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Modelling for Predicting and Optimizing of the Tensile and Flexural Properties of Sisal/Carbon Fibre Nano-Composite through RSM

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ABSTRACT

The purpose of this study was to examine the impact of fibre orientation on the tensile and flexural strength of composites composed of sisal and carbon fibres, with fibre orientation of 10, 25, and 40°. Furthermore, the research sought to ascertain the optimal parameters for the therapeutic procedure. Response Surface Methodology (RSM) with Central Composite Design (CCD) was utilized to develop and analyze the experiments. The main objective was to optimize crucial elements such as, fibre orientation and the composition of sisal and carbon fibres. This methodology was utilized to construct quadratic models for forecasting the tensile and flexural strength of the composites. The optimal parameters are 60° orientation and a composition of 40% of each fibre. Under these circumstances, the composite exhibited a 34.27% increase in tensile strength and a 22.76% increase in flexural strength when compared to the minimum values obtained from RSM optimization. The notable enhancement demonstrates that the fibre orientation can effectively increase the tensile and flexural strength, as well as improve the adhesion between natural fibres and polymer matrices.

Keywords: Natural fibre; Nanofiller; Nanocomposite; Response Surface Methodology; Central Composite Design.

1. INTRODUCTION

There has been an increasing interest in utilizing natural fibres as reinforcements in composite materials in recent years (Haniel *et al*. 2023). These fibres are recognized as a viable and environmentally friendly option to synthetic fibres, leading to a surge in research within the composite sector to find renewable alternatives (Ravikumar *et al.* 2022). The consistent cross-sectional structure of jute fibre has attracted attention because it results in remarkable in its mechanical characteristics (Saada *et al*. 2024; Mahesha *et al*. 2022) The closely arranged chain molecules of this material exhibit remarkable resistance to stretching, which enhances its overall strength (Gopinath *et al*. 2021). In addition, jute fibre is lightweight and possesses a High Specific Strength (HSS), which is corresponding to synthetic fibres (Sambandamoorthy *et al*. 2021; Maharana *et al*. 2021). Benkhelladi *et al*. (2020) investigated the development and evaluation of hybrid composites made from a combination of natural and synthetic fibres. They employed a unique method involving ANOVA and considering the characteristics of the individual fibre composites. The impact of various kinds of fibres, such as flax, jute, and sisal, as well as the type of chemical treatment and the proportion of fibres in a material, on different mechanical qualities like tensile strength, and bending strength was investigated by Sumesh *et al*. (2022). The mechanical characteristics were modeled mathematically using the RSM. The statistical research indicated that the mechanical properties were mostly influenced by the volume fraction of the fibres, while the type of fibres also had a notable impact. Ragunath *et al*. (2021) investigated the variables that influence the mechanical stability of epoxy-based composites by employing a Taguchi optimization technique in conjunction with a grey relational approach. Natural fibres of sisal and banana were utilized as reinforcements in an epoxy matrix. An artificial neural network was employed to study the correlation between the experimental outcomes and forecasts of grey relational grades.

A network architecture of 5-5-1 exhibited a strong correlation, thereby establishing a dependable approach for forecasting the components that impact mechanical qualities. The SEM examination showed that when utilizing either sisal or banana as a single reinforcement, there were instances of fibre pullouts and breakages in the matrix, resulting in the formation of voids. Nevertheless, the utilization of both fibres in a hybrid arrangement resulted in a decrease in surface imperfections, hence improving the overall characteristics of the composite material (Boumaaza *et al.* 2021). To enhance the mechanical characteristics, specifically tensile strength, flexural strength, and impact strength of hybrid composites, Siddique *et al.* (2021) incorporated sisal and glass fibres as reinforcements. Sisal, an easily accessible natural fibre abundant in cellulose, was utilized in short, randomly dispersed lengths to enhance composite material cost-effectively. Glass fibres, known for their affordability and robust mechanical characteristics, were also employed. Khan *et al.* (2023) used epoxy resin and hardener as the binding matrix in the composite fabrication process, achieved through compression molding. The materials were produced in various concentrations based on volume to provide a range of composite compositions. The compositions were obtained using a design of experiments and the best values were determined using RSM.

Over the decades, there has been a notable enhancement in the recognition and interest in environmentally friendly products. Numerous researches specifically investigate the utilization of fibres as replacements for synthetic fibres in the matrix. Nugroho *et al*. (2022) investigated the flexural properties of plaster mortars that were strengthened with treated natural sisal, flax, and jute fibres. Rahman *et al.* (2022) examined varied levels of NaOH (1.5%, 2%, and 4%) and various lengths of fibre (5, 10, and 20 mm). The impact of these experimental factors was assessed using ANOVA. Furthermore, RSM and the Desire-Function Analysis were used to improve the results with the goal of maximizing the bending characteristics. The experimental results matched closely with the statistical forecasts. The production, analysis, and enhancement of composites strengthened by bagasse fibres was studied by Waqar *et al.* (2023) by utilizing RSM to simultaneously maximize numerous outcomes. Singh *et al*. (2021) employed three distinct degrees of process variables, encompassing the amount of NaOH utilized in the treatment of the bagasse fibres. Validation experiments were performed, demonstrating a strong correlation among the measured values and the expected values of the tensile characteristics of the bagasse laminate.

