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Research Article

Modeling and Numerical Prediction on Mechanical Behaviors of Hybrid Fiber Reinforced Polymer Bio Composites Using Fuzzy Logic Algorithm

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ABSTRACT

The present study investigates the mechanical behaviors of hybrid fiber-reinforced polyester composites in developing a new strengthened material. The experiments were planned as per the design of experiments, the selected input parameters were fiber length (mm), NaOH treatment (%), and fiber weight (%) and the output parameters were tensile, flexural, and impact strength conditions. A Non-Linear Regression Modelling (NLRM) and Fuzzy logic model have been designed to predict and analyze the mechanical properties in unknown test conditions. Every input factor was categorized into three linguistic descriptors, while each output factor was classified into three linguistic categories. A triangular membership function was employed to define all these variables. The effectiveness of the nonlinear regression analysis and fuzzy logic model was evaluated through confirmatory experiments. The model predicted the mechanical results with an error of 7.19%, 5.38%, and 2.33% respectively. The proposed approach can significantly simplify real-life multi-response optimization problems, thereby reducing fabrication costs and enhancing composite fabrication efficiency.

1. Introduction

In recent times, a burgeoning industrial consciousness has emerged concerning environmental impact, the diminishing reservoirs of petroleum resources, and a heightened emphasis on human health. This has precipitated a pivot in attention towards ecologically sustainable products, displacing the erstwhile emphasis on synthetic materials [1]. The substantial prevalence of natural fibers and alternative bio-derived products has played a

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pivotal role in augmenting product sustainability in contrast to synthetic materials [2,3]. Furthermore, natural fibers provide notable advantages over synthetic materials, including low cost, low weight, biodegradability, higher strength, and diminished wear [4-6]. These mentioned attributes position natural fibers as suitable aspirants for broader utilization in biomedical, automobiles, furniture, and construction sectors, etc [7-8]. In recent times, plant fibers have been highly effectively utilized as reinforcement materials for preparing polymer matrix composites [9,39]. Examples of plant fiber reinforcement materials such as pineapple leaf, banana, coir, jute, roselle, luffa, and hemp, etc., can very effectively enhance the mechanical behaviors of fabricated composites [10-14]. The development in rigidity is due to greater adhesion between the base matrix and fiber reinforcement contact, which is challenging when using natural fibers. The hydrophilic nature of natural fibers and the hydrophobic nature of the polymer matrix are the main causes of this behavior [15,16]. To address this concern, researchers frequently engage in surface modification of natural fibers by subjecting them to chemical-rich solutions as pre-treatment. Chemically treating natural fibers enhances bond strength, thereby diminishing their hydrophilic behavior and bolstering interfacial strength [17,18]. Different types of chemical pre-treatments involve significantly modify the fiber surface and dimensional stability characteristics [19]. The paddy straw fiber was immersed in 2 wt% sodium hydroxide for the duration of 48 hours [20,21]. Motaleb et al (2022) an examination of the impact of incorporating chemically treated pineapple fiber (ranging from 25 to 45 wt%) to reinforce polypropylene composite through compression molding reveals that formulations prepared with 45 wt% pineapple fiber exhibit improvements in tensile, bending, and impact strength compared to other composite preparations [22]. Soundar et al (2019) Response surface methodology (RSM) was used to organize trials in the fabrication of a hybrid composite that contained 0.78% of silica and 2 wt.% of roselle fiber to get the best flexural and tensile properties [23]. Balasubramanian et al (2016) Drilling operations analyze speed, feed, and depth of cut as input factors, and thrust force and torque as output responses. The average errors of the models, which showed a significant correlation with the experimental data, were 0.77% and 1.22%, respectively. As such, it is possible to regard the fuzzy modeling of thrust and torque as extremely precise. Moreover, within a specified range of values, fuzzy modeling makes it easier to predict reactions with confidence for every combination of cutting speed, feed rate, and depth of cut [24]. Thirumal et al (2016) The study employed fuzzy logic with the goal of forecasting the Indoor Air Quality (IAQ) parameters' transitional response under various input conditions. Comparing the suggested multi-response fuzzy model to nonlinear regression models, the former demonstrated better prediction accuracy. Notably, the fuzzy model's absolute error percentages for temperature, relative humidity, and carbon dioxide levels were 2.05%, 3.81%, and 2.24%, respectively [25]. Sinha et al (2020) the study examined the wear characteristics of epoxy composites reinforced with abaca fiber and augmented by the inclusion of red mud filler. The investigation considered the impact of the weight percentage of abaca, red mud, and the particle size of red mud using a mathematical model (Response Surface Methodology) to optimize the sliding wear of hybrid composites. Additionally, experimental data were utilized to develop a fuzzy logic model for predicting the sliding wear of hybrid composites. The suggested fuzzy model demonstrated a predictive accuracy of 87% in estimating the sliding wear of hybrid composites [26]. Gangwar et al (2022) studied a Taguchi L27 orthogonal array to record the mechanical characteristics of kenaf fiber, NaOH concentration, and fiber immersion time. ANOVA analysis revealed NaOH concentration as the most influencing parameter, followed by kenaf wt.%. The grey-fuzzy approach was used to convert multi-variate features into a single reasoning grade, minimizing ambiguity and providing results close to a position value [27]. Guo et al (2022) study, a fuzzy reasoning technique are employed to identify the combination of input variables that can yield the best overall performance. The input variables include a 0° layup angle, a 260°C nozzle temperature, an 80% fiber filling rate, and a 0.6 mm layer thickness. [28].

