Explicit Dynamic Analysis of Car Body Panels made with Hemp and Flax Composites

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ABSTRACT

Hemp-flax fiber-reinforced composite body panels of automobiles offer a renewable option compared to synthetic composites in the automobile sector. Yet, traditional natural fiber composites are limited in terms of their low mechanical strength, poor bonding at the interfacial area, and excessive moisture absorption, limiting their applications in load-carrying elements like car body panels. This research aims to overcome these challenges by adding titanium dioxide (TiO_2) nanoparticles to hemp-flax epoxy composites. The research tests various concentrations of TiO_2 (0%, 1%, 3%, 5%, and 7%) through a vacuum-assisted resin infusion process to improve the mechanical properties of the composites while making them environmentally friendly. The originality of this approach is in combining TiO_2 nanoparticles to increase fiber-matrix adhesion and nanoparticle dispersion, ultimately improving the mechanical performance of the composite. Tensile, flexural, impact, and hardness tests are complemented with Scanning Electron Microscopy (SEM) analysis to analyze the influence of nanoparticle addition on the mechanical properties and failure mechanisms of the composites. The results indicate that the 3% TiO_2 nanoparticle composite exhibited the optimum mechanical performance with a 39% improvement in tensile strength (47.892 MPa) and a 14% improvement in flexural strength (103.45 MPa) compared to the control composite. The system performed worse because stress concentration occurred when TiO_2 nanoparticles agglomerated at higher concentrations (5% and 7%). The research provides an innovative solution for automobile production through the development of environmentally beneficial TiO_2 nanoparticles strengthened hemp-flax composites that replace current synthetic automobile body panel materials. The end result will help material scientists as well as automobile companies and material companies that develop biodegradable performance materials for sustainable automotive companies.

KEYWORDS: Stress Concentration, Resin epoxy Infusion, Hemp-Flax Fiber, Titanium Dioxide, Car body panels.

1. INTRODUCTION

Motor vehicle structures depend strongly on car body panels for both safety performance and aesthetics functions[1], [2]. During the past few years the automotive industry focused primarily on finding environment-friendly alternatives to synthetic materials by using hemp-flax fiber-reinforced composites[3]. Natural fiber composites lead to several positive characteristics that surpass traditional synthetic materials since they are biodegradable with lightweight properties and have a minor impact on the environment when compared to glass fibers and carbon fibers. Hemp and flax fibers acquire great market value because of their inexpensive nature and abundant availability as well as their outstanding mechanical properties with high tensile strength and stiffness[4]. Hemp and flax fibers represent sustainable resources which enable companies to decrease automobile manufacturing emissions. Structure materials using hemp-flax fiber-reinforced polymer show great promise for multiple applications including automobile body panels since they offer superior mechanical performance and lightweight properties. Widespread automotive usage of load-carrying parts remains limited because of poor matrix-fiber interfacial bond quality and insufficient mechanical properties as well as improved water absorption properties while the advantages reside above these shortcomings[5]. Scientists have initiated various approaches to modify the attributes of natural fiber composites to fulfill automotive requirements.

Conventional natural fiber composites are prone to issues related to weak bonding between the fibers and the epoxy matrix, leading to reduced mechanical strength. High water absorption also imposes a limitation on the long-term performance of the composites since it has a tendency to reduce the fiber-matrix interface strength and leads to swelling[6], ultimately resulting in poor performance In addition, low mechanical strength for natural fiber composite renders them inconvenient for use where high-load-carrying features are necessary, like body parts of a vehicle[7]. Some authors have sought solutions to these using surface treatment, chemical modification, and hybrid composites. Even so, it has not brought substantial improvement on the mechanical strength or sustainability of the composite material. In these regards, the addition of nanoparticles, especially titanium dioxide (TiO_2), has been a potential way to improve the characteristics of natural fiber composites. TiO_2 nanoparticles have great dispersion capability and capacity for improving the adhesion between the fibers and the matrix, resulting in improved mechanical property. Yet, whereas most of the earlier research has aimed to optimize the mechanical characteristics of natural fiber composites with nanoparticles, there are few studies on the influence of TiO_2 nanoparticles in hemp-flax fiber composites and even fewer that consider applications in the automotive industry.

The originality of this study is that it incorporates TiO_2 nanoparticles into hemp-flax fiber-reinforced epoxy composites to improve their mechanical properties without sacrificing their sustainability. Through the addition of various concentrations of TiO_2 (0%, 1%, 3%, 5%, and 7%), this research seeks to explore the optimum nanoparticle content for enhancing the mechanical performance of the composites. Application of a vacuum-assisted resin infusion process guarantees a uniform distribution of TiO_2 nanoparticles in the matrix, hence improving the composite's overall performance. In addition, this work utilizes a multi-test methodology that involves tensile, flexural, impact, and hardness testing, complemented by Scanning Electron Microscopy (SEM) analysis to determine nanoparticle dispersion and fiber-matrix interaction. This holistic method is new in its capacity to study the impact of TiO_2 nanoparticles on the mechanical performance and failure behaviors of hemp-flax composites. The inclusion of nanoparticles within natural fiber composites is predicted to offer a considerable enhancement in the mechanical performance of the materials, rendering them applicable for harsh applications like automobile body panels. Also, the research focuses on sustainability by keeping the environmentally friendly characteristics of the composite materials intact and improving their performance.

The key contributions of the research are:

- ✓ Investigates the incorporation of titanium dioxide (TiO_2) nanoparticles into a green hemp-flax fiber composite in a bid to improve its mechanical strength without losing its sustainable nature.

- ✓ Various concentrations of TiO_2 nanoparticles (0%, 1%, 3%, 5%, and 7%) are sequentially tested to establish the optimum nanoparticle content that achieves the best mechanical strength without compromising material sustainability.

- ✓ Analyse the performance of TiO_2 nanoparticles, the research utilizes various mechanical tests—tensile, flexural, impact, and hardness—to critically examine the strength, durability, and overall performance of the composite under different loading conditions.

- ✓ Scanning Electron Microscopy (SEM) is employed to study the dispersion of TiO_2 nanoparticles in the composite matrix and to determine the effect of the nanoparticles on fiber-matrix bonding, which is essential to enhance the overall mechanical properties of the material.

The remainder of the paper is organized as follows: Section 2 gives an extensive overview of some of the existing literature on natural fiber composites. Section 3 describes the experimental approach, i.e., materials, sample preparation method for the composite samples, and testing methods. Section 4 gives the test results of the mechanical properties, followed by a discussion. Section 7 concludes the paper with some suggestions for future work.

2. LITERATURE REVIEW

Al-Azad, Asril, and Shah [8] examine the viability of natural fiber composites for application in civil engineering, highlighting the benefits of these materials, including sustainability and minimal environmental impact, in industries such as automotive, aerospace, and construction. The authors note the distinct characteristics of natural fiber composites, which have proven to be a green alternative to synthetic composites. However, they also identify some main shortcomings like poor mechanical properties, poor interfacial adhesion, and high-water absorption that are barriers to their use in load-carrying applications like automotive body panels. These weaknesses restrain the extensive use of natural fiber composites in high-performance product-processing industries. Based on these issues, Mohammed et al. [9] investigate the critical role of interfacial bonding (IFB) between the natural fibers and polymer matrix in natural fiber polymer composites (NFPCs). The study further discusses several mechanisms influencing IFB, such as interdiffusion, electrostatic adhesion, and chemical reactions. Further, the authors mention several modification techniques to improve the IFB and mechanical properties, focusing in particular on the addition of nanoparticles (NPs). Even though these alterations hold promise in improving the mechanical performance of NFPCs, dispersion of fibers and incompatibility with the matrix are still significant challenges, preventing the effectiveness of the alterations in delivering the optimum performance in different types of composites.

