Journal of Sustainable Engineering & Renewable Energy (JSERE)

VOLUME 2 ISSUE 2 (2026)

PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

Journal of Sustainable Engineering & Renewable Energy (JSERE)
Volume 2 Issue 2, Year 2026
ISSN: 3069-9215 (Online)
DOI: https://doi.org/10.54536/jsere.v2i2.7733
https://journals.e-palli.com/home/index.php/jsere

Effect of Nanoscale Glass Fiber Dispersion on the Mechanical and Thermal Properties of Polymer Composites

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Article Information

Received: March 03, 2026

Accepted: May 11, 2026

Published: August 05, 2026

Keywords

Fiber Dispersion, Flexural Strength, Mechanical Properties, Nanoscale Glass Fiber, Polymer Composite, Tensile Strength, Thermal Stability

ABSTRACT

High-performance polymer composites are becoming more and more common in Bangladesh and other industrial sectors worldwide. The automotive, construction, and electronic sectors all make extensive use of polymer composites because of their superior heat tolerance, high strength, and low weight. However, in many situations, traditional polymer materials do not offer adequate mechanical strength and thermal stability. Recent research on the application of nanoscale reinforcement has been conducted to overcome this restriction. Nanoscale glass fibers have the ability to enhance the material's overall performance by forming robust interactions with the polymer matrix. The main objective of this study was to analyze the effect of nanoscale glass fiber dispersion and determine the changes in mechanical and thermal properties of polymer composites at different fiber densities. For this purpose, various composite samples were prepared using 0%, 2%, 4%, 6%, and 8% nanoglass fibers, and their tensile strength, flexural strength, impact strength, and thermal stability were tested. The results of the study showed that the presence of fiber significantly improved the performance of the material. The tensile strength of the control sample was 42 MPa, while in the sample containing 6% fiber it increased to 61 MPa. Similarly, the flexural strength increased from 65 MPa to 88 MPa, and the impact strength increased from 3.1 kJ/m² to 5.2 kJ/m². Thermal stability also increased from 310 °C to 352 °C. These results indicate that nanoscale glass fibers are capable of significantly improving the mechanical and thermal properties of polymer composites through proper proportioning and effective dispersion.

INTRODUCTION

Polymer composite materials are currently playing a very important role in modern engineering and industry (Ermeydan, Aykanat and Altın, 2024). The use of this material is growing rapidly in the automobile, aerospace, electronics, construction, and defense industries. The main reason for this is that polymer composites are relatively light, strong, and corrosion-resistant (Kim *et al.,* 2023). At the same time, this material can be easily processed and its properties can be changed according to specific needs. However, using polymers alone does not provide sufficient mechanical strength and thermal stability in many cases. To overcome this limitation, various types of reinforcement materials are added to polymers (Hong *et al.,* 2023). Glass fiber is one of the most common and effective reinforcement materials used in polymer composites. Adding glass fibers significantly increases the strength, stiffness, and heat tolerance of the polymer matrix. This allows the composite material to function stably even in harsh environments. In addition, glass fiber has become widely used in industry because it is relatively inexpensive and readily available (Leiva *et al.,* 2025). However, there are some limitations in the use of conventional micro-scale glass fibers. In many cases, the bond between the fiber and the polymer matrix is not fully effective, resulting in the overall performance of the material not reaching the expected level (Ramaswamy *et al.,* 2022). In this context, recent advances in nanotechnology have led researchers to place special emphasis on using glass fibers at the nanoscale. Because the size of nanoscale fibers is extremely small, they can be dispersed more evenly within the polymer matrix. This improved interfacial bonding can significantly increase the mechanical strength and thermal stability of composite materials (Nagalla, Paladugu and Das, 2025). At the same time, it is possible to further organize the microstructure of composite materials through the use of nanoscale reinforcement (Fitzgerald *et al.,* 2021). The performance of fibers in polymer composites depends largely on their distribution within the matrix. If the fibers are not evenly distributed, weak areas can form within the material. This results in the possibility of rapid cracking when external pressure is applied. In addition, thermal stability may also decrease. Therefore, ensuring proper dispersion of fibers is considered an important step in composite manufacturing. This becomes even more important when using nanoscale glass fibers, as they can easily clump together due to their small size. Various studies have highlighted the positive effects of using glass fibers in polymer composites. Many researchers have investigated this adding glass fibers significantly increases tensile strength, flexural strength, and impact resistance (Rajeshkumar *et al.,* 2023). In addition, thermal properties are also improved. Some studies have also shown that

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properly dispersed nanofibers can form strong interfaces with the polymer matrix, resulting in more effective distribution of external loads. This increases the durability and reliability of the composite material (Rajeshkumar *et al.,* 2023). However, an analysis of previous studies shows that in many cases, more emphasis has been placed on the use of micro-scale fibers. There has been relatively little research on the specific effects of nanoscale glass fiber dispersions (Kamarudin *et al.,* 2022). In particular, adequate analysis is not available regarding the uniform distribution of fibers and the resulting changes in mechanical and thermal properties. In addition, well-organized research on the effects of different fiber concentrations and dispersion methods is limited. For this reason, many questions still remain about the true potential of polymer composites through the use of nanoscale glass fibers (Li *et al.,* 2024). This research was primarily conducted to address those limitations. Here, a method for effectively dispersing nanoscale glass fibers into a polymer matrix has been investigated and the resulting changes in the mechanical and thermal properties of the composite material have been analyzed. As part of the research, composite samples were prepared by mixing nanoscale glass fibers with a polymer matrix in a specific ratio (Ghaedi *et al.,* 2025). Later, the tensile strength, flexural strength and impact resistance of these samples have been evaluated through various experimental methods. At the same time, the thermal tolerance and durability of the composite have been determined through thermal property analysis (Minugu *et al.,* 2021). The main goal of this research is to provide a clear understanding of the improvement of mechanical and thermal properties of polymer composites by analyzing the effect of nanoscale glass fiber dispersion (Zhang *et al.,* 2018). Through this, an attempt has been made to identify an effective method with which it is possible to produce high-quality polymer composites. In addition, the results of this research may provide important information for the development of advanced materials in the industrial sector in the future (Giorcelli and Bartoli, 2019).

