specimen geometry was converted into a sequence of toolpath instructions. Important printing parameters such as layer height, printing speed, infill density, and printing temperature were defined before generating the G-code.

The G-code was transferred to the FDM printer, where the composite filament was heated and deposited through the nozzle in successive layers. Each deposited layer cooled and bonded with the previously deposited layer, gradually producing the required test specimen.

B. Printed Test Specimens

The developed filament was used to fabricate tensile and flexural specimens. The quality of the printed specimens was dependent on the consistency of the filament and its ability to flow continuously through the printer nozzle.

The experimental observations showed that only the first filament sample exhibited suitable filament formation and consistent diameter for successful printing. The second and third samples experienced improper filament flow and poor layer adhesion, while the fourth sample did not maintain sufficient structural integrity for continuous extrusion.

These observations demonstrate that successful FDM fabrication depends on both the material formulation and the quality of the extruded filament. Non-uniform reinforcement distribution and extrusion instability can directly influence the quality of the printed specimen.

C. Experimental Testing

Mechanical characterization was carried out to evaluate the performance of the developed PLA–Kenaf composite. Tensile and flexural tests were selected to determine the response of



Fig. 10. FDM-fabricated tensile and flexural test specimens.



Fig. 11. Universal Testing Machine used for mechanical characterization.

the printed material under tensile and bending loads, respectively.

The fabricated specimens were tested using a Universal Testing Machine (UTM). The tensile test was used to determine the tensile strength of the composite, while the flexural test was used to evaluate its resistance to bending loads.

D. Universal Testing Machine

The Universal Testing Machine applies a controlled mechanical load to a specimen and records the corresponding response. In the tensile test, the specimen is subjected to an increasing axial load until failure occurs.

The tensile test provides information regarding the ability of the composite material to withstand tensile loading. Important characteristics obtained from such testing include tensile strength and deformation behaviour.

E. Tensile Test

The tensile test is one of the primary mechanical tests used to characterize polymer composite materials. During the test, the specimen is held between the grips of the testing machine and subjected to

gradually increasing tensile loading.

The applied load produces tensile stress in the specimen until failure occurs. The tensile strength is determined from the maximum load carried by the specimen and its original cross-sectional area.

The tensile stress can be expressed as:

$$\sigma_t = \frac{F}{A_0} \quad (3)$$

where σ_t is the tensile stress, F is the applied tensile load, and A_0 is the original cross-sectional area of the specimen.

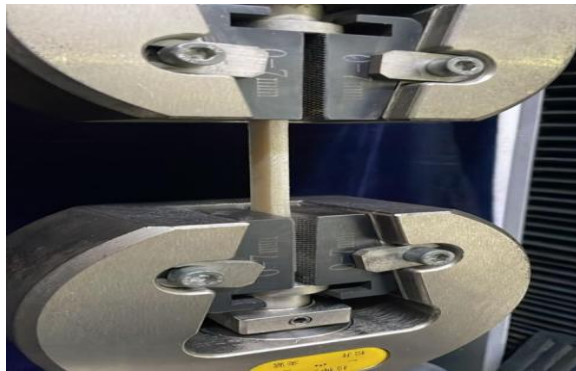


Fig. 12. Tensile specimen during Universal Testing Machine evaluation.

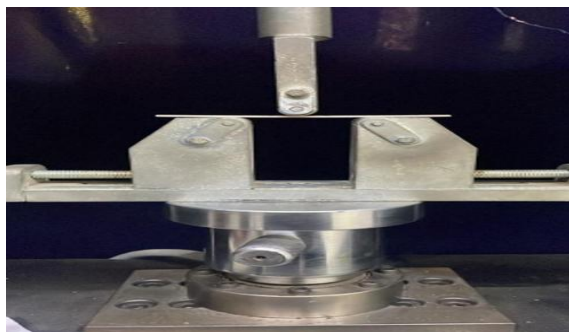


Fig. 13. Flexural specimen during bending test.

The tensile test was conducted on the successfully printed specimen obtained from the first filament sample.

F. Flexural Test

The flexural test was performed to determine the bending strength and stiffness of the developed composite. In this test, the specimen is supported at two locations and a load is applied to produce bending.

The flexural response provides an indication of the

ability of the composite to resist deformation under bending loads. This property is important for lightweight components that may experience bending during service.

The flexural test was performed on the successfully printed specimen obtained from the first filament sample.

