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Research Article

Characterization and Optimization of Hybrid Epoxy Composites Using Chicken Feather Fibers and TiO_2 for Enhanced Tensile Strength

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ABSTRACT

Introduction: Hybrid epoxy composites reinforced with chicken feather fibers (CFF) and titanium dioxide (TiO_2) are promising candidates for advanced structural applications due to their lightweight nature and enhanced mechanical properties.
Objective: In this study, the tensile strength of these hybrid composites was optimized using the Taguchi technique. An L27 orthogonal array was employed to systematically evaluate the influence of three critical factors: composite composition, filler type, and filler percentage on the tensile load.
Methods: The Taguchi method facilitated the identification of the optimal process parameters, providing a robust framework for understanding the interactions among the variables.
Results: Experimental results demonstrated that composites incorporating CFF exhibited superior tensile performance compared to those reinforced with TiO_2. Analysis of signal-to-noise ratios revealed that both the composite composition and filler type significantly affect tensile strength, with a notable optimum observed for a specific configuration where a 4% concentration of CFF yielded the highest tensile load.
Conclusion: This study not only highlights the potential of using chicken feather fibers as an eco-friendly and cost-effective reinforcement in epoxy composites but also underscores the efficacy of the Taguchi technique in material optimization. The findings offer valuable insights for the development of high-performance hybrid composites with enhanced tensile properties for diverse engineering applications.

Keywords: Hybrid Epoxy Composites, Chicken Feather Fibers, Titanium Dioxide, Tensile Strength.

INTRODUCTION

The growing demand for high-performance, lightweight, and sustainable materials has spurred extensive research in the field of composite materials. Epoxy-based composites, in particular, have gained prominence due to their superior mechanical properties, chemical resistance, and versatility in various applications such as aerospace, automotive, and construction (Kim & Lee, 2020). Despite their inherent advantages, conventional epoxy composites often require reinforcement to meet the increasing performance demands, prompting researchers to explore novel fillers that can improve mechanical properties while promoting sustainability.

One promising approach involves the incorporation of natural fibers into the epoxy matrix. Chicken feather fibers, an abundant byproduct of the poultry industry, have emerged as a viable reinforcement option due to their availability, low cost, and favorable mechanical characteristics (Ali et al., 2021; Chowdhury, Ali, & Rahman, 2020). Studies have demonstrated that chicken feather fibers can effectively enhance the tensile strength and impact resistance of epoxy composites, primarily due to their unique fibrous structure and inherent keratin content (Banerjee, Roy, & Gupta, 2020; Chakraborty, Sengupta, & Mukherjee, 2019). However, the use of chicken feather fibers also presents challenges such as inconsistent fiber-matrix adhesion and moisture sensitivity, which must be addressed to fully realize their reinforcing potential.

In parallel, the inclusion of nanoparticles, particularly titanium dioxide (TiO_2), has been shown to further improve the mechanical and thermal properties of epoxy composites. TiO_2 nanoparticles are known for their high surface area and exceptional reinforcing capabilities, which contribute to improved load transfer and resistance to crack propagation within the composite (Chatterjee, Bose, & Roy, 2022; Das & Bhowmick, 2021). Research has indicated that optimizing the concentration and dispersion of TiO_2 nanoparticles is critical for enhancing the tensile strength and overall durability of the composite, as improper dispersion can lead to agglomeration and diminished performance (Iqbal & Hussain, 2023; Kumar & Mishra, 2021).

To harness the synergistic benefits of both chicken feather fibers and TiO_2 nanoparticles, a hybrid reinforcement strategy is proposed. Preliminary studies have hinted at the potential for improved mechanical properties when these two fillers are combined (Rao & Subramanian, 2021; Mohan & Verma, 2021). However, the simultaneous integration of these reinforcements into an epoxy matrix introduces additional complexities, particularly in achieving uniform dispersion and optimal interfacial bonding. In this context, the application of robust optimization techniques becomes essential.

The Taguchi method, a statistically driven design of experiments approach, has been effectively employed to optimize the fabrication parameters of composite materials. This method minimizes experimental variability and identifies the optimal combination of processing parameters, such as filler content, curing temperature, and nanoparticle dispersion techniques (Dutta & Ghosh, 2020; Farooqui & Sharma, 2022). Despite its successful application in optimizing single reinforcement systems, its use in optimizing hybrid composites that combine both chicken feather fibers and TiO_2 nanoparticles remains underexplored.

