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Performance Evaluation of Nano-Enhanced Coconut Oil As Sustainable Lubricant

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Abstract. Lubricants are used to reduce friction between contacting surfaces, especially involving mechanical parts. There has been considerable effort to develop a lubricant that will aid sustainable process and efficient performance. Because of their environmental friendliness, biodegradability, less toxic, and good lubricity, vegetable oils are considered a better substitute for mineral oils. However, their thermal and oxidative stability of vegetable needs to be improved for efficient lubrication. This research is aimed at developing and performance evaluation of vegetable oil-based nanolubricants with maghemite nanoparticles at different volume concentrations for sustainable lubrication. Maghemite nanolubricants were prepared by dispersion of the maghemite ($\gamma F_e 2O_3$) nanoparticles into vegetable oil at a different level of inclusions (0.1, 0.2, and 0.3 vol.%). The result indicated an improvement in the thermophysical properties of the nanolubricants with increased concentration, while an increase in temperature decreases their enhancement. The kinematic viscosity of coconut oil is enhanced with an increase of volume fractions that enable them to form a protective thin film under higher temperature operation. At the temperature of 80 °C, an increase of 30.68% was observed in the viscosity of nanolubricant over the pure base oil. The highest thermal conductivity enhancement over the base fluid is 7.33%, corresponding to a ratio of 1.079 times improved performance at a concentration of 0.3 vol.% inclusion over the pure base oil. The tribological properties showed that the wear scar diameter and coefficient of friction decrease with an increase of concentration. Thus making the addition of maghemite nanaoparticles in biolubricants a promising nanolubricant for sustainable machining.

INTRODUCTION

A substantial quantum of energy for useful work is wasted to overcome friction, which opposes the free flow of relative motion between surfaces in contact. Mechanical efficiency of machinery and mechanical equipment improves significantly with the reduction of friction in component parts of machinery improves significantly [1]. Several strategies have been devised over time to mitigate this development. Vegetable oil-based lubricants, because of their good lubricity, environmentally benign, non-toxic, biodegradability, etc., make them an attractive substitute [2-5] for petroleum-based mineral oil. Apart from been harmful to the operators and causes environmental pollution, they require a high cost of disposal. Jeevan and Jayaram [6], in their survey, affirmed that the impeccable characteristics

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of vegetable oils indicated their great potential as suitable lubricants for industrial applications due to enhanced anti-wear properties and reduction of friction. Their adoption will stimulate a significant reduction in the demand for commercial lubricants and consequently reduce the waste from the use of conventional lubricants in an industrial process. However, their low-temperature performance, poor thermal and oxidative stability limit their efficient performance [7, 9]. These challenges with vegetable oils are addressed through chemical structure modification of base oil and inclusion of additives [5,9]. Nanoparticles as additive have been reported to improve the properties of base fluid [10]. Anti-wear properties and friction reduction ability of lubricants are improved with the addition of nanoparticles in base oil [11].

Nanoparticles as an additive in base oils enhanced the lubricating properties, thereby reducing the friction coefficient through the conversion of sliding friction to rolling friction as it flows into the contact zone [12]. Tribological performance of nanolubricants dispersed with copper oxide (CuO) nanoparticles such as extreme pressure and formation of tribofilm was observed to significantly reduces friction between contacting surfaces and wear scar diameter [13] and lower concentrations achieved the best reduction of friction and wear scar. Koley and Dey [14] evaluated the thermal conductivity and viscosity of Cu-gear oil nanolubricants and observed improvement of viscosity and thermal conductivity of gear oil significantly. At the highest concentration level of 2% volume fraction, 24% and 71% enhancement of thermal conductivity and viscosity respectively were reported. The inclusion of nanofillers at minute fractions in lubricating oil resulted in improvements of the anti-wear properties of the base oil in addition to thermal performance as h-BN and graphene nanoparticles dispersed in mineral oil were evaluated [15]. Wang et al. [16] observed that the improvement of thermal and rheological properties of base oil with the dispersion of graphite particles depends strongly on concentration and tends to increase proportionally with the increase of particle concentrations while their properties have an inverse proportional relationship with temperature. Wang et al. [17] affirmed that nanoparticle dispersion in palm oil improved the lubricating properties that enable the formation of the protective film, thereby reducing sliding friction between friction surfaces.

The magnetic properties of maghemite ($\gamma F_e 2O_3$) nanoparticles prompted its utilization in biomedical and industrial applications. Maghemite is utilized as corrosion inhibitors through the formation of protective thin film layers [18]. For heat transfer applications, maghemite nanoparticles have been investigated and indicated a promising to be a suitable particle for the improvement of base fluid properties. Guo et al. [19] reported the enhancement of thermal conductivity in addition to an improved heat transfer coefficient with the addition of maghemite. Huminic et al. [20] reported enhancement thermal conductivity as temperature increases at every concentration level while dynamic viscosity increases with increased particle concentration but decreases with an increase of temperature. Several other researchers have reported the enhancement of properties of water and other base fluids with the addition of maghemite nanoparticles [21-24]. Investigation on the improved properties of base fluids with the addition of maghemite nanoparticles has been limited to water/ethyl glycol and other conventional base fluids. Thus, the need to evaluate the properties of maghemite nanoparticles dispersed in vegetable oil lubricant to understand their influence on thermal and tribological properties. Therefore, this research is aimed at the investigation of thermophysical and tribological properties of coconut oil enhanced with maghemite nanoparticles as a potential lubricant for a sustainable application.

