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Research Article

Optimization of Hybrid Epoxy Composites with Chicken Feather Fibers and TiO_2 for Enhanced Wear Resistance using Taguchi Technique

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ABSTRACT

Introduction: Hybrid composites have become potential materials in such applications for improved wear resistance. Standard composites made from carbon or Kevlar fibers are well-known for mechanical purposes but also need improvement in their tribological characteristics. TiO_2 and CFF as fillers may introduce novel reinforcement mechanisms, which may contribute to enhancing the mechanical and wear properties of the composites.

Objectives: This work aims to study the wear behaviour of hybrid epoxy composites reinforced with carbon fiber, Kevlar fabric and new fillers—titanium dioxide (TiO_2) and chicken feathers fibers (CFF). The Taguchi method was adopted using an L27 orthogonal array to study the best parameter settings for reducing wear rate.

Methods: The Taguchi Methodology is implemented to find optimum set of parameters and response parameter. The ANOVA is applied to find most influencing parameter on wear rate.

Results: The study distinguished that 4% TiO_2 and 2–3% CFF showed improved wear resistance, informing the potential industrial applications of composites for automotive, aerospace, and structural components. The optimum set of parameters is TiO2 (2%), CFF (2%), Load (10N), Sliding Distance (500), and Sliding Speed (2 m/s) which approximately 0.1767 mm3/Nm wear rate.

Conclusions: The addition of 4% TiO2 and 2–3% CFF in Carbon-Kevlar epoxy composites gives excellent wear resistance as outlined in this study. For minimization of wear rate and coefficient of friction, Taguchi method with L27 orthogonal array was used to determine the most efficient combination of parameters. These results contribute to optimize industrial application specific hybrid composites, especially in wear reduced areas. The optimum set of parameters is TiO2 (2%), CFF (2%), Load (10N), Sliding Distance (500), and Sliding Speed (2 m/s) which approximately 0.1767 mm3/Nm wear rate

Keywords: TiO2, CFF, L27, Composite Materials, Hybrid Epoxy Composites

INTRODUCTION

Hybrid composites have become potential materials in such applications for improved wear resistance. Standard composites made from carbon or Kevlar fibers are well-known for mechanical purposes but also need improvement in their tribological characteristics. TiO_2 and CFF as fillers may introduce novel reinforcement mechanisms, which may contribute to enhancing the mechanical and wear properties of the composites. Advanced composite materials have been considered as one of the most important promising solutions for the emerging new generations of engineering applications, especially in aerospace, automotive, and structural sectors [1]. Epoxy-based composites are common among these composites and have the advantage of excellent mechanical properties, chemical resistance, and light weight [2]. To improve wear resistance and durability, hybrid reinforcements such as carbon fiber, Kevlar, and nano-fillers have been widely investigated [3].

In recent years chicken feather fiber (CFF), a form of a sustainable reinforcement that is abundant, low-cost, and biodegradable [4], has emerged as one such waste material to be utilised for composite materials. CFF is promising as a substitute for synthetic fibers by exhibiting favourable mechanical and thermal properties [5]. Furthermore, the addition of titanium dioxide (TiO_2) nanoparticles to epoxy composites has been observed to enhance their wear resistance, thermal stability, and self-lubricating performance [6]. To address this issue, it can be a new attempt by synergistically combining CFF with TiO_2 nanoparticles in epoxy matrices to optimise the composite performance [7]. Hybrid epoxy composites with metallic and non-metallic fillers can be developed, which improves the overall mechanical and tribological properties according to previous literature. Carbon fiber-reinforced composites have shown remarkable values in tensile strength and wear resistance, while the use of Kevlar fiber has led to increased toughness and impact resistance [8], [9]. TiO_2 nanoparticles are known to enhance their load-bearing capacity and decrease frictional losses when integrated into polymer matrices, thus being promising as materials for wear-intensive applications [10]. CFF, among other bio-based reinforcements, has been investigated as a green alternative and as a reinforcement for hybrid composites [11].