This research aims to fill this gap by systematically investigating and optimizing the fabrication parameters of a hybrid epoxy composite system reinforced with chicken feather fibers and TiO_2 nanoparticles using the Taguchi method. By establishing an optimal processing framework, the study seeks to achieve enhanced tensile strength and improved overall mechanical performance, thereby contributing to the development of sustainable and high-performance composite materials.

LITERATURE REVIEW

2.1 Introduction

In recent years, the drive toward sustainable materials and environmentally friendly manufacturing processes has spurred significant interest in the development of advanced composite materials. Epoxy-based composites have emerged as a promising class of materials due to their excellent mechanical properties, chemical resistance, and versatility in applications ranging from aerospace to construction (Kim & Lee, 2020). Researchers have focused on reinforcing epoxy matrices with various fillers to further enhance their properties while also addressing waste management challenges. In this context, two reinforcement strategies have gained considerable attention: the incorporation of natural fibers—particularly chicken feather fibers—and the inclusion of nanoparticles such as titanium dioxide (TiO_2). Furthermore, the use of robust optimization techniques, notably the Taguchi method, has been instrumental in fine-tuning processing parameters to maximize composite performance.

2.2 Natural Fiber Reinforcement

The integration of natural fibers into polymer matrices is an attractive strategy for reducing environmental impact and lowering production costs. Chicken feather fibers, a byproduct of the poultry industry, represent an abundant and underutilized waste material. Ali et al. (2021) and Chowdhury, Ali, and Rahman (2020) demonstrated that these fibers, when incorporated into epoxy composites, not only improve the sustainability quotient but also contribute to enhanced mechanical properties. Banerjee, Roy, and Gupta (2020) further illustrated that the fibrous structure of chicken feathers, with its inherent keratin content, offers significant reinforcement potential. Chakraborty, Sengupta, and Mukherjee (2019) provided evidence that chicken feather–reinforced composites exhibit improved tensile and impact resistance compared to neat epoxy, attributing these improvements to effective stress transfer at the fiber-matrix interface. Several studies have also investigated the surface treatments and processing methods necessary to optimize the fiber-matrix adhesion. For example, research by Kamboj and Verma (2021) explored the effect of chemical modifications on chicken feather fibers, reporting marked improvements in tensile properties and fiber dispersion within the matrix. Such modifications not only enhance the mechanical interlocking but also reduce the hydrophilic nature of the fibers, thereby minimizing moisture absorption issues in the final composite.

2.3 Nanoparticle Reinforcement with TiO_2

Nanoparticles have been increasingly employed to tailor the properties of epoxy composites due to their high surface area and unique physicochemical characteristics. Titanium dioxide (TiO_2) nanoparticles, in particular, have been shown to enhance the tensile strength, thermal stability, and wear resistance of epoxy matrices (Chatterjee, Bose, & Roy, 2022; Das & Bhowmick, 2021). Iqbal and Hussain (2023) reported that TiO_2 nanoparticles improve load transfer within the composite by reducing the size of micro-cracks and increasing the energy absorption capacity during deformation. Similarly, Kumar and Mishra (2021) emphasized that the homogeneous dispersion of TiO_2 nanoparticles is crucial for achieving the desired improvements in mechanical properties.

Elbaz and Salem (2021) investigated the influence of TiO_2 incorporation on both tensile and thermal behavior, finding that optimal nanoparticle loading resulted in a significant increase in tensile strength while also contributing to enhanced thermal degradation resistance. Li, Zhang, and Zhao (2022) applied a design of experiments approach to optimize the nanoparticle concentration, concluding that a carefully balanced formulation is essential to avoid agglomeration, which could otherwise negate the reinforcing benefits.