Based on the above-mentioned literature review, researchers encounter difficulties in optimizing various mechanical characteristics for composite formulations reinforced with natural fibers. Hybrid fiber (Paddy straw and pineapple leaf fiber) has not yet been reported in any literature study. Utilization of Agro-Wastages is used as reinforcement, turning waste into valuable resources. Hybrid Composites present a sustainable alternative to conventional materials, decreasing dependence on synthetic fibers and mitigating environmental impact. In the same context, hybrid fiber-reinforced polyester composite formulations were prepared using a semi-automatic compression molding machine based on the L27 experimental design.

Literature also supports the requirement for a chemical treatment to increase bond strength in fibers so the the hybrid fibers were chemically treated in varying percentages of NaOH for the duration of 24 hrs. Further influence of different types of fiber length and fiber weight percentage was also taken in this study. The mechanical properties of tensile, flexural, and impact strengths were maximized using nonlinear regression modeling and a fuzzy dual approach. The optimal combinations of fiber length, fiber weight, and NaOH concentration % for treatment.

2. Materials and Methods

2.1. Reinforcement and Matrix Description

Paddy straw fibers are collected from agricultural lands to mitigate wastage globally. The gathered agricultural waste undergoes a thorough cleaning process to eliminate unwanted materials and impurities. Similarly, pineapple leaves are also collected from agricultural fields and the fibers are extracted using a double roller fiber extracting machine. Both paddy straw stems and pineapple leaves undergo a chemical treatment process to enhance fiber surface and strength. NaOH was selected for chemical treatment due to its effectiveness compared to other treatment processes [29,30]. Various NaOH concentrations (1%, 3%, and 5%) are utilized for a duration of 24 hours at room temperature. The main objective of submerging the fibers in a chemical solution is to reduce their hydrophilic behavior, resulting in better interfacial strength with the matrix. This treatment expressively improves the mechanical characteristics of the fibers. Subsequently, the fibers are meticulously cleaned with distilled water to remove any residual chemicals. The fibers are then sunlight-dried for 2 days to complete the process of enhancing their properties [38]. The matrix material used in the present study was polyester resin (thermosetting group), the accelerator (Methyl Ethyl Ketone Peroxide), and catalyst (Cobalt octoate) used as a curing agent [31]. The resin and the curing agent were purchased from Go Green Products, Chennai, India. The polyester resin properties are density -1.132 (g/cm3), viscosity @ 25°C – 470 (cp), volatile content – 36.2 (%), acid value – 25.18 (mg KOH/gm), gel time @ 25°C – 14 min [11]. Figure 1 shows chemically treated paddy straw and pineapple leaf fiber.

Fig. 1. Chemically treated fibers: (a) Paddy straw, (b) Pineapple leaf fiber

2.2. Fabrication of Composites

The fabrication of hybrid fiber-reinforced composite preparations of chemically treated fiber (1%, 3%, 5%), fiber length (25mm, 50mm, 75mm), and fiber weight (30%, 40%, 50%) was carried out using semi-automatic compression molding machine with the mold dimensions of 300 x 300 x 3 mm [32]. The polythene sheet was located between the base plate and mold for easy removal of the composite plate. The Wax content was applied to the mold surface and the polyethylene sheet to prevent the liquid polyester from adhering to the mold and base plate surfaces. Polyester resin, combined with a catalyst and accelerator at a ratio of 1:0.015:0.015, was manually stirred for 2-3 minutes to prevent agglomeration [33]. Now, weighted fiber is placed in the bottom mold and mixed resin is poured into the entire mold uniformly in a circular way in the mold. Further, the upper die was compressed into the bottom mold, in the same context the temperature 50°C and 30 bar pressure was applied for 45 mins. After 45 mins the eject the fabricated composite laminate was placed at room temperature. 27 Laminates were fabricated in accordance with the L27 experimental design. The stepwise experimentation procedure is shown in Figure 2.

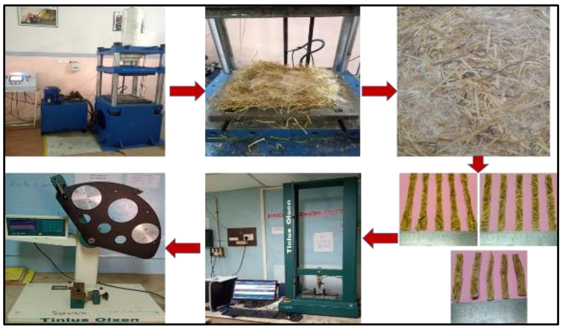

Fig. 2. Stepwise procedure for experimentation methodology

2.3. Mechanical Testing

The fabricated composite laminate cutting with the ASTM standard. Tensile strength tests for composite samples were conducted the ASTM D638 standard [34], utilizing a universal testing machine (UTM) with a gauge length of 100mm and a constant crosshead speed of 1.5 mm/min.