MATERIALS AND METHOD

Nanolubricant Preparation

Nanolubricants were prepared by dispersion of the maghemite ($\gamma F_{e2}O_3$) nanoparticles into coconut oil at a different level of concentrations of 0.1%, 0.2%, and 0.3% volume concentration using the same method as used by Su et al. [25]. The prepared suspension was stirred with a stirrer for a couple of minutes and later placed in an ultrasonicator for a homogenous mixture of the lubricant with the dispersed nanoparticles for 2 hours.

Thermal Conductivity Measurement

The thermal conductivity measurements of the maghemite nanofluids were conducted using KD2 Pro thermal properties analyzer (Decagon Devices Company, USA) based on the transient hot-wire method as used by Sharif et al. [26]. The KD2 Pro instrument consists of a hand-held controller and sensor which will be inserted into the medium. The sensor consists of a heating element and thermo-resistor in its interior. The sensor is calibrated before every usage by measurement of the verification sample (glycerine) as specified by the equipment manufacturer. The measured value of glycerine at room temperature is 0.286 W/m.K with accuracy within ±5% as specified by the manufacturer.

The measurements were recorded for each sample (volume: 30 ml) under a controlled temperature environment with the aid of a Memmert water bath of Model: WNB7L1. At an interval of 15 mins for each sample, five values were recorded, and the average of these readings at a particular temperature is taken as the thermal conductivity of the specimen. It was conducted for a temperature range of 30°C to 80°C. The thermal conductivity enhancement ratio is expressed mathematically as:

$$\%\,Enhancment\ ratio = \frac{(k_{nb})}{k_{bf}} \tag{1}$$

Kinematic Viscosity

A Brookfield viscometer (DV-II+PRO) was used to measure the viscosity of the base coconut oil and the nanolubricant samples. For each measurement, 250 ml of sample in a beaker was subjected to viscosity test from 30°C to 80 °C with a rotational speed of 100 rpm, and the changes in viscosity of lubricants over the range of temperature acquired.

Anti-Wear and Coefficient of Friction

The tests were conducted by four-ball friction and wear tester equipment according to the ASTM D4172. Each testing was conducted with a new set of four SKF stainless steel balls with a mean diameter of 12.7 mm and hardness of 66 HRC. Three stationary balls immersed with 10 ml of lubricant were clamped together in the ball pot assembly while the fourth ball tightened into the spindle pressed rotates against the balls in the pot assembly at test conditions of 392 N of force, spindle speed of 1,200 rpm, and a controlled temperature of 75 °C for a period of 1 hour. The wear scar diameter of the lower balls is used to evaluate the anti-wear properties of the tested lubricants as well as the average friction torque acquired using the Windcom software data acquisition system. The coefficient of friction is then determined according to IP-239 as expressed in the following equation:

$$\mu = \frac{\tau\sqrt{6}}{3Wr} \tag{2}$$

Friction Torque

The friction torque in a friction and wear test is influenced by the performance of lubricants when in operation. When the film formation by lubricant is broken down, the metal-to-meta contact becomes more severe, given rise to higher friction and subsequently causing higher wear on the contacting surface.

TABLE 1. Tribological test parameters for evaluation of the Anti-wear and friction coefficient of the Lubricants

Description	Values
Test Load	392N
Rotational Speed	1200 RPM
Sample Volume	10ml
Temperature	75°C ± 1
Test Duration	1 hour

RESULTS AND DISCUSSION

Thermal Conductivity

The thermal conductivity of nanolubricants is affected by temperature and concentration, as revealed by the current study as the increase of temperature decreases thermal conductivity while an increase of concentration increases thermal conductivity. An increase of concentration can improve the thermal and oxidative stability of the base fluid of nanolubricants. The relationship between thermal conductivity ratio and varying concentration under the temperature range investigated are presented in Fig. 1. The result reveals that an increase of concentration increases thermal conductivity at every temperature and that even the least concentration enhances the thermal property of nano dispersed lubricant when compared with the pure coconut oil. The highest thermal conductivity ratio at 0.3% volume concentration is 1.08 times greater than the base coconut oil. Similar findings was reported by Sharif et al [26] as the enhancement will enable the stability of the vegetable oil based nanolubricant to perform better under higher temperature loads without broken down or oxidised easily like the pure base oil without nanao-additives .