Babu, Chakradharagoud, and Murthy [10] examine the mechanical behavior of flax fiber-reinforced composite posts through finite element (FE) analysis. The research simulates the mechanical behavior of the posts under different loading conditions and compares the stress distribution of flax fiber composites with cast metal and carbon fiber posts. The findings indicate that the flax fiber composite posts have lower root peak stresses comparable to the natural substance (dent) and hence show promise as a more sustainable and biocompatible option as a high-mechanical-performance-demanding application, e.g., dental implants. Still, the research indicates that the composite posts of flax fiber are more susceptible to stresses in the cervical area due to their flexure and lower core material stiffness, showing a requirement for increased material optimization towards optimized stress transfer and performance. Fantuzzi et al. [11] also investigate the potential for using woven fabric reinforced material in automotive application with respect to carbon nanotube-activated composites. Their work contrasts experimental and analytical predictions of mechanical properties for polymeric matrix composites woven with carbon fabric, which show the dramatic increase in strength and toughness when carbon nanotubes are added to the polymeric matrix. Nevertheless, the authors caution that it is difficult to model such intricate composite materials, and the precise prediction of mechanical behavior under different conditions is still the major limitation. These studies highlight the need for optimization of composite material formulations and modeling methods to maximize performance in uses such as automotive parts and load-bearing structures.

Bacciocchi and Tarantino [12] introduce research on the time-dependent mechanical characteristics of three-phase composite materials through a Maxwell rheological model describing the viscoelastic response of the matrix. The materials involved are reinforced by carbon nanotubes (CNTs) as well as aligned fibers, producing a composite structure aimed at application in sandwich plates. The transient response of the composite material is predicted from the Reissner-Mindlin theory and the influence of different mass fractions of the reinforcement phases is outlined. The research provides significant insights into CNT-based composites' mechanical response and design, especially with regard to enhanced structural applications. The limitation of the research lies in the difficulty of the material model, whose complexity might have to be better refined to respond to more advanced behaviors of fiber and CNT interactions under realistic conditions. As for Bacciocchi and Tarantino [13], they formulate a multiscale framework to analyze the buckling behavior of sandwich plates with CNTs and straight aligned fibers as the reinforcements. The work of their research combines Eshelby-Mori-Tanaka approach and Hahn homogenization method to establish critical buckling loads for differing boundary conditions, lamination sequences, and orientation of fibers. The theoretical framework, built on the Reissner-Mindlin theory, includes the Murakami’s function to capture the zig-zag effect in the plate's mechanical behavior. Validation against experimental and theoretical results demonstrates the accuracy of the approach, although the complexity of the multiscale method and the reliance on assumptions may limit its application in broader, real-world scenarios.

Elbadry, Aly-Hassan, and Hamada [14] examine the mechanical properties of jute fiber composites with recycled needle-punched jute mats as core layers and jute fabric cloths as skin layers, utilized in an unsaturated polyester matrix. The hand lay-up method with resin pre-impregnation into the jute fiber was used with modifications to develop these composite materials, and the effect of fiber weight content on the tensile and bending properties of the composites was investigated. The research discovers that raising the fiber weight content and incorporating the jute fabric skin layers greatly enhanced the tensile and flexural properties of the composites. The notch sensitivity, determined by the characteristic distance (d_o) obtained using Finite Element Method (FEM), indicated that notch sensitivity was higher in composites with skin layers. Analysis of fracture behavior using SEM indicated that under bending loads, fiber pull-out mechanisms were predominant, but incorporation of jute fabric cloth altered the mode of failure to a fiber bridge mechanism. Even with these advances, the limitation of this work is that it is difficult to scale up this process for industrial use and that it might be challenging to control the fiber orientation and distribution in mass production. Similarly, Le et al. [15] researched the mechanical properties of starch–hemp composite materials, which are entirely composed of natural fibers. The paper optimized the binder solution in terms of dynamical viscosity and surface tension and developed composites with varying hemp/starch proportions. The mechanical parameters of these composites, such as tensile strength, elasticity modulus, and Poisson's ratio, were experimentally tested. These findings confirm that starch-hemp composites are light and show great displacement before failure. The research confirms the promise of this composite material for sustainable purposes; however, the constraint is the extended drying time of such composites, which might cause difficulty in the manufacturing process efficiency and application at a large scale.

Chandgude and Salunkhe [16] discuss the increasing application of hybrid polymeric composites in automotive parts, highlighting the benefits of combining natural and synthetic fibers in one matrix. Hybrid composites are made to improve physical, mechanical, and thermal properties, offering a better balance of properties than single-fiber composites. The authors discuss recent publications on new fiber types and manufacturing methods required for the production of these hybrid composites. But the shortfalls of this research are in the lack of full investigation of long-term stability, resistance to impacts, and recyclability problems for these composites. The authors further add that although natural fibers have environmental advantages, their problems like sensitivity to moisture and deterioration of fibers at extreme conditions should be resolved before they can find wider application in the automotive sector. Giammaria et al. [17] explore the application of bio-based polymer matrices, particularly poly(lactic acid) (PLA), in the car industry for boosting sustainability. PLA is envisioned as a viable substitute for conventional polyolefin-based matrices because it is compatible with thermoplastic manufacturing processes. They also point to the increasing demand for applying PLA for additive manufacturing and 3D/4D printing, with a view to its future applications in automotive parts. The research also points to the increasing demand for sustainable reinforcement forms, like natural fibers, in automotive composites. Nonetheless, the shortcomings of this work lie with PLA's current limitations with regards to its interactions with the environment, mechanical performance under vehicular conditions, and the insufficiency of studies on its long-term performance in automotive applications. These points deter PLA's instant scalability and large-scale deployment in the automobile industry.

Trzepieciński and Najm [18] give a comprehensive analysis of the application of metallic materials in the automobile sector with regard to the application of lightweight metals like steels, aluminium alloys, titanium alloys, and magnesium alloys. They are investigated for their ability to decrease fuel usage and carbon dioxide emissions without the loss of car performance. The authors explain the rise in the usage of lightweight metals as part of automobile body panels and structural elements, emphasizing how they can be easily recycled compared to composite materials. Nonetheless, its limitations are the lack of extensive investigation of the performance of the material under severe environmental conditions and long-term life, and ongoing improvement in the manufacturing process in order to cut costs further and enhance the productivity of these materials in mass production. The study also mentions that it is a challenge to have the perfect harmony between material strength, weight minimization, and cost-effectiveness for future cars. H.L. Bos [19] describes the evolution of natural fibre-reinforced composites in the automobile sector, where they are utilized in interior components for light weight and increased stiffness. Wood fibres were initially employed as fillers, but their limited length restricted their contribution to increased strength, so longer natural cellulose fibres like flax, hemp, and sisal were introduced. These materials are especially ideal in applications where the requirement is mainly stiffness, since they have very high specific modulus. The development towards natural fibers was motivated by their ability to substitute glass fibre composites since they tend to be cheaper and pose fewer threats to the employees involved in handling them. The limitation of this study is the absence of thorough research into the long-term durability of natural fibre composites in different automotive environments, particularly with regard to their performance in extreme temperatures and humidity.

3. Materials and Methods

The selection process for materials in composite construction and experimental testing occurs with high regard to achieving mechanical and structural goals. The core section details the materials we use starting with titanium dioxide (TiO_2) nanoparticles as reinforcement additives and natural fibres and resin systems as main components.

3.1 Materials

3.1.2 Hemp Fiber

Hemp fibers comprise natural bast fibers that have exceptional strength and resistance properties. They originate from hemp plants and maintain good tensile strength properties which makes them optimal for utilizations that demand solid framework support properties. Hemp fibers possess two desirable characteristics which help manufacturers achieve sustainable operations: biodegradability combined with sustainable renewability. Hemp fibers possess coarser structures which increase material rigidity so they become suitable for creating composites that need strength and flexibility. Hemp demonstrates specific value added in making automotive parts as well as construction materials and technical textiles that need exceptional performance. The cultivation requirements for hemp fibers require fewer environmental resources and energy and therefore establish a greener alternative than artificial synthetic fibers generate[22].

