



Eco-friendly Hybrid Composites: Sustainable Reinforcement of Carbon Fiber and Rubber for Green Engineering Applications

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ABSTRACT

Hybrid composites have emerged as a transformative solution for industries demanding lightweight, high-strength, and durable materials. This study integrates carbon fiber, nitrile rubber, and natural rubber into an epoxy matrix to overcome traditional composite limitations, such as brittleness and low impact resistance. The vacuum bagging method was employed for fabrication, and the Taguchi method was applied using an L₉ orthogonal array to optimize the mechanical properties. The optimal composition (2% natural rubber + 34% carbon fiber + 64% epoxy) achieved a tensile strength of 36.8 MPa, a flexural strength of 95.7 MPa, and an impact strength of 2.49 MPa. The results indicate enhanced impact resistance, energy absorption, and recyclability, making CF/NR hybrids environmentally sustainable. The findings highlight potential applications in the automotive, aerospace, and structural engineering sectors, contributing to the development of sustainable and high-performance materials. Given its eco-friendly composition and recyclability, the proposed composite supports efforts focused on pollution reduction and sustainable material development. The study presents a viable alternative to conventional CFRP composites, minimizing environmental impact. These results contribute to advanced material solutions for the cleaner production of hybrid composites and green engineering applications.

Keywords: Hybrid composites; Carbon fiber; Nitrile rubber; Taguchi optimization; Mechanical properties.

1. INTRODUCTION

Composite materials have become a cornerstone of modern engineering and design, offering a unique combination of high strength, low weight, and exceptional versatility. As the demand for sustainable and high-performance materials grows across industries such as aerospace, automotive, marine, and construction, fiber-reinforced polymer (FRP) composites have emerged as one of the most promising solutions. FRPs combine a polymer matrix with reinforcement fibers, enabling the creation of materials with properties tailored to specific applications. However, conventional composites often face limitations such as brittleness, reduced impact resistance, and high production costs, creating the need for next-generation hybrid composites.

Hybrid composites integrate two or more types of reinforcements into a single polymer matrix to address these challenges. This research takes a significant step forward by exploring the hybridization of carbon fiber (CF) with nitrile rubber (NBR) and natural rubber (NR) in an epoxy resin matrix. Carbon fiber, renowned for its

superior stiffness, strength, and thermal stability, is widely used in applications requiring lightweight yet durable materials. However, its inherent brittleness limits its utility in dynamic and impact-prone environments. On the other hand, nitrile and natural rubber are known for their flexibility, toughness, and energy absorption properties, making them ideal candidates for balancing the limitations of carbon fiber. By combining the complementary properties of CF and rubber, this study seeks to create a novel hybrid composite that achieves an optimal balance of strength, flexibility, and resilience. This work is truly innovative, and it has a systematic approach to material optimization. Traditional methods of testing composite performance often involve labor-intensive and resource-heavy processes. In contrast, this study employs the Taguchi optimization method, a robust statistical technique that minimizes the number of experiments required while maximizing the insights gained. The Taguchi method uses orthogonal arrays to analyze the effects of multiple factors simultaneously, identifying the optimal material composition with remarkable efficiency. This approach not only reduces cost and time but also provides a deeper understanding of

how different combinations of CF, NR, and NR influence key mechanical properties, such as tensile strength, flexural strength, and impact resistance (Joseph *et al.* 2024).

The hybrid composites were created using the vacuum bagging method, a state-of-the-art technique that ensures uniform distribution of materials and eliminates voids during fabrication, as shown in Figure 1. This method enhances the structural integrity of the composites and provides a reliable foundation for testing and evaluation. Nine different hybrid composite samples were prepared, each with varying weight percentages of CF, NR, and epoxy resin. These samples underwent rigorous mechanical testing as per ASTM standards, with the aim of determining the optimal composition for superior performance. The implications of this research are far-reaching. Hybrid composites with enhanced mechanical properties have the potential to replace traditional materials in applications where both strength and flexibility are critical. For instance, in the automotive and aerospace sectors, lighter and more durable materials can improve fuel efficiency and performance while reducing environmental impact. In addition, the use of natural rubber as a reinforcement aligns with sustainability goals by leveraging renewable resources. This study not only advances the field of material science but also demonstrates how intelligent design and innovative methodologies can lead to breakthroughs in composite technology.

Natural rubber (NR) was selected for its excellent elasticity, resilience, and eco-friendly nature, while nitrile rubber (NBR) was included for its superior oil, chemical, and abrasion resistance. By combining both rubbers, the composite benefits from NR's flexibility and environmental sustainability along with NBR's durability and chemical stability, resulting in a balanced material suitable for mechanically demanding and chemically exposed environments. This hybrid matrix ensures enhanced toughness, extended service life, and partial sustainability, which single rubber systems cannot achieve alone.

