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Experimental evaluation and optimization of kenaf-coir based hybrid composite incorporated with titanium carbide nano-fillers

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A B S T R A C T

In the current decade, a number of industries have moved their attention towards emerging sustainable technologies in order to better support socio-economic and environmental considerations. The present research investigates a unique hybrid composite developed by the amalgamation of natural kenaf-coir fibers, with resin of epoxy, incorporated with titanium carbide (TiC) nanoparticles. This study also presents the development process involved in manufacturing the composites, along with mechanical testing and optimization of these composite samples. The nanofillers of TiC are utilized in wt. percentages of 0%, 3%, 4%, and 5%, while coir and kenaf fibers are incorporated at 0%, 3%, 4%, and 5% by weight, and the thickness of the samples is varied at 2, 3, 4, and 5mm. The mechanical attributes of composites are evaluated using a vacuum bag molding process, with subsequent testing and optimization performed through Taguchi and ANOVA analysis to discover the optimal sample combination. The findings indicate that the most effective composite formulation includes 4% TiC, 5% kenaf, 5% coir, and a thickness of 3 mm, which provides the highest tensile modulus and strength among all tested samples. The integration of kenaf fibers with coir fibers and TiCs as fillers significantly improves the tensile and flexural attributes of the hybrid composite in contrast to composites made with coir or kenaf fibers alone.

1. Introduction

Concerning the intense competition in today's market, industries and manufacturers are researching of exploring new and innovative sustainable and environmentally friendly materials (Hanan et al., 2018; Rathee et al., 2018; Asyraf et al., 2020; Sadjadi, 2021; Gupta et al., 2022; Yadav & Chawla, 2022; Yadav & Chawla, 2024). In the manufacturing sector, natural fiber composite (NFCs) have attained huge consideration as sustainable materials (Saxena & Chawla, 2022; Nagarjun et al., 2020). Natural fibers are efficiently utilized as augmentation in the field of composites, for numerous applications, including aerospace, construction, furniture components, defense, and transportation, as seen through various studies and research (Saxena & Chawla, 2023; Alsubari et al., 2021; Sapuan et al., 2021; Kaushal et al., 2021; Amir et al., 2021; Saxena et al., 2024; Chawla et al., 2025). The fact that NFCs are advantageous in comparison to synthetic ones is their low cost, biodegradable nature, widely accessible, renewable, and lightweight (Bajpai et al., 2014; Parashar & Chawla, 2021; Ku et al., 2011; Saxena & Chawla, 2022a; Saxena & Chawla, 2021; Saxena & Chawla, 2024). Natural fibers can be acquired from three individual places; animals, minerals, and plants. Over two thousand different varieties of fiber plants grow globally; they include kenaf, hay, sisal, coir, sugarcane, banana, jute, flax, and cotton (Rognoli et al., 2011; Ilyas et al., 2021). The majority of these plant species are composed of cellulose. NFCs are also known for reducing disposal, lesser energy consumption during production, and almost no carbon footprints.

Industries globally are currently facing new challenges in the development of innovative, eco-friendly, and sustainable products by incorporating natural fibers from agriculture (Faruk et al., 2013). Over the last ten years, there has been notable

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advancement in natural fiber composites, spurred by increasing environmental awareness. These composites are appreciated for their toughness, rapid processing, low abrasion, strength, lightweight nature, affordability, and durability. Researchers are keenly investigating the mechanical and physical attributes of these fibers to explore their potential to substitute synthetic fibers in plenty of applications (Holbery et al., 2006; Parashar & Chawla, 2022; Parashar & Chawla, 2023; Parashar et al., 2024). **Fig. 1** depicts the blending of matrix and fiber to develop a composite material. On an extensive literature survey, natural fibers were observed to have superior mechanical characteristics amongst others, which have been taken in this research. The two primary natural fibers considered here are the fibers derived from the kenaf plant, that is the kenaf fibers, and the fibers obtained from the coconut plant which are the coir fibers. Kenaf fibers are well-known for their ability to replace glass fibers because of their durability and high tensile nature (Parashar & Chawla, 2022a; Parashar & Chawla, 2023a; Saba et al., 2015). Coir fibers, derived from coconut are known for their biodegradability, hardness, strength, and high toughness, along with a certain wear resistance (Lai et al., 2005).

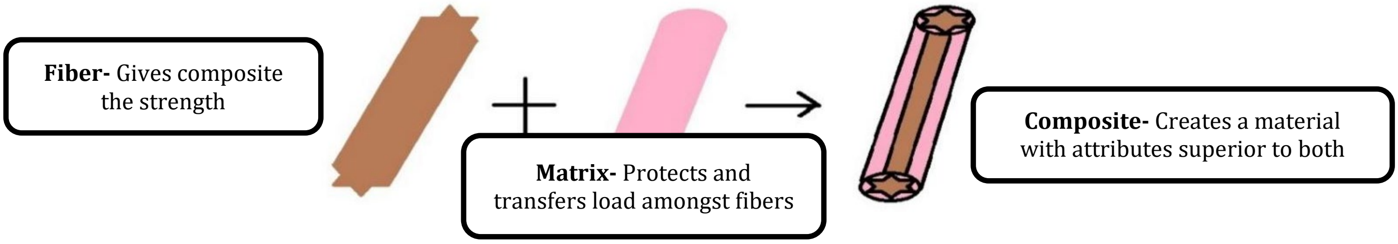


Fig. 1. Blend of matrix and fiber to develop a Composite

Coconut plant is a sustainable and renewable source of natural fibers. Coir fiber obtained from coconut plants is widely available in huge quantities across the world. The annual production of it is observed to be approx. 0.75 million tons globally of which India contributes to about 20% of it every year (Jayabal et al., 2020). Coir fiber has been discovered to possess high tensile strength and elongation. Coir, which makes up roughly 25% of the coconut, is a biodegradable, rigid, fiber obtained from the mesocarp of coconut plants (Bettini et al., 2010; Zainudin et al., 2013; Zhang & Hu, 2014). This is attributed to its high content of lignin which grants strength, high resistance to weather, waterproofing characteristics, and compliance with chemical treatments (Geethamma et al., 2005; Yan et al., 2015). Coir fibers have a high percentage of elongation at break, so they can be stretched past their elastic limit also (Siakeng et al., 2018).

