Research Article

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Optimization of Mechanical Properties of *Cordia dichotoma*/Alumina Nanoparticle Reinforced Epoxy Nanocomposites Under Alkali Treatment Using ANN Techniques

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ABSTRACT

The growing interest in natural fiber- and nano-filler-reinforced composites is driven by their excellent strength-to-weight ratio, recyclability, and environmental sustainability. This study aims to optimize key parameters influencing the mechanical performance of hybrid nanocomposites reinforced with *Cordia dichotoma* (CD) fibers and nano alumina (nAl_2O_3). The composites were fabricated using the conventional hand lay-up technique by varying the content of CD fiber (wt%), fiber length (mm), nAl_2O_3 content (wt%), and CD fiber alkali treatment duration. ASTM standards assess mechanical properties. The Taguchi optimization method was employed to identify optimal process parameters. Maximum tensile strength was achieved with 10 wt% *Cordia dichotoma* fiber (10 mm), 4 wt% nAl_2O_3, and 12 hours of NaOH treatment. Optimal flexural strength was obtained under similar conditions, with an 8-hour treatment, while the best impact strength was observed with a 15 mm fiber length, 6 wt% nAl_2O_3, and 12-hour alkali treatment. Experimental results closely aligned with artificial neural network (ANN) predictions, with deviations within 3-4%, confirming the model's predictive accuracy. ANOVA analysis revealed that fiber content, filler content, and alkali treatment contributed 4%, 1%, and 0.1%, respectively, to the variation in properties, with fiber content yielding approximately 90% influence. The close agreement between experimental data and ANN forecasts highlights the potential of ANN-based models for predicting mechanical behavior and optimizing composite design. This approach provides valuable insights for enhancing reliability and predicting service life in various industrial applications.

Keywords: *Cordia dichotoma* fiber; Nano aluminia; Taguchi; ANN; Natural fibers; Mechanical properties.

1. INTRODUCTION

Researchers have been motivated to develop advanced and effective materials by leveraging natural resources in the current conventional industry due to enhanced ecological consciousness and sustainability. *Cordia dichotoma* fiber offers a synergistic combination of mechanical strength, interfacial compatibility, sustainability, and ease of processing, making it a superior alternative to many conventional natural fibers. *Cordia dichotoma* fiber material offers moderate tensile strength, good flexibility, and biodegradability, making it a sustainable alternative for polymer reinforcement. Its surface roughness after alkali treatment enhances fiber-matrix bonding, improving composite strength. Nano-Al_2O_3 is a high-hardness ceramic nanoparticle that significantly boosts the mechanical, thermal, and physical properties of composites. Its excellent dispersion enhances load transfer and reduces microvoids. Together, *Cordia dichotoma* fiber and nano-Al_2O_3 enable the development of lightweight, eco-friendly nanocomposites with improved structural performance. Natural fiber composites using Abutilon indicum, luffa cylindrica, and Prosopis juliflora were evaluated for mechanical and wear properties with NaOH, KOH, and silane treatments and fillers ($CaCO_3$, Al_2O_3, TiO_2). Silane treatment yielded the best performance. Multi-criteria decision-making (PSI method) was used for optimal combinations. FTIR and SEM confirmed improved fiber-matrix bonding. Polypropylene composites reinforced with 2–4 mm NaOH-treated flax fiber and nAl_2O_3 were fabricated by injection molding. The 10 wt% TFF with 7.5 wt% nAl_2O_3 showed optimal mechanical properties (yield strength

42.8 MPa, tensile 49.5 MPa, impact 18 J/mm², flexural 56 MPa). (Aruna *et al*. 2025). Hybrid composites were made from treated luffa and groundnut shell fibers, with Al_2O_3 fillers at 5–15 vol.%. Best mechanical properties were achieved at 30% fiber and 10% Al_2O_3. XRD confirmed fiber/filler properties. The composites were suitable for low and medium structural applications (Senthil *et al*. 2024). Composite laminates were developed using untreated and 4% alkali-treated Lagenaria siceraria fiber (LSF) with different fiber lengths (3, 5, 7, 9 mm) and contents (15–35 wt%) through compression molding. Mechanical properties improved with a fiber length of 7 mm and 30 wt% fiber content. SEM analysis confirmed better fiber-matrix adhesion for alkali-treated fibers (Natrayan *et al*. 2022). Agave americana fibers were used to reinforce cement mortar, analyzing the effects of fiber length and 2% NaOH pre-treatment. Fiber tenacity increased from 32 to 40 cN/tex and crystallinity from 13% to 44%. The best tensile strength (10.9 MPa) and flexural properties were achieved at 20-25 mm fiber length (El-Oudiani *et al*. 2024).

The impact of bamboo fibers (6, 12, 18 mm) at varying contents (0.5–2.0%) on ultra-high-performance concrete (UHPC) was studied. The 18 mm fibers at 1.0% increased compressive strength by 21.9%, and 1.5% content enhanced flexural strength by 40.5%. MIP and CT imaging revealed an influence on pore structure (Zhao *et al*. 2024). High-impact polyethylene composites strengthened with abaca fiber were analyzed. Maximum tensile strength (TS) (312% higher) and Young's modulus (545% higher) were achieved at 55 wt% fiber loading. Minor increases in hardness and density were observed (Rajakumar *et al*. 2022). Pre-chemical treatment of jute fibers was explored for PMMA polymer composites. The best tensile strength was observed with 4 mm benzoylated fibers, and flexural strength improved by 16.5% with 12 mm alkali-treated fibers. Impact strength also improved with longer-treated fibers (Salih, 2020). Natural fibers are increasingly being used in composite production due to environmental and health concerns associated with synthetic fibers. Testing nine different samples revealed that 15% coir fiber and 5% betel nut fiber yielded the highest impact (9.5 J/cm²) and tensile strength (4.4 MPa). Water absorption was lowest (0.07%) in the sample with 50 mm coir fiber and 15% betel nut fiber (Kabir *et al*. 2024) . Flax fiber-reinforced nanocomposites with nanographene fillers were fabricated to study mechanical and morphological properties under different fiber lengths (15–45 mm), fiber contents (10–20 wt%), and nanofiller loadings (2.5–7.5 wt%). The best mechanical properties were observed with 5 wt% graphene, resulting in 36.59 MPa tensile strength (TS), 40.25 MPa flexural strength (FS), and 31.68 kg/m² impact strength (IS). SEM images were used to analyze failure mechanisms (Natrayan *et al*. 2022).

Investigations on date palm fiber/epoxy composites explored mechanical properties and microstructural characteristics using SEM and EDS analysis. Fiber content, length, and width were varied. Short fibers enhanced tensile strength up to 72.5%, while thin fibers achieved 135.7% improvement at 25 wt%. Maximum impact energy (15.3 kJ/m²) was achieved with long fibers. Good fiber–matrix adhesion was confirmed through SEM imaging (AL-Oqla & Hayajneh, 2024). Washingtonia mesh waste (1% treated with 2.5% NaOH) improved bio-mortar strength. ANN models outperformed RSM, with less than 7% error in prediction (Khelifi *et al*. 2024). Hybrid composites with carbon and *Cordia dichotoma* fibers achieved TS of 367.76 MPa, FS of 646.41 MPa, and IS of 4.74 J. The mechanical strength was close to that of pure carbon fiber composites, demonstrating partial biodegradability. *Cordia dichotoma* (CD) fiber with granite powder filler reinforced composites showed TS of 88 MPa and FS of 125 MPa at 10% granite content. SEM analysis indicated strong filler and fiber bonding. CD-epoxy hybrid composites with granite powder exhibited a tensile strength of 92 MPa and flexural strength of 130 MPa at 10% granite content. Mechanical properties were enhanced compared to composites without filler. Water absorption was also reduced. Hybrid composites of CD and carbon fibers reached a tensile strength of 319.24 MPa, flexural strength of 253.03 MPa, and impact strength of 291.34 J/m. Hybridization significantly improved mechanical properties over pure natural fiber composites (Madhusudhan *et al*. 2025).

CD fiber (20 wt%) and granite powder hybrid composites showed improved mechanical properties. TS and FS increased significantly with 10–15% granite filler. SEM revealed strong bonding and uniform filler distribution. Granite powder improved mechanical behavior and reduced water absorption. Silane-treated *Cordia dichotoma* fibers showed a TS of 105.37 MPa and a modulus of 5.14 GPa. Mechanical properties improved significantly with 1% silane treatment. Excessive silane caused a degradation in strength. Silane treatment enhanced fiber–matrix bonding, making it suitable for high-performance composites(Diharjo *et al*. 2025). *Cordia dichotoma* fiber treated with 5% NaOH achieved optimal mechanical properties. Higher NaOH concentrations decreased tensile strength and elongation. SEM analysis showed rougher fiber surfaces aiding adhesion. The 5% NaOH treatment improved tensile behavior compared to untreated and heavily treated fibers(Hassan *et al*. 2024). *Cordia dichotoma* fiber composites achieved maximum tensile and flexural strengths at 20 wt% fiber content. Beyond 20%, mechanical properties dropped due to poor fiber dispersion. SEM revealed better bonding at optimal fiber loading. The developed composites are suitable for outdoor structural applications.

