



Influence of Zinc Oxide Nanoparticles on the Properties of Banyan Fiber/Epoxy Composites for Biomedical Applications

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ABSTRACT

This study examines the impact of zinc oxide nano particles (n-ZnO) on the mechanical, water absorption (WA) and morphological characteristics of banyan fibre (BF)-reinforced epoxy composite intended of the biomedical uses. The composites were prepared by hand layup procedure with varied weight percentages of n-ZnO (2%, 4%, and 6%) and BF concentrations (6%, 12%, and 18%). The study shows that the incorporation of up to 4 wt% n-ZnO increases tensile strength by 58.97%, achieving its maximum at this concentration. The flexural strength increases by 30.50% with 4 wt% n-ZnO, whilst the impact strength attains its maximum increase of 59.57% with 6 wt% n-ZnO. Water absorption measures exhibit a decline with higher n-ZnO content and prolonged exposure duration, indicating improved water resistance. The uniform distribution of n-ZnO, confirmed by scanning electron microscopy, causes improved water resistance and mechanical properties. Response surface methodology and Taguchi optimization evaluations provide additional evidence for the experimental findings and demonstrate that n-ZnO can enhance natural fiber-reinforced composites. This work illustrates that n-ZnO serves as an efficient filler to enhance mechanical properties and moisture resistance in eco-friendly composite materials.

Keywords: Banyan fiber; ZnO nanoparticles; Mechanical properties; Response surface methodology; Tensile strength.

1. INTRODUCTION

Numerous natural reinforcements are widely employed in composite synthesis; nonetheless, they possess specific disadvantages regarding water absorption properties. The use of natural fibers, specifically banyan aerial roots and banana fibers in composites, emphasizing the improvement of mechanical and thermal properties by hybridization with either natural or synthetic fibers. Prabhakar *et al.* (2022) examined the impact of fiber treatment, size, and orientation on the mechanical properties of natural fibre-based composites, emphasizing their environmental advantages. Kovačević *et al.* (2025) examined biocomposite materials made of biodegradable polylactic acid reinforced with *Spartium junceum* L. and *Sida hermaphrodita* fibers. The composites were also classified as flame-retardant due to reduced heat release rate. In another study, banyan tree roots were employed to extract fibers with intrinsic antibacterial properties, suitable for hygiene products and health (Rana and Chopra, 2022). Prabhakar *et al.* (2024) investigated the bending and tensile characteristics of hybrid composites

reinforced with banyan and banana fibers at different volume fractions (35B/15Ba, 30B/20Ba, 25B/25Ba,) following the treatment with a 5% NaOH solution. Similar synthesis strategies have been employed for TiO₂ nanoparticles, where both chemical and green methods were compared to highlight differences in morphology and functional properties (Blessymol *et al.* 2023). Raja and Anand, (2022) investigated alkali-treated neem fibers and bidirectional woven mats reinforced in an epoxy matrix with sawdust cellulose filler. The hybrid composites, with varying reinforcement, matrix, and filler fractions, showed a maximum storage modulus of 1,343 MPa, with increased stiffness (61%) in bidirectional woven fibers compared to chopped neem fibers. The SEM analyses revealed improved crystallinity and adhesion integrity between the fibers, fillers, and matrix. Baskar *et al.* (2025) reported a composite reinforced within 3% alumina embedded banyan fibers, exhibiting substantial enhancements in tensile strength. The composite showed excellent mechanical properties like compressive strength (67.49 MPa), flexural strength (69.38 MPa), impact strength (19.47 kJ/m²), and superior fatigue resistance (40 MPa for 14,000 cycles). The SEM

analysis confirmed structural integrity, and antibacterial tests exhibited a 12 mm inhibitory zone, rendering it appropriate for applications in medical devices and bioactive environments.

Senniagiri *et al.* (2025) investigated the effect of ZnO nanoparticles on the mechanical characteristics, water absorption, fire retardant, and dynamic mechanical behavior of *Nelumbo nucifera* fiber and epoxy composites. The addition of 12 wt% n-ZnO nanoparticles improved the modulus of elasticity (2117 MPa), tensile strength (48 MPa), and elongation with a 30.48% increase in flexural strength (60 MPa). Water absorption and swelling thickness were reduced, while the dynamic mechanical properties and fire resistance (combustion rate of 18 mm/min) were enhanced. Ganapathy *et al.* (2021) investigated the impact of graphene as an additive in banyan fiber-reinforced epoxy composites. The incorporation of 4% Gr to 40% banyan fiber composite markedly enhanced TS, FS, Shore D hardness, and decreased WA. Lakshmaiya *et al.* (2025) conducted a study on the factors affecting the mechanical behaviour of hybrid composites fabricated from pineapple fiber and nano SiO₂ utilizing hand lay-up technique. The optimal composite, containing 20% pineapple fiber (10 mm length), 5% SiO₂ nanoparticles, and 6 hours of alkali treatment, exhibited the highest mechanical performance. Arunachalam *et al.* (2024) employed RSM (Response Surface Methodology) and CCD (Central Composite Design) to improve immersion duration, silane concentration, and nano-filler content of composites intended for automotive applications. Optimal conditions (15% silane and 30 minutes of immersion) yielded a 36.20% increase in impact strength and a 19.22% enhancement in tensile strength, underscoring the critical influence of silane treatment on composite performance. Through the use of RSM and CCD, the developed predictive models that showed a 23% improvement in flexural strength with the addition of nano-fillers, particularly TiO₂-infused polymers. Sathish *et al.* (2024) studied the impact of silane treatment on Jute/kenaf/glass fiber composites incorporating TiO₂ nano-filler, optimizing, immersion duration, silane concentration and nano-filler content by RSM and CCD. The ideal conditions (15% silane and 30 minutes of immersion) yielded a 32.13% enhancement in tensile strength and an 8.34% rise in impact strength, underscoring the significance of silane treatment in augmenting mechanical properties and fiber-matrix bonding in natural fiber composites.

Kumar *et al.* (2024) demonstrated the influence of nTiO₂ on the sliding wear and mechanical characteristics of basalt-PLA hybrid composites, with nTiO₂ concentration ranging from 0 to 9 wt.%. The findings indicated an enhancement in tensile and flexural strength up to 6 wt.% nTiO₂. However, a greater concentration (9 wt.%) resulted in agglomeration and reduced the performance. The ideal sliding wear

parameters were determined to be 2 m/s sliding velocity, 6 wt.% nTiO₂ concentration, and 40 N normal load, with SEM examination elucidating the wear mechanisms under these conditions.

