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RESEARCH ARTICLE

Optimization of titanium oxide nanoparticle enrichment on the tribological properties of sandbox bio-lubricant

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Abstract

Improvement of Lubricant properties is encouraged in production industries for enhanced performance. This study investigated the effect of titanium oxide nanoparticle additive on the tribological properties of sandbox bio-lubricant. Titanium oxide nanoparticle-enriched sandbox bio-lubricant was developed by adding varying concentrations of the nanoparticle to sandbox lubricant. Central composite design was employed for the experimental design and optimization. The lubricant was enriched with nanoparticle concentration of 0 wt%, 0.75 wt%, and 1.50 wt %. The parameters values used for the evaluation were: load (2 N, 5 N, and 8 N) and speed (150 rpm, 200 rpm, and 250 rpm). Effects of these values on wear rate, friction coefficient and flash temperature parameter were evaluated. The lowest values of coefficient of friction and wear rate were obtained at a speed of 200 rpm and concentration of 0.75 wt% with 2 N load, which lead to a 78.3% and 15.3% reduction in coefficient of friction and wear rate respectively over that of pure sandbox bio-lubricant. The optimal parameters combinations for minimum coefficient of friction and wear rate as well as maximum flash temperature were: 8.0N load, 199.49rpm speed and a 0.71wt% concentration which leads to a coefficient of friction of 0.045 which is lower than that of pure sandbox bio-lubricant at all levels. The wear rate at the optimum setting is 0.0171 which is lower than that of pure sandbox at the same 8.0N load. The observed flash point at the optimal settings is 0.0381 which is higher than that of pure sandbox bio-lubricant at all levels of load and rpm. The titanium oxide nanoparticle added to sandbox lubricant improved the tribological properties of the lubricant by increasing the anti-friction and anti-wear ability of the lubricant. This shows the potential of titanium oxide nanoparticle as additive for bio-lubricant production.

1. Introduction

Lubricants play crucial roles in extending the life of equipment by lubricating, suspending, cooling, cleaning, and protecting metal surfaces [1]. These substances are employed in tribological contacts to separate the contacting surfaces' peak asperities. According to Jackson [2], lubricants defend against corrosion, dissipate heat, exclude impurities, and flush away wear products. According to Khasbage *et al.* [3], a lubricant should be able to transport protection chemicals to the contacts where they are needed while also moving wear particles away from the source. Lubricants should be effective in all driving circumstances, including short trips and cold starts.

According to Gulzar [4] and Shahnazar *et al.* [5], lubricants fall into three categories: mineral lubricants, natural lubricants, and synthetic lubricants. According to Chandan *et al.* [6], the majority of mineral lubricants are petroleum-based and they are widely used. Because of their superior biodegradability and renewable feedstock, natural lubricants—those made from plant- and animal-based fats and oils—are considered to be more environmentally friendly than synthetic lubricants, which are made through chemical synthesis from a variety of materials, including olefins, aromatics, alcohols, acids, and halogenated compounds.

According to Naik and Galhe [7], numerous research has demonstrated that vegetable oils, such as oleic and palmitic, are the optimum feedstock for lubricants since they include monounsaturated fatty acids. Because of the action of the highly polar fatty acids which forms protective hydrocarbon coatings on the metal surfaces, vegetable oils work well as a boundary lubricant. According to Hassan *et al.* [8], the ester groups in sandbox oil give it a strong affinity for metal surfaces, forming protective layers on surfaces that come into touch with it.

Nanoparticles, which have the potential to reduce wear and friction, are emerging additives in the lubricant. It has been reported that nanoparticles lubricating effect depend on their concentration, shape and size [9, 10]. The use of nanoparticles as additives to oil is motivated by a number of factors. The key advantage of using nanoparticles is their tiny sizes that allows them to enter the cavities of contact area, which leads to effective lubrication effect [11]. This small size enables them to pass through the filters of the lubrication system without affecting their concentration during use.

Four possible ways the nanoparticles added to base oil act are; protective film, rolling effect, mending effect, and polishing effect [10, 12]. By forming a thin surface protective film with the friction paired surfaces, the nanoparticle in the protective film lowers wear and friction. Spherical nanoparticles roll between contact surfaces in the rolling effect, altering the sliding friction to provide a mixture of rolling and sliding friction. Nanoparticles are applied to the

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surface to produce a physical tribofilm that makes up for the mass loss in order to produce the mending effect [10]. The nanoparticle abrasiveness reduces the rubbing surface roughness in the polishing effect.