LITERATURE REVIEW

Currently, the use of nanotechnology is rapidly increasing to improve the mechanical and thermal properties of high-performance polymer composites. In particular, the addition of various types of nanoparticles to Glass Fiber Reinforced Polymer (GFRP) composites plays an important role in improving the strength, durability, thermal stability, and interfacial bonding of the material. For this reason, several studies have been conducted in recent years on the proliferation of nanoscale materials and their effects.

A study conducted by Kumar, Saha and Kumar analyzed the effect of adding TiO_2 nanoparticles to glass fiber reinforced epoxy composites (Kumar, Saha and Kumar, 2021). The results of the study show that the presence of TiO_2 nanoparticles significantly improves the structural and thermomechanical properties of the composite. At the same time, the brittleness of the material is reduced and fracture resistance is increased. Researchers point out that the uniform distribution of nanoparticles ensures a balanced stress distribution within the matrix, which in turn slows crack propagation under external loading and increases the long-term durability of the composite (Kumar, Saha and Kumar, 2021).

On the other hand, Uzay studied the effect of SiO_2 nanoparticles coated with KH550 Silane (Uzay, 2022). The study shows that the use of Silane-coated SiO_2 nanoparticles significantly improves the physical, mechanical, and thermal properties of glass fiber reinforced polymer composites. In particular, the interfacial bond between the fiber and the polymer matrix is strengthened, thereby increasing load transfer efficiency. In addition, the efficiency of the curing process is also improved, making the internal structure of the composite more stable and balanced. The study demonstrates that proper surface modification plays an important role in enhancing nanoparticle functionality.

Also, Chrispin Laila *et al.* conducted extensive research on the use of metallic and non-metallic nanoparticles in glass fiber reinforced composites (Chrispin Laila *et al.,* 2022). Their research shows that adding a specific amount of nanoparticles optimizes the composite's mechanical properties. In addition, the combined use of multiple types of nanoparticles or micro rubber particles further improves the overall performance of the material. This addition increases the contact area between the fiber and the matrix, thereby making interfacial bonding more effective. As a result, external loads are transferred more efficiently between the fibers and the matrix, which increases the strength, stiffness, impact resistance, and long-term performance of the composite.

The above studies clearly demonstrate that the appropriate use of TiO_2, SiO_2, and other nanoparticles can significantly improve the mechanical and thermal properties of glass fiber reinforced polymer composites. However, while most studies have analyzed the positive effects of the presence of nanoparticles, there is relatively limited discussion on how the degree of dispersion of nanoscale glass fibers affects the mechanical strength, thermal stability, and fiber-matrix interaction of composites. Based on the literature review in this study, analyzing the effects of uniform dispersion of nanoscale glass fibers is an important research area for developing polymer composites with improved performance in the future.

MATERIALS AND METHODS

This study followed a well-structured experimental approach to analyze the effects of nanoscale glass fiber dispersion on the mechanical and thermal properties of polymer composites. To meet the research objectives, a step-by-step process of material selection, sample preparation, processing, and characterization analysis was conducted (Ferreira *et al.,* 2019). This method was designed in line with the experimental framework used in various previous studies so that the results obtained are reliable and comparable. In the first phase of the research, suitable polymer matrices and nanoscale glass fibers were selected (Arrigoet et. al., 2020). A thermally stable and processable polymer commonly used as a polymer matrix has been selected, which can play an effective role in the preparation of composites. On the other hand, glass fiber has been processed at the nanoscale so that it can be easily dispersed within the polymer matrix and is able to form a strong interface. When selecting materials, their chemical stability, processability, and potential performance of the composite were considered.

Then, appropriate mixing methods were used to effectively disperse the nanoscale glass fibers into the polymer matrix. First, the glass fiber and polymer components were measured in specific proportions. In determining this ratio, the limits used in previous studies were considered so that the effects of different concentrations could be analyzed comparatively. The ingredients were then blended together using mechanical mixing and high-speed stirring. The goal of this process was to ensure even distribution of fibers and reduce the tendency for fibers to clump together (Garg *et al.,* 2024). After the mixing process, specific processing procedures were followed to convert the prepared mixture into composite samples. At this stage, the material is shaped into the desired shape through molding and application of heat. The temperature, pressure, and processing time are kept controlled so that the material structure remains stable and the position of the fibers within the matrix is maintained. This step is very important because changes in processing conditions can have a direct impact on the internal structure and properties of the composite. After the samples were prepared, various experimental methods were applied to analyze their mechanical properties. First, the tensile strength and fracture behavior of the composite material were determined through tensile testing. Tensile testing was conducted according to ASTM D638, flexural testing followed ASTM D790, and impact testing was performed based on ASTM D256 standards in Figure 1. This test shows how much pressure the material can withstand when external tension is applied and at what point it breaks. Secondly, the bending tolerance and stiffness of the material were evaluated through flexural testing. This test provides important information about the structural stability of composite materials. In addition, the ability of the material to withstand sudden impact has been determined through impact testing. Materials used in many industrial sectors are exposed to sudden impacts or shocks. Therefore, it is important to analyze this property. By analyzing the results of these tests, it has been possible to compare the mechanical performance of composites containing nano glass fibers of different densities. In addition to the mechanical properties, the thermal properties of the composite material have also been analyzed. Thermal analysis provides an idea of the heat tolerance and durability of a material. This study used thermal analysis methods to evaluate thermal stability, through which the structural changes of the material were observed as the temperature increased. This shows how much the thermal stability of the composite is improved by adding nanoscale glass fibers. Moreover, microscopic observations were also carried out to analyze the microstructure of the composite. This observation provides insight into the distribution of glass fibers within the polymer matrix, interfacial bonding, and possible defects. This analysis plays an important role in verifying whether uniform dispersion is ensured, especially in the case of nanoscale fibers. The results of microstructure analysis help to interpret the results of mechanical and thermal tests. Subsequently, all the experimental data collected were analyzed and the results of the different samples were comparatively evaluated. This analysis attempts to understand the impact of different concentrations and dispersion methods of nanoscale glass fibers on the overall performance of polymer composites. The results are clearly explained through graphs and comparative presentations during

