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# Full factorial design analysis and optimisation of mechanical behaviour of jute -flax reinforced epoxy composite

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## Abstract

Researchers are always interested in natural fiber-based polymer composite materials because of their specialized features that can be customized in a variety of engineering sectors. The mechanical performance of jute and flax reinforced epoxy composite materials is examined in this study, with variations in fiber ratio and fiber size to maximize performance. In order to predict tensile, impact, and flexural behaviour, testing specimens are produced in accordance with ASTM standards, and samples are prepared utilizing compression moulding processes. Alkali treatment is applied to jute and fibers in order to prepare the composite. The jute and flax fibers are chopped into the necessary sizes of 10 mm, 15 mm, 20 mm, 30 mm, and 35 mm. They are then dispersed at random in an epoxy resin mould with varying fiber weight fractions of 20%, 30%, and 40%. Total 18 runs are experimentally conducted for evaluation of tensile, flexural and impact behaviour. ANOVA is used to optimize the results for full factorial design in order to assess the fiber length and weight fraction parameters and their impact. The weight fiber factor in the samples is shown to be dominated by fiber length, which is the most important element. For tensile, flexural, and impact strength, the fiber length contributes approximately 98.96%, 93.87%, and 96.44%, respectively. At 20% weight percentage and 30 mm fiber length, the tensile strength is 86.1 MPa, the flexural strength is 92 MPa, and the impact strength is 87 kg/m$^2$.

Keyword: Jute & Flax, Composite, Mechanical properties, Polymer composite, ANOVA

## 1. Introduction

Researchers are constantly drawn to natural fiber reinforced composite materials because of their ability to be tailored to different applications. Due to the need for certain qualities in a variety of industries, including automotive, residential, industrial, aerospace, structural, and environmental considerations, the replacement of traditional materials with alternative materials is currently much sought after. Such materials must always be optimized in order to be used economically and to produce superior results at the lowest possible cost. To optimize the process, a variety of experiment design techniques are available. The main elements that can impact a material's performance include its constituent proportion, reinforcement and particle sizes, processing techniques, chemical treatment, and fiber alignments within the matrix. Resin serves as a matrix in the polymer reinforcing composite material, and the literature uses both natural and synthetic fibers for reinforcement. Jute, flax, cotton, coir, sisal, hemp, and banana are the primary fibers used for reinforcement. Because of their sustainable qualities, these plant-based fibers have been effectively used for a variety of technical applications. Because waste fibers are used in appropriate utility applications, the costs associated with natural fibers are also lower. To prepare the composite, artificial fibers like glass fiber, nylon, and many others are also utilized. These synthetic fibers have the best mechanical performance, but their non-biodegradable behaviour makes them rather unreliable. Epoxy resin is a common matrix material because of its many uses and ability to connect with nearly any type of fiber. The performance of natural fiber composites is always impacted by a number of factors, including fiber weight fraction, fiber length, chemical treatment parameters, and manufacturing method. These factor’s interactions with one another always indicate a research gap, and for the same design of experiments, ANOVA approaches confirm their optimal role. The impact of one factor's fluctuation on another and their answers, which are based on statistical and mathematical relationships, assist the researchers in making appropriate use of them. Numerous experimental values for material performance are proposed in the literature, and if a mathematical relationship provides insight into how one aspect affects observation of another, it is always needed and creates a research need.

The goal of this study is to determine the optimal performance parameters for the composites tensile, flexural, and impact behaviour by optimizing the weight percent

of fiber in the matrix and the length of embedded fibers in the epoxy matrix. Future predictions of material behaviour under design criteria will benefit from the data produced by this work.