Zhang *et al*. (2020) utilized carbon fibre to boost mechanical properties and reduce the carbon emissions associated with concrete. Incorporation of carbon fibre into self-compacting concrete mitigated sagging, while an excessive quantity diminished the blockage ratio, resulting in the production of solid clumps. Over time, carbon fibre enhanced the long-lasting nature of the concrete. However, self-compacting concrete that does not contain carbon fibre demonstrated reduced tensile strength. The effect of fibre variables on the bending strength and stiffness of carbon fibre-reinforced polypropylene was studied by Saleh *et al*. (2023). Three levels of Cryo fibre surface treatment, fibre length, and fibre orientation were examined. RSM and ANOVA examined the link between these parameters and flexural characteristics. A significant correlation was found between the model's projected response values and the confirmation test results. Fibre orientation had the greatest impact on composite bending strength. All fibre parameters affected flexural modulus, but fibre orientation was of great importance.

The present study showed that using sisal and carbon fibre results in low weight-to-strength ratios, making them suitable for applications where lightweight materials are important. The sisal fibres were included in the study to decrease dependence on synthetic fibres and integrate natural fibres into composite materials. It is observed that sisal fibres are extensively utilized in various industries due to their robust supportive properties, while also recognizing the benefits of combining carbon fibre with other substances. In addition, the study examined the incorporation of fibre orientation to enhance the mechanical durability of these substances. The study investigated several fibre orientations (10, 25, and 40 °) and found that different fibre orientations played a major role in the composite and improved the strength of the composite.

Table 1. Input parameter factors and their levels

S. No.	Name	Units	L[1]	L[2]	L[3]
1	Sisal fibre	%	10	25	40
2	Carbon fibre	%	10	25	40
3	Fibre orientation	degree	0	30	60

2. MATERIALS AND METHODS

2.1 Materials

The study employed a composite of natural sisal and synthetic carbon fibre to enhance their properties, as depicted in matrix favoured for these composites due to their merits such as, excellent adherence to many fibre types, superior performance at high temperatures, and remarkable mechanical and electrical properties. The epoxy resin (LY 556) and the hardener HY951 were chosen for their distinctive characteristics, such as low shrinkage during curing and strong chemical resistance, which set them apart from conventional thermoset polymers. Before the production of the fibre plates, a series of controlled trials were carried out. With the utilization of the Design Expert software, a set of 20 experiments were run, each having different fibre compositions. The exact specifications of these fibre compositions can be found in Table 1. These tests established the structure for assessing various material arrangements and their potential influence on the ultimate composite characteristics.

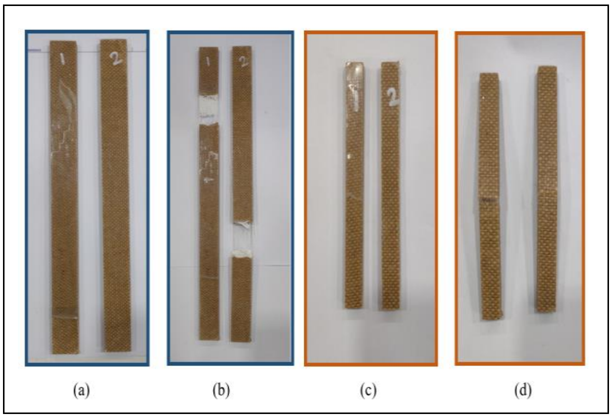


Fig. 1: Testing Sample (a) before tensile test, (b) after tensile test, (c) before flexural test, and (d) after flexural test

2.2 Composite Preparation

Specimens of sisal and carbon nanocomposites were produced using composite laminates of 300 × 300 mm. The specimens had different orientations of degrees (0, 30, and 60). The specimens were prepared using two different fibres with various percentages of fibre (10 wt%, 25 wt%, and 40 wt%). The fabrication procedure entailed the manual application of layers, which were subsequently compressed using molding techniques. The sisal and carbon fabrics were precisely cut and organized according to the stipulated specifications. Then, a mixture of epoxy resin LY556 and hardener HY951, in a weight ratio of 10:1, was applied. The composites were fabricated using a uniform epoxy ratio of 50% by weight. The epoxy resin was applied onto the surface of the fibre, subjected to compression molding and allowed to cure for one day. Afterwards, the composite samples were removed from the steel die and left to cure for an extra 24 hours at room temperature. The tensile and flexural strength of the composite plates were evaluated by cutting them using a water jet machine (WJM) according to ASTM requirements. As a part of the WJM technique, the specimens were subjected to post-curing in a hot air oven at a temperature of 60 °C for 4 hours to remove any moisture that had built up. Table 2 presents comprehensive information regarding different combinations employed in the formation of the composites.