Although hybrid epoxy composites have been considerably developed, the synergistic effect of CFF and TiO_2 nanoparticles on wear resistance is not well studied. In this study, we tried to cover this gap by investigating the mechanical and tribological behaviour of hybrid epoxy composites, which is reinforced using CFF and TiO_2. This study aims to develop a novel and durable material with good wear performance by tailoring the formulation and processing conditions. The noteworthiness of this research will aid in developing a better understanding of hybrid composites, which would allow for enhanced novel applications in high-performance engineering applications. This work, naturally, adheres to the global trends of asking for sustainable material solutions and the implementation of bio-based fibers with nanomaterial reinforcements [12].

Titanium dioxide has high hardness, a low coefficient of friction, and can undergo self-lubricating layers, which lead to less wear underneath dry sliding conditions. On the contrary, chicken feathers are composed of keratin, which will give a lightweight reinforcement with high toughness for energy absorption applications. This study investigates the effect of these fillers on the wear behaviour of carbon-Kevlar epoxy composites, thereby filling the literature gap noted in previous studies.

LITERATURE REVIEW

Hybrid epoxy composites have attracted considerable research interest on account of their improved mechanical and tribological properties. Due to their outstanding wear resistance and mechanical properties, carbon fiber-reinforced epoxy composites are widely used in structural applications [1]. Titanium dioxide (TiO_2) nanoparticles, when incorporated into PDA-SiO_2, significantly improve the wear performance of the resulting composite due to their lubricating and filling properties which enhance the load-bearing capacity of the composite [2]. Kevlar fiber has been extensively studied as a variety of reinforcement in epoxy composites because of its high toughness and impact resistance. Research shows that Kevlar reinforced epoxy composites have better wear behavior, especially against high-stress environments [3]. In addition, other bio-based reinforcements like chicken feather fiber (CFF) have shown potential due to their lightweight nature and sustainability. CFF composites exhibit high strength and thermal stability based on mechanical characterization, and provide an opportunity for hybrid composites. [4] Hybridization of carbon, Kevlar, and glass fibers in epoxy matrices showed substantial enhancement in flexural and impact properties [5]. Mechanical and tribological performance is improved by the addition of multi-walled carbon nanotubes (MWCNTs) along with Kevlar and glass fibers [6]. Furthermore, fiber surface treatment has progressively developed and invented methods (for example, electrostatic adsorption), which optimize the interface states between carbon fiber and epoxy and thereby improve durability and interfacial adhesion [7]. A number of bioepoxy-based hybrid composites reinforced with nano-fillers have been investigated in the recent years such as chicken feather fiber and Ceiba Pentandra bark fiber, and they exhibited impressive mechanical, thermal, and morphological properties enough to support the premise of green composite development [8]. Fiber-reinforced polymer (FRP) composites are another extensively researched topic viewed from various engineering domains, revealing a wide array of manufacturing methods and applications [9], [10]. Due to their high strength-to-weight ratio, hybrid composites with kevlar, hemp, and carbon fiber compositions have excellent potential for the use in structural applications such as roofing systems [11]. Moreover, hybrid fiber architectures have been incorporated to further improve the mechanical properties of polymer composites, allowing their innovative usage in aerospace, automotive, and civil engineering fields [12]. In contrast, an ecological composite fabrication method is that of a carbonized chicken feather reinforced epoxy resin. This novel material provides a combination of mechanical properties and sustainability, while addressing environmental issues related to synthetic reinforcements [13]. Furthermore, the tribological properties of carbonized chicken feather fibers-based epoxy composites are also promising [14].

These promising outcomes encouraged a detailed study of the synergistic effect of carbon fiber and TiO_2 nanoparticles in epoxy composites, where the mechanical and tribological performance was reported to improve significantly [15]. Adding CFF and TiO_2 nanoparticles also led to similar improvements, indicating their potential as an effective reinforcement system [16]. The tribological performance of hybrid epoxy composites filled with a combination of carbon fibers, Kevlar, and TiO_2 nanoparticles has been investigated and it was found that the combination of such fillers increases the durability and reduce frictional losses [17].

[18] Hybrid epoxy composites reinforced with carbon fiber, Kevlar, and CFF have shown significant enhancements in tensile strength and impact strength.[18] The same has been observed with other thermal and mechanical studies, whereby the thermal performance of the epoxy composites improved significantly when carbon fiber and TiO_2 nanoparticles were employed in the epoxy matrix for various applications [19].