The performance of titanium oxide nanoparticles as lubricant additives is good because of their low toxicity, non-volatility, anti-oxidant properties, and other pleasant properties [13]. A nanoparticle additive made of titanium oxide (TiO_2) was reported by Le and Lin [14] to have the potential to increase the applicable load, decrease the friction force, and increase the anti-wear properties of the lubricant. Lubricant with titanium dioxide nanoparticle additive was examined by Battez and Rodriguez [15], and it was discovered that the properties of titanium dioxide make it well suited for use in tribological applications. According to Afzal *et al* [16], for titanium oxide nanoparticles dispersed in lubricating oil obtained through sonication process, nanoparticle agglomeration can be avoided by application of surfactant.

Comparing plain oils without nanoparticle additive to those with TiO_2 nanoparticle lubricant additive, Binu *et al.* [17] showed an improvement in the journal bearing's capacity to carry load. The tribological properties of titanium oxide nanoparticle additive in petroleum-based engine oil were examined by Laad and Jatti [13]. They discovered that adding TiO_2 nanoparticles to engine oil significantly lowers wear rate and friction, which enhances the lubricating properties of the lubricant. The stability and superior solubility of the titanium oxide nanoparticles in the lubricant are further confirmed by the dispersion investigation.

Traditional lubricant additives, due to their sizes have a challenge of protective film formation on contact surfaces, low durability and poor solubility in non-polar lubricants compared to nanoparticles. This research is aimed at replacing traditional lubricant additives with nanoparticles as a step towards sustainable development of bio-lubricants using sandbox oil – which is aboundant in Nigeria. Lubrication potential of titanium oxide nanoparticle and the effect of the nanoparticle on tribological performance of the bio-lubricant were also investigated.

2. Materials and methods

The materials and methods employed in this study are highlighted in this section.

2.1. Materials and equipment

Sandbox (Hura crepitans) oil, methanol, potassium hydroxide, trimethylolpropane (TMP), oleic acid (OA), titanium oxide (TiO_2) nanoparticle, conventional lubricant SAE 40, were among the materials and reagents utilized in this study. Anton Paar ball-on-disc tribometer (Model TRN) was used for the wear test.

Sandbox oil was used because it is aboundand in Nigeria and it has been reported to work well in biodiesel – reducing pollution emmition while maintaining efficiency [18]. Oleic acid was selected to be used as a surfactant because of its ability to enhance the dispersion stability of the nanoparticle [19]. Potassium hydroxide was selected because of its ability to act as catalyst in methyl esther synthesis using methanol [20]. Conventional lubricant SAE 40 is a common lubricant for enginins bearing load within the range of this study and beyond. Thus, it was selected for comparism. Anton Paar ball-on-disc tribometer (Model TRN) was selected to carryout wear test because it is the wear test equipment available where this research was carried out and the range of parameters tested fall within its capacity. Titanium oxide is used for solid lubricant production and it has been found to improve the tribological properties of conventional engine oil [21]. Thus, it was selected for this study. Trimethylolpropane (TMP) has been found to have good performance in biolubricanting oils [22]. It was thus selected for this study.

2.2. Methods

The following sequence was followed in carrying out this research; firstly, the materials were collected and prepared, second stage was the production of nanoparticle-enriched sandbox bio-lubricant and finally the tribological evaluation of the bio-lubricants was performed.

2.2.1. Materials collection and preparation

Sandbox (Hura crepitans) seeds were gathered in Wukari town, Taraba State, and appropriately identified at Federal University Wukari's Department of Biological Science. After being washed, the seeds were manually dehulled and then ground in a mill. Using n-hexane as the extraction solvent, the oil was extracted using a soxhlet extractor. Other chemicals and commercially available titanium oxide nanoparticles were obtained from Bristol Scientific Company Ltd. in Lagos. Sigma-Aldrich, USA, produced the titanium oxide nanoparticles that were used, with a particle size of less than 100 nm.

2.2.2 Formulation of titanium oxide nanoparticle-enriched bio-lubricant

Using sandbox oil as the base oil, a titanium oxide nanoparticle-enriched bio-lubricant was prepared following the guidelines of the ISO 5509 [23] technique as reported by Bilal *et al*. [24]. A double transesterification process—methyl ester synthesis and bio-lubricant synthesis—was used in the formulation. In the initial transesterification, the oil sample was mixed with methanol using potassium hydroxide as a catalyst to produce methyl ester of the oil, an intermediate product. Potassium hydroxide was added at a weight percentage of 0.5% of the oil weight, and the weight ratio of the oil to methanol was 3:1. The required bio-lubricant was produced during the second transesterification by mixing trimethylolpropane (TMP) with the sandbox methyl ester. Attempt was made to enhance the tribological characteristics of the bio-lubricant by adding titanium oxide (TiO_2) nanoparticles at weight percentages of 0.75 wt% and 1.50 wt%. Oleic acid was added as a surfactant to enhance the dispersion stability of the nanoparticle and avoid agglomeration during the dispersion process. Figure 1 shows the formulation process.