Sumesh *et al.* (2022) fabricated hybrid composites using pineapple (P) and sisal (S) fibers, with TiO₂ as a nanofiller. Their mechanical and tribological behaviour were also studied. The 5 wt.% TiO₂ /40 wt.% SP composite exhibited notable enhancement in mechanical properties, and the Taguchi method indicated that increased TiO₂ content (5 wt.%) reduced the specific wear rate. Optimal results were attained using 5 wt.% TiO₂, 20 wt.% SP, a sliding distance of 500 m, a sliding speed of 1 m/s, and an applied load of 5 N. Ashok *et al.* (2022) reported the effect of lead oxide nanoparticles on the thermal, mechanical, and water absorption properties of epoxy composites reinforced with luffa fiber. The research demonstrated that the incorporation of 1.25 wt.% of PbO increased tensile, flexural, and impact properties, in addition to enhancing moisture resistance, indicating its applicability in structural and packaging contexts. The SEM investigation identified flaws such as fiber pull-outs and voids, underscoring the necessity for enhanced fiber-matrix bonding. Padma *et al.* (2022) fabricated jute fiber-reinforced vinyl ester resin composites, both with and without SiO₂ nanoparticles and studied their mechanical characteristics. The research indicated that the incorporation of SiO₂ markedly increased tensile strength by 50% and compressive strength, flexural strength, and hardness by 5-10%, attributable to robust fiber-filler adhesion. The SEM examination validated the beneficial effect of fillers on fiber-matrix interaction, enhancing the suitability of the composites for diverse industrial applications. The study by Rajesh *et al.* (2024) shows the influence of alumina and silica nanoparticles on epoxy composites reinforced with Indian almond fiber. Four composites (C0, C1, C2, C3) with a 70:30 resin-to-fiber ratio and 3 wt% nanoparticles demonstrated marked enhancements in mechanical properties, with C2 displaying the highest TS (84 MPa), FS (122 MPa), and IS (impact strength) (7.31 kJ/m²), in addition to exceptional wear and friction performance. Kumar *et al.* (2025) developed bamboo, ramie, and hybrid bamboo - ramie composites incorporating SiC and Al₂O₃ nano-fillers by hand-layup and compression molding techniques. The ramie-bamboo hybrid composite demonstrated superior TS (50.16 MPa), IS (6.30 kJ/m²), and hardness (79.4), whereas the pure ramie composite displayed the highest flexural strength (101.4 MPa). However, the presence of nano-fillers led to agglomeration, diminishing the overall strength of the hybrid composites.

The composites composed of randomly aligned mudar and snake grass fibers with a 3% SiO₂ nanoparticles exhibited optimal mechanical performance at 30% fiber content, achieving a TS of 45 MPa, a FS of 51 MPa, and an IS of 4.5 J, rendering them suitable for

structural and automotive applications (Jenish *et al.* 2022).

A hybrid composite comprising agro-waste areca fruit husk and *Tamarindus indica* fruit fibers, incorporating SiC nano fillers (1-4 wt.%) inside an unsaturated polyester resin matrix was reported. The composite with 3 wt.% SiC showed superior mechanical, thermal, and wear characteristics, including TS (9.137 MPa), FS (104.056 MPa), IS (7.983 J/cm²), and heat stability (360°C), enhancing its suitability for automotive and marine interior applications (Hariharan *et al.* 2023).

The application of acetic acid-treated *Pithecellobium dulce* seed pod (PD) powder as an economical adsorbent for Reactive Red 195-A dye removal from aqueous solutions was reported by Gaddala *et al.* (2025). The research indicated that adsorption adhered to the Temkin isotherm and pseudo-second-order kinetics, characterized as endothermic and spontaneous, proposing the PD seed pod as an environmentally sustainable substitute for chemical adsorbents.

Sachin *et al.* (2024) developed environmentally friendly green composites utilizing abaca and areca fibers reinforced with epoxy and SiO₂ nanoparticles. The research demonstrated notable enhancements in mechanical properties (flexural, tensile, and impact strengths) at 20% ARF, 76% ABF, and 4% SiO₂, with SEM analysis indicating enhanced fiber-matrix bonding and ecological advantages from hybridization. Gul *et al.* (2021) showed that the addition of zinc oxide (n-ZnO) nanoparticles (0-3 wt.%) to urea formaldehyde (UF) resin for medium-density fiberboard (MDF) applications resulted in significant improvements in thickness swelling (38%) and water absorption (12%) with 3% n-ZnO, alongside enhanced thermal properties and curing. Natural fiber composites using banyan and cotton were fabricated by compression molding in five ratios (B, BC (1:1), BC (3:1), BC (1:3), C). Banyan composites showed the highest tensile (75 MPa), flexural (113 MPa) strengths, thermal resistance (18.1×10⁻³ m²K/W), lowest CTE (1.81 × 10⁻⁵/°C), and highest thermal diffusivity (8.79 × 10⁻⁷ m²/s), making them ideal for insulation applications (Baladivakar *et al.* 2023).

The objective of this work is explicitly centered on the fabrication of sustainable composites utilizing BF reinforcements and ZnO nano filler material. The incorporation of n-ZnO in the development of sustainable polymer composite offers an effective approach to enhancing material performance, owing to its multifunctional properties, including improved mechanical properties, thermal stability and moisture resistance. The disposal of n-ZnO in landfills is raising significant issues over soil, air, and water contamination. Therefore, it is essential to devise eco-friendly strategies for employing n-ZnO to develop composites with enhanced properties and sustainability.

2. MATERIALS AND METHODOLOGY

The matrix materials used in this study, epoxy (LY-556) and hardener (HY-951), were purchased from Kovai Cheenu Enterprises in Coimbatore. Fig. 1 depicts the exact molecular configuration of the hardener and epoxy utilized in this research. Epoxy resins generally comprise linear polymers with epoxide group functions (–CH₂–CH₂–O–), endowing them with a range of properties suitable for various uses. In contrast, hardeners contain amine group functional (–NH₂) that promote crosslinking with epoxy, resulting in a durable 3D network design post-curing. Epoxy resins are valued for their chemical stability, mechanical integrity and adhesive strength, whereas hardeners are essential for improving the material's overall efficiency. They generally possess densities between 1.1 and 1.4 g/cm³, while hardeners typically range from 0.8 to 1.2 g/cm³, with density and other properties dependent on its composition and intended use.