## 2. Literature review

There is a vast amount of literature on epoxy composites made of natural fibers and their mechanical characterization. The article demonstrates that the combination of jute and flax fiber is beneficial for enhancing fracture qualities, while flex fiber tends to improve mechanical properties [1]. Hybrid fibers are added to the matrix to acquire the desired qualities. According to reports in the literature, using hybrid fibers can enhance the performance of individual fibers [2]. According to the research, mixing different fibers can also be helpful for structural applications because it reduces the voids between the fibers and matrix [3]. Because very short fibers readily tear out under tensile loading and result in subpar performance, the factor of fiber length plays a crucial impact. For the best outcomes, the matrix must have an optimization fiber length [4]. The literature also reports that, depending on the type of composite, small fiber length to high fiber length exhibits parabolic features as it drops after a certain length [5]. It has been demonstrated that a full factorial design using ANOVA techniques can be used to study the characteristics of various fiber lengths [6,7]. The literature mostly uses the multi-factor effect, which can be accurate, to confirm the ideal characteristics of composites [8]. The length of fibers is a crucial component for mechanical performance, according to the full factorial design analysis and ANOVA method [9]. The matrix's fiber length promotes effective adhesion, which enhances the composite's bearing capacity [10]. Increased fiber length may result in a curl effect in the matrix, which lowers strength [11]. Additionally, a very short fiber causes shear failure, hence fiber optimization is required to prepare the composite [12]. In a similar vein, it has been found that an excessively long fiber reduces shear stress transfer, matrix dispersion, and performance [13, 14, 22]. The best results for the ideal fiber length in polymer composite modelling are reported [15,26]. For optimal performance, the weight fraction of fiber in the matrix should be at its ideal level. Performance decreased as the weight fraction decreased below the matrix's moisture limit, which decreased bonding capabilities [16, 21]. Morphology shows that a higher weight percentage in the matrix causes void development and decreased performance [17].The literature claims that a weight fraction of 25 to 35% produces

the best outcomes [18]. Impact strength is decreased by a higher weight percentage of fiber relative to matrix [19]. According to reports, jute and flax fibers have a basic affinity for epoxy resin, which influences the selection of fibers, particularly those that are hybrid [20].

## 3. Research Gap

The mechanical characterization of fiber-reinforced epoxy composites based on jute and flax has been extensively studied experimentally [24]. However, only a few studies have examined design parameters, such as the influence of fiber length and weight concentration in the matrix for hybrid (jute and flax) fibers. The optimization of flax and jute with an epoxy matrix for the composites tensile, flexural, and impact behaviour is investigated in this work. It will offer design insights into the effects of fiber weight concentration and length on hybrid polymer composites. The performance of the jute and flax-based composite is also optimized using the ANOVA technique in terms of the optimal fiber length and corresponding weight percentage, producing a useful database for future needs.

## 4. Materials & Methods

The epoxy matrix obtained from a local provider is reinforced with natural fiber flax and jute in different lengths according to the requirements. To remove contaminants, the fibers are cleaned with fresh water and dried for seven days. Alkali treatment was another chemical treatment applied to the fibers. In the lab, the jute and flax fibers are cut into the appropriate sizes of 10 mm, 15 mm, 20 mm, 25 mm, 30 mm, and 35 mm. The right amount of resin and hardeners are combined at room temperature, according to the material data sheet.

### 4.1 Composite preparation & Testing

Once the jute and flax fibers have been combined in equal amounts mix them with epoxy resin. 20, 30, and 40% are the weight percentages of fiber. It is moulded and placed under normal weight for two hours in press moulding to eliminate voids, air pockets, etc. after being mixed for five to ten minutes and thoroughly stirred. The samples are produced and tested in accordance with ASTM standards D638 type-I for tensile testing, ASTM D790 for flexural testing, and ASTM D256 for impact testing following a 24-hour curing period at room temperature. Tensile, flexural, and impact properties are tested on the three samples in each combination, and the results are tabulated for the average of the three samples in Table 1.

Table 1: Mechanical characteristics as determined through experimentation for various combinations

