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MECHANICAL AND STRUCTURAL ENHANCEMENT OF POLYPROPYLENE NANOCOMPOSITES REINFORCED WITH TiO₂ NANOPARTICLES

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Abstract

This study investigates the influence of titanium dioxide (TiO₂) nanoparticles on the microstructure and mechanical properties of polypropylene (PP) based nanocomposites. TiO₂ nanoparticles were incorporated in 1, 3, and 6% into the polypropylene using ultrasonication and then compounding them using screw extruder. Microscopic examination confirmed that the sequential processing of ultrasonic and extrusion treatment was crucial for ensuring even dispersion of TiO₂ nanoparticles throughout the PP matrix while reducing agglomeration. The results demonstrated that the mechanical properties, including hardness, tensile strength, and elastic modulus, improved with the addition of 1–3 wt% TiO₂ nanoparticles, but declined at 6 wt% due to potential particle agglomeration and a decrease in interfacial effectiveness. Likewise, the density of the composites increased with the addition of 1-3 wt% TiO₂, but decreased at the higher loading of 6 wt%. Tribological tests showed that adding TiO₂ nanoparticles led to a

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significant reduction in wear volume loss. The lowest volume loss of wear at a sliding velocity of 0.4 m/s was observed in the PP reinforced with 6 wt% TiO₂.

Keywords: Polypropylene, Nanocomposites, TiO₂.

Introduction

Polymers find application across numerous fields, such as transportation, electronic devices, and various construction tools. Generally, they are utilized after incorporating several minor additives that impart certain characteristics, including shape ratio, density, and workability [1,2]. These different categories of composites enhanced with tiny-scale additives are known as 'nanocomposites.' This has gained a lot of popularity lately. Many researchers have focused on nanocomposites due to the considerable improvements in various characteristics achieved at minimal concentrations [3].

Polypropylene (PP) ranks among the most widely used polymers due to its ease of processing and affordability. It finds application across diverse industries, including packaging, textiles, plastic goods, reusable containers, laboratory instruments, automotive parts, and more [4]. Numerous varieties of additives have been identified to improve the characteristics of PP, such as its ability to withstand ultraviolet radiation, its mechanical strength, and its durability [5].

The composite sector is largely propelled by the increasing need for lightweight substances. Lightweight materials are taking the place of metal components like aluminum and steel across various industries. The composite sector benefits from the growing requirement for lighter materials. The demand for enhanced materials persists in pushing the composite industry to develop improved composites [6].

The remarkable attributes of polypropylene composites, which include being lightweight, Additionally, their remarkable strength and ability to be recycled render them perfect for use in vehicles. The automotive sector is expected to see

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significant growth in the adoption of in the coming ten years, polypropylene composites are anticipated to gain popularity due to their outstanding strength and load compared to weight. The resistance to corrosion presented by polypropylene composites has enhanced the demand in the polypropylene composite market [7].

Nano titanium dioxide (TiO_2) is commonly considered to be non-toxic, inert and is also produced in large quantities and commonly utilized in consumers, goods, because of its chemical photo function. On the surface of the catalyst in the ultraviolet light. exposed, this will lead to a lot of chemical reactions that are dependent on the redox potential of the material. commonly employed as a catalyst for photosynthesis to decimate various water predators, reduce organic pollutants and remove the atmosphere. and it enhances the properties of polymers, allowing the development of new nanocomposites with enhanced behaviors [5].

Despite the extensive use of polypropylene (PP) in industrial applications due to its low cost, lightweight nature, and good chemical resistance, its mechanical properties—particularly impact strength, stiffness, and wear resistance—remain limited for high-performance applications. In recent years, the incorporation of nano-sized titanium dioxide (TiO_2) particles has been explored as a promising approach to enhance these properties. However, several critical gaps still exist in the current literature [8].