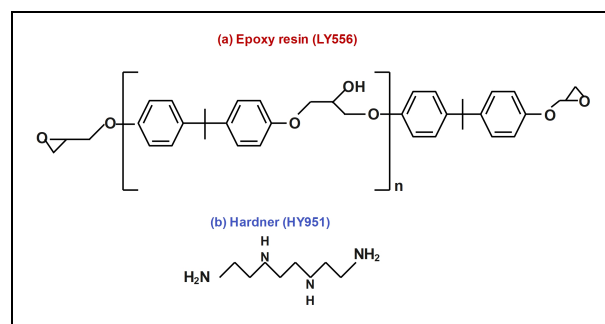


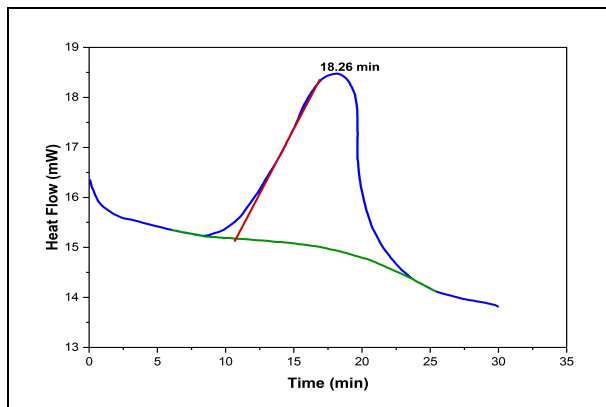
Fig. 1: Molecular structures of (a) epoxy and (b) hardener

Banyan fibre (BF) was sourced from Fiber Source Enterprises in Chennai, Tamil Nadu, India. It was utilized as reinforcement. The cellulose component of BF generally varies between 40% and 50% of its overall composite. The lignin content typically comprises of approximately 20% to 30% of the composition of BF.

To improve the efficiency of the BF reinforced composites, ZnO was used as a nanofiller material. It was acquired from Matrices Enterprises in Nagercoil, Tamil Nadu, India. Preliminary testing and a literature review determined the weight percentage of BF, which varied between 6% to 18%, and n-ZnO varied between 2wt% to 6wt%. A BF percentage below 6 wt% resulted in reduced strength qualities, while a content beyond 18 wt% caused agglomeration and coring, resulting in void formation. Likewise, n-ZnO concentrations below 2 wt% exerted negligible influence on strength; nevertheless, above 6 wt% resulted in fiber debonding attributable to n-ZnO agglomerates inside the matrix. A L9 orthogonal array is utilized in the experimental procedure to establish suitable weight percentages of 4 wt% n-ZnO and 12 wt% BF. Table 1 presents the weight percentage of the various composite specimens.

Table 1. Weight percentage of components for various samples

Sample	BF (wt.%)	n-ZnO (wt.%)	Epoxy + Hardener (wt.%)
S ₁	0	0	100
S ₂	0	4	96
S ₃	12	0	88
S ₄	6	2	92
S ₅	12	2	86
S ₆	18	2	80
S ₇	6	4	90
S ₈	12	4	84
S ₉	18	4	78
S ₁₀	6	6	88
S ₁₁	12	6	82
S ₁₂	18	6	76

**Fig. 3: Differential scanning calorimetry for epoxy resin**

The fabrication process involved stirring chopped banyan fibers and n-ZnO into an epoxy hardener matrix by hand. The slurry was injected into the mold after the mold surface was completely rinsed and a releasing agent was added to avoid adherence. To guarantee adequate bonding and eliminate voids or air pockets, brushes and rollers were employed to meticulously saturate each layer with epoxy resin. The application proceeded incrementally until the specified laminate configuration and thickness were achieved. Following the consolidation of layers and the elimination of trapped air bubbles, the composite was permitted to cure for 24 hours at 90°C. Upon completion of the curing

process, the composite component was polished, trimmed, and demoulded to attain the requisite smoothness and aesthetics. Fig. 2 shows the fabricated composite laminate and specimens for tensile, flexural and impact tests, while Fig. 3 shows the DSC of epoxy curing. The curing reaction exhibits a noticeable peak in the DSC curve at 18.26 minutes. This peak indicates the start of the crosslinking process among the curing agent and epoxy resin, which marks the beginning of epoxy curing. The heat flow during the curing process is indicated by the peak at 1184 mJ.

**Fig. 2: Images of (a) composite laminate specimens of (b) tensile test, (c) flexural test and (d) impact test**

Abrasive jet machining was used to cut the composite laminate as per ASTM standard dimensions for impact, flexural, and tensile testing. Tensile tests using specimens of $50.8 \times 12.7 \times 3.2$ mm were carried out on Instron Universal testing machine in accordance with ASTM D3039/D3039M standards. According to ASTM D790/D790 M, flexural tests use specimens that are $127 \times 12.7 \times 3.2$ mm, whereas Izod impact testing uses specimens that are $63.5 \times 12.7 \times 3.2$ mm, in accordance with ASTM D256 standards. The results were documented and examined to evaluate the influence of n-ZnO on properties. The WA behavior was examined following ASTM D 570-98 criteria, utilizing rectangular specimens of $75 \times 25 \times 3.2$ mm, which were prepared and dried before immersion in distilled water. The WA percentage was calculated using equation (1) and weight measurements taken at regular intervals.

$$(W_t - W_0)/W_0 \times 100 \quad \dots (1)$$

W_t signifies the sample weight at time t , whereas W_0 indicates the initial weight documented prior to water absorption.

This method was adopted for each composite sample to obtain WA across all weight percentages of fiber and filler contents and for differing time durations.

Young's modulus (YM) was calculated from the slope of the initial linear portion of the stress-strain curve obtained in tensile testing (ASTM D3039/D3039M) Flexural modulus (FM) was determined from three-point bending tests (ASTM D790/D790M) using where LLL is span length, mmm is slope of load-deflection curve, bbb is width, and ddd is thickness.