This study introduces a novel hybrid composite fabrication approach by combining *Cordia dichotoma* fibers with nAl_2O_3-enhanced epoxy resin using ultrasonic dispersion and hand layup technique. A key innovation lies in integrating Artificial Neural Network (ANN)-based optimization to model and predict the mechanical performance (tensile, flexural strength) by analyzing the interactions between fiber treatment, length, content, and nano-filler percentage. This reduces experimental effort while improving material design precision. The research demonstrates that ANN can effectively optimize process parameters for enhanced composite performance, offering a data-driven alternative to conventional trial-and-error methods. It also highlights the practical utility of machine learning in real-time material optimization and Engineering applications.

2. EXPERIMENTAL METHODOLOGY

2.1 Materials

The Cordia-Dichotoma plants utilized in this study were collected from the Anthiyur village in the Erode district of Tamil Nadu, India. Fibers were extracted from plant bark using the water retting technique. The first step involved soaking the fresh bark in water for four weeks. The bark was then meticulously pounded until it became fibers, which were subsequently dried in the sun. To further remove moisture, the fibers were placed in a hot air oven at 100 °C for 24 hours. *Cordia dichotoma* fiber mainly comprises cellulose (60%), hemicellulose (22%), and lignin (10%), along with minor amounts of waxes, pectin, and ash. These constituents influence the fiber's strength, moisture absorption, and bonding with the matrix. After processing, the fiber was cut into three different lengths: 5mm,10mm, and 15mm. Epoxy resin LY556, 1.14 g/cm^3 of density, and curing agent HY951, 0.90 g/cm^3 of density were employed as the matrix (Jayaraman *et al*. 2022). The nAl_2O_3 particles (20nm particle size and 3.5 g/cm^3) and epoxy resin were procured from Kovai Cheenu Enterprises in Coimbatore, Tamilnadu, India.

2.2 Alkaline Treatment

NaOH processing is a prevalent method of fiber treatment in nanocomposites (Amjad *et al*. 2021). The disruption of substituents within the surface architecture by enzymatic hydrolysis leads to enhanced wear resistance. Phenol, a compound that typically covers much of the exterior layer of the fiber, was slightly reduced in quantity. Desulfurization of the interior and the exposure of smaller crystallites were also facilitated. A carbonyl group is swiftly reduced by hypochlorous acid, resulting in the formation of an imidazole ring. The NaOH treatment process is shown in Fig. 1.

Fresh *Cordia dichotoma* plant fibers were thoroughly rinsed once more in preparation for acid pretreatment. The *Cordia dichotoma* fibers were carefully cut into sections that ranged from 5 to 15 mm. Based on research, 5% NaOH-treated *Cordia dichotoma* strands were immersed for varying durations of 4, 8, and 12 hours at ambient temperature (~27 °C) (Justin Abraham Baby *et al*., 2025). The modified fibers were then subjected to hydrogen peroxide for additional treatment until the PH reached 7, and oven-dried at 100 °C for 24 hours as measured using fluorochrome. Pure water was used to remove all residual solvents, ensuring the elimination of any remaining compounds. The ionic treatment process was then concluded.

2.3 Ultrasonication Process

Ultrasonication, also known as ultrasonic frequency processing, typically operates in the range of 25 to 45 kHz (Mohit *et al*. 2023). The frequency range is commonly used in industrial and laboratory ultrasonication procedures. The specific frequency chosen depends on a various factor, such as the desired outcomes and the type of material being treated. Higher frequencies, around 40kHz, are often used for finer and more delicate operations, while lower frequencies near 20kHz are more suitable for robust and large-scale applications.

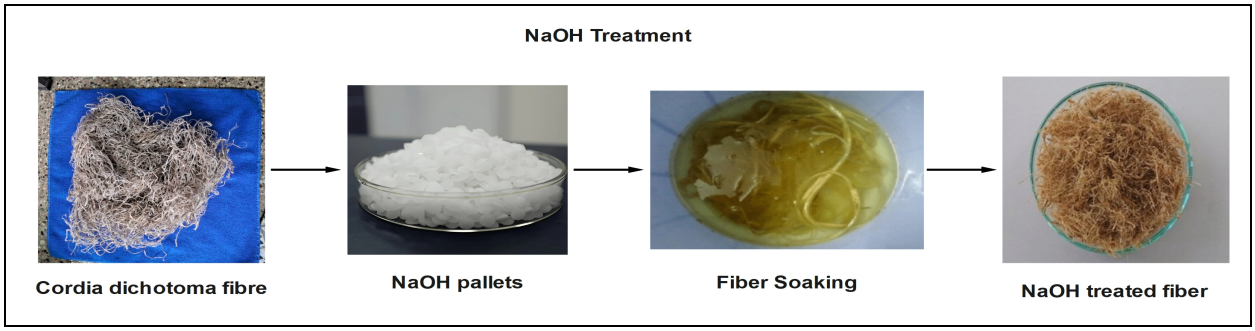


Fig. 1. Illustrations of the NaOH treatment

In this study, a solution was prepared by subjecting a variety of Al_2O_3 nanoparticles to sonication (Thangaraj *et al*. 2022). The sonication process began immediately after mixing and continued for 2 hours at a frequency of 20kHz. To minimize losses during the process, the water bath temperature was maintained at or below 25°C. Following this, 250ml of epoxy resin was heated at 60°C and mixed with the ultrasonicated solution to accelerate formaldehyde vaporization. To ensure proper was mixing, the solution stirred using a blade rod in a mechanical stirrer. The treated fibers were then immersed in the resulting slurry. To achieve a uniform and consistent mixture, the slurry was thoroughly mixed for four minutes.

2.4 Preparation of Composite

A precision machined aluminum mold measuring 300 × 300 × 3 mm^3 was employed. The nAl_2O_3 and chopped *Cordia dichotoma* fiber composite was prepared using the hand lay-up method. Thorough dispersion of the matrix was achieved within the mold. The mold was seated and cured under standard conditions after the fibers were completely soaked in matrix mixtures. The L27 orthogonal array was selected based on the Taguchi method. Considering three variables at three levels resulted in 27 different sample combinations. Desiccators were used to prevent moisture absorption from the hybrid samples.

Table 1 displays the factors and their respective levels. The composite was fabricated using the hand layup technique. Epoxy resin was thoroughly mixed with nAl_2O_3 particles at different weight percentages (2, 4, and 6 wt. %).

Table 1. Input process factors and its levels

Factors	Symbol Code	Levels		
		1	2	3
CD Fiber Content	W	5	10	15
CD Fiber Length (mm)	X	5	10	15
Nano Al_2O_3 (wt. %)	Y	2	4	6
Alkaline Treatment (hrs)	Z	4	8	12

For composite fabrication, the chopped CD fibers were carefully arranged in the mold. The materials were mixed with a catalyst, and the fibers were fully impermeated by submerging them in the resin (e.g., epoxy). The resin and hardener were mixed in a 10:1 ratio. Rollers were used to compress the layers, removing air bubbles and excess resin. After lamination, the composites were cured at room temperature for 24 hours. Mechanical and other property evaluations were carried out following fabrication. The composite preparation process is shown in Fig. 2.