The flexural test was conducted using the 3-point bending test in accordance with the ASTM D790 [35] standard on a universal testing machine. The flexural strength was performed by the following equation:

Flexural strength (σ)= $3pl\ /2bt^2$

where p – Maximum load, l – Span length, b- width of the specimen, t – thickness of the specimen.

The Charpy impact test is a standard method used to measure the impact strength. The test assesses the energy absorbed by a material during fracture. Which is determined according to ASTM D256-10 [36] standards using the Charpy test. In this test, a notch with a depth of 2 mm and a subtended angle of 45° is created, and the energy released upon fracturing the sample is recorded.

2.4. Design of Experiments

Design of Experiments (DOE) is a systematic approach used to determine the relationship between factors that affect a process and the resulting output of that process. Incorporating fuzzy rules into DOE involves considering uncertainty and imprecision in the factors and their levels. The assigned input variables and their level are in Table 1.

Table 1. Input variables and their level

Level	Fiber length (mm)	NaOH Treatment (%)	Fiber weight (%)
Low	25	1	30
Medium	50	3	40
High	75	5	50

According to the full factorial design of experiments, 27 sets of interpretations were recorded and then categorized into three levels for the development of a multipurpose fuzzy model, as shown in Table 2.

Table 2. Output variables and their level

Level	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Strength (KJ/m2)
Low	15-30	30-44	36-61
Medium	31-45	45-59	62-87
High	46-60	60-74	87-112

The tensile, flexural, and impact strength for 27 polyester composite laminates on different settings of input parameters using DOE were recorded and reported in Table 3.

Table 3. Experimental results using Design of experiments

S.No	Fiber length (mm)	NaOH Treatment (%)	Fiber Weight (%)	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Strength (KJ/m2)
1	25	1	30	15.6	29.6	50.6
2	25	1	40	21.8	32.9	62.8
3	25	1	50	27.1	40.7	88.3
4	25	3	30	18.7	33.4	59.3
5	25	3	40	29.4	41.4	71.8
6	25	3	50	36.9	51.2	96.4
7	25	5	30	22.1	40.6	68.9
8	25	5	40	39.2	53.1	83.3
9	25	5	50	47.5	60.2	112.3
10	50	1	30	21.5	33.7	48.4
11	50	1	40	28.7	43.8	53.9
12	50	1	50	44.6	55.7	78.4
13	50	3	30	23.8	42.4	54.3
14	50	3	40	33.6	48.5	58.1
15	50	3	50	51.9	61.3	82.6
16	50	5	30	28.4	55.2	61.7
17	50	5	40	39.3	60.6	73.4
18	50	5	50	60.4	73.1	87.37
19	75	1	30	18.3	32.4	36.8
20	75	1	40	23.6	38.9	41.4
21	75	1	50	37.9	49.5	58.4
22	75	3	30	21.8	37.8	40.7
23	75	3	40	30.6	41.1	49.9
24	75	3	50	38.1	52.4	62.6
25	75	5	30	29.3	36.8	40.8
26	75	5	40	32.7	44.6	50.3
27	75	5	50	39.4	55.4	72.2

2.5. Nonlinear Regression Analysis

Nonlinear regression in statistics involves modeling observational data using a function that is a nonlinear combination of model parameters and depends on one or more independent variables [25].

$$y_u = \varphi\ (x_{1u}, x_{2u}, ..., x_{ku}) + \varepsilon_u \quad (1)$$

where u=1, 2, 3, k, and k represent the number in the factorial experiment. The term x_{iu} represents the level of the ith factor in the uth experiment. The function φ is called the response surface. The residual ε_u measures the experimental error in the uth observation.

The first order polynomials formula,

$$y_u = \beta_0 + \beta_1 x_{1u} + \beta_2 x_{2u} + \cdots + \beta_k x_{ku} + \varepsilon_u \qquad (2)$$

The second-order polynomial, specifically known as the Quadratic response surface has 3−x variables, and takes the form:

$$y_u = \beta_0 + \beta_1 x_{1u} + \beta_2 x_{2u} + \beta_3 x_{3u} + \beta_{12} x_{1u} x_{2u} + \beta_{23} x_{2u} x_{3u} + \beta_{13} x_{1u} x_{3u} + \varepsilon_u + \beta_{11} x_{1u}^2 + \beta_{22} x_{2u}^2 + \beta_{33} x_{3u}^2 \qquad (3)$$

"ε_u" is a term representing additional sources of variability not accounted for. This encompasses measurement errors in the response, other inherent sources of variation in the process or system, and so forth. Quadratic design models were chosen based on superior values of the coefficient of correlation and F-test for all responses in this study using statistical software.