In recent years, a significant amount of attention has been paid to studying the mechanical properties, morphological, thermal properties, and structural arrangement of coir fibers (Essabir et al., 2016; Arrakhiz et al., 2013). Research studies mentioned that the composites of coir fibers along with other composite materials such as rice straws (Zhang & Hu, 2014), kenaf Fiber (Islam et al., 2015), glass fibers (Bhagat et al., 2013), and bamboo fibers (Yusoff et al., 2016) have shown an improvement in the features of these composite materials. Coir fibers are characterized by their low cost and density, low modulus of elasticity, and high elongation at break (Sudhakara et al., 2013; Saw et al., 2014).

Nanoparticle incorporation in composite materials has resulted in the improvement of the attributes of the various hybrid composites (Puchy et al., 2013; Abbas et al., 2013). Titanium carbide (TiC) puts forward exceptional properties such as mechanical properties, and thermal properties, proffering it as an alluring element for reinforcement in material composites (Wetzel et al., 2006; Dasari et al., 2009).

Titanium Carbide is gaining popularity as a filler for materials like metals and polymer-based composites because of its high elastic modulus, melting point, increased wear resistance, and lower thermal expansion coefficient (Chen et al., 2009; Xiuqing et al., 2006; Parashivamurthy, 2001). Due to the high melting point of TiC at 3065ºC, these nanoparticles have been used as reinforcement in creating thermally robust materials that can withstand extremely intense temperatures (Durlu, 1999). Furthermore, there appears to be less curiosity about the physical characteristics of the TiC nanoparticles added to polymer composites (El-Tantawy, 2002). Even though titanium carbide is shown to improve the qualities of many fiber composites, not much research has been carried out in creating coir fiber composites with it as a filler. Due to its rising demand in several application areas, titanium carbide is anticipated to be available at a fair price shortly (Mhadhbi & Driss, 2021).

Poletti et al. (2008) fabricated titanium-incorporated SiC matrix composites using the hot extrusion method at 850ºC-950ºC, with densities near 100%. The authors discovered a satisfactory distribution of particles that is slightly inclined in the direction of extrusion and no reaction zone. Moreover, the specific strength, stiffness, and wear properties are increased while hard ceramic particulates are embedded to the matrix material. Xiao et al. (2009) investigated the creep behavior and stress regions of titanium hybrid composites reinforced with nanofillers of Titanium boride, Titanium Carbide, etc. These composites' creep behavior is primarily governed by dislocation climbing in the high- and low-stress zones and grain boundary movement.

Titanium carbide-aluminum composite is produced by Rastegari et al. (2011) using vacuum induction melting and hot rolling method. It is discovered that three distinct types of TiC precipitation, including trans-granular, eutectic, and grain boundary, are identified in the microstructure. Tensile strength and hardness are magnified by raising the volume fraction of TiC. The existence of brittle TiC nanofillers reduced the ductility of the composites. However, due to refinement in the microstructure of composites because of TiC incorporation, excellent ductility is obtained.

Hybrid composites are valued for their high specific modulus, low weight, and impressive strength, making them suitable for structural applications (Li et al., 2014). Titanium carbides (TiCs) are particularly important for reinforcement because of their magnificent electrical, thermal and mechanical properties, as well as their exceptional stiffness, strength, and durability (Golla et al., 2023).

The literature research available indicates that integrating different reinforcing materials can significantly improve the properties of laminates. The literature review has highlighted several research gaps:

- There is limited research on kenaf fibers and their combination with coir fibers.
- Investigations into the employment of nanofillers in hybrid composites are sparse, and the role of Titanium carbide as nanofiller in composites has not been significantly researched.
- There has been no experimental research evaluating the mechanical attributes of a novel kenaf-coir fiber hybrid epoxy composite augmented with Titanium Carbide and using epoxy as a matrix.
- The Taguchi and ANOVA optimization techniques have not been applied to this proposed composite.

Based on these gaps, the objectives of the proposed work is as follows:

- To construct a novel innovative kenaf-coir epoxy hybrid composite, fortified with titanium carbide particles, utilizing the vacuum bag molding technique, and differing the weight percentages of kenaf-coir fibers, TiC fillers, and sample thickness.
- To conduct mechanical testing, including tensile, flexural, and impact tests on all developed hybrid composite samples, following ASTM standards.
- To analyze and compare the mechanical features, particularly the tensile modulus of the kenaf-coir hybrid epoxy composite, using various analytical models (Parashar et al., 2022) in contrast to the experimental outcomes of this investigation.
- To optimize the fabricated composite samples using Taguchi, ANOVA, and RSM techniques, and identify the best composite formulation based on mechanical performance with varying fiber and filler weight percentages.

2. Materials & Methodology

2.1 Materials

As discussed earlier, the proposed research paper focuses on two natural fibers—coir and kenaf—chosen for their beneficial effects in enhancing the elastic properties of fiber composites. In addition to these fibers, nanofillers made of Titanium Carbide have also been included in the study for experimental testing and optimization.

The coir fiber used in this study is acquired from New Paras Textile in New Delhi. This raw fiber has a diameter of 15 µm. The kenaf fiber, having a diameter of 25 µm is obtained from the Fiber Region, Chennai, Tamil Nadu, in its raw form. The epoxy matrix Grade 520, is obtained from Go Green India Pvt. Ltd., Chennai, Tamil Nadu. The nanoparticles of TiC utilized in this research are obtained from Vedayukt India Pvt Ltd., Jamshedpur, Jharkhand.

2.2 Methodology

Analytical modeling is being utilized for assessing the mechanical attributes of the hybrid composite. The various models utilized here are Tsai Pagano's Model, Hirsch's Model, and Chamis Model (Parashar et al., 2022). The Rule of Hybrid Mixture model utilized in this research is shown by the equation below (1).

Rule of Hybrid Mixtures:
$$E_c = V_{f1}E_{f1} + V_{f2}E_{f2} + V_mE_m \tag{1}$$

where, E_{f1} & E_{f2} illustrate the fiber elastic modulus, E_c depicts the Young's Modulus of the composite, V_m depicts the matrix volume, V_{f1} & V_{f2} illustrate the fiber's volume fractions, and E_m illustrates the matrix modulus of elasticity (Yusoff et al., 2016).

