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Enhancing the Mechanical Performance of High-Density Polyethylene (HDPE) withTiO_2 Nanoparticles for Biomedical Applications

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Abstract

High-density polyethylene (HDPE) has been widely used in biomedical applications due to its high flexibility, durability, exceptional impact resistance at low temperatures, great chemical resistance, low cost, and superior mechanical strength. The usage of titanium dioxide(TiO_2) nanoparticles to improve the mechanical characteristics of HDPE has been recommended since these nanoparticles have an antibacterial and self-cleaning mechanism. Because of these properties, TiO_2 was selected as an effective inorganic reinforcement in the present study. This research aims to investigate the mechanical characteristics of (HDPE) matrix reinforced with Titanium oxide nanoparticles. A twin-screw machine was used to produce HDPE samples with various TiO_2 concentrations (5, 10, 15, and 20%). Transmission electron microscopy (TEM) was conducted of TiO_2after milling for 23 hr. in a planetary ball mill. Scanning electron microscope (SEM) and X-Ray Diffraction(XRD) were used to examine the distribution and characteristics of composite with various concentrations. Tensile, hardness, and wear tests were used to examine the mechanical characteristics. The results revealed that the optimum mechanical properties was achieved by HDPE with 10% TiO_2. Where the tensile strength reached84.3 MPa and the Young's modulus was 1820 MPa at this concentration. Additionally, the modulus of toughness and the hardness increased to 309 MPa, 82±2 HRP respectively. Also,the wear rate dropped to $4.4*10^{-7}$ m^3/m at 30N, a40% reduction compared to pure HDPE.

Keywords: High-Density polyethylene; Titanium dioxide; Composite nanoparticles; biomaterials; nanomaterial characterization.

1 Introduction

Due to aging, accidents, and a variety of other factors that cause problems for human organs, scientific research, and studies requiring a high level of technical and professional expertise were required to find solutions aimed at addressing the deficiencies in these members by enhancing their mechanical properties or adding some elements that lead to an improvement in their performance quality [1, 2, 3]. High hardness, good toughness, high strength, and high resistance to corrosion and biocompatibility are highly required in hip joint replacement [4, 5]. Organic-inorganic nanocomposites are in the spotlight due to their advantages and unique properties. [6, 7]. A semi-crystalline polymer such as (HDPE) has comparatively good physical and mechanical properties [8, 9]. It is usually used in different applications and is a candidate for electronic and orthopedic applications [10]. Furthermore, (TiO_2) plays an important role in hip joint replacement surgery due to its excellent advantages and unique properties such as low cost, non–toxicity, chemical stability, high photocatalytic activity, and use in composites by dispersing into thermoplastics such as polyethylene (PE) and optical electronic properties [11, 12]. On the other hand, it has been shown to enhance biocompatibility, resulting in little immune response and the absence of harm to the adjacent organs [13].

Orthopedics relies on biomaterials that exhibit the necessary amount of osteoconductivity, osteoinductivity, and the capacity to achieve effective osseointegration for bone regeneration [3, 14]. Scaffolds must not only facilitate cell adhesion and proliferation but also exhibit sufficient mechanical strength to retain their structure [15]. Nevertheless, a single material cannot sometimes provide a comprehensive set of needed characteristics. Hence, the collaborative amalgamation of inorganic and organic substances has led to their extensive utilization in the field of biomedical applications [16]. A notable instance of such a composite is the combination of titanium oxide (TiO_2) and (HDPE) [17, 18].

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Artificial hard tissue replacements need prostheses that possess durability and compatibility, along with certain mechanical attributes including tensile strength, stiffness, and ductility [19]. Tensile testing, a kind of destructive test, offers a range of qualities and has been continuously used to evaluate various materials as potential options for bone [11, 20]. The stress-strain behavior is determined using a tensile test. Where the linear section of the curve provides a measure of the material's stiffness, referred to as Young's modulus. Another crucial attribute is the yield strength; by examining the stress-strain curve, one may evaluate the material's capacity to withstand fracture [21].

Nanofillers have often been added to polymers to enhance their mechanical characteristics for specific applications in composite materials. The overall performance of HDPE/ TiO_2nanocomposite is affected by the size, shape, and morphology of the added nanoparticles. Tripathi et al. [22] found that increasing the nanomaterials content in HDPE-Hydroxyapatite (HA) - $Al2O_3$ composite resulted in an increase in the elastic modulus but a reduction in the overall tensile strength. In addition, Mancic et al. [23] discovered that the use of titanate nanotubes as reinforcement enhanced the mechanical and thermal characteristics of polyamide 11. Specifically, the total yield strength of polyamide 11 was increased but a decrease in the strain at break and Young's modulus. Among several types of fillers, TiO_2nanoparticles are considered to be very effective in reinforcing the HDPE matrix. The effect of adding TiO_2nanoparticles with different sizes of (40 to 100 nm) to the HDPE matrix was investigated by Tuan et al. [24].The results showed more bioactivity, uniform composite structure, and thermal stability. Investigations also revealed improvements in mechanical properties such as tensile strength and elastic module of nanocomposites with TiO_2(GRT) compared with HDPE/ORT and pure HDPE samples. Enhanced wear resistance, dielectric, hydrophilicity, antibacterial and mechanical properties of HDPE were achieved by adding TiO_2nanoparticles in a study conducted by Shaji et al. [25], and another study by Ghanbarour et al. [26].

Processing parameters are the most important factor that affects composite characteristics, and the correlation between them is very complex. To achieve the required material properties and performance, careful experimentation and characterization must be done. The highest bending strength and elastic modulus of about 7.5 GPa with 8 g/10min of melt flow rate (MFR) were achieved by Takadama et al. [27] when studying the impact of (MFR) on the mechanical properties of HDPE/ TiO_2composite. The effect of processing parameters, like residence time and barrel temperature, was investigated by Mourad et al. [28]. The results showed that by increasing the barrel temperature, both tensile strength and elastic modulus increased, while the thermal stability decreased.