Most previous works have reported on the general enhancement of mechanical properties, resulting in limited insight to the correlation between nanoparticle treatment and processing conditions with both interfacial adhesion and material performance. The agglomeration of TiO_2 nanoparticles in the PP matrix is a major challenge for achieving optimal reinforcing efficiency, however effective and scalable dispersion strategies are not yet fully optimized. Furthermore, a limited number of detailed investigations have been conducted to study the effects of any type of processing parameters such as extrusion conditions and percentages nanoparticle loading on final mechanical characteristics of Polypropylene

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composites [8]. The role of compatibilizers in promoting interfacial adhesion between the non-polar polypropylene matrix and polar titanium dioxide nanoparticles follows a similar trend, with little information available suggesting that future study is needed to determine ways to improve nanoparticle dispersion, generate superior interfacial environments, or define processing/structure/property correlations. Addressing these knowledge gaps is essential in producing high-performance polypropylene/titanium dioxide nanocomposites suitable for advanced engineering applications.

Materials and Method

Titanium Dioxide Nanoparticles (TiO₂ NPs) were supplied as a powder by (HWNANO/china). with the properties is shown in table 1.

Table 1: The Specification of Titanium Dioxide Nanoparticles.

Properties	Value
Color	White
Particle Size	30-50 nm
TiO ₂ content	>> 99.6%

Polypropylene PP was used as matrix materials in the preparation of composite, was obtained from Reagent World (USA) with properties as shown in table (2).

Table 2: The Specification of Polypropylene polymer.

Properties	value
Density,	0.92 g/cm ³
Processing Temperature,	160 – 170°C
Tensile modulus,	35 MPa

Experimental part

Preparation of the polypropylene nanocomposite samples involved several steps:

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1. Polypropylene was dissolved in xylene and heated to a temperature ranging from 120 to 140 degrees Celsius using a magnetic stirrer for a duration of one hour until a clear and viscous solution was formed.
2. Titanium dioxide was dispersed in xylene at concentrations of 1, 3, and 6 percent using an ultrasonic device, then incorporated into the polypropylene solution, ensuring thorough mixing to achieve a more uniform blend.
3. The resulting uniform mixture was introduced into a twin-screw extruder operating at temperatures between 145 and 160 degrees Celsius and at speeds of 25 to 38 revolutions per minute.
4. The extrudate was processed through rollers to create sheets with a thickness of 3 millimeters, which were subsequently cut and subjected to mechanical machining. The cutting process adhered to international standard specifications relevant to each conducted test, as illustrated in figure 1.