The bio-lubricants, designated SB100 (sandbox oil), SBTiO75 (sandbox oil + 0.75 wt% TiO_2), and SBTiO150 (sandbox oil + 1.50 wt% TiO_2), were formulated utilizing varying concentrations of TiO_2 nanoparticles. The tribological analysis of the bio-lubricant was conducted using Minitab 16.00 software and a three-level, three-factor (3^3) factorial design was used. The codes for the levels were -1, 0 and +1. The three factors, referred to as independent variables used are concentration of titanium oxide (TiO_2) nanoparticles with different weight concentrations, speed, and load. The factors and their levels are shown in Table 1. The values selected for the factors were based on a number of studies on nanoparticles-enriched bio-lubricants by Gulzar [4], Abere

[25], Le and Lin [14], Hassan *et al.* [8], Thottackkad *et al.* [26] and Umaru *et al.* [27].

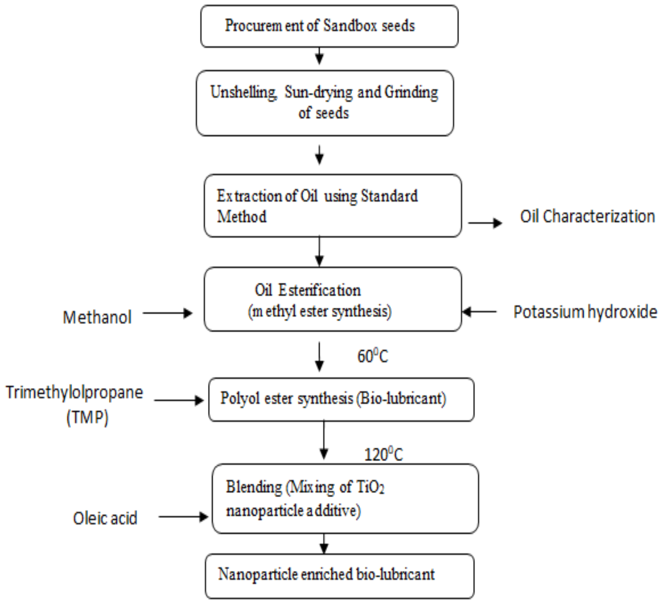


Figure 1. Methodology for formulation of nanoparticle-enriched bio-lubricant

2.3. Tribological evaluation of the bio-lubricant

Evaluation of the tribological behaviours of the produced lubricant was carried out. Comparison was made between the performance of three categories of lubricants - those with titanium oxide nanoparticles, those without titanium oxide nanoparticles and SAE 40 conventional lubricants. ASTM G99-05 (2010) test method was employed to assess the tribological behaviour of the bio-lubricants. Figure 2 shows the schematic diagram of the ball-on-disc tribometer used. Stainless steel balls of 6 mm diameter were placed in the upper stationary ball holder on a tribometer. A 70 mm diameter and 6.35 mm thick aluminium alloy discs were used. Tests were then conducted on the lubricating oils using the design parameters. 50m was set as the sliding distance and all the tests were done for 5 – 12 minutes duration range. To ensure the required contact conditions, the ball specimen was carefully put into the holder and set perpendicularly to the disc surface. Applying lubricant between the disc and the ball satisfied the requirements for boundary lubrication. The system lever was given the proper load to apply the chosen force that pressed the ball up against the disc.

Table 1. Factors and levels for experiment

Factors	Symbol	Level		
		(-1)	(0)	(+1)
Load (N)	A	2.0	5.0	8.0
Speed (rpm)	B	150	200	250
Concentration (wt%)	C	0	0.75	1.50

After adjusting the speed and rotation counter to the proper levels, the electric motor was switched on. Once the required number of revolutions was reached, the test was terminated. After removal, the specimen was cleaned. To determine the wear rate and friction coefficient, the process was repeated for each test. The acquired friction coefficient and wear rate figures were noted. According to Jabal *et al.* [28], the flash temperature parameter—a figure used to represent the critical flash temperature at which a lubricant will perform satisfactorily under specific circumstances—was also determined for each experimental scenario using equation (1).