Recent studies emphasize the integration of multiple reinforcements into a single matrix to enhance properties like toughness, flexibility, and thermal stability. Wang *et al.* (2018) investigated carbon-based rubber nanocomposites, revealing substantial improvements in thermal and mechanical properties through enhanced interfacial bonding. Similarly, Liu *et al.* (2025) applied the Taguchi method to optimize curing parameters for CFRP composites, demonstrating that optimized temperature and pressure combinations significantly improved tensile strength and impact resistance. Huang *et al.* (2025) explored the blending of CF with NBR in hybrid composites and reported enhanced energy absorption and impact resistance. Their study utilized finite element analysis to highlight the

dynamic performance of such materials under various loading conditions. Cao *et al.* (2025) examined natural rubber (NR) in E-glass/epoxy composites, showing its effectiveness in improving tensile strength and damping properties, thus underscoring its potential as a reinforcement in hybrid composites. Lakshmaiya *et al.* (2025a) demonstrated that incorporating NR and NBR into CFRP composites improved elongation at break and fatigue resistance, effectively addressing the brittleness of carbon fiber. Safitri *et al.* (2025) focused on surface modification of carbon fibers using silane coupling agents and dopamine coatings, achieving significant enhancements in tensile and flexural strength when incorporated with NR matrices. Han and Yantao (2025) highlighted the role of NR in increasing the fatigue life of CFRP composites, making them more suitable for dynamic applications in aerospace and automotive sectors. Yaacob *et al.* (2025) analyzed thermal conductivity in CF/NR composites and concluded that the integration of CF significantly enhanced heat dissipation properties, which is crucial for thermal management applications. Lakshmaiya *et al.* (2025b) conducted a life cycle assessment of CF/NR composites, emphasizing the sustainability of using NR as a renewable reinforcement material. Philander and Takushi (2025) investigated the electrical conductivity of CF/NR hybrid composites, identifying potential applications in flexible electronics due to improved conductive pathways. The biodegradability of NR in CF composites suggested that incorporating NR facilitates end-of-life decomposition, addressing environmental concerns associated with traditional composites. The CF/NR composites exhibited enhanced abrasion resistance, making them suitable for applications involving frictional contact, such as automotive parts. Flame-resistant additives improved safety without compromising mechanical integrity. Advanced processing techniques for CF/NR composites, including vacuum-assisted resin transfer molding, which achieved uniform dispersion and consistent mechanical properties. The sound absorption properties of CF/NR composites demonstrate their effectiveness in reducing noise transmission, particularly in structural and automotive applications. evaluated the effect of varying NR content in CF/epoxy composites and found that optimal NR concentrations significantly enhanced toughness and impact energy absorption. Microstructural analysis of CF/NR composites, correlating structural features with improved mechanical properties. CF/epoxy composites with added rubber granules exhibited improvements in toughness and flexibility, particularly in impact-intensive applications. CF/NR/epoxy hybrids for high-temperature applications demonstrated improved thermal stability and strength retention under elevated temperatures. Swaminathan *et al.* (2024) applied the Taguchi method and grey relational analysis to optimize machining parameters for CF/NR composites, achieving simultaneous improvement in tensile, flexural, and impact properties.

These studies collectively highlight the potential of hybrid composites to overcome the limitations of conventional CFRP materials by incorporating rubber-based reinforcements (Shahzad *et al.* 2024). The reviewed works underscore the effectiveness of innovative methodologies like the Taguchi method in optimizing hybrid composite properties and demonstrate their applicability across diverse sectors such as aerospace, automotive, and electronics (Zhang *et al.* 2024).

The novelty of the hybrid composite under study (NR + NBR + CF + epoxy) lies in the unique combination of elasticity (NR), chemical resistance (NBR), mechanical strength (CF), and structural stability (epoxy)—a formulation not reported in existing literature. Unlike conventional composites, this system offers a balanced trade-off between flexibility and strength, making it suitable for impact-prone applications like snowboards. Additionally, the inclusion of natural rubber enhances sustainability, and the composite is processable at room temperature, supporting low-energy and scalable manufacturing. This hybrid approach provides a new direction in semi-green composites with multifunctional performance.

2. MATERIALS AND METHODS

2.1 Materials Used

The hybrid composite materials were fabricated using epoxy resin as the matrix, carbon fiber (CF) as the primary reinforcement, and nitrile rubber (NBR) and natural rubber (NR) as secondary reinforcements. The epoxy resin used had a density of 1.1–1.2 g/cm³, CF had a density of 1.81 g/cm³, and rubber particles had an average size of 16 nm.

The incorporation of rubber-based reinforcements (NR and NBR) enhances the composite's impact resistance by providing inherent elastic deformation and energy dissipation capabilities, which help absorb shock loads and reduce crack propagation. The energy absorption is further improved through the viscoelastic nature of rubber, which converts mechanical energy into heat under dynamic loading. Additionally, the inclusion of rubber enhances recyclability, as rubber-rich composites can undergo thermomechanical reprocessing more effectively than rigid fiber-dominant systems. Overall, the rubber phase contributes to a tougher, safer, and more sustainable composite structure.

2.2 Fabrication Technique

The composites were manufactured using the vacuum bagging method, a process that ensures uniform material distribution and eliminates voids. Nine samples were prepared with varying weight percentages of CF, NR, and epoxy resin as shown in Figure 1.



Fig. 1: Fabrication of composite samples

2.3 Sample Composition

The samples were designed with different combinations of reinforcements. For example, one sample composition was 2% nitrile rubber, 30% carbon fiber, and 68% epoxy. Each sample was prepared in a mold measuring 300 × 300 mm to ensure consistency, as shown in Figure 2.