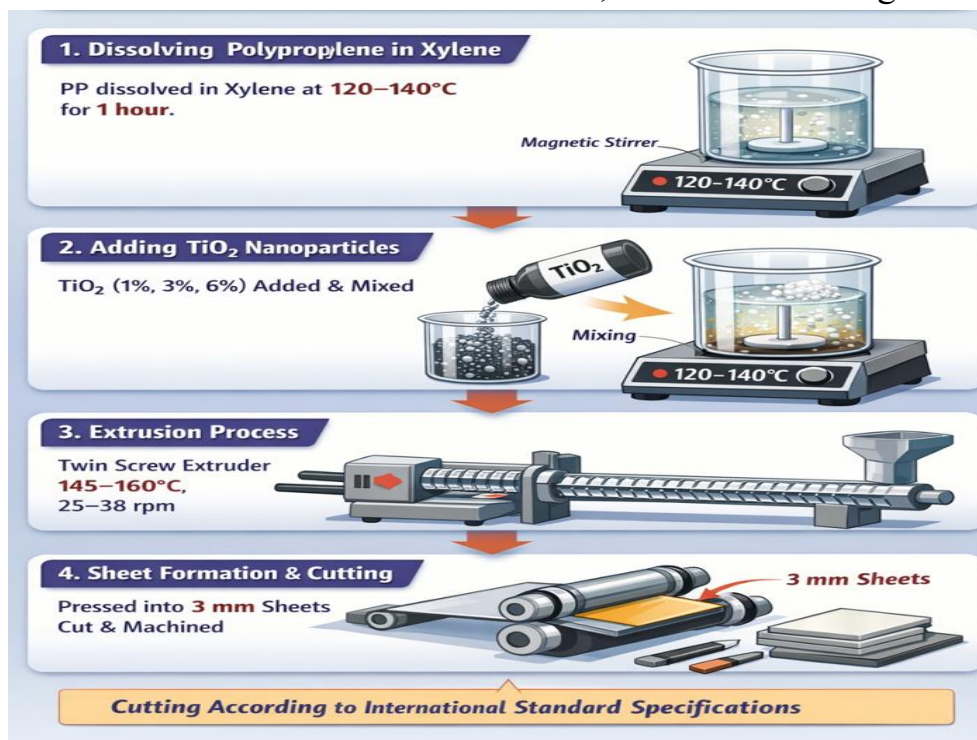


Figure 1. Preparation of PP/TiO₂ nanocomposite samples.

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Results and Dissection

Fourier Transform Infrared Spectroscopy (FTIR)

Figure 2 illustrates the FTIR spectra for pure polypropylene and the nanocomposites enhanced with nano-TiO₂. Characteristic peaks of polypropylene were identified at 2949, 2865, 1652, 1455, 1375, 1167, 1016, 972, 840, and 808 cm⁻¹ within the medium wavenumber range. The peaks located at 1652 cm⁻¹ in the FTIR spectrum of pure polypropylene indicate both thermo-oxidative degradation and the presence of carbonyl groups C=O. A slight shift in the substantial band found between 2865, 1652, 1455, and 1375 cm⁻¹ in the lower wavenumber region occurred due to the addition of nano-TiO₂, which is associated with a reduction in thermo-oxidative degradation. The intensity of these peaks changed according to the mass percentage of TiO₂. A broad band was detected in the low wavenumber region from 650 to 840 cm⁻¹. There is no significant distinction in the characteristic peaks between polypropylene and the nano-TiO₂ within the nanocomposites, which could account for the minimal amount of nano-TiO₂ present. The lack of hydroxyl groups in the spectra of the 3% and 6% PP-TiO₂ nanocomposites indicates the inclusion of nanoparticles within the polypropylene matrix, this agreement with Bendaoued et al., [8].

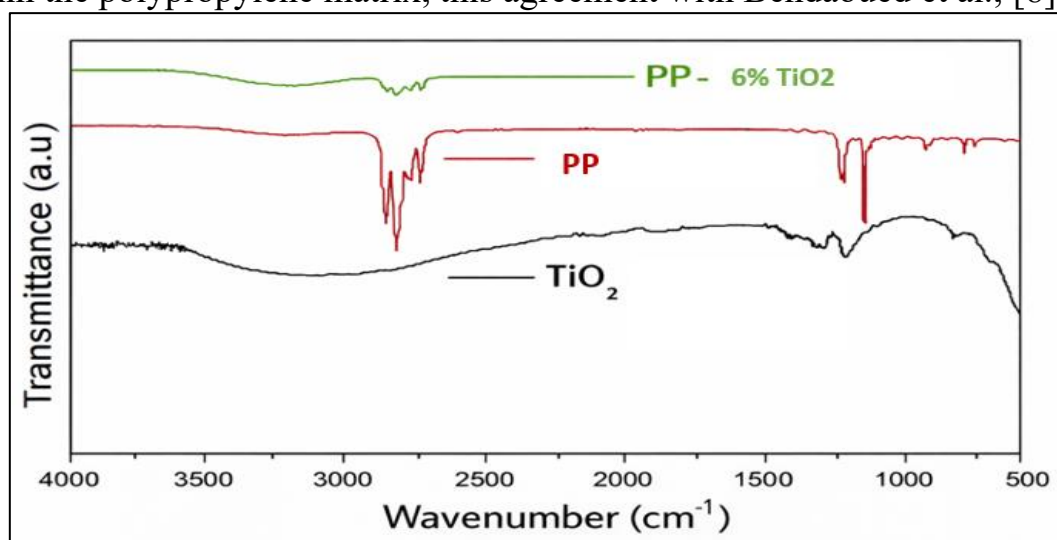


Figure 2. FTIR for neat PP, nano powder for TiO₂ and PP-TiO₂ nanocomposites.