$$\mathrm{FTP} = \frac{\mathrm{W}}{\mathrm{d}^{1.4}} \tag{1}$$

where

$W = load\ (kg)$
$d = mean\ wear\ track\ diameter\ (\mu m)$

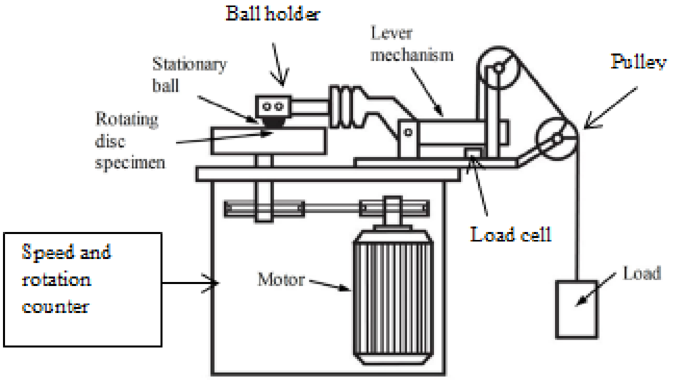


Figure 2. Schematic diagram of the Anton Paar ball on disc tribometer used

The disc specimens' surfaces were analysed in line with Gulzar [4] in order to comprehend the lubricant's lubricating mechanism. The research was conducted using scanning electron microscopy, a flexible technique for examining surfaces at a wide variety of magnifications and high resolution. SEM was utilized to scan the sample surface with a focused electron beam, and the image was captured.

3. Results and discussion

Description of the experimental results and their interpretation as well as the conclusions drawn is contained in this section.

3.1. Tribological performance of the formulated bio-lubricant

Both the developed bio-lubricant and the traditional lubricant SAE 40's tribological capabilities were assessed. Figures 3 through 7 display the observed tribological parameters, such as the wear rate, coefficient of friction, and flash temperature.

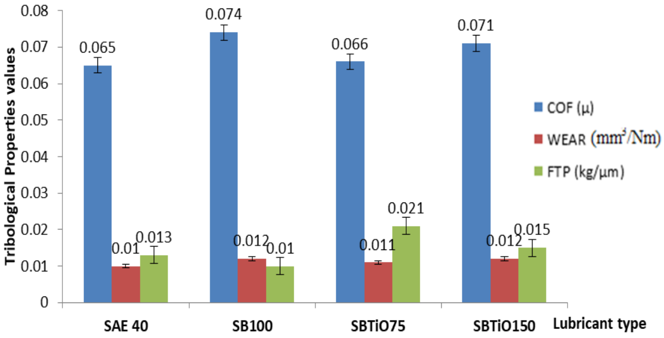


Figure 3. Effect of nanoparticle enrichment on coefficient of friction of the bio-lubricants (2 N, 150 rpm)

SAE 40: Conventional lubricant, SB100: Sandbox oil only, SBTiO75: Oil + 0.75 wt% TiO_2, SBTiO150: Oil + 1.50 wt% TiO_2

3.2. Effect of nanoparticle enrichment on friction coefficient

Figures 3 through 7 illustrate the effect of nanoparticle enrichment on the friction coefficient at various speeds and loads. The findings demonstrate that nanoparticle-enriched sandbox oil exhibited superior anti-friction properties at some concentrations, weights, and speeds, and poor properties at others. When SBTiO75 and SBTiO150 were compared to pure sandbox oil at 150 rpm and 2 N load, the friction coefficients of the two bio-lubricants were reduced by 10.81% and 4.05%, respectively. Additionally, at 150 rpm with an 8 N load, the friction coefficient decreased by 14.80% for SBTiO75 and 36.40% for SBTiO150. At 200 rpm with a 5 N load, the reductions were 38.96% and 18.18% for SBTiO75 and SBTiO150, respectively, and at 250 rpm with a 2 N load, the reductions were 78.30% and 33.02% for SBTiO75 and SBTiO150, respectively. Friction coefficient increased by 9.33% for SBTiO75 at 250 rpm with an 8 N load, but decreased by 5.88% for SBTiO150. These findings demonstrated that sandbox oil loaded with nanoparticles provides substantially lower friction coefficients than sandbox oil without nanoparticles.