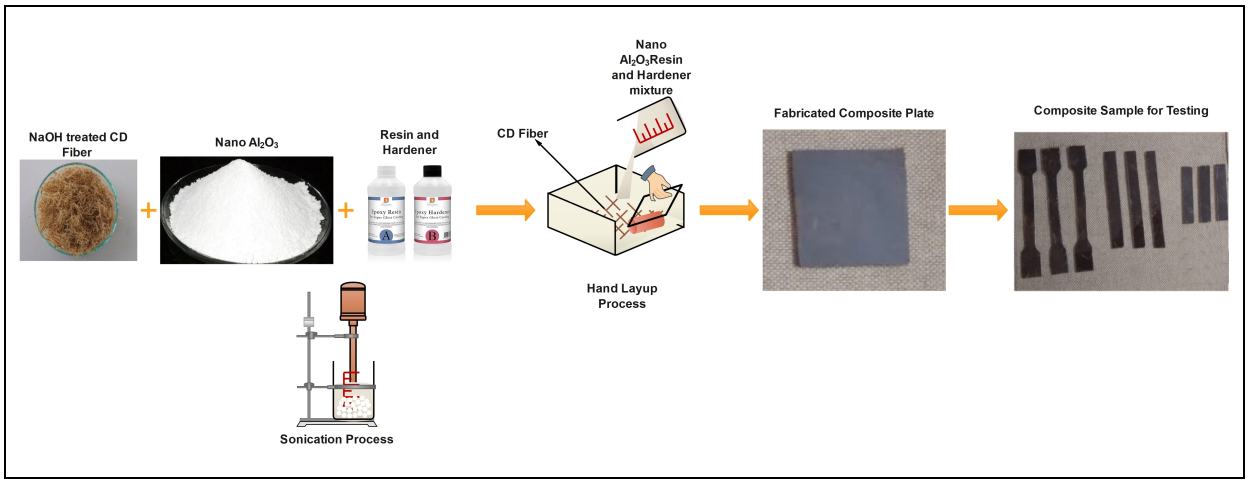


Fig. 2: The procedure of composite fabrication

2.5 Mechanical Properties of the Fabricated Composites

The tensile testing was carried out using a universal testing machine (INSTRON) that can handle loads up to 15,000 kg by ASTM D3039. The dimensions of the specimens used for testing were 250 x 25 x 3 mm^3. During the test, a fixed gauge length of 50 mm and a constant crosshead speed of 2 mm/min were maintained. Flexural properties were evaluated according to ASTM D790 standards using the same INSTRON universal testing machine. The specimen dimensions were 127 x 12.7 x 3 mm^3. A deformation test was performed at a crosshead speed of 2 mm/min to assess the flexural behavior. The impact strength was evaluated using an Izod impact tester in compliance with ASTM D256 standards. The specimen dimensions for the impact test were 63.5 x 12.7 x 3 mm^3. This test evaluated the material's resistance to sudden impact loading. To ensure data reliability and repeatability, each test was repeated three times, and the average values were recorded.

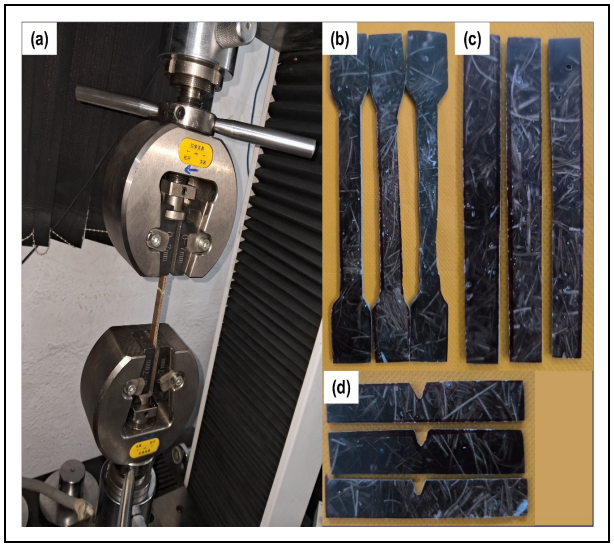


Fig. 3: (a) Universal testing machine, composites specimens of (b) Tensile (c) Flexural (d) Impact

2.6. Numerical Analysis

This analysis aims to optimize the performance while simultaneously reducing the cost. The Taguchi technique was developed by Genichi Taguchi and employed to evaluate the relevance of each control factor, optimize parameters to minimize variation, and assess performance metrics. After verifying the degree of freedom for the variables, an orthogonal array was selected accordingly. Genichi Taguchi emphasized three critical concepts. First, high product quality must be prioritized; second, the most effective way to achieve quality is to minimize deviations from the target. Finally, inefficiencies should be measured at the system level, and the degree to which a product deviates from the standard should be used to evaluate its value. The Taguchi method uses the signal-to-noise ratio (S/N) approach to measure the deviation of a subjective quality from its objective value (Sumesh and Kanthavel, 2020). The S/N ratio technique is also applied in optimal parameter analysis to convert the experimental variation into a numerical value for evaluating characteristics rather than relying on averages. The growing interest in cordia dichotomy/ Al_2O_3 / epoxy-based nanocomposites inspired this work due to their potential to combine sustainability with mechanical strength. The increasing demand for materials that are both environmentally friendly and high-performing motivates this research. However, there remains a significant gap in the area of manufacturing variable optimization, particularly when the composite undergoes alkaline treatment. This takes the development of efficient methods to enhance mechanical performance. NaOH-treated castor oil fiber composites improved tensile (28%), flexural (39%), and impact strength (115%). The ANN-multi hidden layer model gave better property predictions than the single hidden layer (Egala and Gangi, 2022).

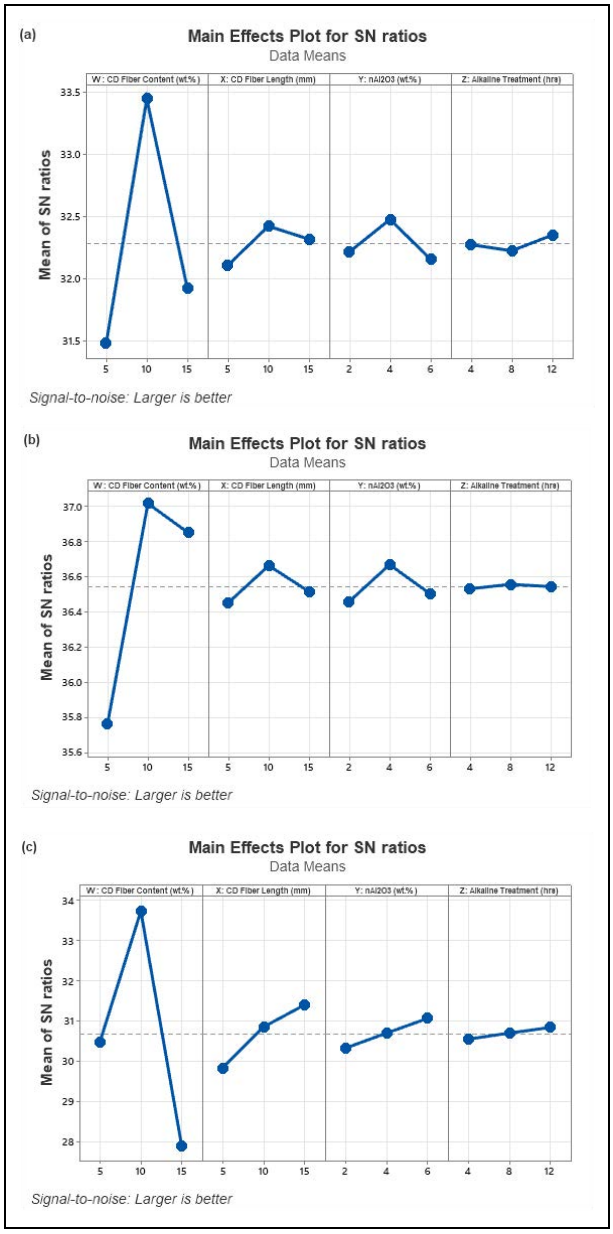


Fig. 4: Main effect plot for (a) TS (b) FS (c) IS of composites

3. RESULT AND DISCUSSION

The usage of ANN in the methodology is crucial for accurately modeling and optimizing the nonlinear and complex relationships between multiple input parameters such as A, B, C, and D concentrations and the resulting mechanical properties of the nanocomposites. ANN enables the prediction of performance outcomes like tensile and flexural strength with high precision, reducing the reliance on exhaustive experimental trials. By training the ANN model using experimental data and validating it through performance metrics like Mean Squared Error (MSE) and R-values, the methodology ensures efficient parameter optimization. This approach not only enhances the reliability and reproducibility of the composite fabrication process but also streamlines

material design, making it more cost-effective and time-efficient compared to traditional methods.

The results from a factorial design using the Taguchi framework (L27) were analyzed. The S/N ratio determined mechanical properties by the "Larger the Better" principle. The optimal hybridized composite factors are those with the maximum S/N ratio. The mechanical properties' L27 orthogonal array (OA) and corresponding S/N ratios are displayed in Table 2. For each of the 27 test conditions, the average response rate was calculated. To evaluate the influence and identify the best-case condition for the selected parameters, ANOVA and the S/N ratio were used (Boumaaza *et al*. 2021). The S/N ratio excelled in reducing the data to its most salient features. The "Larger the Better" principle was applied in this experiment. The S/N ratio was calculated using the following equation (1).

$$\frac{S}{N}\text{Ratio} = -10\log 10\frac{1}{e}\sum_{a=i}^{e}\frac{1}{X_{ab}^2} \quad \ldots (1)$$

The larger is preferable on the SN ratio for material qualities, as shown in Fig. 4 (a) to (c).