An L9 orthogonal array (Taguchi method) was employed to optimize banyan fiber (BF) and n-ZnO contents. Control factors were BF (6–18 wt%) and n-ZnO

(2–6 wt%). Responses included tensile, flexural, impact strengths, YM and FM. Signal-to-noise (S/N) ratios were calculated using the “larger-is-better” criterion for mechanical properties.

Analysis of Variance (ANOVA) determined the significance and percentage contribution of each factor. Statistical analysis, including S/N ratios and ANOVA, was performed using MINITAB 19, with a 95% confidence level ($p < 0.05$) to identify optimal levels.

3. RESULTS AND DISCUSSION

Table 2 displays the mechanical characteristics of banyan fibre and n-ZnO-reinforced epoxy composites, with n-ZnO content changing from 2 to 6 wt% and banyan fibre content ranging from 6 to 18 wt%. Furthermore, two distinct combinations of S_3 and S_4 are analyzed to assess the effects of the addition of n-ZnO and BF on the characteristics of the composites.

Table 2. Mechanical characteristics of epoxy composites reinforced with banyan fiber and zinc oxide nanoparticles

Samples	TS (MPa)	Young's Modulus (GPa)	FS (MPa)	Flexural Modulus (GPa)	IS (kJm ⁻²)
S ₁	57.72	1.7	130.62	5	28.1
S ₂	75.46	3.1	147.76	5.3	37.97
S ₃	70.76	2.9	137.66	5.2	29.6
S ₄	61.72	2	127.22	4.8	28.81
S ₅	66.36	2.4	136.66	5.2	29.72
S ₆	63.86	2.3	131.76	5	30.89
S ₇	78.52	3.1	160.02	5.6	34.53
S ₈	91.76	3.9	170.46	5.9	38.72
S ₉	83.36	3.5	168.56	5.8	40.35
S ₁₀	71.02	2.7	139.12	5.1	43.15
S ₁₁	74.56	3.1	149.06	5.4	44.84
S ₁₂	78.46	3.3	154.16	5.5	39.09

3.1 Ultimate Tensile Strength (UTS)

As the weight percentage of banyan fiber exceeds 12 wt%, a decline in the ultimate tensile strength of the composites is observed. This is probably attributable to the inherent properties of natural fibers, which possess lesser TS relative to synthetic fibers or alternative reinforcing materials. The incorporation of n-ZnO appears to enhance the UTS. Composites with increased n-ZnO content and reduced BF percentage generally demonstrate elevated ultimate tensile strength. The composite S_8 demonstrated the greatest tensile strength, reflecting a 58.97% enhancement relative to clean epoxy. Fig. 4 presents a comparison bar chart illustrating the UTS for varying weight percentages of BF and n-ZnO. Likewise, the impact of nano-SiO₂ fillers

(0%, 1%, 2%, 3%, 4%) on the mechanical properties of kenaf fiber polymer composites was observed by Jotiram *et al.* (2022). Their results showed that up to 2% filler, the composite exhibited a significant enhancement in tensile strength (20.61%), compressive strength (23.71%), and impact strength (22.88%), with no further improvements beyond this concentration.

3.2 Young's Modulus (YM)

It was observed that increasing the n-ZnO concentration above 4 wt% leads to a reduction in Young's modulus. This is due to the inherent lower stiffness of natural fibres compared to synthetic fibres. The n-ZnO is noted to positively influence Young's modulus, indicating its role as a reinforcing filler that

enhances the rigidity of the composite. The composite S₈ demonstrates the greatest stiffness, possessing a YM of 3.9 GPa. Fig. 5 displays a comparative bar chart depicting YM for different weight percentages of BF and n-ZnO.

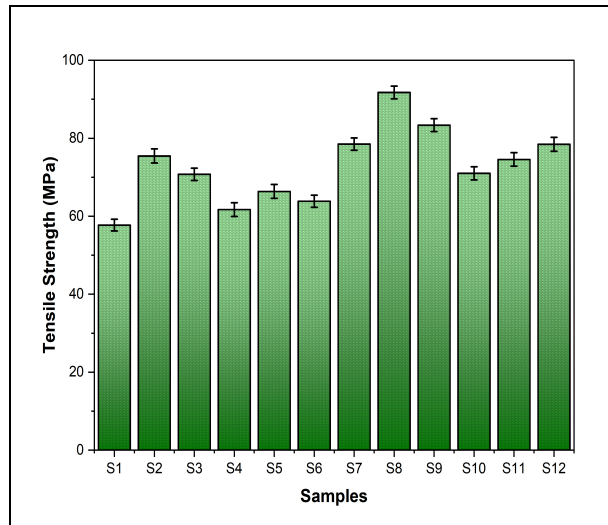


Fig. 4: TS for various samples

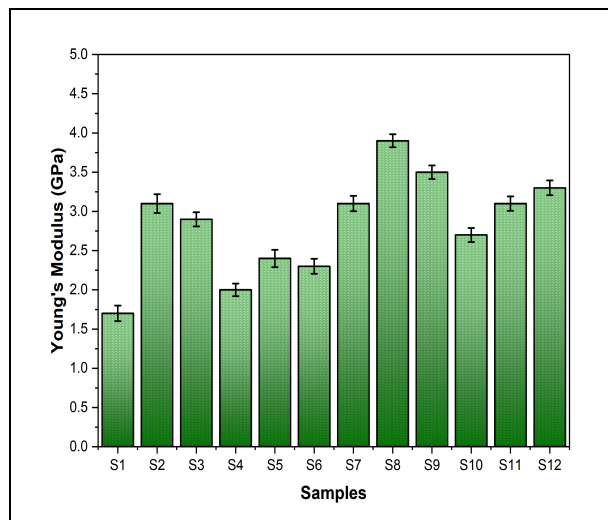


Fig. 5: Young's modulus for various samples

3.3 Flexural Strength and Flexural Modulus

Flexural strength and flexural modulus are critical parameters for assessing the capacity of composites to endure bending or flexural loads. The findings demonstrate that an increase in the weight percentage of BF resulted in a marginal reduction in both FS and FM. This aligns with the tendency noted in the TS, where the reduced strength of natural fibers influences these qualities. Conversely, as demonstrated by the UTS and YM, the incorporation of n-ZnO appears to positively influence FS and FM, hence augmenting the composite's resistance to bending. The composite S₈ had a peak FS of 170.46 MPa, reflecting a 30.50% improvement relative to unmodified epoxy. Fig. 6

presents comparative bar charts illustrating the FS and FM for varying weight percentages of BF and n-ZnO. Similarly, Mayakannan *et al.* (2023) studied hybrid polymer composites made from PALF/sisal fibers and SiO₂ nanoparticles with varying concentrations (0-8 wt.%). They showed that composites with 4 wt.% SiO₂ demonstrated superior mechanical properties (53.36 MPa tensile, 61.25 MPa flexural) and reduced wear by 8–13%. Thus, the incorporation of SiO₂ in the composite enhanced mechanical strength and wear resistance, which could be of use in automotive, aerospace, and packaging industries.