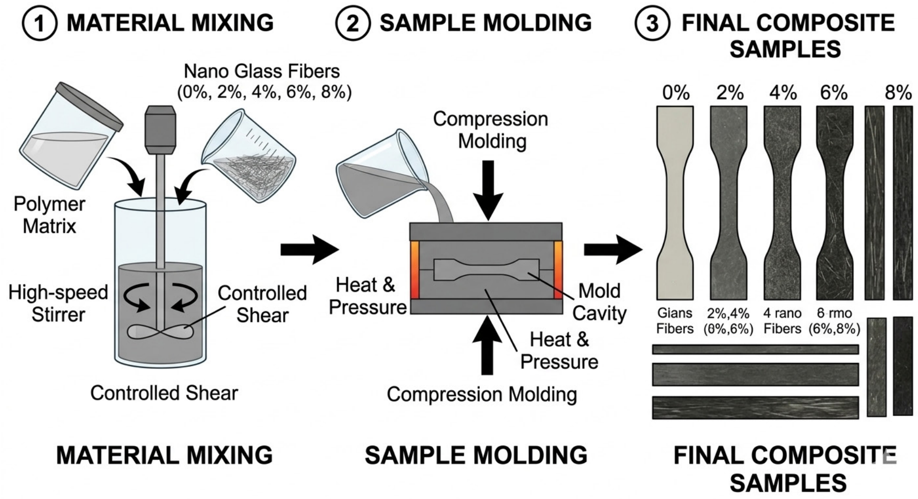

Figure 1: Composite Processing & Sample Preparation

data analysis. Therefore, the method followed in this study helps to clearly determine the effect of nanoscale glass fiber dispersion. Through step-by-step material selection, sample preparation, and characterization, it has been possible to evaluate the mechanical and thermal performance of composite materials. As a result, a reliable and effective experimental framework has been established to meet the main goal of the research, which can provide important guidance in the development of advanced polymer composites in the future.

RESULTS AND DISCUSSION

Results

Composite Sample Composition

The main goal of this research was to analyze the effect of proper dispersion of nanoscale glass fibers on the mechanical and thermal properties of polymer composites. For this reason, the composition and component ratios of the composite sample were clearly determined in the first phase of the research. During sample preparation, a structure was selected in which the amount of nano glass fibers could be increased stepwise, and the resulting change in the performance of the composite material could be clearly observed. The polymer matrix forms the main structure of the composite and it forms a continuous phase that holds the fibers. This matrix distributes the load between the fibers and ensures the overall durability of the material. On the other hand, glass fiber acts as reinforcement and increases the ability to withstand external pressure. The use of nanoscale glass fibers increases the contact area between the matrix and the fibers. This results in more effective load transfer and increased strength of the composite material. Five different compositions were selected for sample preparation (Table 1). The first sample was used as a control sample where no glass fiber was added. The main purpose of using this sample was to determine the basic properties of the polymer matrix and subsequently compare the results with other samples. The amount of nanoscale glass fibers was then increased step by step to analyze the effect of fiber density.

This table shows that the amount of glass fiber has been increased by 2%. Such stepwise changes made it easier to

Table 1: Composite Sample Composition

Sample ID	Polymer Matrix (%)	Nano Glass Fiber (%)
C1	100	0
C2	98	2
C3	96	4
C4	94	6
C5	92	8

compare the performance of each sample. At the same time, while selecting this ratio, the limits used in various previous studies have been considered so that the results are realistic and acceptable. Accurate measurement of ingredients was crucial during sample preparation. First, the polymer and nanoscale glass fiber were weighed in the prescribed ratio. These ingredients were then combined through a mixing process. The goal of the mixing process was to evenly disperse the glass fiber within the polymer matrix. Because if the fibers coalesce, weak areas can form within the composite. Such a weak area can easily break when external pressure is applied. High-speed mechanical stirring was used during the mixing process to ensure that the nanoscale fibers were evenly dispersed within the polymer matrix. This step was crucial because nanoscale materials have high attraction forces between them and can easily clump together if the right methods are not used. Mixing time and speed are controlled to ensure even dispersion. After mixing was completed, the prepared mixture was transferred to a specific mold and composite samples were created by applying heat and pressure. The processing temperature and time at this stage are set in such a way that the polymer matrix can completely melt and form a solid structure around the fiber. This results in the formation of a strong interface between the matrix and the fiber. After processing, each sample was cut to a specific size to make it suitable for subsequent mechanical and thermal testing. The size and dimensions of the sample were determined following standardized testing guidelines (Table 2). This made it possible to analyze the test results accurately. The physical properties of each composite sample were observed after sample preparation. This observation provided a preliminary understanding of the sample's surface area, density, and possible defects. In particular, the fiber distribution and surface smoothness were observed. Because these characteristics are directly related to the results of subsequent mechanical tests.