| Sample coding | Length (mm) | Fiber Content (wt%) | Tensile Strength (MPa) | Flexural Strength (MPa) | Impact Strength (kJ/m²) |
|---|---|---|---|---|---|
| JHE-1 | 10 | 20 | 71.6 | 78.9 | 73.2 |
| JHE-2 | 15 | | 77.9 | 84.7 | 78.9 |
| JHE-3 | 20 | | 82.5 | 88.5 | 83.6 |
| JHE-4 | 25 | | 85.2 | 91.1 | 85.8 |
| JHE-5 | 30 | | 86.1 | 92 | 87 |
| JHE-6 | 35 | | 84.8 | 90.9 | 85.8 |
| JHE-7 | 10 | 30 | 70.3 | 79.1 | 73.1 |
| JHE-8 | 15 | | 78.1 | 83.2 | 79.2 |
| JHE-9 | 20 | | 83.2 | 88.1 | 83.8 |
| JHE-10 | 25 | | 85.7 | 92.1 | 85.8 |
| JHE-11 | 30 | | 86.2 | 92.2 | 86.4 |
| JHE-12 | 35 | | 85.1 | 91.7 | 85.5 |
| JHE-13 | 10 | 40 | 70 | 77.9 | 72.7 |
| JHE-14 | 15 | | 76.1 | 78.1 | 74.1 |
| JHE-15 | 20 | | 81.6 | 89.7 | 84.1 |
| JHE-16 | 25 | | 85.1 | 90.3 | 85.3 |
| JHE-17 | 30 | | 86.5 | 91.5 | 86.8 |
| JHE-18 | 35 | | 84.3 | 89.7 | 86.2 |

## 5. Results and Optimisation

### 5.1 Full factorial design & ANOVA analysis

The implemented full factorial design for the given data set considers two factors: fiber length (factor A) and fiber weight fraction (factor B). Factor A considers six levels of each length between 10 and 35 mm, whereas factor B considers three levels between 20 and 40%. Consequently, different tensile, flexural, and impact values are evaluated for the jute flax embedded composite through 6x3=18 trials. The following model used for the two level factorial design:

$$R_{ijk}=\mu+A_i+B_j+(AB)_{ij}+\varepsilon_{ijk}$$

Where R stands for response, $\mu$ for overall mean, $A_i$ for fiber effect length, $B_j$ for fiber effect content, $(AB)_{ij}$ for interaction effect, and $\varepsilon_{ijk}$ for random error.

1. For the two way ANOVA calculation two null hypothesis (H0) is considered as

   H01=No effect of fiber length on samples

   H02= No effect of weight fraction on samples

   H03=No relation between fiber length and weight fraction
2. Calculation of Degree of freedom (DOF)

   $(DOF)_{\text{length of fiber}}$ =Total level-1=5

   $(DOF)_{\text{wt. fraction of fiber}}$ =Total level-1=2

   $(DOF)_{\text{interaction of fiber}}=(DOF)_{\text{length of fiber}} * (DOF)_{\text{wt. fraction of fiber}}=10$

   $(DOF)_{\text{Total}}$= No of runs-1=17
3. Calculations of variance
   a) Square Sum for all $(SS)_{\text{all}}$ = for all 18 runs from the total mean
   b) Square Sum for fiber length $(SS)_{\text{fiber length}}$ = for all 6 level of fiber length
   c) Square Sum for fiber weight fraction $(SS)_{\text{fiber wt. fraction}}$ = for all 3 levels
   d) Square Sum for residual $(SS)_{\text{resid}}$ = for all uncountable variance
4. Mean Square $(S_{\text{mean}})$= SS/DOF
5. $F_{\text{value}}=(S_{\text{mean}})/(S_{\text{error}})$
6. $P_{\text{value}}$ calculation , if $P_{\text{value}} < 0.05$, significant factor for the process .

### 5.2 Effect of length of fiber

Figure 1 compares the composite's tensile strength and fiber length for various weight fractions. Figure 2 compares the composite's flexural strength and fiber

length for various weight fractions. Figure 3 compares the composite's impact strength and fiber length for various weight fractions. Table 2 shows the effect of fiber length. According to the table, mechanical qualities rise as fiber length grows up to 30 mm and decrease as length increases beyond 30 mm. Because there is less connection between long fibers and the matrix, there is a modest decrease in mechanical characteristics, which increases the likelihood of void formation. Additionally, as the length of the fiber increases, curling of the fiber is replicated in the matrix, which reduces load transfer and, consequently, strength. Researchers have found that longer fibers have better mechanical qualities [23]. In this investigation, 30 mm fiber length was shown to be the ideal length for optimal mechanical qualities.