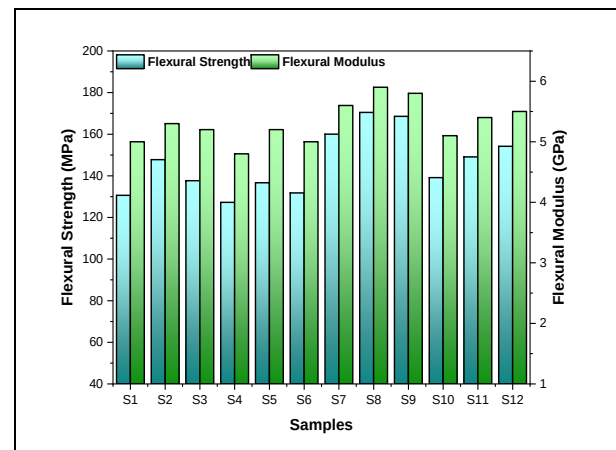


Fig. 6: Flexural strength and modulus for different samples

3.4 Impact Strength

Impact strength quantifies the capacity of the materials to absorb energy under impact loading conditions. The IS exhibits no consistent correlation with the changing weight percentages of banyan fiber and n-ZnO. The IS enhances with the incorporation of BF and n-ZnO in the S₅, S₆, S₇, S₈, S₉, S₁₀ composites, peaking at 44.84 kJ m⁻² for S₁₁ composite, reflecting a 59.57% improvement over neat epoxy; however, it experiences a slight decline in the S₁₂ composite. This behavior can be ascribed to the complex interaction of variables such as interfacial bonding, fiber dispersion, and fiber orientation inside the material. The homogeneous dispersal of reinforcing fibers inside the matrix, the strength of the bond between the matrix and fibers material, and the orientation of these fibers are all strongly related to the IS of composite materials. Deliberate fiber orientation that increases the material's ability to withstand impact loads, strong interfacial bonding that facilitates efficient stress transmission, and a more uniform fiber distribution that reduces stress concentration all contribute to improved impact strength. These components work together and are interdependent. Thus, a thorough approach to optimizing these factors can greatly increase impact resistance and make composite materials incredibly versatile for a range of uses. Fig. 7 presents a comparison bar chart illustrating the impact strength for varying weight percentages of BF and n-ZnO.

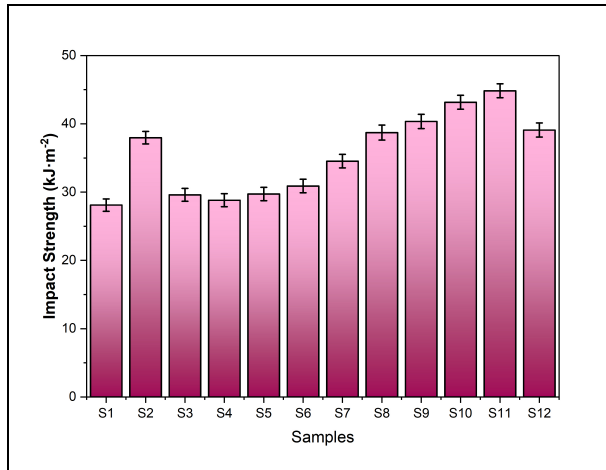


Fig. 7: Impact strength for different specimens

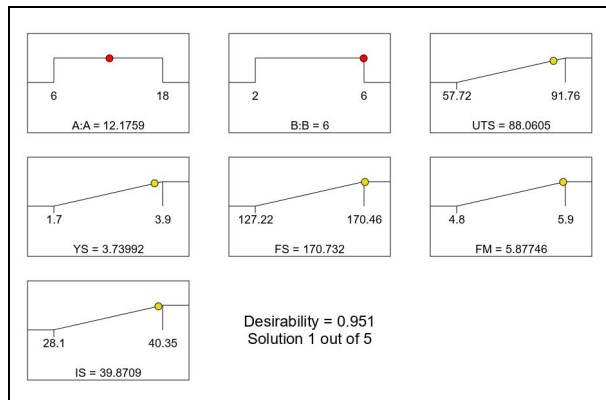


Fig. 8: Optimality experimental findings

3.5 Optimization

The data relates to a design experiment in which numerous parameters and responses were assessed across multiple trials. This study employed Design-Expert for experimental design and process optimization through the analysis of intricate experimental data. For optimization analysis, samples with 12.18 wt% BF and 6 wt% n-ZnO were considered. The optimality test evaluates desirability values for goal achievement, assesses established optimization criteria, and accounts for standard mistakes in measurement accuracy. Table 3 presents the findings of the optimality run, which is near 12 wt% BF and 6 wt% n-ZnO, yielding comparatively superior mechanical properties. Fig. 8 illustrates the results of the optimization experiment.

The initial phase of Taguchi and RSM analysis was conducted for TS to evaluate the results of the optimality experiment, specifically to examine the effect of weight percentage of BF and n-ZnO on properties of composites. Tables 4 shows the means and signal-to-noise (S/N) ratios for TS and Fig. 9 illustrates the main effect plots for the same.