The kenaf-coir hybrid epoxy composite embedded with titanium carbide nanoparticles is assessed for its mechanical characteristics (Parashar et al., 2022). The outcomes of this hybrid composite are specified in **Table 1**.

Table 1. Attributes of proposed hybrid composite reinforced with TiC nanoparticles (Parashar et al., 2022)

Models/Properties	Chamis Model	Hirsch Model	Tsai-Pagano Model	RVE
Transverse Modulus (GPa)	13.30	12.98	12.50	13.18
Longitudinal Modulus (GPa)	19.21	19.21	19.21	19.21

The proposed research work focuses mainly on the experimental and optimization of the kenaf-coir hybrid composite reinforced with the nanoparticles of TiC and also compares the outcomes of experimental properties with the results of the analytical evaluation. The vacuum bag molding process is utilized for the development and fabrication of the proposed hybrid composite (Biswas & Anurag, 2019). The steps involved in this process initiates with the development of a mold surface of toughened glass (Biswas & Anurag, 2019). To give a good surface finish, a layer of wax is glued to the toughened glass surface, on which the coating of Polyvinyl Acetate (PVA) is also provided acting as a release agent and helping in the extraction of the fabricated sheet, post the completion of the process.

The epoxy grade 520 and hardener are mingled in a 10:1 ratio, making use of a stirrer. The hardener, LY951, acts as a curing agent, which converts the liquid epoxy into a gel and then to a solid state. The epoxy Grade 520 is perfect to be used for developing of high-performance composites, and having brilliant characteristics to be applied as a matrix material (Abdellaoui et al., 2019; Ciesielski et al., 2017). The nanoparticles of TiC are then added to the epoxy resin in various weight percentages, as depicted in **Table 2**. This epoxy resin mixture containing TiC nanoparticles is applied over the PVA coat using a brush.

Next, a reinforcement layer comprising unidirectional kenaf and coir fibers, with different weight percentages determined by the Taguchi analysis in **Table 2**, is laid over the epoxy coat using the hand layup technique. After this, a peel ply is placed on top to ensure a smooth finish, followed by a perforated release film and a breather cloth. The entire assembly is then sealed to the mold using a vacuum bag film that includes a hole for the vacuum port. Sealant tape is employed to attach the vacuum bag to the tool.

A vacuum pressure of 140 kPa is employed to the mold to extract the surplus resin and trapped air. After four hours, the hybrid composite samples are successfully detached from the mold and allowed to cure at ambient temperature for 24 hours. Figure 2 provides an illustration of the Vacuum Bag Molding process.

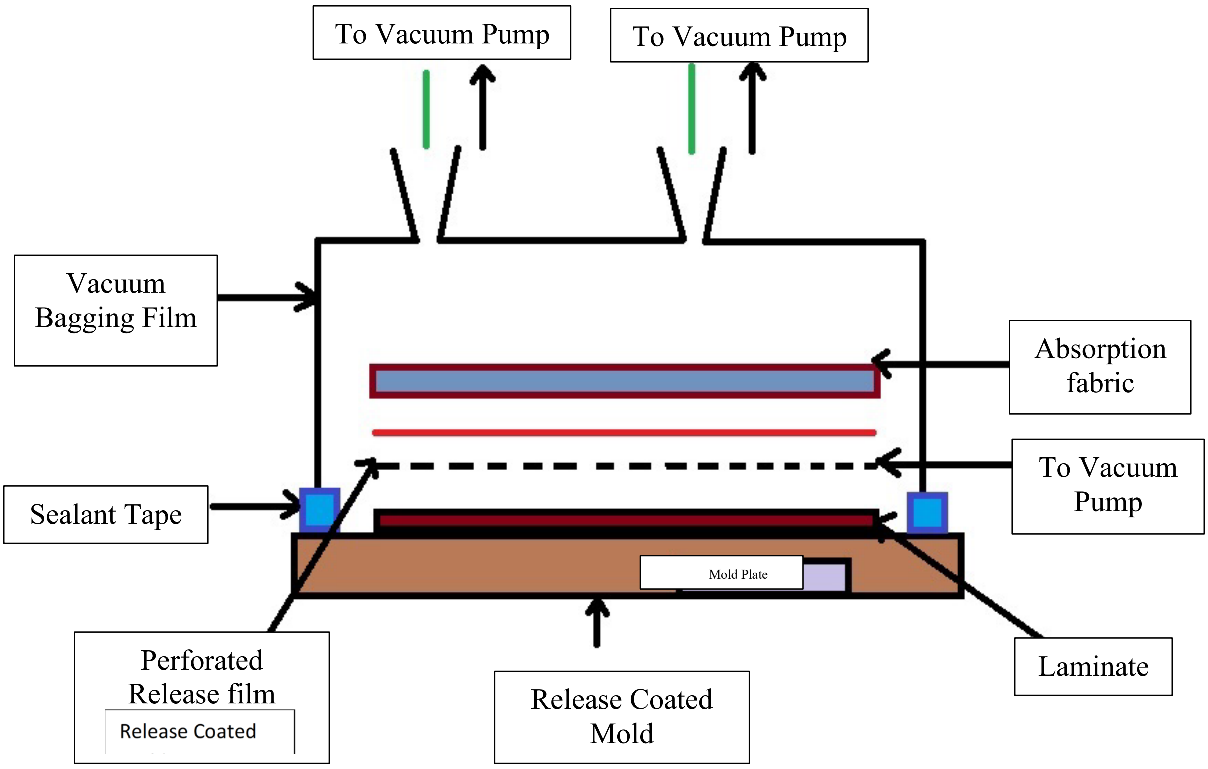


Fig. 2. Illustration of Vacuum Bag Molding Process.

Table 2 below shows the various four process parameters which are utilized to fabricate different samples. A 4×4 matrix is considered in the Taguchi method, with different process parameters. The weight percentages of TiC nanofiller varies between 0, 3, 4, and 5 wt.%, while the weight percentages of coir and kenaf fibers varies between 0, 3, 4, and 5 wt.%. The sample thickness varies between 2, 3, 4, and 5 mm (Parashar et al., 2022).