2.2.1 Evaluating the Composite Materials

2.2.1.1 Tensile Strength

The tensile strength test sample was evaluated in accordance with the 2008 ASTM D3039 standard. The experiment strictly followed the ASTM D3039 protocol, setting the gauge length at 50 mm and the crosshead speed at 2 mm, as required.

2.2.1.2 Flexural Testing

The nanocomposites underwent flexural testing using a flexural testing machine, following ASTM D790 standards. The test specimens, with dimensions of 127 × 12.7 × 3 mm, were evaluated under specific conditions, including, a 58 kN load, a crosshead speed of 1.3 mm/min, and a 50 mm span length. The ultimate flexural stresses were calculated when the deflection reached 6 mm. Fig. 1 illustrates the specimens before and after the tests for both evaluations.

2.3 Experimental Design

The objective of this study is to utilize RSM to forecast outcomes by analyzing the impact of various input parameters on tensile and flexural characteristics. The research utilizes the Analysis of Variance (ANOVA), a statistical technique for assessing experimental data, to determine the important impacts of sisal%, carbon%, and orientation of fibre on the final technical parameters. The data were collected using Design Expert V13 in a sequence of trials where the ratios were established utilizing a statistical experimental design technique.

The study encompassed a total of 20 experiments, specifically targeting 2 response variables: tensile and flexural strength. The experimental design included 3 variables, labelled as (i) sisal fibre%, (ii) carbon fibre%, and (iii) fibre orientation. The data were obtained from a design that included three factors. This design methodology facilitated a thorough examination of the impacts of these elements on the performance of the composite.

3. RESULTS AND DISCUSSION

3.1 Assessment of the Residual Plots for Tensile and Flexural Strength

The residual data measured indicate the possibility of a closely fitting curve that aligns with the patterns observed in the data of the precise model. The residuals depicted in Fig. 2 do not appear to display any abnormalities. Fig. 3 presents a juxtaposition of the measured and anticipated values for tensile strength. The real values correspond to the observed outcomes of the empirical tests, whilst the predicted values are obtained through the utilization of the RSM and the CCD model. Significantly, both sets of data demonstrate a significant level of closeness, suggesting that the proposed model is highly suitable. The high R-squared values, particularly the value of 0.9736 for tensile strength, indicate a significant correlation between the observed data and the projected outcomes.

Table 2. Outcomes from tests examining the tensile and flexural properties of nanocomposites

Std	Run	A:Sisal fibre (%)	B:Carbon fibre (%)	C:Fibre Alignment Degree	Tensile Strength (MPa)	Flexural Strength (MPa)
2	1	40	10	0	104	79
20	2	25	25	30	117	92
11	3	25	10	30	109	85
4	4	40	40	0	109	83
6	5	40	10	60	126	103
15	6	25	25	30	114	93
7	7	10	40	60	128	106
1	8	10	10	0	94	71
18	9	25	25	30	116	92
17	10	25	25	30	117	91
13	11	25	25	0	100	77
3	12	10	40	0	107	82
14	13	25	25	60	123	101
10	14	40	25	30	122	96
8	15	40	40	60	131	108
12	16	25	40	30	125	99
9	17	10	25	30	112	90
5	18	10	10	60	119	95
19	19	25	25	30	114	90
16	20	25	25	30	115	91