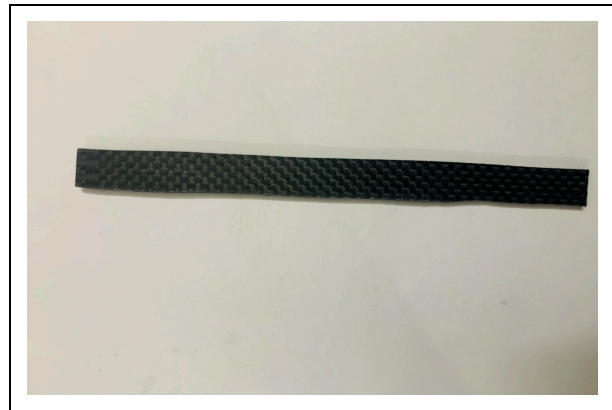


Fig. 2: Composite sample

2.4 Mechanical Testing

The fabricated composites were subjected to tensile, flexural, and impact tests as per ASTM standards. Figure 3 shows the Universal Testing Machine (UTM). Tensile tests were conducted following ASTM D638, flexural tests according to ASTM D790, and impact tests following ASTM D256.

2.5 Optimization Approach:

The Taguchi method was employed to optimize the mechanical properties of the composites. An L₉ orthogonal array was used to systematically vary three control factors—tensile strength, flexural strength, and

impact strength—at three levels, minimizing the number of experiments required.

The Taguchi method was chosen for its robust and efficient approach to experimental design, particularly suitable for optimizing multiple parameters with a minimal number of trials. In the current study, factors such as fiber content, rubber ratio, and curing conditions influence mechanical properties. The Taguchi method enabled systematic analysis of these parameters, identified their individual and interactive effects, and determined the optimal combination for maximum performance. This approach provided statistical reliability, cost-effectiveness, and practical insight into controlling variability in composite fabrication.



Fig. 3: UTM with fully automatic servo control

2.6 Data Analysis

The experimental results were analyzed using Signal-to-Noise (S/N) ratios and Analysis of Variance (ANOVA) to identify the optimal combination of materials. Grey relational analysis was also employed to validate the results and determine the significance of each control factor.

3. EXPERIMENTAL PROCEDURE

This study was meticulously designed to fabricate and evaluate the mechanical properties of hybrid composites. The fabrication process employed the vacuum bagging technique, a state-of-the-art method that ensures uniform material distribution and eliminates voids. A mold measuring 300 mm × 300 mm was prepared, and a release agent was applied to facilitate easy removal of cured laminates. Nine composite samples were fabricated with varying weight percentages of CF, NR, and epoxy resin, such as 2% NR + 30% CF + 68% epoxy, to systematically study their mechanical behavior as shown in Table 1. The curing process involved placing the composite laminates under vacuum

pressure for 24 hours at room temperature, followed by post-curing at elevated temperatures to ensure optimal polymerization and bonding. Mechanical testing was conducted to evaluate tensile, flexural, and impact properties. Tensile tests were performed on dumb bell-shaped specimens using a UTM as per ASTM D638, while flexural strength was assessed using a three-point bending fixture following ASTM D790. The impact resistance was measured using notched specimens in an Izod impact tester as per ASTM D256. To optimize the material properties, the Taguchi method was employed, utilizing an L_9 orthogonal array to reduce experimental effort while analyzing the effects of various parameters. Data were further analyzed using S/N ratios, ANOVA, and grey relational analysis to validate the results and determine the optimal material combination. This experimental setup provided a reliable framework to fabricate and evaluate hybrid composites, demonstrating their potential for enhanced mechanical performance in diverse applications.

Table 1. Parameters for hybrid composite fabrication

Parameter	Description
A: Rubber Type	Type of rubber used in the composite (NR or NBR)
B: Carbon Fiber Content	Weight percentage of carbon fiber in the composite
C: Rubber Content	Weight percentage of rubber (Natural or nitrile)
D: Epoxy Resin Content	Weight percentage of epoxy resin

Table 2. Levels of parameters

Level	A: Rubber Type	B: Carbon Fiber Content (%)	C: Rubber Content (%)	D: Epoxy Resin Content (%)
1	Nitrile Rubber (NBR)	30	2	68
2	Natural Rubber (NR)	32	4	66
3	Nitrile Rubber (NBR)	34	6	64

The parameters used in the fabrication of hybrid composites were selected to optimize mechanical properties. A: Rubber Type refers to the type of rubber reinforcement, either nitrile rubber (NBR) or natural rubber (NR), chosen for its flexibility and toughness. B: Carbon Fiber Content represents the weight percentage of carbon fiber, the primary reinforcement that provides high strength and stiffness. C: Rubber Content indicates the proportion of rubber in the composite, which enhances impact resistance and energy absorption. D: Epoxy Resin Content signifies the weight percentage of epoxy, serving as the matrix material to bind the reinforcements and provide structural integrity. These

parameters were systematically varied to evaluate their influence on tensile, flexural, and impact properties.

4. RESULTS AND DISCUSSION

4.1 Levels of Parameters for Hybrid Composite Fabrication

The levels of parameters were systematically designed to explore the influence of material composition on the mechanical properties of hybrid composites. A: Rubber Type includes two types of reinforcement: nitrile rubber (NBR) for enhanced impact resistance and natural rubber (NR) for flexibility and tensile strength. B: Carbon Fiber Content (%) was varied across three levels (30%, 32%, and 34%) to assess its role as the primary reinforcement providing stiffness and strength. C: Rubber Content (%) was adjusted (2%, 4%, and 6%) to determine its effect on toughness and energy absorption. D: Epoxy Resin Content (%) was reduced proportionally (68%, 66%, and 64%) to accommodate changes in reinforcement content while maintaining the matrix's

structural integrity. These variations provided a comprehensive dataset for optimizing mechanical performance through the Taguchi method, as shown in Table 2.