Table 3. Experimental results of optimality

A (wt.%)	12.18
B (wt.%)	6
TS	88.06
YM	3.74
FS	170.73
FM	5.88
IS	39.87
Desirability	0.951

Table 4. Means and S/N ratios for tensile strength

Level	Means		S/N Ratio	
	A (wt.%)	B (wt.%)	A (wt.%)	B (wt.%)
1	36.12	36.91	63.98	70.42
2	38.52	37.71	84.55	77.56
3	37.46	37.47	74.68	75.23
Delta	2.41	0.80	20.57	7.14
Rank	1	2	1	2

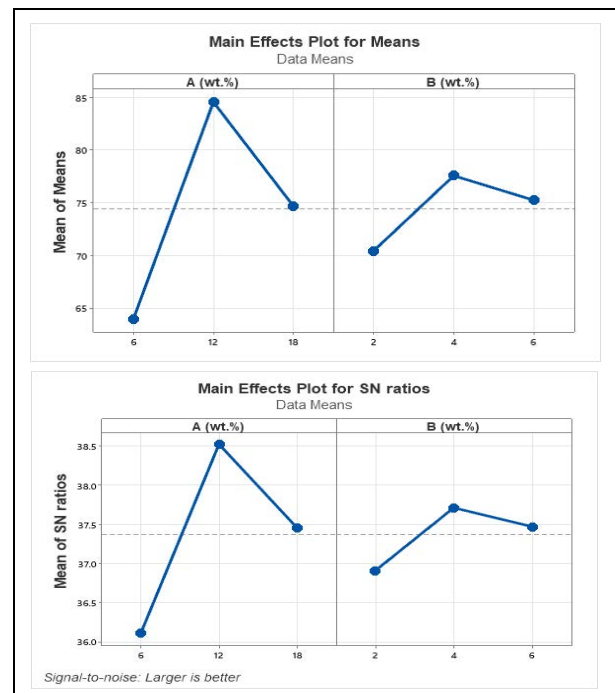


Fig. 9: Main effects plot for means and S/N ratios for tensile strength

The main effects plot and response tables demonstrate that level 2 (A_2 and B_2) produces the highest tensile strength for the "larger the better" signal-to-noise ratios, with the weight percentage (wt%) of n-ZnO identified as the foremost contributor to TS, succeeded by the weight percentage of BF.

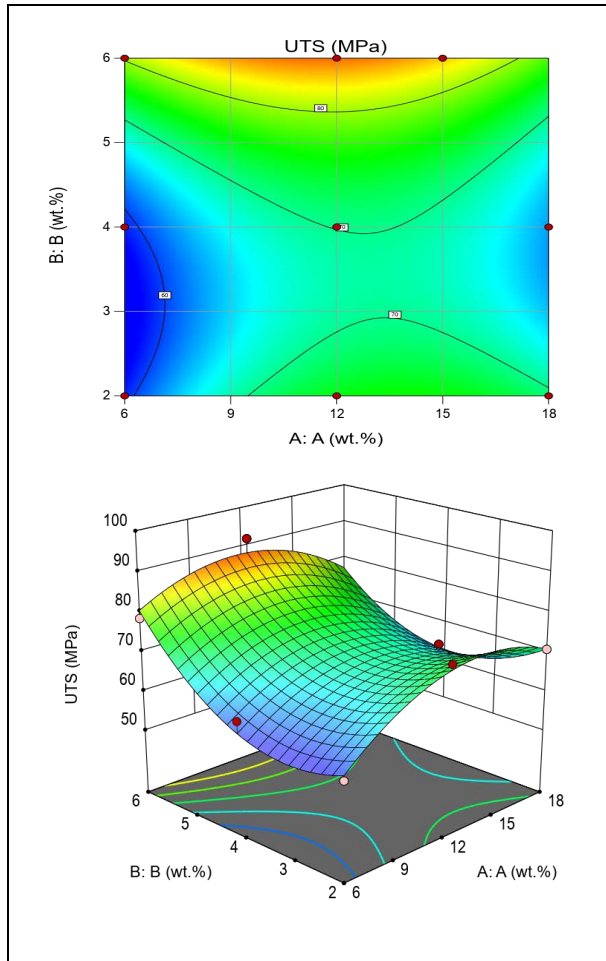


Fig. 10: Counter and surface plot tensile strength

The RSM was performed utilizing Design-Expert 13 to determine the best weight percentage of BF

and n-ZnO for ultimate tensile strength in MPa for the composites. Fig. 10 displays the contour and surface plot for several design points associated with varying weight percentages of BF and n-ZnO. The figures clearly indicate that the highest UTS occurs within 4 wt% to 4.5 wt% range for n-ZnO filler and 12 to 14 wt% range for BF reinforcements. The predicted and actual plots for the TS exhibit a strong correlation, as illustrated in Fig. 11.

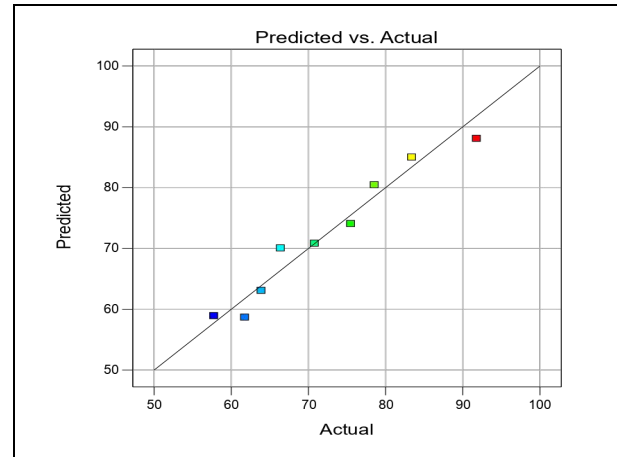


Fig. 11: Actual versus predicted tensile strength

Table 5 presents the analysis of variance table, indicating that the model's F-value of 11.96 demonstrates its significance. An F-value of this size is only 2.43% likely to be the result of random noise. It is implied that the model terms are not significant by P-values of 0.1. Model reduction can improve the model if it contains many insignificant words, provided that essential terms for maintaining hierarchy are retained.