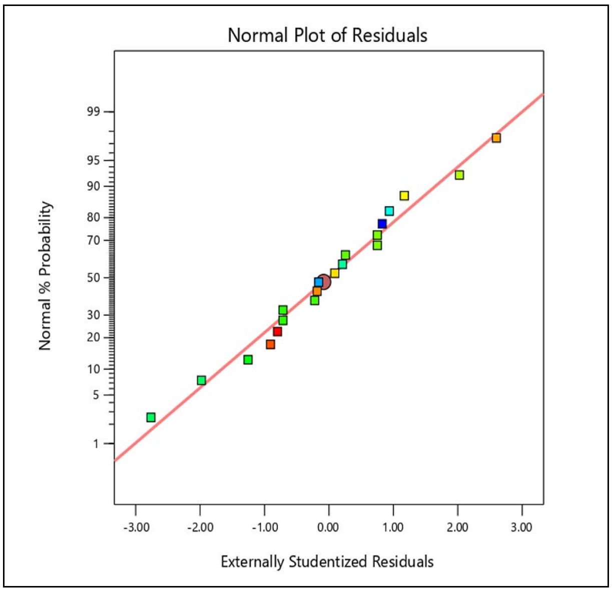


Fig. 2: Normal probability for tensile strength

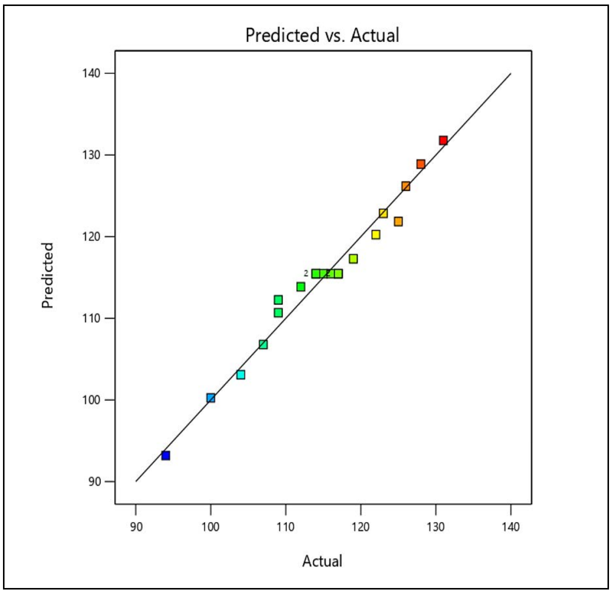


Fig. 3: Predicted vs actual plot for tensile strength

The residual data points indicate the presence of a dependable plot that thoroughly corresponds to the model data. As seen in Fig. 4, there are no significant deviations from normality in the residual values. In Fig. 5, the real values correspond to the investigational response data, whereas the predicted values are obtained using RSM. Significantly, both sets of data demonstrate a strong level of closeness, emphasizing the efficiency of the suggested model. The high R^2 value of 0.9878 for flexural strength demonstrates a strong correlation between the actual and anticipated responses, highlighting the model's trustworthiness.

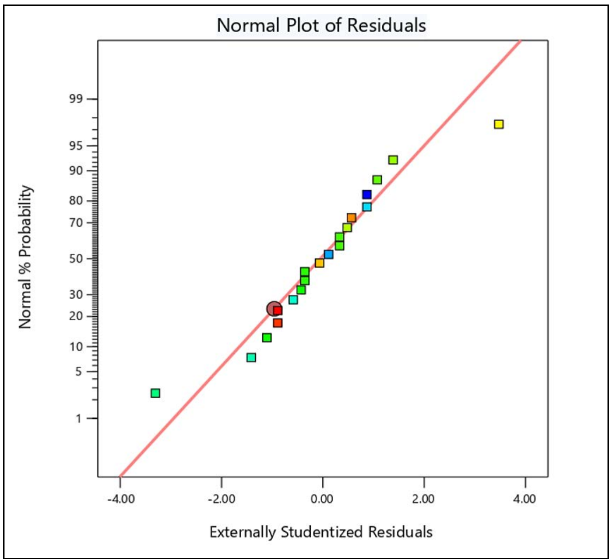


Fig. 4: Normal residual plot for flexural strength

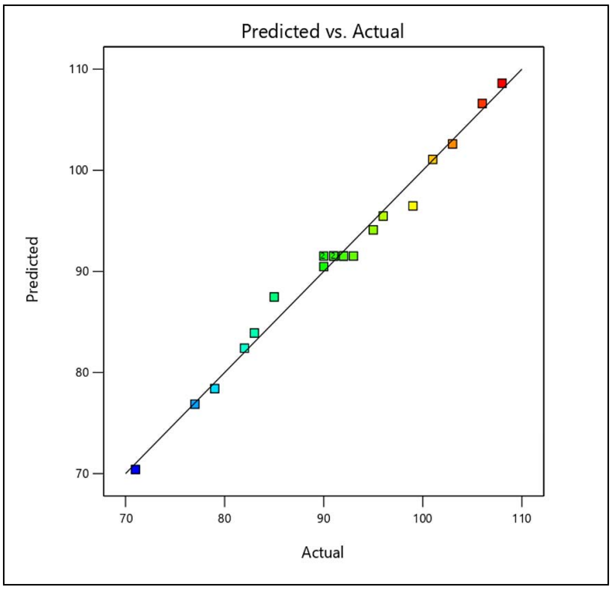


Fig. 5: Predicted vs actual plot for flexural strength

3.2 Building a Model using Mathematical and Independent Variables for Tensile Strength

Tensile Strength = 115.464 + 3.2 × A + 4.8 × B + 11.3 × C + -1.5 × AB + -0.25 × AC + -0.5 × BC + 1.59091 × A^2 + 1.59091 × B^2 + -3.90909 × C^2 (Equation 1)

