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Development of Green Composite Utilizing Sisal Strands and Sustainable 3-D Printed PLA Layers

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ABSTRACT

PLA/Sisal hybrid composites have been used in cars and technical textile applications. When utilized in composites, 3-D-printed PLA layers can improve performance and homogeneity. The primary goal of this research was to use sisal and 3-D-printed polylactic acid (PLA) layers to develop a sustainable bio-composite. To enhance the bonding of sisal fibres with the PLA matrix, sisal fibres were given a sodium hydroxide treatment. This would improve the mechanical and thermal properties of composites. Sisal fibre (between 4 wt% and 8 wt%), epoxy concentration (between 85 wt% and 90 wt%), and PLA 3-D printing infilling percentage (between 90 wt% and 100 wt%) were the independent parameters. The Taguchi L8 orthogonal array design was used to make the composite samples. The changes in the amounts of PLA infill, epoxy matrix concentration, and sisal fibre content were considered for test sample development. The optimal settings for improving their tensile, flexural, and impact capabilities were determined by analyzing their signal-to-noise ratio (S/N). The PLA/sisal fibre composite showed a remarkable level of mechanical properties in Sample 8, surpassing those of the other samples. To improve mechanical and thermal properties, the appropriate values for sisal fibre composition, PLA infilling percentage, and epoxy concentration percentage were 8 per cent, 95 per cent, and 85 per cent, respectively. After testing, the tensile (293–295.4 Megapascal) (Mpa), impact (2.73–4.84 Mpa), and flexural strength (188.5–270.4 Mpa) results show that the new composite has better mechanical behaviour properties. Additionally, FTIR, SEM, and DSC experiments were run to examine the composite's structural characteristics. Using less volatile epoxy resin, a sustainable 3-D-printed PLA layer and Sisal fibre bio-composite were developed.

KEYWORDS

bio-composites, PLA, sisal, epoxy, Taguchi, 3-D printing

INTRODUCTION

The use of 3D-printed PLA layers in hybrid composites made from natural fibres like sisal and polylactic acid (PLA) has garnered attention because of its potential to improve mechanical and thermal performance [1,2]. PLA/sisal composites are made from polylactic acid (PLA) and natural sisal fibre. They are biodegradable materials with better mechanical and thermal properties. Recyclable materials, lightweight, low energy usage, and environmental friendliness are just a few of its many benefits. By adding sisal and other bio-based materials to the 3-D printed PLA layers, the composite that is made can have better mechanical properties than regular PLA materials [3]. This might improve sustainability.

Research on moulding, mechanical attributes, and interfacial bonding has demonstrated that shape, measurement, and strength are influenced by the qualities of natural fibres. For effective load transfer between fibres and matrix, critical fibre loading was essential [4,5]. Renewable resources like sugarcane or maize starch are used to make PLA. PLA is a great alternative to traditional plastics made from oil because it is a flexible aliphatic polyester with a low melting point, resilience, the ability to expand and contract somewhat when heated, and a rapid rate of breakdown [6,7]. PLA layers that are 3D printed are used to create films, fibres, and filaments for 3D printing. Natural plant fibres were used to reinforce a greater variety of fibre-reinforced polymers because of their high specific strength, low density, and renewability (FRP).

Numerous uses of 3D printing technology have been investigated recently, such as the creation of complex, incredibly detailed parts [13,14]. Using 3-D-printed PLA/Sisal layers could enhance the hybrid composite's mechanical and thermal qualities. Careful handling is necessary when using Sisal/PLA 3-D-printed PLA layers in the 3-D printing process to create a hybrid composite [11,12,15]. It was imperative to modify the printing temperature, layer height, and infill density to ensure adequate connectivity between the PLA and sisal fibres. Printing speed modulation prevents formation and ensures uniform fibre dispersion. Through enhanced mechanical and thermal performance, this optimization yields 3D-printed objects with greater robustness, heat resistance, and longevity suitable for a variety of applications. PLA is biodegradable, and sisal fibres have special properties like being strong, stiff, thermally stable, and able to conduct heat well [16]. They make a composite material with better overall qualities.

This research goal was to develop a green composite from sustainable resources by employing sisal as reinforcement and a 3-D-printed PLA layer as a matrix [17,18]. As far as we are aware, no studies have been conducted using this combination as a PLA matrix reinforcement. Using the Taguchi design of the experiment, the effects of process parameters on the mechanical properties of the bio-composite were investigated in this work. Additionally, optimization through the Taguchi approach was examined and assessed.

The research also focused on textile composites' mechanical, thermal, and fibre-to-matrix adhesion qualities. Structural stability is achieved through the matrix's ability to arrange the reinforcing fibres in an orderly fashion [21]. Its responsibilities include transferring stresses and loads, spreading the load evenly throughout the composite material, and shielding the fibres from environmental degradation. The matrix was crucial to achieving the required mechanical qualities, including strength, flexural strength, and stiffness. Natural sisal fibre is produced by the Agave sisalana plant and is used to make rope, paper, cloth, carpets, and geotextiles, among other things [29,30]. Synthetic resins were more widely employed, even though they were stiffer and stronger than glass fibre. Sisal fibre was a terrific addition to a wide range of materials thanks to its adaptability and a vast range of utilitarian purposes [7,28].

Developing a sisal and PLA hybrid composite, the PLA layer was printed via a fused deposition modelling (FDM) 3-D printer with PLA filament. The sisal fibre must then be extracted and treated with sodium hydroxide before the composites are created through compression moulding and epoxy resin impregnation [25,26,27]. Taguchis and S/N ratio analysis with Minitab software were used to look at the mechanical, thermal, chemical composition, and morphological properties of the composites to get the best results and make the best use of these properties.

The primary research question was how to develop and evaluate the mechanical properties of a 3-D-printed PLA layer or sisal fibre. The characteristics and fabrication difficulties of PLA and sisal composites have been investigated in this research [29]. Sisal fibre hybrid composites and 3-D printed PLA layers demonstrated enhanced tensile, flexural, and impact strength characteristics. These composite materials provide numerous possible applications and are safe for the environment [28,39]. The study presented here indicates that sisal fibres greatly enhance the composite's mechanical qualities, which makes them a good alternative to conventional materials in a range of applications. It was suitable for high-performance applications needing heat resistance as well, thanks to its improved thermal properties. In addition to decreasing the quantity of non-biodegradable waste generated, the use of sisal fibres can strengthen the PLA material [46]. A more environmentally friendly substitute for conventional plastics made of petroleum might be provided by using natural plant-based ingredients [55].

EXPERIMENTAL

Materials

The sisal fibres are made of wax, lignin, pectin, cellulose, and hemicellulose. The composition may vary depending on the plant's age and location. Sisal fibres included between 65% and 71.5% cellulose, between 12.8 and 18%, 1% lignin, and between 5.9 and 9.9% hemicellulose. Pectin makes up between 0.8 and 2.3%, whereas wax makes up between 0.3 and 0.5%. Sisal fibres were water-soluble in 1.7% of them. Sisal is particularly interesting when compared to other lignocellulosic fibres since its composites exhibit moderate tensile and flexural capabilities, together with a high impact strength.

Renewable raw materials are used in the production of PLA. Polyester may be recycled and biodegraded. It melts more readily since its melting point is lower. When burned, it releases non-toxic vapours. In biological applications, PLA breaks down into harmless acids. One possible method for creating poly (d-lactic acid) is by directly melting and polymerizing lactic acid derivatives.

The cellulose, hemicellulose, and lignin chemical structures that are present in sisal are shown in Figure 1. These substances help the fibre have qualities including resilience to moisture, strength, and durability.

Methods

Lactic acid and condensation polymerization methods are used in the synthesis of thermoplastic polyester, also known as polylactic acid (PLA). It might be produced through ring-opening polymerization from the chiral molecule lactide (Figure 2). PLA is gaining popularity since it is simple to make with renewable materials such as fermented plant starch from sugarcane, maize, or sugar beet pulp.