Table 5. Mix proportions of the geopolymer concrete

Source	SS	DF	MS	F-value	P-value	
Model	935.99	5	187.20	11.96	0.0339	significant
A-A	21.94	1	21.94	1.40	0.3217	
B-B	262.03	1	262.03	16.74	0.0264	
AB	38.08	1	38.08	2.43	0.2167	
A ₂	134.26	1	134.26	8.58	0.0610	
B ₂	232.64	1	232.64	14.87	0.0308	
Residual	46.95	3	15.65			
Cor Total	982.94	8				

SS – Sum of Square, MS – Mean Square

Table 6 presents the fit statistics, indicating that the projected R^2 of 0.9522 is not in close proximity to the corrected R^2 of 0.8726. This may suggest a substantial block impact or a potential issue with the simulation. The

critical components for assessing fit statistics encompass model decrease, outliers, response alteration, and additional elements. All experiments were validated using confirmation runs. Adequate accuracy measures

the S/N ratio. A ratio greater than 4 is ideal. The ratio of 9.1006 indicates an acceptable signal. The design space can be traversed using this model. Equation (2) is the regression model based on the fit statistics for tensile strength calculated using RSM.

$$UTS = 43.95 + 7.74 A - 14.75 B - 0.313 A * B - 0.255 A^2 + 2.75 B^2 \quad \dots (2)$$

A represents the BF in weight percent, whereas B is denoted as zinc oxide nanoparticles in weight percent.

Table 6. Fit statistics for tensile strength

Standard Deviation	3.96	R ²	0.9522
Mean	72.17	Adj. R ²	0.8726
C.V. %	5.48	Pred. R ²	0.5791
Adeq Precision		9.1006	

A verification test was carried out to assess the model's validity and compare its projections within the measured results. The results of the validation test are displayed in Table 7.

Table 7. Confirmation test results

A (wt%)	B (wt%)	Tensile Strength		Error %
		Experimental	Predicted	
12.18	6	91.76	88.06	1.84

The table, in conjunction within the optimum test findings and Taguchi method generated utilizing Minitab Software, indicates that the predicted TS, rounded to four decimal places, closely aligns with the experimental TS, hence corroborating the RSM model developed with Design-Expert.

3.6 Comparison of the Composites

Due to inherent strength and stiffness of the BF and n-ZnO's potential as a composite filler, epoxy composites enhanced with these two materials were studied as a sustainable alternative to synthetic composites. This investigation analyzed the mechanical characteristics of different epoxy materials including varying quantities of n-ZnO and BF, alongside neat epoxy counterparts for comparative purposes. The findings demonstrated that the S₈ composite showcased the greatest overall efficiency, exhibiting exceptional FS (170.46 MPa), FM (5.9 GPa), and S₁₁ exhibiting exceptional IS (44.84 kJ m⁻²). While the S₇ and S₈ composites exhibited commendable performance, S₉ demonstrated marginally superior outcomes. All composites exhibited superior mechanical properties

relative to clean epoxy, highlighting the efficacy of BF and n-ZnO as reinforcing agents. The selection of suitable reinforcing filler combinations is contingent upon specific application requirements and the necessary balance of stiffness, strength, and IS. Additional optimization and experimentation can be required for the exact customization of composite properties for certain technical uses. The ideal weight percentage of fiber and filler in the S₅ composite exhibits improved overall efficiency, rendering it appropriate for applications that prioritize these characteristics. The optimization indicated that around 21 wt% BF and 6.5 wt% n-ZnO accurately forecasted results in close accordance within the experimental results, thereby minimizing the value differential to achieve the optimum ratio of reinforcing agent and filler of the material.

3.7 Water Absorption

Water absorption measurements were meticulously observed for 24-hour period for a total of 5 days, with the results documented and organized in Table 8. The original pilot studies lasted 5 days, indicating that water absorption approaches a near-constant level after this period.

Table 8. WA data for each 24-hour period over a 5-day period

Sample	Percentage of Water Absorption (Day)				
	1	2	3	4	5
S ₁	6.53	6.03	5.83	5.63	4.52
S ₂	7.36	6.95	6.66	6.05	5.46
S ₃	10.12	9.01	7.99	6.41	5.31
S ₄	3.53	2.83	2.71	2.51	2.31
S ₅	5.74	5.01	4.55	4.34	4.34
S ₆	7.56	8.26	7.74	6.74	5.43
S ₇	4.40	4.08	3.91	3.47	3.38
S ₈	6.62	5.72	5.13	4.32	4.03
S ₉	8.63	7.03	6.33	5.22	4.61
S ₁₀	3.57	2.66	2.46	2.37	2.26
S ₁₁	4.49	3.97	3.79	3.70	3.59
S ₁₂	5.51	5.10	5.02	4.81	4.61

The supplied data delineates WA percentages for different samples. In samples S₄, S₅, and S₆, a rise in the weight percentage of n-ZnO corresponds with a general reduction in WA, indicating the filler result that reduces overall material porosity. This tendency continues in samples S₇, S₈, and S₉, where there is elevated n-ZnO content. Likewise, the trend persists in S₁₀, S₁₁, and S₁₂, where increased n-ZnO concentration is associated with less WA owing to the filling effect and a general decrease in porosity. Similarly, Velmurugan *et al.* (2022) evaluated hybrid composites using banyan and peepal fibres with 70% epoxy in four combinations:

banyan, peepal, BPB (20% banyan, 10% peepal), and PBP (10% banyan, 20% peepal). BPB composite showed the lowest density, 5% porosity, and superior mechanical properties with increases in tensile (2.7%), flexural (4.9%), and impact (13.5%) strength over PBP. Water absorption was also lowest in BPB (9% after 12 hours), rendering it a promising material for industrial uses.

A comparative investigation with S_1 , S_2 , and S_3 indicates that the incorporation of BF typically enhances WA relative to S_1 , likely attributable to the hydrophilic characteristics of these fibers. Generally, specimens with increased banyan fibre content demonstrate enhanced water absorption, perhaps due to the introduction of hydrophilic properties and extra porosity. In contrast, the inclusion of n-ZnO appears to reduce WA, suggesting its possible function in decreasing porosity and improving water resistance. Furthermore, WA reduced during five days due to the saturation of the fibers with water, together with the n-ZnO filler-induced micro-coring as well as void and micro-gap closure between the matrix and fibers. The water absorption patterns demonstrate the intricate relationship between banyan fibre and n-ZnO, wherein banyan fibre increases WA, whereas n-ZnO creates a filling effect that diminishes WA, with results dependent on the weight fraction of various additives within the epoxy matrix. Fig. 12 illustrates the proportion of WA for different specimens, with error bars, throughout a 5-day period at 24-hour intervals. Following 120 hours of water absorption, all composite specimens demonstrated saturation in WA and thickness swelling. The addition of reinforcements led to increased WA compared to pure epoxy. The composite with the optimal weight ratio of natural reinforcement and filler exhibited a significant decrease in WA, attributable to uniform mixing and improved bonding between the reinforcements and the matrix.

