



Design and Optimization of a Biocompatible Polyethylene Composite with Nelumbo Nucifera Fiber and Nano-banana Peel Filler for Sustainable Environmental Applications

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ABSTRACT

The present study examines the formulation of a biocompatible polyethylene composite that integrates Nelumbo nucifera natural fiber (NNNF) and Nano - banana peel waste filler (NBPF) for prospective environmental applications. The composite was made with compression molding and then fine-tuned with the use of ANN (Artificial Neural Network) prediction models and Taguchi-based multi-criteria decision-making tools (CRITIC and EDAS). The hybrid amalgamation of these composite materials has been little investigated in the environmental domain. The FTIR analysis showed that the banana peel waste filler was more compatible with the PE matrix, since there was a peak maximum at 1451 cm^{-1} . This peak indicates asymmetric displacement of the Carbon–Oxygen (C–O) and Carbon–Hydrogen (C–H) functional groups. The NF exhibited homogeneous distribution, enhancing stress transmission and flexural characteristics. There was a statistically significant increase in accuracy using the ANN model ($r=0.61523$). The ideal configuration was found by multi-response optimization to be a combination of 4% NaOH treatment, 3.5 wt% NBPF, 35 wt% NNNF, and a length of fiber 3 cm. This resulted in a TS of 24.75 MPa, FS of 31.25 MPa, and IS of 21.47 kJ/m². These produced composites were biodegradable and lightweight, which made them appropriate for a range of environmental uses, including biodegradable goods, eco-friendly building materials, and sustainable packaging.

Keywords: Nelumbo nucifera fiber; Banana peel waste filler; MCDM optimization; linear low-density polyethylene; Mechanical behavior.

1. INTRODUCTION

The rapidly evolving world is significantly focused on environmental ecology and new rules from governmental authorities. Consequently, scientists and researchers seek biodegradable and renewable natural fiber-reinforced composites as alternative materials (Laxshaman *et al.* 2021). Composite materials are extensively utilized across diverse applications owing to their enhanced characteristics. They are suitable for industries such as aviation, automation, and building due to their exceptional strength, toughness, and less-weight properties (Chaudhari *et al.* 2021). According to the concurrent engineering methodology, material selection must occur within the product design process to efficiently satisfy client requirements. Conflicting requirements frequently result in improper material selection, leading to premature product failure and substantial losses (Mahajan *et al.* 2022). The evaluation

of performance metrics in comparison to prescribed material requirements is a necessary step in the process of selecting natural fibers for composites used in aircraft or spacecraft cabin interiors. The selection process requires the implementation of statistical approaches due to the abundance of accessible alternatives and their diverse criteria, which creates a Multi-Criteria Decision-Making (MCDM) technique (Bhadra *et al.* 2022). The EDAS multi-attribute decision making techniques used to choose the optimum alternative from hybrid composites. Various weighing methods were employed in EDAS to obtain the significance of each factor, like CRITIC (Singh *et al.* 2023).

The demand for biodegradable materials has caused the increasing use of organic fibers in modern technical and structural applications. The properties of the NaOH-treated fiber are investigated, as well as the mining of novel cellulose fiber from the stalk of Nelumbo

nucifera fiber (Elango *et al.* 2022). Lotus, an aquatic plant with robust fibers that is currently underutilized, can serve as a primary material for biodegradable packaging. The samples that contained banana fibers (LB) demonstrated the highest explosive strength (7.09 KPa) and tensile strength (12.81 MPa) (Warrier *et al.* 2024). Fiber sequencing significantly influences the bending and hardness of fiber-reinforced composites. The attachment of fibers to the matrix, their orientation, and sequencing enhances the strength of composites, mainly when nanoparticles are used to augment mechanical qualities (Arunachalam *et al.* 2024). The study seeks to improve the performance of flax fiber in composite applications by investigating diverse treatment methods. This research enhances the comprehension of natural fiber improvements for superior material characteristics (Samant *et al.* 2023).

Empirical relations and experimental design were employed to modify the fiber length and concentrations of the specimens. The composite's properties were enhanced for alkali-treated *Lagenaria siceraria* fiber with a fiber length of 7 mm and a 30 wt.% fiber concentration (Saravanan *et al.* 2023). The mechanical properties of carbon, bamboo fibers, and polypropylene were investigated regarding consolidation pressure, fiber content, surface treatment, and fiber length (Kore *et al.* 2021). The breaking strength was 1.45 cN/dtex, the elongation at break was 6.81%, and the splitting degree was 50.3 dtcx under the optimal process conditions. The length of the lotus fiber was 127.8 mm. The fiber's overall performance index was enhanced. Using absorbent scaffold constituents is essential in developing tissue Engineering to restore damaged organs and tissues. This is because the failure or loss of these tissues and organs is a primary health concern. The lotus (*Nelumbo nucifera*) plant is capable of producing ultrafine fibers. These fibers are highly biocompatible and can be readily converted into nanofibers that could be employed in tissue Engineering (Zhang *et al.* 2020).

Recent research indicates that these materials are more attention to researchers than fiber-strengthened composites because of their environmentally benign, non-abrasive, and cost-effective characteristics. Natural fibers have the potential to be a significant solution to the current ecological and environmental issues by facilitating the development of biodegradable composites (Kharbanda *et al.* 2023). The constituents and chemical content of the lotus fiber were determined using fiber characterization utilizing FTIR and XPS techniques. The lotus fiber exhibits a similarity to cotton fibers and the presence of cellulose in its chemical characterization (Pandey *et al.* 2020). The possible applications of banana peel detritus could mitigate environmental concerns; nonetheless, the efficacy of banana peels as an antidiabetic agent remains unexamined (Zaidan *et al.* 2021).

The elevated mandate for bananas circuitously leads to a rise in banana waste in contemporary times. This study aligns with sustainable development goals by reducing banana peel trash disposal, benefiting several businesses, including health, nutraceuticals, and pharmaceuticals, and enhancing the national economy (Ibrahim *et al.* 2024). Compared to the banana peel fiber-epoxy composites, the composites strengthened with both varieties of hybrid banana fibers demonstrated superior tensile behavior. This is due to bacterial cellulose's considerable strength and rigidity (Naeem *et al.* 2022). The ideal content of banana peel waste (BPW) filler was determined to be 5.1% relative to PVA. This filler is appropriate for use as a film in everyday applications. The tensile strength of the PVA/BPW films was inferior to that of 0% PVA film (80MPa), exhibiting a range of 32.52–46.97 MPa (Ng *et al.* 2021). The regression model, ANN, and experimental data were compared to verify the reliability of the ANN predictions. The optimal composition for flexural strength was determined to be 5 wt % nanoparticles, a 10 wt % silane treatment, and a 20-minute dipping duration (Arunachalam *et al.* 2024).

Micro-cracks are identified as the primary wear mechanism, and enhanced interfacial bonding is revealed by scanning electron microscopy (SEM) analysis. Optimization of hyperparameters using artificial neural networks at 1050 rpm, 60 seconds and a 4% NaOH treatment (Sengottaiyan *et al.* 2024). To examine the effect of the reinforcement percentage of coir fiber, fly ash, and CNT on the tensile properties of the composite, an analysis of variance (ANOVA) is conducted. The experimental data align closely with the ANOVA results for Young's modulus, tensile strength, and yield strength, exhibiting a variance of less than 10% (Venkatachalam *et al.* 2023). The maximal preset performance criteria were met by a composite containing 5 wt.% ramie fiber, as evidenced by implementing an MCDM approach called CRITIC- multiplicative exponent weighting (MEW) (Pratap *et al.* 2021). Various characterisation techniques, including FTIR, FE-SEM, and TGA examined the manufactured composites. The tensile (52.26 MPa), flexural (37.76 MPa), and impact (36.87 J/m) properties of Borassus Fruit Fiber (30 wt%) combined with untreated Cigarette Butts Fiber (30 wt%) and Egg Shell Powder (5 wt%) were analyzed (Kavimani *et al.* 2024).

This investigation aims to establish a methodology for the selection and classification of motorized braking systems composed of natural fibers and agro-waste. The proposed approach's reliability and effectiveness are demonstrated by the substantiation of the ranking using various decision-making tools (Singh *et al.* 2024). This research employed a Taguchi design consisting of 27 trials (L27 OA) to optimize NaOH treatment (4 wt %–8 wt %), NBPF content (1.5 wt %–3.5 wt %), NNNF content (15 wt %–35 wt %), and fiber

length (1cm–3 cm), focusing on tensile strength, flexural strength, and impact strength as primary responses. The outcomes derived from the MCDM methodologies (CRITIC – EDAS) validated the ideal configuration, guaranteeing that the Engineered composites can endure the mechanical properties commonly needed in environmental usages.

2. MATERIALS AND METHODS

This research employed Nelumbo nucifera natural fiber as the basic reinforcement owing to its mechanical characteristics and natural availability, rendering it appropriate for ecological applications. The fiber of Nelumbo nucifera was obtained from Go Green Enterprises, Chennai. Additionally, banana peel, an environmentally -friendly filler, was selected for its capacity to improve the mechanical characteristics of composites. The banana peel was obtained from local farmers in Tamil Nadu. Combining fibers sourced from Nelumbo nucifera and banana peel waste with LLDPE—a polymer matrix commonly used for environmental applications because of its biocompatibility, adaptability, and chemical resilience. The grade E24065 of LLDPE was procured from Kovai Cheenu Enterprises, Coimbatore. NaOH pellets were used for surface treatments to enhance fiber-matrix adhesion, a crucial element in environmental applications where composite durability and efficacy are essential. NaOH treatment (4–8 wt%) improved the surface morphology and chemical composition of Nelumbo nucifera natural fiber (NNNF) by removing impurities, wax, and hemicellulose, exposing more cellulose for better fiber-matrix adhesion. SEM analysis showed a rougher fiber surface, enhancing mechanical interlocking, while FTIR results confirmed increased cellulose content, improving compatibility with the polyethylene matrix. The treatment reduced moisture absorption, minimized voids, and strengthened bonding, resulting in enhanced tensile, flexural, and impact properties. These modifications made NNNF a superior reinforcement for polyethylene composites.

