Enhancement of Mechanical Properties in Hybrid Polymer Composites through Titanium Nanoparticles and Kenaf Fiber Integration

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Abstract. Aerospace, home goods, and automobiles all have a need for high-performance composites manufactured using polymer matrix that are lightweight, and durable. This research looks at the mechanical properties of hybrid polymeric composites supplemented with titanium nanoparticles and Kenaf fiber ranging from 0 to 20 wt.%. During the production process, titanium nanoparticles (NPs) are dispersed inside the polymer matrix using mechanical mixing and sonication. The next step is to calculate the mechanical properties of the nanocomposites, including their impact, bending, and tensile strengths. Out of the five different hybrid types, the S3 hybrids had the best mechanical properties, including a tensile strength of 60 MPa, a flexural strength of 68.41 MPa, and an impact energy of 5.17 J. Volumetric degradation is reduced by 10-15% under typical load conditions after 17.5 wt.% titanium nanoparticles are added, in comparison to Sample S1 hybrids. One possible explanation for the reduced propensity for volumetric deterioration is the inclusion of titanium nanofillers in the fiber matrix composition. Additionally, the physical characteristics are examined in order to grasp the overall performance of the nanocomposites. The results will be useful in developing eco-friendly materials with good performance for applications in various fields, like construction, the packaging industry, and the automotive industry, where improved mechanical properties are required. Titanium nanoparticles have the potential to significantly enhance the functionality of organic fiber-reinforced polymeric composites, as this work has shown.

Keywords: Titanium nanoparticles, sonication, tensile strength, moisture absorption, nanocomposites, impact strength.

1 Introduction

Natural fibers can break down in nature and be released back into the environment without causing any long-term pollution. To tackle the global problem of plastic waste, this quality is essential. Contrarily, synthetic fibers contribute to the accumulation of non-biodegradable waste and remain in the environment for an extended period. Through the incorporation of

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natural fibers into bio-composites, we may promote more sustainable waste disposal procedures while decreasing our dependency on synthetic ingredients. The production of synthetic fibers involves energy-intensive processes that release a significant amount of carbon dioxide into the atmosphere [1,2]. Conversely, natural fibers have a smaller impact on the environment due to their lower power requirements and, in many cases, the absence of chemical reaction steps. By combining biodegradable polymers with organic fibers, bio-composites pave the way for a circular economy. By beginning the manufacture of natural fibers with agricultural resources or byproducts, we might potentially decrease waste and boost resource efficiency. Biological composites have the potential to be reusable or biodegradable, which would be great for the environment since it would encourage less wasteful disposal methods and less reliance on nonrenewable resources [3]. The use of FRPC with criteria for these materials, degraded endurance and a number of psychological and chemical properties, which are increasingly important due to the ever-increasing repercussions of environmental pollution. Many people are worried about the environmental impact of synthetic fibers and man-made resins, despite their prominence in the industry for years due to their superior strength and rigidity [4]. To solve major problems including biocompatibility, health effects, and recyclability, several researchers [5,6] concentrated on finding synthetic material alternatives. There has been a recent uptick in interest in natural fabrics; as a result, a viable replacement for synthetic reinforcements is being considered. These threads form naturally and are intricately linked to creatures of every type. Natural fabrics derived from plants have the potential to produce hybrids with enhanced qualities; these materials are accessible, affordable, and recyclable [7,8]. The material's properties fracture toughness, stiffness, chemical inertness, and temperature resistance will be enhanced by the combination of fillers and fibers. Hybridization with other botanicals, filler, or conventional fibers has been pursued by researchers due to the high moisture content and low compliance of plant fibers. To enhance the mechanical properties of lightweight materials, researchers have looked at adding stiff tiny or nanoparticles. Excellent durability, stiffness, and low densities are some of PALF's positive mechanical properties. Thermoplastic and thermosetting polymer matrix architectures are highly compatible with PALF. It offers a wide range of composite material options due to its ease of incorporation into numerous polymeric architectures. One of PALF's unique qualities is its ability to absorb sound, as well as its effectiveness in insulating against heat and moisture. In applications calling for these specific characteristics, PALF-based composites may be the way to go [9,10]. The toughness of a fracture is increased if two or more scattered stages trap a fracture ahead, causing the fracture face to extend and deflect. The fracture toughness within polymer matrix phases has been significantly enhanced by the use of titanium fillers [11]. A combination of factors, including foam stress concentration initiated by tensile stress round to the edges of nanofillers and delamination of nanomaterials leading to expansion of the polycarbonate void inside the epoxy, may account for the hardening mechanism observed when titanium nanofillers are diffused [12]. A critical component in increasing the mechanical features of bio-composites has also been found as the distribution of nanoparticles. The wall effect is a significant tendency for nanoparticles to clump together, both within themselves and around spherical particles [13]. Nanomaterials made of titanium dioxide are more affordable and easier to obtain than other types of extremely small particles. They improve the hybrids' mechanical and physical properties, and it is easy to disseminate and integrate with a polymer matrix [14, 15]. Titanium nanoparticles enhance composites' wear ability and endurance due to their hardness and abrasion resistance. Titanium nanoparticles are well-suited for applications necessitating a high level of wear resistance due to their ability to reduce friction and wear between composites [16,17]. Adding nanoparticles to synthetic fiber-reinforced polymer has reportedly sparked a flurry of research into their physical, mechanical, and wear properties. Hybrid polymeric materials based on organic fibers and loaded with nanomaterials have surprisingly little research on how to quantify their performance. Despite the extensive research on natural fiber-reinforced composites, including titanium nanoparticles (NPs) provides a new way to address the limitations of natural fibers. This is particularly true in polymer hybrid nanocomposites that include Kenaf fibers. Composites manufactured from kenaf fiber are reinforced with titanium nanoparticles to enhance their mechanical properties in this study. Investigating the nanocomposites' wear resistance is a novel approach to satisfying the demand for durable materials in a wide range of industrial contexts. By exploring the potential combinatorial effects of organic fibers and titanium nanoparticles in polymeric hybrid nanocomposites, this research contributes to the advancement of environmentally friendly and high-performance materials. Together, Kenaf fiber, and titanium nanoparticles open up hitherto unimaginable avenues for the development of environmentally friendly composites that are strong.