TABLE 1: COMPARISON OF HEMP AND FLAX FIBERS

Property	Hemp Fiber	Flax Fiber
Source	Hemp plant (Cannabis sativa)	Flax plant (Linum usitatissimum)
Type	Bast fiber (from the stalk of the plant)	Bast fiber (from the stem of the plant)
Strength-to-Weight Ratio	High – Excellent for load-bearing applications	High – Ideal for structural applications
Young's Modulus	30-50 GPa (varies with processing)	30-40 GPa
Tensile Strength	400-800 MPa	500-800 MPa
Flexural Strength	80-200 MPa	100-250 MPa
Density	1.47-1.5 g/cm³	1.45-1.50 g/cm³
Renewability	Highly renewable (grows in 3-4 months)	Highly renewable (grows in 90-120 days)
Biodegradability	Biodegradable and compostable	Biodegradable and compostable
Environmental Impact	Low environmental impact, less water and pesticide usage	Low environmental impact, less water and pesticide usage
Cost	Generally cost-effective and abundant	Cost-effective, may vary by region
Health Risks	Non-toxic, no major health risks	Non-toxic, no major health risks

Applications	Automotive parts, construction materials, textiles	Automotive parts, construction materials, textiles

3.1.2 Flax Fibers

Flax fibers from the flax plant are a natural reinforcement material highly regarded for their strength-to-weight ratio and flexibility. Flax fibers are finer and smoother compared to hemp, and they have a good combination of strength, flexibility, and looks. Flax fibers are commonly used in uses where there is a requirement for a tough, lightweight, and aesthetically pleasing material. Flax is renewable and biodegradable and is, therefore, an eco-friendly material to use in composite materials. The fibers' silky feel facilitates ready processing and use in many of the composites including automotive, furniture, and sports equipment. Flax fibers are a healthier option compared to synthetic materials like glass because they do not present major health hazards when handled[23]. Composites made with flax offer a low-weighing, sustainable solution for high-performance materials in a wide range of industries. The comparison table for hemp and flax fibers are shown in Table 1.

3.1.3 Epoxy resin with anime-based hardener

Epoxy resin is a matrix material in composite production because of its superior mechanical properties, good adhesion, and adaptability to many applications. Bisphenol-A-type epoxy resins, widely used in composite materials, exhibit high toughness, low shrinkage on curing, and chemical degradation resistance[24]. When mixed with an amine-based hardener, they create a cross-linked polymer that increases the strength, durability, and thermal resistance of the resin. Epoxy resins are especially apt for high-performance property applications like automotive components, aerospace components, and industrial use and the properties are shown as in Table 2.

TABLE 2: PROPERTIES OF EPOXY RESIN AND ANIME HARDENER

Property	Epoxy Resin (Bisphenol-A-based)	Amine Hardener
Tensile Strength	60-90 MPa	40-70 MPa
Flexural Strength	90-120 MPa	50-100 MPa
Hardness (Shore D)	80-90	70-85
Thermal Stability	120-150°C	130-180°C
Viscosity	800-1500 cP	300-700 cP
Curing Time at room temperature	6-8 hours	4-6 hours
Glass Transition Temp. (Tg)	120-150°C	130-170°C

3.1.4 Titanium Dioxide (TiO_2) Nanoparticles

Titanium dioxide (TiO_2) nanoparticles are being used in natural fiber-reinforced composites, e.g., epoxy matrices reinforced with hemp or flax fibers, because of their superior physical, mechanical, optical, and chemical properties. These nanoparticles, normally between 10 and 50 nm in diameter, provide added performance by increasing the overall mechanical strength of the composite, raising thermal stability, and offering UV protection[25].

TABLE 3: PROPERTIES OF TiO_2

Property	Value
Size	30-50 nm

Crystal Structure	Anatase, Rutile
Density	4.2 g/cm³ (Rutile phase)
Mechanical Strength	Tensile Strength: Increased by 10-20%
Thermal Stability	> 1000°C
UV Protection	UV Absorption (λmax 380 nm)
Moisture Resistance	Water Absorption: Reduced by 15-30%
Chemical Inertness	Inert in most conditions
Photocatalytic Activity	Decomposes organic pollutants

The moisture resistance of the composite improves through TiO_2 nanoparticles because they restrict water absorption and extend resistance under humid situations. The protection granted by TiO_2 nanoparticles against UV radiation prevents breakdown of natural fibers that makes them suitable for outdoor use. The incorporation of TiO_2 nanoparticles gives composites better thermal resistance so they remain stable under high temperatures. Using TiO_2 nanoparticles in natural fiber composites represents an economical eco-friendly way to enhance the mechanical strength alongside thermal properties and functional behavior of composite materials before and after manufacturing as in Table 3.

3.2 Fabrication of Composite Plates

Making composite plates stands as a primary manufacturing step to preserve optimal mechanical properties together with material uniformity across the entire structure. Vacuum-assisted plate manufacturing occurred in the present research because it represents a commonly used technique for advanced composite processing. High-performance composite applications require fiber-matrix bonding, low void content and high-quality finish that the technique delivers effectively[26].

Vacuum-Assisted Manufacturing Process

Vacuum Bagging represents a vacuum-aided manufacturing method which produces high-quality composite laminates at affordable costs through an efficient production process. During vacuum pressure application for compacting matrix resin and fiber reinforcement layers the process ensures complete consolidation and prevents formation of voids or air pockets.

3.2.1 Fabrication Steps

1. **Preparation**

First the processing sets the hemp-flax fiber layers into precise directions (0° and 45°) to achieve outstanding mechanical features within the final composite. Both the integrity and the load-carrying capacity of the composite receive enhancement by means of the proper orientation. The fibers receive a deliberate placement inside a mold while staff maintain maximum precision to avoid final material property alterations. A proper distribution of fibers demands ultimate attention at this step because it directly affects both strength output and overall composite lifespan.

2. **Resin Infusion**

The dispersion process for TiO_2 nanoparticles inside epoxy resin occurs through ultrasonic mixing to stop aggregation and achieve uniform resin distribution. The composite achieves enhanced mechanical properties and thermal stability while increasing its UV resistance when nanoparticles are distributed evenly throughout it. Transferring the prepared resin mixture by vacuum pressure serves to penetrate deep into the structure of the fibers. Under vacuum pressure the interfacial bonding strength between matrix and fibers increases while void formation decreases to generate a defect-free composite material.

3. Vacuum Application and Curing

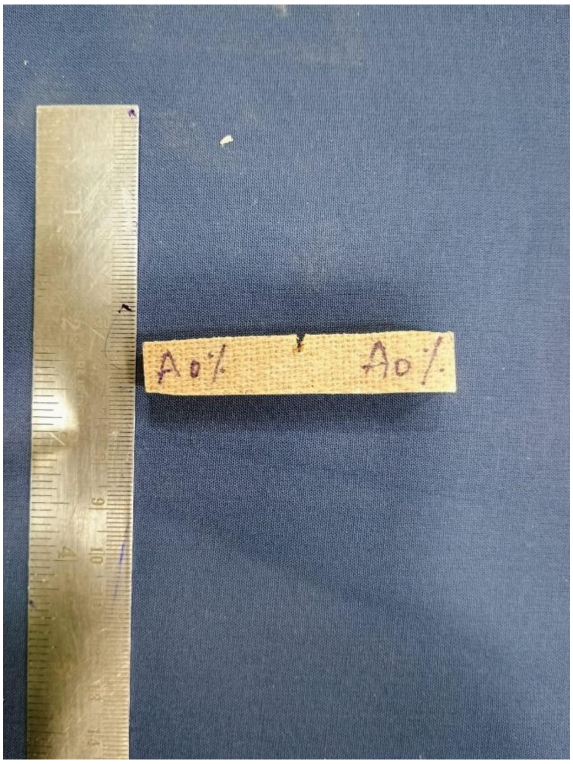
The fiber infusion process requires vacuum pressure to remove both air bubbles and surplus resin so the composite material obtains balanced resin distribution. Vacuum pressure creates an efficient resin flow that eliminates various defects which enhances the mechanical properties of the material. Under vacuum conditions at room temperature for 24 hours the plates receive curing treatment which enables resin to form a strong matrix. Time under post-cure conditions at 60 °C for four hours results in enhanced mechanical strength and thermal stability as well as durability of the plates.