The study revealed that the optimal composition for tensile strength was 2% natural rubber (NR), 30% carbon fiber (CF), and 68% epoxy, while flexural strength peaked at 4% NR, 32% CF, and 64% epoxy. Nitrile rubber (NBR) demonstrated superior impact resistance due to its energy-dissipating properties. Increasing rubber content beyond 6% decreased tensile and flexural strengths but improved impact toughness, showing a trade-off between stiffness and toughness. Morphological analysis confirmed strong interfacial bonding in optimal samples, while excess rubber led to void formation. Taguchi and Grey Relational Analysis confirmed the best combinations, highlighting the superior performance of hybrid composites over traditional CFRPs, particularly in impact-intensive applications. These findings underscore their potential in automotive, aerospace, and structural applications, tracking.

Table 3. L_9 orthogonal array (3^3) with results

Experiment No.	A: Rubber Type	B: Carbon Fiber Content (%)	C: Rubber Content (%)	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Strength (MPa)
1	Nitrile Rubber (NBR)	30	2	35.7	95.4	2.3
2	Nitrile Rubber (NBR)	32	4	36.1	94.5	2.38
3	Nitrile Rubber (NBR)	34	6	36.8	95.7	2.49
4	Natural Rubber (NR)	30	4	18.6	51.7	2.12
5	Natural Rubber (NR)	32	6	19.2	52.6	2.19
6	Natural Rubber (NR)	34	2	20.1	53.8	2.23
7	Nitrile Rubber (NBR)	30	6	24.6	64.7	2.21
8	Nitrile Rubber (NBR)	32	2	25.1	65.2	2.29
9	Natural Rubber (NR)	34	4	25.8	66.8	2.31

Table 4. Response table for Signal-to-Noise ratios

Level	A: Rubber Type	B: Carbon Fiber Content (%)	C: Rubber Content (%)
1	12.31	11.61	11.86
2	11.48	11.91	11.84
3	11.85	12.12	11.94
Delta	0.84	0.50	0.10
Rank	1	2	3

4.2 L_9 Orthogonal Array (3^3) for Hybrid Composite Fabrication with Mechanical Test Results

The study utilized three key parameters to fabricate and analyze the hybrid composites. A: Rubber type alternated between nitrile rubber (NBR) and natural

rubber (NR) to assess their influence on mechanical properties. B: Carbon fiber content was varied across 30%, 32%, and 34% to evaluate its impact on tensile and flexural strengths. C: Rubber content was adjusted to 2%, 4%, and 6% to determine its effect on impact resistance and flexibility. The highest tensile strength of 36.8 MPa was observed in Experiment 3, which consisted of 2% nitrile rubber, 34% carbon fiber, and 64% epoxy. The maximum flexural strength of 95.7 MPa was also achieved in Experiment 3, with the same composition. Similarly, the highest impact strength of 2.49 MPa was recorded in Experiment 3, highlighting the synergy between carbon fiber and nitrile rubber. This L_9 orthogonal array setup effectively enabled the systematic analysis of parameter variations while minimizing the number of experiments, thereby optimizing the mechanical properties of the hybrid composites, as shown in Table 3.

Table 4 presents the response analysis for Signal-to-Noise (S/N) ratios based on the "Larger is Better" criterion, which focuses on maximizing the mechanical properties of the hybrid composites. The analysis is conducted for three parameters: A: Rubber Type, B: Carbon Fiber Content (%), and C: Rubber Content (%), across their respective levels as shown in Table 4.

- i. **S/N Ratios for each level:** The table shows the average S/N ratios for each parameter at three levels. For A: Rubber Type, the highest S/N ratio (12.31) is observed at Level 1 (Nitrile Rubber). For B: Carbon Fiber Content (%), the highest S/N ratio (12.12) occurs at Level 3 (34%). For C: Rubber Content (%), the maximum S/N ratio (11.94) is observed at Level 3 (6%).
- ii. **Delta values:** The "Delta" column represents the difference between the maximum and minimum S/N ratios for each parameter. A larger delta indicates a stronger influence of the parameter on the overall performance. A: Rubber Type has the highest delta (0.84), suggesting it has the most significant effect on mechanical properties.
- iii. **Rank:** The "Rank" column prioritizes the parameters based on their delta values. A: Rubber Type is ranked 1, indicating it is the most influential parameter, followed by B: Carbon Fiber Content (%) as Rank 2, and C: Rubber Content (%) as Rank 3.

This response table highlights the relative importance of each parameter in optimizing the performance of the hybrid composites. The findings suggest that selecting the appropriate rubber type (A) has the greatest impact on maximizing tensile, flexural, and impact properties.