Table 2. Process Parameters for development of kenaf-coir composite

Process Parameters	TiC, wt% (A)	Kenaf, wt% (B)	Coir, wt% (C)	Thickness, mm (D)
Level 1	0	0	0	2
Level 2	3	3	3	3
Level 3	4	4	4	4
Level 4	5	5	5	5

Table 3
Different samples for experimental analysis of TiC fortified kenaf coir hybrid epoxy composite

Sample NO.	TiC (wt.%)	Coir (wt.%)	Kenaf (wt.%)	Thickness (mm)
1	0	3	0	2
2	0	0	3	3
3	0	4	4	4
4	0	5	5	5
5	3	0	3	4
6	3	3	0	5
7	3	4	5	2
8	3	5	4	3
9	4	0	4	5
10	4	3	5	4
11	4	4	0	3
12	4	5	3	2
13	5	0	5	3
14	5	3	4	2
15	5	4	0	5
16	5	5	3	4

Using Taguchi analysis that is performed on Minitab Statistical Software version 22.1.0, sixteen different samples of TiC-fortified kenaf-coir epoxy hybrid composites have been developed. All the 16 samples developed vary in the TiC content, coir content, kenaf content, and thickness. Vacuum bag molding technique is utilized to fabricate all the different samples which are then subjected to test their mechanical properties. **Table 3** describes the 16 hybrid composite samples which are used for experimental analysis of the TiC-fortified kenaf-coir hybrid epoxy composite. **Fig. 3** shows the texture of titanium carbide nanoparticles in powder form and **Fig. 4** depicts the different samples placed for vacuum bag molding.

Fig. 3. Titanium Carbide Nanoparticle Powder

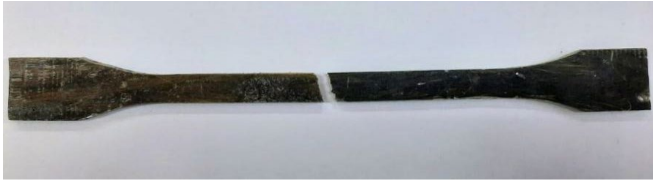
Fig. 4. Samples placed on the sheet for Vacuum Bag Molding Process

Fig. 5 shows a selection of the fabricated samples from the 16 TiC-reinforced coir-kenaf hybrid epoxy composites. The dimensions of these composite samples are 12 inches by 12 inches, with thicknesses of 2mm, 3mm, 4mm, and 5mm, respectively. Experimental images of different testing samples have been shown in **Fig. 6.**

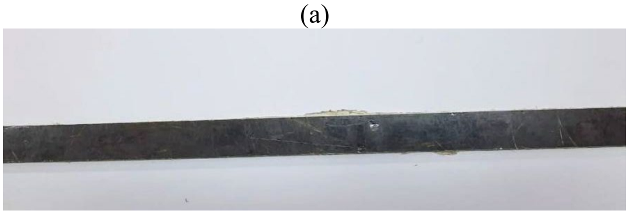
(a) (b) (c) (d)

Fig. 5. The different fabricated samples of Titanium carbide nanoparticles reinforced kenaf-coir hybrid epoxy composite sample with (a) 0 wt.% of TiC (b) 3 wt.% of TiC (c) 4 wt.% of TiC (d) 5 wt.% of TiC

(a)



(b)



(c)

(d)

(e)

Fig. 6. (a) to (e) Images of some experimental testing kenaf-coir-based hybrid composite incorporated with titanium carbide nano-fillers samples for mechanical testing.

3. Mechanical Testing

To demonstrate the mechanical attributes of the TiC-reinforced kenaf-coir epoxy hybrid composites, various mechanical tests have been performed, including flexural, tensile, impact, and hardness tests. All of the mechanical testing was conducted following the ASTM standards.

3.1 Tensile Testing

Tensile testing is employed to measure the yield deformation, of a material. The tensile attributes of the Titanium Carbide (TiC) incorporated kenaf-coir hybrid epoxy composite specimens were evaluated employing a Universal Testing Machine (UTM) with a maximum load capacity of 5000 N. The test has been performed at a crosshead speed of 5mm/min in accordance to ASTM D638-2014 standards.

3.2 Flexural Testing

Flexural testing is a mechanical test, utilized to examine the stiffness of a composite material. A Universal Testing Machine (UTM) with a 5000 N capacity, equipped with a three-point bending fixture is utilized for testing the flexural resistance of the proposed hybrid composite. The conducted test was in accordance to the ASTM D790-2017 standard, with a 10 kN load cell.

3.3 Impact Testing

Izod impact testing machine, with a pendulum hammer possessing a drop height of 610 ± 2 mm and an initial potential energy of 2.7 J, is being used for evaluating the material's resistance to deformation and the ability to withstand shocks, testing the impact resistance of the proposed hybrid epoxy composite by following ASTM D256-2010 standards.

3.4 Hardness Testing

Barcol hardness Tester, with Model 934-1 used to test the hardness of a variety of materials such as fiberglass, aluminum, plastics, etc., is being utilized to discover the hardness of the proposed hybrid composite. The testing is been done following the ASTM D2583-1981 standards.

4. Modelling and Optimization

The optimization is accomplished once the results of the experimental testing have been obtained. Design of experiments involves a significant part of choosing the appropriate process parameters involved in research (Manjula & Narendra, 2024; Kumar et al., 2024). In the proposed research the ANOVA and Taguchi are employed to determine the optimized composite sample. Taguchi method, a statistical tool for determining the quality is currently promoted in this research (Freddi, 2018; Tsui, 2007). The parameters employed in the proposed research involve four different levels each for nanofillers of TiC (wt.%), thickness (mm), fibers of kenaf (wt.%), and fibers of coir (wt.%). All four parameters are appraised to develop 16 different samples to be developed during fabrication. Table 1 depicts all the four process parameters involved in research. After this, the RSM and ANOVA tests are employed to assess the outcome of these variables on the flexural, tensile, and impact strength.

The optimization is employed using Minitab Statistical Software version 22.1.0, to minimize the total number of experiments and also analyze the optimum sample among all the tested samples. The composites are fabricated corresponding to Taguchi's L16 array design, involving 16 experimental runs (Vankanti & Ganta, 2014; Uysal et al., 2012).