4. Specimen Preparation

The curing process ends by manufacturing the composite plates according to ASTM standards regarding their dimensional requirements. The standardized practice yields identical sample dimensions for exact and repeatable mechanical experimental methods. The specimens are prepared for tensile, flexural, impact, and hardness tests, which give a comprehensive assessment of structural performance, durability, and the mechanical behavior of the composite. Test specimen preparation is of primary importance in the achievement of reproducible and standardized test data for material characterization.

3.2.2 Fabricated Plates Configuration

The experiment consisted of manufacturing composite plates in varying configurations for evaluating their structural performance. There were three major configurations: No Angle plates, with the fiber layers being placed without any angle orientation; Angle 45° plates, where fibers were aligned at 45° for improvement of multi-directional strength; and TiO_2-reinforced configurations. The TiO_2 variants comprised composites with 0%, 1%, 3%, 5%, and 7% TiO_2 nanoparticles added to the epoxy matrix to assess their influence on mechanical properties. These setups were created to allow for an overall comparison of the effect of fiber orientation and nanoparticle reinforcement on composite strength and durability. Thus, the configuration of the composites are given in Table 4.



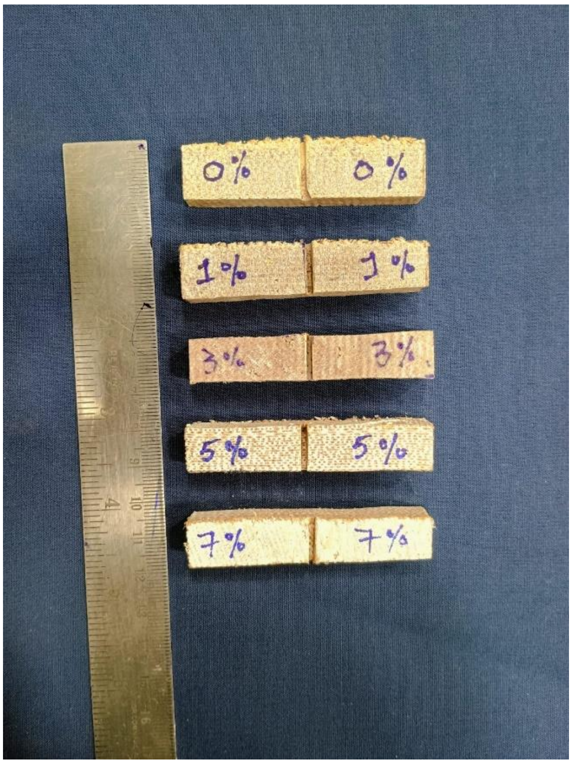


Figure 1: **a)** Composite Samples with Different TiO_2 Concentrations **b)** Control Composite Sample (A0%)

TABLE 4: CONFIGURATION OF THE COMPOSITES

No Angle	Angle	1% Angle	3% Angle	5% Angle	7% Angle
All composites in same direction	Hemp-0 degrees	Hemp-0 degrees	Hemp-0 degrees	Hemp-0 degrees	Hemp-0 degrees
	Flax-45 degrees	Flax-45 degrees	Flax-45 degrees	Flax-45 degrees	Flax-45 degrees
	Hemp-0 degrees	Hemp-0 degrees	Hemp-0 degrees	Hemp-0 degrees	Hemp-0 degrees
	Flax-45 degrees	Flax-45 degrees	Flax-45 degrees	Flax-45 degrees	Flax-45 degrees
	Hemp-0 degrees	Hemp-0 degrees	Hemp-0 degrees	Hemp-0 degrees	Hemp-0 degrees
	Flax- 45 degrees	Flax- 45 degrees	Flax- 45 degrees	Flax- 45 degrees	Flax- 45 degrees

The Figure 1a) shows the composite samples reinforced by different concentrations of TiO_2 nanoparticles within the epoxy matrix, which have been prepared for mechanical testing. The samples bear respective labels and are accompanied by a ruler that will be used to measure scales. These samples were probably prepared in order to assess the effects of TiO_2 on structural stability and the mechanical properties of the composite material. Also, another 1b) with the label "A0%" seems to be a control or reference sample. The recording of these samples assists in the examination of the failure modes, strength fluctuations, and general performance of the composites under test conditions.

3.3 Experimental Procedures for Mechanical Testing

Experimental techniques were adopted for assessing the microstructural and mechanical properties of the composite plates manufactured. Standard series of tests comprising hardness, impact, tensile, and flexural tests and microstructural evaluation by Scanning Electron Microscopy (SEM) were carried out. These experiments were designed for validating the mechanical properties of the composite material and analyzing the impact of TiO_2 nanoparticles on their properties.

3.3.1 Hardness Testing

Hardness testing was done according to ASTM D2240 for Shore hardness or ASTM E10 for Brinell hardness, based on the composition of the material. The test evaluated the composite resistance to surface deformation through the determination of indentation hardness. Hardness testing using a calibrated indenter in a hardness tester was used to load the composite surface by a known force for a controlled dwell time. The samples were washed, placed on a firm surface, and several measurements of hardness were made at various points. The mean value of hardness was obtained to determine the effect of TiO_2 nanoparticles on surface resistance[27].

3.3.2 Impact Testing

The composite's impact resistance was determined through ASTM D256 for pendulum impact testing of notched specimens or ASTM D6110 for Charpy impact testing. This test assessed the composite's energy absorption ability when subjected to impact loading suddenly. The pendulum impact testing machine was utilized, where composite specimens were ground to standard size, loaded in the test machine and struck with the pendulum. The fracture energy absorbed was measured to obtain the composite's impact resistance and toughness[28].

3.3.3 Tensile Testing

The tensile properties of the composite were investigated in accordance with ASTM D3039 for assessing tensile strength, Young's modulus, and elongation at break. The UTM was charged with a load cell and extensometer to perform the test. Smooth edge specimens were inserted into UTM grips and loaded with constant crosshead velocity up to failure. The stress-strain curve was plotted, upon which tensile strength and modulus were measured in order to evaluate how resistant the material is against stretching forces.[29].

3.3.4 Flexural Testing

The flexural modulus and the flexural strength of the composite were determined following ASTM D790 using a three-point bending test set-up. Three-point bending fixture and Universal Testing Machine (UTM) was used to test the material. Next the composite specimens received a size reduction cut before they received placement on the support section of the bend. Every specimen received a nose load at its center before the test load increased stepwise until failure took place. Bending tests produced data regarding both the material stiffness and strength through the recorded flexural strength and modulus values[30].

3.4 Microstructural Analysis

The examination of the processed composite plates by scanning electron microscopy (SEM) allowed researchers to determine the relationship between fibers and matrix interfaces as well as nanoparticle dispersion status and failure patterns. Characterization methods delivered better knowledge about composite internal structure and the influence of TiO_2 nanoparticle additions on mechanical response.

Sem analysis proceeded with the collection of tensile and flexural fracture specimens directly following the tests to determine failure methods. Meticulous preparation of samples involved fragmenting the materials and applying a thin gold or carbon coating which served to boost electrical conductance for obtaining quality imaging results. Under the SEM with 1 nm resolution the researchers observed precise microstructural features of the examined samples. The SEM images showed the existence of fiber pull-out which indicated poor matrix-fiber bonding weaknesses along with voids and microcracks that could weaken the mechanical properties of the composite.

Researchers investigated TiO_2 nanoparticle distribution across the epoxy matrix in order to establish their distribution uniformity as well as the extent of aggregation present. The effective performance of nanoparticles requires proper dispersion because this will allow efficient loading transfer to increase composite strength. The research examined the failure mechanisms between matrix cracking and delamination with fiber fracture to understand composite structural variations under load conditions. The SEM observations allowed researchers to determine how extensive TiO_2 nanoparticles were in enhancing the strength and toughness and endurance of composite materials by comparing them to mechanical test results. The microstructure study represented the essential method for gauging both the composite performance and discovering improvement strategies for better mechanical characteristics.