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Density Test

TiO₂ nanoparticles possess a higher density compared to polypropylene (PP), and incorporating these nanoparticles as reinforcement can elevate the density of PP. This is illustrated in figure 3, which depicts the correlation between the experimental density of PP nanocomposites and the proportion of TiO₂ nanoparticles added, ranging from 1% to 6% by weight. It is evident from the data that the density of the nanocomposites increased with the addition of TiO₂ nanoparticles up to 3% by weight, but subsequently decreased at the 6% weight mark. The reason for the initial rise in density with the introduction of a small amount of TiO₂ nanoparticles is that they fill the spaces between the chains of PP, reducing the available volume for movement and limiting the mobility of the PP chains. When TiO₂ nanoparticles occupy these sites, there is no room for additional nanoparticles, leading to a decrease in density at 6% TiO₂ nanoparticles. This finding aligns with Rajendra's results [9].

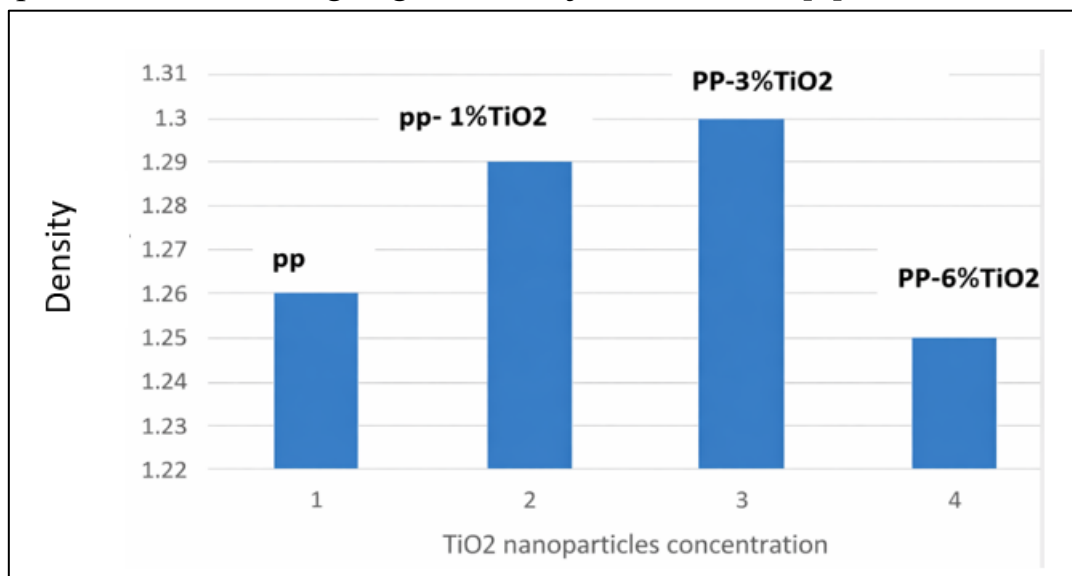


Figure 3. The Density of PP Reinforced with Titanium Dioxide Nanoparticles.

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Elastic Modulus

Figure 4 shows the elastic modulus of PP and its nanocomposites. The elastic modulus rises as the amount of TiO_2 nanoparticles increases. The increased modulus of the composites indicates that stress has been transferred from the PP matrix to the high modulus implanted TiO_2 . As a result, strong interfacial connection between the PP and TiO_2 is preferred to stiffen the composite. The elastic modulus reduced as the TiO_2 concentration increased, most likely because TiO_2 nanoparticles raised stress concentration in the composites, leading to a decrease in elastic modulus. Based on the adhesive wear theory, the resistance to wear is closely associated with the elastic modulus. A high elastic modulus diminishes the true contact surface, causing weak adhesion and increased wear.