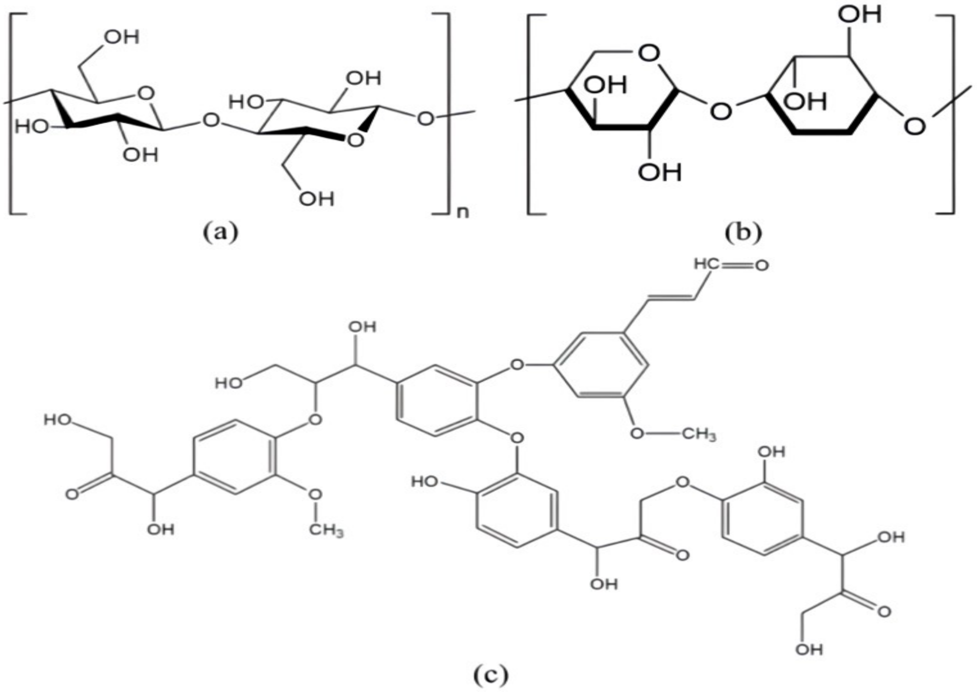


Figure 1. Chemical structure of sisal fibre (a) Cellulose (b) Hemicellulose (c) lignin

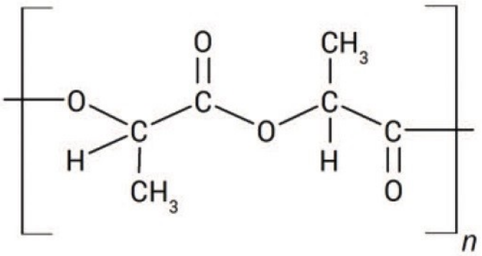


Figure 2. Chemical structure of polylactic acid (PLA)

Sisal natural fibre was utilized as reinforcement for the biodegradable PLA polymer, which is widely used in 3D printing. To create the PLA layer that would serve as the composite matrix during the composite manufacturing process, PLA filaments were 3-D printed into the required forms. The final product was formed by loading and compressing sisal fibres on top of a PLA pellet sheet coated with epoxy. In this research, the materials used were Sisal fibres, polylactic acid (PLA) pellet sheets, epoxy and hardener, mould releaser, and sodium hydroxide. The methodology and steps followed in this research are shown in Figure 3.

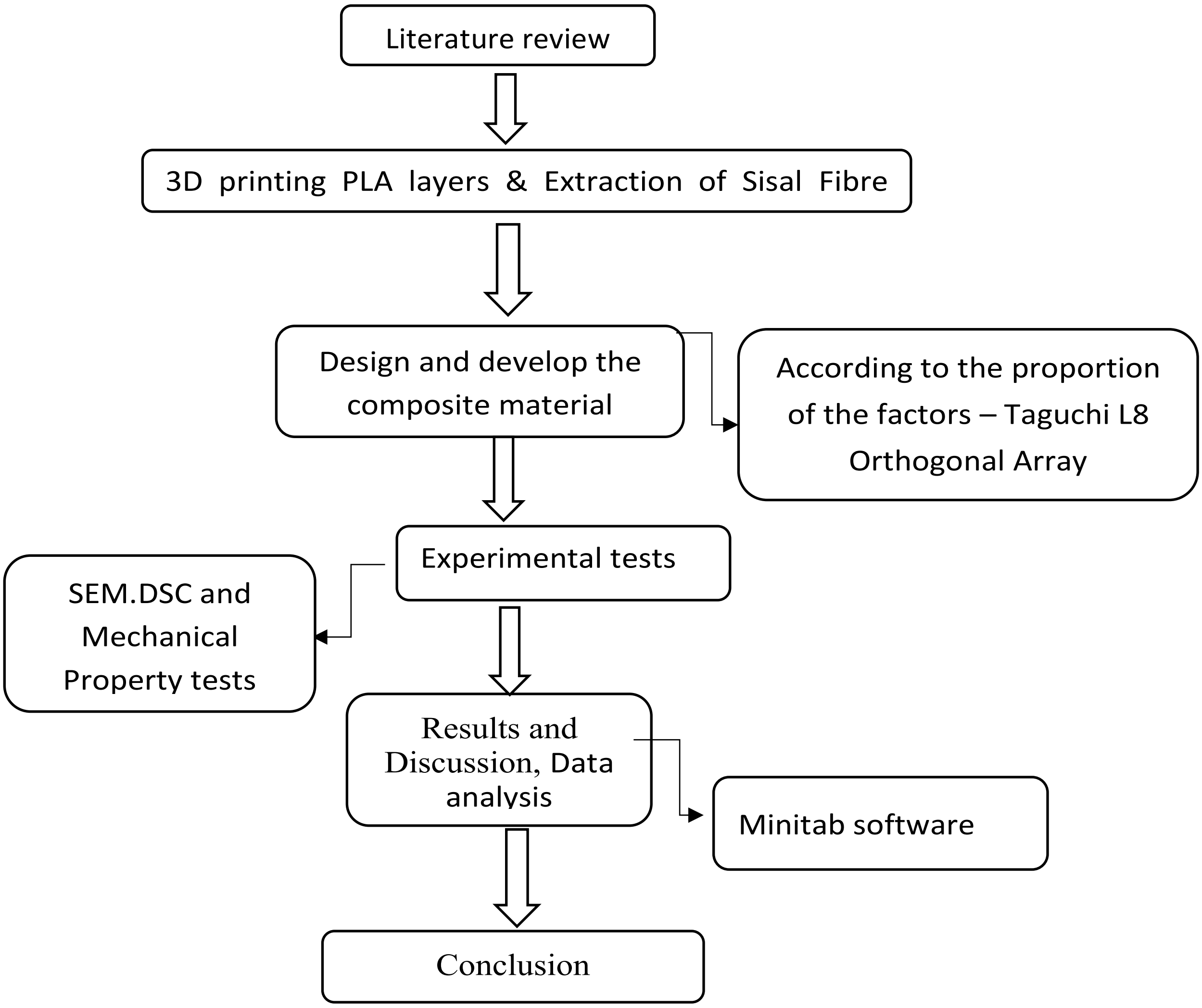


Figure 3 . Methodology followed in this research paper

Mould-release chemicals were used to stop the epoxy from adhering to the mould while the laminate was being disassembled. The most popular type of mould release for this purpose was wax. The mould used for the development of the biocomposite is shown in Figure 4.

Figure 4 . Compression mold used for development of bio-composite

Techniques of fabrication of Sisal/PLA composites

A step-by-step process was used to build a composite out of sisal and PLA. First, pretreat the sisal fibres to increase their adherence to the PLA layer matrix used in 3-D printing. The treated sisal fibres were mixed with PLA resin in the appropriate ratio. To create the final bio-composite product, the moulded layers were allowed to cure or solidify. The process for a biocomposite is schematically shown using SolidWorks software, as shown in Figure 5. Layers of dry fibres were manually laid down on a tool surface to create composites using the compression moulding process.

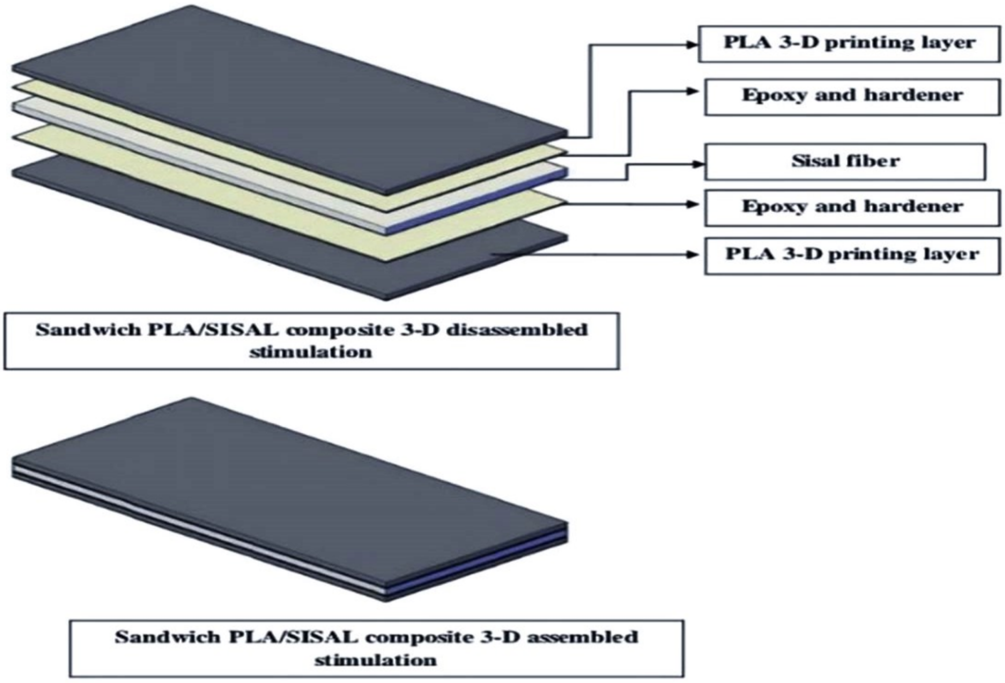


Figure 5. Solid works software simulated the output of hybrid composite design

To construct the composite practically, a calculated amount of sisal fibres based on the weight of the 3-D printed PLA layer is taken as reinforcement material. PLA, which forms the matrix layer, is impregnated with epoxy resin and stacked in the compression mould. The composite was allowed to cure for 48 hours under a dead weight of 40 kg. Figure 4 illustrates how PLA, sisal, epoxy, and PLA composites are formed. The inside surface of the mould was covered with plastic to guarantee that the composite could be removed from the surface with ease and a smooth surface finish.