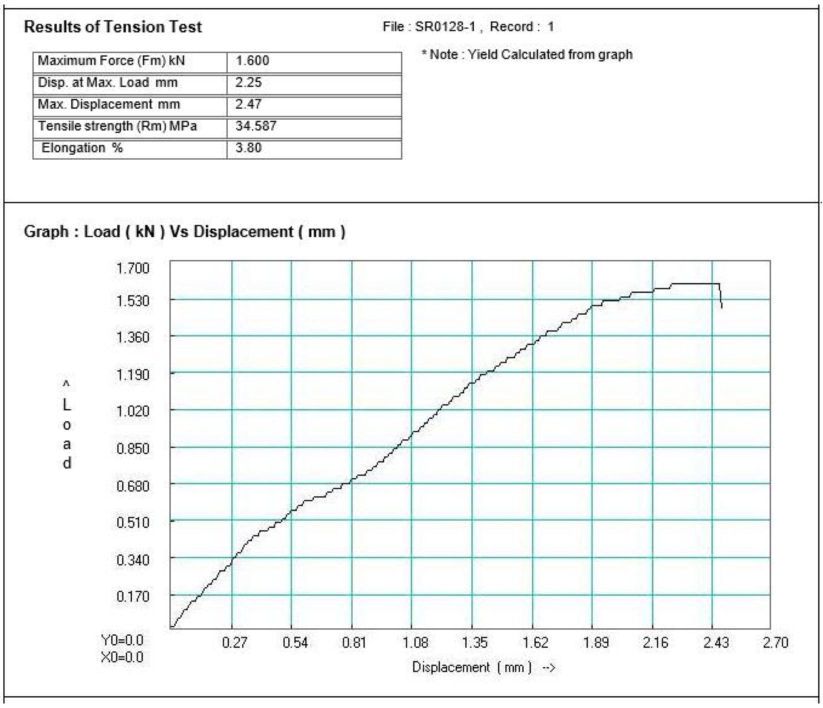
4. Results and Discussion

The incorporation of TiO_2 nanoparticles into epoxy composites from hemp-flax was to advance mechanical properties with no loss in environmental sustainability. The study varied different concentrations of TiO_2 to determine their influence on the adhesion and dispersion of fiber-matrix as well as general composite performance. Different mechanical examinations, including tensile, flexural, impact, and hardness tests, coupled with SEM analyses, were undertaken to investigate the influence of inclusion of nanoparticles. The results shed light on the most suitable concentration that enhances composite strength without leading to nanoparticle agglomeration, which might be detrimental to performance. This study underscores the prospects of TiO_2-modified natural fiber composites in automotive uses as a way to overcome the constraints of conventional natural fiber composites.

4.1 Tensile Properties

The tensile strength of the composite material also displayed substantial variability with varying TiO_2 nanoparticle content and orientations of the fibers. First, the unreinforced baseline composite recorded tensile strengths of 34.578 MPa and 59.212 MPa for 0° and 45° fiber orientation, respectively, to reflect the vital role of the fiber alignment in distributing stresses. The addition of 1% TiO_2 resulted in a moderate rise in tensile strength to 43.188 MPa, reflecting a better load transfer through better fiber-matrix bonding. It reached the highest tensile strength at 3% TiO_2 of 47.892 MPa, reflecting perfect dispersion of the nanoparticles, which effectively supported the matrix and delivered excellent mechanical performance. This improvement was most evident in the 45° orientation of fibers, which always ranked higher than the 0° setup, reiterating the significance of fiber orientation in bearing tensile loads. Yet, above the 3% TiO_2 level, there was a drop in tensile strength as in Figure (2-7) and Table 5.

4.1.1 0% TiO2- 0 angle



Results of Tension Test

File : SR0128-1 , Record : 1

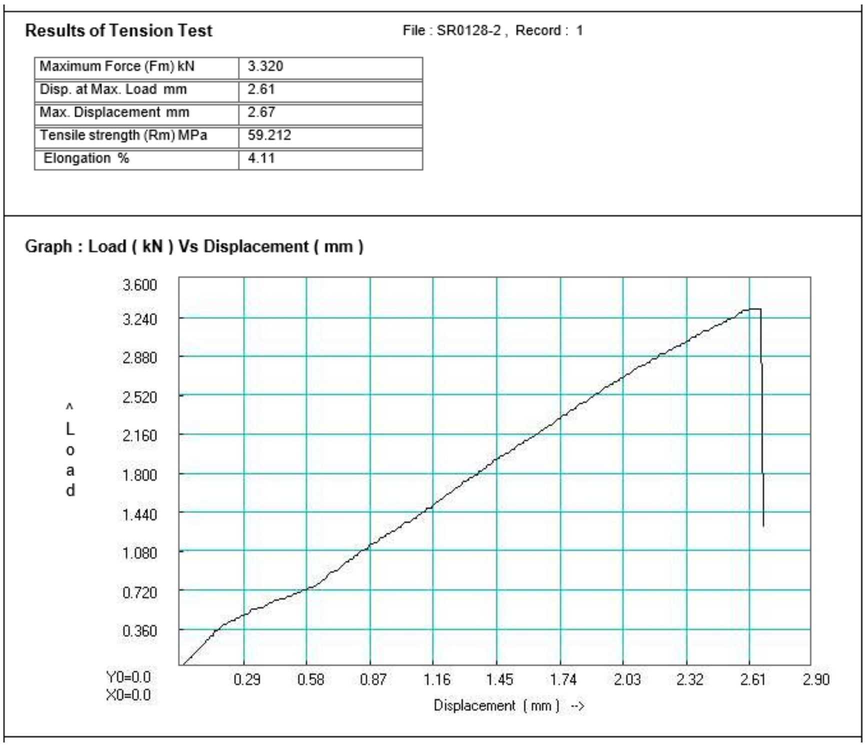
* Note : Yield Calculated from graph

Maximum Force (Fm) kN	1.600
Disp. at Max. Load mm	2.25
Max. Displacement mm	2.47
Tensile strength (Rm) MPa	34.587
Elongation %	3.80

Graph : Load (kN) Vs Displacement (mm)

Figure 2: 0% TiO2- 0 angle

4.1.2 0% TiO2- 45 angle



Results of Tension Test

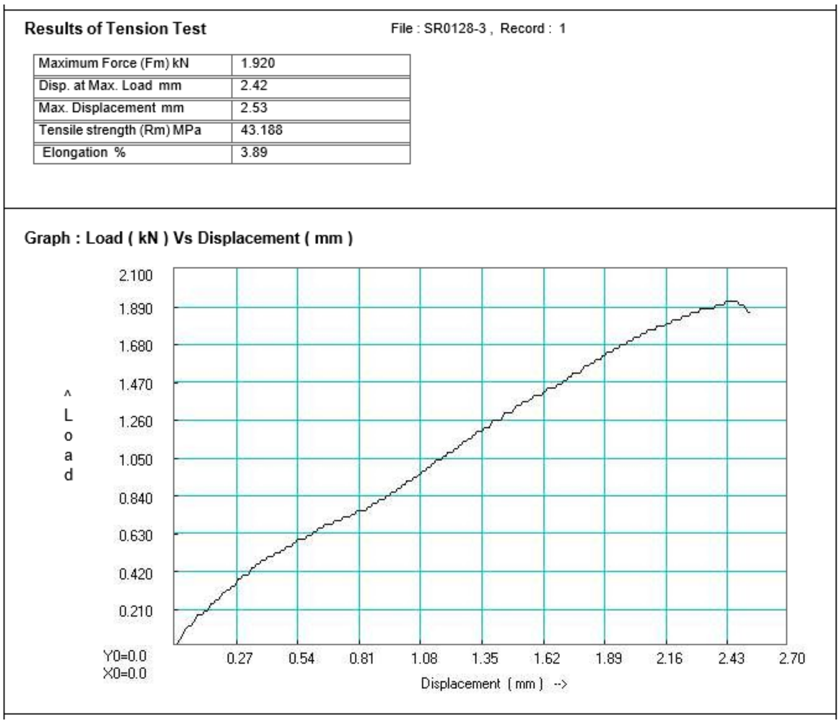
File : SR0128-2 , Record : 1

Maximum Force (Fm) kN	3.320
Disp. at Max. Load mm	2.61
Max. Displacement mm	2.67
Tensile strength (Rm) MPa	59.212
Elongation %	4.11