2.1 Natural Fibers and Nano-fillers Surface Treatment

The Nelumbo nucifera fibers were subjected to surface treatment with 4, 6, and 8 wt% sodium hydroxides to eliminate waste and dust particles while augmenting the cellulose content of the natural fiber. A requisite quantity of sodium hydroxide pellets was dissolved in 1000 cc of filtered water and carefully mixed. The NNNFs were incorporated into the solution and remixed after thorough agitation. The solution was subjected to ultrasonication at 50°C for 4 hrs. After completion of the procedure, the fibers were meticulously rinsed with purified water and permitted to air dry at ambient temperature. The natural fibers were subjected to an oven at 80°C for 4 hrs to guarantee total dryness. The dried fibers were further severed into

shorter lengths (1, 2, and 3 cm) for experimental purposes. Table 1 presents the characteristics of Nelumbo nucifera fiber before and following surface treatment. An increase in cellulose content was noted, rising from 47.32% to 54.98% after NaOH treatment at concentrations of up to 4 wt%. The TS increased from 179.6 MPa to 197.85 MPa following treatment with Sodium hydroxide.

Table 1. Properties of untreated and treated NNNF

Parameters	Untreated NNNF	Treated NNNF (wt %)		
		4	6	8
Cellulose (%)	45.21	56.01	51.11	49.4
Density (g/cm3)	1.53	1.53	1.53	1.53
Hemicellulose (%)	24.60	20.1	22.4	25.1
Lignin (%)	18.90	16.2	18.6	17.6
Moisture (%)	10.20	7.02	7.21	7.34
Wax (%)	0.34	0.19	0.19	0.21
Tensile Strength (MPa)	163.75	197.86	195.77	192.41

In the next stage of the Sodium hydroxide treatment, banana peel was employed. The banana peel was thoroughly cleansed with distilled water. In S1, 6 wt% sodium hydroxide pellets were dissolved in pure water, and the banana peel was immersed in the solution for a duration of 4 hrs. After an hour of stirring with a magnetic stirrer at 300 rpm, the mixture was ultrasonicated at 55 °C for three hours. The banana peel was allowed to desiccate at ambient temperature and then heated in an oven at 95°C for 6 hrs. After dehydrating the banana peel, it was ground into a fine powder using a high-powered ball mill set at 710 rpm and a powder-to-ball ratio of 1:3. The powder underwent additional grinding for refinement.

2.2 Composite Fabrication

The materials were manufactured using a Brabender mixer and compression molding to confirm the even dispersal of fillers and fibers, critical for environmental usages requiring consistent mechanical characteristics. The NNNF subjected to Sodium hydroxide treatment and cut into lengths of 1–3 cm, were employed in this study. The PE resin and banana peel waste filler (1.5 wt.% – 3.5 wt.%) were subjected to ball milling to get a homogeneous mixture, which is crucial for assuring biocompatibility and preventing filler agglomeration in the polymer matrix. The NF was added into the filler/Polyethylene mixture and subsequently treated with a Brabender Plastic order at 165°C for 15 mins at 75 rpm to improve fiber–PE matrix bonding. Compression molding at 165 °C for 20 minutes was the next step for the Brabender-mixed specimens. Finally, a rectangular mold with dimensions of 300 mm x 300 mm x 3 mm was designed to produce test specimens for flexural, tensile, and impact testing.

2.3. Testing of Specimens

The synthetic specimens were manufactured per ASTM specifications for all mechanical testing to guarantee the outcomes related to biomedical-grade materials. Tensile testing followed ASTM D638-17 standards utilizing a UTM with a dog-bone-shaped sample. A 50 mm gauge length and a 20 mm/min crosshead velocity were used for the test. The FS testing followed ASTM D790-17 specifications with the Universal Testing Machine (UTM) configured for three-point bending, effectively replicating real-world bending circumstances for biomedical equipment.

The impact testing, essential for evaluating the strength of composite materials under abrupt stress, was performed using an Izod impact test machine by ASTM D256-10, featuring a 2 mm fluted balance. An SEM was performed utilizing a ZEISS Gemini 1 instrument. To preserve the NNNF/NBPF/PE matrix interface for investigation, the specimens were cryogenically fragmented in liquid N₂. The Cr was used to laminate the damaged specimens to improve scanning electron microscopy imaging, assess the filler dispersion inside the polyethylene matrix, and determine the adhesion between the nanofiller, polyethylene matrix, and fiber. Lotus fibers are treated alkaline in a NaOH solution to improve the grip between the fiber and the matrix. The molds were constructed following ASTM standards for tensile and flexural testing, and the composite components were produced using the traditional hand lay-up technique. (Tej *et al.* 2023). Utilizing a Perkin Elmer STA 6000 thermal analyzer, the thermal stability of each composite was assessed. The nitrogen atmosphere was used to heat the samples at a rate of 20 °C/min and circulate them at a rate of 20 mL/min. Samples weighing between 9 and 12 milligrams were utilized for the analysis. This experiment quantified the mass loss of composites that contained and removed nanoparticles in relation to temperature. The composites were subjected to temperatures ranging from 30 to 700 °C in order to conduct the measurements.

2.4. Using the Taguchi Method to Optimize Fiber and Filler Combinations

Taguchi optimization is a resilient DoE method frequently employed to improve many variables affecting a singular response across diverse applications. This work optimized mechanical responses, including TS, FS, and IS, as critical factors for biomedical applications, including orthopedic implants, prosthetic devices, and tissue scaffolds, through a 4-factor, 3-level experiment. An L27 OA was used to improve each mechanical feature separately.

The principal variables analyzed included NaOH surface treatment (4 to 8 wt.%), NBPF content (1.5 to 3.5 wt.%), the addition of NNNF reinforcement

(15 to 35 wt.%), and fiber length (1 to 3 cm). The selected criteria aim to improve mechanical efficiency and environmental sustainability in biomedical polyethylene composites. Table 2 has comprehensive descriptions of these characteristics and levels. Minitab 20.2 analytical software was utilized to optimize the Taguchi tests.

Table 2. Experimental factors and their levels

Parameters	Symbol	Units	Levels		
			-1	0	+1
NaOH Treatment	A	wt. %	4	6	8
Nano Banana peel Filler	B	wt. %	1.5	2.5	3.5
NNNF	C	wt. %	15	25	35
Fiber length	D	cm	1	2	3

The mechanical testing results were transformed into S/N ratios (SNR) to obtain the best levels of each parameter. Optimizing mechanical strength while reducing variability is essential in polymer composite materials, especially for bearing load implantation or significant impact on medical devices. The "larger-the-better" principle was utilized to improve mechanical properties, which are crucial in biomedical applications, necessitating enhanced mechanical strength and durability for patient comfort and safety. The equation for determining the SNR for optimizing mechanical characteristics is presented below (Eqn. (1)). This optimization technique enabled the study to obtain the optimal levels of sodium hydroxide treatment, filler content, and fiber length to yield the most advantageous mechanical characteristics, rendering the composite appropriate for environmental applications.

$$SNR = -10 \log_{10} \left[\frac{1}{n} \sum_{i=1}^n (1/y_i^2) \right] \quad \dots (1)$$

Here, 'y_i' denotes the results and 'n' represents the number of results for each experimental run.

2.5. Multi-response Optimization Approach

2.5.1 Rank Calculation: Criteria Importance through InterCriteria Correlation (CRITIC) Technique

The Criteria Importance Through InterCriteria Correlation is an impartial weighting technique. The methodology employed for attribute weight estimation by the Criteria Importance Through InterCriteria Correlation technique is outlined as follows (Tej *et al.* 2023).

The Criteria Importance Through InterCriteria Correlation weighting approach employs normalization using a decision matrix with the subsequent formulas;

$$\Re_{ij} = \frac{A_{ij} - A_j^{\min}}{A_j^{\max} - A_j^{\min}}, \text{ if } j \in \text{beneficial attribute} \quad \dots (2)$$

$$\mathfrak{R}_{ij} = \frac{A_j^{\max} - A_{ij}}{A_j^{\max} - A_j^{\min}}, \text{ if } j \in \text{non - beneficial attribute} \dots (3)$$

Subsequently, the standard deviation denoted as (δ_j) is calculated for each attribute as follows:

$$\delta_j = \sqrt{\frac{\sum_{i=1}^h (\mathfrak{R}_{ij} - A_j)^2}{h-1}}; j = 1, \dots, \Pi \dots (4)$$

Here, A_j represents the mean of the j^{th} attribute calculated as follows:

$$A_j = \frac{\sum_{i=1}^h \mathfrak{R}_{ij}}{h}; j = 1, 2, \dots, \lambda \dots (5)$$

Subsequently, the coefficient of correlation (ρ_{jk}) is established for each factor pair utilizing the following equation;

$$\rho_{jk} = \frac{\sum_{i=1}^n (\mathfrak{R}_{ij} - A_j)(\mathfrak{R}_{ik} - A_k)}{\sqrt{\sum_{i=1}^n (\mathfrak{R}_{ij} - A_j)^2 \sum_{i=1}^n (\mathfrak{R}_{ik} - A_k)^2}} \dots (6)$$

The mean of the k^{th} attribute (A) is calculated using Equation (6) for the k^{th} attribute.