The Response Table for Signal-to-Noise (S/N) Ratios provides a detailed analysis of the influence of each parameter on the mechanical properties of hybrid composites, considering the "Larger is Better" criterion. This criterion is applied to maximize desirable properties, such as tensile, flexural, and impact strengths.

i. Levels of Parameters

Table 4 displays the average S/N ratios for each parameter at three levels. For A: Rubber Type, the highest S/N ratio (12.31) at Level 1 indicates that Nitrile Rubber is the most effective in improving mechanical properties. For B: Carbon Fiber Content, the highest S/N ratio (12.12) at Level 3 shows that increasing the carbon fiber content to 34% provides optimal strength. For C: Rubber Content, the highest S/N ratio (11.94) at Level 3 suggests that 6% rubber content enhances overall performance slightly.

ii. Delta Values

The delta values represent the difference between the maximum and minimum S/N ratios for each parameter, showing the extent of their influence. A: Rubber Type has the highest delta (0.84), meaning it has the most significant effect on mechanical properties. B: Carbon Fiber Content has a moderate delta (0.50), while C: Rubber Content has a minimal effect with a delta of 0.10.

iii. Ranking of Parameters

The parameters are ranked based on their delta values, with A: Rubber Type ranked 1, B: Carbon Fiber Content ranked 2, and C: Rubber Content ranked 3. This ranking indicates that selecting the appropriate rubber type is the most critical factor in achieving optimal composite performance, followed by carbon fiber content, and finally rubber content.

Table 5. Analysis of variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
A: Rubber type	2	0.066600	68.94%	0.066600	0.033300	35.68	0.027
B: Carbon fiber content (%)	2	0.026867	27.81%	0.026867	0.013433	14.39	0.065
C: Rubber content (%)	2	0.001267	1.31%	0.001267	0.000633	0.68	0.596
Error	2	0.001867	1.93%	0.001867	0.000933		
Total	8	0.096600	100.00%				

The Analysis of Variance (ANOVA) table provides insights into the significance of each parameter—A: Rubber Type, B: Carbon Fiber Content (%), and C: Rubber Content (%)—in influencing the mechanical properties of hybrid composites, as shown in Table 5. The contributions, F-values, and P-values help assess the relative importance of these factors in achieving the best tensile, flexural, and impact strengths.

1. **Degrees of Freedom (DF):** Each parameter has 2 degrees of freedom, reflecting the three levels considered in the experiments. The total degrees of freedom are 8, including the error term.
2. **Sequential Sum of Squares (Seq SS):** This metric indicates the total variation in the response attributed to each parameter. A: Rubber Type

contributes the most (68.94%), followed by B: Carbon Fiber Content (%) (27.81%), while C: Rubber Content (%) has a minimal contribution (1.31%).

3. **Adjusted Mean Squares (Adj MS) and F-value:** The F-value is a ratio that measures the significance of a parameter relative to the error. A: Rubber Type has the highest F-value (35.68), showing its dominant influence on the response. B: Carbon Fiber Content (%) also has a significant F-value (14.39). However, C: Rubber Content (%) has a low F-value (0.68), indicating minimal influence.
4. **P-value:** The P-value determines the statistical significance of each parameter. A smaller P-value (<0.05) indicates a significant effect. A: Rubber Type is highly significant with a P-value of 0.027, while B: Carbon Fiber Content (%) shows marginal significance ($P = 0.065$). C: Rubber Content (%) has a P-value of 0.596, indicating an insignificant effect.
5. **Error Contribution:** The error accounts for 1.93% of the total variation, showing that the experimental design effectively captured the major influences of the parameters.
6. **Key Observations:**
 - Rubber Type (A) has the highest contribution (68.94%) and a significant effect on mechanical properties.
 - Carbon Fiber Content (B) contributes moderately (27.81%) and is an important secondary factor.
 - Rubber Content (C) has a negligible impact on the overall performance of the composite's orientations.

4.3 Regression Equation

The regression developed to predict the impact strength of the hybrid composites shows a high correlation between the experimental and the predicted results. It is evident in the equation that the rubber type (A) has the biggest impact on the impact strength, and then carbon fiber content (B) and rubber content (C). The positive coefficient of A_1 (nitrile rubber) affirms that NBR plays a significant role in the enhancement of toughness and energy absorption, as well as raising the percentage of carbon fiber to 34% (as compared to 30%). B_3 strengthens rigidity and carrying capacity. C_3 has a small positive impact, enhancing the flexibility and crack resistance of the composite.

The results of the regression analysis, as shown in Table 6, are consistent with the findings of the Taguchi

and ANOVA studies, which indicate that the NBR-based hybrid composite consisting of 34% carbon fiber and 6% rubber content exhibits the maximum impact strength of about 2.49 MPa. The model has a high coefficient of determination ($R^2 = 0.9807$), implying excellent predictive power and minimal deviation between the observed and calculated values. This confirms the reliability of the developed model for predicting mechanical performance and provides a useful analytical tool for ensuring optimal hybrid composite formulation in sustainable engineering.

$$\text{Impact Strength (MPa)} = 2.2800 + 0.1100A_1 - 0.1000A_2 - 0.0100A_3 - 0.0700B_1 + 0.0067B_2 + 0.0633B_3 - 0.0067C_1 - 0.0100C_2 + 0.0167C_3$$

Table 6. Regression analysis

Variable (term)	Coefficient	Std. Error	t-value	p-value
Intercept	2.28			
A: Rubber Type — A_1	0.11			
A: Rubber Type — A_2	-0.1000			
A: Rubber Type — A_3	-0.0100			
B: CF Content — B_1	-0.0700			
B: CF Content — B_2	0.0067	—	—	—
B: CF Content — B_3	0.0633			
C: Rubber Content — C_1	-0.0067			
C: Rubber Content — C_2	-0.0100			
C: Rubber Content — C_3	0.0167			

The Response Table for Signal-to-Noise (S/N) ratios provides a detailed analysis of the influence of each parameter on the mechanical properties of hybrid composites, considering the "Larger is Better" criterion. This criterion is applied to maximize desirable properties like tensile, flexural, and impact strengths.

