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Optimization of PLA Infill Percentage for Mechanical properties in PLA/Sisal Hybrid Bio-Composites Using the Taguchi Method

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This study's main objective was to create sustainable bio-composite using sisal and 3-D-printed polylactic acid (PLA) layers. The sisal fibers were treated with sodium hydroxide to improve their adhesion with the PLA matrix. Composites' mechanical and thermal qualities would be enhanced as a result. The independent parameters were the percentage of PLA 3-D printing infill (between80, 90 and 100 weight percent), the concentration of epoxy (between 75,80 and 85 weight percent), and the percentage of sisal fiber (between 3,6 and 9 weight percent). The composite samples were created using the Taguchi L27 orthogonal array design.
The production of the test sample took into account variations in the concentration of epoxy matrix, sisal fiber content, and PLA infill amounts. By examining their signal-to-noise ratio (S/N), the ideal parameters for enhancing their tensile, flexural, and impact capabilities were identified. In Sample 9, the PLA/sisal fiber composite had exceptional mechanical capabilities that outperformed the other samples. The optimum percentages for sisal fiber composition, PLA infilling percentage, and epoxy concentration percentage were 8%, 95%, and 85%, respectively, to enhance mechanical and thermal qualities.
Keywords: sisal fibre, PLA, Taguchi technique, SN ration UTM, Impact testing machine.

1. Introduction

Manufacturers are being forced to create and supply end-use produced parts with improved mechanical and physical qualities due to the current highly variable global manufacturing industry economics. The researcher is under pressure to consider a new technology that overcomes the limits of geometrical complexity, traditional production techniques, high tooling costs, design, time-consuming pre and postprocessing procedures, etc. Therefore, the manufacturer's focus has shifted to a new process that fabricates parts in an additive manner rather than a subtractive one, namely three-dimensional printing (3-DP), in order to satisfy end goals like customer specifications and realization. The manufacturer's focus has therefore shifted toward a new method that fabricates parts in an additive rather than subtractive manner, namely three-dimensional printing (3-DP), in order to satisfy end goals like customer needs and realization.

3-DP produces the finished item by manufacturing the part straight from any database of design software. The pieces are produced using subtractive manufacturing procedures in non-traditional techniques including electrical discharge machining (EDM). These methods are known as subtractive nature manufacturing techniques because they create the parts by eliminating material. Conversely, 3-DP is the method that deposits the ingredients in layers to produce the final product. Therefore, the 3-DP technique is an additive manufacturing approach due to the layer-by-layer material deposition process. It eliminates the need for tools, jigs, fixtures, and manufacturing preprocess preparation by fabricating three-dimensional (3D) final items straight from CAD (computeraided design)-designed solid models.

However, the acceptance of 3-DP techniques in different manufacturing units is increasing in multi-level steps. Between 1990 and 2000, 3-DP technique-based different 3D printers are developed, which can print using plastic polymers and different metal alloys. These characteristics prompted the taking up of 3-DP toward rapid tooling. All traditional manufacturing processes require jig and fixtures to manufacture the parts. The die casting and injection moulding, like traditional machining processes, require moulds. Such processes are very time-consuming and costly. In this perspective, these processes can be reasonably expensive, and there is little flexibility for improving or upgrading the manufactured parts

3D printing allows for rapid prototyping and onsite manufacturing of products. Initially done with plastic, 3D printing now uses new techniques with new materials, such as aluminium, bronze, and glass. Biomaterials are also being incorporated, such as 3D printing ear cartilage and liver tissue. As the 3D printing industry grows, 3D printing will become a big part of many engineering fields .

The Tensile properties and scanning electron Microscope analysis of Bamboo/glass fibers Reinforced epoxy Hybrid composites were studied. The effect of alkali treatment of the bamboo fibers on these properties was also studied. It was observed that tensile properties of the hybrid composite increase with glass fiber content. These properties found to be higher when alkali treated bamboo fibers were used in the hybrid composites. The elimination of amorphous hemi-cellulose with alkali treatment leading to higher crystallinity of the bamboo fibers with alkali treatment may be responsible for these observations. The author investigated the interfacial bonding between Glasses / Bamboo reinforced epoxy composites. The effect of alkali treatment on the bonding between Glass / Bamboo composites was also studied [3].