5. Results and Discussions

A total of 16 different composite samples are developed employing the Vacuum bag molding technique. The weight percentages of all the different samples with different content of TiC, kenaf, coir, and thickness, are detailed and listed in **Table 2.**

5.1 Results from experimental testing

All of the different hybrid composite samples are then forwarded for mechanical testing such as flexural impact and tensile tests, to evaluate their mechanical attributes, as demonstrated in **Table 4.**

Table 4. Results from experimental testing for TiC reinforced Composite

Sample No	TiC (wt%) (A)	Coir (wt%) (B)	Kenaf (wt%) (C)	Thickness (mm) (D)	Tensile Modulus (GPa)	Tensile Strength (MPa)	Flexural Modulus (GPa)	Flexural Strength (MPa)	Impact Strength (kJ/m^2)
1	0	3	0	2	4.79	65.4	3.7	75.0	3.2
2	0	0	3	3	5.42	67.7	4.1	82.0	3.6
3	0	4	4	4	5.98	68.3	5.3	90.6	4.0
4	0	5	5	5	5.83	67.4	4.8	89.4	3.8
5	3	0	3	4	10.15	76.9	5.8	96.0	5.2
6	3	3	0	5	10.36	77.3	6.0	97.3	5.4
7	3	4	5	2	11.57	79.7	6.3	98.8	5.7
8	3	5	4	3	12.42	81.4	6.4	101.7	6.2
9	4	0	4	5	10.42	77.2	6.9	105.3	5.6
10	4	3	5	4	10.67	78.1	7.1	106.2	5.7
11	4	4	0	3	10.46	77.8	6.7	104.5	5.2
12	4	5	3	2	11.03	78.7	7.2	107.0	5.6
13	5	0	5	3	9.17	76.3	7.3	108.6	5.4
14	5	3	4	2	9.59	77.2	7.6	110.2	5.5
15	5	4	0	5	10.02	78.4	7.4	109.5	5.3
16	5	5	3	4	9.23	79.7	7.7	111.0	5.4

Moreover, it is observed that under the load vs displacement curve, the displacement range respectively indicates a material's elasticity, ductility, and toughness behavior. The more a material is elastic, the more will be its displacement range, whereas in contrast the more the material is tougher the higher will be the area under the load vs. displacement curve. Figure 7 depicts the graph for load versus displacement plotted for different load and displacement points for all samples. It is reported that the incorporation of fine Titanium carbide nanoparticles into a kenaf coir hybrid epoxy composite enhances the toughness of the hybrid composite, leading to greater strength and ductility at 4 wt% of titanium carbide nanoparticles. This improvement can be attributed to the larger surface area of the nanofiller TiC particles, which facilitates stronger interfacial interactions within the composite material. These enhanced interactions help distribute stress more effectively, contributing to improved mechanical performance.

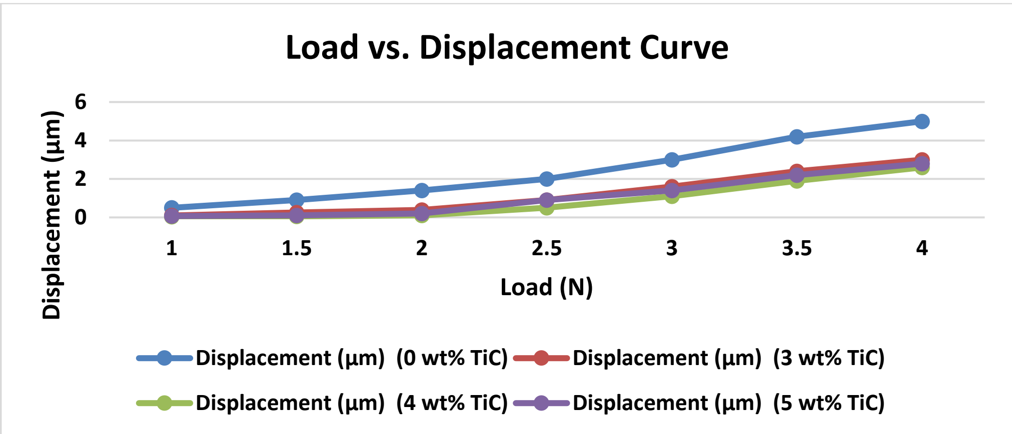


Fig. 7. Load vs Displacement curve

5.2 Results from ANOVA analysis

Interaction Plots and Main effects plots are utilized to illustrate the outcomes of ANOVA analysis for the 16 different combinations of composite. These plots reveal the mechanical attributes of the composite samples, such as tensile strength, flexural strength, flexural modulus, tensile modulus, and impact strength.

5.2.1 Main Effects Plot

The Main Effects plot is used to explore how changes in different factors affect the mean response. This plot displays the mean response for each level of a factor and connects these means with a line to show the factor's impact. Separate Main Effects plots have been created for each mechanical test and are presented below. These plots are designed to examine the variations in response means for one or more factors. **Figs. 8-12** illustrate the Main Effects plots for Tensile Strength, Tensile Modulus, Impact Strength, Flexural Strength, and Flexural Modulus of the TiC-reinforced kenaf-coir hybrid composite. **Fig. 8** manifests that the Tensile strength of the composite is observed to be highest at 3 wt.% of TiC, 5 wt.% of coir, 4 wt.% of kenaf, and 3 mm thickness of the sample. **Fig. 9** shows that the Tensile modulus of the composite is observed to be highest at 3 wt.% of TiC, 5 wt.% of coir, 4 wt.% of kenaf, and 3 mm thickness of the sample. **Fig. 10** manifests that the Impact strength of the composite is observed to be highest at 3 wt.% of TiC, 5 wt.% of coir, 4 wt.% of kenaf, and 4 mm thickness of the sample.