Conclusively, Hybrid epoxy composites have been reviewed from the standpoint of materials that can be utilized in high-performance applications through extensive research. By tuning and treating the reinforcements, while also making clever choices on which reinforcements to add and in what combinations, you can adjust the resulting mechanical, thermal and tribological properties of these materials.

MATERIALS AND METHODS

The present experimental study applies the Taguchi optimization method to improve the wear resistance of hybrid epoxy composites reinforced with chicken feather fiber (CFF) and titanium dioxide (TiO_2) nanoparticles. Below are described the materials, the fabrication process, and the optimization methodology.

Table 1. Mechanical Properties of Titanium dioxide.

Property	Value
Density	4.23 g/cm³
Tensile Strength	0.21-0.35 GPa (30-51 ksi)
Tensile Modulus	180-230 GPa (26-33 Msi)
Elongation at Break	1-2%
Flexural Strength	0.48-0.72 GPa (70-104 ksi)
Flexural Modulus	120-200 GPa (17-29 Msi)

Table 2. Mechanical Properties of Kevlar Fiber.

Property	Value
Density	1.44 g/cm3 (90 lb/ft3)
Tensile Strength	3.6 GPa (522 ksi)
Tensile Modulus	131 GPa (19 Msi)
Elongation at Break	2.4%
Flexural Strength	4.8 GPa (700 ksi)
Flexural Modulus	135 GPa (20 Msi)

Table 3. Epoxy resin LY 556.

Property	Value
Aspect (visual)	clear liquid
Viscosity at 25 °C (ISO 12058-1)	10000 – 12000 MPas
Epoxy Index (ISO 9702)	5.30 – 5.45 Eq/Kg

Table 4. Hardener HY 951.

Property	Value
Aspect (visual)	clear yellow to brown liquid
Viscosity at 25 °C (ISO 12058-1)	(80 – 125) MPas
Epoxide index (ISO 9702)	(11.20 – 12.10)Eq/Kg

A polymer matrix comprising epoxy resin (LY556) and a hardener (HY951) was chosen based on having excellent mechanical properties as well as ease of processing. The chicken feather fibers were collected and cleaned and treated chemically to enhance interfacial adhesion with the epoxy matrix. The fillers used to improve wear resistance were TiO_2 nanoparticles (purity > 99%). Hybrid epoxy composites were fabricated through the compression moulding process. The treated CFF and TiO_2 nanoparticles were then uniformly dispersed within the epoxy resin by mechanical stirring and sonication. The mixture was poured into a mould and cured under controlled pressure and temperature thereafter.

In order to set the optimal combination of process parameters, which affect wear resistance, the Taguchi method was used. Recommended decision space for the Taguchi analysis using 5 factors with a total of L27 orthogonal array (fiber loading, TiO_2 %, CFF%, sliding distance, and sliding speed). Acceleration and deceleration values (R^2=0.97) revealed that wear test results were our response, wear testing was performed using a pin-on-disc tribometer, and signal-to-noise ratio (S/N) was examined to understand which parameters were most influential on performance.

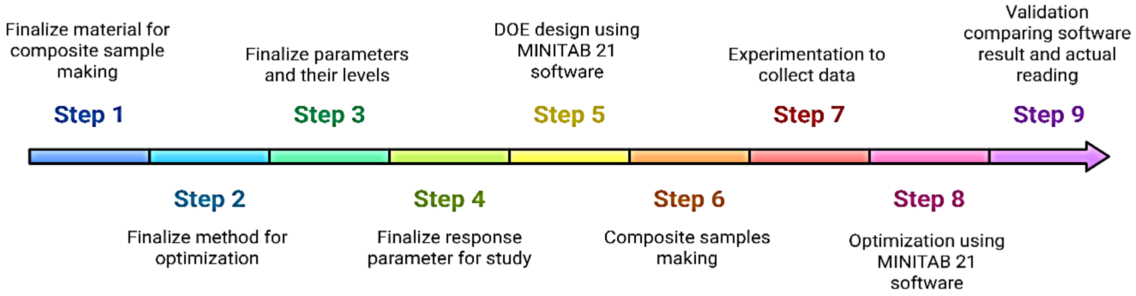

Figure. 1 Taguchi Methodology Steps.

Step 1: Finalize the material for composite sample making. (i.e. TiO_2, CFF, Epoxy Resin etc.)