Optimizing 3-D Printing Process Parameters

The finished composite's mechanical integrity and quality are determined by many critical factors in the 3-D printing process. Among the most difficult parameters to optimize are [19,20].

Layer Thickness

Each material layer that is deposited during the printing process is measured for layer thickness. Determining the ideal layer thickness is essential since it directly affects the mechanical characteristics, surface quality, and resolution of the printed product. Higher resolutions can be achieved by using thinner layers, but doing so can also increase printing time and resource consumption.

Printing Speed

The printing speed determines how quickly the printer deposits material to create each layer. Balancing printing speed is essential to achieving a good surface finish and mechanical properties. The overall strength of the item may be impacted by printing too quickly, which can cause errors and poor layer adhesion.

Temperature Control

Maintaining precise temperature control is critical in 3-D printing, especially for materials like thermoplastics that require specific heating and cooling cycles. Temperature variations can affect material flow, adhesion between layers, and overall part strength. Optimizing temperature settings for both the print bed and extruder nozzle is essential to ensuring proper fusion between layers and preventing warping or delamination issues.

Infill Density

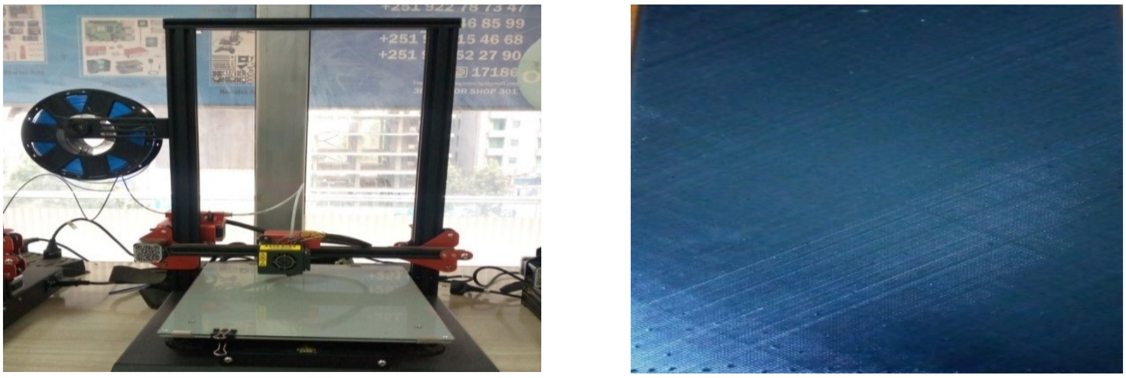
The term "infill density" describes how much interior structure is there in a printed part. Although stronger pieces are produced with higher infill densities, printing times and material consumption also increase. Finding the right balance between infill density and part strength is crucial for optimizing mechanical properties while minimizing material waste.

Material Selection

Achieving the required mechanical properties in 3-D-printed composites requires selecting the appropriate filament or resin type for the given application. Factors such as tensile strength, flexibility, impact resistance, and heat resistance vary among different materials and directly influence the overall performance of the final part.

Preparation of PLA Layers

Figure 6a shows the fused deposition modelling (FDM) 3D printer that is used to create PLA layers. The 3D printer was computer-controlled to generate three-dimensional objects from digital models. It was set to melt PLA filament at 200 °C and print PLA layers at 60 °C on the printing table, producing the necessary dimensions (12 x 25 x 5 mm, 10 x 15 x 5 mm, and 12 x 25 x 5 mm). The slicer software creates instructions (G-code) for the 3-D printer by breaking down the 3-D model into a set of layers. The next step is to adjust the temperature, layer height, and print speed according to the PLA filament that is being used. Typical configurations for PLA layer printing used some process parameters such as the warmth of the nozzle between 190 °C and 220 °C (depending on the specific filament), and the Comfort zone between 40 °C and 60 °C (depending on the specific filament and desired bed adhesion). The height of the layer was between 0.1 and 10 mm (depending on desired print quality and time), and Print speed was between 30 and 100 mm/s (depending on time and necessary print quality), and the infill percentage was between 10% and 100% (depending on required strength and weight).



(a) (b)

Figure 6. (a) 3D printing machine and printed PLA layer (b) 3D printed PLA layer

The filament is fed into the extruder until it smoothly extrudes from the nozzle after the nozzle has been heated to the required temperature. For the extruder to adequately grab the filament during printing, the tension is tightened. Using the control panel on the printer, initiate printing (Figure 6b).

Preparation of Sisal Fibres

The manual method of extracting sisal fibre involved steps like retting and mechanical decortication, which separated the pulp from the fibres (breaking down non-fibrous material and loosening the fibres). Before the fibres were treated with alkali, they were removed and dried. The extracted sisal fibres are depicted in Figure 7 below.

Figure 7. Extracted sisal fibre

Alkali treatment is a chemical process that breaks down hydrogen bonds in fibres and increases the amount of amorphous cellulose (Figure 7).

$$\text{Sisal} - \text{OH} + \text{NaOH} \quad > \quad \text{sisal-O}^{-}\,\text{Na}^{+} + \text{H}_2\text{O} \qquad (1)$$

Figure 8. Alkali-treated sisal fibre

Subsequently, the sisal fibres were prepared and subjected to a 10% alkali solution for a full day of retting (Figure 8). Afterwards, they were taken out and rinsed with water, using acetic acid as a neutralizing agent. After being conditioned, the fibres were dried. The technique of treating alkali enhances mechanical characteristics and enhances water absorption. The fibres were cut and utilized to make the PLA/Sisal Sandwich composite once they had dried.

Development of PLA/Sisal fibre composites

The Taguchi method was used to make biocomposite samples with PLA layers printed in three dimensions and sisal fibre as a reinforcing layer. Sisal fibres were dried and trimmed into small, between 20 and 30 mm-long pieces, and then 3-D printed PLA layers were used for preparing sandwich composite layers as matrix components. The binding agent utilized was epoxy resin. A manually constructed compression mould, manual loading, and a 48-hour curing period were used to manufacture the composite materials. In this experimental design, the dependent variables were tensile strength, impact strength, and flexural strength (Taguchi L8 orthogonal array). The sisal fibre/PLA pellet composites' interfaces were made of an epoxy matrix. The independent variables used during composite development were sisal fibre loading, the percentage of PLA infilling, and epoxy concentration (%). Table 1 lists the factors along with their respective level ranges.

Using the Taguchi method with two levels and three parameters, eight trial-run samples were made, and their mechanical and thermal behaviour were assessed [22]. Since sisal fibre has high tensile properties in the between 500 and 600 Mpa range [23,24], it is used as one of the independent variables. As a result, when sisal fibre is utilized as a reinforcement material, the composite's mechanical qualities are improved. The PLA layers were prepared via 3-D printing. A distinct procedure was used to prepare the layers that were 3D printed. The percentage of PLA infilling shows how much PLA is occupied within the PLA layer. In this study, the PLA layer serves as the matrix component and gives the finished product additional mechanical properties.

Table 1. PLA /Sisal fibre composite experimental design plan based on mould casting

Factor	Factor Name	Min	Max
A	Sisal Fibre loading	4	8
B	PLA infilling %	90	100
C	Epoxy concentration (%)	80	90

Since the proportion of PLA infill affects the composite's mechanical qualities, it is utilized as an independent variable in 3-D printing. This research uses low-volatile epoxy resin to bond or glue the PLA layer and reinforcement together without sacrificing any mechanical qualities. The purpose of resin is to distribute stress uniformly between the reinforcing fibres and the matrix. In addition, it keeps the fibres together and guards against mechanical and environmental harm. The epoxy concentration is one of the independent variables in this study to examine the impact of the epoxy concentration on stress transmission.

Importance of Taguchi Experimental Design

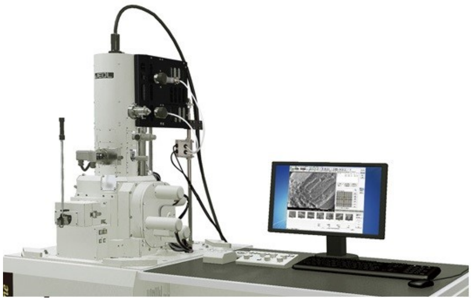
Robust parameter design is an important component of the Taguchi technique, which aims to reduce the sensitivity of a process or product to noise or changes. By considering both controllable (design) and uncontrollable (noise) factors during experimentation, the Taguchi method helps in developing fabrication parameters that are robust against variations in operating conditions. This robustness leads to improved quality and reliability of the fabricated products.

Signal-to-noise ratios are used as performance metrics in the Taguchi technique to assess a process's or product's quality attributes. The best combination of manufacturing parameters to provide the required output quality can be found by optimizing S/N ratios. Through its systematic experimental design and optimization techniques, the Taguchi method helps reduce the costs associated with trial-and-error approaches. For many chemical engineering applications, the Taguchi technique, with its eight experimental runs and basic effects graphs, is a reasonable substitute [38].

Mechanical Testing of PLA/Sisal Fibre Composite

To conduct tensile testing, the composite sample was sliced in compliance with ASTM D790 (specimen dimensions are 190 x 24 x 13 cm^3). An extreme load rating of 200 MPa was tested using a universal testing machine from Addis Ababa Science and Technology University.