In recent years, there has been a marked increase in interest in biodegradable materials for use in packaging, agriculture, medicine, and other areas. In particular, biodegradable polymer materials (known as bio composites) are of interest. Polymers form the backbones of plastic materials, and are continually being employed in an expanding range of areas. As a result, many researchers are investing time into modifying traditional materials to make them more user-friendly, and into designing novel polymer composites out of naturally occurring materials. A number of biological materials may be incorporated into biodegradable polymer materials, with the most common being starch and fiber extracted from various types of plants.

The belief is that biodegradable polymer materials will reduce the need for synthetic polymer production (thus reducing pollution) at a low cost, thereby producing a positive effect both environmentally and economically. This paper is intended to provide a brief outline of work that is under way in the area of biodegradable polymer research and development, the scientific theory behind these materials, areas in which this research is being applied, and future work that awaits by reference of 4 past and present and future [4].

Yan Le at all presents a summary of recent developments of sisal fiber and its composites. The properties of sisal fiber itself interface between sisal fiber and matrix, Properties of sisal fiber-reinforced composites and their hybrid composites have been reviewed. Suggestions for future work are also given. In the review they describe in detail about the properties of sisal fiber, Interface properties between sisal fiber and matrix; Properties of sisal-fiber-reinforced composites; Sisal/glass-fiber-reinforced hybrid composites; Price; Interface modifications; Treatment of sisal fiber; Alkali treatment; Isocyanate treatment; Peroxide treatment; Permanganate treatment; surface Treatment of fiber/matrix interfaces; Sisal/polyester composites; Sisal/epoxy composites; Sisal/phenol formaldehyde composites; Sisal/polyethylene composites; Sisal-fiber-reinforced thermo set matrices; Sisal-fiber-reinforced thermoplastics matrices; Processing methods; Properties of sisal fiber reinforced polyethylene; Properties of sisal fiber-reinforced polystyrene matrices; Properties of sisal-fiber-reinforced PVC composite; Sisal-fiber-reinforced rubber matrix; Sisal-fiber-reinforced gypsum and cement matrices; Sisal and synthetic hybrid-fiber composites; and they evaluate the Dynamic mechanical properties [5]

2. MATERIALS AND METHODS

2.1 Natural fibres such as Sisal/Coconut coir/ Jute Mat/coconut coir Powder

Fiber-reinforced polymer composites have played a dominant role Long time in a variety of applications for their high specific strength and modulus. The manufacture, use and removal of traditional fiber–reinforced plastic, usually made of glass, carbon or aramid fibers reinforced thermoplastic and thermoset resins are considered critically because of environmental problems. By natural fiber composites we mean a composite material that is reinforced with fibers, particles or platelets from natural or renewable resources, in contrast to for example carbon or aramid fibers that have to be synthesized , Table 1.1 Shows Properties of Natural Fiber.

Table1.1: Properties of natural fiber

Plant fiber	DensityKg/m^3	Tensile strength (MPa)	Youngs modulus(Gpa)
Jute fiber	1300-1500	200-450	20-55
Sisal fiber	1300-1500	80-840	9-22
Coconut coir	1150-1250	106-175	6-8
Coconut coir powder	1050-1150	99-120	5-6

2.2 Preparation of PLA Layers

Figure1.1 shows the fused deposition modeling (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.

(a) (b)

Fig 1.1 . (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 4b).

2.3 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 below.

Fig 1.2: Sisal Fiber

Subsequently, the sisal fibres were prepared and subjected to a 10% alkali solution for a full day of retting (Figure 1.2). 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.

2.4 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 L27 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.

Table 1.2. PLA /Sisal fibre composite experimental design plan based on mould casting

Factor	Factor Name	levels		
A	Sisal Fibre loading	3	6	9
B	PLA infilling %	80	90	100
C	Epoxy concentration (%)	75	80	85