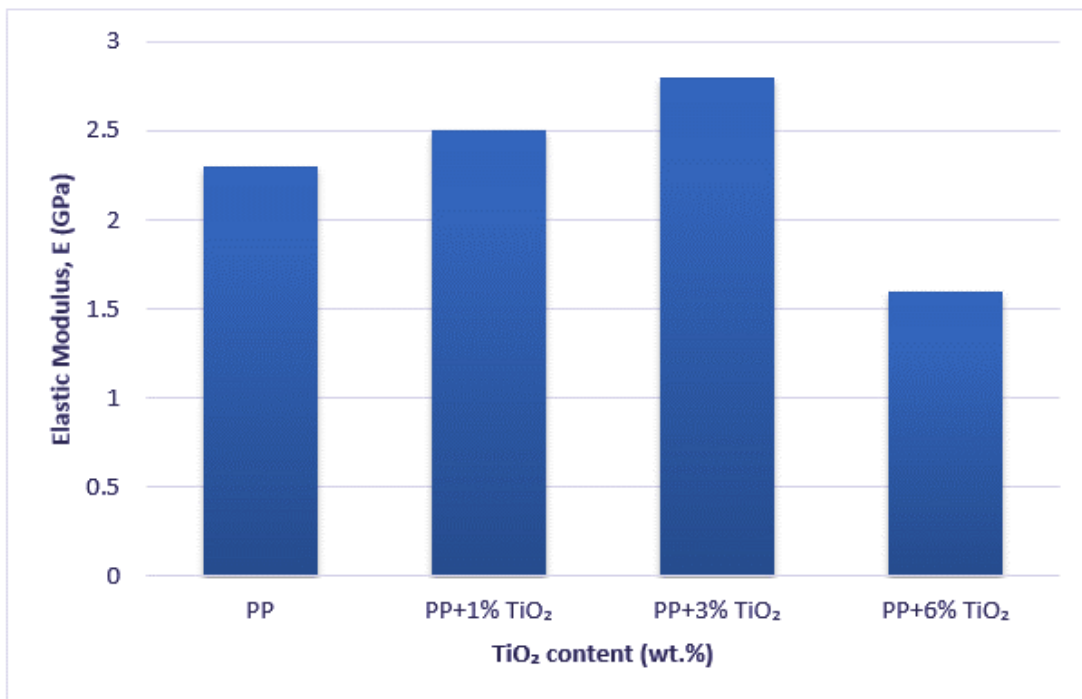


Figure 4. The Elastic Modulus of Polypropylene Enhanced with Titanium Dioxide Nanoparticles.

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Wear test

Figure 5 illustrates the reduction in wear volume of PP nanocomposites at a sliding velocity of 0.4 m/s. It is evident that the unmodified PP exhibits a greater wear volume compared to the other nanocomposites, with a decline occurring as TiO₂ nanoparticles are incorporated. This slight reduction can be attributed to the remarkable strength of TiO₂, which inhibits the rubbing and adhesion of the PP matrix throughout the sliding action, thereby offering substantially improved resistance compared to pure PP.

The nanofillers enhance the durability of polypropylene by serving as a protective layer, stopping the polypropylene matrix from breaking down extensively. The exterior of the polypropylene nanocomposites is rendered smoother and more resilient to wear, while the movement of TiO₂ nanoparticles functions like tiny bearings between the contact surfaces, lowering friction and consequently decreasing the temperature during sliding interaction, the amount of wear volume decrease intensifies with the rise in TiO₂ concentration. Therefore, the maximum decline in wear volume loss aligns with the decrease in friction coefficient observed in PP nanocomposites (6%), which exhibit the least wear volume. The presence of ultrafine TiO₂ nanoparticles contributed to partially smoothing the counter face, leading to a reduction in both the friction coefficient and wear volume. This agreement with Najim results [10].