(a)



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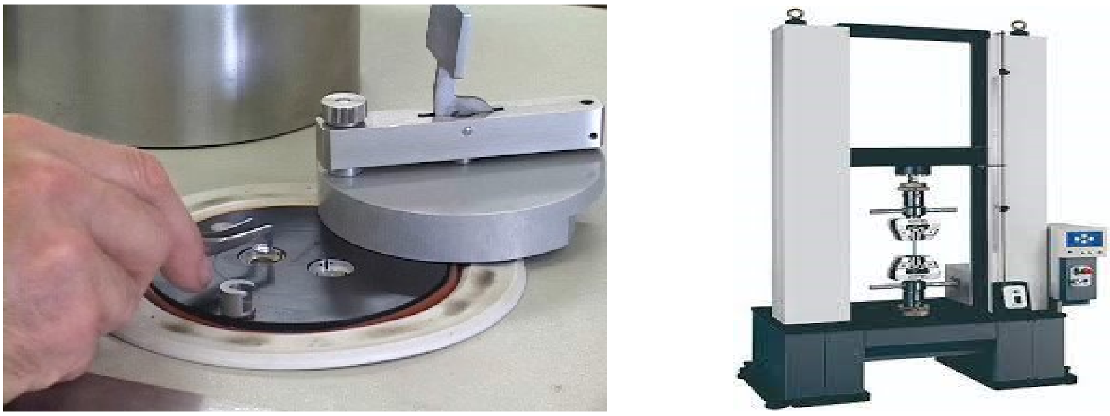


(c) (d)

Figure 9. (a) FTIR equipment (b) Scanning electron microscopy (c) DSC apparatus (d) UTM Mechanical testing equipment

A picture of the tensile test specimens is displayed in Figure 10. Tensile strength measurements were taken when each of the eight studied specimens failed. In compliance with ASTM D790, the specimen's flexural strength was assessed during its bending and splitting. Additionally, the same flexural test was performed using the UTM (Figure 9d). The preparation and testing of the Charpy Impact Test specimens followed ASTM D790. After inserting the specimen into the measurement device, the pendulum was allowed to swing freely until the specimen broke. To find the energy required to break the material, the impact test was employed.

Figure 10. PLA/ Sisal mechanical tested samples

SEM (scanning electron microscope) (Figure 9b) testing was performed on the composite materials. Using a scanning electron microscope, the shapes and sizes of the epoxy and sisal fibre/PLA composite interfaces were studied. Thermal behaviour parameters were analyzed through the use of DSC experiments (Figure 9c). Fourier transform infrared spectroscopy (FTIR) was used to find the functional groups in the composite material (Figure 9a).

RESULTS AND DISCUSSION

SEM or Scanning Electron Microscopy

Scanning electron microscopy (SEM) can be used to look at sisal fibres in a polylactic acid (PLA) matrix and learn more about the microstructure of the composite material. To get the best mechanical properties and functionality from composite materials, we need to understand how the polymer matrix and reinforcing fibres interact by looking at the surface structure and morphology under a microscope. An investigation using scanning electron microscopy (SEM) was conducted on the composite samples. PLA/Sisal SEM micrographs are displayed in Figure 11. Using a high-vac SED PC standard, 15 kV SEM images were obtained. The SEM experiment was carried out at various magnifications. The SEM picture in Figure 11 was taken with a 50 µm scale bar at x300 magnification. The PLA layer's and the sisal fibre composite's interactions with the matrix had a major effect on the composites' attributes. The PLA matrix layer and the epoxy resin-firmly affixed sisal fibre reinforcing layer are seen in Figure 11's SEM image. The PLA layer and sisal fibre exhibited excellent interfacial performance, with no evidence of pores or mesopores. The PLA layer is shown in the picture as a solid area. The sisal fibre part can be found by fibre streaks that are lined up horizontally and show how much adhesion there is at the fibre-matrix interface [29,36].

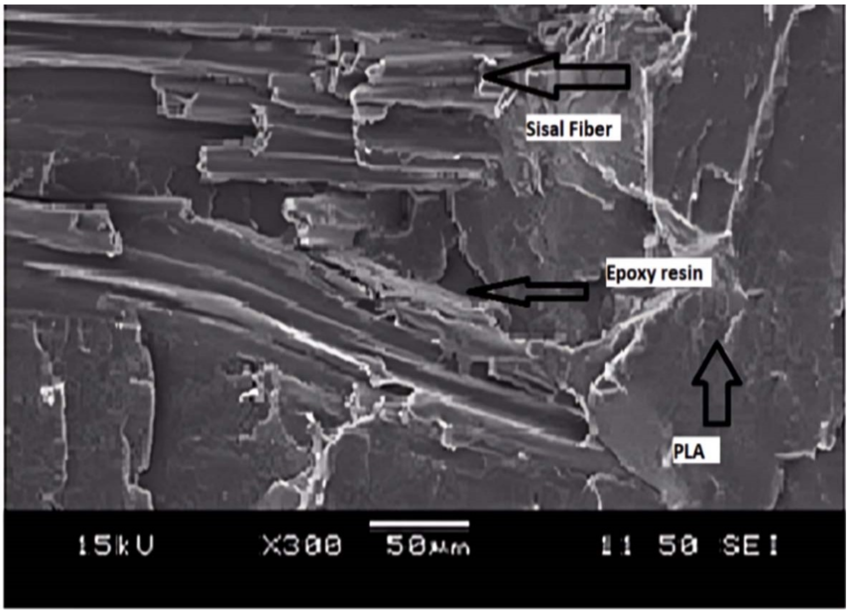


Figure 11. PLA /Sisal fibres SEM micrographs image

SEM analysis allows for the visualization of the orientation of sisal fibres within the PLA matrix. Figure 11 shows how the fibres are horizontally distributed, aligned, and randomly dispersed in the matrix. Figure 11 helps to clarify how fibre orientation affects mechanical characteristics like stiffness and strength. Effective load transfer between the fibres and matrix requires a robust interfacial connection. There are no holes or flaws at the fibre-matrix contact in Figure 11, which might cause the composite material to deteriorate. In Figure 11, when closely observed, there are no signs of broken adhesion, coating, or impregnation of the fibres by the polymer matrix, which directly impacts properties like toughness and durability. In Figure 11, these defects are absent, which is crucial for improving manufacturing processes and enhancing overall quality control to prevent failure under mechanical stress. Assuring uniform fibre dispersion throughout the matrix is essential for maintaining qualities like homogeneity and dimensional stability. This is achieved through the detection of fibre distribution.

FTIR – Fourier Transform Infrared Spectroscopy results

FTIR is an analytical method that differentiates between organic, polymeric, and inorganic materials using wavelength-specific absorption measurements. Identification is made feasible by the chemical relationships revealed by this procedure. One way to look at the chemical groups in sisal fibre and PLA-printed layers with epoxy-impregnated biocomposite (Thermoscientific, iS50) is with Fourier transform infrared (FTIR) spectroscopy. Because of the bio-physical composite's chemical interaction with the matrix and the fact that it became harder after curing, the sisal/PLA transmittance changed to lower wavenumbers (3000–1000 cm^{-1}), which led to a wider band and a frequency shift. The peaks that showed up at 1749 and 1078 cm^{-1} (Figure 12) were caused by physical interactions between the Sisal layer and the PLA layer.

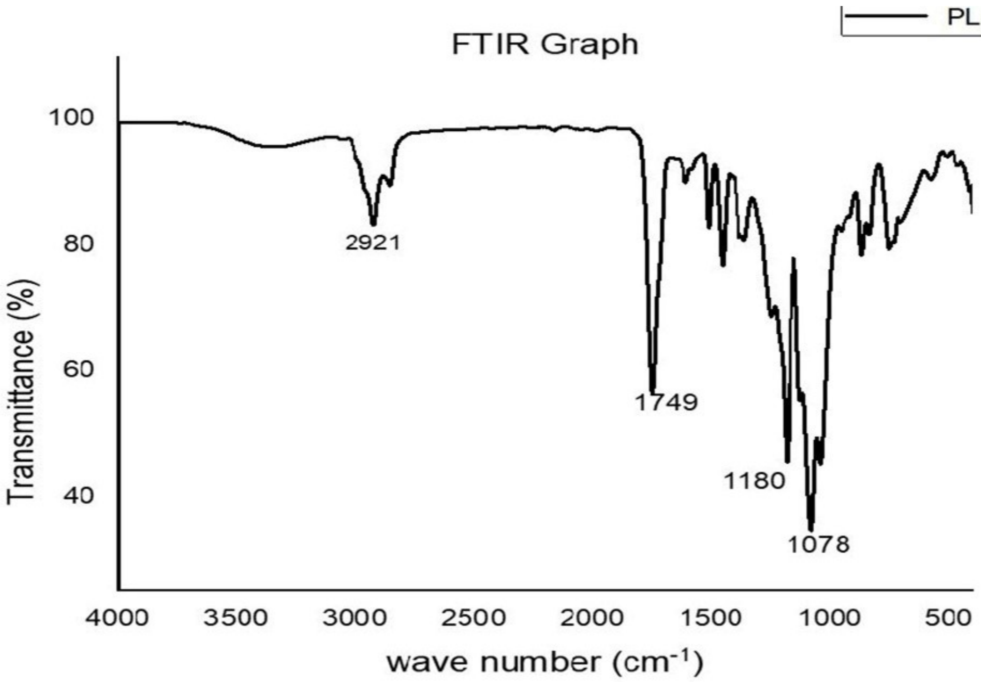


Figure 12. PLA/Sisal fibre bio-composites: FTIR spectroscopy

Thermal Behavior analysis of Composite using Differential Scanning Calorimeter.