The mechanical and tribological properties of HDPE- TiO_2nanocomposites have been the subject of numerous studies, but it is still unclear what concentration of TiO_2nanoparticles will produce the best results wirhout leading to agglomeration of the nanoparticles. In order to address this deficiency, work was done on the interaction and dispersion quality between TiO_2nanoparticles and HDPE matrix at concentrations ranging from 5 to 10% of TiO_2. This allowed for the determination of the ratio that would result in balance between mechanical properties and tribological performance. Furthermore, this study provides new insights on the behavior of crystallization during mixing. Additionally, it offers additional information on wear behavior under varying loads, wich aids in comprehending how TiO_2nanoparticle concentration affects tribological behavior and durability.

Nanoparticle composites are widely used in biomedical applications, but many challenges still exist in the use of such materials. The most important difficult relate to mechanical strength, bioactivity, and thermal stability. Many previous studies have been conducted, but they have not fully investigated the combined effects of TiO_2 size and surface properties on HDPE performance. Therefore, the aim of this study is to fill these gaps bymodifying TiO_2 filler amount at volumetric increments of 0, 5, 10, 15, and 20 %. Particle size is given in nm by the TEM. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) studies were conducted at each step, including composite manufacturing and experiments, to establish a relationship between the structure and qualities of HDPE materials. Then mechanical properties such as tensile strength, hardness, and elastic modulus were studied. Tribological characteristics including wear resistance, wear rate, and coefficient of friction (COF) were investigated.This work's benefit is the comparative investigation of TiO2 nanoparticles' sizes, which offers fresh perspectives on how to optimize nanocomposite structures for improved biomedical applications.

2 Experimental Work

2.1 Materials:

High-density polyethylene SHD7255LS-L with an average particle size of (3~4 mm) was provided by The Middle East Company, the petrochemical sector. Table 1 reveals the physical and mechanical properties of HDPE from the SHD7255LS-L datasheet. This grade has a minimum biological content of (94%), established by ASTM D6866.

The structure of HDPE is shown in Figure (1-a). (TiO_2) anatase has been selected for production by Millipore Sigma-Aldrich as an enhancer of HDPE/ TiO_2composite nanoparticles. TiO_2particles properties from the datasheet of Specification: PRD.1.ZQ5.10000003572, and as specified in Regulation (EC) No. 1907/2006 as follows: powder size (44 μm), molecular weight (79.87g/mol), melting point (1825 ^oC), and the density (3.9 g/ml at 25 ^oC). The chemical structure of $TiO_2$is shown in Figure (1-b).

Table 1: Physical and mechanical properties of HDPE.

	ASTM standard	Units	Values
Melt flow rate (190/2.16)	D 1238	g/10 min	4.5
Density	D 792	g/cm^3	0.954
Yield strength	D 638	MPa	23.0-29.5
Tensile strength break at 23°C	--------	MPa	30.5-33
Flexural modulus – 1% Secant	D 790	MPa	1270
Hardness (Shore D)	D 2240	----------	63

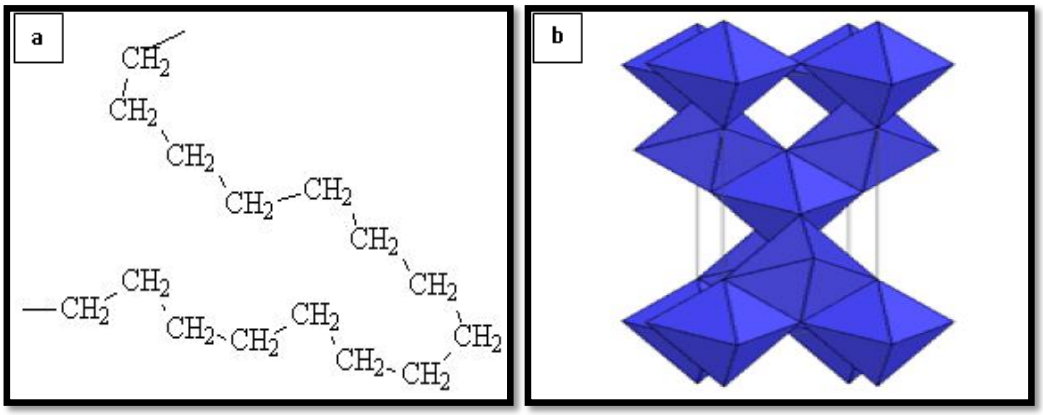

Fig 1. Chemical structure of (a) HDPE and (b) TiO_2 in the anatase phase [29].

2.2 Sample preparation:

At first, the TiO_2particles underwent milling in the PQ-N2 Planetary Ball Mill, with the planetary jar rotating at a speed of 580 rpm, the power supply operating at 110 V and a frequency of 50-60 Hz, the equipment operated continuously for 23 hours. This procedure was used by Liu et al. [30]. TiO_2particles obtained were then imaged with a TEM microscopy (JEM-2100 JEOL Japan). TEM images showed that the particle size of the TiO_2powder was reduced from (44 μm) to a range of (150-400 nm), as shown in Figure 2 (a, b).

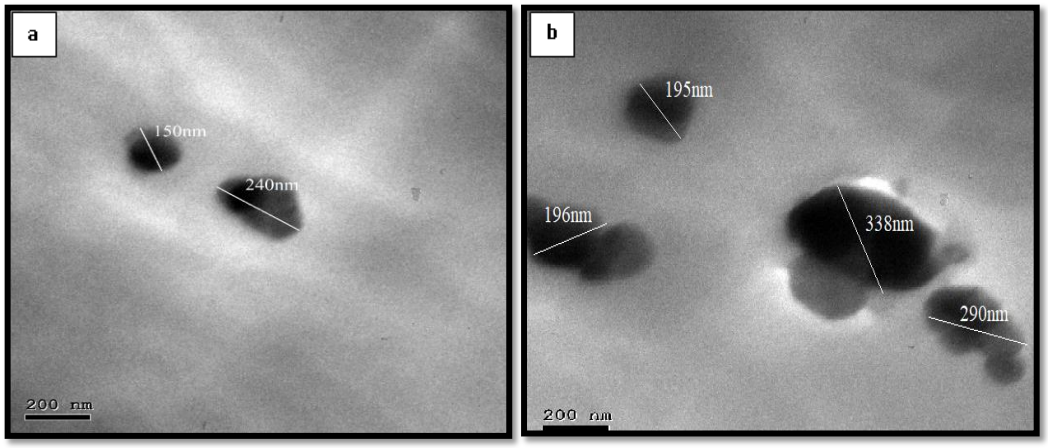

Fig 2. (a, b) TEM images of TiO_2nanoparticles after 23 hours ofmilling in planetary ball mill.