2 Materials and Methods

2.1 Materials

Kenaf fiber (1.4 g/cm^3 density, 57% cellulose, 22% hemicellulose) was supplied by Go green Enterprises, Chennai, Tamil Nadu, India. To acquire superior mechanical characteristics, these fibers were soaked in 5% NaOH solution for 24 hours at room temperature before utilization. This helped with mechanical and interface bonding between fiber and matrix. After that, distilled water was used to rinse the fibers, and then they were oven-dried for 5 hours at 65°C. The fibers are dried in the oven is then used to form composites after being cut into lengths of 300×300 mm. The curing agent and epoxy matrix were purchased from Kovai Cheenu Enterprises, Coimbatore, Tamil Nadu, India. Fig. 1 shows the extraction process of Kenaf-based natural fiber.

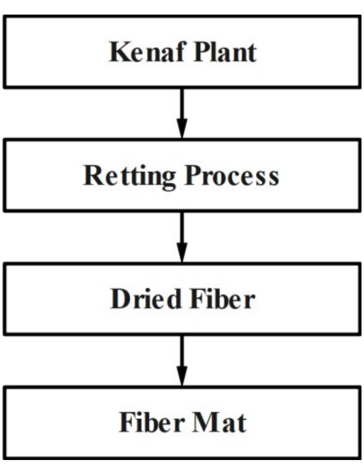

Fig. 1. Kenaf-based natural fiber extraction process

2.2 Composite Fabrication

The appropriate amount of titanium nanoparticles was mixed with methanol using a stirring rod (operating at 400-2000 rpm and 0.7-W rating) for 10 minutes. Then, a probing ultrasonicator was used for 15 minutes. This mixing technique was repeated once the necessary amount of epoxy resin was poured. There was a 20-minute period of vigorous mixing after the required quantity of chopped natural fibers were added. The material was heated in oven at 70 °C for 15 min to remove any remaining methanol. Finally, a 1:10 ratio was used to automatically combine the curing ingredient for 15 minutes. After that, the composites were poured into a steel mold and let too dry for 24 hours with a 30-kilogram load on top. The mold substrates have been covered with wax films to stop the mixture from sticking to the plates. Various characterization tests made extensive use of the produced materials after they were machined into samples with required dimensions. The different combinations of polymer, filler, and fiber for hybrid composites are shown in Table 1. Fig. 2 displays the specimens used for tensile and flexural tests.