Graph : Load (kN) Vs Displacement (mm)

Figure 3: 0% TiO2- 45 angle

4.1.3 1% TiO2- 45 angle



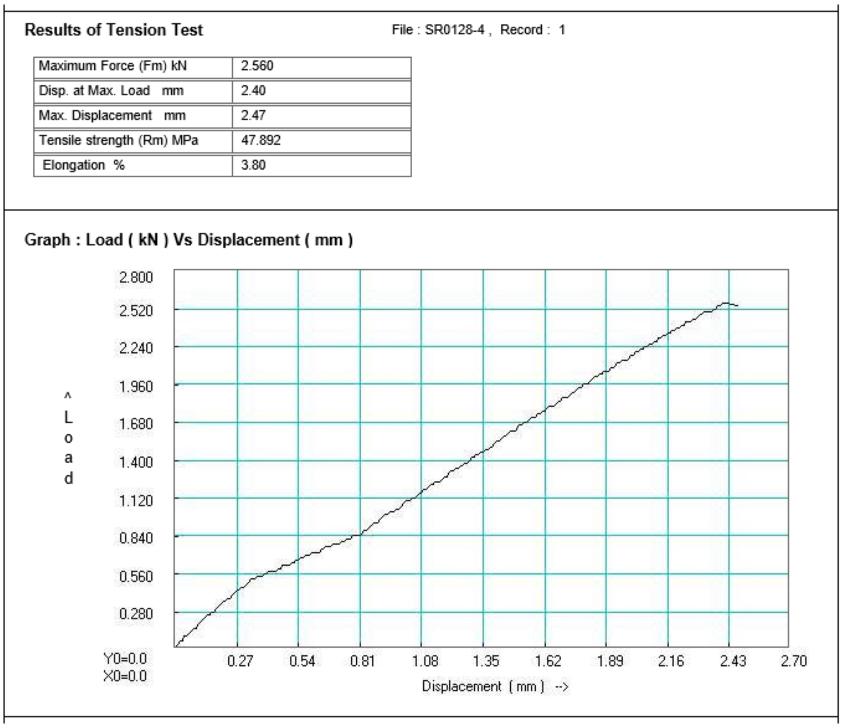
Results of Tension Test File : SR0128-3 , Record : 1

Maximum Force (Fm) kN	1.920
Disp. at Max. Load mm	2.42
Max. Displacement mm	2.53
Tensile strength (Rm) MPa	43.188
Elongation %	3.89

Graph : Load (kN) Vs Displacement (mm)

Figure 4: 1% TiO2- 45 angle

4.1.4 3% TiO2- 45 angle



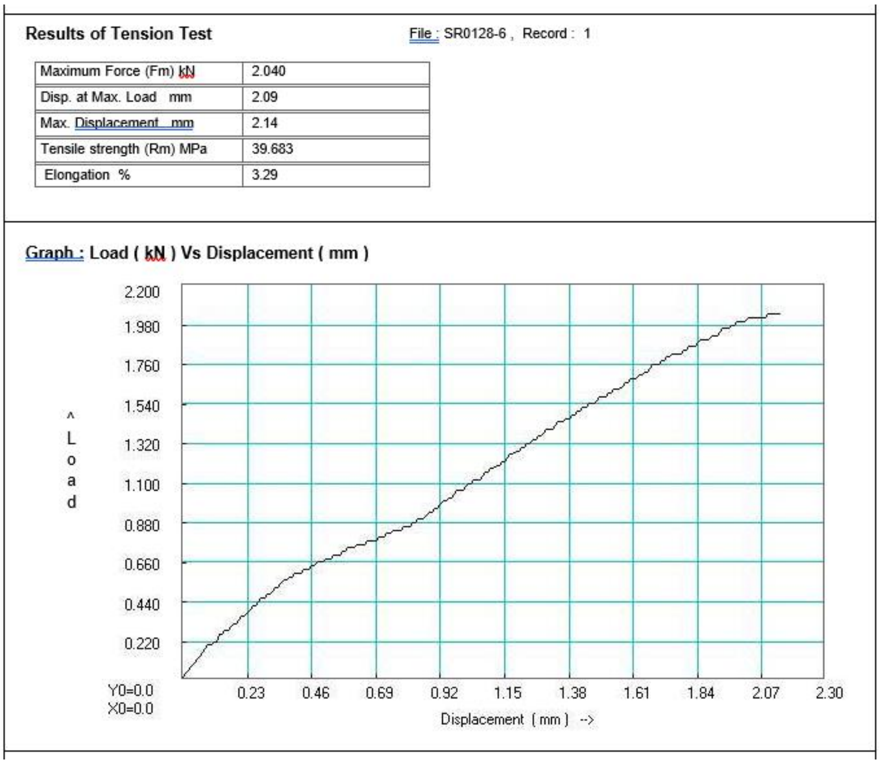
Results of Tension Test File : SR0128-4 , Record : 1

Maximum Force (Fm) kN	2.560
Disp. at Max. Load mm	2.40
Max. Displacement mm	2.47
Tensile strength (Rm) MPa	47.892
Elongation %	3.80

Graph : Load (kN) Vs Displacement (mm)

Figure 5: 3% TiO2- 45 angle

4.1.5 5% TiO2- 45 angle



Results of Tension Test

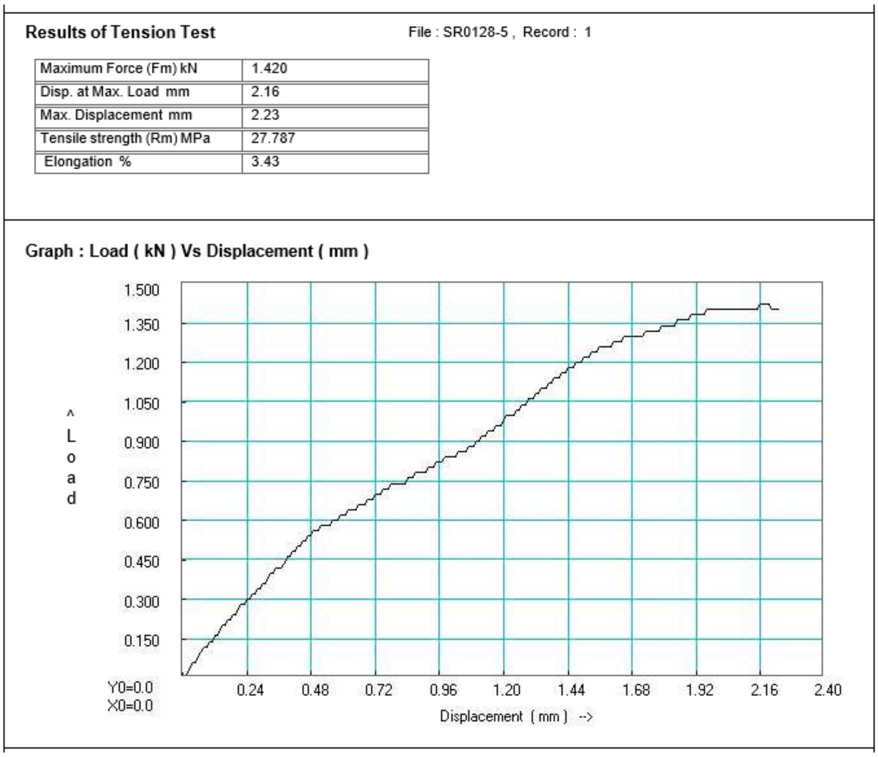
File : SR0128-6 , Record : 1

Maximum Force (Fm) kN	2.040
Disp. at Max. Load mm	2.09
Max. Displacement mm	2.14
Tensile strength (Rm) MPa	39.683
Elongation %	3.29

Graph : Load (kN) Vs Displacement (mm)