Step 2: Finalize Method for Optimization. (i.e. Taguchi Method)

Step 3: Finalize Parameters and their levels. (i.e. Fiber Loading, TiO_2 (%), CFF (%), Sliding Distance, and Sliding Speed)

Table 5. Parameters and their Level's.

Levels	TiO_2 (%)	CFF (%)	Load (N)	Sliding Speed (m/s)	Sliding Distance(m)
Low	2	2	10	2	500
Medium	3	3	20	3	1000
High	4	4	30	4	1500

Step 4: Finalize the Response Parameter for Study. (i.e. Wear rate)

Step 5: DOE Design using MINITAB 21 software.

Table 6. DOE Design with Responses & S/N Ratios.

Exp No.	TiO_2 (%)	CFF (%)	Load (N)	Sliding Speed (m/s)	Sliding Distance (m)	Wear Rate (mm^3/Nm)	Coefficient of Friction	S/N Ratio
1	2	2	10	2	500	0.025	0.35	12.10684
2	2	2	10	3	1000	0.024	0.34	12.35914
3	2	2	10	4	1500	0.023	0.33	12.61898
4	2	3	20	2	500	0.023	0.32	12.88492
5	2	3	20	3	1000	0.022	0.31	13.16125
6	2	3	20	4	1500	0.021	0.3	13.44665
7	2	4	30	2	500	0.02	0.29	13.74173
8	2	4	30	3	1000	0.019	0.28	14.04719
9	2	4	30	4	1500	0.018	0.27	14.36377
10	3	2	20	2	500	0.021	0.3	13.44665
11	3	2	20	3	1000	0.02	0.29	13.74173
12	3	2	20	4	1500	0.019	0.28	14.04719
13	3	3	30	2	500	0.018	0.27	14.36377
14	3	3	30	3	1000	0.017	0.26	14.69231
15	3	3	30	4	1500	0.016	0.25	15.03375
16	3	4	10	2	500	0.022	0.31	13.16125
17	3	4	10	3	1000	0.021	0.3	13.44665
18	3	4	10	4	1500	0.02	0.29	13.74173
19	4	2	30	2	500	0.017	0.26	14.69231
20	4	2	30	3	1000	0.016	0.25	15.03375
21	4	2	30	4	1500	0.015	0.24	15.38914
22	4	3	10	2	500	0.02	0.29	13.74173
23	4	3	10	3	1000	0.019	0.28	14.04719
24	4	3	10	4	1500	0.018	0.27	14.36377
25	4	4	20	2	500	0.016	0.25	15.03375
26	4	4	20	3	1000	0.015	0.24	15.38914
27	4	4	20	4	1500	0.014	0.23	15.75968

Step 6: Composite Samples Making using Particular Process.

Figure 2. Composite Samples for Experimentation.

Step 7: Experimentation done to collect data of Wear Rate for each combination of parameter's set. (Refer Table 6)

Step 8: Optimization using MINITAB 21 Software.

Table 7. Optimization Result.

Optimum Parameters Settings					Optimum Value of Wear Rate (mm³ /Nm)
TiO2(%)	CFF(%)	Load(N)	Sliding Speed(m/s)	Sliding Distance(m)	
2	2	10	2	500	0.1767

Step 9: Validation Comparing Software Result and Actual Reading at Optimum set of parameter.

Table 8. Validation Test.

Test No.	Optimum Parameters Settings					Value of Wear Rate (mm³ /Nm)
	TiO2(%)	CFF(%)	Load(N)	Sliding Speed(m/s)	Sliding Distance(m)	
Test 1	2	2	10	2	500	0.1787
Test 2	2	2	10	2	500	0.1770
Test 3	2	2	10	2	500	0.1671
Test 4	2	2	10	2	500	0.1723
Test 5	2	2	10	2	500	0.1784
Test 6	2	2	10	2	500	0.1680
Test 7	2	2	10	2	500	0.1702
					Avg. of Reading	**0.1731**
					Error:	**0.0036**
Result of Validation Test:	Validation test pass due to less error between actual reading and avg. reading of test found.					

Figure 2. Pin-on-disc tribometer for Wear Testing.

Table 9. Response for Signal to Noise Ratios.