Table 1. Composition of filler and fibers

Notations	Kenaf fiber wt.%	Epoxy resin wt.%	Titanium nanoparticles
S1	35	65	0
S2	20	65	15
S3	17.5	65	17.5
S4	15	65	20

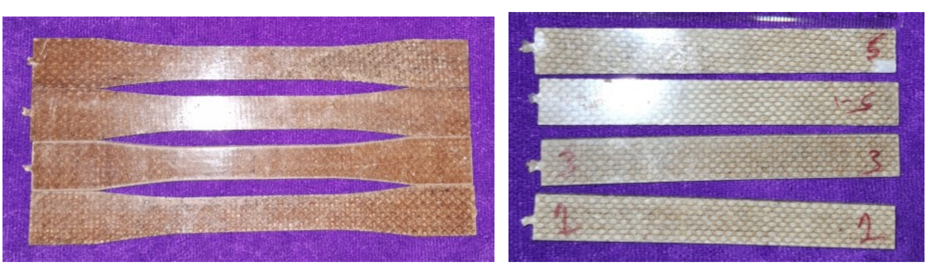

Fig. 2. Photographic images of a) tensile specimen; b) flexural specimen

2.3 Mechanical Characterization

The manufactured composites were tested for water absorption, tensile strength, impact resistance, and bending rigidity. The Instron 1195 type Universal Testing Machine (UTM) was utilized to assess the flexural and tensile strengths of each sample [18, 19]. A crosshead speed of 2 m/min and a maximum load capacity of 5 KN characterizes this equipment. The specimen's impact strength was estimated using Izod Impact testing machine, in conformity with ASTM D6110 standard.

2.4 Moisture Absorption Behavior

The nano titanium-based nanocomposite, Kenaf fiber were subjected to a 60-hour immersion in distilled water at room temperature to conduct a moisture absorption experiment in accordance with ASTM 570 standard [20, 21]. The nanocomposite was heated at 65°C for 24 hours to eliminate remaining moisture before testing. The weight was then determined. After the composites were weighed, they were immediately placed in water. Every 24 hours, the composite samples were removed from the water bath and cleaned using tissue paper. To determine the total volume of water collected, the composite samples were weighed. The water uptake percentages were monitored by routinely measuring composite samples until saturation was reached. All of the composites in this investigation were saturated after 60 hours of immersion. The investigation was conducted over a 60-hour period because there was no increase in the water absorption percentage beyond that. Applying Eq. (1) below yields the moisture absorption proportion [22].

$$Moisture\ absorption\ = \frac{W_a - W_b}{W_b} \times 100 \tag{1}$$

3 Results and Discussions

3.1 Mechanical Properties

3.1.1 Tensile Strength

The results of tensile test and modulus properties of the composites are displayed in Fig. 3. The polymeric material's mechanical properties are mostly dictated by the reinforcement's type, weight proportion, and adherence to the resin matrix. Composites from Sample S1 that did not contain nanofillers had a tensile strength of 40 MPa (Fig. 3). Adding 15 wt. % titanium nanofillers to the mixture, however, results in a 22% improvement in tensile strength compared to the composite in Sample S1. Only at loadings of 17.5 % can titanium nanoparticles increase tensile strength. With 17.5 wt. % titanium nanoparticles, the composite in Sample S3 reached 60 MPa, which is 43 % stronger than the composite in Sample S1. However, the tensile strength decreased by 14-31% but stayed higher than the Sample S1 composite after increasing the titanium nanomaterial concentration beyond 17.5 wt.%. Reduced interfacial bonding among fibers, additives, and matrices, leading to reduced strength qualities, may be the consequence of insufficient wetting of nanofillers at higher loading. The study conducted by the authors [23,24] confirmed that adding a small number of nanomaterials improved the polymeric matrix's tensile strength, the tensile strength declined regardless of the concentration of titanium nanoparticles. The efficiency of kenaf hybrid nanocomposite was studied by the authors [25] with and without titanium nanofillers. The study's author found that composites with 4 wt. % nanoparticles had the highest tensile strength, and that as the titanium nanomaterial composition increased, the tensile strength decreased. Research has shown that similar results can be achieved with larger quantities of nanoparticles.