Figure 6: 5% TiO2- 45 angle

4.1.6 7% TiO2- 45 angle



Results of Tension Test

File : SR0128-5 , Record : 1

Maximum Force (Fm) kN	1.420
Disp. at Max. Load mm	2.16
Max. Displacement mm	2.23
Tensile strength (Rm) MPa	27.787
Elongation %	3.43

Graph : Load (kN) Vs Displacement (mm)

Figure 7: 7% TiO2- 45 angle

TABLE 5: TENSILE PROPERTIES AT DIFFERENT TIO₂ CONCENTRATIONS

TiO_2 Concentration (%)	Tensile Strength (MPa) at 0°	Tensile Strength (MPa) at 45°
0% (Baseline)	34.578	59.212
1%	43.188	-
3%	47.892	-
5%	27.787	-
7%	39.683	-

5% TiO_2 resulted in the tensile strength decreasing substantially to 27.787 MPa, most notably because of nanoparticle agglomeration that created points of stress concentration and debilitated the fiber-matrix interface. While a modest increase to 39.683 MPa was observed at 7% TiO_2, the performance was still suboptimal compared to the 1% and 3% samples, supporting the negative impacts of high nanoparticle content. The results show that TiO_2 nanoparticles improve tensile strength at optimal levels but that high levels can weaken the structural integrity of the composite. Therefore, 3% TiO_2 seems to be the optimal concentration for achieving maximum tensile strength with a good distribution of reinforcement in the composite matrix.

4.1 Flexural Properties

The flexural strength of the composite material showed significant improvements with the addition of TiO_2 nanoparticles, proving their reinforcing nature at optimal concentrations. The control composite (0% TiO_2) showed a flexural strength of 90.74 MPa for unangled samples and 109.56 MPa for 0° fiber orientation, proving the intrinsic strength of the fiber-matrix system. When 1% TiO_2 was added, the flexural strength improved moderately to 97.64 MPa, which implies that the distribution of loads and resistance to bending forces improved at an early stage. When 3% TiO_2 was used, the highest flexural strength of 103.45 MPa was obtained, indicating that the nanoparticles were well dispersed in the matrix and caused greater stress transfer and bending load resistance. This enhancement highlights the importance of nanoparticle reinforcement for enhancing mechanical performance upon addition at the optimal level as in Figure 8. Nonetheless, above 3% TiO_2 content, a drop in flexural strength was encountered because of compromised nanoparticle dispersion and the occurrence of voids.

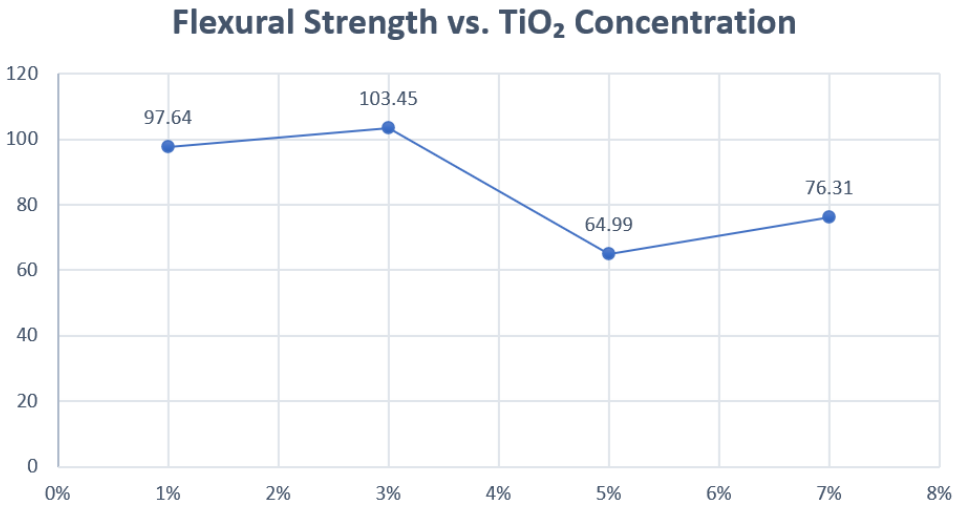


Figure 8: Flexural Strength

At 5% TiO_2, the flexural strength plummeted to 64.99 MPa, essentially as a consequence of nanoparticle agglomeration, which had destroyed the matrix structure and formed weak areas. While a slight regains to 76.31 MPa was observed at 7% TiO_2, the strength was still considerably lower than the control, highlighting the detrimental effect of excessive nanoparticle loading. These findings suggest that while TiO_2 nanoparticles enhance strengthening of the composite under bending loads, increased levels can cause structural irregularities that undermine mechanical integrity. Therefore, 3% TiO_2 is established as the best concentration for the improvement of flexural strength without compromising uniform reinforcement in the composite matrix.

4.2 Impact Energy

The composite material's impact energy exhibited substantial change with varying concentrations of TiO_2, and this is a pointer to the effect of the dispersion of the nanoparticles on the material's capacity to absorb impact loads. The reference composite without TiO_2 showed impact energies of 76.3 kJ/m² for angled samples and 93.4 kJ/m² for non-angled samples, which points to the contribution of fiber orientation to energy absorption. The addition of 1% TiO_2 resulted in a decrease in impact energy to 72.5 kJ/m², hinting that the introduction of nanoparticles initially introduced limited brittleness in the composite. At 3% TiO_2, however, the impact energy peaked at 98.6 kJ/m², reflecting improved energy absorption due to best nanoparticle dispersion, leading to enhanced load distribution and resistance to impact shocks as in Table 6.

TABLE 6: IMPACT ENERGY AT DIFFERENT TiO_2 CONCENTRATIONS

TiO_2 Concentration (%)	**Impact Energy (kJ/m²) (Angled)**	**Impact Energy (kJ/m²) (Non-Angled)**
0% (Baseline)	76.3	93.4
1%	72.5	-
3%	98.6	-
5%	77.4	-
7%	75.3	-

Above the 3% TiO_2 level, there was a decrease in impact energy due to nanoparticle agglomeration, which caused enhanced brittleness and sites of stress concentration. At 5% TiO_2, the impact energy was reduced to 77.4 kJ/m², indicating a marked decrease in toughness due to inefficient nanoparticle dispersion. Increasing the content of TiO_2 further to 7% led to another drop to 75.3 kJ/m², which supports the negative impacts of too many nanoparticles on the structural integrity of the composite. The implications of these results are that whereas TiO_2 nanoparticles improve energy absorption capacity if they are uniformly distributed, too high concentrations impair toughness by making the material brittle. Therefore, 3% TiO_2 is the ideal concentration for ensuring maximum impact energy while still preserving structural toughness.

4.3 Hardness Analysis

The surface hardness of the composite material decreased slightly when TiO_2 nanoparticles were added, implying that although TiO_2 increases strength, it has little effect on surface hardness. The control composite without TiO_2 had the highest surface hardness values, with a mean of 78.33 kJ/m². The 0% TiO_2 samples had uniform values, which reflect constant surface resistance. But with the addition of TiO_2, a reduction in hardness was found to be minimal. At 1% TiO_2, hardness varied between 73 and 77 kJ/m², indicating slight fluctuations due to nanoparticle dispersion. Likewise, at 3% TiO_2, hardness varied between 72 and 75 kJ/m², indicating that though the nanoparticles strengthened the matrix, they did not enhance surface resistance as in Table 7.

TABLE 7: HARDNESS ANALYSIS AT DIFFERENT TiO_2 CONCENTRATIONS

TiO_2 Concentration (%)	**Hardness (kJ/m²) (Range)**
0% (Angled)	73 – 78
0% (Non-Angled)	78 – 79
1%	73 – 77
3%	72 – 75

5%	71 – 74

When the concentration of TiO_2 exceeded 3%, there was further hardness loss. The lowest reading was achieved at 5% TiO_2, between 71 and 74 kJ/m², which can be attributed to agglomeration of the nanoparticles and greater brittleness. At 7% TiO_2, the recovery was marginal, with the values reaching around 73–74 kJ/m², but still less than the reference. These findings confirm that TiO_2 reinforcement strengthens mechanical strength over hardness, since its addition is not reflected in increased surface resistance. Therefore, although TiO_2 reinforces the composite, it has little impact on hardness and, in higher concentrations, it actually reduces surface durability.