The calculation for the information measure (σ_j) value for each parameter is as follows:

$$\sigma_j = \delta_j \sum_{k=1}^{\lambda} (1 - \rho_{jk}); j = 1, \dots, \lambda \dots (7)$$

The CRITIC method is used to determine the objective weight (w_j) of every parameter in the following way:

$$w_j = \frac{\sigma_j}{\sum_{j=1}^{\lambda} \sigma_j}; j = 1, \dots, \lambda \dots (8)$$

2.5.2 Alternative Ranking: Evaluation Based on Distance from Average Solution (EDAS) Technique

The EDAS-based MADM model was employed to assess the effects of several subjective and objective weighting approaches for ranking analysis. The EDAS is an extensively and reliably employed MADM method that identifies the best alternative based on its closeness to the average solution. The experimental findings are presented as a decision matrix, as specified in Equation (2), utilized in the analysis of the EDAS technique. The following procedures were used for EDAS analysis (Singh *et al.* 2023):

Step 1: The mean solution (Δ_j) for every parameter is initially calculated from the established decision matrix as follows:

$$\Delta_j = \frac{\sum_{i=1}^n A_{ij}}{n}; j = 1, 2, \dots, \lambda \dots (9)$$

Step 2: Based on the non - beneficial or beneficial attributes, the negative (NDA) and positive

(PDA) distances from the calculated Δ_j value are determined using the subsequent equations.

$$PDA_{ij} = \begin{cases} \frac{\text{Max}(0, (A_{ij} - \Delta_j))}{\Delta_j} & \text{if } j \in \text{beneficial attribute} \\ \frac{\text{Max}(0, (\Delta_j - A_{ij}))}{\Delta_j} & \text{if } j \in \text{non - beneficial attribute} \end{cases} \dots (10)$$

$$NDA_{ij} = \begin{cases} \frac{\text{Max}(0, (\Delta_j - A_{ij}))}{\Delta_j} & \text{if } j \in \text{beneficial attribute} \\ \frac{\text{Max}(0, (A_{ij} - \Delta_j))}{\Delta_j} & \text{if } j \in \text{non - beneficial attribute} \end{cases} \dots (11)$$

Step 3: The weighted normalized values for the total of the negative (ϖ_i^-) and positive (ϖ_i^+) distances for the evaluated alternatives are calculated using the subsequent formulae.

$$\varpi_i^+ = \sum_{j=1}^q \omega_j \times PDA_{ij} \dots (12)$$

$$\varpi_i^- = \sum_{j=1}^q \omega_j \times NDA_{ij} \dots (13)$$

Step 4: Subsequent to calculating the weighted total, the weighted normalized values are established for the negative (Φ_i^-) and positive (Φ_i^+) distances as follows:

$$\Phi_i^+ = \frac{\varpi_i^+}{\max_i(\varpi_i^+)}; i = 1, 2, \dots, h \dots (14)$$

$$\Phi_i^- = 1 - \frac{\varpi_i^-}{\max_i(\varpi_i^-)}; i = 1, 2, \dots, h \dots (15)$$

Step 5: The following equation is used to estimate the appraisal index (Φ_i) for each composite alternative.

$$\Phi_i = \frac{\Phi_i^+ + \Phi_i^-}{2}, \text{ where } 0 \leq \Phi \leq 1 \dots (16)$$

The ranking was determined according to the calculated Φ_i values, with the option possessing the maximum (Φ_i) value ranked first and the alternative with the minimum (Φ_i) value ranked last.

3. RESULTS AND DISCUSSION

3.1 SEM and FTIR Analysis of Banana Peel Filler

The SEM pictures (Fig. 1a) demonstrate a fibrous architecture inside the banana peel filler, indicating its possibility as a reinforcing agent in PE composites. The interaction between the PE and filler matrix can be significantly improved by combining the filler's fiber characteristics with surface alterations caused by sodium hydroxide treatment. This research establishes the feasibility of utilizing sodium hydroxide-

treated NBPF as a functional addition in PE composites, supported by FTIR and SEM analyses, particularly for biomedical applications requiring improved mechanical characteristics and biocompatibility. Fig. 1b shows the FTIR spectrum of the banana peel filler treated with Sodium hydroxide. The filler is now more compatible with PE matrices used in biomedical devices because of the noticeable peaks that indicate chemical changes. A prominent peak indicates the stretching vibrations of the C-C and C-O functional groups at 1052 cm^{-1} . This means that the filler and polymer matrix adhere better to one another, which is vital for boosting the composite's mechanical strength. Cellulose is essential for increasing the composite's tensile strength and flexibility, and its existence is confirmed by the maximum at 1451 cm^{-1} , which indicates asymmetric distortion in the Carbon-Hydrogen and Carbon-Oxygen groups. The signal at 1767 cm^{-1} indicates the production of ester bonds through stretching vibrations in carbonyl groups. The stretching of the O-H (oxygen-hydrogen) bond, as indicated by the prominent peak at 3452 cm^{-1} , confirms the existence of -OH, which enhances the filler's hydrophilic characteristics. Banana peel waste is a substantial portion of the banana refining industry, indicating an environmental issue. The mineral content was determined to be 55.19 for calcium (Ca), 293.53 for magnesium (Mg), 21.33 for iron (Fe), 229.81 for sodium (Na), and 8859.84 mg/100 g for potassium (K) (Rodrigues *et al.* 2024).

3.2 Thermogravimetric Analysis

The TGA curves of the NNNF/NBPF samples exhibited a weight loss trend with increasing temperature, whereas the DTG curves distinctly revealed the decomposition temperature at each stage of thermal degradation, as depicted in Figure 2. The sample exhibited three stages of thermal degradation. The initial stage of decomposition, taking place at temperatures ranging from 60 to 150°C , is marked by moisture loss, leading to a weight decrease of about 8 to 16%. The second phase of thermal degradation, occurring between 200 and 380°C , exhibited the disintegration of the polymeric structures of lignin, cellulose, and other organic molecules. The third phase of thermal deterioration, occurring between 400 and 550°C , exhibited a decline in wax and ash content in NNNF/NBPF, resulting in an 80–92% decrease in weight. PVA exhibited a two-phase breakdown at roughly 280 and 430°C , due to the elimination of the acetate group at lower temperatures, followed by the degradation of the polymer at higher temperatures.

3.3 Results of Optimization through the Taguchi Technique

This study employed the Taguchi optimization method to determine the ideal combination of sodium hydroxide treatment, NNNF, NBPF content, and fiber

length to improve TS, FS, and IS. The 27-trial experiment utilizing the OA (Table 3) maximized TS with a formulation including 4% NaOH treatment, 2.5 wt% NBPF, 25 wt% NNNF, and a 3 cm fiber length, achieving a TS of 26.21 MPa. This result synthesizes hardness and adaptability, rendering the composite appropriate for environmental applications necessitating structural integrity and flexibility, including load-bearing implantations and adaptable prosthetics.