The polymer composite nanoparticles were produced by combining various weight percentages of TiO_2as a reinforced material with an HDPE matrix. The weight ratios used were (5%, 10%, 15%, and 20%), resulting in a final weight of 150 g for each sample. Initially, the pure HDPE and TiO_2powders were subjected to a dry process in an oven at 110 °C for 2 h before the implementation of melting. Subsequently, the pure HDPE was introduced to the system with a screw speed of 80-90 rpm at a temperature of 200 °C for 10 minutes until reached a softened state. ThenTiO_2particles were incorporated, and the screw speed was raised to 150 rpm, while the temperature was increased to 220 °C for another 10 min. The mixed powders were melted in a twin-screw machine from C.W. Brabender GmbH. Finally, the sample weight of each mix was 150 g and it was divided into samples of 30-40 g per kneading. Following the dispersion process, the distinct samples were ready to be formed into compaction machines.

The samples were compressed then in a mold of (10 cm X 10 cm X 4 mm) using Makey Bowely hydraulic press with a force of 150 tons at 190 ℃ for (3-5 min). Subsequently, the samples were set as follows: Pure HDPE, HDPE with 5% TiO_2, HDPE with 10% TiO_2, HDPE with 15% TiO_2, and HDPE with 20% TiO_2. Finally, the specimens were precisely cut into standardized forms and sizes as per the specified testing requirements. Figure 3 displays the flow chart of the manufacturing process.

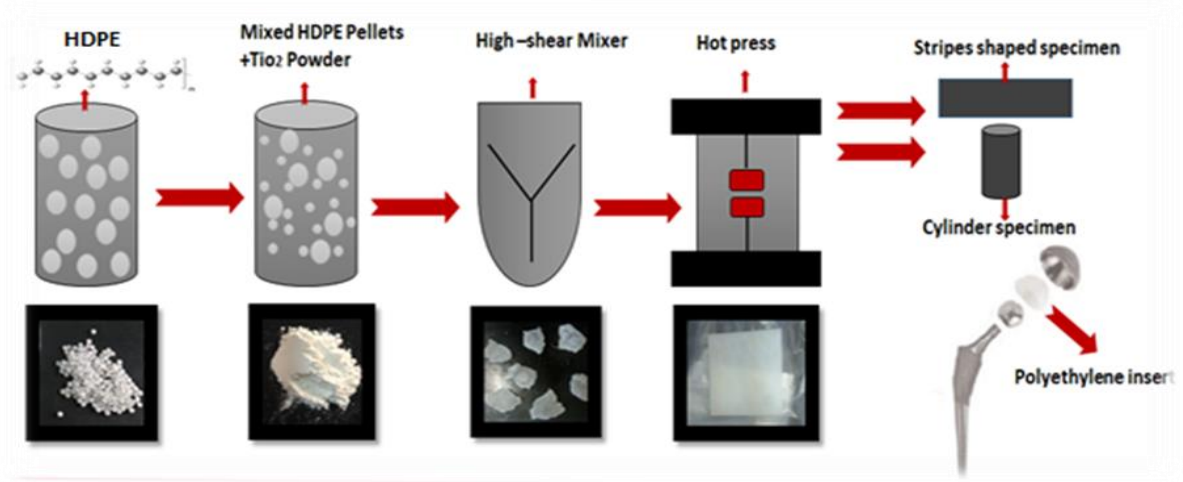

Fig 3. Schematic diagram of the HDPE/TiO_2composite manufacturing process.

2.3 Characterization and mechanical properties:

2.3.1 Scanning Electron Microscope (SEM)

Electron microscopy (SEM) was conducted utilizing the Quanta FEG 250 instrument from the Czech Republic to study the particle morphology of the HDPE/ TiO_2composite nanoparticle. To enhance the resolution of the image, small fragments of the composite nanoparticles were extracted and sputter-coated with a layer of gold, and then the specimen was positioned on the SEM multi-holder which is embedded inside the device chamber. After a while, a high accelerating charge was applied to precisely focus and examine the morphology.

2.3.2 X-ray diffraction (XRD)

X-ray diffraction (XRD) was used to determine the level of crystallinity. The instrument used in this procedure was (Empyrean-Expert XRD Diffractometer). The X-ray diffraction (XRD) patterns were obtained at room temperature within the 2θ range of (10-80°). The X-ray generator was set at (30 mA and 45 kV). The step size (2θ) for collecting data was 0.0260°.

2.3.3 Tensile test

The tensile test machine used was a (SHIMADZU equipment manufactured in Japan). ASTM D3039 was used to calculate the sample size and the cross head speed. Where the sample measurements were displayed in Figure 4 (L = 100.00 mm, W = 25 mm, t = 4 mm) and the cross head speed was between 1 and 10 mm/min. The extensometer was used to measure the elongation and tensile modulus.A tensile test was conducted to ascertain the parameters of elastic modulus, yield stress, and strain-hardening exponents. Also, the modulus of toughness is determined by calculating the integral of the stress-strain curve.