10% *Cordia dichotoma* fiber, 10mm in length, 4% nAl_2O_3 filler, and 12 hours of NaOH processing were the ideal conditions for tensile strength. Similarly, Polypropylene composites reinforced with 2–4 mm NaOH-treated flax fiber and nAl_2O_3 were fabricated by injection molding. The 10 wt% TFF with 7.5 wt% nAl_2O_3 showed optimal mechanical properties (yield strength 42.8 MPa, tensile 49.5 MPa, impact 18 J/mm², flexural 56 MPa) (Aruna *et al.* 2025).

The 10% *Cordia dichotoma* fiber, 10mm in length, 4% nano Al_2O_3 filler, and 8 hours of NaOH processing were the ideal conditions for flexural strength. The 10% *Cordia dichotoma* fiber, 15mm in length, 6% nAl_2O_3 filler, and 12 hours of NaOH processing were the ideal conditions for impact strength. The mechanical properties were directly proportional to the S/N response. The control factor significantly influenced the S/N proportion response's tensile, flexural, and impact properties, as shown in Table 3.

Table 2. Experimental design of input factors and its results

Run	W (wt%)	X(mm)	Y(wt%)	Z(wt%)	Tensile	S/N Ratio	Flexural	S/N Ratio	Impact	S/N Ratio
1	5	5	2	4	37.09	31.38	60.30	35.61	28.14	28.99
2	5	5	4	8	37.53	31.49	63.14	36.01	29.30	29.34
3	5	5	6	12	36.83	31.32	61.08	35.72	31.21	29.89
4	5	10	2	8	37.75	31.54	60.45	35.63	31.21	30.12
5	5	10	4	12	38.87	31.79	64.23	36.16	32.37	30.20
6	5	10	6	4	37.75	31.54	61.39	35.76	35.38	30.98
7	5	15	2	12	36.92	31.35	59.52	35.49	34.64	30.79
8	5	15	4	4	37.42	31.46	62.05	35.85	38.81	31.78
9	5	15	6	8	37.31	31.44	60.57	35.65	40.72	32.20
10	10	5	2	4	45.49	33.16	69.07	36.79	46.42	33.33
11	10	5	4	8	46.08	33.27	70.23	36.93	48.75	33.76
12	10	5	6	12	44.72	33.01	68.04	36.66	48.75	33.65
13	10	10	2	8	48.81	33.77	72.14	37.16	49.49	33.89
14	10	10	4	12	49.91	33.96	72.76	37.24	52.56	34.41
15	10	10	6	4	48.92	33.79	72.29	37.18	47.59	33.55
16	10	15	2	12	46.49	33.35	71.36	37.07	48.32	33.68
17	10	15	4	4	47.19	33.48	71.82	37.13	47.22	33.48
18	10	15	6	8	45.60	33.18	70.70	36.99	48.75	33.76
19	15	5	2	4	38.42	31.69	68.51	36.72	18.63	25.40
20	15	5	4	8	39.19	31.86	69.76	36.87	20.53	26.25
21	15	5	6	12	38.76	31.77	68.98	36.77	24.70	27.90
22	15	10	2	8	37.75	31.54	69.92	36.89	24.70	27.86
23	15	10	4	12	41.84	32.43	70.89	37.01	25.50	28.14
24	15	10	6	4	37.20	31.41	70.17	36.92	26.60	28.52
25	15	15	2	12	40.52	32.15	68.92	36.77	27.77	28.87
26	15	15	4	4	42.28	32.52	69.28	36.81	27.77	28.92
27	15	15	6	8	39.41	31.91	69.77	36.87	28.57	29.12

Table 3. Response table for Tensile, Flexural and Impact Strength (S/N ratio)

Level	W: CD Fiber Content (wt.%)	X: CD Fiber Length (mm)	Y: nAl_2O_3 (wt.%)	Z: Alkaline Treatment (hrs)
Tensile Strength (MPa)				
1	31.48	32.11	32.21	32.27
2	33.44	32.42	32.47	32.22
3	31.92	32.32	32.15	32.35
Delta	1.96	0.31	0.32	0.13
Rank	1	3	2	4
Flexural Strength (MPa)				
1	35.76	36.45	36.46	36.53
2	37.02	36.66	36.67	36.56
3	36.85	36.51	36.50	36.54
Delta	1.25	0.21	0.21	0.03
Rank	1	2	3	4
Impact Strength (KJ)				
1	30.48	29.83	30.33	30.55
2	33.73	30.85	30.70	30.70
3	27.89	31.40	31.06	30.84
Delta	5.84	1.56	0.74	0.29
Rank	1	2	3	4

Table 4. Results on ANOVA for Tensile, Flexural and Impact strength

Source	DF	Seq SS	Contribution	Adj MS	F-Value	P-Value
Tensile Strength (MPa)						
W: CD Fiber Content (wt.%)	2	454.544	89.48%	227.272	147.70	0.000
X: CD Fiber Length (mm)	2	12.234	2.41%	6.117	3.98	0.037
Y: nAl_2O_3 (wt.%)	2	11.876	2.34%	5.938	3.86	0.040
Z: Alkaline Treatment (hrs)	2	1.645	0.32%	0.822	0.53	0.595
Error	18	27.697	5.45%	1.539		
Total	26	507.996	100.00%			
Flexural Strength (MPa)						
W: CD Fiber Content (wt.%)	2	477.440	91.89%	238.720	259.24	0.000
X: CD Fiber Length (mm)	2	13.250	2.55%	6.625	7.19	0.005
Y: nAl_2O_3 (wt.%)	2	12.158	2.34%	6.079	6.60	0.007
Z: Alkaline Treatment (hrs)	2	0.179	0.03%	0.090	0.10	0.908
Error	18	16.575	3.19%	0.921		
Total	26	519.603	100.00%			
Impact Strength (KJ)						
W: CD Fiber Content (wt.%)	2	2559.84	90.88%	1279.92	227.76	0.000
X: CD Fiber Length (mm)	2	124.91	4.43%	62.46	11.11	0.001
Y: nAl_2O_3 (wt.%)	2	26.42	0.94%	13.21	2.35	0.124
Z: Alkaline Treatment (hrs)	2	4.38	0.16%	2.19	0.39	0.683
Error	18	101.15	3.59%	5.62		
Total	26	2816.70	100.00%			

3.1 Analysis of Variance

The importance of interrupted processing was assessed using ANOVA. Table 4 shows the influence percentages for each trial component. The F-test indicates that control parameters affect tensile, flexural, and impact properties. Figure 4 shows the percentage contribution of each factor. The percentage of trial variance attributed to each significant factor is known as the contribution percentage.