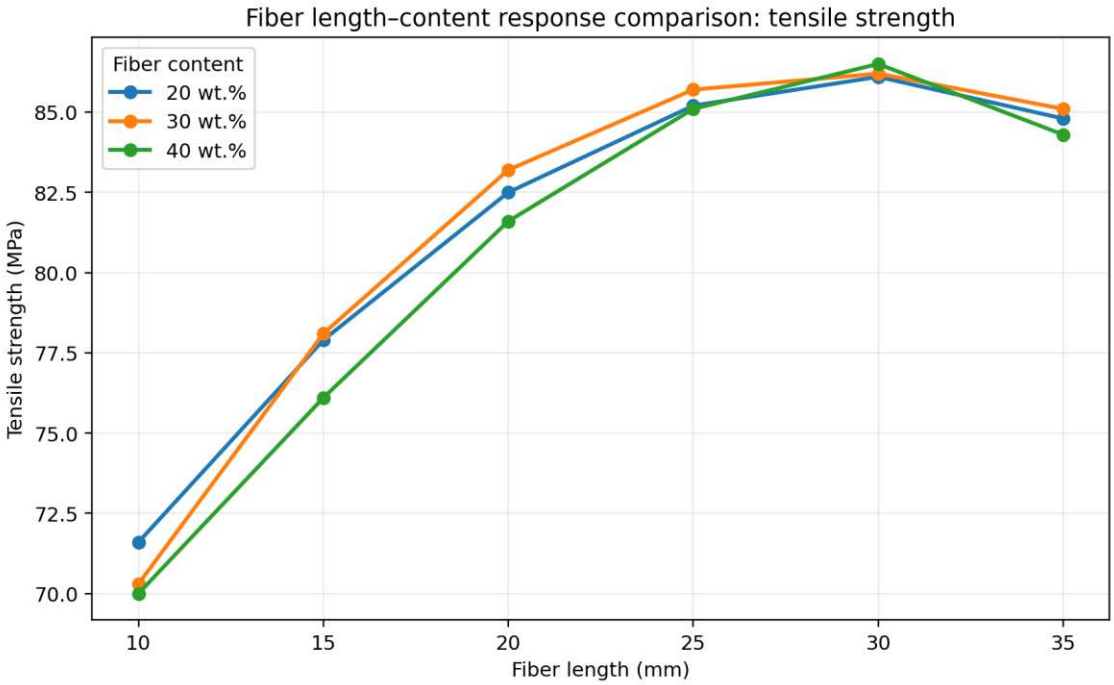



Figure 1: Variation of tensile strength with fiber length for different weight fraction