Table 3. ANOVA for tensile strength

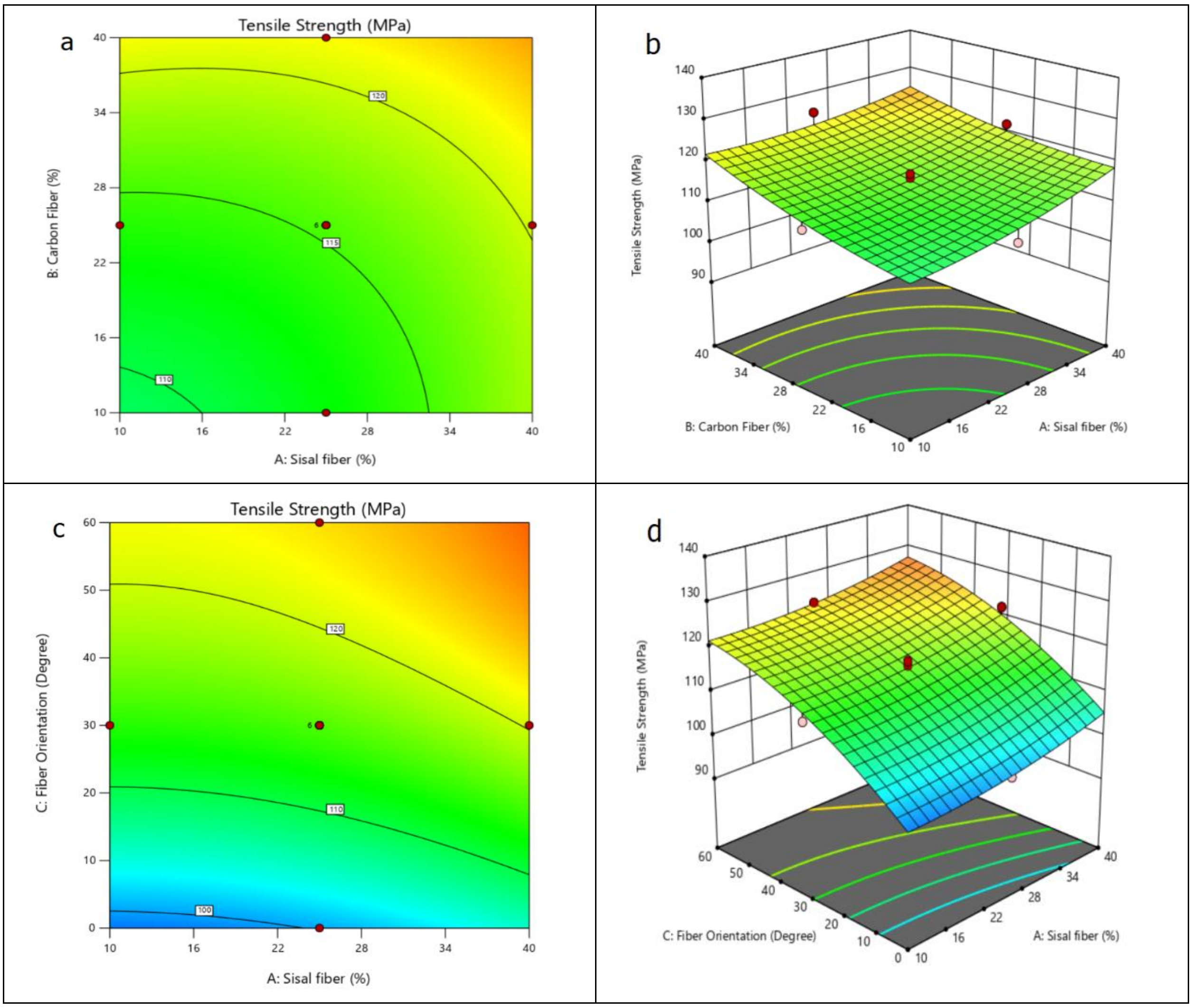
Source	Sum of Squares	df	Mean Square	f-value	p-value	
Model	1672.47	9	185.83	41.00	< 0.0001	significant
A-Sisal fibre	102.40	1	102.40	22.59	0.0008	
B-Carbon fibre	230.40	1	230.40	50.83	< 0.0001	
C-fibre orientation	1276.90	1	1276.90	281.71	< 0.0001	
AB	18.00	1	18.00	3.97	0.0743	
AC	0.5000	1	0.5000	0.1103	0.7466	
BC	2.00	1	2.00	0.4412	0.5215	
A^2	6.96	1	6.96	1.54	0.2436	
B^2	6.96	1	6.96	1.54	0.2436	
C^2	42.02	1	42.02	9.27	0.0124	
Residual	45.33	10	4.53			
Lack of fit	35.83	5	7.17	3.77	0.0857	not significant
Pure error	9.50	5	1.90			
Cor total	1717.80	19				

Table 3 presents the p and f values that support the reliability of the suggested model analyzed using ANOVA (f=41.00, p<0.0001). The p and f factors are used as indicators to evaluate the validity of linear terms (A, B, C), interaction terms (AB, BC, AC), and quadratic terms (A^2, B^2, C^2) in the model. The p-values for A, B, C,

C^2 are very significant, with values of <0.0001, <0.0001, 0.0001, and <0.0124, respectively. The difference between the expected tensile strength using R^2 and the modified tensile strength using R^2 is less than 0.2. These data validate the suitability of the model, and Equation 1 confirms the validity of the mathematical model. Fig. 7 presents two-dimensional (2D) and three-dimensional (3D) charts that clearly illustrate the relationship between tensile strength and several process parameters.