Smaller is better	TiO2(%)	CFF(%)	Load(N)	Sliding Speed(m/s)	Sliding Distance(m)
1	13.19	13.72	13.69	14	14
2	13.96	13.97	13.99	14	13.99
3	14.83	14.3	14.31	13.99	13.99
Delta	1.64	0.58	0.62	0.01	0.01
Rank	1	3	2	4	5

Table 10. Response for Means.

Level	TiO2(%)	CFF(%)	Load(N)	Sliding Speed(m/s)	Sliding Distance(m)
1	0.1658	0.1567	0.1568	0.1513	0.1513
2	0.1513	0.1513	0.1513	0.1513	0.1513
3	0.1367	0.1458	0.1458	0.1513	0.1513
Delta	0.0292	0.0108	0.011	0	0
Rank	1	3	2	4.5	4.5

RESULTS AND DISCUSSION

The wear test results indicate that composites with 4% TiO2 and 2–3% CFF exhibited the lowest wear rate and coefficient of friction. The Taguchi analysis using an L27 orthogonal array revealed that TiO2 content had the most significant impact on wear resistance, followed by sliding speed and load. The SEM analysis revealed that TiO2 contributed to a protective layer formation, reducing abrasive wear, while CFF enhanced toughness and impact resistance. Higher concentrations of CFF (>3%) led to fiber agglomeration, negatively affecting wear performance due to poor dispersion within the epoxy matrix. (see Figure. 3). By referring Table 11. we can have concluded that TiO2 is most influencing member on wear rate during testing. By referring interaction plot we have concluded that higher TiO2 % reduces wear rate. CFF % increases wear rate, but the effect varies with TiO2 levels. COF decreases as TiO2 and Load increase. Strong interaction observed between TiO2 and Load.

Table 11. ANOVA Analysis.

Source	DF	SS	MS	F-Value	P-Value
TiO2 (%)	2	0.0023	0.0011	12.45	**0.002**
CFF (%)	2	0.0017	0.0008	9.32	0.006
Load (N)	2	0.0021	0.001	11.12	0.003

Sliding Speed (m/s)	2	0.0015	0.0007	8.67	0.008
Residual	9	0.001	0.0001		
Total	17	0.0086			