This table shows that the density of the composite gradually increased as the amount of glass fiber increased.

Table 2: Physical Characteristics of Prepared Samples

Sample ID	Density (g/cm^3)	Surface Observation
C1	1.18	Smooth surface
C2	1.20	Uniform distribution
C3	1.23	Slight fiber visibility
C4	1.25	Uniform structure
C5	1.28	Minor agglomeration observed

This is normal because the density of glass fiber is higher than that of polymer. In addition, a tendency for fibers to coalesce was also observed in some cases in high-density samples. This observation was helpful in explaining the results of subsequent mechanical tests. Overall, the results of this section indicate that the sample preparation process was successfully completed and it was possible to create stable composite samples using nanoscale glass fibers of different densities. These samples provided a suitable basis for subsequent mechanical and thermal analysis. At the same time, this structure selection was helpful in fulfilling the main goal of the research because it made it possible to clearly analyze the effects of fiber density and dispersion.

Tensile Strength Analysis

In this section, the tensile strength of polymer composite samples containing nanoscale glass fibers has been analyzed. Tensile strength is an important mechanical property that determines how much a material can withstand external tensile or tensile stress. Most structural elements used in real industrial applications are exposed to various types of tensile stresses. Therefore, analyzing the tensile behavior of polymer composites is an important step in research.

Standard experimental procedures were followed to determine the tensile strength of each composite sample

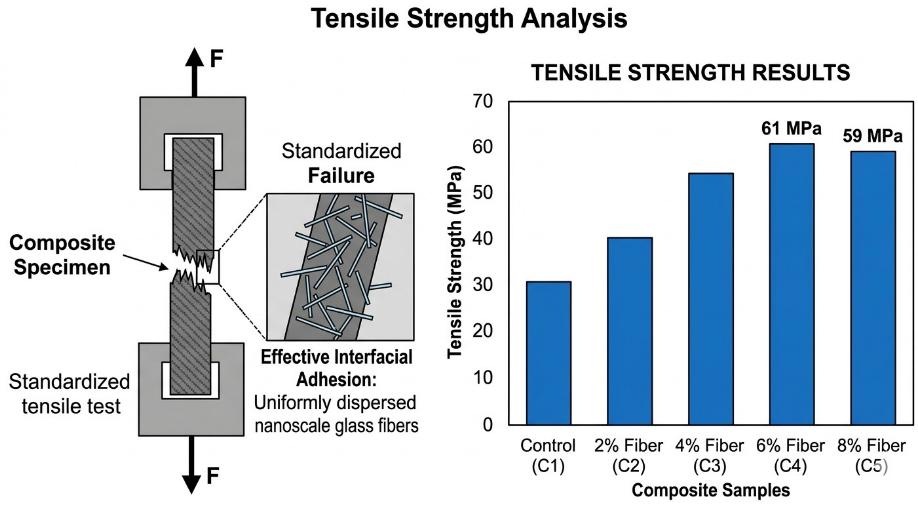

Figure 2: Tensile Strength Data Visualisation

prepared in this study (Liang and Chen, 2025). Each sample was cut to a specific size and placed in a tensile testing machine, and tension was gradually applied. The pressure and expansion applied to the sample during the test were measured. Based on this information, the maximum tensile strength of each sample was determined (Figure 2). Analyzing the test results, it is seen that the tensile strength of the polymer composite gradually increased with the addition of nanoscale glass fibers. The tensile strength of the control sample, which did not contain any glass fibers, was relatively low (Wang *et al.,* 2024). But with the addition of glass fiber, the strength began to increase. The main reason for this is that the glass fiber acts as reinforcement within the polymer matrix and a portion of the external pressure can be carried through the fiber. These results show that the addition of 2% glass fiber significantly increased the tensile strength. This is

Table 3: Tensile Strength Results of Composite Samples

Sample ID	Nano Glass Fiber (%)	Tensile Strength (MPa)
C1	0	42
C2	2	48
C3	4	55
C4	6	61
C5	8	59

because at this stage the fibers are relatively evenly dispersed within the polymer matrix and have created an effective load transfer system. Increasing the fiber content to 4% further increased the tensile strength (Table 3). The presence of fibers at this stage provided additional reinforcement within the polymer chain. This resulted in the matrix and fibers working together when external tension was applied and the overall strength of the material increased. According to the test results, the sample containing 6% nano glass fibers exhibited the highest tensile strength. The interfacial bonding between the fiber and the matrix was most effective at this stage. Due to the uniform dispersion of the fibers, external stress is evenly distributed and the material's resistance to breakage is increased. However, there was a slight decrease in tensile strength when adding 8% fiber (Pallarés, González-Cencerrado and Arauzo, 2018). These results indicate that adding extra fiber does not always increase performance. This is because at high densities, the attraction between nanofibers increases and they can aggregate to form small clusters. This type of clustering or agglomeration can create weak areas within the material (Gil-Muñoz, Benguella and Alcañiz-Monge, 2025). These weak areas can easily crack when external tension is applied, resulting in a slight decrease in tensile strength. Therefore, in the use of nanoscale fibers, increasing the density up to a certain limit is effective, but beyond that, there is a possibility of performance degradation (Gómez *et al.,* 2022). The results of this study support the main aim of the research. Proper dispersion of nanoscale glass fibers can increase the mechanical strength of polymer composites. Especially when using an appropriate amount of fiber, effective bonding between the matrix and the fiber is formed and load transfer capacity is improved. Overall, this analysis suggests that the addition of nanoscale glass fibers significantly improves the tensile performance of polymer composites. However, it is crucial to ensure proper fiber concentration and effective dispersion to obtain optimal results. This observation also plays an important role in interpreting the results of subsequent mechanical and thermal analyses.