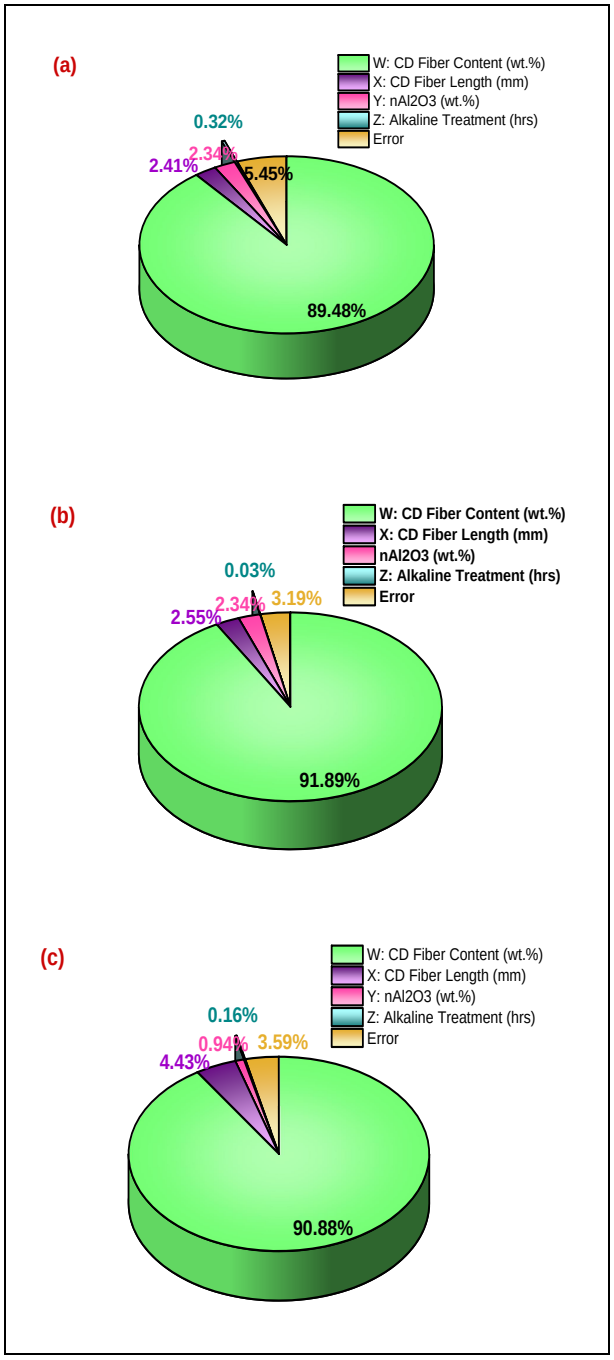


Fig. 5: Evaluation of (a) TS (b) FS (c) IS results

Table 4 indicates that maximum tensile strength is determined by the controllable factors' F-values and their contribution percentages. The probability of repeated significance is denoted by the P-value. Factor W contributes 89.48%, followed by factor X (2.41%), factor Y (2.34%), and factor Z (0.32%). Consequently, the primary contributor to achieving high mechanical performance is chemical treatment. Fiber content as shown in Table 4, also plays a crucial role in determining flexural strength. It contributed 91.89% and 2.55% through factors W and X, respectively, with Y and Z following in third and fourth positions with 2.34% and 0.03%. For impact strength, factor W contributes 90.88%, followed by factor X (4.43%), Y (0.94%), and Z (0.16%). According to the data, *Cordia dichotoma* fiber content and fiber length (mm) are the most critical components. This is consistent with earlier studies, such as one involving vinyl ester composites reinforced with Phoenix sp. fibers treated with sodium bicarbonate solution. In that study, the composites exhibited enhanced tensile (61.35 MPa), flexural (152.63 MPa), and impact (24.67 kJ/m²) properties when 20 wt% of 15 mm fibers treated for 120 hours were used (Rajeshkumar, 2025).

Fig. 5 shows the tensile strength of the CD-based hybrid nanocomposite with varying weight fractions of Al_2O_3 nanofillers. The strain percentage decreases as Al_2O_3 concentration increases, indicating higher brittleness in the composite. This increased brittleness restricts molecular chain mobility, reducing elongation. Importantly, all specimens demonstrated pseudoplastic behavior during testing, with no abrupt failure before reaching their maximum stress levels.

Fig. 5 shows the flexural strength (FS) influence of various fibers in the epoxy/CD fiber hybridized nanocomposites. As the nanofiller concentration increases, the strain percentage decreases from 2% to 6%. This indicates a reduction in the composite's ductility. The incorporation of stiffer nanofillers diminishes the ductility of the matrix and polymer chains by restricting their mobility and deformability. However, the bending properties are improved because the crystalline regions within the matrix are prevented from deforming. Flexural strength values generally follow a similar trend, although they tend to be more variable among formulations compared to tensile strength values. This variability is an important factor to consider. The above observations are further supported by the SEM images (Fig. 6 (a), (b), and (c)). Compared to untreated *Cordia dichotoma* fiber composites, those treated with NaOH exhibited improved tensile and flexural properties. SEM analysis confirmed the enhanced fiber-matrix adhesion. The improvement in mechanical properties is directly attributed to the NaOH treatment. However, higher fiber loading slightly reduced strength due to poor dispersion.

The microstructural analysis (Figure 6) provides clear evidence correlating the variations in mechanical performance with processing parameters such as fiber length, filler content, and alkali treatment duration. In Figure 6(a), the presence of voids and fiber pull-out indicates weak fiber–matrix bonding, commonly observed in composites with shorter fiber lengths (5 mm) and insufficient filler dispersion. Figure 6(b) shows improved fiber distribution and reduced void content, attributed to the optimal fiber length (10 mm) and 4 wt% nano-Al_2O_3, which enhances stress transfer and interfacial bonding. In contrast, Figure 6(c) reveals agglomeration of fillers, likely due to excessive nano-

Al_2O_3 content (6 wt%) or prolonged treatment, leading to stress concentration zones that deteriorate mechanical integrity. Thus, the SEM images validate that optimal processing—10 mm fiber length, 4 wt% filler, and 8–12 h treatment—promotes better fiber-matrix interaction and mechanical performance, while deviations from these conditions introduce interfacial defects.

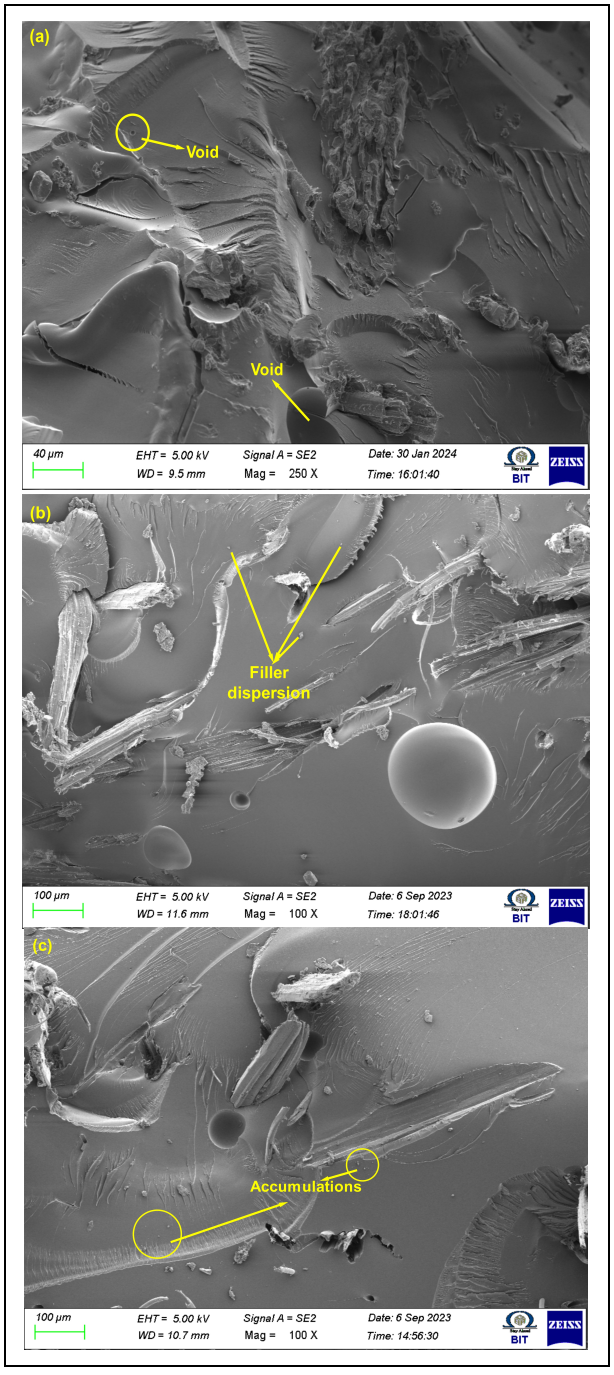


Fig. 6: Scanning electron microscopic images of tensile testing of CD fiber + nano Al_2O_3 based composites after (a) 2 wt. % (b) 4 wt. % and (c) 6 wt. % of Al_2O_3

Fig. 7 shows the SEM image demonstrates a well-developed surface topology and microstructural roughness, which are indicative of strong fiber–matrix interaction. Such morphology contributes to efficient stress transfer and mechanical interlocking, leading to improved composite performance. The absence of significant voids or fiber pull-out further supports the effectiveness of surface treatment and optimal processing conditions. The accompanying EDX spectrum identifies carbon (C) and oxygen (O) as the dominant elements, which is consistent with the organic composition of *Cordia dichotoma* fibers and the epoxy matrix. A minor peak for calcium (Ca) is also observed, likely originating from natural mineral traces within the fiber structure. The elemental composition validates the compatibility of natural fiber reinforcement within the polymer matrix, affirming its potential for use in sustainable composite applications.