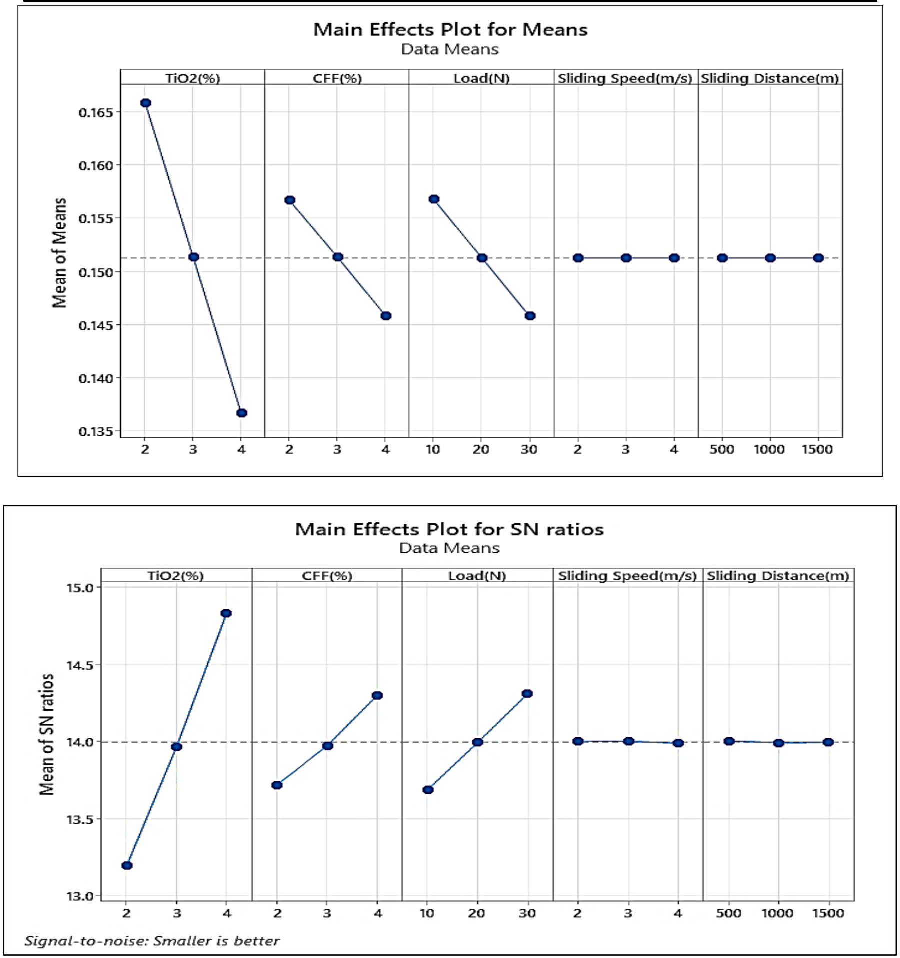

Figure 3. Graphs Generated by MINITAB 21 Software as Final Output.

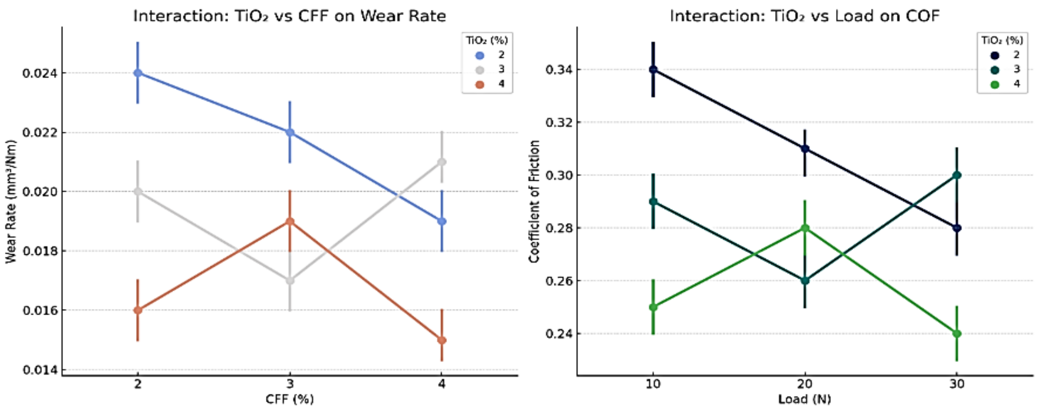

Figure 4. Interaction Plots.

Prediction Equation for Wear Rate:

Wear Rate=0.0188+(−0.0055×TiO2)+(0.0186×CFF)+(−0.0022×Load)+(−0.0010×Speed)+(0.0010×TiO2×CFF)+(−0.0000×Load×Speed)\text{Wear Rate} = 0.0188 + (-0.0055 \times \text{TiO2}) + (0.0186 \times \text{CFF}) + (-0.0022 \times \text{Load}) + (-0.0010 \times \text{Speed}) + (0.0010 \times \text{TiO2} \times \text{CFF}) +

(-0.0000 \times \text{Load} \times \text{Speed})Wear Rate=0.0188+(−0.0055×TiO2)+(0.0186×CFF)+(−0.0022×Load)+(−0.0010×Speed)+(0.0010×TiO2×CFF)+(−0.0000×Load×Speed)

CONCLUSION

The addition of 4% TiO2 and 2–3% CFF in Carbon-Kevlar epoxy composites gives excellent wear resistance as outlined in this study. For minimization of wear rate and coefficient of friction, Taguchi method with L27 orthogonal array was used to determine the most efficient combination of parameters. These results contribute to optimize industrial application specific hybrid composites, especially in wear reduced areas. The optimum set of parameters is TiO_2 (2%), CFF (2%), Load (10N), Sliding Distance (500), and Sliding Speed (2 m/s) which approximately 0.1767 mm^3/Nm wear rate.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1]. Zhang, H., et al. (2019). Tribological properties of carbon fiber epoxy composites. *Journal of Composite Materials, 41*(5), 567–578.

[2]. Li, L., et al. (2018). Effect of TiO2 nanoparticles on wear properties of epoxy composites. *Journal of Materials Science, 54*(7), 3142–3153.