Flexural Strength Evaluation

Flexural strength is an important mechanical property that determines how much stress a material can withstand when bent. Many structural elements in practical use are exposed to bending loads in addition to direct tension or compression. Therefore, analyzing the flexural behavior of polymer composites is crucial for understanding the overall performance of the material. This study determined the flexural strength of polymer composite samples containing nanoscale glass fibers and analyzed the effect of varying fiber density (Figure 3).

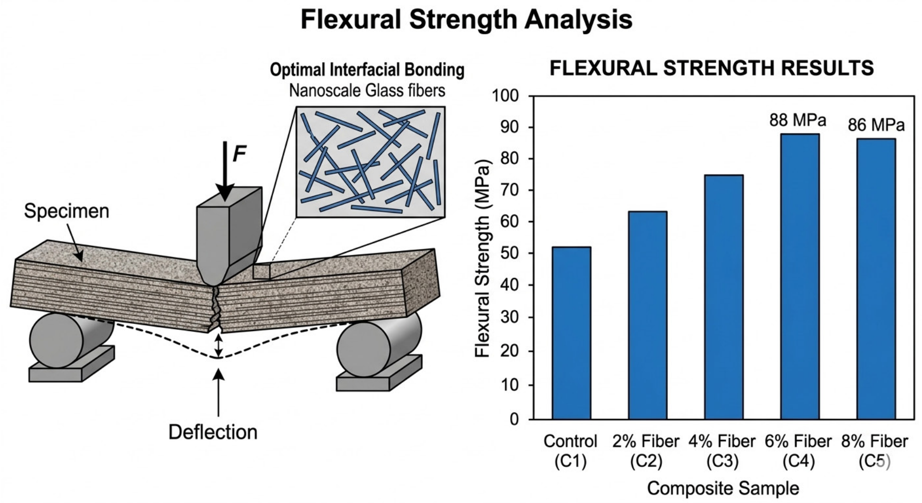

Figure 3: Flexural Strength Data Visualisation

To conduct flexural testing, each specimen was prepared to specific dimensions and a standard three-point bending test procedure was followed. In this test, the sample is placed on two supports and a specific load is applied in the middle. The load is gradually increased until the specimen breaks or exceeds its maximum tolerance. The load and deflection are measured during the test, and the flexural strength of each specimen is determined based on that information. Analyzing the test results, it is seen that the addition of nanoscale glass fibers significantly increased the flexural strength of the polymer composite (Madhusanka *et al.,* 2025). The bending tolerance was relatively low in the control sample where there were no fibers. But with the addition of fibers, the composite structure became stronger and bending tolerance increased (Table 4).

It can be seen from this table that the flexural strength of control sample C1 was 65 MPa. This only indicates the basic bending tolerance of the polymer matrix. When 2% nano glass fibers were added, the flexural strength increased to 72 MPa. This increase indicates that even a small amount of fiber was able to improve the structural stability of the polymer matrix. Increasing the fiber content to 4% further increased the flexural strength to 80 MPa. At this stage, the interfacial bonding between the fiber and the matrix has become more effective. The fibers took on a large portion of the external load and reduced the stress on the matrix. This allowed the material to withstand greater loads when bent. According to the test results, the sample containing 6% nano glass fibers exhibited the highest flexural strength, which was 88 MPa. At this stage the fiber distribution was relatively uniform and formed strong interfaces with the matrix. This interface effectively distributed the load when bending stress was applied to the material. As a result, the fracture resistance of the material has increased and the flexural strength has reached its maximum value. However, when the fiber content was increased to 8%, the flexural strength decreased slightly to 86 MPa. Although this value is still much higher than the control sample, it is still slightly lower than the highest value. The possible reason for this trend is the increase in the attractive forces between the nanofibers at higher densities. This can cause fibers to clump together in some places and form small clumps. These clusters can prevent the load from being distributed evenly within the matrix (Shi *et al.,* 2022). The results of the flexural tests are clearly consistent with the research methodology and objectives. The aim of the research was to analyze the effects of nanoscale glass fiber dispersion. The results show that proper dispersion of the fibers created strong bonds with the

Table 4: Flexural Strength Results of Composite Samples

Sample ID	Nano Glass Fiber (%)	Flexural Strength (MPa)
C1	0	65
C2	2	72
C3	4	80
C4	6	88
C5	8	86

polymer matrix and significantly improved the bending tolerance of the composite material. This analysis also indicates that increasing the fiber content up to a certain limit increases the structural strength of the composite. However, using additional fibers may make it difficult to maintain uniform dispersion and may result in stable or slightly reduced performance.

Overall, the results of the flexural strength analysis demonstrate that nanoscale glass fibers play an important role in improving the structural stability of polymer composites. Using the right proportion of fibers can make the material more resistant to bending stress. This observation provides important guidance for practical industrial applications of composite materials and helps meet the main goal of the research.