DSC detects heat flow in a material by contrasting the sample's temperature with a reference temperature. Given that both chemical reactions and physical change entail the absorption or release of heat, it was classified as a difference. Exothermic processes produce heat, whereas endothermic reactions absorb it. The temperature of the sample and the difference in heat flow between it and the reference (TGA-55-TA Instruments) were measured using DSC (Figure 13).

Figure 13 illustrates how the bio-composite's physical and chemical properties led to different temperature peaks. Additionally, it was discovered that there were inconsistent results from the DSC tests on the bio-composite material reinforced with sisal fibre. This is due to the composite material's inherent nature. Sisal, a naturally occurring composite material, breaks down quickly, although PLA melts at a greater temperature. Composite materials' resistance to temperature greatly affects their overall behaviour as well as their thermal behaviour. The material is shown in Figure 13 changing from a glassy to a rubbery condition or increasing in temperature to 79.40 °C. Between 232.90 °C and 250 °C, endothermic events are linked to melting and breakdown.

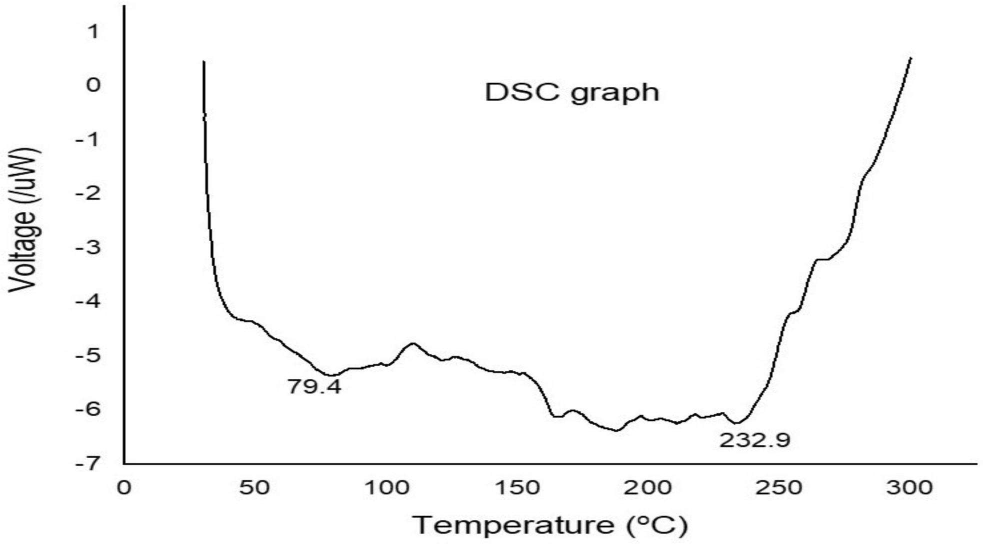


Figure 13. DSC graph of PLA pellet /sisal fibre composite

Thermal Properties of Composites in High-Temperature Applications

The performance of a composite material in high-temperature applications is significantly influenced by its thermal conductivity. Better heat transport within the material is made possible by higher thermal conductivity, which can aid in the effective dissipation of heat. In high-temperature environments, materials with good thermal conductivity can prevent localized overheating and maintain structural integrity [36].

The amount that a composite material expands or contracts in response to temperature variations is determined by its coefficient of thermal expansion (CTE). Low-CTE materials are favoured in high-temperature applications because they are less likely to undergo dimensional changes that could result in stress or mechanical failure. The thermal stability of a composite at elevated temperatures shows no significant degradation. The composites have good thermal stability and can withstand harsh temperatures [Figure 13]. The composite shows high heat resistance and can operate effectively in extreme temperature environments without compromising its performance. The PLA matrix and Sisal reinforcement used in the composite significantly influence its thermal properties and performance at high temperatures. Different matrix materials (e.g., polymers, ceramics, metals) and reinforcements (e.g., carbon fibres, glass fibres) have varying thermal conductivities, expansion coefficients, and heat resistance levels that impact the overall behaviour of the composite in elevated temperature conditions. The thermal properties of composites directly influence their performance in high-temperature applications by affecting heat transfer efficiency, dimensional stability, structural integrity, heat resistance, insulation capabilities, and overall durability under extreme temperature conditions. Choosing composites with tailored thermal properties based on specific application requirements is essential for ensuring optimal performance and reliability in demanding environments [41].

Grams per square centimetre [Grammage -GSCM] and Thickness

The weight and thickness of the composite materials are the primary factors examined in a biocomposite. The weight and layer thickness of the 3-D printed material are kept constant in this study. Other 3-D printing process variables, such as the combination of sisal fibre and epoxy resin, were also investigated, starting with the weight of the 3-D printed layer. The outcomes demonstrated an improvement in the mechanical qualities. The ultimate weight of bio-composite materials is revealed by the GSM test.

Table 2. GSM and thickness data of developed 3-D printed PLA layer and composite samples

Sample No	3-D printed PLA layer thickness(mm)	3-D printed PLA layer weight(g/cm^2)	Final Composite Physical Characteristics	
			Thickness(mm)	Weight in g/cm^2
1	0.17	5	0.53	5.9
2			0.55	7
3			0.57	7.2
4			0.58	7.7
5			0.62	12.3
6			0.65	12.5
7			0.69	14.9
8			0.75	15.5

Typically, a sheet with a cross-section of 10 cm by 10 cm is cut for the GSM test, and its weight is then accurately measured using an electronic weight measuring device. To ascertain the change in the material, the GSM test is thus performed following the moulding and completion of the bio-composite. These findings provide insight into the degree to which various process variables affect the generated composite's GSM.

Every bio-composite material's thickness was also measured by sandwiching measurement discs from a thickness gauge between its two sides. The thickness gauge's dial reads thickness with an accuracy of 0.01 mm. Table 2 contains a tabulation of the thickness readings. The weight and thickness of the composite increase linearly with the number of independent variables used in its design, as shown in Table 2 and Figure 14. The weight and 3-D-printed PLA layer were maintained throughout the biocomposite development.

Tensile strength values for each of the eight samples are shown in Table 3. Sample 8's PLA/Sisal fibre composite combination was higher and had a much higher tensile strength than any of the other samples (395 MPa).

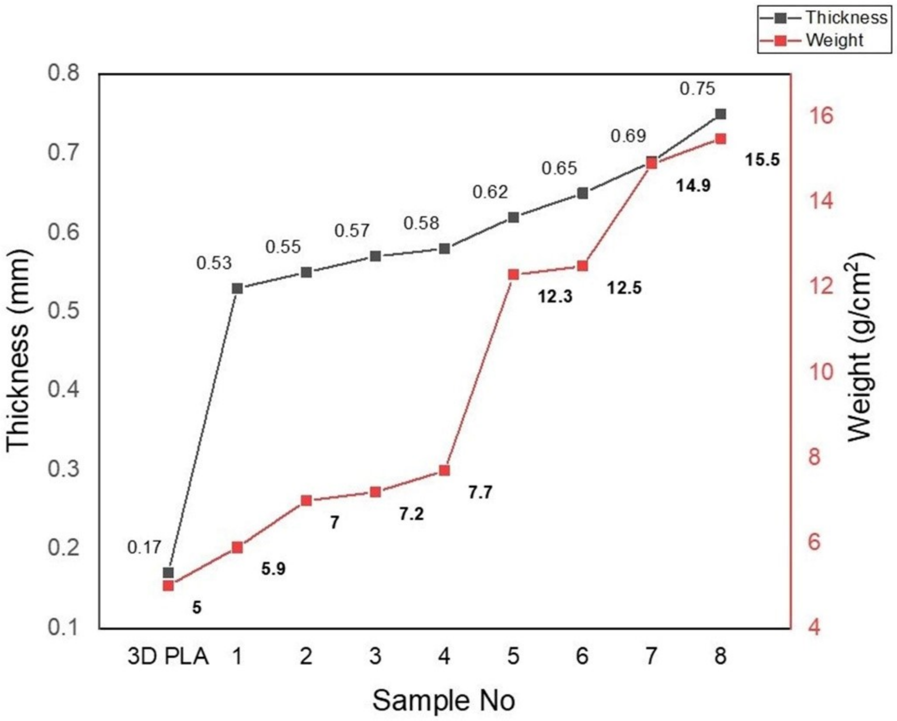


Figure 14. Comparative weight and thickness plot of 3DPLA and composite samples

The tensile strength of sample 1's PLA/Sisal fibre composite was pitiful at 284 MPa. Sample 8 PLA/Sisal hybrid specimen, on the other hand, has stronger characteristics than sample 1. When 3D-printed PLA fabric is utilized as the outer ply or skin layer, the tensile characteristics gradually improve. The findings demonstrate that, in comparison to all other sets of composites, the hybrid composites with the largest weight percentage of PLA filler material have the highest tensile strength values. This implies that the PLA layer incorporating sisal fibres has better tensile qualities than sisal fibres alone. The resistance of composites to higher tensile weights is improved by the addition of sisal fibre and the combination of PLA and sisal fibres. The tensile strength of the PLA and Sisal polymer hybrid composites was measured in a UTM using a tensile test that followed the rules set out in ASTM D790.