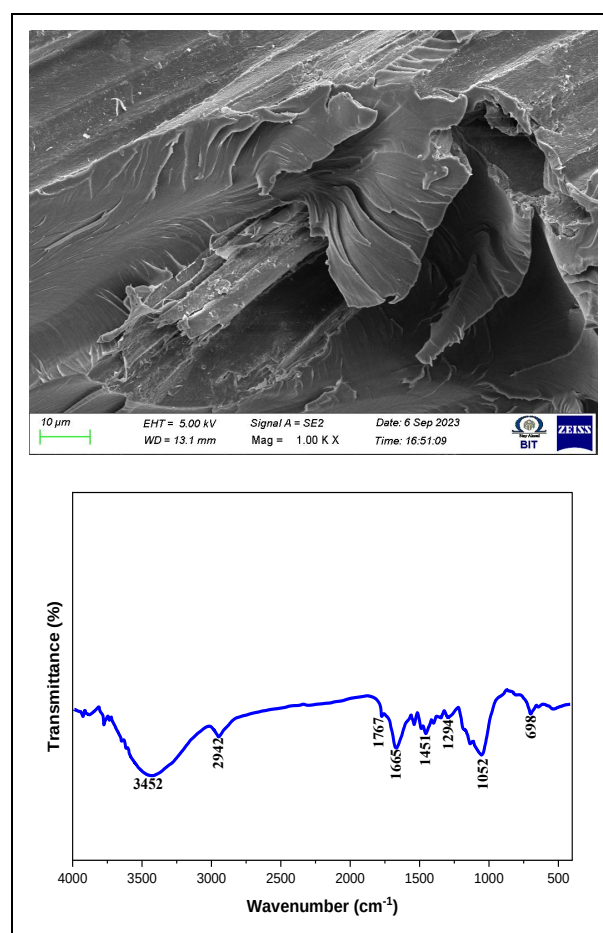


Fig. 1: (a) SEM and (b) FTIR for NBPF Powder

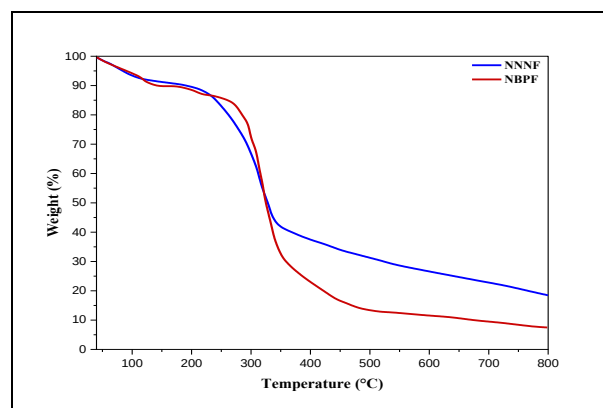


Fig. 2: TGA analysis NNNF and NBPF of the hybrid composites

Table 3. Experimental outcomes for the L27 orthogonal array

A	B	C	D	Tensile Strength	Flexural Strength	Impact Strength	Signal to Noise Ratio		
	wt. %		cm	MPa		KJ/m ²	TS	FS	IS
4	1.5	15	1	24.38	28.72	20.06	27.741	29.164	26.047
4	1.5	25	2	23.24	30.32	21.25	27.325	29.635	26.547
4	1.5	35	3	25.77	31.26	21.93	28.222	29.900	26.821
4	2.5	15	2	24.52	29.77	20.65	27.790	29.476	26.298
4	2.5	25	3	26.21	28.21	21.74	28.369	29.008	26.745
4	2.5	35	1	23.91	31.05	21.45	27.572	29.841	26.629
4	3.5	15	3	26	28.51	20.76	28.299	29.100	26.345
4	3.5	25	1	24.73	30.39	21.59	27.864	29.655	26.685
4	3.5	35	2	24.75	31.25	21.47	27.872	29.897	26.637
6	1.5	15	1	22.1	29.67	19.39	26.888	29.446	25.752
6	1.5	25	2	23.16	30.2	20.71	27.295	29.600	26.324
6	1.5	35	3	23.69	32.1	21.36	27.491	30.130	26.592
6	2.5	15	2	23.97	29.59	20.28	27.593	29.423	26.141
6	2.5	25	3	25.11	29.02	21.09	27.997	29.254	26.482
6	2.5	35	1	22.99	31.88	20.9	27.231	30.070	26.403
6	3.5	15	3	25.84	27.3	20.07	28.246	28.723	26.051
6	3.5	25	1	24.79	29.16	21	27.886	29.296	26.444
6	3.5	35	2	24.04	29.97	20.47	27.619	29.534	26.222
8	1.5	15	1	20.32	28.49	17.91	26.158	29.094	25.062
8	1.5	25	2	21.39	29.13	19.29	26.604	29.287	25.707
8	1.5	35	3	22.08	31.02	20.02	26.880	29.833	26.029
8	2.5	15	2	22.24	28.33	18.79	26.943	29.045	25.479
8	2.5	25	3	23.87	27.74	19.83	27.557	28.862	25.946
8	2.5	35	1	21.95	30.56	19.72	26.829	29.703	25.898
8	3.5	15	3	24.85	26.84	19.35	27.907	28.576	25.734
8	3.5	25	1	24.39	29.72	21.08	27.744	29.461	26.477
8	3.5	35	2	24.15	31.32	21.2	27.658	29.916	26.527
Average				23.87	29.69	20.49	27.540	29.442	26.223

The optimal results for FS and IS were obtained using a 4% A, 1.5 wt% B, 35 wt% C, and a 3 cm D. The FS attained 31.26 MPa, while the IS was 21.93 kJ/m². However, the diversity in optimal settings for TS, FS, and IS challenges the assessment of the significance of each component based only on mechanical findings. The SNRs for every result were computed, offering insight into the material's performance stability across various testing conditions. Table 4 presents the response data for the SNR, elucidating these findings and facilitating the optimization of the manufacturing process to attain the most balanced features in PE composites for biomedical applications.

Table 4 shows the importance of each component in the studies. The TS property increased the tensile strength signal-to-noise ratio from 27.18 to 27.90, with filler percentages ranging from 1.5 to 3.5 wt%. The filler reduced the space between the NF and matrix, enhancing TS. Fiber length demonstrated improvement with an increase from 1 to 3 cm. This could be attributed

to the improved distribution of natural fiber linked to the longer fiber lengths. Composites made of polyethylene diminished their tensile strengths due to structural damage caused by an enhanced surface treatment with sodium hydroxide (4 wt %). Adding *Nelumbo nucifera* fibers at 25 wt % yielded superior results, enhancing fiber distribution and contributing to increased TS. The NaOH treatment and filler incorporation improved the tensile properties, succeeded by NF addition and fiber length (Tables 4 and 5). Fig. 3 presents a contour plot of tensile strength about various parameters, indicating an enhancement in characteristics by adding banana peel filler and fiber lengths up to level 3. The Analysis of Variance table demonstrates the experimental importance of all parameters in the TS studies (Table 5).

The response table 6 showed the importance of diverse parameters influencing flexural strength, an essential characteristic for biomedical applications requiring materials to withstand considerable loads without deformation or failure. The findings

demonstrated that the filler percentage, varying from 1.5 to 3.5 wt%, reduced the SNR for FS, decreasing from 29.57 to 29.35. This indicates that although fillers may mitigate voids in the composite, their effect on improving FS is constrained. A signal-to-noise ratio (S/N) of 29.87 was achieved for flexural strength when NF was added to the PE matrix, an improvement over 30 years ago. The enhanced stress transfer capability, made possible by the evenly distributed fibers within the matrix, is responsible for this improvement. The optimal FS was achieved by combining a 4% NaOH treatment with 35% NNNF, 1.5% filler, and a 2 cm fiber length.

Table 4. Response table for signal to noise ratios tensile strength

Level	A: NaOH Treatment	B: Banana peel Filler	C: NNNF	D: Fiber length
1	27.89	27.18	27.51	27.32
2	27.58	27.54	27.63	27.41
3	27.14	27.90	27.49	27.89
Delta	0.75	0.72	0.14	0.56
Rank	1	2	4	3

Table 5. Analysis of variance table for TS

Source	DF	Seq SS	Contribution	Adj MS	F-Value	P-Value
A: NaOH Treatment	2	18.6721	33.00%	9.3361	21.67	0.000
B: Banana peel Filler	2	16.8397	29.77%	8.4198	19.55	0.000
C: NNNF	2	0.7628	1.35%	0.3814	0.89	0.430
D: Fiber length	2	12.5463	22.18%	6.2732	14.56	0.000
Error	18	7.7537	13.71%	0.4308		
Total	26	56.5746	100.00%			
		R ² 86.29%	Adj. R ²	80.20%	Pred. R ²	69.16%

Table 6. Response table for signal to noise ratio for FS

Level	A: NaOH Treatment	B: Banana peel Filler	C: NNNF	D: Fiber length
1	29.52	29.57	29.12	29.53
2	29.50	29.41	29.34	29.53
3	29.31	29.35	29.87	29.27
Delta	0.21	0.21	0.75	0.27
Rank	4	3	1	2

Along with the impacts of Sodium hydroxide treatment, NNNF, NBPF, and fiber length illustrated in Table 6 and Table 7, this result emphasizes the necessity of including natural fibers into environmental composites to improve their flexural characteristics. With the addition of natural fibers up to 35 wt%, the contour plot of FS (Fig. 4) shows that the properties are significantly improved, which helps design environmental composites

with increased mechanical characteristics. According to the ANOVA table, these factors were confirmed to affect FS (Table 7).

Table 7. Analysis of variance table for FS

Source	DF	Seq SS	Contribution	Adj MS	F-Value	P-Value
A: NaOH Treatment	2	2.717	5.41%	1.3586	2.74	0.092
B: Banana peel Filler	2	2.486	4.94%	1.2429	2.50	0.110
C: NNNF	2	31.673	63.00%	15.8366	31.92	0.000
D: Fiber length	2	4.464	8.88%	2.2319	4.50	0.026
Error	18	8.932	17.77%	0.4962		
Total	26	50.271	100.00%			
		R ² 82.23%	Adj. R ²	74.34%	Pred. R ²	60.03%

This finding highlights the significance of sodium hydroxide treatment, NBPF content, NNNF content, and fiber length in improving the mechanical characteristics of polymer-based composites used in environmental applications. Analysis of variance (ANOVA) shows that mechanical strength is considerably affected by filler content and NaOH treatment. The filler makes up about 80% of the total and has the most impact (Periyappillai *et al.* 2024).

The significance of numerous criteria in the evaluation of IS is illustrated in Table 8, which is crucial for environmental applications that require impact resistance and impact strength. The IS exhibited an enhancement in characteristics with filler percentages ranging from 1.5 to 3.5 wt%, which improved the SNR from 26.10 to 26.35. This enhancement results from the filler reducing gaps between the NF and the PE matrix, augmenting the material's capacity to endure impact forces. The fiber length favorably influenced the material qualities, with lengths ranging from 1 to 3 cm demonstrating enhancements. The addition of Nelumbo nucifera fiber at 15 wt% yielded ideal results since this concentration facilitated a more uniform fiber dispersion, improving the composites' impact strength. The NaOH treatment emerged as the most influential element in improving impact characteristics, succeeded by NNNF content, NBPF content, and fiber length illustrated in tables 8 and 9.

Table 8. Response table for signal to noise ratio (IS)

Level	A: NaOH Treatment	B: Banana peel Filler	C: NNNF	D: Fiber length
1	26.53	26.10	25.88	26.16
2	26.27	26.22	26.37	26.21
3	25.87	26.35	26.42	26.30
Delta	0.65	0.25	0.54	0.15
Rank	1	3	2	4

Table 9. Analysis of variance table for IS

Source	DF	Seq SS	Contribution	Adj MS	F-Value	P-Value
A: NaOH Treatment	2	10.5536	42.21%	5.2768	24.93	0.000
B: Banana peel Filler	2	1.4281	5.71%	0.7140	3.37	0.057
C: NNNF	2	8.6731	34.69%	4.3365	20.49	0.000
D: Fiber length	2	0.5365	2.15%	0.2682	1.27	0.306
Error	18	3.8093	15.24%	0.2116		
Total	26	25.0005	100.00%			
		R ² 84.76%	Adj. R ²	77.99%	Pred. R ²	65.72%

This signifies that surface treatment is essential for improving the composite's efficacy, crucial for environmental applications demanding high-performance criteria. Likewise, the traditional fibers are having various environmental benefits, such as research on abaca-fiber bio-polyethylene composites showed a lower carbon footprint than HDPE composites, emphasizing the sustainability of bio-based reinforcements of Birch Fiber Composites (Seculi *et al.*, 2023). Fig. 5 presents a contour plot depicting the influence of various parameters on impact strength, highlighting the benefits of including banana peel filler and optimizing fiber length on IS. The analysis of the variance table verifies the significance of all parameters except natural fiber addition, which exhibited a negligible effect on IS, illustrated in Table 9.