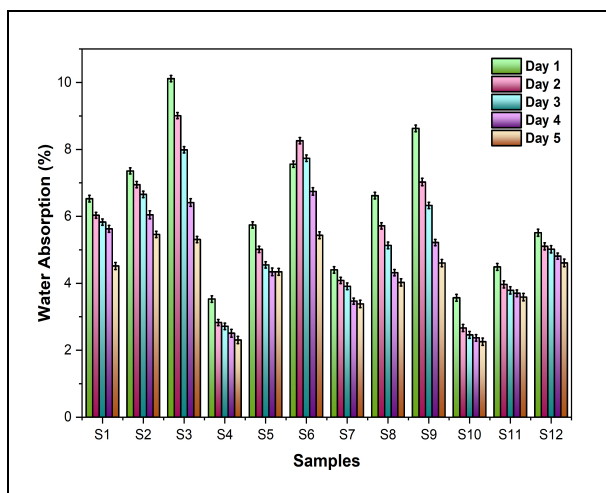


Fig. 12: Percentage of water absorption for various samples at 24-hour intervals for a duration of 5 days

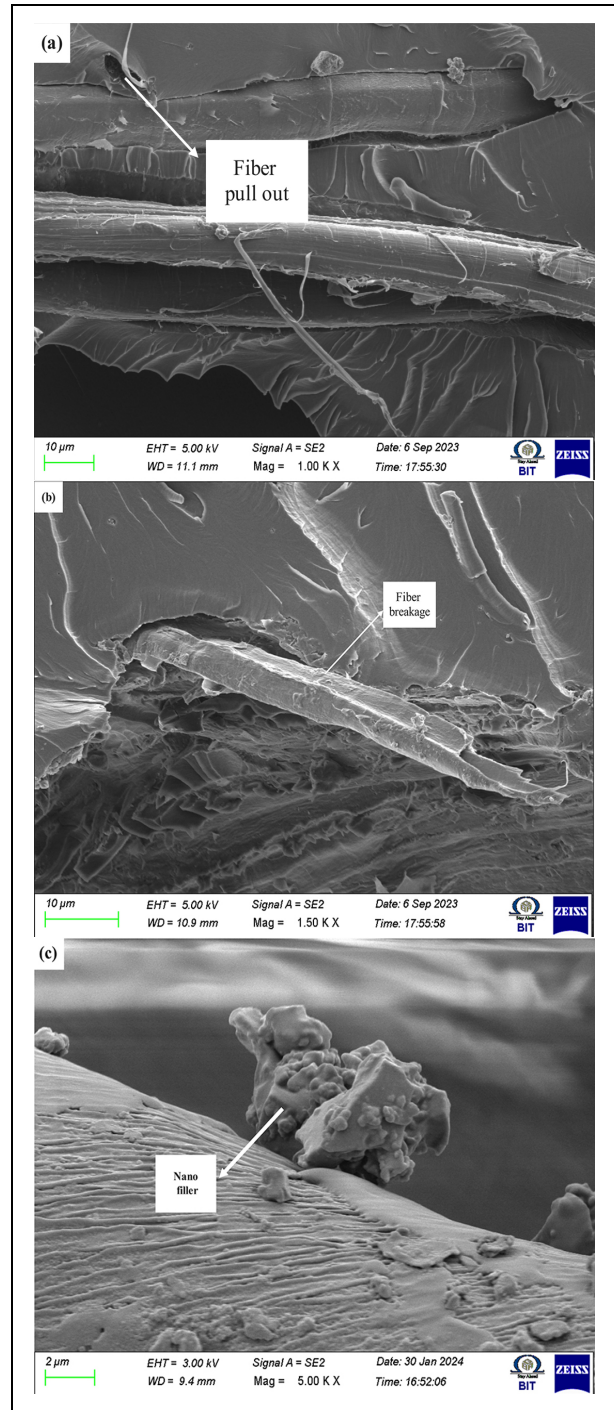


Fig. 13: SEM images of S_8 sample

3.8 Scanning Electron Microscopic Analysis

A morphological analysis of the S_8 specimen was conducted using a Zeiss apparatus at an examination voltage of 10 kV. The microstructure of the composite material was thoroughly illustrated by the SEM images, which also clarified the orientation and distribution of n-ZnO and BF within the epoxy matrix.

The SEM images provide significant insights into the influence of n-ZnO on the integration between the matrix and the reinforcements. Furthermore, it was noted that fracture cracking and propagation were caused by the filaments from the lattice due to laminar debonding and the detachment of the grid through strand extraction. Fig. 13 illustrates the morphology of the composite at different magnifications. These images clearly depict two core elements: the fibre pullout and homogeneous distribution of n-ZnO inside a matrix bonding. The FESEM analysis confirmed the wear surface morphology and failure process, with optimization performed using Taguchi's experimental design (Meravi and Panchore, 2025).

4. CONCLUSIONS

This investigation highlights significant advancements in BF-reinforced composites with the integration of n-ZnO filler. The addition of 4 wt% n-ZnO significantly enhanced mechanical properties, increasing tensile strength by 58.97% and flexural strength by 30.50% compared to clean epoxy. Impact strength improved notably with 12 wt% BF and 6 wt% n-ZnO, achieving a 59.57% rise relative to S₁. Taguchi analysis identified 4 wt% n-ZnO and 12 wt% BF as the optimal levels (A₂ and B₂), yielding the highest TS, validated by both signal-to-noise ratios and RSM predictive modeling with under 2% error. Additionally, water absorption decreased with n-ZnO incorporation, with composite S₄ reaching a low of 1.1% on the fifth day, indicating enhanced water resistance comparable to that of pure epoxy. The work emphasizes the utilization of n-ZnO as an eco-friendly filler that enhances the mechanical characteristics and reduces WA in epoxy composites reinforced with BF. This method supports the utilization of agricultural byproducts to create economically viable and sustainable materials appropriate for biomedical purposes.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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