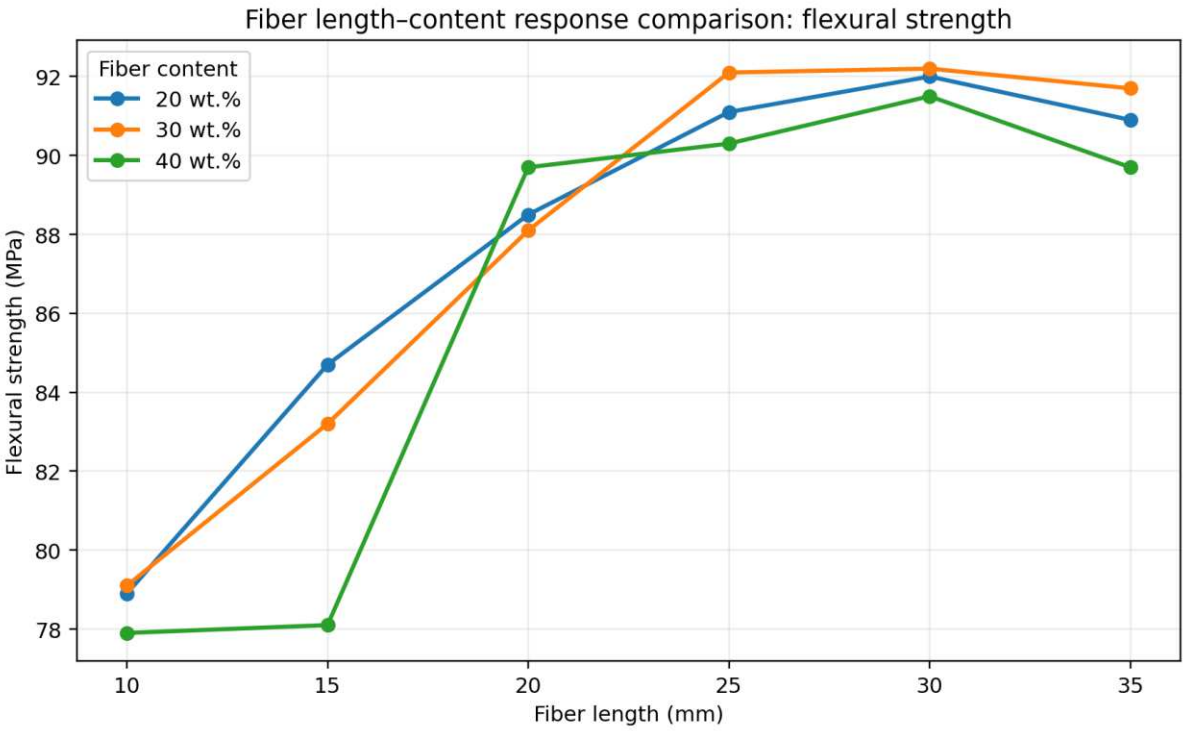



Figure 2: Variation of flexural strength with fiber length for different weight fraction

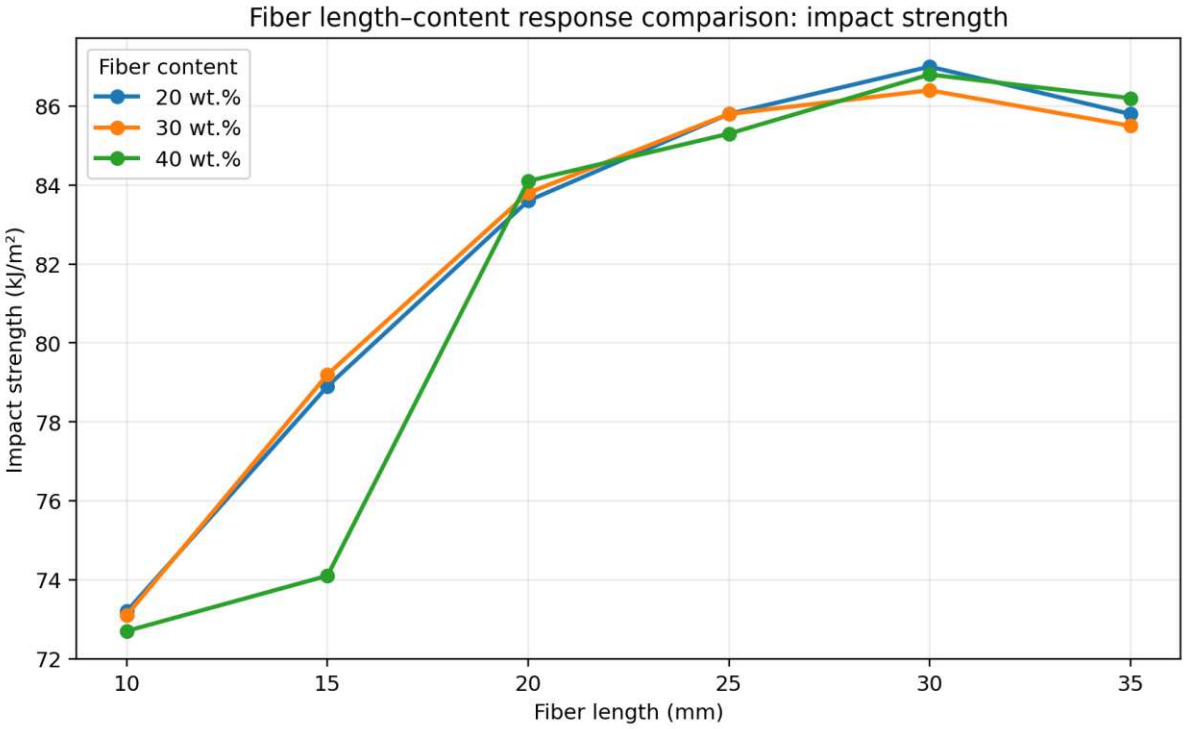



Figure 3: Variation of impact strength with fiber length for different weight fraction