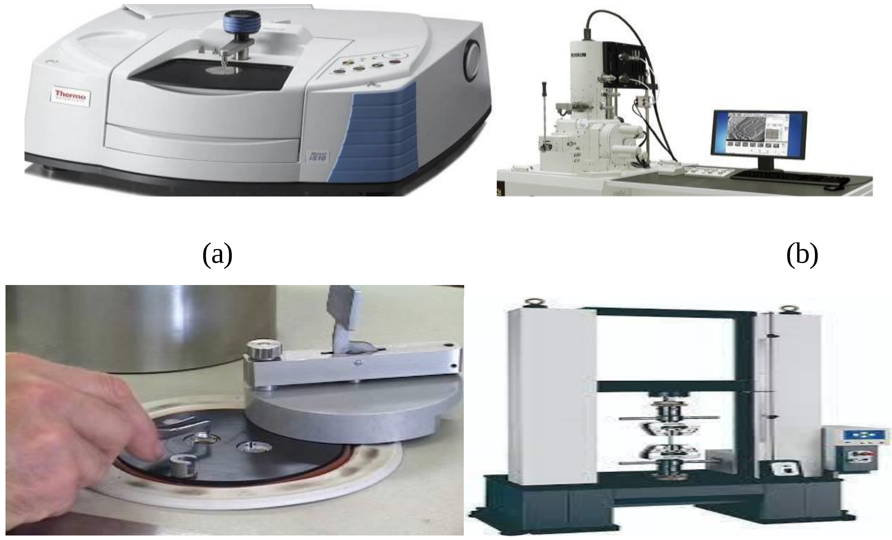
2.5 Importance of Taguchi Experimental Design

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 .

2.6 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 .



(a) (b)

Figure 1 .3. (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 1.3. 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 . 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.

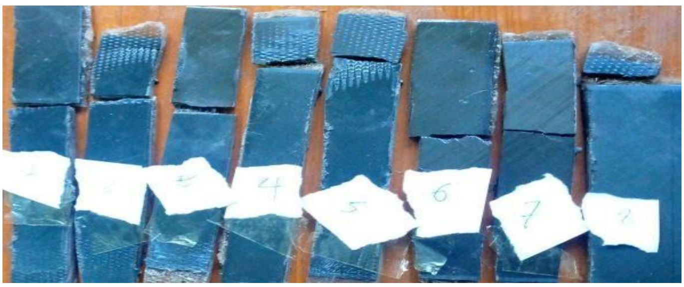


Fig 1.4. PLA/ Sisal mechanical tested sample

3. RESULTS AND DISCUSSION

Data set presents table 5.1 ,the mechanical properties of PLA/Sisal hybrid bio-composites for 3D printing applications. The focus is on understanding how sisal fibre loading, PLA infill percentage, and epoxy concentration affect the tensile strength and flexural strength of the composite materials. The experimental design you provided follows a Taguchi orthogonal array (OA) approach, which is commonly used to systematically study the influence of multiple factors and their levels on performance outcomes

Table 1.2. Taguchi L27 orthogonal array experimental runs

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)
1	3	80	75	218	188
2	3	80	80	222	190
3	3	80	85	225	200
4	3	90	75	229	203
5	3	90	80	235	204.68
6	3	90	85	237	205.26
7	3	100	75	239	209
8	3	100	80	246	211
9	3	100	85	252	214
10	6	80	75	288	215
11	6	80	80	295	217
12	6	80	85	302	220
13	6	90	75	309	221.12
14	6	90	80	315	223.06
15	6	90	85	321	224.57
16	6	100	75	324	226
17	6	100	80	329	227.12
18	6	100	85	333	228.56
19	9	80	75	339	229.9
20	9	80	80	345	230.04
21	9	80	85	356	232.6
22	9	90	75	365	242
23	9	90	80	373	260.67
24	9	90	85	382	270.40
25	9	100	75	390	272.19
26	9	100	80	395	275.67
27	9	100	85	398	279.28