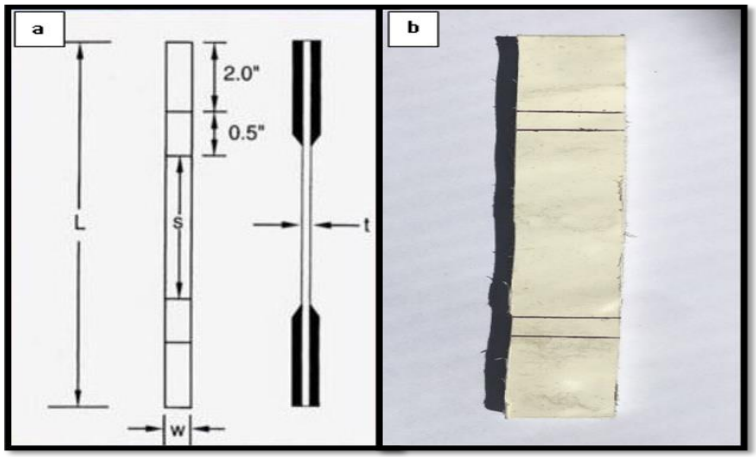

Fig 4. Tensile test specimen:(a) sample size according to ASTM D3039 standard; (b) prepared sample.

2.3.4 Hardness Test

In this study, Rockwell an instrumented indentation device (WPM, made in the German Democratic Republic) was used to perform a hardness test. A steel ball indenter with a 21.5875 mm diameter was used, exerting a maximum load of 62.5 kg on the Rockwell (B) HRB scale for 10 to 15 seconds according to ASTM D785. The zone of the inclined surfaces of the indentation and the hardness of Rockwell were studied by dividing the weight load (kg) by the area of the indentation (mm^2).

2.3.5 Wear test

A pin-on-disk tribometer testing machine was used to examine tribological characteristics, including COF and wear rate. The pin-on-disc material is composed of 3.4% carbon, 2.5% silicon, 0.01% phosphorus, and 0.02% sulfur, and the remainder is martensitic stainless steel with a surface hardness of 63 HRC. The sliding speed applied in the tribology test was (3 m/sec) with various friction forces (10, 30, and 50 N) for (5 min). The test was carried out five times for each type of composite and the results were presented as mean values. The wear volume was determined by measuring the mass loss of the sample before and after the test, expressed as wear volume in (mm^3) and wear rate (g/N.m) $*10^{-4}$ for the materials.

3 Results and discussion

3.1 Characterization of HDPE/TiO_2 Nanocomposites.

3.1.1 SEM characterization:

The SEM micrograph of pure HDPE is displayed in Figure 5, and the HDPE/ TiO_2composites with addition ratios of nanoparticles (5%, 10%, 15%, and 20%) are shown in Figure 6. SEM images were used to explain the differences in particle sizes generated by the varied weight percentages of TiO2 reinforcement (5%, 10%, 15%, and 20%) by measuring the electro-spun particle size. The size and distribution of TiO_2-dispersed particles in the HDPE matrix are shown in Figure 6 (a, b, c, d, e, f, g, and h). It is evident that the HDPE pellets were successfully broken down and the TiO_2particles were incorporated into the matrix through the Brabender machine's mixing process. Consequently, all samples exhibit homogeneous distributions of the reinforced particles, and the polymeric chains of HDPE/ TiO_2overlap mutually. The same homogeneous distributions were obtained by Tuan et al [23] and Shaji et al. [24] when studying the morphology of HDPE/ TiO_2.

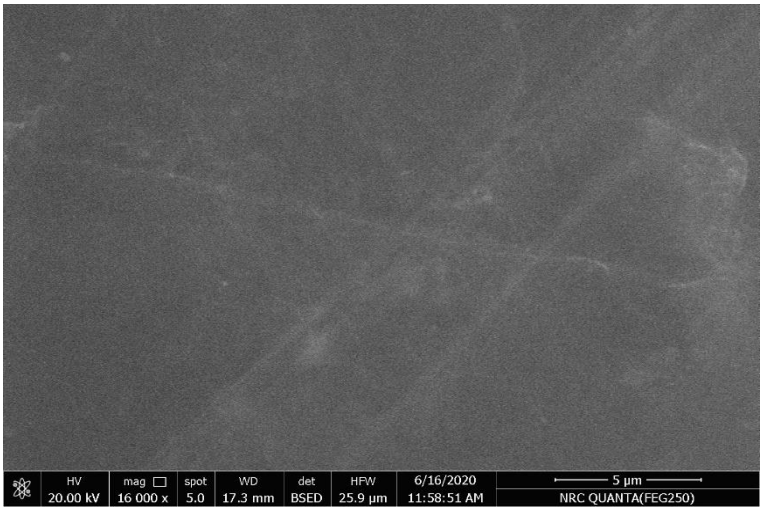

Fig 5. SEM micrograph of pure HDPE

The SEM images demonstrated the overlap of the HDPE/ TiO_2polymeric chains, and as seen in Figure 6 (c and d), the good matrix dispersion was achieved at a weight percentage of 10% TiO_2. The following explanation fits this phenomenon: The TiO_2powder was reduced to a nanosize using the ball mill method, which improved the flaws and filled in the gaps in the matrix. Furthermore, $TiO_2$was well disseminated throughout the matrix by the Brabender process. When the TiO_2particles agglomerate after dispersion the HDPE tends to break down during compression molding (hot press). TiO_2nanoparticles repair polymer material flaws such as vacancies and dislocations by enhancing the magnification of the samples. Furthermore, the molecules in a polymer undergo a reorganization from ordered to disordered molecular states during melting. Where the structure, molecular chemistry, and melting temperature are all impacted by the rearrangement capacity of polymer chain molecules.

Additionally, the SEM images showed that when the percentage of TiO_2content exceeds 10%, agglomeration occurs, as described by the red circles in Figure 6 (e, f, g, and h). This explains that the higher the percentage of TiO_2addition, the higher the percentage of agglomerates [31]. It also suggests that the ideal TiO_2content for treating the HDPE defects without causing nanoparticle agglomeration is 10%.