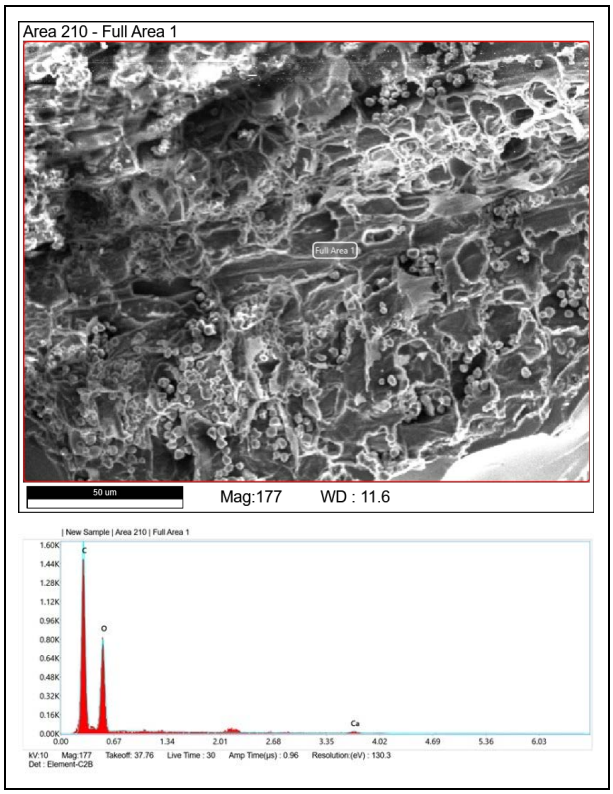


Fig. 7 SEM micrograph and EDX spectrum of the optimized *Cordia dichotoma*/nano-Al_2O_3/epoxy composite (10 wt% fiber, 4 wt% filler, 12 h treatment)

3.2 Regression Equation

The model was constructed using three levels and four input conditions that were examined in this investigation. The tensile, flexural, and impact formulations were generated by minimizing the total squared error using the standard regression model. The resulting regression equations are as follows(Rajkumar *et al*., 2025):

$$\text{Tensile Strength (MPa)} = (41.335 - 3.838\,W1 + 5.688\,W2 - 1.850\,W3 - 0.880\,X1 + 0.755\,X2 + 0.124\,X3 -$$

$$0.308\ Y1 + 0.921\ Y2 - 0.613\ Y3 - 0.029\ Z1 - 0.287\ Z2 + 0.316\ Z3) \quad \ldots (2)$$

$$\text{Flexural Strength (MPa)} = (67.309 - 5.895\ W1 + 3.626\ W2 + 2.269\ W3 - 0.740\ X1 + 0.940\ X2 - 0.200\ X3 - 0.622\ Y1 + 0.932\ Y2 - 0.309\ Y3 - 0.100\ Z1 + 0.100\ Z2 - 0.000\ Z3) \quad \ldots (3)$$

$$\text{Impact Strength (KJ)} = (35.743 - 2.114\ W1 + 12.841\ W2 - 10.727\ W3 - 2.856\ X1 + 0.520\ X2 + 2.336\ X3 - 1.278\ Y1 + 0.146\ Y2 + 1.132\ Y3 - 0.547\ Z1 + 0.136\ Z2 + 0.411\ Z3) \quad \ldots (4)$$

Factors with positive coefficients in the regression equations influence mechanical attributes. Conversely, negative coefficients indicate a lesser contribution to material strength. The optimal results for tensile and impact strength were achieved with 10% *Cordia dichotoma* fiber (10 mm length), 4% nAl_2O_3 filler, and 12 hours of NaOH treatment. For flexural strength, the optimal condition was similar, except that NaOH treatment was for 8 hours.

Among the tested fiber contents, 10% *Cordia dichotoma* fiber exhibited superior mechanical properties compared to 5% and 15%. The inadequate performance of the 5% hybrid content is attributed to poor stress transfer within the fiber arrangement across the matrix. This resulted in hexagonal zones with minimal interfacial bonding. Consequently, the composites lacked structural integrity and could not effectively withstand external stresses. The implication is that 5% fiber content may not provide adequate reinforcement. As the fiber content increased from 5% to 15%, both the nanocomposite strength and Young's modulus improved primarily due to stronger interfacial fiber bonds. These bonds enhance crack resistance by bridging gaps and evenly distributing stress. However, with 15% fiber content, structural integrity declined. This is likely due to an insufficient matrix-to-fiber ratio, which caused poor wettability and improper bonding among fibers.

The poor test results of the nanocomposites at a fiber length of 5 mm were caused by apertures or thread misalignment. Increasing the fiber length to 10 mm enhanced the mechanical properties. The molecular structure is predicted to possess superior strength compared to its load transfer capacity, which otherwise weakens the composite. The elastic modulus of the strands consistently decreases, regardless of the amount of threading. This may be due to minor defects during the fabrication process, resulting in insufficient adhesive bonding between the polymer and the fiber. The laminated structure undergoes fractures due to matrix disintegration, column collapse, filament spalling, and fiber peeling. Ductile behavior is observed when the applied load exceeds the strain threshold at which strand tearing becomes significant in nanocomposites. As a result, the overall surface strength of the fibers reduces. Fracture occurs when stress exceeds the strand's capacity to withstand it.

Compared to the improvements at 2 and 6 wt.% nanofiller, the mechanical properties were most favorable at 4 wt.% nAl_2O_3 filler. This enhancement was attributed to better stress generation and transfer. However, higher levels of compacted Al_2O_3 in the composite altered the bonding dynamics, leading to more frequent and larger interfacial voids. As a result, combinations of adhesive and *Cordia dichotoma* fiber at five wt.% Al_2O_3 showed strong interfacial bridging. Nevertheless, the tensile modulus declined with 2 and 6 wt.% titanium dioxide addition.

The results of these experiments indicate that the strength properties were enhanced by a limited soaking duration of 4 hours and a 4% alkaline concentration. The reduction in performance beyond this is due to inadequate fiber absorption during sodium hydroxide treatment exceeding 4 hours. Enhanced mechanical properties were obtained through the application of a 5% alkaline medium concentration throughout 4 to 12 hours. After treatment, the fibers demonstrated remarkable durability. The alkali treatment removed hemicellulose, waxes, and surface impurities, increasing surface roughness and exposing more hydroxyl groups. This enhanced fiber–matrix interfacial adhesion, leading to improved mechanical properties. SEM images confirmed better bonding, and composites with 12-hour treated fibers showed ~45% higher tensile strength compared to other. However, beyond this duration, the treatment showed reduced effectiveness for most of the material processed. The crystalline structure of the fibers was influenced by the fiber preparation process, which causes a reduction in fiber flexibility during polymerization when the treatment exceeds 8 hours. The fibers become rigid and stiff due to crystallization growth, leading to increased resistance but reduced flexibility. These fibers were unable to effectively transmit stress at the interface, resulting in a decline in material properties, and they experienced increased shrinkage under pressure due to their brittleness.

3.3 Optimization Using Artificial Neural Network

In recent years, Artificial Neural Networks (ANNs) have emerged as powerful tools for modeling complex, nonlinear relationships in materials engineering. Unlike traditional statistical methods, ANNs can learn from experimental data and accurately predict performance outcomes based on multiple interdependent variables. In the present study, ANN was employed to predict the mechanical behavior—tensile, flexural, and impact strengths—of *Cordia dichotoma*/nano-Al_2O_3/epoxy hybrid composites. The

model utilized four critical input parameters: fiber content, fiber length, nano-Al_2O_3 filler content, and alkali treatment duration. Given the complexity of the interactions between these factors, ANN offers a reliable and efficient approach for capturing the material response trends. This data-driven method not only enhances prediction accuracy but also reduces the need for extensive experimental trials, thereby optimizing the composite design process(Arunachalam *et al*. 2025).

Quadratic regression techniques are outperformed by artificial neural network (ANN) methodologies in multivariate optimization. The ANN structure used in the present research is illustrated in Fig. 8.

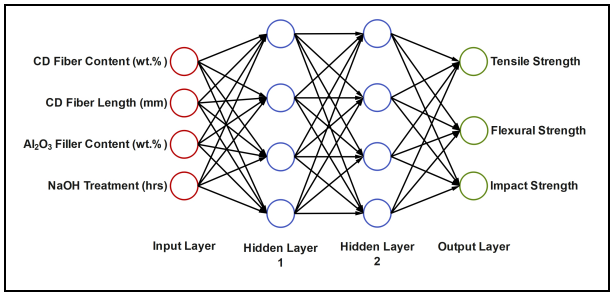


Fig. 8: An artificial neural network (ANN) structure is implemented in the present investigation

Training, validation, and testing were performed as sub-divisions to evaluate the study's empirical outcomes of the study. 31% of the data was used for training, 15% for validation, and 15% for testing. Parametric weighting was applied. The procedure continued until the expected and actual debonding values were as close as possible, with a small mean square error.