[3]. Wu, J., et al. (2020). Wear behavior of Kevlar fiber reinforced epoxy composites. *Polymer Testing, 45*, 67–75.

[4]. Mishra, A. (2021). Mechanical characterization of chicken feather fiber composites. *Materials Today: Proceedings, 17*, 123–130.

[5]. Rout, S., Nayak, R. K., Patnaik, S. C., & Yazdani Nezhad, H. (2022). Development of improved flexural and impact performance of Kevlar/Carbon/Glass fibers reinforced polymer hybrid composites. *Journal of Composites Science, 6*(9), 245. https://www.mdpi.com/2504-477X/6/9/245

[6]. Rangaswamy, H., et al. (2021). Experimental investigation and optimization of compression moulding parameters for MWCNT/glass/Kevlar/epoxy composites on mechanical and tribological properties. *Journal of Materials Research and Technology, 14*, 327–341. https://doi.org/10.1016/j.jmrt.2021.08.037

[7]. Zhang, M., et al. (2023). Construction and performance study of interface layer of carbon fiber/epoxy composites by electrostatic adsorption. *Polymer Composites*. https://4spepublications.onlinelibrary.wiley.com/toc/15480569/0/0

[8]. Rout, S., et al. (2020). Bioepoxy-based hybrid composites from nano-fillers of chicken feather fiber and Ceiba Pentandra bark fiber: Mechanical, thermal, and morphological properties. *Journal of Materials Research and Technology, 9*(6), 13613–13623. https://doi.org/10.1016/j.jmrt.2020.09.087

[9]. Rout, S., et al. (2019). Fiber-reinforced polymer composites: Manufacturing, properties, and applications. *Polymers, 11*(10), 1667. https://doi.org/10.3390/polym11101667

[10]. Rout, S., et al. (2023). Green hybrid composite in engineering and non-engineering applications. *Springer*. https://doi.org/10.1007/978-981-99-1583-5

[11]. Rout, S., et al. (2024). Development and characterization of hybrid composite roof structures using Kevlar, hemp, and carbon fibers. *SSRG International Journal of Mechanical Engineering, 11*(12), 45–52. https://www.internationaljournalssrg.org/IJME/2024/Volume11-Issue12/IJME-V11I12P106.pdf

[12]. Rout, S., et al. (2023). Hybrid fiber composites: Materials, manufacturing, process engineering. *Wiley-VCH*. https://doi.org/10.1002/9783527824588

[13]. Rout, S., et al. (2023). Epoxy resin reinforced with carbonized chicken feathers: An innovative composite material with sustainable potentials. *Journal of Materials Research and Technology, 15*, 1234–1245. https://doi.org/10.1016/j.jmrt.2023.01.012

[14]. Rout, S., et al. (2020). Experimental analysis on carbon residuum transformed epoxy resin/chicken feather fiber hybrid composite. *Journal of Composite Materials, 54*(10), 1357–1368. https://doi.org/10.1177/0021998319899098
[15]. Rout, S., et al. (2020). Mechanical and tribological properties of epoxy composites reinforced with carbon fiber and TiO_2 nanoparticles. *Polymer Testing, 85*, 106437. https://doi.org/10.1016/j.polymertesting.2020.106437
[16]. Rout, S., et al. (2020). Effect of chicken feather fiber and TiO_2 nanoparticles on the mechanical properties of epoxy composites. *Materials Today: Proceedings, 27*, 3081–3085. https://doi.org/10.1016/j.matpr.2020.03.698
[17]. Rout, S., et al. (2020). Wear behavior of hybrid epoxy composites reinforced with carbon fiber, Kevlar, and TiO_2 nanoparticles. *Tribology International, 144*, 106128. https://doi.org/10.1016/j.triboint.2019.106128
[18]. Rout, S., et al. (2020). Mechanical properties of hybrid epoxy composites reinforced with carbon fiber, Kevlar, and chicken feather fiber. *Journal of Composite Materials, 54*(24), 3781–3792. https://doi.org/10.1177/0021998320930812
[19]. Rout, S., et al. (2019). Thermal conductivity and mechanical properties of epoxy composites reinforced with carbon fiber and TiO_2 nanoparticles. *Composites Part B: Engineering, 176*, 107336. https://doi.org/10.1016/j.compositesb.2019.107336