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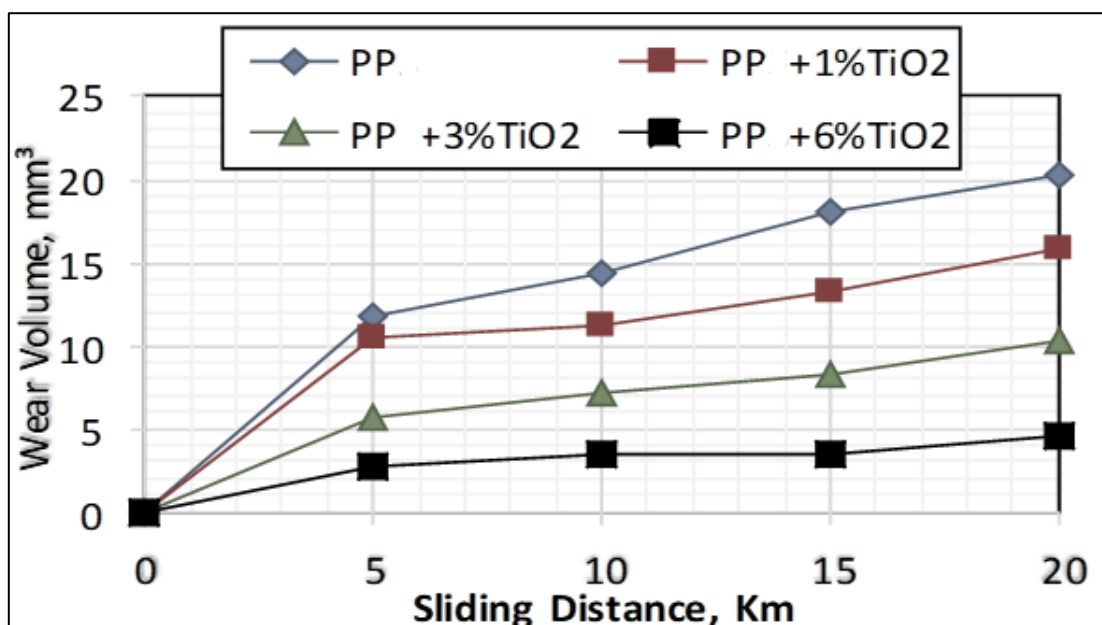


Figure 5. Alteration in Wear Volume Reduction Based on Sliding Distance for Polypropylene Strengthened with Titanium Dioxide Nanoparticles.

Tensile Strength

The characteristics of the composites are determined by the mode of particle dispersion, particle aggregation, and interaction between particles and polymers. The materials, technique, specimen condition and preparation, as well as the amount of reinforcement, all have a substantial impact on the composites' tensile properties. The tensile strength of PP nanocomposites is shown in Figure 6. It appears that the addition of TiO₂ nanoparticles improves PPS's tensile strength, and the improvement increases with TiO₂ nanoparticles addition up to 3% before falling with additional nanoparticles addition. The PP chains' unrestricted mobility contributes to an increase in tensile strength, although it is limited. The opposite trend of reduced tensile strength was attributed to poor contact between TiO₂ and the PP matrix, which prevented effective stress transfer, resulting in

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simple crack propagation and eventual collapse. The drop in tensile strength with high nanoparticles loading agreed with Nassar and Nassar [11].