Impact, flexural, and tensile characteristics of the PLA/Sisal biocomposite

According to the data, the Sample 8 specimen yielded the best results. The results of the tensile properties show that, before the specimen breaking, the hybrid composites' maximum functional strength was 395 MPa. The experimental results from the tensile tests that were conducted to determine the final tensile strength are shown in Table 3. Figure 15 shows the tensile strength of the specimens. Liang et al. reported conducting research on sisal fibre composites without the use of a 3D-printed PLA layer [63]. The findings demonstrated that the tensile strength increased to a maximum of 200.44 MPa at 40 weight per cent of fibre content, which is 3.06 times higher than that of pure PLA. Shorter fibres can lead to problems that longer fibres help avoid. The hybrid composite is a robust material that has the potential to replace a variety of different materials, according to the findings of this study, which looked at the tensile and flexural strengths of the composite material built of Sisal fibre and 3D-printed PLA.

Table 3. Taguchi L8 orthogonal array experimental runs, independent and response variables

Sample No	Sisal Fibre loading (wt % of PLA layer)	PLA infilling %(3-D printing variable)	Epoxy concentration (wt % of PLA layer)	Tensile strength (Mpa)	Flexural strength (Mpa)	Impact strength (J)
1	4	90	80	284	188	2.73
2	4	90	90	298	190	2.81
3	4	100	80	324	200	3.5
4	4	100	90	327	203	3.74
5	8	90	80	356	232.6	4.01
6	8	90	90	367	242	4.04
7	8	100	80	377	260.67	4.64
8	8	100	90	395	270.4	4.84

One important feature of the bio-composite materials was their flexural strength. Flexural strength, a measurement of the composite materials' capacity to withstand bending, had an impact on the use of bio-composites in components exposed to bending stresses. Here, the highest flexural strength (270.4 MPa) for S8 composite samples was found. These samples were made with 8% sisal fibre and 100% filling of a 3-D printed PLA layer with epoxy that is 90% PLA.

The flexural strength test data was summarized in Table 3, which compared the flexural strength of various composite combinations. In comparison to all other samples, the sample 8 sisal fibre/PLA composite had an extremely high flexural strength (270.4 Mpa), while the sample 7 sisal fibre/PLA composite exhibited the second greatest flexural strength of the other samples, which was 260.67 Mpa. The sample 1 sisal fibre/PLA composite had 188 MPA flexural strength, which was extremely low. Thanks to the high flexural strength that was shown in that region, sample 8 of the sisal fibre/PLA composite was superior to the others. The outcomes showed that the flexural and dynamic mechanical parameters were enhanced by the inclusion of PLA-coated sisal fibres.

The increased load-carrying capability along the transverse direction led to a notable improvement in the hybrid composites' flexural strength. It also demonstrates how flexural capabilities were increased when sisal fibres and PLA layers were combined. It was shown that sample 8, which was the hybridization of Sisal with PLA layer, had a higher flexural strength. The findings demonstrated that the tensile strength increased to a maximum of 200.44 MPa at 40 weight per cent of fibre content, which is 3.06 times higher than that of pure PLA. Strong, stiff PLA layers were used to create skin plies, which improved their tensile and flexural qualities. The flexural test experimental findings were tabulated and shown in Table 3. The predicted flexural strength for each specimen was analyzed and displayed in Figure 15.

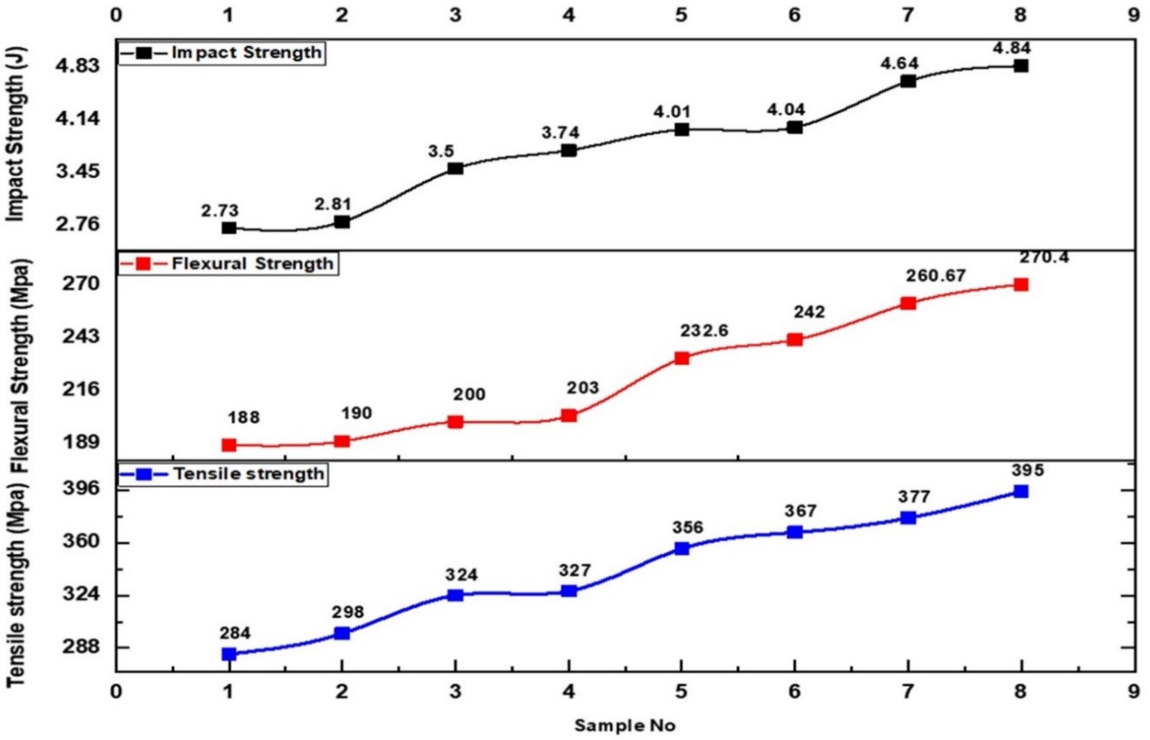
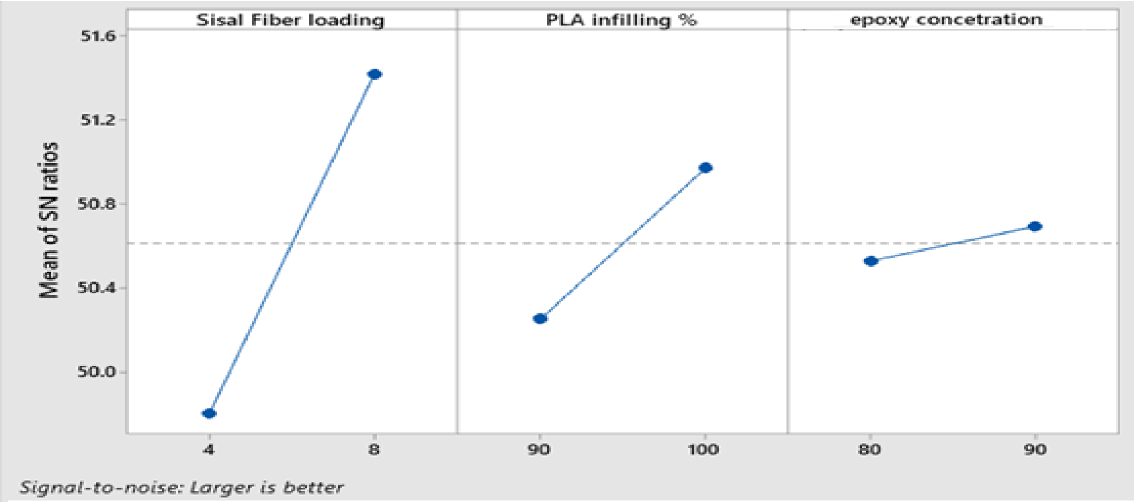


Figure 15. Tensile, flexural, and impact strength comparison graph for PLA/Sisal fibre composites