2.6. Fuzzy Logic Algorithm

Fuzzy logic simulates human decision-making by employing linguistic reasoning, integrating a mathematical theory that combines multi-valued logic, probability theory, and artificial intelligence methods. It has been proven to be effective in addressing complex problems. Mamdani and Sugeno represent two distinct types of fuzzy inference systems (FISs) within the fuzzy logic toolbox. These two types of inference systems vary in the manner in which they specify outputs. The Mamdani-type fuzzy inference produces a fuzzy set output, whereas the Sugeno-type inference provides either a constant output or a linear mathematical expression [37]. In this present investigation, Mamdani FIS was used and the structure of the fuzzy logic system is shown in Figure 3.

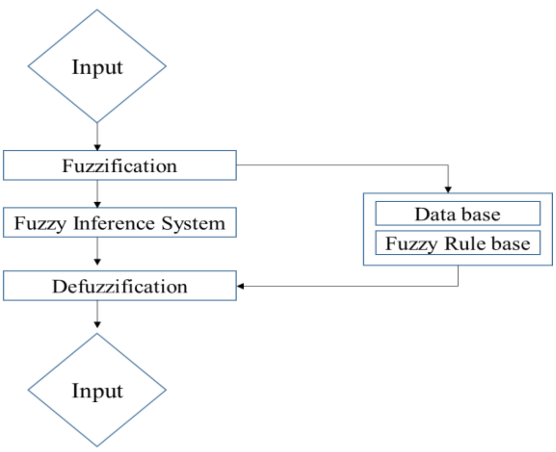

Fig. 3. Fuzzy model for Mechanical strength parameters

Meaningful linguistic statements are selected for each variable and represented using appropriate fuzzy sets, such as "low," "medium," and "high." The concept of fuzzy reasoning for a three-input–three-output multi-response fuzzy logic model is described as follows. The fuzzy rule base consists of a group of IF-THEN statements with three inputs, x_1, x_2, and x_3, and three outputs y_1, y_2, and y_3,

Rule 1: If x_1 is A_1 and x_2 is B_1 and x_3 is C_1 then y_1 is P_1 and y_2 is Q_1 and y_3 is R_1

Rule 2: If x_1 is A_2 and x_2 is B_2 and x_3 is C_2 then y_1 is P_2 and y_2 is Q_2 and y_3 is R_2

Rule n: If x_1 is A_n and x_2 is B_n and x_3 is C_n then y_1 is P_n and y_2 is Q_n and y_3 is R_n (4)

A_n, B_n, and C_n function as input membership functions for the fuzzy models, while P_n, Q_n, and R_n serve as output membership functions for the multi-response fuzzy models.

Triangular and trapezoidal membership functions were applied to both input and output conditions in the fuzzy model. The generated membership function plots for input and output variables are depicted in Figures 4 and 5, respectively. The triangular membership function (trimf) is the most basic, created using three points to form a triangle, while the trapezoidal membership function (trapmf) is a truncated triangle defined by four points.

The Fuzzy Rule Editor is employed to generate 27 sets of rules based on the specified input and output variables using the FIS editor. Within the Fuzzy model, these rules are organized in such a way that the first three columns correspond to the input variables, while the remaining columns pertain to the output variables. These rules provide a comprehensive definition of the Fuzzy Inference System, encompassing variables, membership functions, and the essential rules for computing intermediate mechanical strength parameters.

The Fuzzy Rule Viewer illustrates the entire fuzzy inference process, presenting each row as an if-then rule following a specific syntax. In this representation, each column corresponds to a variable, and the rule numbers are positioned next to each row. The rule viewer provides a detailed microview of the Fuzzy Inference System, showcasing every calculation in great detail. Furthermore, the Surface Viewer displays the comprehensive output of the fuzzy system, encompassing the entire span of the input set.