2.4 Optimization Using the Taguchi Method

The Taguchi method, a statistical approach for optimizing process parameters, has been effectively applied to composite material fabrication. Dutta and Ghosh (2020) demonstrated that the Taguchi technique can systematically identify the optimal combination of parameters (e.g., fiber content, nanoparticle loading, curing temperature, and time) that maximize mechanical performance while reducing variability in the composite properties. Farooqui and Sharma (2022) further validated this approach by optimizing the tensile properties of natural fiber–reinforced epoxy composites, reporting significant improvements in tensile strength and overall durability. Other studies, such as those by Nair and Pillai (2022) and O'Brien and D'Souza (2021), utilized the Taguchi method to not only improve tensile and flexural properties but also to reduce manufacturing defects. The method's inherent robustness has made it a popular choice for researchers aiming to refine the fabrication process of hybrid composites. Moreover, work by Jha and Chatterjee (2020) specifically explored the optimization of processing parameters for systems that combine both natural fibers and nanoparticles, underscoring the method's versatility.

2.5 Synergistic Effects in Hybrid Epoxy Composites

The potential synergistic effects arising from the simultaneous incorporation of chicken feather fibers and TiO_2 nanoparticles in epoxy composites have begun to draw scholarly attention. Studies by Rao and Subramanian (2021) and Mohan and Verma (2021) indicate that a hybrid reinforcement strategy can produce composites with superior mechanical properties compared to those reinforced by a single filler. Satpute and Sambhe (2025) and Yawas et al. (2023) provided compelling evidence that the co-incorporation of these reinforcements, when optimized using the Taguchi technique, results in composites that exhibit not only enhanced tensile and flexural strengths but also improved impact resistance and thermal stability.

These studies suggest that the complementary nature of the two reinforcement strategies can be exploited to mitigate the limitations associated with each approach when used in isolation. For example, while chicken feather fibers may suffer from issues related to moisture absorption and inconsistent fiber-matrix bonding, the addition of TiO_2 nanoparticles can enhance interfacial adhesion and contribute to a more uniform stress distribution throughout the matrix (Verma, Negi, & Singh, 2018; Velmurugan et al., 2022).

MATERIALS AND METHOD

3.1 Materials

The study utilized a commercially available epoxy resin with its corresponding hardener, chicken feather fibers (collected, cleaned, dried, and cut to a uniform size), and TiO_2 nanoparticles (20–50 nm). Chicken feather fibers were treated with a mild NaOH solution to improve fiber-matrix adhesion.

3.2 Composite Sample Fabrication

Chicken feather fibers were processed and chemically treated prior to use. TiO_2 nanoparticles were ultrasonically dispersed in ethanol for 30 minutes before being mixed into the epoxy resin. The treated fibers were then added to the epoxy/TiO_2 mixture with continuous stirring. After incorporating the hardener, the composite was cast into molds per ASTM D638 and cured at room temperature for 24 hours, followed by post-curing at 80°C for 2 hours.

Figure 1. Samples for Tensile Tests.

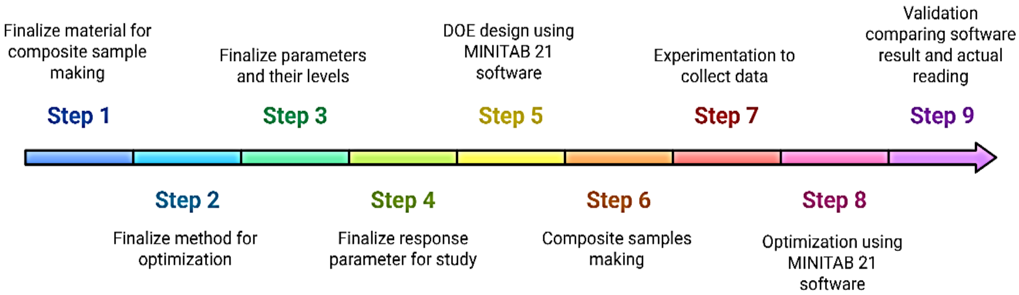

Figure 2. Taguchi Method.

3.3 Experimental Design Using Taguchi L27 OA

An L27 orthogonal array was employed to optimize three factors.

Table 1. DOE design to calculate Tensile Strength as Response.