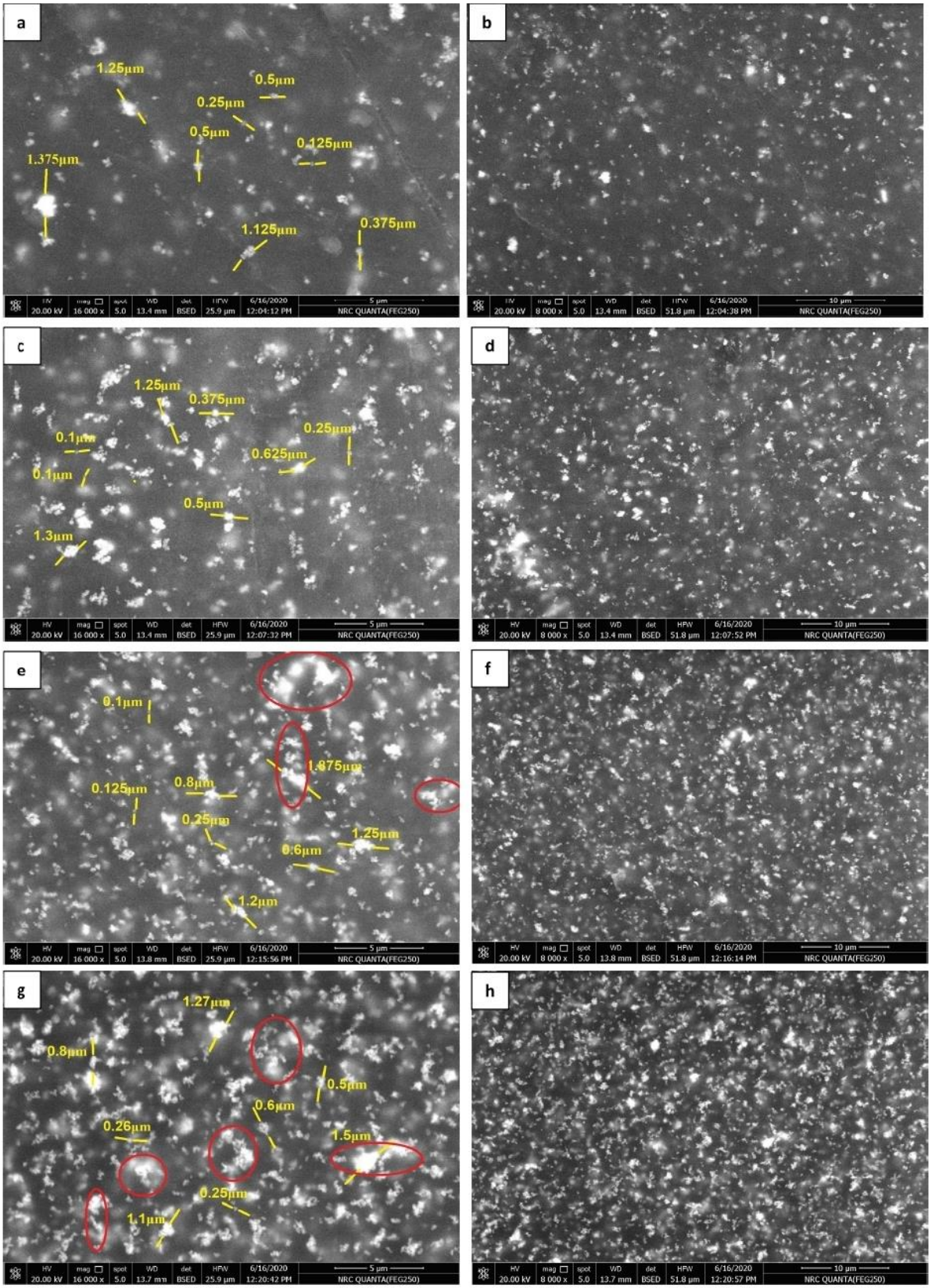

Fig 6. SEM micrographs of HDPE composites containing (a, b) 5%, (c, d) 10%, (e, f) 15%, and (g, h) 20% of TiO_2.

3.1.2 X-ray diffraction (XRD)

The XRD charts in Figure 7 only display peaks for the $TiO_2$and HDPE phases, and the degree of crystallinity was 94% and 6% amorphous as well. This is because HDPE exhibits more crystallinity than other polypropylene/polyethylene blends, such as PP and LDPE, due to its more linear structure. The blends' higher crystallinity is correlated with their higher HDPE content [24]. At diffraction angles 2θ=(110) and (200), with 2θ = 21.382 and 2θ = 23.741, respectively, the XRD pattern for pure HDPE exhibits two unique reflecting peaks in addition to sharp typical peaks of HDPE. TiO_2peaks are found at 25.2°, 36.9°, and 55.03°, with additional peaks found at 79.1°.