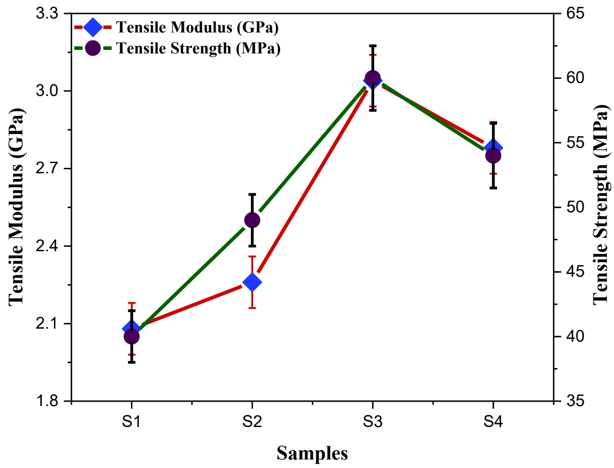

Fig. 3. Tensile strength and modulus of nano titanium-filled hybrid composite based on Kenaf at varying concentrations

At different filler loadings, the graph for tensile modulus of Titanium composites is also shown in Fig. 3. A hybrid titanium nanocomposite containing 17.5% filler by weight has its maximum tensile modulus documented. Strength improvement is less than that of the 17.5 wt. % hybridized nano-composites (Sample S3), but it is still more than that of the empty (Sample S1) composite. Titanium particles attach to the epoxy resin through a chemical reaction between silica and the oxygen molecules in the resin, and carbon and the hydrogen atom [26]. But, unlike hybridized Titanium nano-composites, this material does not contain oxygen-hydrogen bonds, which are more significant than carbon-hydrogen binding, and hence its modulus and load-carrying capacity are lower. The formation of clusters or aggregations of nanoparticles, known as agglomeration, becomes more likely at concentrations of Titanium nanofiller exceeding 17.5 wt. %. The total tensile modulus of the composite might be reduced and localized weaknesses could be caused by agglomerates acting as stress concentrators. The more nanofillers there are, the better the chances of filler-to-filler interaction. The composite's ability to convey stress was compromised by these interactions, and raise the possibility of material flaws [27].

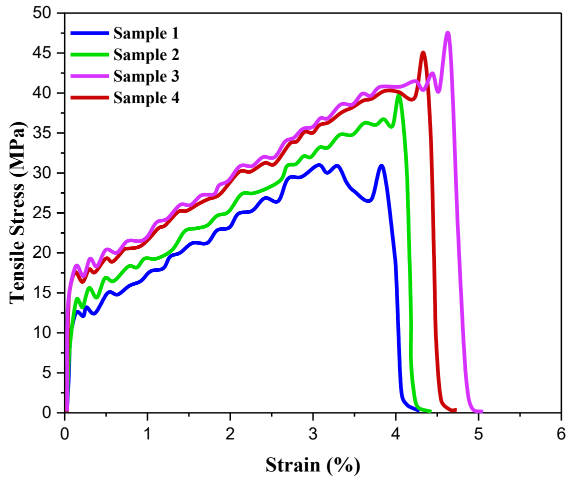

Fig. 4. Tensile stress-strain curve of a hybrid composite loaded with nano titanium at varying concentrations based on Kenaf fiber

3.1.2 Flexural strength

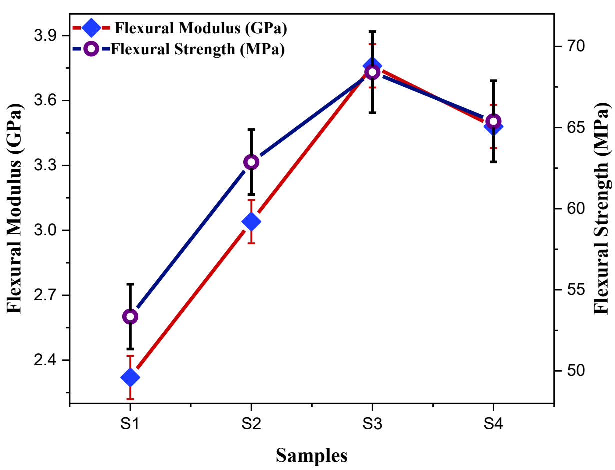

Fig. 5. Flexural strength and modulus of nano titanium-filled Kenaf-based hybrid composite at various concentrations