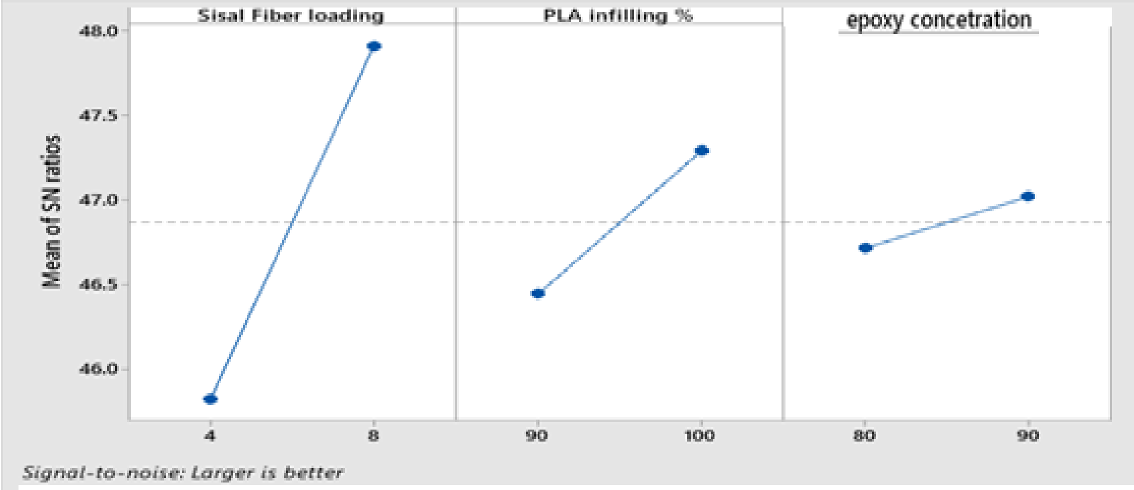
The hardness of a substance can be determined using impact tests. Artificial fibres generally produce resin borders with low forces, leading to an increase in force preoccupation at these boundaries. Because the fibre/matrix force of a typical fibre is larger, force cannot be absorbed at the interface. According to studies conducted on the Charpy impact test, a small quantity of sisal fibre can improve impact strength, increase the region under the stress-strain curve, and improve connection competency. The amount of sisal, which connects even more brittlely than PLA, significantly affects the composite materials' ability to withstand impact. The impact test results for composites with different percentages of reinforcing weight were analyzed and shown in Table 3. Thus, the testing's findings indicated that composites with an 8 per cent weight sisal content and a 100% 3-D printed PLA layer had greater strength. This is because the higher cellulose content and lower microfibril angle of natural fibre made it more resistant to breaking under impact loading. The impact strength of the specimens was analyzed and displayed in Figure 15.

Main impact plot of S/N Ratio

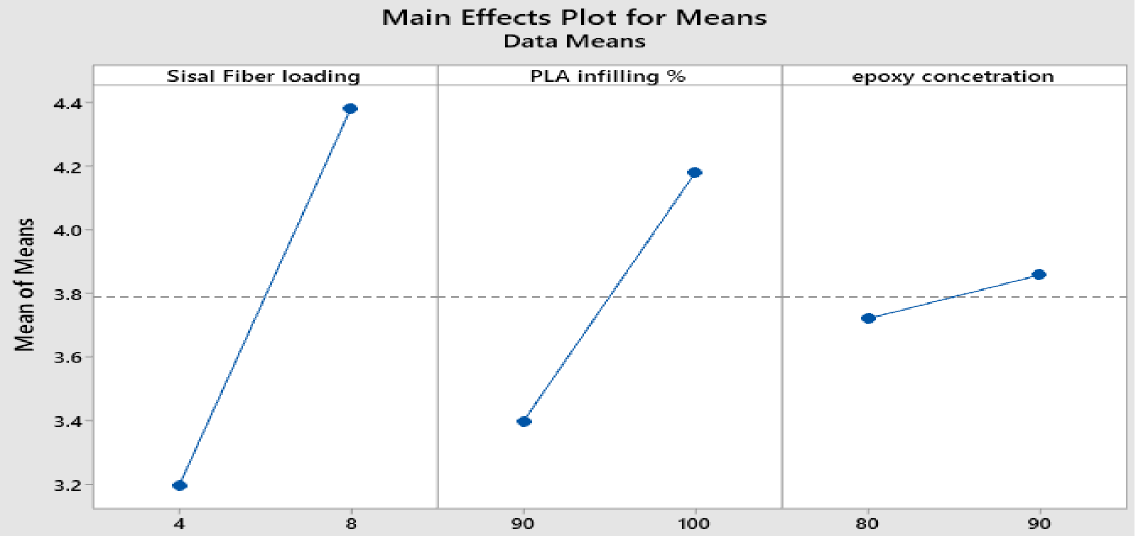
The desired value in the Taguchi approach was a signal, and the undesirable value was noise. An elevated S/N ratio was favoured as it indicated the points at which quality attributes deviated from intended thresholds.



(a)



(b)



(c)

Figure 16. (a) Main effect plots tensile strength; (b) Main effect plots flexural strength; (c) Main effect plots impact strength

The impact, flexural, and tensile strengths of the biocomposites' SN ratios were shown as the principal impacted plot in Figure 16. Using 3 weight per cent of epoxy, 2 weight per cent of PLA layer infill, and 1 weight per cent of sisal fibre as control elements was the best way to go, as shown by the principal impacted plot for the SN ratios. The principal impacted plot displayed a similar pattern for the SN ratio, flexural resistance, and impact resistance. As a result, the S/N ratio in Tables 4 to 6 illustrated the ideal values to maximize the hybrid bio-composites tensile, flexural, and impact strengths.

Table 4. Tensile strength signal-to-noise ratios

Level	Sisal Fibre loading	PLA infilling %	Epoxy concentration (%)
1	49.80	50.25	50.53
2	51.42	50.97	50.69
Delta	1.62	0.72	0.16
Rank	1	2	3

Table 5. Flexural strength signal response to noise ratios

Level	Sisal Fibre loading	PLA infilling %	Epoxy concentration (%)
1	45.83	46.45	46.72
2	47.91	47.29	47.02
Delta	2.09	0.85	0.30
Rank	1	2	3

Table 6. Impact strength signal-to-noise ratio responses

Level	Sisal Fibre loading	PLA infilling %	Epoxy concentration (%)
1	10.02	10.68	11.46
2	12.86	12.20	11.42
Delta	2.84	1.51	0.04
Rank	1	2	3

The response characteristic averages for each factor level were analyzed and displayed in response tables 4, 5, and 6. The ranks in Tables 4, 5, and 6 compare the relative magnitudes of impacts and were based on Delta statistics. The delta statistic was the highest average for each factor minus the lowest. Based on the Delta values, Minitab provided rankings: rank 1 indicates the highest Delta value, rank 2 indicates the second highest, and so forth. The sisal fibre loading percentage, PLA infilling percentage, and epoxy concentration were ranked according to the delta value in Tables 4, 5, and 6. These rankings corresponded to the magnitude of their respective effects.

The logic chosen for the S/N ratio in these Taguchi trials was that the greater the mechanical characteristics, the better the composite material. The sisal fibre loading percentage had the biggest effect on the mean and the S/N ratio, as the ranks in this case demonstrate. You can control the amount of sisal fibre loading and 3D-printed PLA infilling when making the bio-composite by using the analysis and S/N ratios to make a better composite material.

The mechanical property results of this study on 3D printed/Sisal composite materials showed better performance than the existing natural fibre-reinforced composite, which was based on a review of many literature sources. Improved tensile, flexural, and impact performance were demonstrated by the produced composites. The higher decomposition temperature was revealed by the DSC.

Influence of 3-D Printing Parameters on Mechanical Integrity of Final Composite

Numerous research investigates the effects of important printing parameters on Charpy impact strength, including infill density, raster angle, layer height, and print speed. The modelling of fused deposition (FDM). An analysis using the Taguchi technique produced an impact strength of 38.54 kJ/m^2, 1.39 per cent higher than the experimental design, with optimal parameters including 100 per cent infill density, 45/−45° raster angle, 0.25 mm layer height, and 75 mm/s print speed. To confirm the effectiveness of the improved parameters, validation trials were used [11,15]. Tensile and flexural strength first rises and subsequently falls with rising bed temperature. Tensile strength and flexural strength both rise with increasing main layer thickness. Triangular and honeycomb infill patterns have superior flexural and tensile strengths, respectively [17]. The number of contours and print speed are shown to be the most significant determinants of the final component of the FDM process's quality [18]. Regularly altering the nozzle's standoff distance can improve the interlayer bond strength under shear by an average of 41%

[19]. Tensile strength is mostly determined by changes in infill density [40]. Combining a rectilinear design with a 100 per cent infill results in a greater tensile strength of 36.4 Mpa, which differs from raw ABS material by less than 1% [20,22,23,24].

Impact of alkali Treatment on PLA/Sisal composite's mechanical characteristics

Polylactic acid is one biodegradable polymer that's commonly used in composite composites with natural fibres like sisal (PLA). The alkali treatment is primarily responsible for improving sisal fibre adhesion to the PLA matrix. The alkali treatment gets rid of impurities and roughens up the surface, which makes the fibre surface have more active sites that help it stick to the PLA matrix better. The alkali treatment also changes the composition of the PLA matrix, which makes the connection between the sisal strands stronger. Composite materials with better bonding at the fibre-matrix interface are stronger and stiffer. Additionally, it enhances load transfer between the material's two phases. When intercrystalline and intercrystallite lignin, as well as other waxy surface components, are removed with an alkali, the chances of chemical bonding and mechanical interlocking go up a lot [8,9,10].

Impact of Changing Epoxy Concentration on Composites' Mechanical Properties

A composite material's overall mechanical properties, particularly its tensile and flexural strength, can be significantly impacted by changes in the epoxy concentration. Increasing the concentration of epoxy can improve the tensile strength of a composite material. This is so that a higher concentration of epoxy resin can strengthen the bond between the fibres and the matrix, increasing the load transmission capacities. Additionally, the cohesive strength of the epoxy itself increases the composite's overall tensile strength. On the other hand, a reduced epoxy content could result in lower tensile strength. A decreased epoxy resin concentration could result in insufficient adhesion between the fibres and matrix, which would lower the composite material's overall capacity to sustain load. A composite material's overall mechanical properties, particularly its tensile and flexural strength, can be significantly impacted by changes in the epoxy concentration in the material. The kind and quantity of reinforcement material utilized, the manufacturing process, and the matrix material—such as epoxy resin—all affect the mechanical properties of composites [33,34,35].