3.1 ANOVA for Tensile Strength

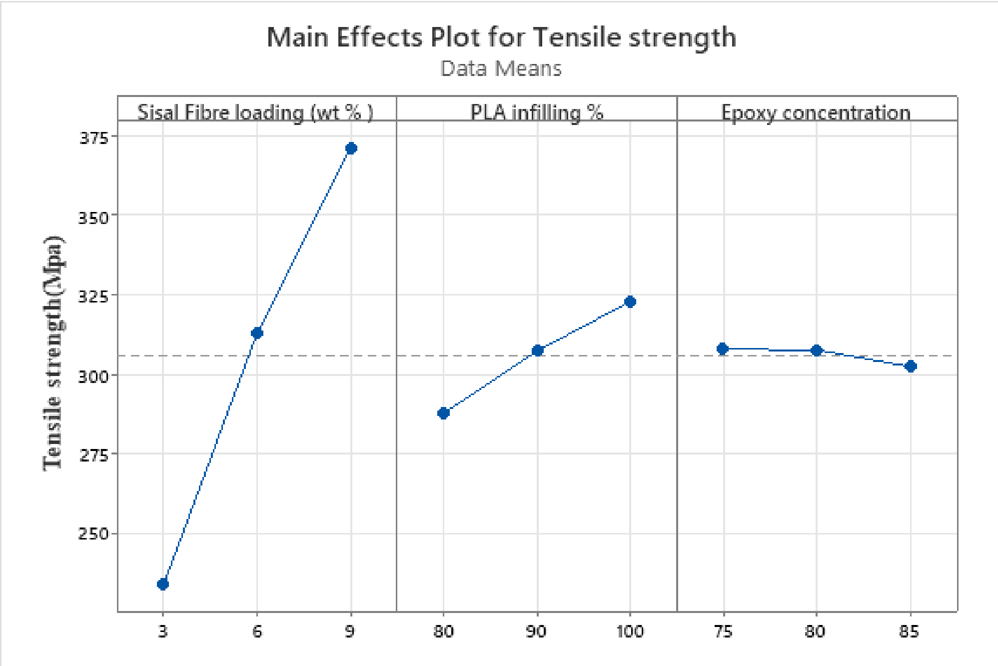


Fig 1.5: Main effect plot for tensile strength

The main effects plot (fig 1.5) for tensile strength shows the influence of three independent parameters sisal fiber loading (wt%), PLA infill percentage, and epoxy concentration on the tensile strength of the PLA/Sisal hybrid bio-composite. A strong positive correlation is observed. As sisal fiber loading increases from 3% to 9%, tensile strength increases significantly. This suggests that higher sisal fiber content enhances reinforcement within the PLA matrix, leading to improved tensile properties. An increasing trend is seen with higher PLA infill percentages. The tensile strength improves as infill increases from 80% to 100%, likely due to the denser material structure providing better mechanical integrity. The effect of epoxy concentration is minimal compared to the other two factors. A slight decline in tensile strength is observed as epoxy concentration increases beyond 80%, which could be due to excess epoxy reducing fiber-matrix bonding efficiency.