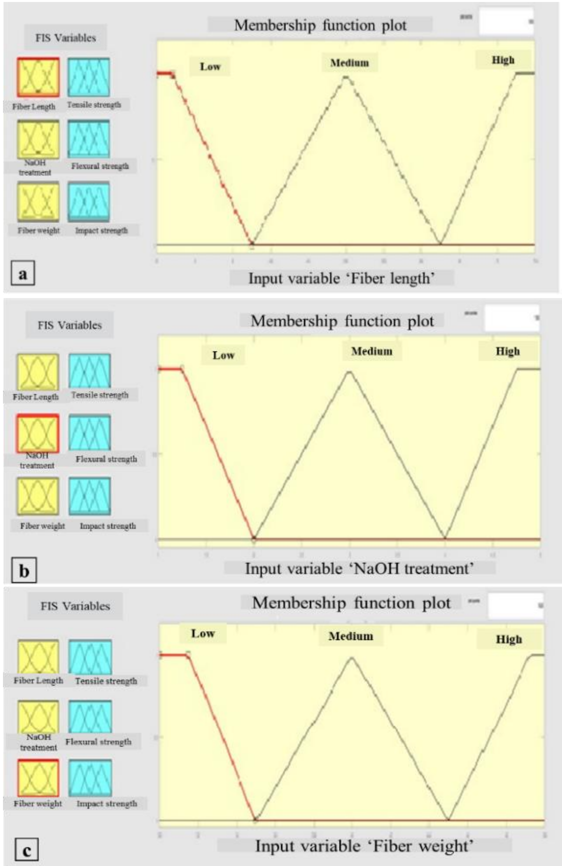

Fig. 4. (a-c) Input parameters and their membership plots

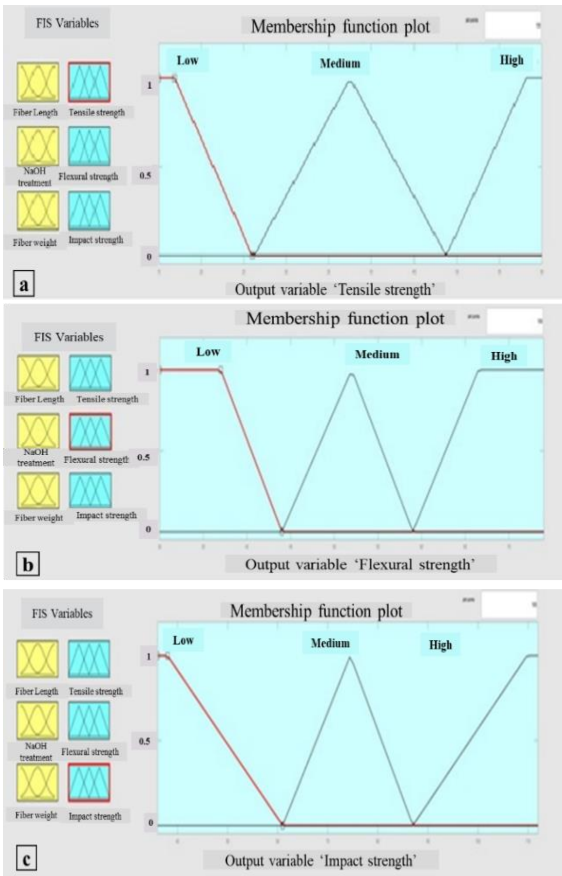

Fig. 5. (a-c) Output parameters and their membership plots

3. Results and Discussion

3.1. Prediction Using NLRM

In statistics, the coefficient of determination, R-squared (R2), signifies the portion of variability in a dataset that the statistical model can account for. R2 values of 0.90, 0.98, and 0.94 were achieved for the fiber length, NaOH treatment, and fiber weight models, respectively. The scientific relationships for correlating the input process variables are derived from the coefficients obtained through the use of Design Expert software. The terms l, n, and w are Fiber length, NaOH treatment, and Fiber weight whereas Ts, Fs, and Is represents Tensile strength, Flexural strength, and Impact strength respectively.

$$Ts = -26.35 + 1.45928\, l + 1.78056\, n - 0.124028\, w - 0.037833\, ln - 0.003033\, lw + 0.055417\, nw - 0.011947\, l^2 + 0.108333\, n^2 + 0.014167\, w^2 \quad (5)$$

The relevance of adding new model terms beyond those in the original model was assessed using the F-value. It was evident from a decreased p-value (Probability > F) that the addition of second-order variables enhanced the model. The coefficients derived from the Design Expert software output correspond mathematically to the flexural strength (Fs) and the process variables under consideration.

$$Fs = -8.45185 + 1.73217\, l + 3.825\, n - 0.632639\, w - 0.057833\, ln + 0.0006\, lw + 0.024583\, nw - 0.015698\, l^2 + 0.247222\, n^2 + 0.017556\, w^2 \quad (6)$$

The coefficients produced by the Design Expert software output are used to establish the mathematical relationship between the Impact strength (Is) and the process variables under consideration.

$$Is = 72.87644 + 0.663522\, l + 3.30389\, n - 2.77957\, w - 0.060167\, ln - 0.014433\, lw + 0.046542\, nw - 0.004404\, l^2 + 0.248194\, n^2 + 0.061261\, w^2 \quad (7)$$

3.2. Prediction using Fuzzy Logic

The input and output variables undergo fuzzification and are expressed using membership functions. The output variables are categorized into three levels each, resulting in a formulation of 27 fuzzy rules (Table 4).

Table 4. Fuzzy set of rules

Rule no	Fiber length	Treatment	Weight (%)	Tensile	Flexural	Impact
1	Low	Low	low	low	low	low
2	Low	Low	medium	low	low	medium
3	Low	Low	high	low	low	high
4	Low	medium	low	low	low	low
5	Low	medium	medium	low	low	medium
6	Low	medium	high	medium	medium	high
7	Low	high	low	low	low	medium
8	Low	high	medium	medium	medium	medium
9	Low	high	high	high	high	high
10	Medium	Low	low	low	low	low
11	Medium	Low	medium	low	low	low
12	Medium	Low	high	medium	medium	medium
13	Medium	medium	low	low	low	low
14	Medium	medium	medium	medium	medium	low
15	Medium	medium	high	high	high	medium
16	Medium	high	low	low	medium	medium
17	Medium	high	medium	medium	high	medium
18	Medium	high	high	high	high	high
19	High	Low	low	low	low	low
20	High	Low	medium	low	low	low
21	High	Low	high	medium	medium	low
22	High	medium	low	low	low	low
23	High	medium	medium	medium	low	low
24	High	medium	high	medium	medium	medium
25	High	high	low	low	low	low
26	High	high	medium	medium	medium	low
27	High	high	high	medium	medium	medium

The fuzzy rule viewer for the confirmation test is depicted in Figures 6 and 7. To validate the fuzzy system, an experimental value (Fiber length 75, NaOH treatment 5%, and fiber weight 50%) was provided, yielding output values (Tensile strength 37.5 MPa, Flexural strength 51.7 MPa, and Impact strength 74.2 KJ/m^2) that closely match the experimental results.