The chemical and mechanical interactions between NBPF, NNNF, and the PE matrix enhance composite performance. NaOH treatment removes impurities, exposing hydroxyl (-OH) groups that improve hydrogen bonding and fiber-matrix adhesion. FTIR analysis confirms ester and ether linkages, while NBPF's nano-scale structure increases surface area, improving dispersion and compatibility. Mechanically, the roughened fiber surface enhances interlocking, preventing fiber pullout and improving stress transfer. NBPF fills voids, increasing tensile and flexural strength, while optimal fiber length and filler content ensure uniform reinforcement, making the composite durable for biomedical applications.

3.4 Numerical Modeling with the Artificial Neural Network (ANN) Methodology

The application of computational modeling in testing materials, specifically for TS, FS, and IS, was essential for accurately predicting material behavior under diverse fiber loading conditions. This approach improves the comprehension of deformation, strain, and stress relationships, as well as the causes of failure,

without requiring significant experiments. The numerical models are essential for enhancing material behaviors since they save costs, accelerate the development process, and minimize the necessity for several designs. The linear regression models are frequently utilized in polymer materials to examine and predict the impact of diverse input parameters on essential mechanical characteristics. In environmental applications, models are beneficial for measuring the impacts of various treatment procedures, NF content, filler types, and fiber length on critical metrics, including TS, FS, and IS. By employing ANN and RSM models, the mechanical efficacy of the proposed nano-composites was predicted with a reliability of up to 95% using the Kevlar mat and TiO₂ filler. Impact (0.9864), flexural (0.9842), and tensile (0.9764) are the values that the ANN shows (Narayan *et al.* 2023).

An identified relationship between the mechanical characteristics of the polymer composite and the input factors can be found using regression models. Using a regression line on the experimental results quantifies the influence of changes in these parameters on TS, FS, and IS. This predictive ability is especially beneficial in environmental applications, where accurate material performance is essential. Equations (17) – (19) demonstrate the construction of an equation using linear regression for predicting the output response. The input and output variables are used to build this equation.

$$TS = 23.079 - 0.5075 A + 0.967 B - 0.0049 C + 0.770 D \dots (17)$$

$$FS = 29.265 - 0.1758 A - 0.358 B + 0.1288 C - 0.424 D \dots (18)$$

$$IS = 20.173 - 0.3808 A + 0.282 B + 0.0626 C + 0.169 D \dots (19)$$

ANN provides considerable benefits by employing treatment methods, NF content, filler content, and fiber length as input variables to predict biomedical composites' TS, FS, and IS. This function facilitates more precise and dependable predictions of mechanical characteristics than conventional linear models, which may insufficiently capture this complexity. Furthermore, artificial neural networks improve mechanical behavior prediction by assimilating experimental results and discerning complex designs and relationships. This results in enhanced predictions regarding the influence of various treatments and compositions on the effectiveness of composites.

For example, by analyzing the impact of surface treatments, NNNF, NBPF, and fiber length on the mechanical properties of PE composites. The adaptability and malleability of artificial neural networks are beneficial. They can assess a wide array of input variables and adapt to new information, making them highly adept at predicting the characteristics of composites with different treatments and compositions.

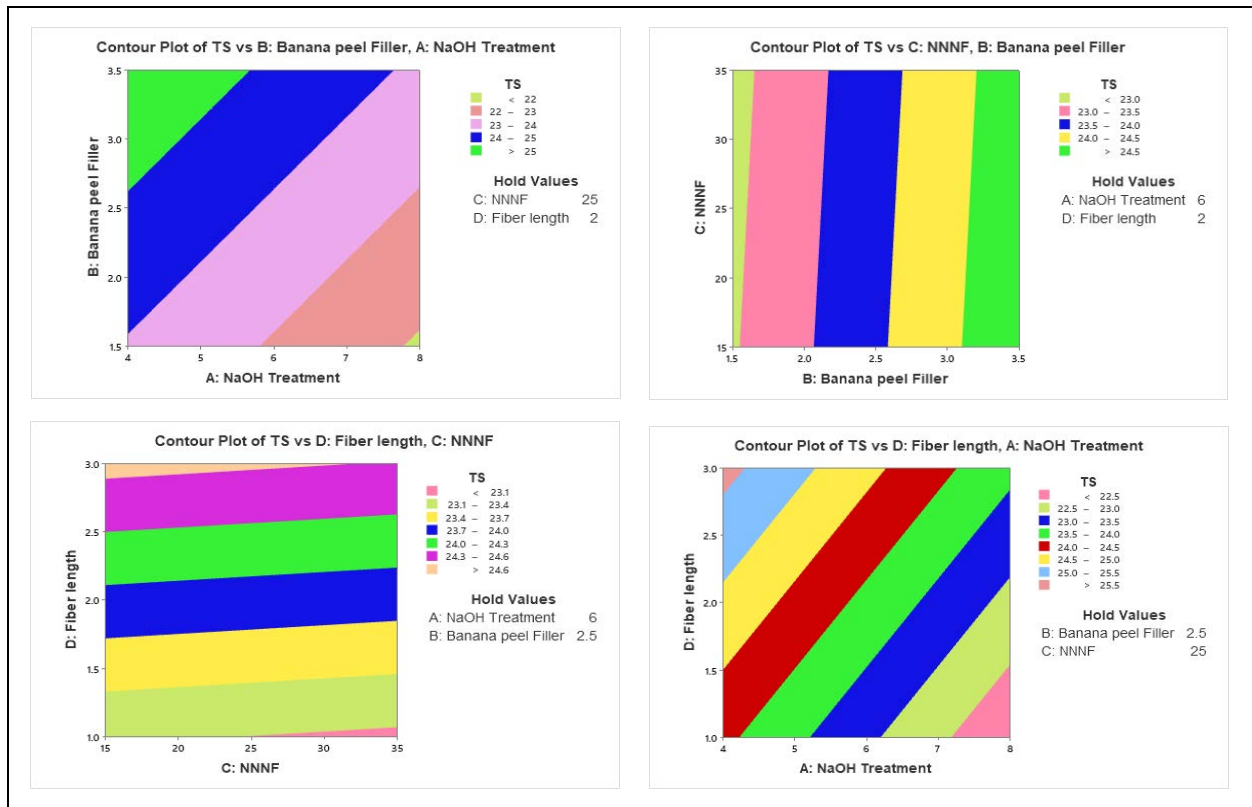


Fig. 3: Contour plot for TS about (a) filler and NaOH treatment (A, B), b) NNNF and Filler (B, C), (c) fiber length and NNNF (C, D), and (d) Fiber length and NaOH Treatment (A, D)

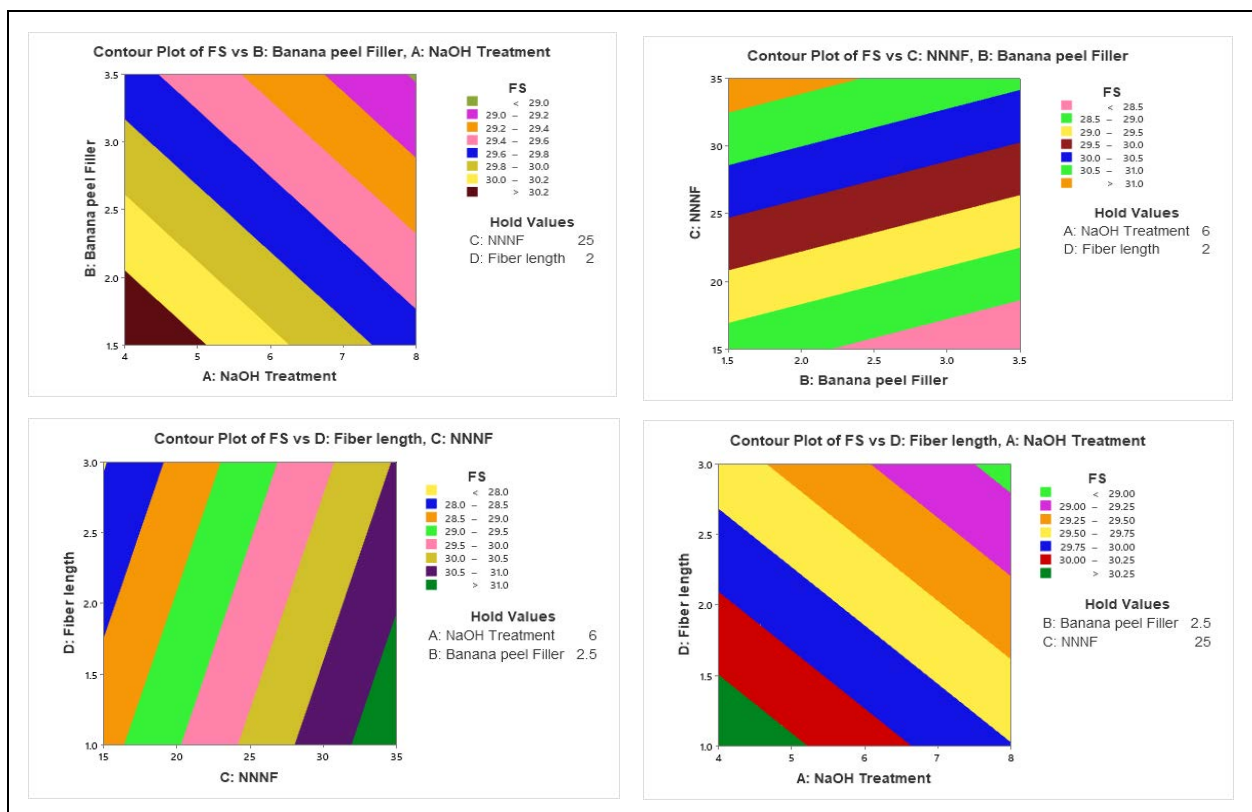


Fig. 4: Contour Plot for FS about (a) filler and NaOH treatment (A, B), (b) NNNF and filler (B, C), (c) fiber length and NNNF (C, D), and (d) Fiber length and NaOH Treatment (A, D)