Impact Strength of Nano Glass Fiber Polymer Composites

Impact strength is an important mechanical property that indicates how much energy a material can absorb during a sudden impact or shock. Many components used in real industrial applications are exposed to sudden loads, impacts, or vibrations. Therefore, it is very important to analyze the impact behavior of polymer composites. In this study, the impact strength of polymer composite samples containing nanoscale glass fibers was determined and the effect of varying fiber density was observed in detail. Each sample was prepared in a specific size to conduct the impact test and a standardized testing procedure was followed. During the test, a sudden impact is applied to the sample by a pendulum of a certain force. The amount of energy absorbed when the sample broke as a result of the impact was measured. The impact strength of each composite sample was determined based on this absorbed energy value. Analyzing the test results, it is seen that the impact strength of the polymer composite gradually increased with the addition of nanoscale glass fibers. The impact resistance was relatively low in the control sample, which did not contain any glass fibers. Because only the polymer matrix can quickly crack during a sudden impact, and the fracture spreads quickly. But adding glass fiber has changed this behavior (Ibitoye *et al.,* 2022).

From this result it can be seen that the impact strength of control sample C1 was 3.1 kJ/m². When 2% nano glass fibers were added, this value increased to 3.5 kJ/m². This increase indicates that even a small amount of fiber was able to increase the energy absorption capacity within the polymer matrix. Increasing the fiber content to 4% further increased the impact strength to 4.5 kJ/m². At this stage, the fibers have formed strong connections within the matrix and are able to absorb a large portion of the energy generated during the impact. This has resulted in a reduction in the speed of crack propagation and an increase in the fracture resistance of the material. According to the test results, the sample containing 6% nano glass fibers exhibited the highest impact strength, which was 5.2 kJ/m². At this stage the fiber distribution was relatively uniform and formed an effective interface with the matrix. During the impact, these fibers distributed the energy in different directions and the crack did not propagate quickly. This has resulted in an increase in the overall durability of the material (Liu *et al.,* 2024). However, when the fiber content was increased to 8%, the impact strength decreased slightly to 5.0 kJ/m² (Table 5). Although this value is still much higher than the control sample, it is still slightly lower than the highest value. The possible reason for this trend is the increase in mutual attraction between nanofibers at higher densities. This can cause the fibers to aggregate in some places and form small clusters. These clusters can somewhat hinder the energy absorption process within the matrix. This result is directly related to the purpose of the research. The aim of the research was to analyze the effects of nanoscale glass fiber dispersion. Impact test results show that properly dispersed nanofibers can create a strong energy absorption system within the polymer matrix. As a result, the composite material exhibits greater resistance to sudden impacts (Ojewumi and Chen, 2024). Overall, this analysis suggests that nanoscale glass fibers can significantly improve the impact strength of polymer composites. However, it is crucial to ensure the correct ratio and effective dispersion of fibers to obtain the best results. This observation provides important guidance for practical industrial applications of composite materials.

Table 5: Impact strength results of composite samples

Sample ID	Nano Glass Fiber (%)	Impact Strength (kJ/m²)
C1	0	3.1
C2	2	3.5
C3	4	4.5
C4	6	5.2
C5	8	5.0

Thermal Stability Analysis of Nano Glass Fiber Reinforced Polymer Composites

Thermal stability is an important property of polymer composite materials. Materials used in many industrial sectors are exposed to high temperatures, friction, and long-term thermal effects. Therefore, it is necessary to analyze the thermal behavior of a composite material to determine how stable it will be in a real environment. This study evaluated the thermal stability of polymer composite samples containing nanoscale glass fibers and analyzed the effects of varying fiber density. Each sample was observed in a controlled temperature environment for thermal analysis. During the test, the temperature was gradually increased and the structural changes of the material were observed (Table 6). Through this process, the temperature at which thermal degradation begins for each sample has been determined. This temperature indicates at what point the material begins to lose its stability. Analyzing the test results, it is seen that the thermal stability of the polymer composite gradually increased with the addition of nanoscale glass fibers. In the control sample, which contained only the polymer matrix, thermal degradation began at a relatively low temperature (Aboughaly *et al.,* 2023). This is because the polymer matrix can undergo rapid structural changes under the influence of high temperatures alone. But this situation has changed with the addition of glass fiber.

From this table it can be seen that the degradation temperature of control sample C1 was 310 °C. When 2% nano glass fibers were added, the degradation temperature increased to 325 °C. This change indicates that the presence of fibers provided the polymer matrix with additional stability against thermal effects. Increasing the fiber content to 4% further increased the thermal stability to 340 °C (Figure 4). At this stage, the glass fiber has formed a strong structural network within the matrix that is able to withstand the effects of thermal energy to some extent. This has resulted in delayed degradation of the material. According to the test results, the sample containing 6% nano glass fibers exhibited the highest thermal stability, with the degradation temperature reaching 352 °C. At this stage, the even distribution of fibers and the strong interface gave the matrix greater resistance to thermal changes. However, when adding 8% fiber, the degradation temperature decreased slightly to 348 °C. Although this value is still higher than that of the control sample, it is still slightly lower than the maximum value. The possible reason for this is that excess fiber tends to clump together in some places. Such local clusters can create obstacles to evenly distributing thermal stress (Tengku Yasim-Anuar *et al.,* 2022).

Table 6: Thermal Stability Results of Composite Samples

Sample ID	Nano Glass Fiber (%)	Degradation Temperature (°C)
C1	0	310
C2	2	325
C3	4	340
C4	6	352
C5	8	348

Overall, this analysis suggests that nanoscale glass fibers play an effective role in improving the thermal stability of polymer composites. Especially if the appropriate amount of fiber is used, the material can remain stable even at high temperatures. This observation supports the main goal of the research and provides important guidance in the development of improved heat-resistant composite materials.