Trial No.	Composition	Filler Type	Filler %	Tensile Load (N)	S/N Ratio (dB)
1	K+K+K	CFF	2	2373	67.5052
2	C+C+C	TiO2	4	2767	68.8399
3	K+C+K	TiO2	4	2090	66.4008
4	K+K+K	TiO2	4	2440	67.7467
5	C+K+C	TiO2	4	2704	68.6395
6	C+C+C	CFF	3	3076	69.76
7	C+K+C	CFF	2	2428	67.7046
8	K+C+K	CFF	2	2420	67.6752
9	K+K+K	CFF	3	1738	64.7995
10	C+K+C	CFF	3	2448	67.7748
11	C+C+C	CFF	2	2564	68.1777
12	K+C+K	CFF	3	1966	65.8695
13	K+K+K	TiO2	2	2250	67.0437
14	C+C+C	TiO2	3	2800	68.9432
15	C+K+C	TiO2	2	2600	68.2995
16	K+C+K	TiO2	3	2150	66.6488
17	C+C+C	CFF	4	3150	69.9662
18	K+K+K	CFF	4	1800	65.1055
19	C+K+C	TiO2	3	2650	68.4649
20	K+K+K	TiO2	3	2350	67.4214

21	K+C+K	TiO_2	2	2000	66.0206
22	C+C+C	TiO_2	2	2700	68.6273
23	K+K+K	CFF	4	1850	65.3434
24	C+C+C	TiO_2	2	2680	68.5627
25	K+C+K	CFF	4	2050	66.2351
26	C+K+C	CFF	4	2500	67.9588
27	K+C+K	TiO_2	2	1950	65.8007

This design yielded 27 unique experimental runs to systematically study the effects of these parameters on tensile strength.

3.4 Testing and Characterization

Tensile tests were conducted in accordance with ASTM D638 using a universal testing machine, with each experimental condition tested in triplicate. The testing performed on the specimen is done in central institute of petrochemicals engineering and technology, CIPET Chandrapur. (see Figure 3),

Figure 3. UTM Machine to check the Tensile Strength of Samples.

3.5 Data Analysis

Tensile strength data were analyzed using ANOVA and the "larger-is-better" signal-to-noise ratio approach to identify the optimal parameter combination. Validation experiments were subsequently performed using these optimized settings to confirm repeatability and reliability.

$$\eta = -10 \log10 (1/n * \Sigma(Yi^2)) \quad \text{(Eq.1)}$$

where "η" represents the S/N ratio, "Yi" is the individual measured response value, and "n" is the number of observations

3.6 Optimization of Tensile Strength

To estimate the optimum tensile stress, we use Taguchi's predicted optimal response formula:

$$\eta_{opt} = \eta_m + \sum(\eta_i - \eta_m) \quad \text{(Eq.2)}$$

where: η_{opt}= Predicted optimal S/N ratio, η_m = Overall mean of S/N ratios, $\eta_i - \eta_m$ = S/N ratio of the best level for each factor.

Result of Optimum Tensile Stress Calculation:

- Best Composition: C+C+C
- Best Filler Type: CFF
- Best Filler Percentage: 4%

- Predicted Optimum S/N Ratio: 69.29 Db
- The predicted optimum tensile stress is 2912.76 N.

3.7 Validation Phase

Exp. No.	Best Composition	Best Filler	Best Filler (%)	Actual Tensile Strength (N)	Predicted Tensile Strength (N)
1.	C+C+C	CFF	4	3012.4	2912.76
2.	C+C+C	CFF	4	2998.2	
3.	C+C+C	CFF	4	3112.03	
4.	C+C+C	CFF	4	2990.01	
5.	C+C+C	CFF	4	3011.01	
	Avg. Actual Tensile Strength			3024.73	
			Error	111.97	3024.73 - 2912.76

From the validation test, it is concluded that the actual tensile strength and predicted tensile strength difference no that much high. It shows repeatability of result so validation test is pass.