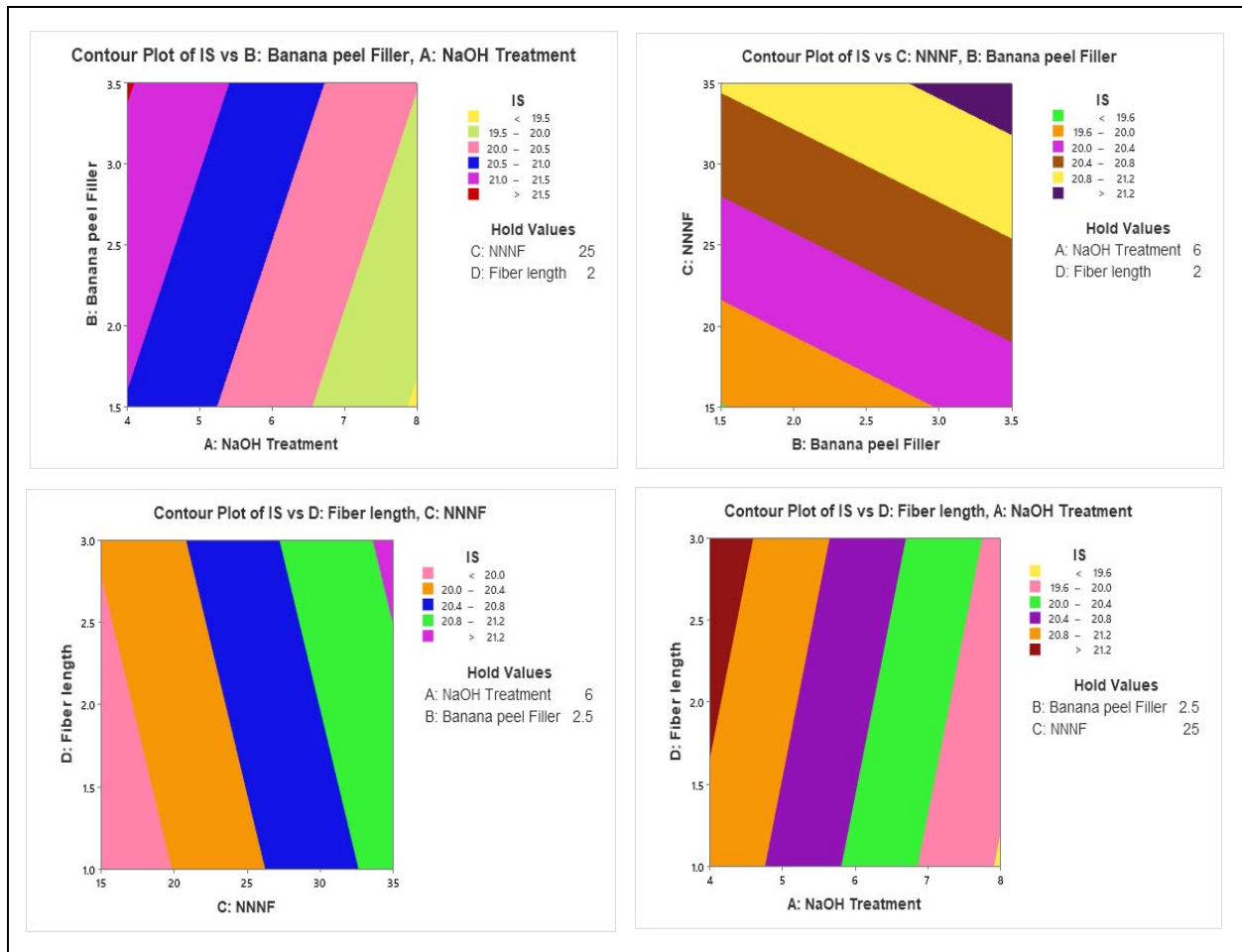


Fig. 5: Contour Plot for IS (a) NBPF and NaOH Treatment (A, B), (b) NNNF and NBPF (B, C), (c) Fiber length and NNNF (C, D), and (d) Fiber length and NaOH Treatment (A, D)

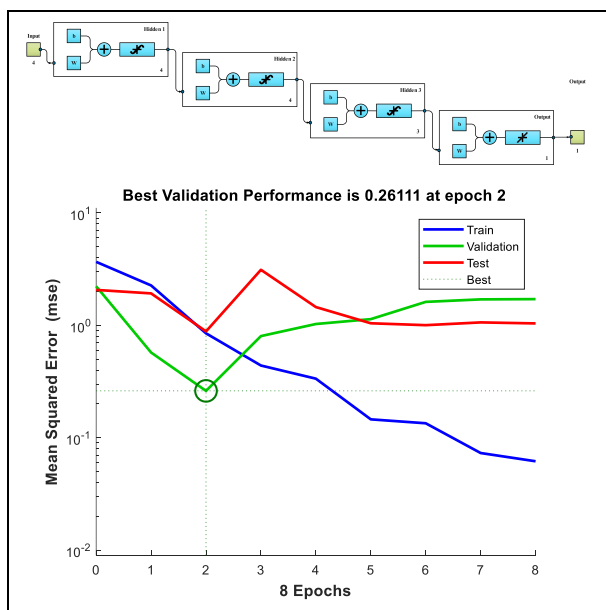


Fig. 6: (a) ANN model and (b) Performance validation of the generated model

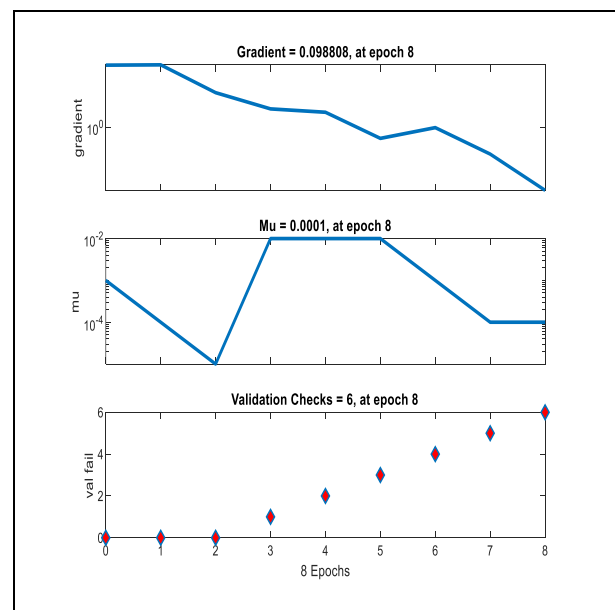


Fig. 7: Performance of trained model

This study utilizes the natural fiber tool for artificial neural network modeling in MATLAB R2023b. The network comprises six hidden nodes to predict outcomes, ensuring accurate forecasting of the mechanical characteristics of composites. Figure 6a illustrates the network design, showcasing the application of ANN to improve the mechanical characteristics of PE materials for environmental purposes.

The neural network model attained its highest accuracy or minimum rate of error on the dataset used for validation in the third training epoch, as illustrated in Figure 6b, with a validation efficiency of 0.26111 in epoch 2 of the ANN simulation. Essential metrics throughout the eighth epoch of the ANN development procedure yield essential insights into the model's performance and effectiveness (Fig. 7). As a function of the model parameters, the loss function changes at a rate of 0.098808. The substantial gradient shows that the model consistently makes minor alterations to its factors to reduce the loss function, signifying effective training. In addition, the function "Mu" valued at 0.0001 denotes a specific loss or error metric applied during training. Epoch 8 also shows the execution of six validation tests. Validation checks are routinely employed during training to assess the model's effectiveness using a distinct validation dataset. The training phase may be terminated prematurely if the model's performance on the validation dataset fails to increase with successive assessments, which are conducted to assess the model's ability to generalize to new data. A critical parameter for evaluating the efficacy of a predictive model during its development and evaluation phases is the coefficient of determination (r). Fig. 8 shows a good correlation between the anticipated and actual values throughout the training period, with an r -value of 0.65042.

The model has learned to correctly predict this subset of data after recognizing patterns in the training set. An r -value of 0.96604 during validation confirms the model's robustness, showing its ability to generalize to novel data. The testing stage shows a minor decline in results ($r = 1.000$); however, it maintains a significantly high level of predictive accuracy. An average r -value of 0.61523 indicates that the model demonstrates consistent and reliable performance throughout all phases. The linear regression model inadequately captures the dataset's intricacies, reducing predictive accuracy. This constraint is especially troubling in environmental applications, where even little errors could affect the efficacy of the composites. The artificial neural network model's ability to manage a small change and composite designs in data provides a significant advantage, confirming more reliable and accurate simulation of composite parameters.