G. Testing Procedure

The experimental testing sequence adopted in the study can be summarized as follows:

- 1) Fabricate the PLA–Kenaf composite filament.
- 2) Identify the filament sample suitable for continuous FDM printing.
- 3) Fabricate tensile and flexural specimens using FDM.
- 4) Inspect the printed specimens for visible defects and dimensional consistency.
- 5) Mount the tensile specimen in the Universal Testing Machine.
- 6) Apply gradually increasing tensile load until failure.
- 7) Record the tensile response.
- 8) Mount the flexural specimen on the testing supports.
- 9) Apply bending load until significant deformation or failure occurs.
- 10) Record and compare the resulting mechanical properties.

The experimental procedure enabled the mechanical behaviour of the successfully fabricated composite filament to be evaluated under both tensile and bending loading conditions.

H. Evaluation of Printability

The fabrication stage revealed that printability is an important criterion in addition to mechanical performance. A composite filament may contain a higher reinforcement concentration, but if the material cannot maintain continuous extrusion and stable deposition, it cannot be effectively used in FDM printing.

Therefore, the present study considers filament formation, continuous extrusion, layer adhesion, and successful specimen fabrication as important indicators of composite suitability for additive manufacturing.

VI. RESULTS AND DISCUSSION

A. Overview of Experimental Results

After fabrication of the PLA–Kenaf composite filament and FDM test specimens, tensile and flexural tests were conducted to evaluate the mechanical performance of the developed material.

The experimental investigation showed that filament quality had a significant influence on the successful fabrication of test specimens. Among the four fabricated filament samples, only the first sample produced a stable filament with suitable characteristics for successful FDM printing. The remaining samples experienced difficulties during the printing stage and could not be used to obtain proper mechanical test specimens. The observed difficulties included improper filament flow, poor layer adhesion, and inadequate structural integrity of the extruded filament. These observations indicate that reinforcement distribution and extrusion conditions are important factors governing the printability of natural fibre reinforced polymer filaments.

B. Filament Fabrication Results

During filament fabrication, variations in fibre distribution and extrusion conditions affected the quality and stability of the produced filaments. The first sample showed proper filament formation and consistent diameter, allowing tensile and flexural specimens to be successfully fabricated.

The second and third samples experienced improper filament flow and poor layer adhesion during the printing process. These problems may be associated with non-uniform fibre dispersion or instability during extrusion. The fourth filament was unsuitable for printing because it did not maintain sufficient structural integrity and continuous extrusion.

The results indicate that increasing the amount of reinforcement must be accompanied by appropriate control of mixing and extrusion conditions. A higher fibre content alone can-not guarantee improved performance if the resulting filament cannot be continuously extruded and successfully printed.

TABLE III
FILAMENT FABRICATION AND PRINTABILITY OBSERVATIONS

Sample	Observation
Sample 1	Proper filament formation, consistent diameter, and successful FDM printing.
Sample 2	Improper filament flow and poor layer adhesion during printing.
Sample 3	Improper filament flow and poor layer adhesion during printing.
Sample 4	Insufficient structural integrity and discontinuous extrusion.

TABLE IV
REPORTED TENSILE TEST RESULTS

Sample ID	Tensile Strength (MPa)
A1	29.04
A2	29.14
A3	27.27
Average	28.48

C. Tensile Test Results

The tensile properties of the successfully printed composite specimen were evaluated using a Universal Testing Machine. The source report identifies the machine as an FIEE-50KN Universal Testing Machine with a maximum testing load of 5 tons and a load accuracy of 0.01 N.

Only the first filament sample produced a stable filament that could be successfully printed into a tensile specimen. The tensile test showed a tensile strength of approximately 29 MPa.

The individual tensile test values reported in the study are presented in Table IV.

The average tensile strength calculated from the three reported values is:

$$\sigma_{avg} = \frac{29.04 + 29.14 + 27.27}{3} = 28.48 \text{ MPa} \quad (4)$$

The reported tensile strength of approximately 29 MPa indicates that the developed PLA–Kenaf composite possesses moderate tensile resistance. The result demonstrates that the incorporation of natural fibre reinforcement can contribute to the mechanical performance of PLA-based materials used in additive manufacturing.

D. Tensile Strength Discussion

The tensile results show relatively close values for specimens A1 and A2, while specimen A3 exhibits a

lower value. The three measurements remain within a relatively narrow range, indicating reasonably consistent tensile behaviour for the successfully fabricated specimen set.

The observed tensile performance can be associated with the reinforcing contribution of kenaf fibre within the PLA matrix. Effective fibre dispersion and interaction with the polymer matrix are important for transferring the applied tensile load. However, the experimental results also demonstrate that the mechanical performance cannot be considered independently

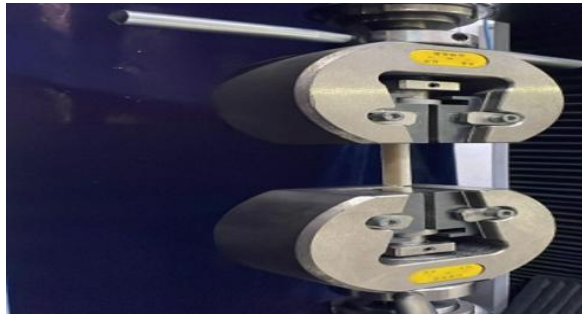


Fig. 14. Tensile test result of the successfully printed PLA-Kenaf composite specimen.