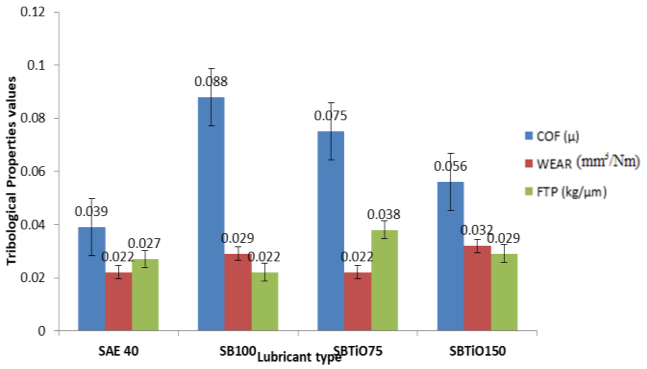


Figure 4. Effect of nanoparticle enrichment on coefficient of friction of the bio-lubricants (8 N, 150 rpm)

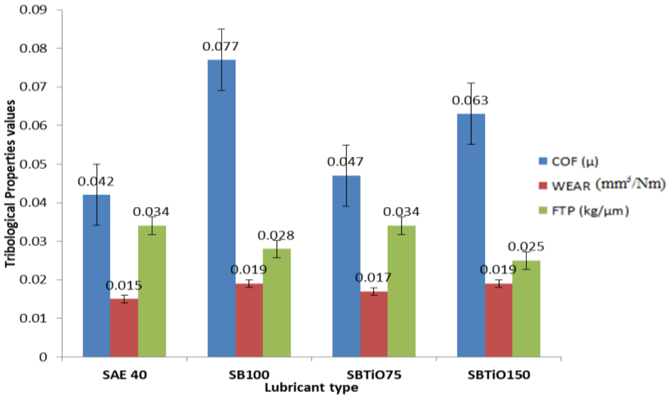


Figure 5. Effect of nanoparticle enrichment on coefficient of friction of the bio-lubricants (5 N, 200 rpm)

When the effect of percentage enrichment was compared for the lubricants, it was found that SBTiO75 had a lower friction coefficient than SBTiO150 at 150 rpm with a 2 N load, 200 rpm with a 5 N load, and 250 rpm with a 2 N load. However, SBTiO150 had a lower friction coefficient than SBTiO75 when subjected to an 8 N load at two distinct speeds—150 rpm and 250 rpm. This demonstrates that the lubricant's anti-friction behavior was significantly influenced by the percentage or amount of enrichment and load.When the lubricant was first enriched with 0.75 weight percent of nanoparticles at 2 N and 5 N load, the friction coefficient significantly decreased; however, when the enrichment was increased to 1.50 weight percent, the friction coefficient rose in comparison to the 0.75 weight percent enrichment. These findings demonstrate that higher load requires high enrichment and lesser load demands low enrichment. These findings are consistent with studies published by Ali et al. [10], Shahnazar *et al.* [5], Ali and Xianjun [11], Jabal *et al.* [23], Patil *et al.* [9] and Alves *et al.* [12], which found that oils enriched with nanoparticles had lower friction coefficients than oils without nanoparticles. These results also compare favorably with the friction coefficient of conventional lubricant, SAE 40.

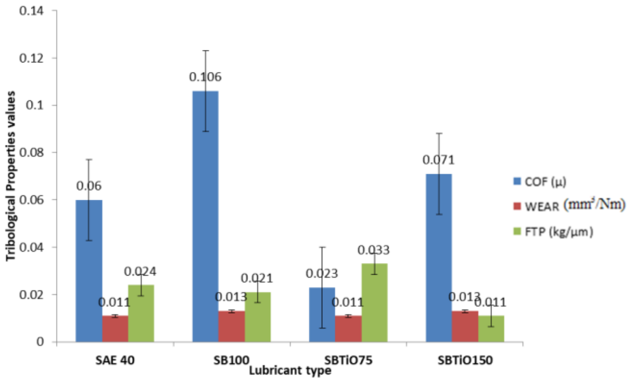


Figure 6. Effect of nanoparticle enrichment on coefficient of friction of the bio-lubricants (2 N, 200 rpm)

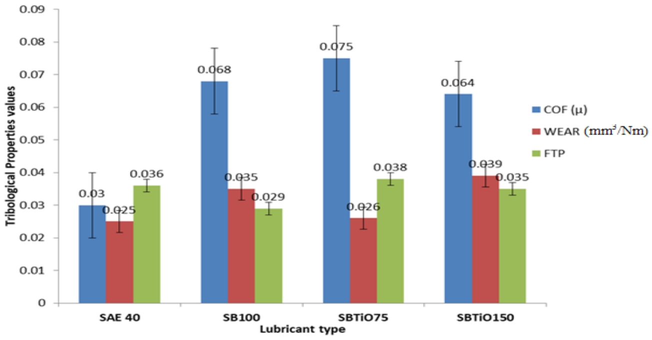


Figure 7. Effect of nanoparticle enrichment on coefficient of friction of the bio-lubricants (8 N, 250 rpm)