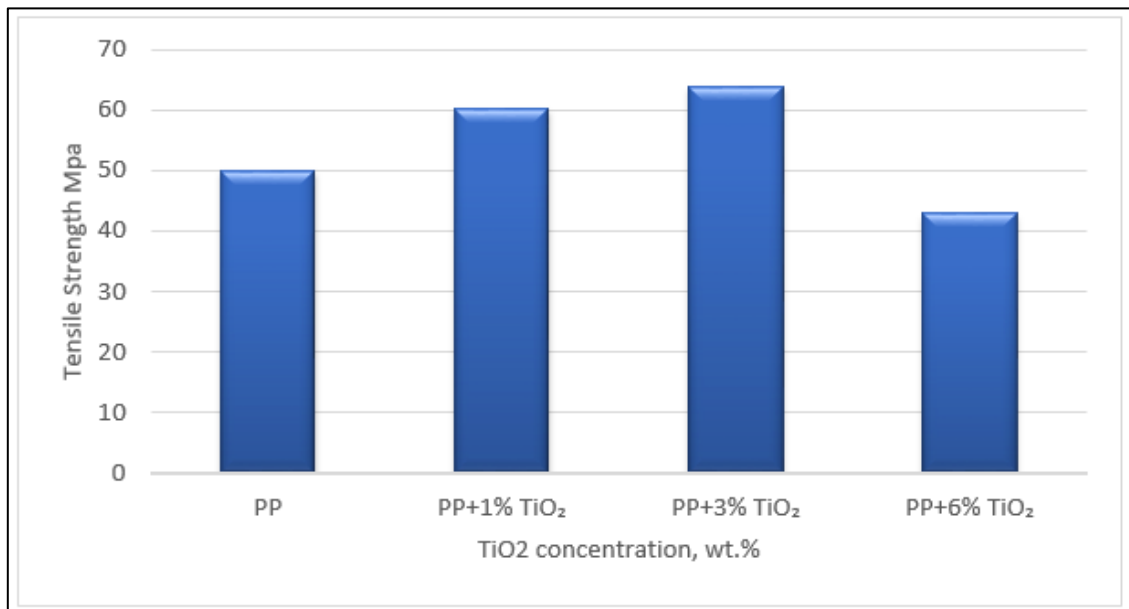


Figure 6. The tensile strength of polypropylene enhanced with titanium dioxide nanoparticles.

Hardness

Material hardness refers to a material's ability to withstand damage to its surface when subjected to an external force. Figure 7 illustrates the Shore D hardness assessment for PP nanocomposite. As more nanoparticles are included, the hardness level of the PP rises. The addition of TiO₂ nanoparticles improves the crystallinity while decreasing the flexibility and resilience of the PP chains, which restricts the movement of the chains and leads to higher hardness. When 6% wt. of TiO₂ nanoparticles is incorporated, the hardness of the composite decreases due to weak interaction between TiO₂ and the PP matrix. These findings align well with the results obtained by Cho [12].

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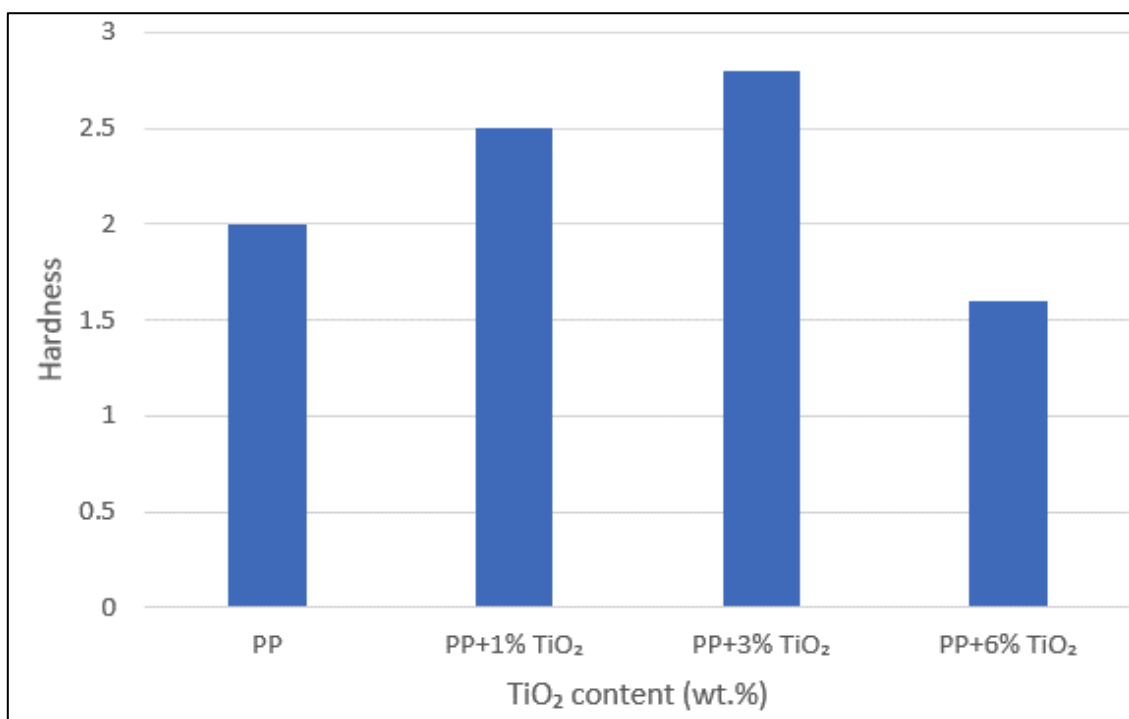


Figure 7. The hardness of Polypropylene Enhanced with Titanium Dioxide Nanoparticles.