TABLE V
SUMMARY OF REPORTED MECHANICAL PROPERTIES

Mechanical Property	Reported Value
Tensile Strength	≈29 MPa
Flexural Strength	≈56 MPa

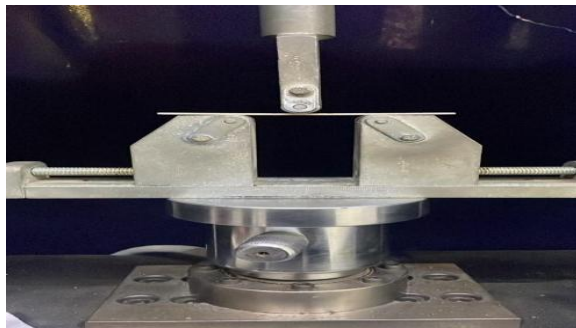


Fig. 15. Flexural test result of the PLA-Kenaf composite specimen.

of filament quality. The inability to successfully print the remaining filament samples limited the comparison of mechanical properties across all intended fibre concentrations.

E. Flexural Test Results

Flexural testing was performed to evaluate the bending behaviour of the successfully printed composite specimen. The test determines the resistance of the material to deformation under bending loads.

The source report summarizes the flexural strength of the successfully tested composite as approximately 56 MPa. The higher flexural strength compared with the tensile strength indicates good resistance to bending loads.

The flexural strength suggests that the developed composite can withstand moderate bending loads. The reinforcing effect of kenaf fibre within the PLA matrix contributes to the stiffness and bending resistance of the printed composite.

F. Comparison of Tensile and Flexural Performance

The experimental results demonstrate a higher reported flexural strength compared with tensile strength. The tensile strength was approximately 29 MPa, whereas the flexural strength was approximately 56 MPa.

$$\frac{\text{Flexural Strength}}{\text{Tensile Strength}} = \frac{56}{29} \approx 1.93 \quad (5)$$

Thus, the reported flexural strength is approximately 1.93 times the reported tensile strength.

This behaviour indicates that the developed PLA-Kenaf composite demonstrated comparatively good resistance to bending. Such behaviour is relevant to lightweight components where bending loads may be more significant than direct tensile loading.

G. Effect of Fibre Dispersion and Extrusion

The fabrication results highlight the importance of fibre distribution and extrusion stability. Proper dispersion of reinforcement within the PLA matrix is required to maintain continuous material flow during extrusion.

Non-uniform fibre distribution can cause local variations in material flow and may lead to poor filament formation. During FDM printing, these variations can further result in poor layer adhesion, inconsistent deposition, or interruption of filament feeding.

Therefore, the mechanical properties of a natural

fibre reinforced FDM component depend not only on the inherent properties of PLA and kenaf fibre but also on the quality of composite preparation and filament fabrication.

H. Overall Discussion

The experimental results demonstrate that kenaf fibre reinforced PLA has potential as a sustainable material for FDM applications. The successfully fabricated specimen achieved a tensile strength of approximately 29 MPa and a flexural strength of approximately 56 MPa.

At the same time, the filament fabrication results demonstrate that successful processing is a major requirement for practical application. Only one of the four fabricated filament samples exhibited characteristics suitable for successful print-ing and mechanical testing.

Consequently, future optimization should focus on fibre dispersion, extrusion parameters, filament diameter stability, and continuous material flow. Improved control of these parameters would allow more consistent fabrication and enable a more comprehensive comparison of different kenaf fibre concentrations.

VII. CONCLUSION

The present study investigated the development and mechanical characterization of kenaf fibre reinforced PLA composite filament for FDM 3D printing applications. The work involved kenaf fibre preparation, alkaline treatment, grinding and sieving, material drying, composite mixing, filament extrusion, CAD-based specimen development, FDM printing, and mechanical testing.

Four different PLA–Kenaf composite formulations were prepared with varying kenaf fibre contents. The prepared materials were processed through an extrusion route to obtain composite filament. The experimental investigation demonstrated that the filament fabrication process was strongly influenced by fibre distribution and extrusion conditions.

Among the four fabricated filament samples, only the first sample demonstrated suitable filament formation and consistent diameter for successful FDM printing. The second and third samples experienced improper filament flow and poor layer adhesion, while the

fourth sample did not maintain sufficient structural integrity and continuous extrusion.