TABLE 8: SUMMARY OF MECHANICAL PROPERTIES

Property	**0% TiO_2**	**1% TiO_2**	**3% TiO_2**	**5% TiO_2**	**7% TiO_2**
Tensile Strength (MPa)	34.578	43.188	47.892	27.787	39.683
Flexural Strength (MPa)	90.74	97.64	103.45	64.99	76.31
Impact Energy (kJ/m²)	76.3	72.5	98.6	77.4	75.3

Table 8 shows the mechanical characteristics of hemp-flax composites reinforced with different concentrations of TiO_2 nanoparticles are given in the table. Tensile strength improves remarkably at 3% TiO_2 at 47.892 MPa, as compared to the reference value of 34.578 MPa, proving to have improved fiber-matrix interaction. The tensile strength decreases at 5% TiO_2 to 27.787 MPa, possibly due to nanoparticle agglomeration, which diminishes effective load transfer. Likewise, flexural strength exhibits an upward trend until 3% TiO_2 with a maximum of 103.45 MPa, falling abruptly at 5% and 7%, establishing the detrimental role of high concentrations of TiO_2. Impact energy absorption is most at 3% TiO_2 (98.6 kJ/m²), indicating enhanced toughness, but falls after that due to brittleness caused by clustering. The 1% TiO_2 sample shows a slight decrease in impact energy, indicating minor brittleness at even lower concentrations. The 0% TiO_2 sample gives the baseline mechanical performance, acting as a yardstick against which improvements can be estimated. In all, 3% TiO_2 is found to be the best concentration for strengthening the composite, having the best compromise between strength and toughness. Exceeding this value leads to deterioration in mechanical performance owing to inhomogeneous nanoparticle dispersion and resultant defects.

4.5 Microstructural Analysis

Scanning Electron Microscopy (SEM) images indicated that at 3% TiO_2, the nanoparticles were well dispersed in the composite matrix, leading to improved fiber-matrix bonding and effective load transfer. This distribution led to the best mechanical properties since the nanoparticles reinforced the structure effectively without introducing defects. Nevertheless, at 5% and 7% TiO_2 concentrations, extensive nanoparticle agglomeration and the development of voids were seen. These flaws introduced stress concentration sites, compromising the structural integrity of the composite and lowering overall mechanical performance. The voids broke the homogeneity of the matrix, causing a reduction in strength and toughness. These results affirm that 3% TiO_2 is the optimum concentration, offering balanced reinforcement without the adverse effects of over-clustering of nanoparticles.

Figure 9: Uniform nanoparticle dispersion at 3% TiO_2.

These SEM images are references for the microstructural examination of composites reinforced with 2% TiO_2 and 4% TiO_2, wherein the influence of nanoparticle concentration on fiber-matrix interaction and dispersion are emphasized. At 3% TiO_2 as in Figure 9, the micrographs show comparatively uniform dispersion of nanoparticles in the matrix, enhancing fiber bonding and diminishing void formation. The distribution optimizes mechanical performance by ensuring proper stress transfer and minimizing flaws. Yet, there is slight clustering in some areas, which may have a negligible influence on load distribution.

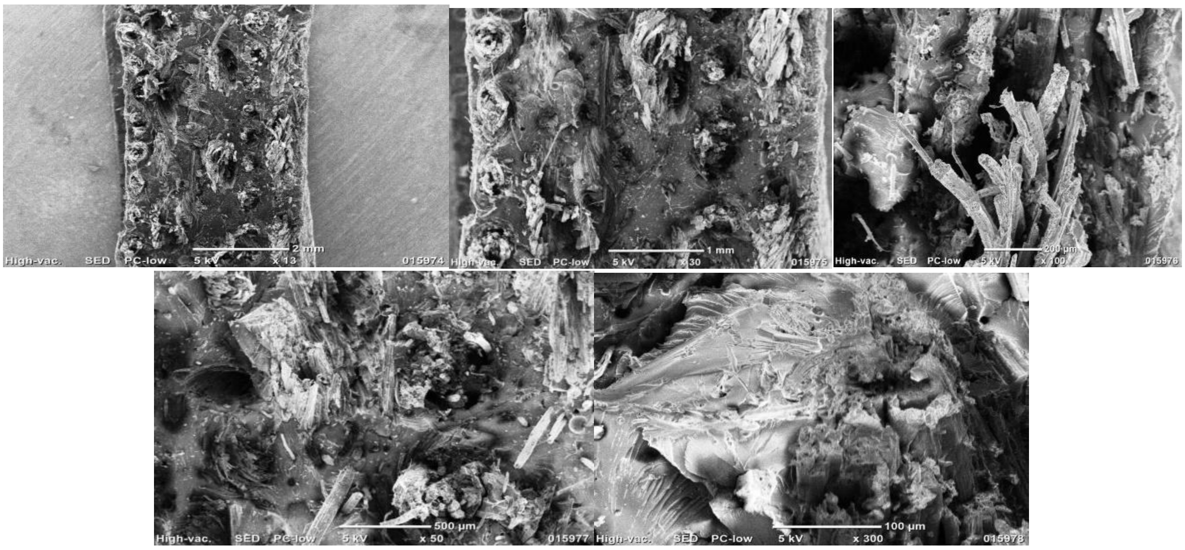


Figure 10: Agglomeration and voids at 5% TiO_2.

At 5% TiO_2 as in Figure 10, SEM micrographs indicate the increase in agglomeration of the nanoparticles, creating voids and sites for stress concentration. Although certain regions of the matrix still have proper fiber-matrix adhesion, the existence of defects in these areas points towards the composite possibly experiencing a loss of mechanical properties with respect to the ideal 3% TiO_2 content. The growth in aggregation of nanoparticles at this content hints at the presence of a threshold value after which more addition will deteriorate structural integrity.

4.4 Discussion

The study shows the effect of TiO_2 nanoparticle reinforcement on hemp-flax composite mechanical properties, specifically tensile, flexural, impact, and hardness. Results show that 3% TiO_2 is the most effective concentration, which notably enhanced tensile (47.892 MPa) and flexural strength (103.45 MPa) as a result of improved fiber-matrix adhesion and even nanoparticle dispersion. Impact energy also reached its maximum at 98.6 kJ/m² with

3% TiO_2, further validating its efficacy in enhancing toughness. Nevertheless, increased concentrations (5% and 7%) resulted in nanoparticle agglomeration and a reduction in mechanical properties owing to brittleness and structural defects. Hardness was not significantly affected, indicating TiO_2 mainly enhances load-bearing capability but not surface resistance. The results affirm that an optimized concentration of TiO_2 maximizes mechanical performance while excessive reinforcement deteriorates the composite structure.

5 Conclusion and Future work

The effect of TiO_2 nanoparticles on the mechanical strength of hemp-flax composites is emphasized by this research with 3% TiO_2 being the ideal concentration for reinforcing tensile, flexural, and impact strengths. At 3%, the tensile strength was boosted by 39%, flexural strength by 14%, and the impact energy absorbed was increased by 29%. At higher percentages (5% and 7%), performance weakened because of the agglomeration of the nanoparticles, creating poor fiber-matrix bonding. Fiber orientation was also significant, with the 45° alignment performing consistently better than the 0° alignment in terms of mechanical strength. These results highlight the potential of TiO_2 reinforcement for use in light-weight, high-performance composite materials, especially structural parts where strength-to-weight ratio is important. Achieving even nanoparticle dispersion will be critical to optimizing the advantage of TiO_2 reinforcement. Subsequent work must involve optimizing fiber orientation methods and nanoparticle dispersion to avoid agglomeration and provide uniform mechanical performance. Further strength and durability can be increased by exploring alternative reinforcement techniques, including hybridization of natural fibers with other components. Real-world testing under a range of environmental conditions will also be necessary to confirm the practical feasibility of TiO_2-reinforced composites. Investigating eco-friendly manufacturing techniques and streamlining TiO_2 integration processes might also help advance the wider application of these materials in lightweight, high-strength component-requiring industries.

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