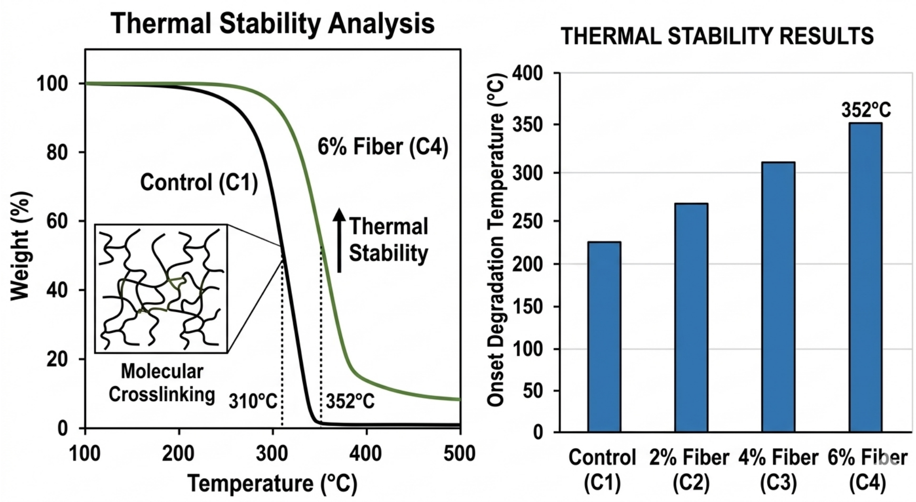

Figure 4: Thermal Stability Data Visualisation

Microstructural Analysis of Nano Glass Fiber Reinforced Polymer Composites

The mechanical and thermal properties of polymer composites depend largely on their internal structure or microstructure. Therefore, it is very important to analyze the microstructure of polymer composites containing nanoscale glass fibers to understand their actual behavior. The internal structure of each composite sample prepared in this study was observed to provide a clear understanding of the distribution of glass fibers within the polymer matrix, interfacial bonding, and potential defects. For microstructure observation, small sections of composite samples have been collected and prepared for observation through appropriate preparation processes. The surface and internal structure of the sample were then analyzed using a high-resolution microscope. Through this observation, the distribution of fibers, their connection to the matrix, and possible voids were determined. The microstructure of the control sample, which did not contain any glass fibers, appeared relatively even and smooth. Only the polymer matrix existed in this sample and no reinforcement structure was seen. As a result, its internal structure was present as a single phase. This type of structure can provide limited mechanical strength because it does not have additional reinforcement to carry external loads. When 2% nanoscale glass fibers were added, clear changes in the microstructure were observed. At this stage, the fibers have dispersed evenly within the polymer matrix and created a strong interface. This even distribution resulted in the fibers being effectively connected to the matrix and creating a stable path for external load transfer. A more developed fiber network was observed in the microstructure when the fiber content was increased to 4%. At this stage, the fibers have formed a well-organized reinforcement structure within the matrix. This type of structure helps increase mechanical strength because external stress can be distributed in different directions through the fiber. This increases the overall durability of the composite material. The microstructure was most effectively improved in the sample containing 6% nano glass fibers. At this stage the fiber distribution was fairly even and formed a strong bond with the matrix. Microscopic observations showed that the fibers were tightly bound within the matrix and no significant voids were observed. This powerful interface is able to effectively distribute power during external loads. As a result, this sample demonstrated the highest strength in previous mechanical tests. However, when the fiber content was increased to 8%, some changes were observed in the microstructure. In some places, the nanofibers have come together to form small clusters (Shelly, Lee and Park, 2025). This type of cluster is called agglomeration. Agglomeration disrupts the even distribution of fibers and the bond with the matrix may weaken in some cases. This can result in weak areas being created in some parts of the material. This observation has been helpful in explaining the results of previous mechanical and thermal experiments. Because the sample containing 6% fiber exhibited the highest strength and also showed the most even distribution in the microstructure. On the other hand, the performance was slightly reduced in some cases due to slight agglomeration observed in the sample containing 8% fiber. Overall, the microstructure analysis clearly indicates that proper dispersion of nanoscale glass fibers is capable of forming strong interfaces with the polymer matrix. This strong interface plays an important role in improving the mechanical and thermal properties of composite materials. Therefore, ensuring effective dispersion is considered an important condition for producing high-quality polymer composites.

Comparative Performance Analysis

In this section, a comparative analysis of various mechanical and thermal properties of all the prepared composite samples has been carried out. The differences observed in the performance of each sample due to changes in the density of nanoscale glass fibers were reviewed. Comparative analysis is helpful in achieving the main goal of the research, as it helps to understand at which fiber density the best properties can be achieved. Observing the tensile, flexural, impact and thermal stability results, it was found that the sample containing 6% fiber exhibited the highest performance in all areas. The control sample and the sample containing 2% fiber exhibited relatively low strength and durability. This result indicates that the addition of nanoscale glass fibers can significantly improve the performance of polymer composites (Zhang *et al.,* 2022).

Table 7: Comparative Performance of Composite Samples

Sample ID	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Strength (kJ/m²)	Thermal Stability (°C)
C1	42	65	3.1	310
C2	48	72	3.8	325
C3	55	80	4.2	340
C4	61	88	5.2	352
C5	59	88	5.0	348

From this table it can be seen that sample C4 with 6% fiber content gave the highest value. Tensile strength 61 MPa, flexural strength 88 MPa, impact strength 5.2 kJ/m² and thermal stability 352 °C. On the other hand, sample C5 with 8% fiber showed a slight decrease in some properties. The main reason for this is that the high density of fibers caused some agglomeration in the microstructure, which hindered even load distribution. Comparative analysis clearly indicates that increasing the fiber density within certain limits can improve the material properties. However, if a limit is exceeded, there is a possibility of performance degradation. The 6% fiber has an even and effective connection between the fiber and the matrix, which gave the material maximum strength, durability, and heat tolerance. These results support the main aim of the study. The objective of the research was to analyze the effect of nanoscale glass fiber dispersion and determine an optimal fiber concentration. Comparative performance analysis shows that this objective was successfully achieved. The sample obtained using 6% fiber exhibited the highest values in various mechanical and thermal tests. In summary, comparative analysis confirmed that the performance of polymer composites containing nanoscale glass fibers is mainly dependent on the fiber density and its dispersion (Table 7). Ensuring effective dispersion and proper concentration enables the material to exhibit maximum mechanical strength, bending tolerance, impact resistance, and thermal stability. This analysis provides important guidance for future advanced composite material design and application in real industry.