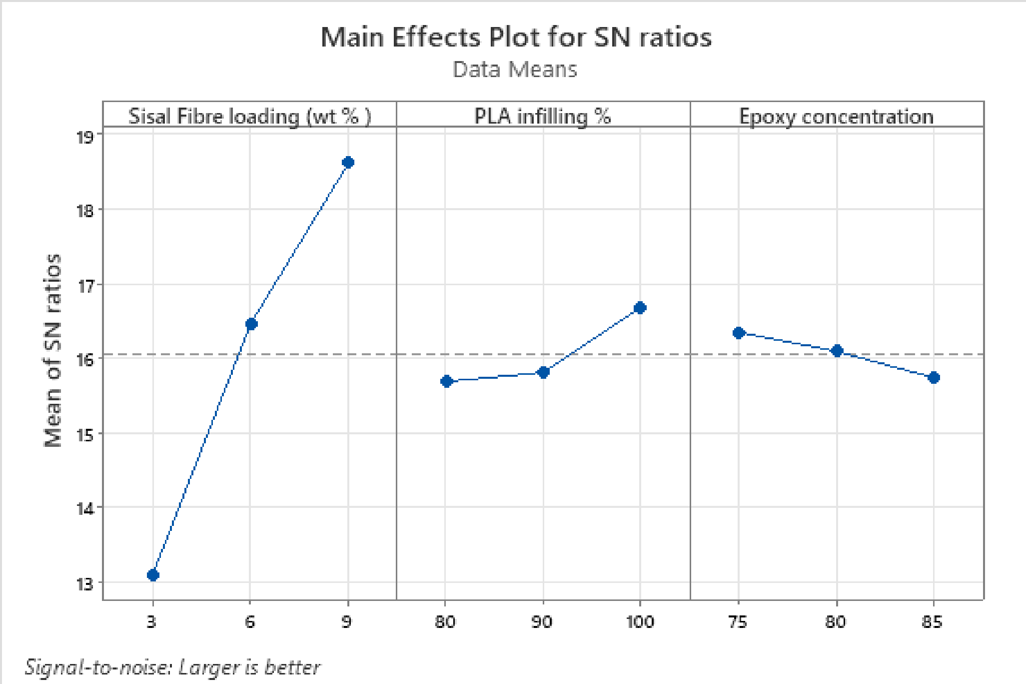


Fig 1.6: Main effect plot for SN ratio

Fig 1.6 evaluates the effect of sisal fiber loading (wt%), PLA infilling %, and epoxy concentration on the signal-to-noise (S/N) ratio, which helps identify the most robust settings for maximizing performanceA strong increasing trend is observed, indicating that higher sisal fiber content (9%) significantly improves the S/N ratio.This suggests that sisal fibers enhance the composite's structural integrity and tensile strength, making the material more resistant to variations and improving robustness. Increasing the PLA infill from 80% to 100% improves the S/N ratio slightly.

This means that denser PLA structures contribute to better mechanical stability, reducing variability in tensile strength. The highest S/N ratio appears around 75-80% epoxy concentration, but a small decline is seen at 85%.This suggests that excess epoxy may not significantly contribute to strength and could even weaken fiber-matrix interactions. Sisal fiber loading is the most influential factor, with 9% fiber content yielding the best performance. PLA infill percentage also positively affects robustness, with 100% infill being optimal. Epoxy concentration has a minor influence, but 75-80% appears to be the best range for maintaining tensile strength consistency.

Table 1.3: Response for Signal to Noise Ratios

Larger is better

Level	Sisal Fibre loading (wt %)	PLAinfilling %	Epoxyconcentration
1	13.10	15.68	16.34
2	16.46	15.80	16.09

3	18.61	16.68	15.73
Delta	5.51	0.99	0.61
Rank	1	2	3

Analysis ranks the significance of each factor based on Delta values, which represent the difference between the highest and lowest means. Increasing epoxy concentration slightly reduces tensile strength. Higher PLA infill improves tensile strength, but the effect is smaller compared to fiber loading. Higher sisal fiber loading significantly increases tensile strength

Table1.4 : Analysis of Variance of Tensile strength

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Sisal Fibre loading(wt %)	2	86062.9	92.79%	86062.9	43031.4	847.11	0.000
PLA infilling %	2	5571.6	6.01%	5571.6	2785.8	54.84	0.000
Error	22	1117.6	1.20%	1117.6	50.8		
Lack-of-Fit	4	436.9	0.47%	436.9	109.2	2.89	0.052
Pure Error	18	680.7	0.73%	680.7	37.8		
Total	26	92752.0	100.00%				

The Analysis of Variance (ANOVA) table provides statistical insights into how sisal fiber loading, PLA infill percentage, and experimental error contribute to tensile strength variations. Sisal Fiber Loading (wt%) is the most critical factor in tensile strength, contributing over 92% of the total variation. PLA infill percentage also influences strength, but its contribution is much lower (6.01%). Epoxy concentration was not included, meaning its impact was likely negligible. Experimental error is very low (1.20%), confirming that the experiment was conducted with high precision.