Graphical representations demonstrate similar patterns in the changes in tensile strength when other combinations of process parameters, such as, sisal fibre%, carbon fibre%, and fibre orientation. Fig. 6 (a) and (b) illustrate the impact of fibre orientation of sisal% and carbon fibre%, respectively. A favourable association was found between the tensile strength and the increase in orientation in the hybrid nanocomposite. Furthermore, the fibre orientation has a substantial influence on the strength of the laminate. More precisely, when the material is exposed to a 60° orientation with both the fibre 40% has a noticeable improvement in the material's characteristics. Fig. 6(c) and (d) demonstrate how the % of carbon fibre affects the orientation and sisal fibre in tensile strength.

The fibres oriented parallel to the load direction often exhibit greater tensile strength, while those positioned at angles to the load might confer additional benefits such as, flexibility or resistance to torsion. The incorporation of various fibre orientation boosts the mechanical properties, resulting in an enhanced tensile strength. Fig. 6(e) and (f) demonstrate the impact of sisal fibre% on the carbon fibre% and fibre orientation. Furthermore, it emphasizes that the orientation and carbon fibre enhanced the strength. Moreover, the orientation of fibre and fibre% are critical components in influencing the characteristics of the composite. Essentially, the statistics offer insights into the complex correlation between both the fibre and their orientation, and the final strength of the material.



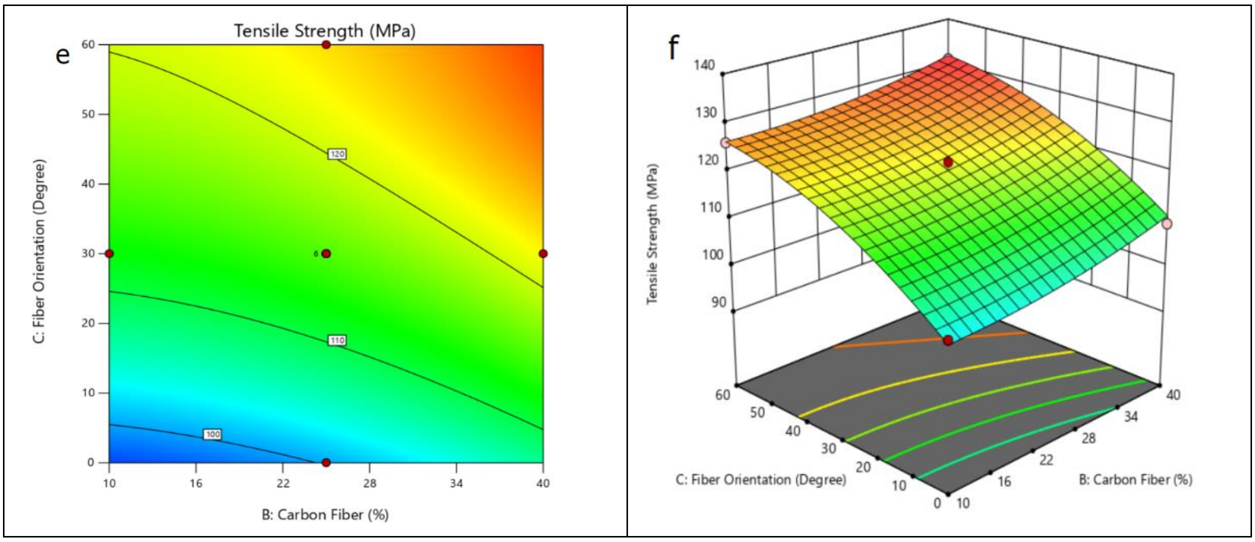


Fig. 6: 2D and 3D surface plots for tensile strength (a) A-B interaction, (b) A-C interaction, (c) B-C interaction

Table 4. ANOVA for Flexural strength

Source	SOS	df	Mean Square	f-value	p-value	
Model	1769.29	9	196.59	89.74	< 0.0001	significant
A-Sisal fibre	62.50	1	62.50	28.53	0.0003	
B-Carbon fibre	202.50	1	202.50	92.44	< 0.0001	
C-Fibre orientation	1464.10	1	1464.10	668.33	< 0.0001	
AB	21.13	1	21.13	9.64	0.0111	
AC	0.1250	1	0.1250	0.0571	0.8160	
BC	0.1250	1	0.1250	0.0571	0.8160	
A^2	5.82	1	5.82	2.66	0.1342	
B^2	0.5682	1	0.5682	0.2594	0.6216	
C^2	17.82	1	17.82	8.13	0.0172	
Residual	21.91	10	2.19			
Lack of fit	16.41	5	3.28	2.98	0.1278	not significant
Pure error	5.50	5	1.10			
Cor total	1791.20	19				

3.3 Creating a Model Using Mathematical and Independent Variables to Predict Flexural Strength

Flexural =91.5182 + 2.5 * A + 4.5 * B + 12.1 * C + -1.625 * AB + 0.125 * AC + 0.125 * BC + 1.45455 * A^2 + 0.454545 * B^2 + -2.54545 * C^2 (Equation 2)