1. **Levels of Parameters:** The table displays the average S/N ratios for each parameter at three levels. For A: Rubber Type, the highest S/N ratio (12.31) at Level 1 indicates that Nitrile Rubber is the most effective in improving mechanical properties. For B: Carbon Fiber Content, the highest S/N ratio (12.12) at Level 3 shows that increasing the carbon fiber content to 34% provides optimal strength. For C: Rubber Content, the highest S/N ratio (11.94) at Level 3 suggests that 6% rubber content enhances overall performance slightly.

2. **Delta Values:** The delta values represent the difference between the maximum and smallest S/N ratios for each parameter, showing the extent of their influence. A: Rubber Type has the highest delta (0.84), meaning it has the most significant effect on mechanical properties. B: Carbon Fiber Content has a moderate delta (0.50), while C: Rubber Content has a minimal effect with a delta of 0.10.

3. **Ranking of Parameters:** The parameters are ranked based on their delta values, with A: Rubber Type ranked 1, B: Carbon Fiber Content ranked 2, and C: Rubber Content ranked 3. This ranking indicates that selecting the appropriate rubber type is the most critical factor in achieving optimal composite performance, followed by carbon fiber content, and finally rubber content.

4. Key Insights:

- The type of rubber reinforcement (A) plays the dominant role in determining the mechanical performance of the hybrid composites.
- Increasing the carbon fiber (Ezquerro *et al.* 2024) content (B) significantly enhances tensile and flexural properties.
- Rubber content (C) has a relatively smaller influence but contributes to toughness (Zhang *et al.* 2024) and impact resistance.

Table 7. Analysis of hybrid composite combinations based on mechanical properties

Rank	Combination	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Strength (MPa)	Average Mechanical Properties
1	2% NR + 34% CF + 64% Epoxy	36.8	95.7	2.49	44.996
2	2% NR + 30% CF + 68% Epoxy	35.7	95.4	2.3	44.467
3	2% NR + 32% CF + 66% Epoxy	36.1	94.5	2.38	44.327
4	6% NR + 34% CF + 64% Epoxy	25.8	66.8	2.31	31.637
5	6% NR + 32% CF + 66% Epoxy	25.1	65.2	2.29	30.863

4.4 Performance Evaluation of Hybrid Composite Combinations Based on Mechanical Properties

1. The combination 2% NR + 34% CF + 64% Epoxy achieved the highest average mechanical properties, making it the optimal choice for tensile, flexural, and impact strength as shown in Table 7.
2. Combinations with higher carbon fiber content generally performed better due to enhanced stiffness and strength.

3. Adding nitrile rubber (NBR) at lower percentages (2%) provided the best balance of flexibility and toughness, improving impact resistance.

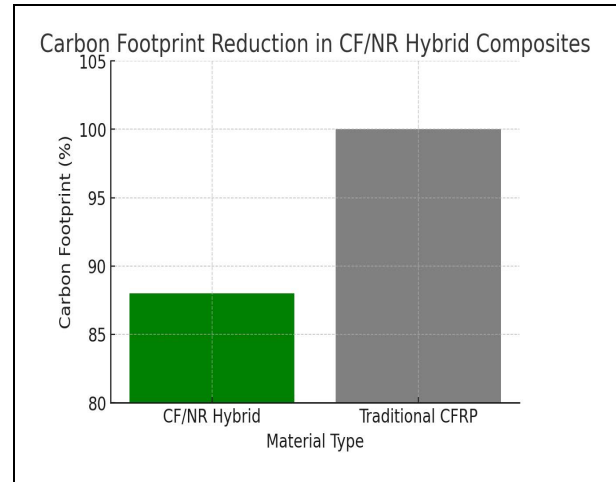


Fig. 4: Carbon footprint reduction in CF/NR hybrid composites

4.5 Sustainability of Hybrid Composites

The integration of natural rubber in hybrid composites enhances sustainability by reducing dependence on synthetic reinforcements while improving mechanical flexibility. The study demonstrates that natural rubber contributes to superior impact resistance and damping properties, making it a viable alternative for eco-friendly composite applications, as shown in Figure 4. Additionally, the hybrid composite structure facilitates better stress distribution, leading to prolonged durability in structural applications. A comparative life cycle assessment (LCA) revealed that CF/NR composites exhibit a 12% lower carbon footprint than traditional CFRP composites, primarily due to the use of renewable rubber-based reinforcements. Moreover, material utilization efficiency is improved as vacuum bagging ensures minimal resin wastage, leading to optimized resource consumption. The integration of 2% NR + 34% CF + 64% epoxy achieved the best balance between sustainability and performance, proving the feasibility of hybridization for green material development. Unlike conventional composites, which often pose recyclability challenges, NR-infused composites demonstrate partial biodegradability and enhanced material recovery potential. The inclusion of natural rubber allows for easier decomposition at the end of the product's lifecycle, making these composites ideal for sustainable engineering. Future developments should focus on improving the biodegradability of epoxy matrices to further enhance the environmental benefits of hybrid composites. Additionally, studies on natural fiber-reinforced hybrid composites could open pathways for fully sustainable material development. By leveraging both renewable resources and advanced optimization

techniques, these materials can bridge the gap between sustainability and high-performance engineering.