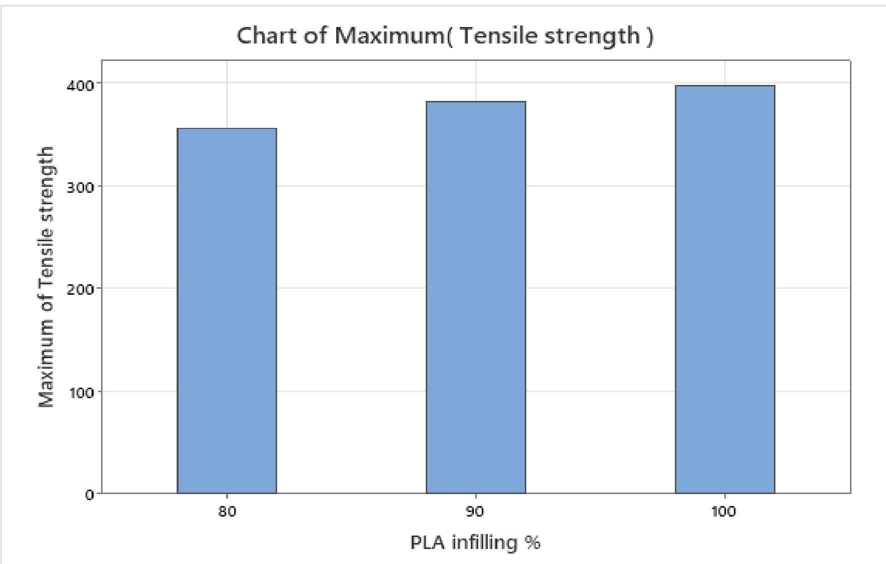


Fig 1.6: Bar chart for tensile strength

Fig 1.6 represents the maximum tensile strength at different PLA infill percentages (80%, 90%, and 100%). The trend shows that tensile strength increases as the PLA infill percentage increases. At 80% infill, tensile strength is lower compared to 90% and 100%. 90% infill, tensile strength improves, 100% infill, the highest tensile strength is observed.that increasing PLA infill density enhances the mechanical performance of the 3D-printed composite

3.2 ANOVA for Flexural Strength

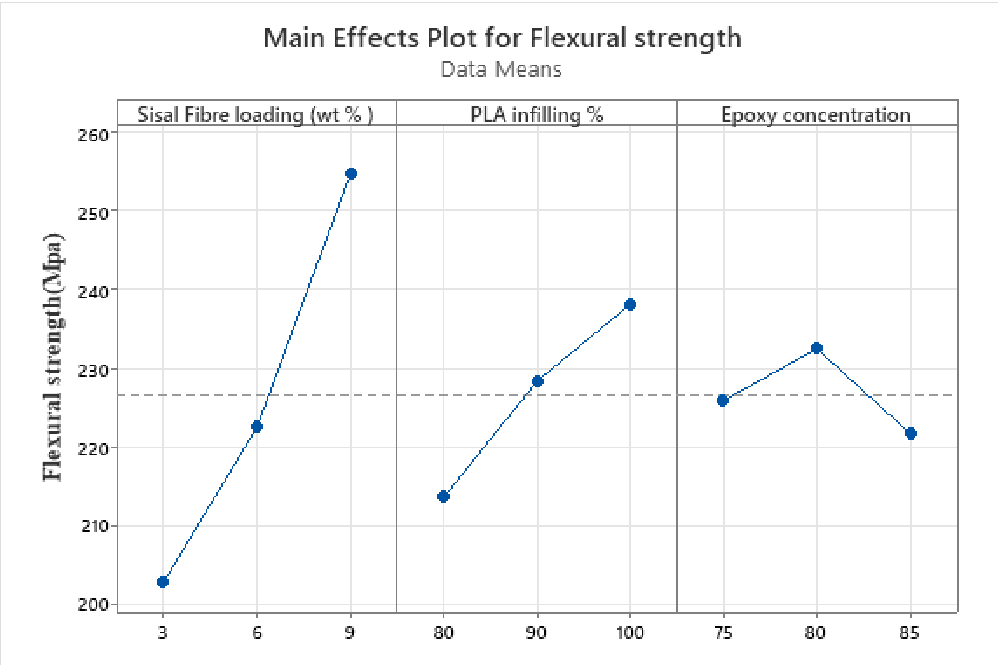


Fig 1.7: Main effect plot for Flexural strength

The main effects plot provides insights into how each parameter Sisal fibre loading, PLA infilling percentage, and Epoxy concentration affects flexural strength in the PLA/Sisal hybrid bio-composite. Strong positive correlation between fiber loading and flexural strength. Increasing fiber content enhances load transfer, improving mechanical performance. At 9 wt%, flexural strength is maximized (260 MPa). Increasing PLA infilling percentage improves flexural strength. The highest flexural strength (240 MPa) occurs at 100% infill. Beyond a certain fiber content (typically >10 wt%), fiber agglomeration and poor dispersion may lead to reduced mechanical properties. A fully dense structure (100%) increases weight and material usage, which may not be ideal for weight-sensitive applications. Too much epoxy can cause embrittlement, leading to premature failure.