The f-value of 89.74, along with a p-value of less than 0.0001, provides strong evidence that the CCD-RSM model is very suitable for forecasting flexural strengths (Table 4). All of the process variables (A, B, C, AB, and C^2) have a p-value less than 0.05. Furthermore, the substantial p-values obtained from the observed data, together with a small difference between the anticipated R^2 and adjusted R^2 values, confirm the consistent impact of process factors on flexural strength, with an agreement of 0.2. Equation 2 gives the proposed mathematical model. Fig. 8 depicts the impact strength through 2D and 3D response and contour plots. The presentation incorporates a 3D surface plot and a 2D contour plot to highlight the impacts of various arrangements.

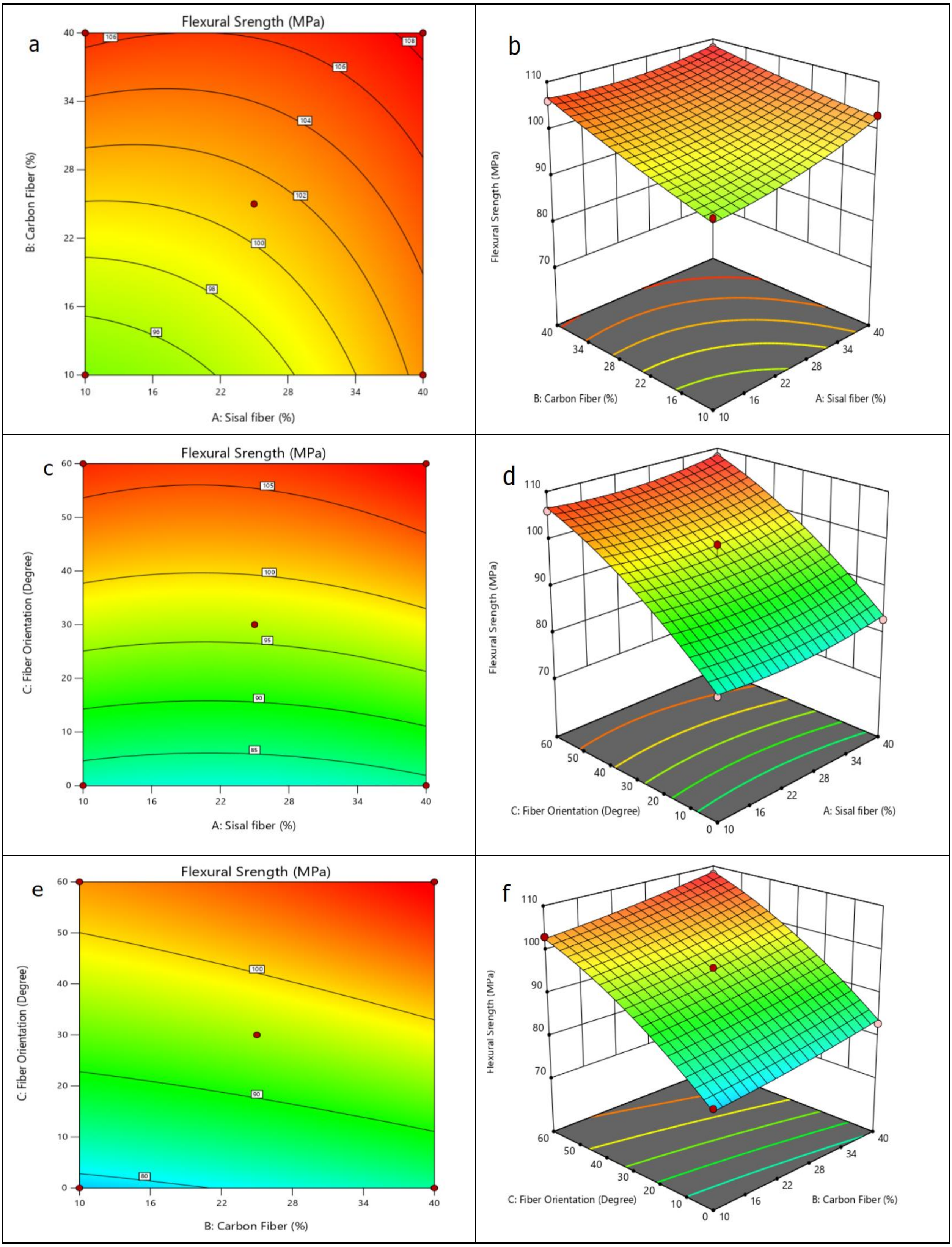


Fig. 7: 2D and 3D surface plot for flexural strength (a) A-B interaction, (b) A-C interaction, (c) B-C interaction