When the friction coefficient results were analysed, it was shown that the nanoparticle-enriched bio-lubricant show a significant improvement over the pure sandbox oil. The coefficient of friction reduces until it reaches a specific point where it begins to increase as the concentration of the nanoparticle in the bio-lubricant increases from 0.75 weight percent to 1.50 weight percent. According to Thottackkad *et al.* [26], this demonstrates that there is an optimal enrichment level at which the friction coefficient is at its lowest for a given weight and speed. As the lubricant's nanoparticle enrichment level is raised to the optimum level, the friction coefficient (COF) rises as well. Thottackkad *et al*. [29], Laad and Jatti [13], and Gulzar [4] have all observed similar trends of higher friction coefficient with greater concentration of nanoparticle towards the optimum concentration. It was found that a uniform and steady dispersion of titanium oxide nanoparticles in the base oil significantly contributed to the improvement in the friction coefficient of the lubricants. According to Gulzar [4], nanoparticle concentration is important for the creation of stable dispersion, which leads to better friction behaviour. Stable dispersion contributed to the steady resistance to friction. The lubricant's homogeneous distribution of nanoparticles increased the likelihood of improving the rubbing surfaces. According to Ali *et al.* [10], the ability of the nanoparticle to convert pure sliding friction to rolling friction due to reduced interfacial interaction for frictional surfaces as well as the secondary effect of surface enhancement due to the surface polishing nature of the nanoparticle are additional reasons for the decrease in friction coefficient of the nanoparticle-enriched bio-lubricant.

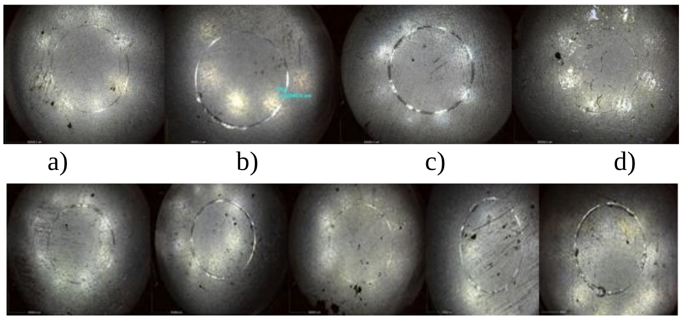
When the concentration of nanoparticles is smaller, the lubricant's nanoparticles create a third body rolling effect between the sliding surfaces which reduces friction. Thottackkad *et al.* [26] and Ghaednia *et al* [30] stated that this impact is significantly more noticeable at greater loads when the nanoparticles agglomerate and give the contacting area more supportive effort. Friction is raised as a result of the solid particle contact becoming more prevalent as the enrichment level is raised. According to Zulkifli *et al.* [31]'s report on the mechanical entrapment theory, nanoparticles in the lubricant are deposited at the contacting surfaces and form a layer that is later removed during further sliding, resulting in a decrease in friction. Additional causes include the formation of tribo-film on worn surfaces, which reduces the lubricant's ability to withstand shearing, and the effectiveness of fatty acids. Bahari [32] claims that the creation of the mono-molecular layer is also aided by the strong polarity of the fatty acids found in vegetable oils, which attracts the carboxyl group (COOH) to metallic surfaces.

3.3. Effect of nanoparticle enrichment on wear behaviour

Figures 3 through 7 further illustrate how the wear rate of the bio-lubricants is affected by the enrichment of nanoparticles. The findings demonstrated that whereas pure sandbox oil had poor anti-wear qualities at some concentrations, loads, and speeds, nanoparticle-enriched sandbox oil exhibited superior anti-wear properties at others. The findings demonstrate that, as long as the proportion of enrichment remained within the optimal level, nanoparticle enrichment increased the bio-lubricant's wear rate. When the percentage of enrichment exceeded the optimum concentration, the bio-lubricant's wear rate rose. Battez and Rodriguez [15] stated that this was caused by granule abrasions brought on by an overabundance of nanoparticles in the contact area. When the effect of percentage enrichment was compared to the bio-lubricants' wear rates, SBTiO75 was shown to have a lower wear rate than SBTiO150 at the loads (2, 5, and 8 N) and speeds (150, 200, and 250 rpm). As the concentration of the nanoparticle additions increases from 0.75 weight percent to 1.50 weight percent, the anti-wear advantages gradually diminish. At varying speeds of 150 rpm and 250 rpm, it was found that the wear rate for a 2 N load was less than that of an 8 N load. Additionally, it was noted that wear rate increased as load and speed increased.