Scanning Electron Microscope (SEM)

The assessment of TiO₂ nanoparticle dispersion is a critical step in improving the microstructure of PP. A well-dispersed system typically produces improved composite properties. Figure 8 shows SEM images of the sample (TiO₂ nanoparticles) and the surfaces of (PP and PP with (1, 3, and 6 wt. %) respectively. It can be observed that the TiO₂ nanoparticles are evenly dispersed in the PP matrix. TiO₂ particles are clearly spherical in shape and have a consistent size distribution. Excellent distribution was achieved through the use of an ultrasonic technique and mixing throughout the extrusion process. Good dispersion is seen with minimal filler content, allowing the applied stress to be successfully transmitted from the matrix to the particles. However, TiO₂ nanoparticles clump

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at high TiO_2 concentrations. The uniformity observed in this stage using the SEM method suggests that the PP nanocomposites have a nano-distributed structure due to effective mixing methods.

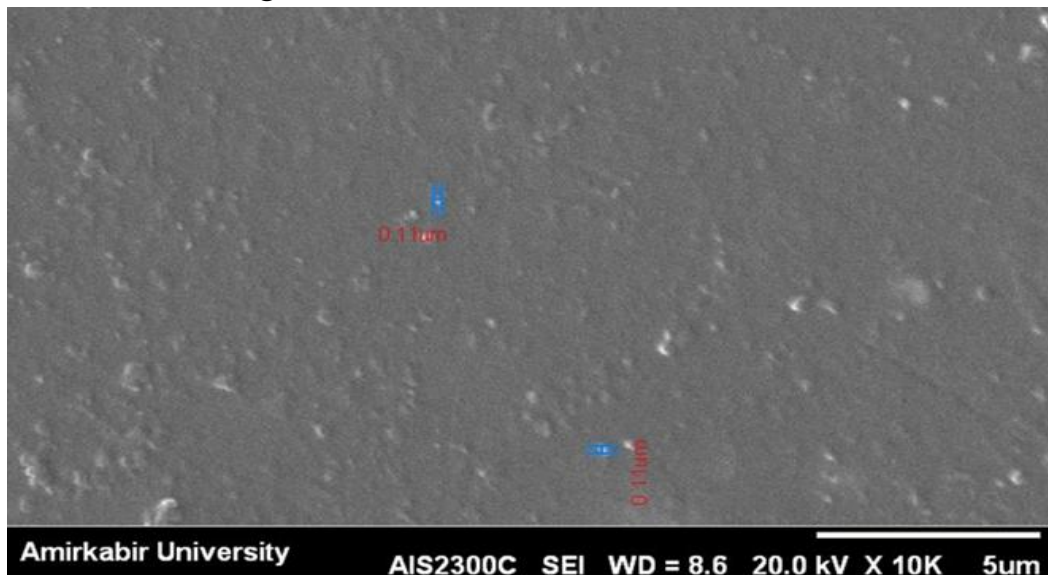


Figure 8. SEM image of composite material PP / TiO_2 at concentration of 3%.

Conclusion

From this study, the following findings were drawn:

1. The investigation focused on the microstructural characteristics of polypropylene and polypropylene combined with 1%, 3%, and 6% titanium dioxide nanoparticles. The findings indicated that the ultrasonic treatment and mixing processes in the screw extruder were essential for achieving a consistent distribution of TiO_2 nanoparticles throughout the polypropylene matrix while reducing clumping.
2. The mechanical properties observed are as follows: Incorporating 1–3% titanium dioxide nanoparticles resulted in higher hardness, improved tensile strength, and increased elastic modulus, whereas the inclusion of 6% titanium

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dioxide nanoparticles led to a decline in these attributes. The improvement in mechanical properties can enhance resistance to wear.

3. The incorporation of 1-3% titanium dioxide nanoparticles led to an increase in density, while introducing 6% caused a reduction in density.

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