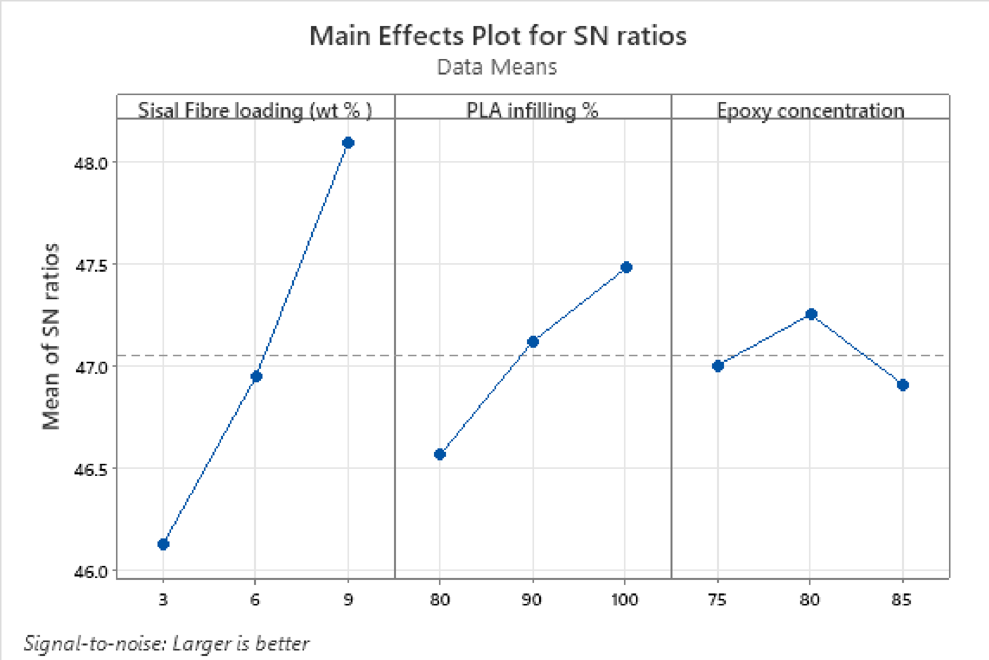


Fig 1.8: Main effect plot for SN ratio

This Main Effects Plot for SN Ratios represents the influence of Sisal Fiber loading (wt%), PLA infilling (%), and Epoxy concentration on the signal-to-noise (S/N) ratio, where a higher ratio is preferred. Sisal Fiber Loading ,S/N ratio increases significantly with higher fiber loading (from 3% to 9%).Higher fiber content improves mechanical properties. PLA Infill Percentage,The S/N ratio increases as PLA infill increases from 80% to 100%.Higher infill leads to better strength and stiffness. Epoxy Concentration, The S/N ratio peaks at 80% epoxy concentration and then decreases at 85%.80% epoxy might be the optimal level for improved bonding and mechanical performance.

Table 1.5: Response for Signal to Noise Ratios

Larger is better

Level	Sisal Fibre loading	PLAinfilling %	Epoxyconcentration
1	46.13	46.56	47.00
2	46.94	47.12	47.25
3	48.09	47.48	46.91
Delta	1.96	0.91	0.34
Rank	1	2	3

Table 1.6: Analysis of Variance for flexural strength

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Sisal Fibre loading (wt %)	2	12393.9	74.22%	12393.9	6196.94	118.64	0.000
PLA infilling %	2	2731.9	16.36%	2731.9	1365.93	26.15	0.000
Epoxy concentration	2	529.3	3.17%	529.3	264.66	5.07	0.017

Error	20	1044.6	6.26%	1044.6	52.23		
Lack-of-Fit	2	478.3	2.86%	478.3	239.13	7.60	0.004
Pure Error	18	566.4	3.39%	566.4	31.47		
Total	26	16699.7	100.00%				

Response tables 1.3, and 1.5, show the analysis and averages of the response characteristics for each level of the component. Based on Delta statistics, the ranks in Tables 1.4, and 1.6 contrast the respective magnitudes of impacts. The highest average for each element less the lowest was the delta statistic. Minitab produced ranks based on the Delta values: the highest Delta value is indicated by rank 1, the second-highest by rank 2, and so on. The delta value in Tables 1.4, and 1.6, was used to rank the sisal fiber loading percentage, PLA infilling

In these Taguchi trials, the S/N ratio was chosen based on the reasoning that a composite material is better if its mechanical properties are higher. The ranks in this instance show that the sisal fiber loading percentage had the largest impact on the mean and the S/N ratio. When creating the bio-composite, you can use the analysis and S/N ratios to manage the quantity of sisal fiber loading and 3D-printed PLA infilling to create a better composite material.