Understanding and enhancing the mechanical characteristics of composites is essential for effective

development, and the artificial neural network model's excellent precision makes it a fantastic match for environmental application predictions. This capacity renders the ANN model a preferred option for scenarios necessitating great precision in forecasting material properties under different conditions. The ANN results ($R^2=0.99$ and $RMSE=1.99$) indicate that the enhanced model is more effective in predicting the content of delamination than the RSM results ($R^2=0.97$ and $RMSE=2.24$) (Shireesha and Govind, 2021).

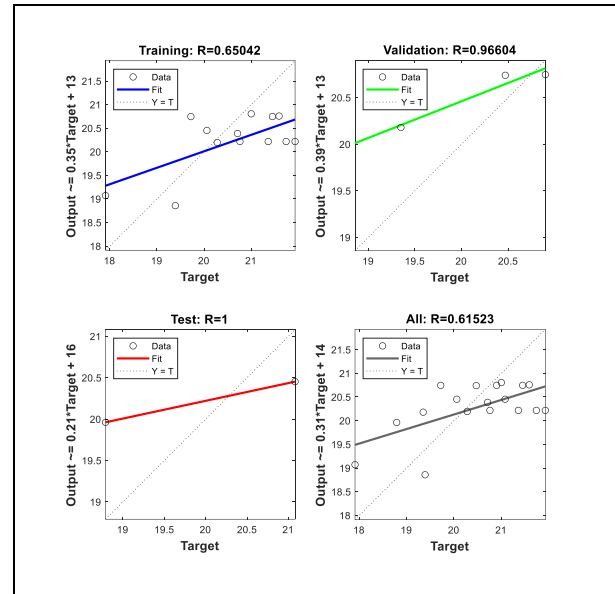


Fig. 8: Regression analysis of datasets

3.5 Optimization using Multi Decision Criteria Making (MCDM) Techniques

3.5.1 CRITIC Weighting Method

Similarly, the decision matrix for the CRITIC weighting approach was normalized utilizing Equation (19). Following normalization, the values of standard deviation (δ_j), information measure (σ_j), and correlation coefficient (ρ_{jk}) were calculated. The attribute weight (ω_j) was obtained and is tabulated in Table 10.

Table 10. Results of the CRITIC approach

Weight	TS	FS	IS
ω_j	0.370	0.435	0.195

3.5.2 EDAS for Alternative Ranking

The previously mentioned weighing methodologies are now utilized in the decision-making analysis for selecting composite materials (Table 3). The weights from each weighting techniques were used as input for the EDAS strategy to identify the optimal composite among the 27 choices provided. The EDAS approach operates on the structured decision matrix using

tensile strength (maximization preferred), flexural strength (maximization preferred), and impact strength (maximization preferred). The EDAS approach established the initial average solution for the decision matrix. Subsequently, negative and positive distances were computed and are tabulated in Table 11.

Subsequently, the weighted total of the positive distances, denoted as w_i^+ and negative distances, denoted as w_i^- for all composite alternatives was calculated using the CRITIC weighting methods and presented in Table 12. Subsequently, the weighted normalized values are calculated for the negative (Φ_i^-) and positive (Φ_i^+) distances. The appraisal index (Φ_i) values for each composite option were calculated and presented as a ranking in Table 13. Table 13 presents the EDAS results and rankings of composite alternatives derived from the CRITIC weighting method. Of the 27 composite alternatives, 3 consistently ranks top across all objective weighting techniques, exhibiting the highest closeness coefficient value of 1.000 for CRITIC. Simultaneously, 19 is the least favorable composite for the CRITIC approach. The results from EDAS (Table 13) exhibited accurate optimization results, as shown in the main effect plots for SN ratios shown in Figure 9a. Figure 9b shows the interaction plot. The best combinations for increasing the mechanical characteristics of PE composites were found to be 4% A, 3.5 wt% B, 35 wt% C, and a 3 cm D, according to the multi-response optimization methodologies.

Table 11. Positive and Negative distance results

Positive distance (PDA)			Negative distance (NDA)		
TS	FS	IS	TS	FS	IS
0.0214	0.0000	0.0000	0.0000	0.0325	0.0212
0.0000	0.0214	0.0368	0.0263	0.0000	0.0000
0.0797	0.0530	0.0700	0.0000	0.0000	0.0000
0.0273	0.0028	0.0076	0.0000	0.0000	0.0000
0.0981	0.0000	0.0608	0.0000	0.0497	0.0000
0.0018	0.0460	0.0466	0.0000	0.0000	0.0000
0.0893	0.0000	0.0129	0.0000	0.0396	0.0000
0.0361	0.0237	0.0534	0.0000	0.0000	0.0000
0.0369	0.0527	0.0476	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0741	0.0005	0.0539
0.0000	0.0173	0.0105	0.0297	0.0000	0.0000
0.0000	0.0813	0.0422	0.0075	0.0000	0.0000
0.0043	0.0000	0.0000	0.0000	0.0032	0.0105
0.0520	0.0000	0.0290	0.0000	0.0224	0.0000
0.0000	0.0739	0.0198	0.0368	0.0000	0.0000
0.0826	0.0000	0.0000	0.0000	0.0804	0.0207
0.0386	0.0000	0.0246	0.0000	0.0177	0.0000
0.0072	0.0096	0.0000	0.0000	0.0000	0.0012
0.0000	0.0000	0.0000	0.1487	0.0403	0.1261
0.0000	0.0000	0.0000	0.1038	0.0187	0.0588
0.0000	0.0449	0.0000	0.0749	0.0000	0.0232
0.0000	0.0000	0.0000	0.0682	0.0457	0.0832
0.0001	0.0000	0.0000	0.0000	0.0656	0.0324
0.0000	0.0294	0.0000	0.0804	0.0000	0.0378
0.0411	0.0000	0.0000	0.0000	0.0959	0.0559
0.0219	0.0011	0.0286	0.0000	0.0000	0.0000
0.0118	0.0550	0.0344	0.0000	0.0000	0.0000

Table 12. The weighted sum of the PDA (m_i^+) and NDA (m_i^-) distances

Weighted sum of PDA				Weighted sum of NDA			
TS	FS	IS	w_i^+	TS	FS	IS	w_i^-
0.0079	0.0000	0.0000	0.0079	0.0000	0.0142	0.0041	0.0183
0.0000	0.0093	0.0072	0.0165	0.0097	0.0000	0.0000	0.0097
0.0295	0.0231	0.0137	0.0662	0.0000	0.0000	0.0000	0.0000
0.0101	0.0012	0.0015	0.0128	0.0000	0.0000	0.0000	0.0000
0.0363	0.0000	0.0118	0.0481	0.0000	0.0217	0.0000	0.0217
0.0006	0.0200	0.0091	0.0297	0.0000	0.0000	0.0000	0.0000
0.0330	0.0000	0.0025	0.0355	0.0000	0.0172	0.0000	0.0172
0.0133	0.0103	0.0104	0.0341	0.0000	0.0000	0.0000	0.0000
0.0137	0.0229	0.0093	0.0459	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0274	0.0002	0.0105	0.0381
0.0000	0.0075	0.0020	0.0096	0.0110	0.0000	0.0000	0.0110
0.0000	0.0354	0.0082	0.0436	0.0028	0.0000	0.0000	0.0028
0.0016	0.0000	0.0000	0.0016	0.0000	0.0014	0.0020	0.0035
0.0192	0.0000	0.0057	0.0249	0.0000	0.0098	0.0000	0.0098
0.0000	0.0322	0.0039	0.0360	0.0136	0.0000	0.0000	0.0136

0.0305	0.0000	0.0000	0.0305	0.0000	0.0350	0.0040	0.0390
0.0143	0.0000	0.0048	0.0191	0.0000	0.0077	0.0000	0.0077
0.0027	0.0042	0.0000	0.0068	0.0000	0.0000	0.0002	0.0002
0.0000	0.0000	0.0000	0.0000	0.0549	0.0175	0.0246	0.0971
0.0000	0.0000	0.0000	0.0000	0.0384	0.0082	0.0115	0.0580
0.0000	0.0196	0.0000	0.0196	0.0277	0.0000	0.0045	0.0322
0.0000	0.0000	0.0000	0.0000	0.0252	0.0199	0.0162	0.0613
0.0000	0.0000	0.0000	0.0000	0.0000	0.0285	0.0063	0.0349
0.0000	0.0128	0.0000	0.0128	0.0297	0.0000	0.0074	0.0371
0.0152	0.0000	0.0000	0.0152	0.0000	0.0417	0.0109	0.0526
0.0081	0.0005	0.0056	0.0141	0.0000	0.0000	0.0000	0.0000
0.0044	0.0240	0.0067	0.0350	0.0000	0.0000	0.0000	0.0000
Max			0.0662				0.0971

Table 13. EDAS outcomes for L27 OA

Φ_1^+	Φ_1^-	Φ_1	Rank
0.1197	0.8114	0.4656	20
0.2490	0.8998	0.5744	14
1.0000	1.0000	1.0000	1
0.1934	1.0000	0.5967	13
0.7268	0.7770	0.7519	6
0.4493	1.0000	0.7247	7
0.5369	0.8223	0.6796	9
0.5150	1.0000	0.7575	5
0.6931	1.0000	0.8465	2
0.0000	0.6073	0.3036	24
0.1448	0.8870	0.5159	17
0.6593	0.9716	0.8154	3
0.0238	0.9645	0.4941	18
0.3761	0.8994	0.6377	10
0.5445	0.8599	0.7022	8
0.4613	0.5978	0.5296	16
0.2883	0.9205	0.6044	12
0.1032	0.9976	0.5504	15
0.0000	0.0000	0.0000	27
0.0000	0.4026	0.2013	25
0.2956	0.6682	0.4819	19
0.0000	0.3683	0.1842	26
0.0004	0.6408	0.3206	23
0.1937	0.6181	0.4059	21
0.2297	0.4578	0.3437	22
0.2137	1.0000	0.6069	11
0.5294	1.0000	0.7647	4

The results highlight the critical significance of nano-based fillers and natural fibers in enhancing the mechanical behaviors of PE composites, which are essential for their use in environmental applications.