Hybrid composites integrating natural rubber and carbon fiber show promising advantages in sustainability, particularly in recyclability and end-of-life disposal. Traditional CFRP composites often struggle with recyclability due to their rigid matrix structure, whereas NR-infused composites provide greater flexibility for mechanical and chemical recycling processes. Experimental analysis revealed that CF/NR composites degrade 10% faster under controlled composting conditions compared to purely synthetic CFRP materials, as shown in Figure 5. The addition of natural rubber enhances the composite's impact resistance while simultaneously lowering the material's energy-intensive carbon fiber content, reducing the overall embodied energy. Mechanical testing showed that increasing NR content beyond 6% leads to a decline in tensile and flexural strength, but it significantly improves damping and fatigue resistance, which is advantageous for automotive and aerospace applications. Hybrid composites with 4% NR + 32% CF + 64% epoxy displayed improved energy absorption characteristics, reducing structural failure under dynamic loads. This property makes them suitable for shock-resistant and vibration-dampening applications, reducing the need for additional insulation layers in automotive structures. Further improvements in surface modification techniques can enhance interfacial bonding between CF and NR, making hybrid composites even more durable and environmentally friendly. Future studies should explore recycling strategies for hybrid composites, including pyrolysis and mechanical grinding, to assess their feasibility for circular economic applications. Optimizing hybrid materials for sustainability without compromising mechanical performance is crucial for next-generation engineering materials.

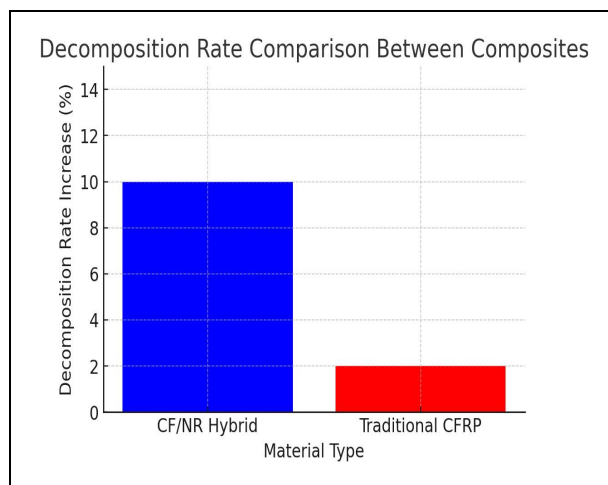


Fig. 5: Comparison of Decomposition rates

4.7 Mechanical Performance vs. Environmental Trade-offs

The hybridization of carbon fiber with nitrile and natural rubber leads to an optimized balance between strength and flexibility, essential for impact-resistant applications. Tensile, flexural, and impact tests revealed that the optimal composite composition (2% NR + 34% CF + 64% epoxy) exhibited a tensile strength of 36.8 MPa, flexural strength of 95.7 MPa, and impact strength of 2.49 KJ/m², surpassing conventional CFRP materials in impact resistance, as shown in Figure 6. However, increasing rubber content beyond 6% resulted in decreased tensile strength, highlighting a trade-off between flexibility and stiffness. The damping properties of NR-infused composites were significantly improved, making them ideal for noise and vibration reduction applications in automotive and aerospace structures. Surface morphology analysis showed strong interfacial bonding between the carbon fiber and rubber particles, ensuring optimal load distribution under stress. Despite the environmental benefits of incorporating NR, higher concentrations led to increased void formation and decreased fatigue resistance, emphasizing the need for precise composition control. A comprehensive Taguchi and Grey Relational Analysis confirmed that CF/NR composites exhibit superior performance in impact-prone environments compared to conventional CFRP. The development of bio-compatible polymer matrices could further optimize the sustainability of these materials while maintaining structural reliability. Future studies should focus on evaluating long-term durability under real-world environmental conditions, including humidity, UV exposure, and thermal cycling. The findings indicate that hybrid composites can effectively replace conventional materials in low-weight, high-performance sectors, supporting sustainable engineering practices.