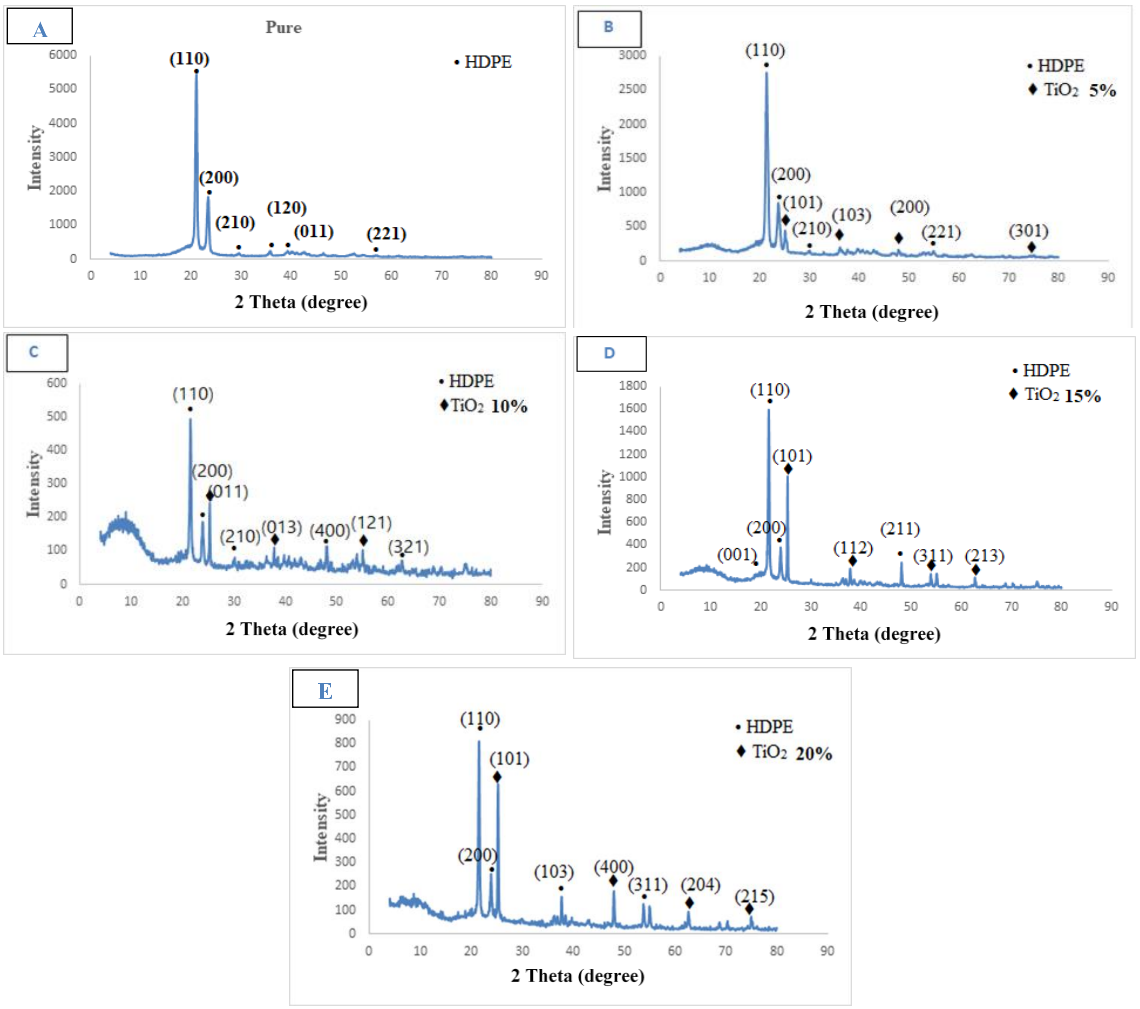

Fig 7. XRD patterns of (A) pure HDPE (B) HDPE with 5% TiO_2 (C) HDPE with 10% of TiO_2 (D) HDPE with 15% of TiO_2 (E) HDPE with 20% of TiO_2.

3.2 Mechanical Properties

3.2.1 Tensile test results:

Figure 8 illustrates the stress-strain curves of pure HDPE and HDPE/TiO_2 composite with varying weight percentages of TiO_2ranging from 5 wt. % to 20 wt. %. The ultimate tensile strength values for all samples are shown in Figure 9. The data indicate that the HDPE/ TiO_2composite nanoparticles exhibit a significant elongation percentage. The ultimate stress increased as the TiO_2content in the composite grew up to 10 wt. % to a value of 84.3 MPa. Then decreased as the TiO_2concentration increased. The polymer matrix transfers some of the applied stress to the particles due to the enhanced chemical bond strength and uniform dispersion of TiO_2. Moreover, enhancing the crystallinity of a polymer often improves its mechanical properties [32]. Many polymers have a pattern where tensile strength rises with higher molecular weight but declines as the TiO_2concentration increases. This might be caused by the fractures that form at the boundary between the clustered particles and the HDPE matrix [33]. Hence, the breakdown happens abruptly, causing a significant shift in the mechanical properties of the composite. On the other hand, the first increase in tensile strength may be attributed to the reinforcing properties of nanofillers and their effective dispersion within the polymer matrix [34]. High loading can cause filler particles to clump together inside the polymer matrix, leading to a decrease in strength beyond a certain filler

concentration in HDPE/ TiO_2nanocomposites [35]. Nanoparticle dispersion in the polymer matrix may be seen by SEM examination. Nevertheless, this value remains greater than the pure HDPE value [23].

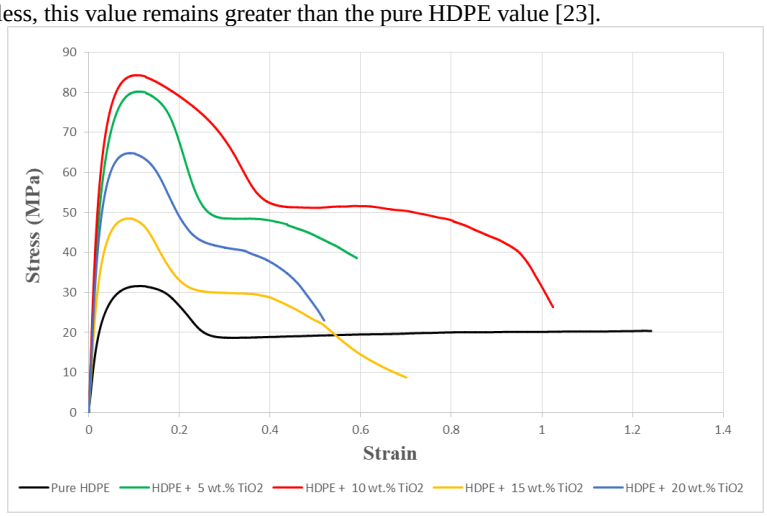

Fig 8. Stress-strain curves for samples.

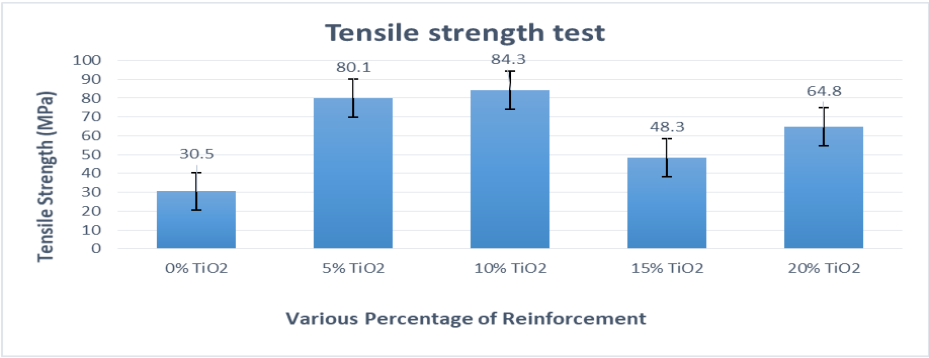

Fig 9. Tensile strength test of HDPE composites with varying TiO_2 nanoparticle content.