Compression molding was used to construct the final composite formulation that was derived from EDAS after optimization. The composite demonstrated a TS of 24.75 MPa, a FS of 31.25 MPa, and an IS of 21.47 kJ/m². These numbers indicate substantial enhancements compared to the outcomes derived from alternative Taguchi combinations. In environmental applications, these enhanced PE composites present compelling potential. The combination of NF increases mechanical characteristics while offering cost efficiency and biodegradability benefits.

3.6 Scanning Electron Microscopy (SEM) Results

The SEM findings shed light on the structural strength of PE composites in various mixes. The combination of 8wt.% NaOH treatment, 1.5 wt.% NBPF, and 15 wt.% NNNF resulted in visible voids within the resin and natural fiber phases, matrix fracture, and fiber fissuring, with a fiber length of 1cm (Fig. 10a). These faults resulted in diminished mechanical characteristics. Likewise, the combination of 8 wt% A, 1.5 wt% B, 25 wt% C, and 2 cm D (Fig. 10b) demonstrated matrix fractures, debonding, and fiber cracking. Conversely, 4 wt% A, 3.5 wt% B, 15 wt% C, and 3 cm D (Fig. 10c) exhibited gaps between the resin and matrix phases, and surface distortions. Although these defects were less pronounced, they nonetheless affected the mechanical qualities. The combination of 4 wt% A, 3.5 wt% B, 35 wt% C, and 3 cm D (Fig. 10d) exhibited markedly enhanced interfacial bonding between the NF phases and PE resin, with negligible surface deformations. The SEM findings highlight the need to customize the composite composition to achieve appropriate mechanical characteristics. A scanning electron microscope (SEM) was implemented to examine the surface morphology of specimens at the cross-sectional level (Antham *et al.* 2022).

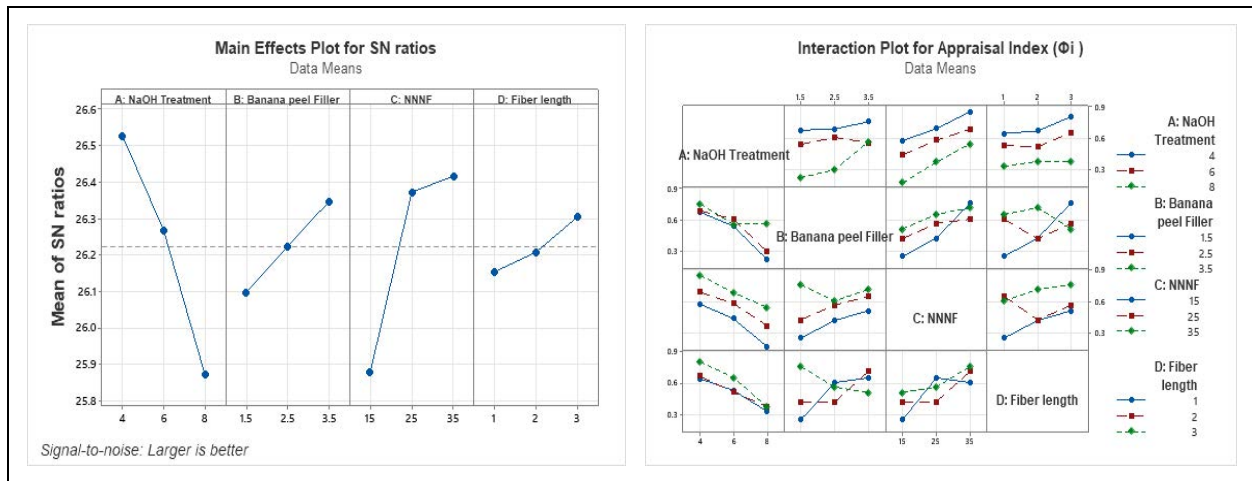


Fig. 9: (a) Main effect plot for SNR and (b) Interaction plot of appraisal index (EDAS)

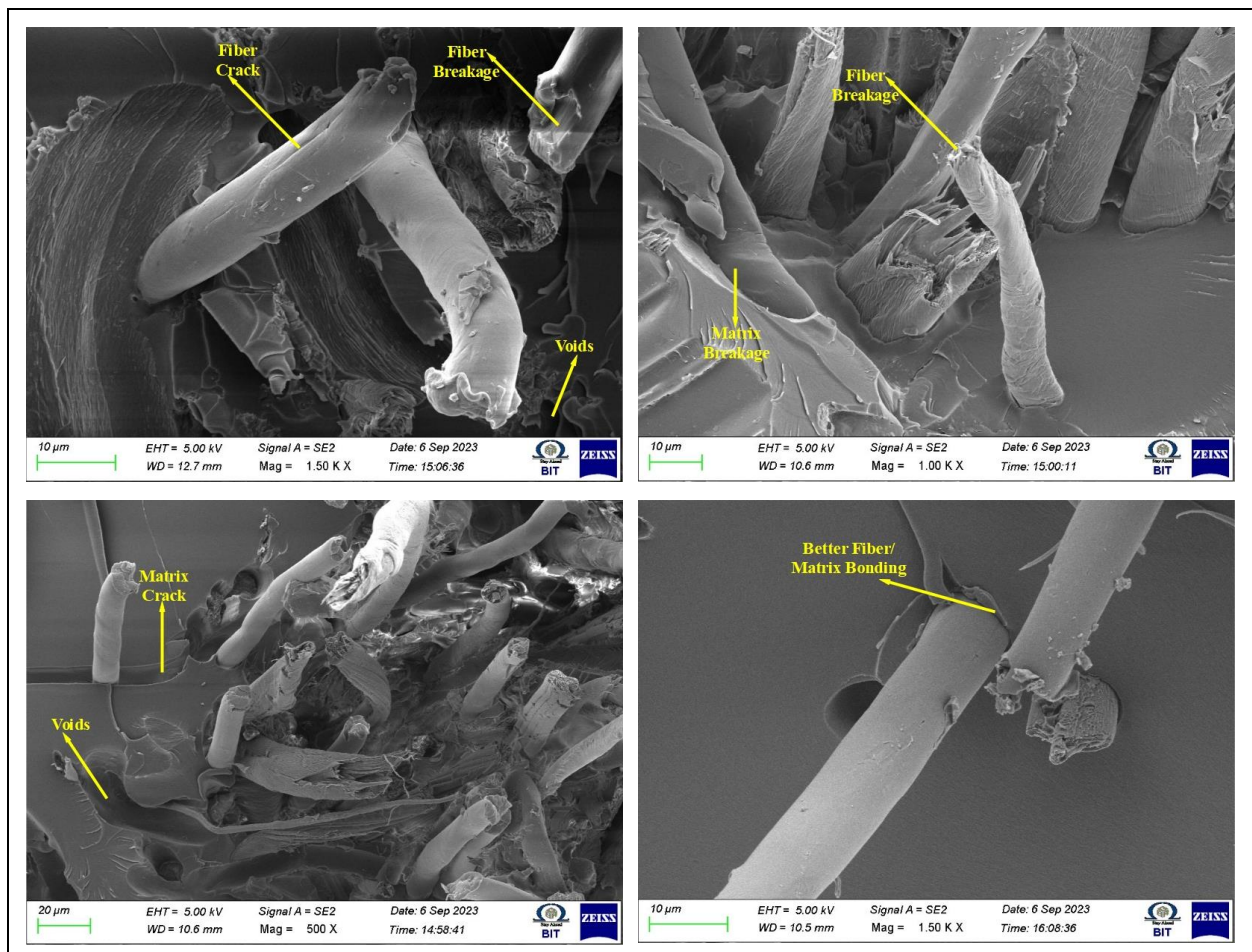


Fig. 10: Results of SEM analysis for (a) 8 wt % A/1.5 wt % B/15 wt % C/1 cm D, (b) 8 wt % A/1.5 wt % B/25 wt % C/2 cm D, (c) 4 wt % A/3.5 wt % B/15 wt % C/3 cm D and (d) 4 wt % A/3.5 wt % B/35 wt % C/3 cm D Combinations

4. CONCLUSIONS

This study developed a bio-based polyethylene composite using *Nelumbo sssnucifera* natural fiber (NNNF) and Nano-banana peel filler (NBPF), demonstrating improved mechanical properties through

NaOH treatment and optimized filler incorporation. FTIR confirmed strong polymer-filler interactions with characteristic peaks at 1451 cm^{-1} , 1052 cm^{-1} , and 1767 cm^{-1} , validating cellulose and $-\text{COO}-$ presence. Multi-response optimization identified an optimal composition of 4% NaOH treatment, 3.5 wt% filler, 35 wt% fiber, and

3 cm fiber length, achieving a tensile strength of 24.75 MPa, flexural strength of 31.25 MPa, and impact strength of 21.47 kJ/m². SEM analysis confirmed enhanced interfacial bonding with minimal surface defects. The ANN model reliably predicted mechanical performance with a validation performance of 0.26111 at epoch 2 and an overall r-value of 0.61523. This lightweight, durable composite presents a sustainable alternative for environmental applications, with future research focusing on hybrid fiber integration and enhanced thermoplastic properties.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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