The minimum mean square error recorded was 0.0001 at 20 timesteps, which is very close to the acceptable threshold of 0.001. The Levenberg-Marquardt algorithm was applied within the hidden layers, utilizing 15 neurons, as shown in Fig. 8. The optimal configuration for the ANN was 4:10:3. The tensile strength (TS), flexural strength (FS), and impact strength (IS) of the fabricated composites were predicted by the ANN, as illustrated in Fig. 9.

The reliability of the constructed neural model was evaluated by comparing the correlation coefficients derived from the actual and predicted outcomes. The R^2 values of the ANN model during the training, validation, and testing phases were 0.92211, 0.98497, and 0.9749, respectively, as shown in Fig. 8. The empirical results and ANN predictions were in satisfactory agreement, as indicated by the R^2 results.

The performance evaluation of experimental and predicted ranges is shown in Fig. 10. Consequently, the developed ANN model accurately predicts the mechanical performance of composites with a higher degree of flexibility and can establish relationships based on non-linear characteristics. Using Eq. (5), the ANN system calculated the expected error percentage. Table 5 presents a comparison between experimental results and ANN predictions. Table 6 displays the best mechanical property responses obtained from experimental, regression, and ANN data. Figure 11 shows the outcomes of the ANN analysis of the *Cordia dichotoma* (CD) composites' performance.

$$Percentage\ of\ Predicted\ Error = \frac{Experimental\ Data - ANN\ Data}{Experimental\ Data} \times 100 \quad \ldots (5)$$

All three types of analysis, experimental, predictive, and ANN, are shown in Figure 12. Analysis of experimental data revealed that both the Taguchi and ANN methods produced reliable outcomes. However, the ANN provided more accurate predictions, surpassing the results of the Taguchi methods with a 95% confidence level. The optimal model facilitates the integration of process variables and supports the successful development of target components. This approach is highly suitable for the natural fiber-based automotive sector, effectively reducing both time and cost. The optimal mechanical property results are presented in Table 6, based on experimental data, regression analysis, and ANN predictions.

The experimental results showed a strong correlation with predicted values, as evidenced by R values consistently above 0.94, confirming the reliability of the ANN models. Similarly, pineapple fiber and potato filler in polyethylene composites achieved the optimized mechanical properties (tensile strength of 22.3 MPa, flexural strength of 23.8 MPa, and impact strength of 18.3 kJ/m²). The ANN model confirmed high prediction accuracy (R = 0.9972) (Keerthiveettil *et al*. 2024). The addition of 5 wt.% nAl_2O_3 significantly improved the mechanical performance of the materials by preventing cavities and reinforcing the component interfaces. However, increased infill content led to stress concentrations and substrate defects, reducing the mechanical properties of the matrix. The experimental results support the established principle that five wt.% Al_2O_3 yields optimal composite strength. Alkaline treatment was the most significant factor in improving mechanical properties, leading to approximately a 45% increase in fiber-matrix bonding. The NaOH treatment enhanced mechanical strength by removing surface impurities and improving stress transfer between the epoxy and fiber. This results in improved tensile and flexural strength.

Optimization of NaOH treatment in natural fibers results in enhanced mechanical performance and interfacial bonding. Approximately 25% of the mechanical enhancement is due to fiber content. However, optimization becomes essential when fiber

loading exceeds critical levels, as excessive fiber leads to accumulation and weak stress transfer zones. The fiber aspect ratio had a major influence on mechanical behavior, contributing over 20% to overall improvement. It also improved load distribution and fracture resistance. Selecting the right fiber length is crucial for matrix reinforcement. Short fibers may lack strength, while longer fibers can be difficult to disperse and align. Although nAl_2O_3 particles enhanced properties by reducing microcavities and increasing matrix toughness, the overall increase in strength was moderate, approximately 5-6%.

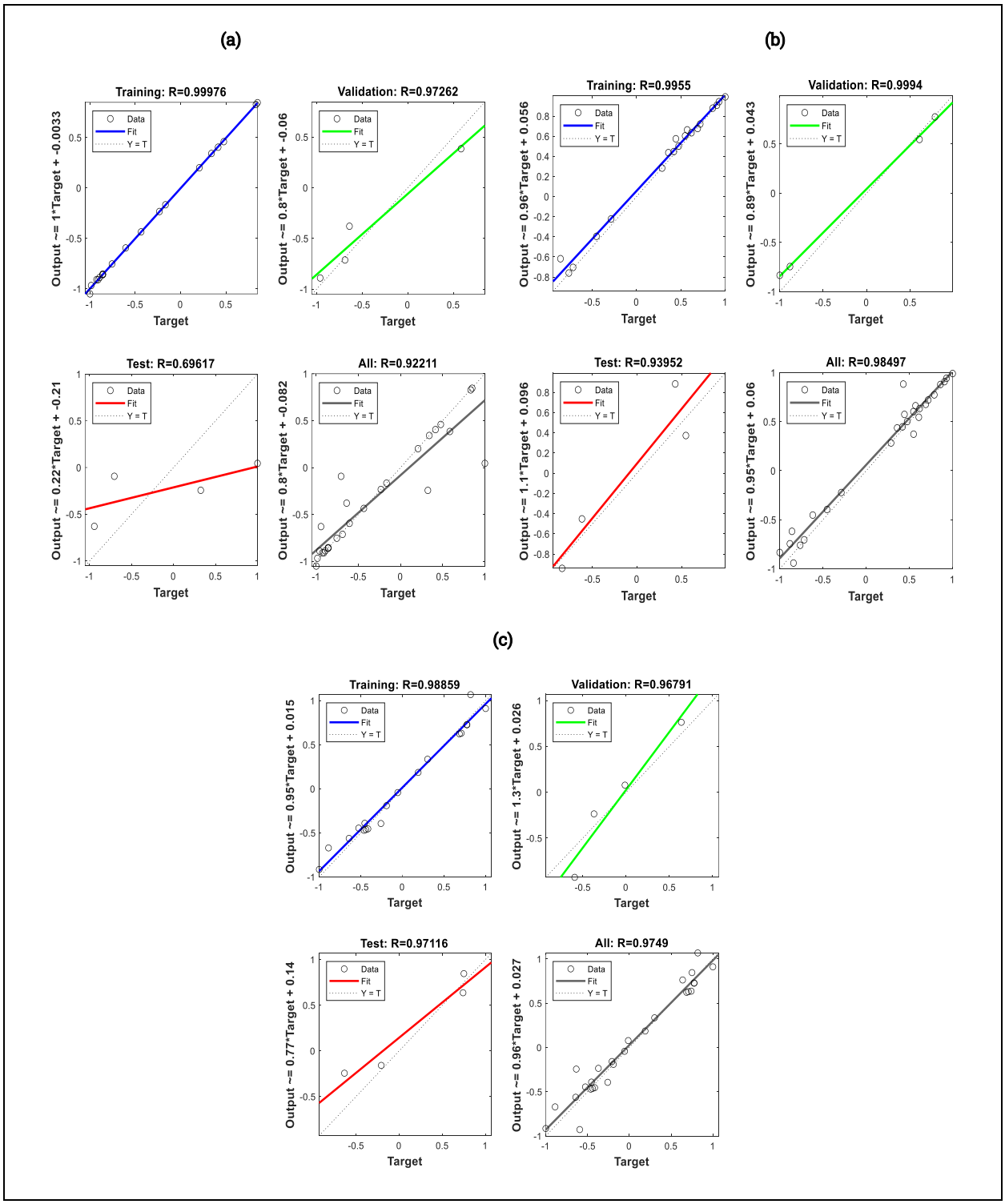


Fig. 9: *Cordia dichotoma*/nano Al_2O_3 /epoxy-based hybrid composites predicted by ANN to exhibit (a) TS, (b) FS, and (c) IS