The successful filament was subsequently used to fabricate tensile and flexural test specimens. Mechanical characterization was performed using a Universal Testing Machine.

The tensile testing results showed values of 29.04 MPa,

29.14 MPa, and 27.27 MPa for the three reported specimens. The calculated average tensile strength was approximately

28.48 MPa, which is consistent with the approximately 29 MPa tensile strength reported in the study.

The flexural testing result was reported as approximately 56 MPa. The comparatively higher flexural strength indicates that the developed composite possesses good resistance to bending loads.

Overall, the experimental results demonstrate the feasibility of producing kenaf fibre reinforced PLA filament for FDM applications. The material provides a combination of biodegradable polymer matrix and natural fibre reinforcement, offering potential for lightweight and environmentally friendly additive manufacturing.

A. Major Findings

The major findings obtained from the experimental investigation are summarized below:

- 1) Kenaf fibre can be incorporated into a PLA matrix to develop a natural fibre reinforced composite filament.
- 2) Alkaline treatment, grinding, sieving, and drying are important preparation stages before mixing the natural fibre with PLA.
- 3) Fine kenaf fibre particles can support improved dispersion within the polymer matrix and facilitate filament fabrication.
- 4) Among the four fabricated filament samples, only the first sample demonstrated suitable filament formation and successful FDM printability.
- 5) The remaining samples exhibited processing difficulties including improper filament flow, poor layer adhesion, and inadequate filament structural integrity.
- 6) The successfully printed composite specimen achieved a tensile strength of approximately 29 MPa.

- 7) The reported flexural strength of the developed composite was approximately 56 MPa.
- 8) The results demonstrate comparatively good bending resistance of the developed PLA–Kenaf composite.
- 9) Proper fibre mixing, extrusion control, and filament dimensional stability are essential for successful natural fibre reinforced FDM filament production.

B. Potential Applications

The developed PLA–Kenaf composite filament has potential for applications where moderate mechanical performance, low weight, and sustainable material selection are desirable.

Possible applications include:

- Rapid prototyping and concept models.
- Lightweight brackets and supports.
- Small mechanical housings.
- Decorative components.
- Educational models and demonstration components.
- Low-load functional components produced through FDM.

The use of kenaf as a natural reinforcement provides an opportunity to reduce dependence on conventional synthetic reinforcement materials while maintaining the advantages of a biodegradable PLA matrix.

C. Limitations of the Present Study

Although the developed composite demonstrated promising mechanical performance, several limitations were identified during the experimental investigation.

First, only one of the four fabricated filament samples was successfully converted into suitable FDM test specimens. Consequently, a complete mechanical comparison between all intended fibre concentrations could not be performed.

Second, variations in fibre distribution and extrusion behaviour affected filament quality. The unsuccessful samples demonstrated that increasing fibre content introduces additional processing requirements.

Third, the experimental investigation was primarily focused on tensile and flexural mechanical performance. Other properties such as impact resistance, thermal behaviour, moisture absorption, long-term durability, and detailed microstructural characteristics were not comprehensively evaluated

in the present study.

Finally, improved control of filament diameter and extrusion parameters is required to obtain more consistent filament production.

D. Future Work

Future investigations can focus on improving the processing conditions and expanding the characterization of kenaf fibre reinforced PLA filament.

The following areas are recommended for further study:

- 1) Optimize the extrusion temperature, screw speed, and material feed conditions.
- 2) Improve the dispersion of kenaf fibre within the PLA matrix.
- 3) Investigate the influence of a wider range of fibre concentrations on filament formation and mechanical properties.
- 4) Optimize filament diameter and dimensional stability for continuous FDM printing.
- 5) Investigate the influence of FDM parameters such as layer height, infill density, printing speed, and printing temperature.
- 6) Conduct microscopic analysis to evaluate fibre distribution and fibre–matrix interaction.
- 7) Evaluate impact, thermal, moisture, and fatigue properties of the developed composite.
- 8) Compare the developed material with commercially available PLA and other natural fibre reinforced filaments.
- 9) Investigate the recyclability and environmental performance of the developed composite filament.

E. Overall Research Outcome

The study establishes the feasibility of producing a biodegradable natural fibre reinforced filament using PLA and kenaf fibre. The experimental tensile and flexural results demonstrate that the developed composite can provide useful mechanical performance for selected lightweight FDM applications.

However, the fabrication results emphasize that material composition alone is not sufficient to achieve a reliable composite filament. Proper fibre preparation, uniform mixing, controlled extrusion, and stable filament dimensions are essential for achieving consistent FDM printability and mechanical performance.

Therefore, the developed PLA–Kenaf composite represents a promising starting point for further research into sustainable natural fibre reinforced materials for additive manufacturing.

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