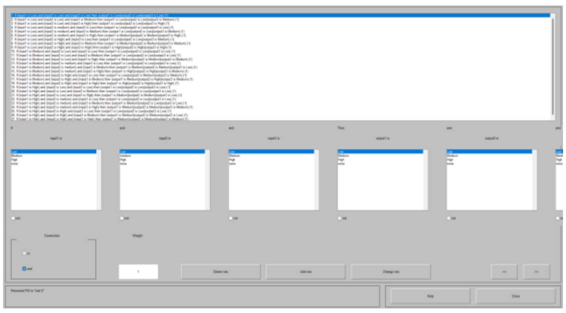

Fig. 6. Fuzzy rule reading

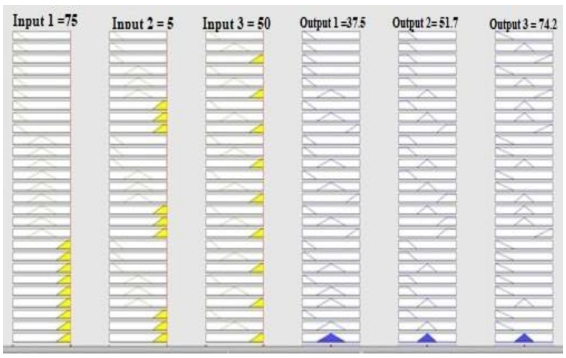

Fig. 7. Fuzzy rule viewer of mechanical strength parameters

The interaction effects of input parameters on the responses were examined using surface plots. The interaction effects of Fiber length, NaOH treatment, and Fiber weight on Tensile strength, Flexural strength, and Impact strength are shown in Figures 8,9,10.

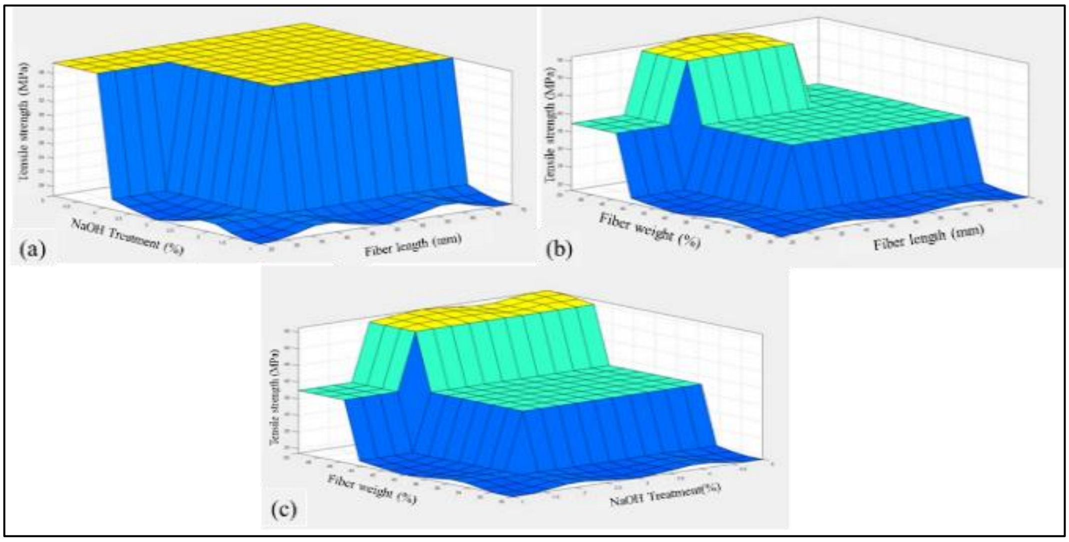

Fig. 8. Surface view plots for tensile strength: (a) NaOH treatment vs Fiber length, (b) Fiber weight vs Fiber length, and (c) Fiber weight vs NaOH treatment