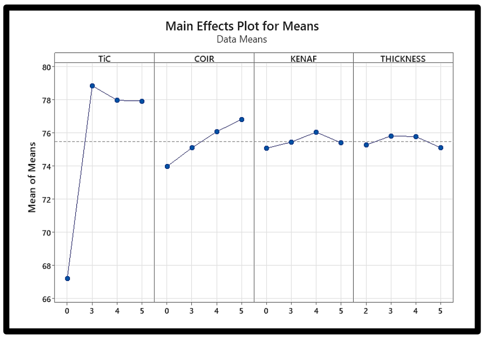


Fig. 8. Main effects plot of Tensile Strength for TiC reinforced kenaf coir hybrid composite

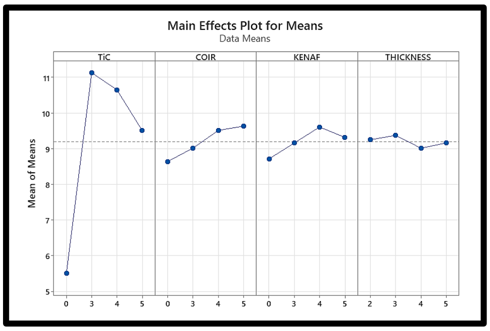


Fig. 9. Main effects plot of Tensile Modulus for TiC reinforced kenaf coir hybrid composite

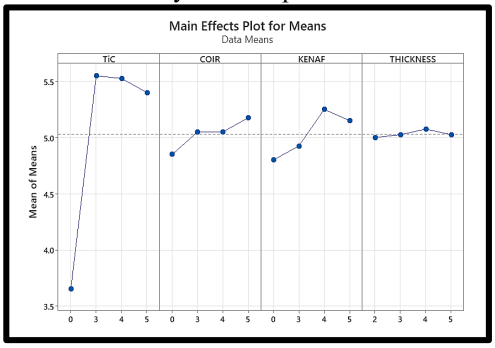


Fig. 10. Main effect plot of Impact Strength for TiC reinforced kenaf coir hybrid composite

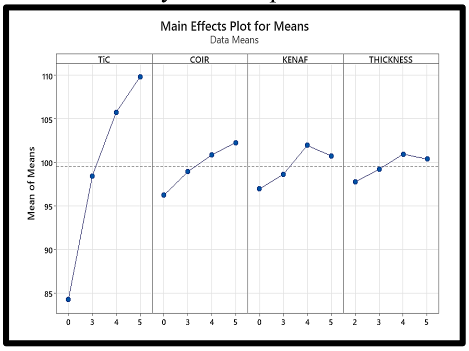


Fig. 11. Main effects Plot of Flexural Strength for TiC reinforced kenaf coir hybrid composite

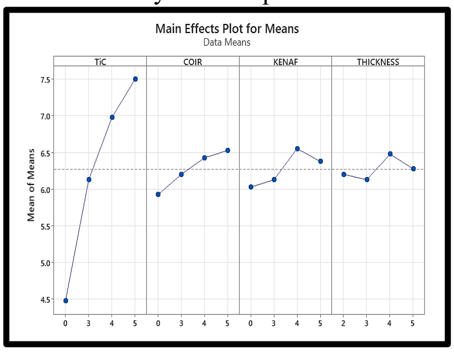


Fig. 12. Main effects plot of Flexural Modulus for TiC reinforced kenaf coir hybrid composite

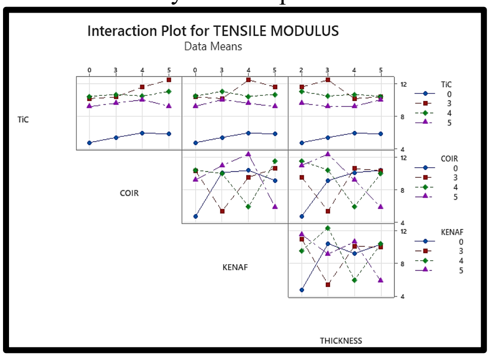


Fig. 13. Interaction Plot of Tensile Modulus for TiC reinforced kenaf coir hybrid composite

Fig. 11 shows that the Flexural strength of the composite is observed to be highest at 5 wt.% of TiC, 5 wt.% of coir, 4 wt.% of kenaf, and 4 mm thickness of the sample. **Fig. 12** shows that the Flexural modulus of the composite is observed to be highest at 5 wt.% of TiC, 5 wt.% of coir, 4 wt.% of kenaf, and 4 mm thickness of the sample.

5.2.2 Interaction Plots

An interaction effect transpires when the impact of one variable on the outcome alters depending on the level of the other variable. Interaction plots are used to examine how one variable's behavior is influenced by the values of other variables. These plots are commonly utilized in the Design of Experiments and ANOVA analysis to illustrate the relationships between variables and to evaluate how different process parameters interact at various levels. The following interaction plots illustrate the effects of different mechanical tests performed on the TiC-reinforced kenaf-coir hybrid epoxy composite samples, highlighting how one variable interacts with others. These plots are illustrated **in Figs. 13** to **17**. **Fig. 13** shows an interaction plot illustrating how Titanium Carbide nanoparticles interact with coir fiber, kenaf fiber, and sample thickness in relation to the Tensile Modulus. The plot indicates that the highest Tensile Modulus is achieved when 3 wt% of titanium carbide nanoparticles interact with 5 wt % of Coir, 4 wt % of kenaf, and 3 mm thickness of the sample.

Fig. 14 presents an interaction plot that depicts the combined effects of TiC nanoparticles, coir fiber, kenaf fiber, and thickness on Tensile Strength. The plot reveals that the highest Tensile Strength occurs when 3 wt% of titanium carbide nanoparticles interact with 5 wt % of Coir, 4 wt % of kenaf, and 3 mm thickness of the sample, taking into account the interactions among all variables.