Table 2: Mechanical characteristics variation with fiber length

| Length of fiber (mm) | Tensile Strength- Mean (MPa) | Flexural Strength- mean (MPa) | Impact Strength- mean (kJ/m²) |
|---|---|---|---|
| 10 | 70.63 | 78.63 | 73.00 |
| 15 | 77.37 | 82.00 | 77.40 |
| 20 | 82.43 | 88.77 | 83.83 |
| 25 | 85.33 | 91.17 | 85.63 |
| 30 | 86.27 | 91.90 | 86.73 |
| 35 | 84.73 | 90.77 | 85.83 |

**5.3 Effect of fiber weight**

The data in Table 3 show that the mechanical properties are somewhat impacted by changes in fiber length. The values are in the range of 20 to 30 weight percent, and when the fiber content rose to 40%, the values dropped because the fibers were not as moist by the matrix. It has been discovered that the fiber weight contributes as much as possible to improving the composite's mechanical behaviour [25]. The ideal weight percentage of fiber in the matrix for this investigation is 20%.

Table 3: Mechanical characteristics variation with fiber weight fraction

| Fiber content (wt.%) | Tensile mean (MPa) | Flexural mean (MPa) | Impact mean (kJ/m²) |
|---|---|---|---|
| 20 | 81.35 | 87.68 | 82.38 |
| 30 | 81.43 | 87.73 | 82.30 |
| 40 | 80.60 | 86.20 | 81.53 |

### 5.4 ANOVA table analysis

#### a) For tensile properties

According to the p value found in Table 4, which displays the ANOVA findings for tensile strength, length of fiber significantly affects tensile strength, contributing 98.96%. For the set of composite samples, fiber length predominates over fiber content. The effects of fiber weight and length on and impact properties are depicted in Figure 4.