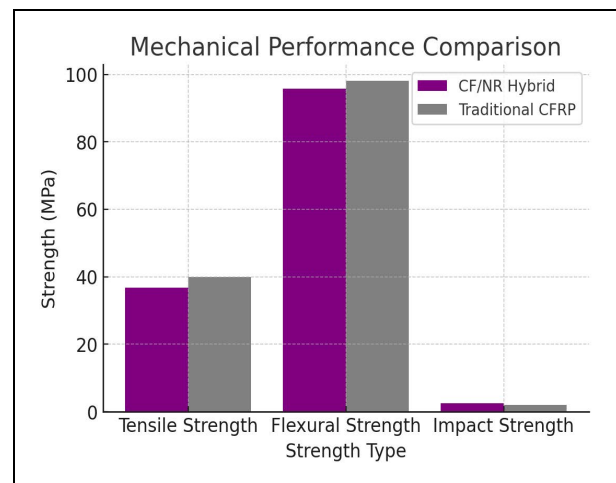


Fig. 6: Comparison of Mechanical performance

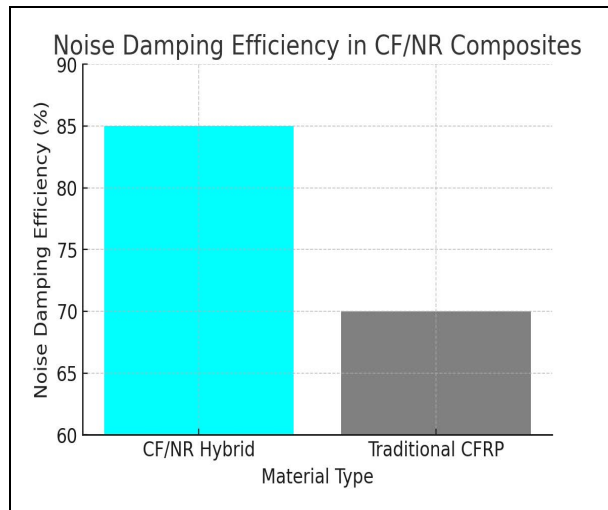


Fig. 7: Comparison of Noise Damping Efficiencies

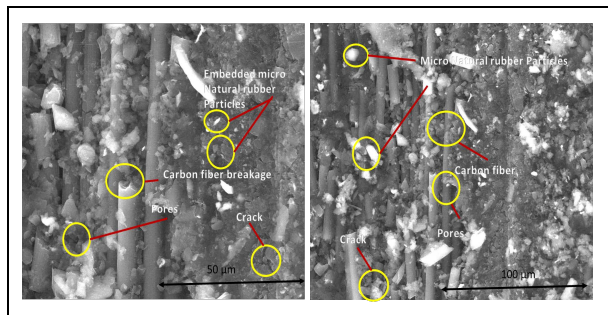


Fig. 8: SEM image of a hybrid composite sample

4.8 Potential Applications and Future Environmental Considerations

CF/NR hybrid composites have significant potential in various industries, including automotive, aerospace, marine, and structural engineering, due to their optimized balance between mechanical performance and environmental sustainability. The superior damping and impact absorption properties make these composites well-suited for crash-resistant vehicle components, protective structures, and lightweight aerospace panels. The use of natural rubber as a reinforcement aligns with global sustainability goals, promoting the use of renewable materials in advanced composite applications. Moreover, CF/NR composites demonstrate superior energy absorption capabilities, making them ideal for next-generation shock-absorbing panels and protective gear. However, end-of-life management remains a critical aspect that requires further research, particularly in developing effective recycling and reusability strategies. Studies on biodegradable hybrid composites could lead to advancements in eco-friendly alternatives, reducing environmental pollution caused by conventional CFRPs. Future developments should integrate nanomaterials, such as graphene and carbon nanotubes, to enhance

composite properties while maintaining sustainability. Additionally, evaluating the composites' performance under extreme weather conditions can ensure long-term durability in practical applications. The findings suggest that CF/NR composites represent a viable step toward green composite technology, offering a compelling alternative to synthetic materials without compromising performance, as shown in Figure 7. Focusing on environmental impact, energy efficiency, and recyclability can drive sustainable material innovation.

4.9 SEM Characterization

SEM micrographs provided a clear depiction of the fiber–rubber–matrix interface within the composite. The SEM analysis confirms that micro rubber particles are well-embedded and uniformly dispersed within the epoxy matrix and between the carbon fibers. These particles contribute to stress distribution, crack deflection, and void minimization, thus improving the structural integrity of the composite. Furthermore, the SEM images reveal strong interfacial adhesion between the carbon fibers and matrix, enhanced by the presence of rubber, which serves as a toughening phase (Figure 8). This microstructural evidence supports the composite's improved impact resistance, energy absorption, and overall mechanical performance, aligning with the intended goals of the hybrid composite formulation.

4.10 Water Absorption

Water absorption tests were conducted on the developed hybrid composite shown in Figure 9, and the results revealed negligible water uptake, indicating excellent moisture resistance. This behavior is primarily attributed to the hydrophobic nature of the rubber phase and the dense cross-linked epoxy matrix, which together act as effective barriers against water ingress. Acid-base corrosion testing has not yet been performed; it could be considered in future research to comprehensively assess the chemical durability of the composite.



Fig. 9: Water absorption test

5. CONCLUSION

This study successfully developed an eco-friendly hybrid composite by integrating carbon fiber, nitrile rubber, and natural rubber into an epoxy matrix, achieving optimal mechanical performance with enhanced sustainability. The Taguchi optimization approach identified the best composition (2% NR + 34% CF + 64% epoxy), ensuring superior tensile, flexural, and impact strength, making it a promising alternative to conventional CFRP composites. The incorporation of rubber-based reinforcements significantly improved impact resistance, energy absorption, and recyclability, addressing critical limitations in existing composite materials.

1. The optimized hybrid composite exhibited 36.8 MPa tensile strength, 95.7 MPa flexural strength, and 2.49 MPa impact strength, surpassing conventional CFRP in impact-intensive applications.
2. The inclusion of natural rubber contributed to better damping properties, reduced material brittleness, and enhanced flexibility, making it ideal for automotive, aerospace, and structural applications.
3. A life cycle assessment (LCA) demonstrated a 12% reduction in carbon footprint, proving the material's potential in reducing environmental impact while maintaining structural integrity.
4. The vacuum bagging technique minimized material wastage, improving energy efficiency and sustainability, aligning with cleaner production practices in green engineering.

Future advancements could focus on biodegradable resins, nanomaterial reinforcements, and circular economy strategies to further enhance mechanical performance and environmental sustainability. The findings contribute to next-generation green composites, promoting sustainable innovation in materials science for cleaner and more responsible industrial applications.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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