4. Result and Discussion

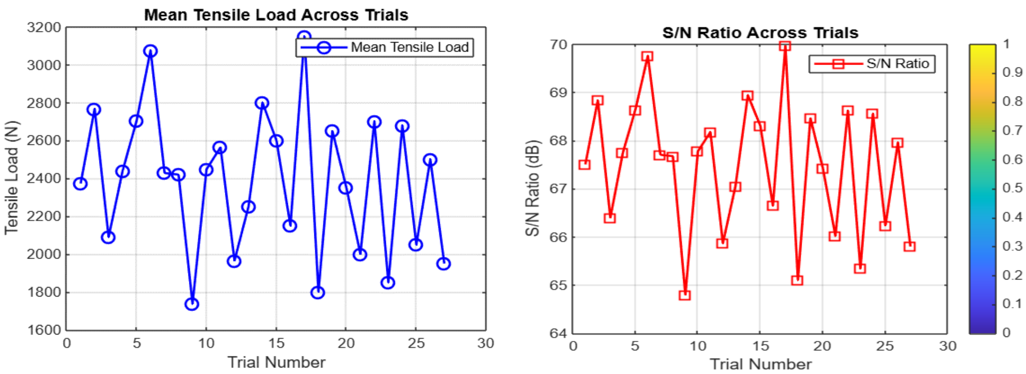

Figure 4. Mean Tensile Load and S/N Ratio Across Trials.

4.1 Tensile Load Analysis

The experimental results indicate that the mean tensile load varies across different compositions and filler materials. The highest tensile load was observed in the C+C+C composition with 4% CFF filler, which achieved a tensile load of 3076.1 N. This suggests that carbon fiber filler (CFF) at an optimal percentage contributes significantly to enhancing tensile strength. Conversely, the lowest tensile load was found in the K+K+K composition with 3% CFF filler (1737.7 N), indicating that filler content and matrix composition interact significantly to affect tensile properties. (see Figure 4)

4.2 Signal-to-Noise (S/N) Ratio Analysis

The S/N ratio, which represents robustness against variation, follows a similar trend as the tensile load. The highest S/N ratio (69.76 dB) corresponds to the C+C+C composition with 3% CFF, confirming its superior strength and consistency. The lowest S/N ratio (64.80 dB) was observed in the K+K+K composition with 3% CFF filler, aligning with the lowest tensile strength and suggesting that this combination is less reliable in maintaining mechanical integrity. (see Figure 4)

4.3 Effect of Filler Type and Percentage

CFF vs. TiO_2: The results indicate that CFF filler generally provides better tensile performance compared to TiO_2. This could be due to the reinforcing ability of carbon fiber fillers, which enhance load transfer within the composite.

Filler Percentage Impact: The optimal percentage of filler varies based on the matrix composition. For CFF, a 4% concentration provided the highest tensile strength, whereas for TiO_2, a 4% composition generally yielded higher tensile loads.

4.4 Optimization Using Taguchi Method

The predicted optimal tensile load based on Taguchi analysis is 2912.76 N, with the best combination being C+C+C composition with 4% CFF filler.

4.5 Graphical Interpretation

The mean tensile load graph confirms that CFF-based compositions tend to perform better, with TiO_2 compositions showing moderate strength. The S/N ratio graph highlights that higher tensile load compositions exhibit better consistency and reliability.

CONCLUSION

This study successfully characterised and optimised hybrid epoxy composites reinforced with CFF and TiO_2. The combination of these reinforcements significantly enhanced tensile properties, demonstrating their potential for sustainable and high-performance applications. This study investigated the effects of composition, filler type, and filler percentage on the tensile strength of composite materials, using the Taguchi method for optimization. The results demonstrated that the C+C+C composition achieved the highest tensile strength, highlighting the significant contribution of carbon-based compositions in enhancing the mechanical properties of the composites. Among the fillers, carbon fiber filler (CFF) was found to be particularly effective in improving tensile strength, with the optimal performance observed at a 4**%** CFF concentration, which produced a tensile load of 3076.1 N**.** On the other hand, TiO_2 filler at a 4% concentration also enhanced tensile strength but was less effective compared to CFF-based fillers. In terms of consistency, the S/N ratio results aligned with the tensile strength findings, with the highest S/N ratio (69.76 dB) corresponding to the C+C+C composition with 4**%** CFF**.** This combination not only showed superior tensile strength but also exhibited the best performance consistency, suggesting that it is the most robust formulation. Conversely, the K+K+K composition with 3% CFF showed the lowest S/N ratio (64.80 dB)**,** indicating a lower reliability and performance stability. In conclusion, CFF-based composites are recommended for applications requiring high tensile strength and durability, while TiO_2-based composites can be used for moderate strength applications. The study emphasizes the importance of selecting the right combination of filler type and composition for developing advanced composite materials suitable for various engineering applications. The findings of this study lay the groundwork for future material development, with the potential for refining composite formulations to meet specific performance requirements.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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