Compared to speed, this rate of increase is more noticeable in relation to load. According to Mohan *et al.* [33], wear increases with load and speed beyond the deposition of nanoparticles created by tribo-film production. This further demonstrates the significant influence that load and enrichment percentage or level had on the lubricant's anti-wear properties. Abere [25] suggests that the impact of the chemical makeup of the bio-lubricants on film formation could be the cause of the wear rate reduction resulting from this nanoparticle addition. The nanoparticle formed a stable and homogeneous solution in the lubricant, penetrated the contact area, and deposited on the mating surfaces to form a tribo-film through a deposition mechanism during lubrication.

The wear scar on the disc was altered by the addition of titanium oxide nanoparticle additive to the basic oil. A surface that is comparatively smooth, as seen in Figure 8 was produced after testing. Tao *et al.* [34] claim that the less severe disc wear is probably caused by the bio-lubricant's capacity to create a protective tribo-film. The nanoparticle's enhanced behaviour may be attributed to its minuscule size and consistent, stable dispersions, which allowed them to permeate the rubbing surfaces and fill in the worn scar. Numerous researchers have reported on this material filling technique using nanoparticles [4,20,27].

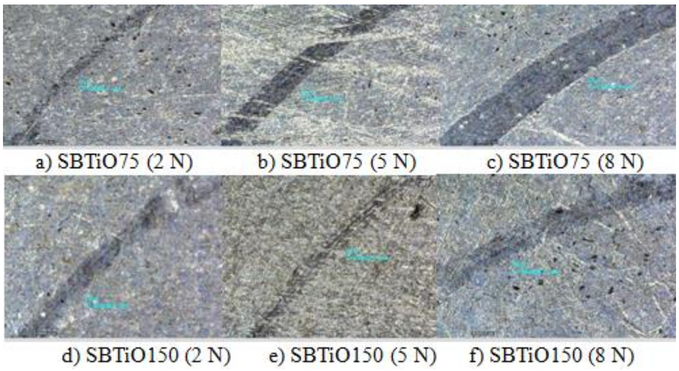

a) b) c) d)

e) f) g) h) i)

Figure 8. Typical optical micrographs of wear track on the discs; a) SB100 (2 N), b) SB100 (5 N), c) SB100 (8 N), d) SBTiO75 (2 N), e) SBTiO75 (5N), f) SBTiO75 (8N), g) SBTiO150 (2N), h) SBTiO150 (2N), and i) SBTiO75 (2N)

Some of the worn tracks in Figure 8 were so hardly noticeable. It shows that the nanoparticle was successful in forming a protective layer. This demonstrates enhanced wear resistance. According to Gulzar [4], this could be explained by the bio-lubricant's stable and uniform nanoparticle dispersion as well as the presence of fatty acid, which might aid in the lubricant layer's ability to maintain thickness and adhere well to the surface in order to lessen metal-to-metal contact. The creation of a protective layer and the significantly smaller size of the nanoparticles, which allowed them to more easily penetrate the contact zones, are other possible explanations for this anti-wear mechanism. Nanoparticles also deposit between interaction surfaces. The disc specimens' surfaces were analysed in order to comprehend the lubricant's lubricating mechanism. Figure 9 shows that the surface mending caused by the nanoparticle deposition on the disc surface was enhanced by an increasing concentration of nanoparticles. Figures 9(a), (b), and (c) demonstrate a larger tendency of wear tracks at low nanoparticle concentrations. However, as the concentration of nanoparticles increased, the tracks were filled in and the surface mended effect enhanced (Fig. 9(d), (e), and (f)).

Running-in or breaking-in wear mechanism was observed in figures 8 and 9. According to Bahari [32], in this mechanism the wear rate is often initially high, but as the surface become smother and the more prominent asperities are flattened or lost, the wear rate falls. After a suitable time, the full-service conditions can be applied without any sudden increase in wear rate and the steady low wear rate is maintained for the operational life of the component. It is evident from the analysis of wear and friction that when applied at the ball-disc interface, titanium oxide nanoparticle-enriched bio-lubricant exhibits superior tribological capabilities than the base oil lubricant. These findings were in line with earlier studies by Laad and Jatti [13], who found that the addition of titanium oxide (TiO_2) nanoparticle improved the tribological properties of lubricating oil, as well as studies by Ali and Xianjun [11] who found that base oil containing nanoparticle additives had exceptional anti-friction and anti-wear qualities.


a) SBTiO75 (2 N) b) SBTiO75 (5 N) c) SBTiO75 (8 N)

d) SBTiO150 (2 N) e) SBTiO150 (5 N) f) SBTiO150 (8 N)

Figure 9. SEM micrographs of disc specimens tested with the formulated bio-lubricants

3.4. Effect on flash temperature parameter (FTP)

A value known as the flash temperature parameter is used to indicate the critical temperature below which a lubricant can form a film and endure without breaking down. It is a single number that is frequently used to convey the censorious flash temperatures that occur when lubricants totally fail in specific circumstances. The bonding between the lubrication molecules was broken at that point, according to Syahrullail *et al*. [35], and the surface began to starve of lubricant. The effect of nanoparticle enrichment on the bio-lubricant's flash temperature parameter is displayed in Figs. 3–7. Because of the increased frictional force caused by an increase in load, the flash temperature parameter generally rose when the load was increased from 2 N to 8 N. Similar patterns were noted by Singh [36] for the Jatropha bio-lubricant, showing an increase in the flash temperature parameter from 50 N to 150 N of load.