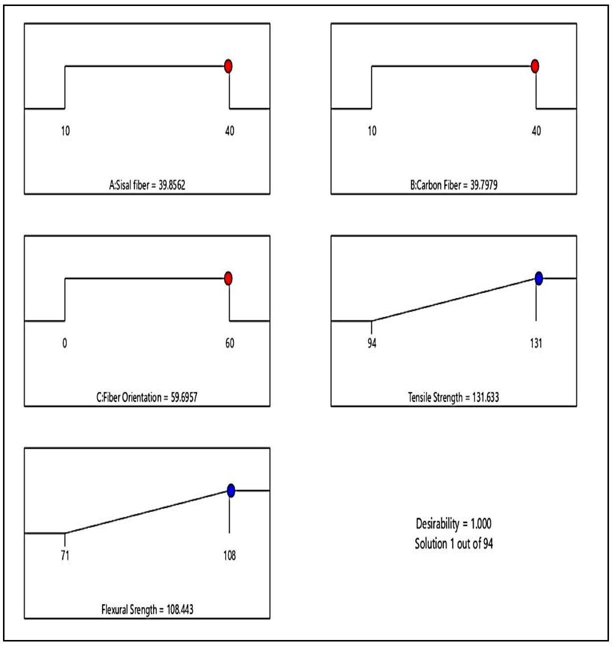


Fig. 8: Ramp functional plot for hybrid composite

An evident augmentation is detected in the interaction pattern between sisal fibre% and carbon fibre% as illustrated in Fig. 7(a) and (b). Fig. 7(c) and (d) provide additional insights into the correlation between changes in sisal fibre% and fibre orientation. Fig. 7(e) and (f) illustrate the positive impact of sisal fibre%, carbon fibre% and orientation of fibre on the strength of nanocomposite. The findings provide significant evidence for the idea of increasing the importance of biodegradable sisal fibre in various industrial sectors. After conducting a thorough analysis of many parameters, it becomes clear that the application of fibre orientation significantly improves mechanical properties. The configuration that stands out is the one that involves 60° fibre orientation with both the fibre 40 wt%. This configuration produces a greater value associated to another variable examined using RSM.

3.4 Confirmation Using Ramp Numerical Optimization

Fig. 8 demonstrates the outcome of optimization of flexural and tensile strength, displaying the specific operational parameters necessary to attain the maximum levels of both the parameters. The ideal circumstances involve using a 60° orientation with 40 wt% of sisal and carbon fibre.

The intricate process of optimization is clearly illustrated in Fig. 9, showcasing the laborious step taken to determine the most favourable conditions for improving the flexural strength and tensile of the desired outcome. The selection of these particular characteristics was done with great care and thorough investigation to guarantee the achievement of optimal condition in tensile and flexural properties. To validate the technical validity of the results, extensive impact tests were carried out underneath these optimum settings. The findings of these experiments confirmed the appropriateness of our model's adequacy, demonstrating a significant agreement between the projected result and the actual experimental results.

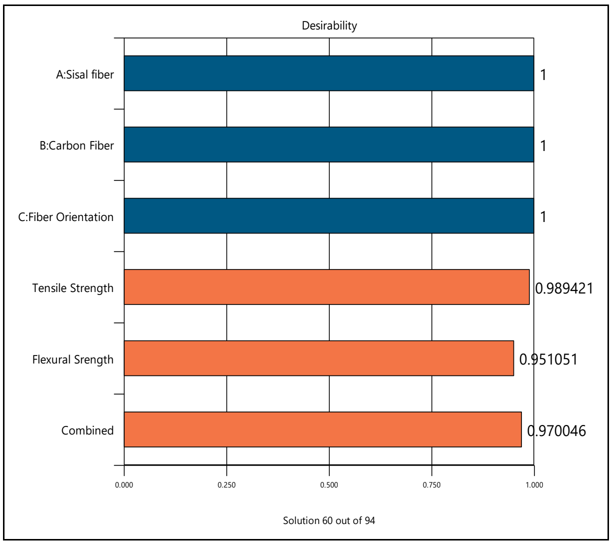


Fig. 9: Desirability plot

4. CONCLUSION

The study investigated the impact of sisal fibre%, carbon fibre% and fibre orientation on the tensile and flexural strengths of materials that were incorporated with sisal and carbon fibres. The study utilized the CCD approach of RSM to thoroughly examine the parameters involved in preparing laminates. The primary emphasis was placed on the modelling and optimization of tensile and flexural strengths, resulting in the identification of numerous noteworthy findings. Utilizing sisal fibres in combination with carbon fibres led to significant improvements in both tensile and flexural strengths. These enhancements showcase the efficiency of this integrated strengthening method. Furthermore, the mechanical characteristics of the composite were notably improved by the application of fibre orientation, resulting in a substantial 34.27% increase in tensile strength and a 22.47% increase in flexural strength, when compared to 20 trials in RSM nanocomposites. An optimal combination consisted of a 60° orientation of fibre with 40 wt% of sisal and carbon fibre.

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CONFLICT OF INTEREST

The authors declared no conflict of interest in this manuscript regarding publication.

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