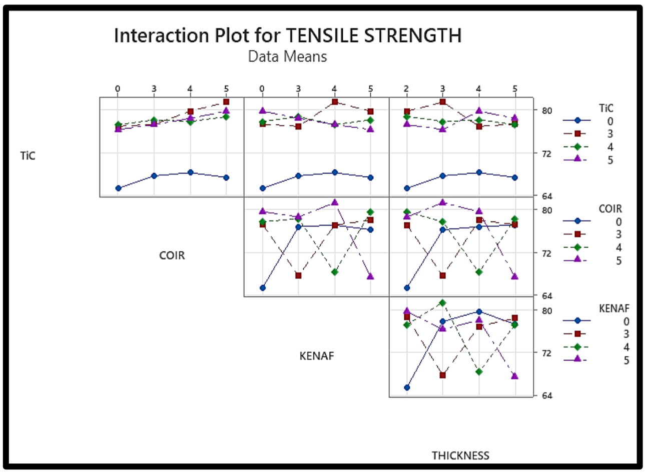


Fig. 14. Interaction plot of Tensile Strength for TiC reinforced kenaf coir hybrid composite

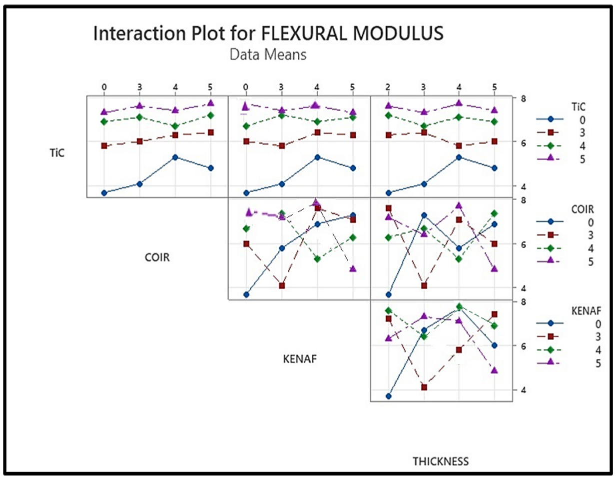


Fig. 15. Interaction plot of Flexural Modulus for TiC reinforced kenaf coir composite

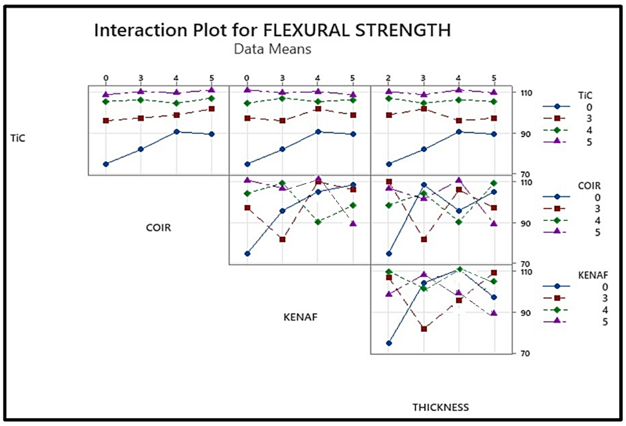


Fig. 16. Interaction Plot of Flexural Strength for TiC reinforced kenaf coir hybrid composite

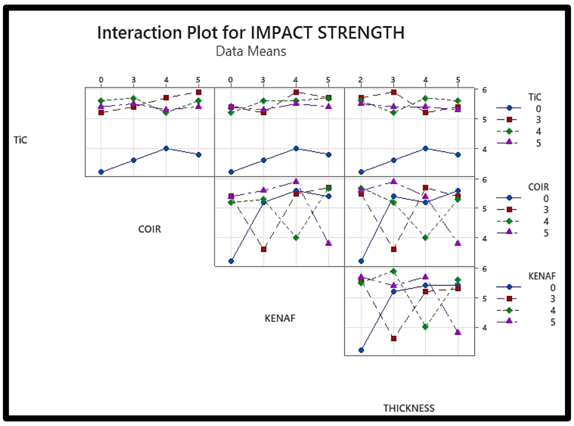


Fig. 17. Interaction Plot of Impact Strength for TiC reinforced kenaf coir hybrid composite.

Fig. 15 provides an interaction plot for the Flexural Modulus, showing the interaction effects of TiC nanoparticles, coir fiber, kenaf fiber, and thickness. The plot suggests that the highest Flexural Modulus is observed when 5 wt.% of titanium carbide nanoparticles interact with 5 wt.% of Coir, 4 wt. % of kenaf, and 4 mm thickness of the sample. **Fig. 16** illustrates an interaction plot for Flexural Strength, demonstrating how TiC nanoparticles interact with coir fiber, kenaf fiber, and thickness. The plot indicates that the maximum Flexural Strength is attained with 5 wt.% of titanium carbide nanoparticles interacting with 5 wt.% of Coir, 4 wt. % of kenaf, and 4 mm thickness of the sample, when considering the combined effects of all variables. Finally, Fig. 17 depicts an interaction plot showing the relationship between TiC content, coir fiber, kenaf fiber, and thickness for Impact Strength. The outcomes suggest that the highest Impact Strength is achieved at 3 wt.% of titanium carbide nanoparticles interact with 5 wt.% of Coir, 4 wt.% of kenaf, and 3 mm thickness of the sample, reflecting the interactions among all four factors.

5.2.3 Optimization

The optimal conditions for different process parameters in single-response optimization, derived from the main effects and interaction plots, are demonstrated in Table 5. This table describes the optimal parameter values for various mechanical attributes of composite, like Tensile Modulus, Flexural Strength, Tensile Strength, Flexural Modulus, and Impact Strength. The outcomes of a combined optimization using Multi-response optimization are also detailed in Table 5, which identifies the most effective kenaf coir hybrid composite reinforced with titanium carbide nanoparticles, along with the optimal process parameter values.

This study focuses on determining the best process parameters to optimize the mechanical attributes of kenaf coir epoxy hybrid composites enhanced with titanium carbide (TiC) nanoparticles.

Table 5. Optimization of Mechanical Attributes

Method	Responses	Optimal Conditions	Optimal Values
Single response optimization	Tensile Modulus	A2 B4 C3 D2	12.42 GPa
	Tensile Strength	A2 B4 C3 D2	81.4 MPa
	Flexural Modulus	A4 B4 C2 D3	7.6 GPa
	Flexural Strength	A4 B4 C2 D3	110.2 MPa
	Impact Strength	A2 B4 C3 D2	6.2 kJ/m2
Combined optimization	Tensile Modulus	A3 B4 C4 D2	10.87 GPa
	Tensile Strength		81.49 MPa
	Flexural Modulus		7.822 GPa
	Flexural Strength		112.69 MPa
	Impact Strength		6.066 kJ/m2