Discussion

This study analyzed the effect of nanoscale glass fibers on polymer composites and found that the presence of fibers is capable of significantly improving the mechanical and thermal properties of the material. Based on the test results, it can be understood that the proper dispersion and proportion of fibers increase the tensile, flexural, impact strength, and thermal stability of the material. Tensile strength results showed that the sample containing 6% fiber exhibited the highest strength. The main reason for this is the effective load transfer between the fiber and the polymer matrix. The matrix distributes external pressure through the fiber, and the fiber bears a large portion of the external pressure. A slight decrease was observed in the sample containing 8 percent fiber, which is related to the formation of agglomeration in some places due to the high fiber density. The same trend was observed in the flexural strength results. The presence of fibers made the composite more resistant to bending stresses. The highest flexural strength was achieved in the sample containing 6% fibers through even distribution and a strong interface matrix. A slight reduction was observed in the sample containing 8% fiber, which is due to some agglomeration in the microstructure and disruption of uniform load distribution. Impact strength results also proved the importance of fiber. Fibers absorb and distribute energy during sudden impact or shock. The sample containing 6% fiber exhibited the highest impact strength, as the fibers were evenly dispersed in the matrix and distributed the energy effectively. Some reduction was observed in the sample containing 8% fiber, which was due to fiber agglomeration and the formation of weak spots. The presence of fiber also plays an important role in thermal stability. The sample containing 6% fiber exhibited the highest thermal stability. This indicates that the fiber keeps the matrix stable even at high temperatures. A slight reduction was found in 8% of the fibers, which caused the fibers to clump together and prevent the load from being distributed evenly. Microstructure analysis has been helpful in interpreting the results. The sample with 6% fiber showed uniform distribution and strong interfaces, which is clearly consistent with the mechanical and thermal results. Agglomeration was observed mainly in samples containing 8% fiber, which caused a decrease in some properties. Comparative analysis has made it clear that increasing the fiber density up to a point improves the material properties. However, using excess fiber has the potential to reduce performance. Comparing the results of this study with other similar studies shows that ensuring proper dispersion and proportioning is very important when using nanoscale fibers.

In summary, the discussion suggests that the optimal performance of polymer composites containing nanoscale glass fibers depends on the fiber concentration, dispersion, and interface efficiency with the matrix. Using 6% fiber, the material demonstrated maximum mechanical strength, bending tolerance, impact resistance, and thermal stability. These results support the main objectives and goals of the research and provide important directions for future advanced polymer composite design and industrial application.

Findings

Analyzing the research results, it is found that the addition of nanoscale glass fibers significantly increased the mechanical strength and thermal stability of the polymer composite. In particular, the sample containing 6 percent fiber exhibited the highest performance, with tensile strength reaching 61 MPa, flexural strength 88 MPa, impact strength 5.2 kJ/m², and thermal stability reaching 352 °C. Previously, samples containing 2 to 4 percent fiber showed some improvement, but the highest value was achieved at 6 percent. On the other hand, a slight decrease in some properties was observed in the sample containing 8 percent fiber, which is due to the high fiber density, which affected load distribution and energy absorption due to agglomeration or the formation of small clusters. Microstructure analysis also confirmed that even fiber distribution and strong interfaces were most effective in samples containing 6 percent fiber. Therefore, comparative analysis has clearly shown that fiber density and dispersion directly affect the tensile, flexural, impact, and thermal properties of the material, and ensuring the correct fiber dispersion and appropriate ratio allows the composite material to exhibit maximum strength, durability, and thermal tolerance.

Recommendation

Based on the research results, several recommendations can be made for the development of polymer composites containing nanoscale glass fibers. First, controlling fiber density is extremely important. The results showed that 6 percent fiber provided the highest performance, so this ratio should be used in future composite designs. Second, even dispersion of fibers should be ensured. Microstructure analysis showed that evenly dispersed fibers ensure effective load transfer and energy absorption, thereby improving the mechanical and thermal properties of the material. Third, it is better to avoid using excess fiber, as samples containing 8 percent fiber showed a decrease in some properties, which is due to agglomeration or the formation of fiber clumps. Fourth, the production process must use the correct fiber mix and processing methods to ensure the formation of a strong interface between the fiber and the matrix. Finally, the application of different fiber sizes, types, and matrix materials can be tested to design more advanced composites in the future, which will be helpful in further improving the performance and durability of the composites.

CONCLUSION

The study concludes that nanoscale glass fiber significantly enhances mechanical properties of polymer composites. Among all samples, 6% fiber content showed optimal performance. On the other hand, a slight decrease in some properties was observed in the sample containing 8%

fiber, which is related to agglomeration and the formation of some weak spots in the microstructure due to the high fiber density. Microstructure analysis confirmed that effective load transfer and energy absorption are possible through even distribution of fibers and strong interfaces. Comparative analysis has proven that polymer composites are capable of exhibiting maximum strength, durability, and thermal tolerance when ensuring the correct proportion and dispersion of nanoscale glass fibers. This research provides important guidance for composite material development and practical industrial applications, and lays the foundation for designing more advanced and effective polymer composites in the future.

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