Impact of Humidity and Temperature on PLA/Sisal Composites' Durability and Performance

Temperature and humidity levels have a big influence on how well PLA/sisal composites work and last over time. Because of their environmentally beneficial qualities, these biodegradable materials are frequently utilized in composite applications and 3D printing, but they are also vulnerable to environmental deterioration. A composite material with better mechanical and biodegradable qualities is produced when PLA and sisal are combined. The PLA/sisal composites' deterioration process can be accelerated by high temperatures. Humidity is vital to PLA/sisal composites' lifespan because it absorbs moisture. When a substance is exposed to high humidity levels, water molecules seep through its surface and into its interior [32]. The chemical disintegration of polymers by water, or hydrolysis, can happen under severe circumstances and further jeopardize the material's structural integrity.

Sisal Fibre Orientation's Effect on Mechanical Properties

The mechanical properties of a composite material are greatly influenced by the direction in which its sisal strands are oriented. The orientation and dispersion of the reinforcing fibres inside the matrix have a significant impact on the mechanical properties of a composite, including strength, stiffness, toughness, and impact resistance. The orientation of sisal fibres is a critical factor in influencing their load-bearing capacity and resistance to external forces [41].

Effects of Fibre Orientation

The reinforcing fibre orientation has a direct impact on a composite material's strength. Simultaneously oriented parallel to the direction of the tension allows sisal fibres to effectively support the load and improve the composite's overall strength [43]. The stiffness, or rigidity, of the composite is also influenced by the orientation of the fibres. Higher stiffness is provided by fibres aligned in the loading direction as opposed to randomly arranged fibres. Proper alignment can improve the toughness of sisal-fibre composites. Fibre orientation influences this property by controlling the path along which cracks propagate. In the hand lay-up method, fibres are manually placed in desired orientations within a mould before resin impregnation. This allows for flexibility in aligning fibres but may not be suitable for large-scale production due to labour intensity [44,45].

Properties of PLA/Sisal Composite Vs Common Bio-composites

The properties of PLA/sisal composites compare favourably to other common bio-composites used in similar applications, offering a unique balance of strength, flexibility, and sustainability. PLA/sisal composites exhibit good tensile strength and modulus compared to other bio-composites like flax/PLA or hemp/PLA. One of the primary advantages of using bio-composites over traditional fossil fuel-based composites is their biodegradability. PLA/sisal composites are no exception. In contrast to other bio-composites like glass fibre-reinforced polymers (GFRPs), which can take hundreds of years to decompose, they can do so under the conditions of industrial composting in around six months. Due to the higher cost of sisal fibres than less expensive alternatives like wood fibres or rice husks, they may generally be more expensive than some other bio-composites [31,32,33].

Applications of PLA/Sisal Composites

Composites made of PLA and sisal show better heat resistance than PLA alone. Better thermal stability can result from sisal fibres' propensity to obstruct heat transfer within the material. The enhanced mechanical properties of PLA/sisal composites make them suitable for various construction applications. These composites could be used in building materials such as panels, roofing tiles, or insulation due to their strength, durability, and thermal stability. With the increasing demand for sustainable packaging solutions, PLA/sisal composites' mechanical qualities and low weight may make them appropriate for use in several aircraft applications [29]. Given their potential resistance to moisture and improved mechanical properties, PLA/sisal composites could be explored for marine applications such as boat components or marine structures where durability and environmental sustainability are key considerations [25,28].

Recycling and PLA/Sisal Composites' Degradation Processes

PLA and sisal materials are sorted based on their composition, with PLA and sisal components separated from other materials. Once sorted, the PLA/sisal composites are shredded into smaller pieces to facilitate further processing [42,46]. Shredding helps in breaking down the materials into manageable sizes for subsequent steps. After shredding, the next step involves separating the PLA from the sisal fibres. This separation process is crucial to ensuring that each component can be recycled effectively [50,51,52]. The separated PLA and sisal components undergo a cleaning and washing process to remove any contaminants or residues. The cleaned PLA and sisal fibres are then reprocessed using techniques such as extrusion or injection moulding to create new composite products. Several studies have investigated the long-term degradation behaviour of PLA/sisal composites to understand their performance over time in various environmental conditions [47,53,54].

The degradation of PLA/sisal composites can occur through multiple pathways [49]. One of the main ways PLA degrades is through hydrolysis, a process in which water molecules dissolve the ester bonds in the polymer chain. This causes chain scission, which lowers the composite's mechanical strength. Elevated temperatures can accelerate the degradation of Exposure to ultraviolet (UV) radiation and can cause photo-oxidation of PLA/sisal composites, leading to discolouration, surface cracking, and loss of mechanical properties over time [48,56,57]. In environments rich in microorganisms, such as soil or composting facilities, PLA/sisal composites can undergo biodegradation, where microorganisms break down the polymer into simpler compounds [58,59].

Environmental Impacts Compared to Traditional Non-Biodegradable Composites

Traditional non-biodegradable composites rely on fossil fuels as their primary raw material, contributing to resource depletion and increased carbon emissions during extraction and production. In contrast, recycling PLA/sisal composites promotes a circular economy by utilizing renewable resources like plant-based PLA and natural sisal fibres. The production of traditional non-biodegradable composites typically requires higher energy inputs compared to recycling processes for PLA/sisal composites. One significant advantage of PLA/sisal composites is their biodegradability compared to traditional non-biodegradable composites [37,55].

Cost-Effectiveness of PLA/Sisal Composites vs. Traditional Materials

PLA is generally more expensive than traditional petroleum-based plastics. However, its cost has been decreasing due to advancements in production techniques and increased demand. Sisal fibres are relatively inexpensive compared to synthetic fibres like carbon fibre or glass fibre. The overall cost of raw materials for PLA/sisal composites can be competitive or even lower than traditional composite materials, depending on market conditions and availability. The manufacturing process of PLA/sisal composites involves blending PLA resin with sisal fibres, followed by processing through techniques like compression moulding or extrusion. Compared to traditional composite manufacturing processes that may involve higher energy consumption and complex procedures, the production of PLA/sisal composites can be more straightforward and energy-efficient [60,61,62,64].

Challenges in Scaling up Production of Composites from Laboratory to Industrial Scale

When scaling up the production process of composites from a laboratory to an industrial scale, several challenges may arise. One of the primary challenges is the need for larger and more sophisticated equipment to handle the increased production volume. Investing in new machinery and infrastructure can be costly and time-consuming. The transition from laboratory-scale to industrial-scale production often requires significant process optimization. Fine-tuning the production process to ensure consistency, quality, and efficiency at an industrial scale is crucial for minimizing the cost of production but can be complex [37].

CONCLUSION

The investigation's findings demonstrated that hybrid PLA/Sisal composites outperformed traditional bio-composites in terms of tensile strength, flexural strength, and impact resistance. The Taguchi technique helped to decrease the number of tests and identify the combination of parameters needed to conduct trials (L8). The following is a list of this study's significant findings.

i) The maximum values of impact resistance were 4.84 J, flexural strength was 270 MPa, and tensile strength was 395 MPa.

ii) The highest tensile strength was achieved with 8% sisal fibre loading, 100% PLA infilling percentage, and 90% epoxy concentration. The lowest tensile strength was achieved with 4% sisal fibre loading, 90% PLA infilling percentage, and 80% epoxy concentration in sample 1.

(iii) As per the findings, the mechanical characteristics of PLA matrix material will rise with an increase in reinforcement loading and infilling loading.

(iv) The S/N ratio shows that the percentage of Sisal fibre loading is the most important factor. It is followed by the percentage of PLA infilling and the concentration of epoxy. All of these factors affect the mechanical properties of PLA/Sisal hybrid composites.

According to the findings, the hybrid composites exhibited superior tensile and flexural capabilities, rendering them more suitable for application as building materials, vehicle parts, and machine components. Further characteristics of these composites, such as their morphological, thermal, and functional group behaviour and properties, were investigated. The epoxy matrix material and the alkali treatment both made the material stronger by making the bond between the 3-D printed PLA layer and the sisal fibre stronger.

Optimizing 3-D printing parameters has a direct impact on the final composite's mechanical integrity. Environmental elements like temperature and humidity have a big impact on how well the bio-composites work. The cost of producing PLA/sisal composites might vary depending on several factors, such as raw material availability and processing methods employed. Recycling PLA/sisal composites makes use of renewable resources such as natural sisal fibres and PLA derived from plants, hence advancing the circular economy. PLA is degraded when composite materials are exposed to several elements, including moisture, temperature, UV light, microbiological activity, and the chemical treatment process.

Author Contributions

Conceptualization – Ramaiah G; methodology – Tilahun A; formal analysis – Ramaiah G, Tilahun A; investigation – Tilahun A, Negawo TA; writing-original draft preparation – Ramaiah G, Tilahun A; writing-review and editing – Barak SY; visualization Ramaiah G, Tilahun A; supervision – Legese R, Asfaw D. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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