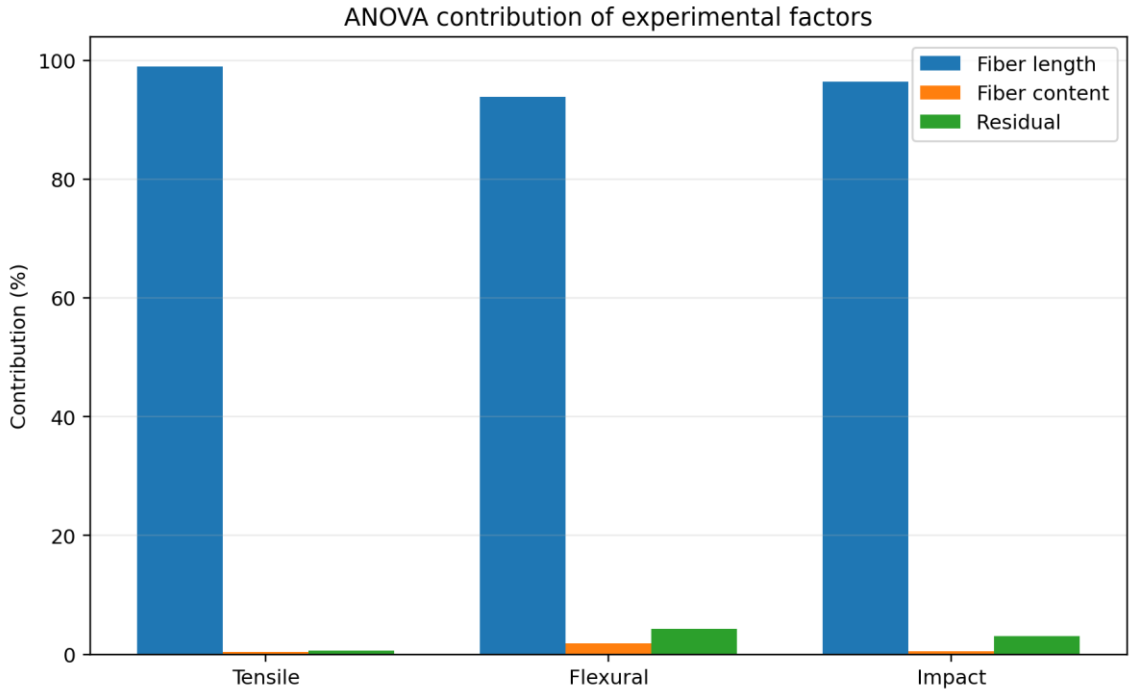



Figure 4: Significance of fiber length and fiber weight contribution

Table 4: ANOVA results for tensile strength

| Source | SS | df | MS | F-value | p-value | Contribution |
|---|---|---|---|---|---|---|
| Fiber length | 549.236 | 5 | 109.847 | 337.761 | 8.23e-11 | 98.96% |
| Fiber content | 2.528 | 2 | 1.264 | 3.886 | 0.0564 | 0.46% |
| Residual | 3.252 | 10 | 0.325 | — | — | 0.59% |
| Total | 555.016 | 17 | — | — | — | 100.00% |

**b) For flexural properties**

According to Table 5, ANOVA results for flexural strength, fiber length significantly affects flexural strength, contributing 93.87% of the total, according to the p value. For the set of composite samples, the fiber length predominates over the fiber content.

Table 5: ANOVA results for flexural strength

| Source | SS | df | MS | F-value | p-value | Contribution |
|---|---|---|---|---|---|---|
| Fiber length | 460.283 | 5 | 92.057 | 43.922 | 1.739e-06 | 93.87% |
| Fiber content | 9.108 | 2 | 4.554 | 2.173 | 0.1646 | 1.86% |
| Residual | 20.959 | 10 | 2.096 | — | — | 4.27% |
| Total | 490.349 | 17 | — | — | — | 100.00% |

**a) For impact properties**

According to Table 6, ANOVA results for impact strength, fiber length significantly affects impact strength, contributing 96.44% of the total. For the set of composite samples, fiber length predominates over fiber content.

Table 6: ANOVA results for impact strength

| Source | SS | df | MS | F-value | p-value | Contribution |
|---|---|---|---|---|---|---|
| Fiber length | 467.369 | 5 | 93.474 | 63.970 | 2.891e-07 | 96.44% |
| Fiber content | 2.634 | 2 | 1.317 | 0.901 | 0.4366 | 0.54% |
| Residual | 14.612 | 10 | 1.461 | — | — | 3.02% |
| Total | 484.616 | 17 | — | — | — | 100.00% |

According to ANOVA results for every combination of mechanical parameters, fiber content contributes up to 2% and fiber length contributes more than 93%. Therefore, it is evident from the preceding study that, for the provided set of data range, length of fiber has a substantial significant effect when compared to weight fraction. The sample JHE-5 exhibits the greatest values that can be obtained with a fiber length of 30 mm and a weight percentage of 20%. The attained values are 86.1 MPa for tensile strength, 92 MPa for flexural strength, and 87 kJ/$m^2$ for impact strength.

## 6. Conclusion and future scope

This study examines the effects of fiber length and fiber fraction on the tensile, flexural, and impact properties of an epoxy composite implanted with jute and flax. The fibers range in length from 10 to 35 mm and in weight percentage from 20 to 40%. To determine the ideal fiber length and weight fiber fraction for the composite's mechanical performance, a full factorial design with two-way ANOVA is used. In contrast to the fiber weight fraction, it is discovered that fiber length is a crucial determining factor. For tensile, flexural, and impact strength, the fiber length contributes approximately 98.96%, 93.87%, and 96.44%, respectively. It has been found that fibers longer than 30 mm contribute less because of the long fiber's waviness effect, which lowers load transmission, reduced wetting from matrix and void formation, and a modest decline in mechanical performance. For this investigation, the tensile strength is 86.1 MPa, the flexural strength is 92 MPa, and the impact strength is 87 kg/$m^2$ at 20% weight percentage and 30 mm fiber length.

By including fillers in the composite to examine the tensile, flexural, and impact behaviour, the work can be further expanded. The water aging impact can also be investigated in relation to appropriate applications by conducting a SEM analysis, which is followed by composite failure at various fiber lengths and weight fractions.

## Declarations

### Funding Declaration

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### Ethics, Consent to Participate, and Consent to Publish

Ethics, Consent to Participate, and Consent to Publish declarations: not applicable.

### Clinical Trial Registration

Not applicable. This study does not involve any clinical trials.

### Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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