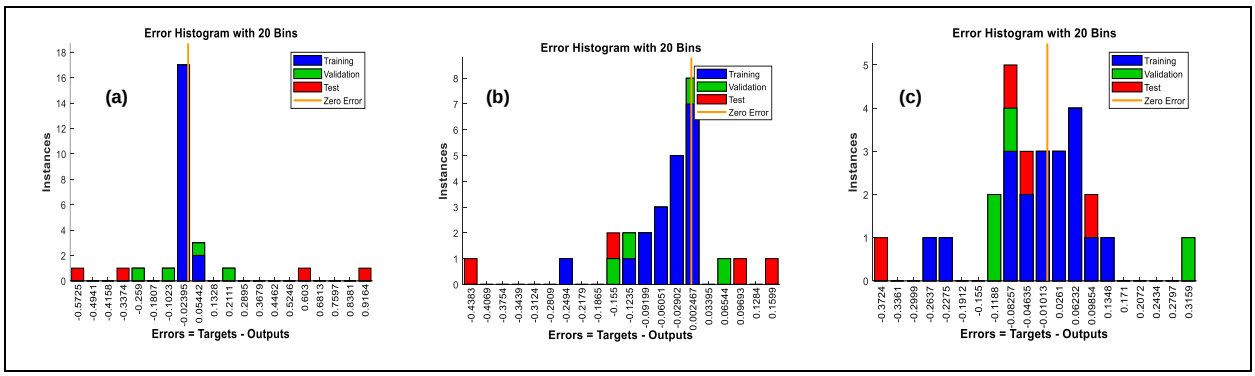


Fig. 10: Histogram plots for ANN error prediction for (a) TS (b) FS (c) IS

Table 5. Evaluation of experimented vs artificial neural network outcomes

Experimented Results			ANN Results			Predicted Error		
TS	FS	IS	TS	FS	IS	TS	FS	IS
31.38	35.61	28.99	37.55	61.20	27.75	-1.25	-1.51	1.39
31.49	36.01	29.34	37.56	63.52	31.60	-0.09	-0.60	-7.77
31.32	35.72	29.89	36.50	61.10	28.92	0.90	-0.04	7.35
31.54	35.63	30.12	37.74	62.05	32.90	0.03	-2.63	-2.60
31.79	36.16	30.20	38.71	64.66	32.36	0.41	-0.67	0.04
31.54	35.76	30.98	37.78	61.47	36.92	-0.07	-0.14	-4.34
31.35	35.49	30.79	37.04	60.62	34.87	-0.33	-1.85	-0.66
31.46	35.85	31.78	37.42	63.14	38.75	0.00	-1.77	0.16
31.44	35.65	32.20	37.42	59.90	41.28	-0.31	1.10	-1.38
33.16	36.79	33.33	41.77	69.94	48.53	8.16	-1.26	-4.55
33.27	36.93	33.76	46.01	70.34	47.95	0.15	-0.15	1.65
33.01	36.66	33.65	44.68	68.01	46.39	0.10	0.05	3.68
33.77	37.16	33.89	48.78	72.15	53.71	0.07	-0.02	-8.53
33.96	37.24	34.41	43.66	72.70	51.05	12.52	0.08	2.88
33.79	37.18	33.55	48.90	72.38	46.29	0.05	-0.13	2.74
33.35	37.07	33.68	46.37	71.26	49.94	0.25	0.13	-3.36
33.48	37.13	33.48	45.88	71.96	46.16	2.77	-0.19	2.24
33.18	36.99	33.76	45.60	70.62	47.92	-0.01	0.11	1.70
31.69	36.72	25.40	38.44	69.03	20.07	-0.04	-0.75	-7.73
31.86	36.87	26.25	40.89	70.13	24.21	-4.33	-0.53	-17.94
31.77	36.77	27.90	42.76	71.99	31.45	-10.32	-4.36	-26.68
31.54	36.89	27.86	37.75	70.53	26.05	0.00	-0.87	-5.44
32.43	37.01	28.14	41.84	70.91	19.86	0.01	-0.04	22.19
31.41	36.92	28.52	39.25	69.75	28.03	-5.52	0.60	-5.11
32.15	36.77	28.87	40.52	69.10	27.61	0.00	-0.26	0.56
32.52	36.81	28.92	42.28	69.46	28.96	0.00	-0.26	-3.76
31.91	36.87	29.12	39.48	68.61	27.89	-0.18	1.67	2.39

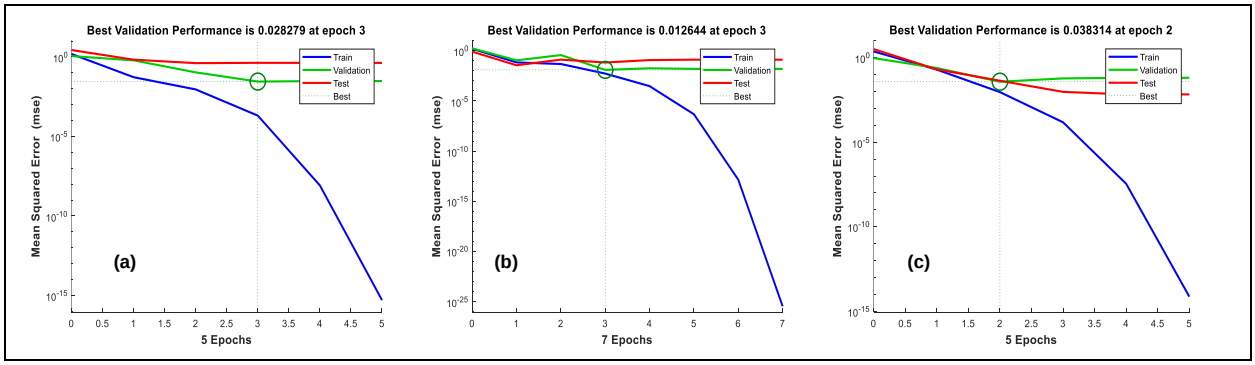


Fig. 11: Experimented and predicted ANN Performance graph for (a) TS; (b) FS; (c)IS of Nanocomposite

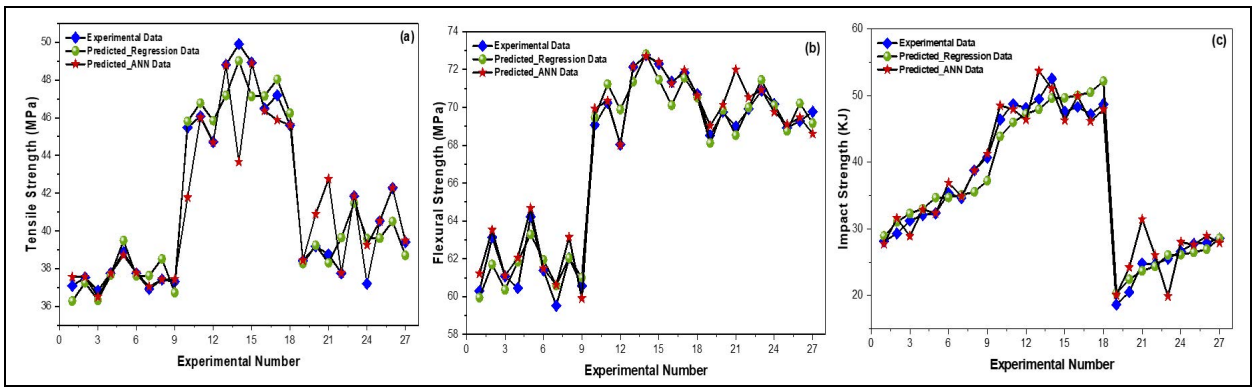


Fig. 12: Evaluation of (a) TS; (b) FS; (c) IS of nano composites

Table 6. Optimal results of nanocomposites

Results	Factor Levels	Experimental Model	Regression Model	ANN Model
TS (MPa)	W2, X2, Y2, Z3	49.91	49.02	43.66
FS (MPa)	W2, X2, Y2, Z2	72.76	72.81	72.70
IS (kJ)	W2, X3, Y3, Z3	48.75	52.19	47.92

5. CONCLUSION

The hand lay-up technique was utilized to produce *Cordia dichotoma* and nAl_2O_3-infused epoxy natural nanocomposites, yielding significant findings regarding their mechanical characteristics.

The results suggest that the mechanical and physical properties of these composites were enhanced by a fiber weight increase of up to 10%. Composites with fiber lengths of 10-15 mm exhibited superior mechanical properties in comparison to those with 5 mm lengths. The primary factor that reduced the formation of cavities was the uniform dispersal of 10 mm *Cordia dichotoma* fibers throughout the matrix.

The significance of nAl_2O_3 addition in mitigating void effects was underscored by the enhanced mechanical strength observed with the addition of 4-6 wt.% Al_2O_3 in comparison to other concentrations. The ANOVA analysis demonstrated that the mechanical strength of *Cordia dichotoma* composites was significantly influenced by the fiber content, with contributions of 89.48%, 91.89%, and 90.88% attributed to fiber length, nAl_2O_3 content, and NaOH treatment, respectively.

The results of the ANN model further support the agreement between the expected and observed responses, with R^2 values of 0.92211 for training, 0.98497 for validation, and 0.9749 for overall testing. This information further demonstrates the reliability of our experimental results. The improved TS, FS, and IS properties of these composites make them exceptional structural materials for use in a variety of industries, including aerospace, automotive, and construction. The combination of 10 mm fiber lengths with 4 wt.% nAl_2O_3 enhances these materials' outstanding mechanical properties, making them ideal for lightweight and durable applications such as building facades, airplane interiors, and car panels.

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CONFLICT OF INTEREST

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

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