The results implies that the lubricant could keep the lubrication layer intact for a longer amount of time. This is because the bio-lubricant performs better at higher FTP values. As a result, it is noted that, in comparison to base oil, the nanoparticle enrichment increased lubricity overall performance and decreased the likelihood of lubricant film breakup.

3.5. Optimum enrichment level

The projected operating conditions required to achieve the lowest coefficient of friction and wear rate as well as the maximum flash temperature parameter were, according to the optimization result in Figure 10, a load of 8 N, a speed of 199.4949 rpm, and a concentration of 0.7121 weight percent of TiO_2 nanoparticles. At the optimum setting, the wear rate and coefficient of friction has values of 0.0171 and 0.0490 (mm3/Nm), respectively, and the flash temperature parameter had value of 0.0381.

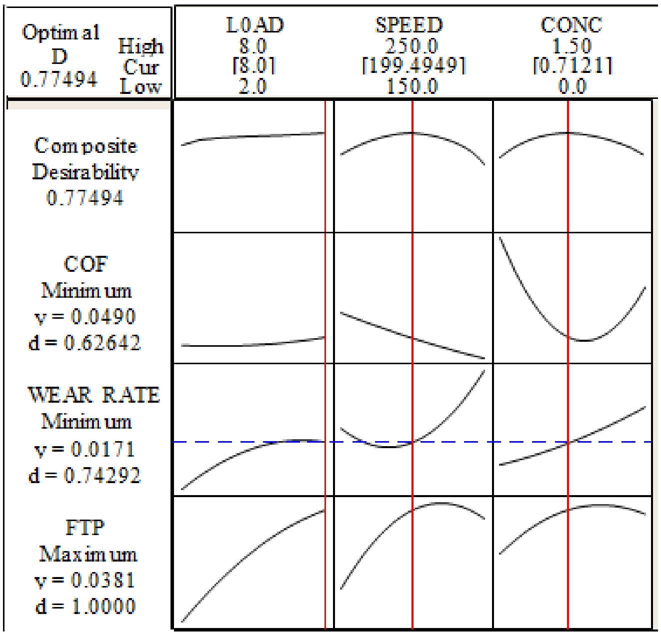


Figure 10. Optimization results for titanium oxide nanoparticle-enriched bio-lubricant

4. Conclusions

The bio-lubricant's tribological behaviour revealed that the titanium oxide nanoparticle enhanced the flash temperature parameter, decreased friction and wear rate because the particles were deposited on the worn surfaces and between the rubbing surfaces, and ultimately decreased the shearing resistance. When SBTiO75 and SBTiO150 were compared to pure sandbox oil at 150 rpm and 2 N load, the friction coefficients of the two bio-lubricants were reduced by 10.81% and 4.05%, respectively. Additionally, at 150 rpm with an 8 N load, the friction coefficient decreased by 14.80% for SBTiO75 and 36.40% for SBTiO150. At 200 rpm with a 5 N load, the reductions were 38.96% and 18.18% for SBTiO75 and SBTiO150, respectively, and at 250 rpm with a 2 N load, the reductions were 78.30% and 33.02% for SBTiO75 and SBTiO150, respectively. Friction coefficient increased by 9.33% for SBTiO75 at 250 rpm with an 8 N load, but decreased by 5.88% for SBTiO150. These findings demonstrated that sandbox oil loaded with nanoparticles provides substantially lower friction coefficients than sandbox oil without nanoparticles. The nanoparticle created a stable and homogeneous solution in the lubricant, penetrated the contact area, and deposited on the mating surfaces to form a tribo-film through the deposition mechanism during lubrication. In order to enhance the bio-lubricant's tribological qualities, titanium oxide nanoparticles can be employed as an anti-friction and anti-wear additive.

Author contributions

Caleb Abiodun Popoola: conceptualization, methodology, validation, formal analysis, investigation, resources, data maintenance, writing-creating the initial design, visualization, monitoring and management, funding procurement

Okwuchi Smith Onyekwere: methodology, software, validation, resources, data maintenance, writing-reviewing and editing, funding procurement

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