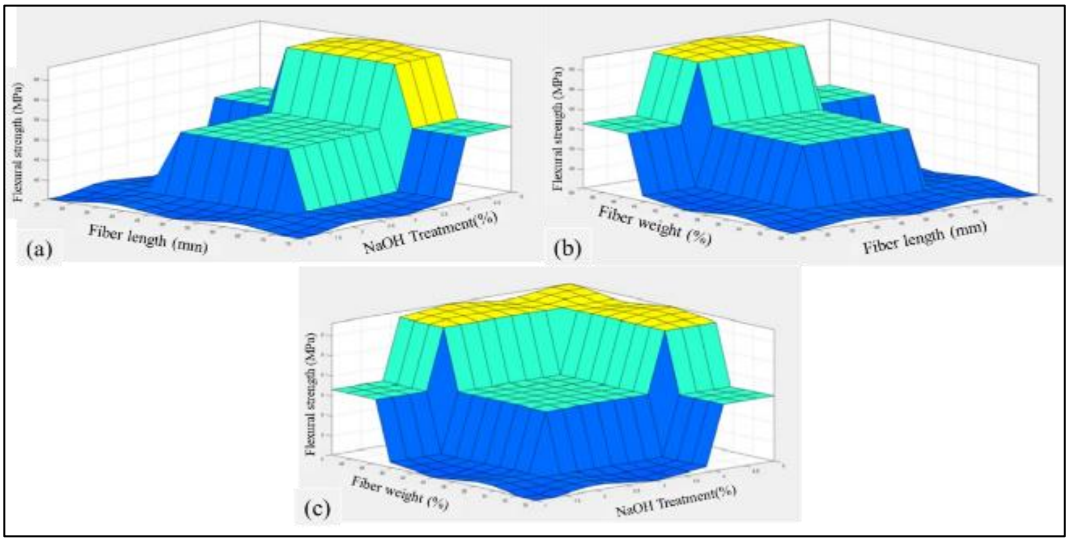

Fig. 9. Surface view plots for Flexural strength: (a) NaOH treatment vs Fiber length, (b) Fiber weight vs Fiber length, and (c) Fiber weight vs NaOH treatment

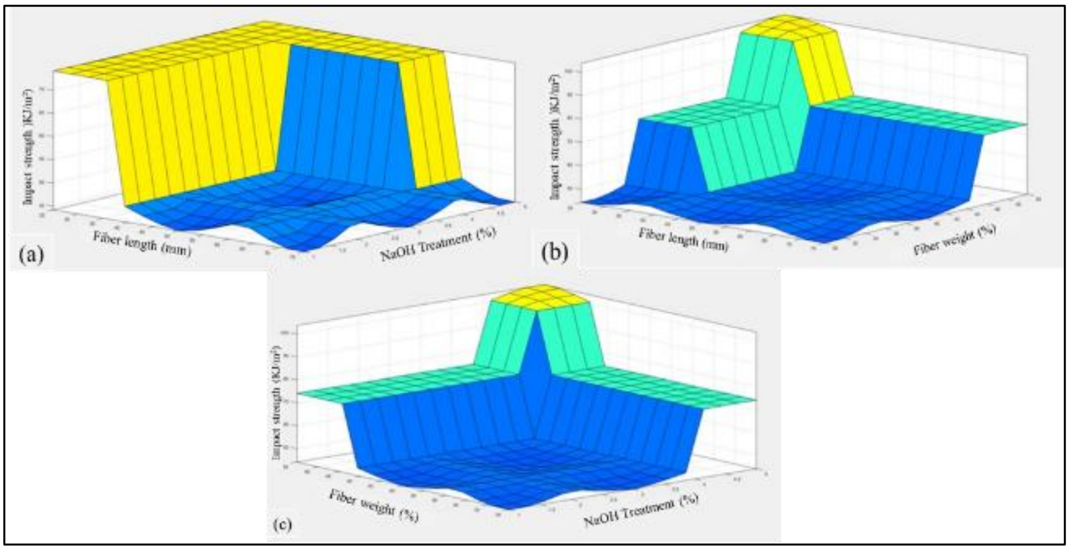

Fig. 10. Surface view plots for Impact strength: (a) NaOH treatment vs Fiber length, (b) Fiber weight vs Fiber length, and (c) Fiber weight vs NaOH treatment

3.3. Validation of fuzzy models

Confirmation experiments were conducted under six distinct sets of input conditions. The experimental data and the predicted values obtained from both the mathematical model and fuzzy logic were compared (see Table 5).

% of error = (Experimental value - Predicted value) × 100 / Experimental value

It was obtained that the average absolute error percentages for input parameters in the Nonlinear regression model are shown in Table 6.

Tensile strength = 7.19 %

Flexural strength = 5.38 %

Impact strength = 2.33 %

It was obtained that the average absolute error percentages for input parameters in the fuzzy model are shown in Table 6.

Tensile strength = 6.61 %

Flexural strength = 6.22 %

Impact strength = 9.09 %

Table 5. Comparison of experimental values with predicted values

Run	Fiber length (mm)	NaOH treatment (%)	Fiber weight (%)	Experimental values			Predicted values using NLRM			Predicted values using the Fuzzy model		
				Ts	Fs	Is	Ts	Fs	Is	Ts	Fs	Is
1	25	3	30	18.7	33.4	59.3	17.9	33.9	59.4	18.6	35.3	44.1
2	25	3	50	36.9	51.2	96.4	39.9	51.1	97.5	37.5	51.7	104
3	50	1	30	21.5	33.7	48.4	22.8	38.5	47.1	18.6	35.3	44.1
4	50	5	40	39.3	60.6	73.4	41.6	58.6	70	37.5	68.3	74.2
5	75	3	30	21.8	37.8	40.7	20.9	34.2	39.9	18.6	35.3	44.1
6	75	5	50	39.4	55.4	72.2	45	57.4	69.7	37.5	51.7	74.2