Fig. 5 displays the epoxy composites' flexural modulus and strength based on hybridized organic fibers at different loadings of titanium nanoparticles. Incorporating titanium nanoparticles into the composites significantly improves their bending strength, as shown by the results. Without titanium nanoparticles, the flexural strength of Sample S1 materials was 47.26 MPa. Adding 15 wt. % of titanium nanoparticles increased this strength by 16% and maintained it at 62.87 MPa. Estimates for the bending behavior of Sample S3 material were 68.41 MPa, or about 26% higher than that of Sample S1 specimen. In addition, flexural strength starts to decline after 17.5 wt. % titanium nanoparticle loading, which may be because of increased filler-fiber interactions or because a higher void content leads to a less efficient stress transfer process among the fillers and the fibers [28]. Similar to Sisal fiber-reinforced composite, maximum flexural strength found at 17.5 wt. % titanium nanoparticles and dropped as the nanomaterial loading increased further. The flexural properties' stress-strain curve is displayed in Fig. 6.

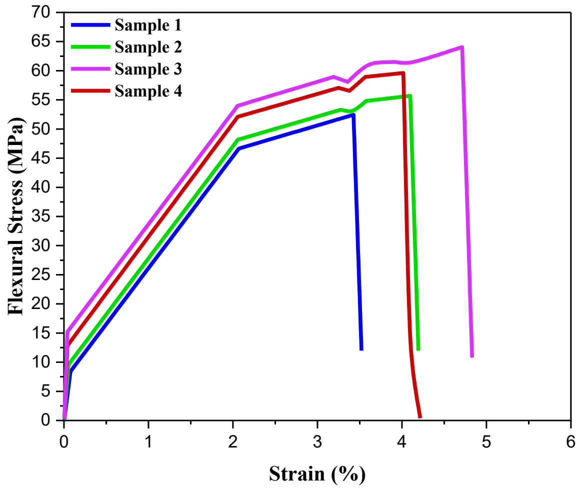

Fig. 6. Flexural stress-strain curve of various titanium nanoparticle in a hybrid composite based on Kenaf

Titanium nanoparticles can form strong bonds with the hybrid material's matrix ingredient as much as 17.5 wt. % of the time. Results in improved load-bearing capacity and higher flexural modulus as the result of improved stress transmission and interaction at filler-matrix interfaces. Unfortunately, the previously observed trend disappeared after adding 17.5 % titanium by weight. This is because it becomes increasingly challenging to maintain a uniform distribution of the nanofillers as their concentration rises. Reduced flexural modulus and limited load transmission capacity could result from filler and matrix adhesion due to inadequate distribution [29,30]. Crucial is the interaction between the matrix component and the titanium nanofiller. At some point in time, the filler-matrices bonds may lose some of their beneficial properties, leading to a decrease in flexural modulus and reduced reinforcing effects. Composite composition, processing circumstances, and other environmental factors may all play a role in why flexural modulus drops below 17.5 wt. % Titanium nanofiller.

3.1.3 Impact Strength

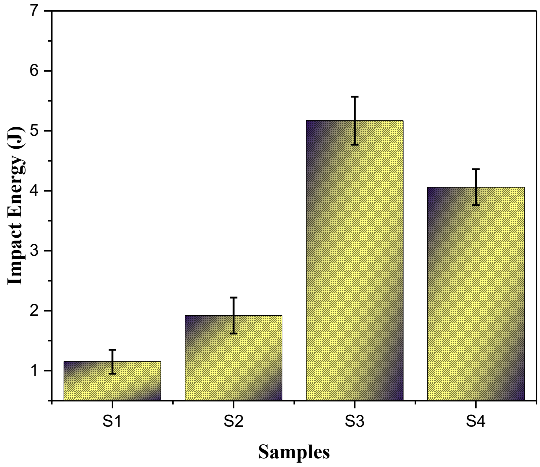

Fig. 7. Absorbent impact energy of various nano titanium-filled Kenaf-based hybrid composite concentrations