Based on a review of numerous literature sources, the mechanical property results of this study on 3D printed/Sisal composite materials demonstrated superior performance above the current natural fiber-reinforced composite. The resulting composites showed improved impact, flexural, and tensile properties.

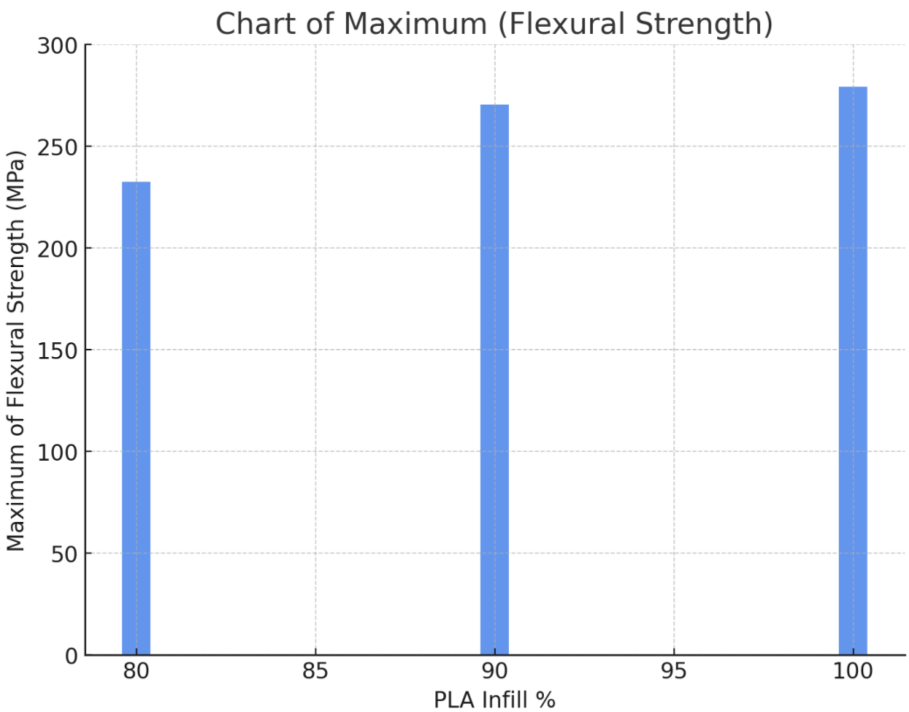


Fig 1.8: Bar chart for Flexural strength

Fig 1.8 represents the maximum flexural strength of PLA/Sisal hybrid bio-composites at different PLA infill percentages (80%, 90%, and 100%).The 279.28 MPa recorded at 100% PLA infill is the maximum across all samples. This indicates that a denser internal structure provides better resistance to bending forces

4. CONCLUSION

The results of the study showed that hybrid PLA/Sisal composites performed better than conventional bio-composite materials in terms of impact resistance, tensile strength, and flexural strength. By identifying the combination of parameters required to run trials, the Taguchi technique assisted in reducing the number of tests (L27). The key findings from this study are listed below.

- Higher sisal fiber content and PLA infilling percentage enhance tensile strength, while excessive epoxy concentration slightly reduces it.
- Higher sisal fiber content and proper epoxy concentration improve flexural strength, with a significant boost seen at 9 wt% sisal fiber and 100% PLA infilling.
- Higher sisal fiber loading and optimal epoxy concentration enhance the composite's ability to absorb energy under impact.
- According to the results, adding reinforcement loading and infilling loading would improve the mechanical properties of PLA matrix material.
- The S/N ratio indicates that the most crucial element is the fraction of Sisal fiber loading. The concentration of epoxy and the percentage of PLA infilling come next. The mechanical characteristics of PLA/Sisal hybrid composites are influenced by each of these elements.
- The Best Combination of Parameters for Maximum Robustness are Sisal Fiber Loading 9 wt%,PLA Infill Percentage 100%, Epoxy Concentration 75-80%.
- Optimal mechanical properties in PLA/Sisal hybrid bio-composites, the best settings based on S/N ratio analysis are 9 wt% Sisal fiber 100% PLA infilling, 80% Epoxy concentration.

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