Figure 10 shows Young's modulus for all samples, where (E) increases gradually with TiO_2content. The Young's modulus of the pure HDPE was 1094.5 MPa and the highest Young's modulus was obtained at 10%wt, reaching 1820 MPa.

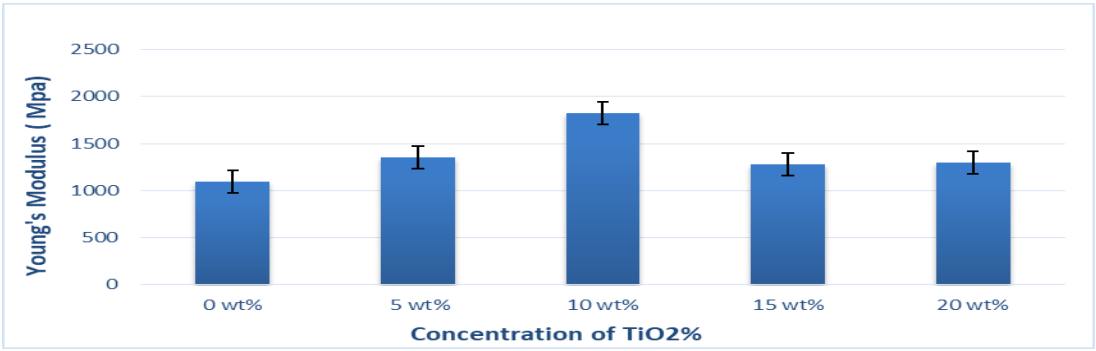

Fig 10. Young's modulus of Pure HDPE and HDPE composites with varying TiO_2 nanoparticle content.

3.2.2 Toughness test results

The modulus of toughness results are displayed in Table 2, derived from the integration of stress-strain curves. The toughness modulus of the pure polymer was around 200±5 MPa, and this value increases when $TiO_2$is included in the polymer. The toughness modulus improves by 10% with the addition of TiO_2, reaching 309±5MPa. Increasing the reinforcing content to 15% and 20% resulted in a drop in the modulus of toughness. The reason for this might be the clustering of TiO_2particles in high amounts inside the HDPE matrix, leading to a reduced concentration of nano-particles required for creating point and line defects [36]. On the other hand, the increase in modulus of toughness might be attributed to the nano-particles segregating into vacancies and dislocations [11, 37].

Table 2: Modulus of toughness for different HDPE/TiO_2 composite samples.

The samples	Modulus of Toughness / MPa
Pure HDPE	200±5
5% TiO2	220 ±5
10% TiO2	309±5
15% TiO2	248±5
20 % TiO2	217±5

3.2.3 Hardness test results

Figure 11 shows the hardness values of pure HDPE and HDPE/ TiO_2nanocomposites. The hardness exhibits a consistent increase with the addition of the TiO_2reinforcement to the HDPE matrix up to a 10% concentration. It is observed that the hardness increased from 67 HRA to 82 HRA. This enhancement is due to good dispersion and diffusion of TiO_2in the HDPE polymer for 10% wt, the same results were obtained by Shaji, et al. [24].

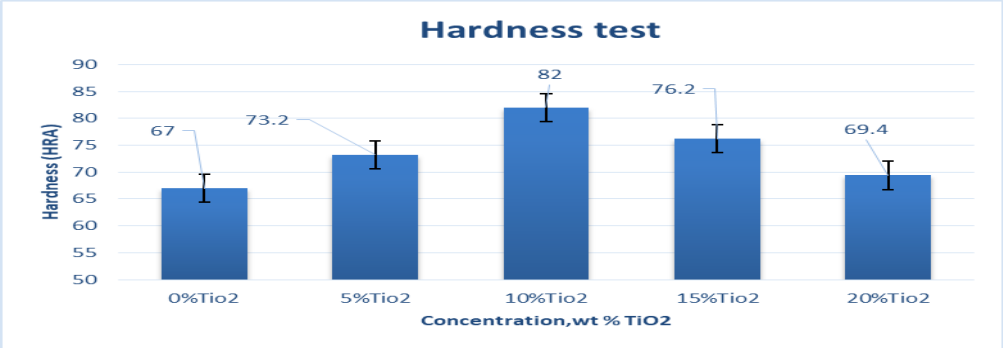

Fig 11. Hardness test results of different HDPE/TiO2 composite samples.

3.2.4 Wear test results

The wear rates of pure HDPE and HDPE with different content of TiO_2nanoparticles under varied loads are shown in Figure 12. The results showed that at all loads, the HDPE/ $TiO_2$with 10% HDPE/ TiO_2addition had a superior wear resistance compared with pure HDPE and other HDPE/ TiO_2composites. The wear rate gradually increases as the TiO_2percentage in the matrix increases above 10%. This may be due to the supersaturation of the material by increasing TiO_2additions above (10%), this is consistent with the explanation provided by Shaji, et al. [24]. However, the wear rate was improved by adding TiO_2nanoparticles more undoubtedly compared with pure. The reason for this is that friction during wear causes a rise in contact temperature owing to heat production from the rubbing motion between the components [38]. The high temperature facilitates wearing soft materials such as HDPE. Incorporating filler particles will enhance both thermal stability and wear resistance [24, 39].