Table 6. Comparison of error percentage

Run	Fiber length (mm)	NaOH treatment (%)	Fiber weight (%)	Predicted values using NLRM			Predicted values using the Fuzzy model		
				Ts	Fs	Is	Ts	Fs	Is
1	25	3	30	4.34	-1.45	-0.26	-0.53	5.68	-25.63
2	25	3	50	-8.08	0.19	-1.09	1.62	0.97	7.88
3	50	1	30	-6.44	-14.39	2.72	-13.48	4.74	-8.88
4	50	5	40	-5.91	3.20	4.62	-4.58	12.70	1.08
5	75	3	30	4.16	9.44	1.87	-14.68	-6.61	8.35
6	75	5	50	-14.24	-3.66	3.44	-4.82	-6.67	2.77
Average error percentage				7.19	5.38	2.33	6.61	6.22	9.09

The comparisons of experimental and predicted values of Tensile, Flexural, and Impact strength are shown in Figures 11, 12, and 13 respectively. The accuracy of NLRM (Non-linear regression model) compared with fuzzy model prediction was studied using these validation plots. Include surface plots comparing experimental and predicted values to visually assess the model's performance across different conditions.

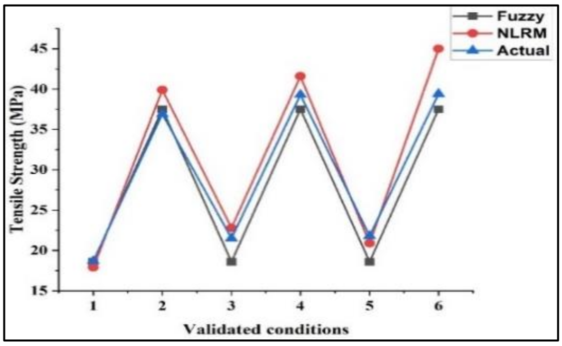

Fig. 11. Comparison of experimental and predicted values of Tensile strength

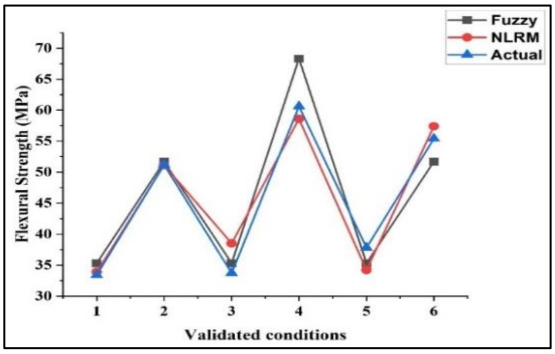

Fig. 12. Comparison of experimental and predicted values of Flexural strength

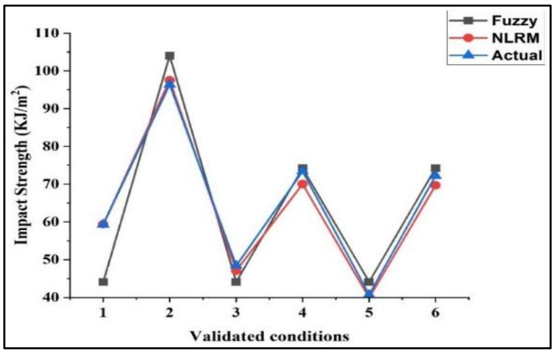

Fig. 13. Comparison of experimental and predicted values of Impact strength

4. Conclusions

This paper showcases the optimization of diverse mechanical characteristics in hybrid fiber-reinforced polyester composite formulations. The methodology integrates nonlinear regression analysis and fuzzy logic to facilitate the identification of optimal input fabrication parameters. A total of 27 experiments were performed to evaluate different input parameter configurations, during which multiple mechanical properties were documented. The input fabrication parameters encompassed hybrid fiber length (mm), NaOH concentration in a chemical solution (%), and fiber weight percentage (%). The corresponding output characteristics included tensile strength, flexural strength, and impact strength. The study analyzed the interaction effects and significance of variables on the outputs through surface plots. Additionally, a systematic fuzzy model was formulated to predict the responses within the specified range of conditions. The optimal input parameter levels that maximize tensile strength, flexural strength, and impact strength are as follows: a fiber length of 75, NaOH concentration at 5%, and a fiber weight of 50%. The Nonlinear Regression Model (NLRM) accurately predicted the mechanical characteristics and validation results indicated an error percentage of 4.96% for all the models, whereas the error percentage ranged up to 7.30% in the fuzzy model. This suggested approach has the potential to significantly simplify the complexity inherent in real-life multi-response optimization problems, ultimately reducing fabrication costs and enhancing efficiency in composite fabrication. In this composite can be used in a wide range of applications including automotive parts, building materials, packaging, furniture, and consumer goods, demonstrating their versatility and broad market potential. The biodegradability of many agricultural fibers improves the composites' environmental friendliness and aids in waste disposal at the end of their life cycle.

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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