Composite samples with titanium nanoparticles were subjected to impact force measurements, as shown in Fig. 7. Titanium nanoparticles greatly enhanced the impact strength of organic fiber-reinforced epoxy composite. The lowest impact strength of a Sample S1 combination was three times lower than that of composites containing 17.5 wt. % titanium nanoparticles, which achieved an impact force of 5.17 J. However, a decrease of 10-33% was seen for composites (Sample S5 and D) that contained 17.5 wt. % titanium nanoparticles. This study looked at the impact resistance of a blended nanostructure that was reinforced with Kevlar fibers. Impact resistance is highest for polymer composites packed with 15 wt. % nanomaterials and declines with decreasing concentrations of titanium nanoparticles, according to the author's research. Due to inherent flaws in the manufacturing process, fiber-reinforced polymer combinations often have a high void density [31,32]. Void structures can accelerate the formation and spread of fractures by acting as maximal stress locations. Titanium nanoparticles help fill these voids, which prevents microcracks in hybrids from forming and spreading [33]. Improving interfacial bonding and resulting to the rise in impact force, nanoparticles can function as connecting pins in matrix and reinforcement. The higher impact strength could be explained by the fact that titanium nanoparticles absorbed more energy than their smaller counterparts because their surface to volume ratio was higher. Empirical evidence shows that the impact strength of material decreases as deposition of titanium particles rises, making it more brittle.

3.2 Physical Properties

3.2.1 Moisture Absorption Behavior

At room temperature, composites based on kenaf and titanium with varying percentages of titanium by matrix weight show a link between percentage weight growth and immersion

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period square (Fig. 8). The water absorption behavior of these samples adhered to the Fickian rule, where the water uptake curves exhibit an initial linear trend followed by a deceleration until reaching saturation gradually over an extended duration. Under all of the tested soaking times, hybrid fiber-reinforced epoxy composites that had titanium nanoparticles added to the epoxy matrix absorbed less water than their titanium-free counterparts. This is because the epoxy matrix contains titanium nanoparticles that act as a water barrier [34,35].

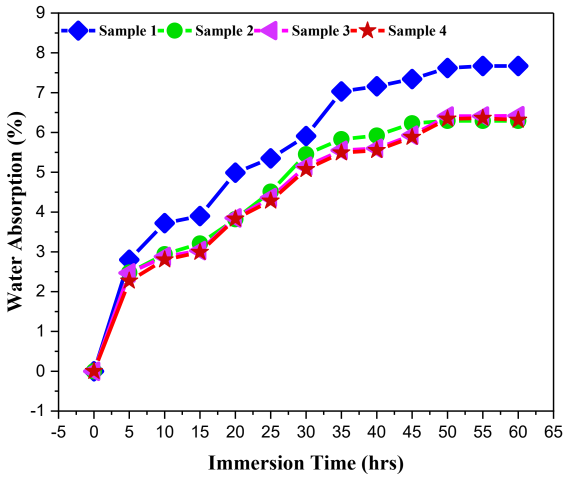

Fig. 8. Moisture absorption characteristics of nano titanium-filled Kenaf-based hybrid composite at varying concentrations

Furthermore, these results demonstrate that both the initial moisture absorption rate and the maximum moisture content values diminish with increasing amounts of titanium nanoparticles. The nanofiller's optimal aspect ratio creates a twisted path and strengthens the binding at the contact point, leading to this outcome. Titanium specimens with a content of more than 17.5% absorbed more water than titanium specimens with a content of 15%. These inevitable cracks and holes within the composite have been associated with the densification and production procedures. Since the hydroxyl groups on the surface of Kenaf fiber are responsible for its hydrophilic characteristics, unfilled (Type-A) hybrid composites show low hydrophilicity for different soaking periods. That the control samples could hybridize continuously better than the hybridization specimens are also explained by this. We can learn more about this phenomenon by looking at the absorption rate of natural fibers. Due to the high cellulose content of the natural fiber, the composites absorb a lot of water, which in turn causes the fiber to swell.

4 Conclusions

The incorporation of titanium nanoparticles into polymeric hybrid nanocomposites based on Kenaf fiber has greatly enhanced their mechanical and physical properties. The incorporation of titanium nanoparticles has enhanced the material's hardness, stiffness, and durability, making it more suitable for structural uses. This study found that nanocomposites containing 17.5 wt. % titanium nanoparticles absorbed more water and had improved mechanical properties (i.e., tensile strength of 60 MPa, flexural strength of 68.41 MPa, and impact energy of 5.17 J). It is now obvious that the distribution and interactions of titanium nanoparticles throughout the polymer matrix are crucial for achieving these enhanced properties. In addition, the composite strength starts to decline after adding 17.5 wt. % titanium nanoparticles. This could be because there are more filler-fiber interactions and because there is more void content, which leads to a poor stress transmission process among the fillers and the fibers. By demonstrating the enormous promise of titanium nanoparticles as a reinforcing component in polymeric hybrid nanocomposites based on Kenaf fiber, these findings pave the way for the development of new materials with improved performance and sustainability.

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