The Taguchi method, Response Surface Methodology (RSM), ANOVA analysis, and draw conclusions from experimental data. These methods help in identifying the ideal settings for process parameters in multi-response optimization. The Response Optimizer is particularly useful for finding the combination of optimal values that combinedly optimize one or more responses. The optimal parameters and their levels for each response are listed in **Table 6**. According to the Taguchi method, ANOVA, and RSM analysis, the best coalition of process parameters for multi-response optimization is A3 B4 C4 D2, which corresponds to 4 wt% TiC, 5 wt% Kenaf, 5 wt% Coir, and a sample thickness of 3 mm, as shown in **Table 6.**

Table 6. Optimum Levels of Process Parameters

Fibre	Weight Percentage
Titanium Carbide	4 wt%
Coir fibre	5 wt%
Kenaf fiber	5 wt%
Thickness of sample	3 mm

6. Comparison of Mechanical properties for Kenaf-coir hybrid composite

The optimized titanium carbide-reinforced kenaf coir hybrid epoxy sample, characterized by the optimal conditions of A4 B4 C4 D3 (comprising 4 wt% TiC, 5 wt% kenaf fiber, 5 wt% coir fiber, and a thickness of 3 mm), was subjected to further experimental testing following the optimization analysis. Hardness testing was conducted on this optimized composite sample, with results indicating a hardness range of 38-42 Barcol. A comparison was made between the results from the optimization analysis and the experimental testing, as detailed in **Table 7.**

Table 7. Comparison between Optimized and experimental results (TiC Composite)

Properties	TiC-KENAF-COIR-EPOXY COMPOSITE	
	Optimization	Experimental
Tensile Modulus (GPa)	10.87	9.89
Tensile Strength (MPa)	81.49	80.30
Flexural Modulus (GPa)	7.822	7.25
Flexural Strength (MPa)	112.69	110.57
Izod Impact (kJ/m^2)	6.066	5.95

The literature review reveals that kenaf fibers excel in tensile strength, while coir fibers offer better impact strength despite lower tensile strength. Combining these fibers in a hybrid composite is expected to enhance the material's overall properties. Titanium Carbide nanoparticles, known for their high tensile strength, are known to serve as effective nanofillers in composite materials. Therefore, integrating kenaf fibers, coir fibers, and titanium carbide nanoparticles into a single composite is anticipated to significantly improve its mechanical properties.

The findings from our research confirm that hybridizing kenaf and coir fibers, along with incorporating TiC nanofillers, has indeed magnified the tensile strength and flexural strength, of the hybrid composite compared to using coir fibers alone. The tensile strength of the proposed hybrid composite is observed to increase by 5.24 times the tensile strength of the coir epoxy composite (Biswas et al., 2011). The flexural strength of the proposed hybrid composite is observed to increase by 2.18 times the flexural strength of the coir epoxy composite (Biswas et al., 2011). The optimized composite sample displayed remarkable strength, making it highly suitable for applications that demand durability. In terms of practical use, the high-performing composite identified in this study could be ideal for manufacturing furniture applications. This furniture would benefit from the natural strength of kenaf and coir fibers, combined with epoxy resin and reinforced by titanium carbide nanoparticles. The TiC-reinforced kenaf-coir epoxy hybrid composite is well-suited for areas including the defense sector and military applications, which are durable as well as capable of bearing high capacity load.

7. Conclusion

The proposed research work analyzed the mechanical performance of TiC nanoparticles embedded in kenaf-coir hybrid epoxy composites, using experimental testing, Taguchi, RSM, and ANOVA analysis. Optimization is employed in the present research to minimize the total number of experiments and determine the ideal parameters and their percentages that contribute to enhancing the composite's performance. The four process parameters, including coir fiber content, kenaf fiber content, TiC concentration, and sample thickness, were varied to traverse the effect and interaction of these on the mechanical attributes of hybrid composite. The outcomes of the present study are illustrated below.

- The novel and unique TiC-fortified kenaf-coir hybrid composites, were produced employing the Vacuum Bag Molding technique, with varying concentrations of TiC in the range of 0%, 2%, 3%, and 4% by weight. Both the coir and kenaf fibers are examined at different weight percentages of 0%, 3%, 4%, and 5%, whereas the thicknesss is altered between 2, 3, 4, and 5 mm.
- A 4*4 Taguchi design matrix is used and 16 different samples have been generated using Minitab software. The 16 samples generated from the Taguchi design with different weight percent of the process parameters are fabricated with the help of Vacuum Bag Molding and subjected to mechanical tests such as flexural, tensile, and impact tests, in accordance with ASTM standards.
- The outcomes of these mechanical tests were utilized in the Taguchi design matrix, so as to optimize the composites and discover the most optimum TiC-fortified hybrid composite sample. This optimization helped in minimizing the total number of experiments to be carried out for various composite combinations.
- The generated interaction and main effect plots are used to assess the combined effect of various process parameters on each other, as well as the overall attributes of the composites.
- The effect of interaction amongst the different four parameters is being observed, and it is found that the amalgamation of TiC*Kenaf, TiC*Coir*Thickness, TiC*Coir, and TiC*Kenaf*Coir substantially governed the attributes of the TiC incorporated hybrid composite samples.
- RSM is being utilized to optimize the samples of composite out of all the 16 samples considered, in order to determine the best composite with respect to all the mechanical attributes.
- The composite that has been found to be the most optimized among the samples of the Titanium Carbide-embedded kenaf-coir-epoxy hybrid composite consists of 5% kenaf, 4% TiC, 5% coir, and a 3 mm thickness of the sample. This optimized composite possesses a tensile strength of 81.49 MPa, tensile modulus of 10.87 GPa, flexural strength of 112.69 MPa, flexural modulus of 7.82 GPa, and an impact strength of 6.06 KJ/m².
- The outcomes depict that the reinforcement of titanium carbide nanofillers along with coir has substantially led to a refinement in the mechanical features such as flexural strength and tensile strength in comparison to the composites developed with only kenaf and coir fiber. The tensile strength of the proposed hybrid composite is observed to increase by 5.24 times and the flexural strength of the proposed hybrid composite is observed to increase by 2.18 times the tensile and flexural strength of the coir epoxy composite individually. This indicates that the amalgamation of coir fiber, TiC nanofillers, and kenaf fiber along with the matrix of an epoxy successfully augments the mechanical characteristics of the hybrid composites.

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