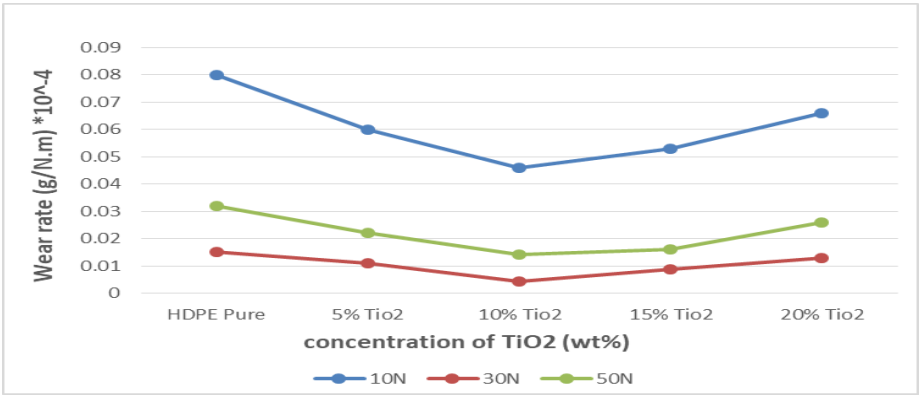

Fig 12. The wear rate of different HDPE/TiO2 composite samples.

3.2.5 Evaluation of the Coefficient of friction

Figure 13 shows the COF for pure HDPE and HDPE with different TiO_2nanoparticles content at different loads. The COF results clearly show that adding $TiO_2$to HDPE reduces the COF. The coefficient of friction decreased in composites containing small concentrations of TiO_2nanoparticles (5% and 10%). As the nanoparticle concentration increased, the wear resistance of the steel counter body also increased, leading to the disruption of the steel counter body due to the higher number of hard particles. Furthermore, the increase in the nanoparticles as seen in the 15% and 20% content initially increased the steel counter body bond strength but later decreased it. The latter made peeling of the pin on the disc from the counterface

easier hence the increased wear [40]. Also, it became clear that the COF value had dropped blatantly. Because of the agglomeration that appeared in the SEM image, resulted in the appearance of defects in the composite by 15% and 20%, which affected the mechanical results [24, 30]. On the other hand, HDPE-TiO_2composites have hard TiO_2ceramic particles that are pushed out during wear and function as wear debris together with polymer wear debris [41, 42]. Lower COF with greater nanoparticle concentration HDPE-TiO_2composites lost weight in a variety of ways, and a 10% composite had a modest weight loss due to its high hardness, high strength, and high toughness, which are shown from the mechanical tests.

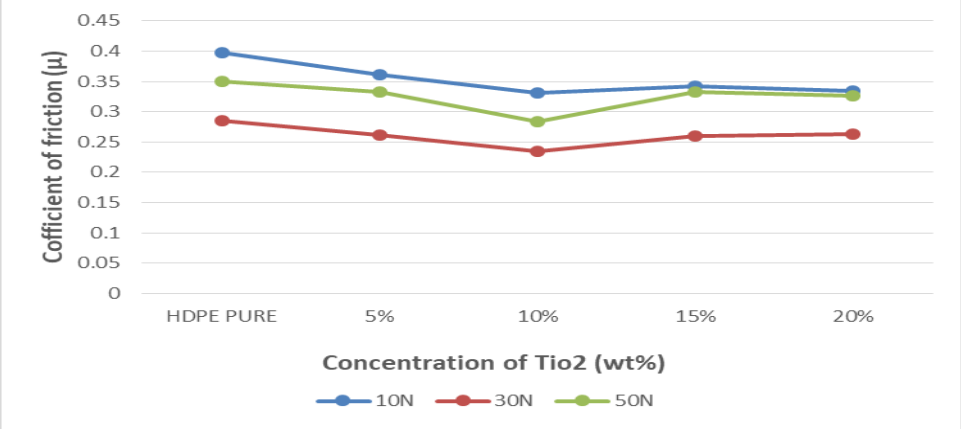

Fig 13. COF results of different HDPE/TiO2 composite samples at different loads

Conclusion

1. Composite nanoparticles with various concentrations of TiO_2were successfully prepared using Brabender's technique without any defects during melting. At low TiO_2concentrations of 5% and 10%, homogeneous distribution of TiO_2nanoparticles occurred, whereas agglomeration occurred at higher TiO_2concentrations of 15% and 20%.
2. The XRD analysis showed that the degree of crystallinity is 94 % this could happen as a result of the interaction and crystallization behavior of TiO2 with HDPE during the blending process.
3. The tensile strength of the composite increased with the increase of TiO_2content up to 10% wt. and then started to decrease due to the agglomeration of nanoparticles. The tensile strength was increased by 64% at 10% TiO_2compared to pure HDPE.
4. The homogeneous distribution of TiO2 in the matrix eliminates the defects of HDPE and enhances the mechanical properties of HDPE. Hardness was increased by adding 10% TiO_2up to 82 HRA compared with pure HDPE of 76 HRA.
5. Young's modulus of the matrix was increased by 42 % for a sample of 10% TiO_2compared to pure HDPE; however, the modulus of toughness for the same composite has been improved by 55% compared to the pure HDPE.
6. The wear rate of 10% TiO_2composite is $4.4*10^{-7}$ m^3/m which is lower than that of pure HDPE but further increase in the TiO_2content shows higher wear rates due to the agglomeration of TiO_2.
7. The wear rate was decreased from 94% at 10 N to 70% at 30 N for 10% TiO_2composite, and the coefficient of friction was decreased by 18% at 10 N, by 28% at 30 N, and by 25% at 50 N. The increase in TiO_2percentage in the matrix increased the wear rate gradually, that is according to the supersaturation of the material at 10% TiO2 composite.

Author Declarations:

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Consent to Participate

Informed consent was obtained from all individual participants included in the study.

Consent for Publication

Informed consent for publication was obtained from all individual participants included in the study.

Availability of Data and Materials

Any Data and Materials related to this study are available upon request.

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Authors' contributions

A.E.M. Mahmoud: research conceptualization, methodology, preparation, analysis, discussion, and writing.
E.E.D. El-kashif: analysis, interpretation, experiment, and editing.
S.A. Abd El Rahman: conceptualization, methodology, writing, and editing.
All authors have read and approved the publication of this version of the manuscript.
M. Saood: idea generation, methodology, visualization, review, and editing.

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