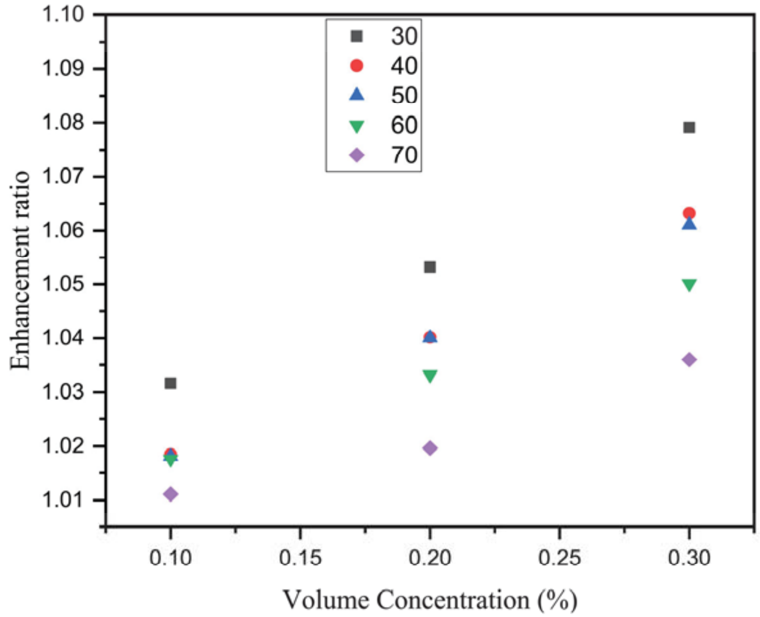

FIGURE 1. Thermal conductivity enhancement ratio for all concentrations under varying temperature

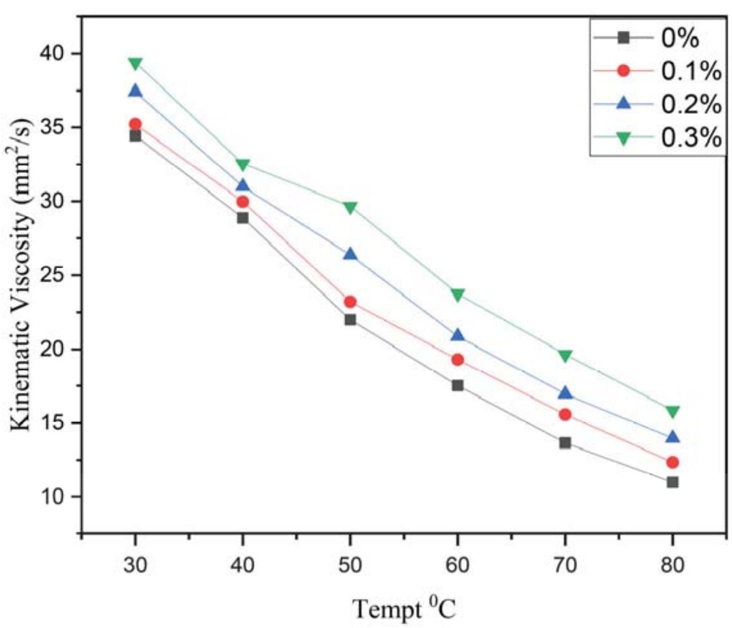

FIGURE 2. Kinematic viscosity of lubricants under varying concentrations and temperature

Viscosity

Viscosity of lubricant is an important property of a lubricant that is used to determine its suitability for efficient lubrication. It is a measure of internal resistance to flow or shear stress between contacting surfaces, and it influences the friction and wears behavior of the surfaces in contact. The viscosity of lubricant decreases with an increase of temperature while it increases with increased concentration [12, 26]. The enhancement of kinematic viscosity of nanolubricants over pure vegetable oil at 30°C and 80°C considering the highest level of concentration are 12.55% and 30.68%, respectively, as shown in Fig. 2. It's good that nanoparticle inclusion increases the viscosity of the lubricant, thereby making it to form a protective film layer while in operation. However, nano-dispersion in base lubricants should be made in such a way not to inhibit ease of penetration to the contacting surfaces when highly viscous.

Coefficient of Friction

Figure. 3 shows the variation of friction coefficient, and the 0.2% concentration indicated best performing maghemite nanolubricant. In Fig. 4, the coefficient of friction (COF) decreases up to the mid-level concentration before a slight increase was observed. This slight increase could be attributed to increased viscosity of nanolubricants beyond the optimum level of concentration. This finding agrees with the findings of Thottackkad et al. [10]. The lowest COF was achived at 0.2% volume concentration. The reduction of friction by the enhanced maghemite nanolubricant when compared to the base coconut oil is minimal which was also observed by Alves et al [13] when they evaluated friction reduction of PAO oil dispersed with CuO tiny nanoparticles. Tribo-film formation is influenced by concentration and as such, too high concentration can impede the performance of enhanced lubricant. Since the essence of friction reduction is to improve efficiency of machineries and equipment, achieving friction reuction with optimum concentration should be encouraged.

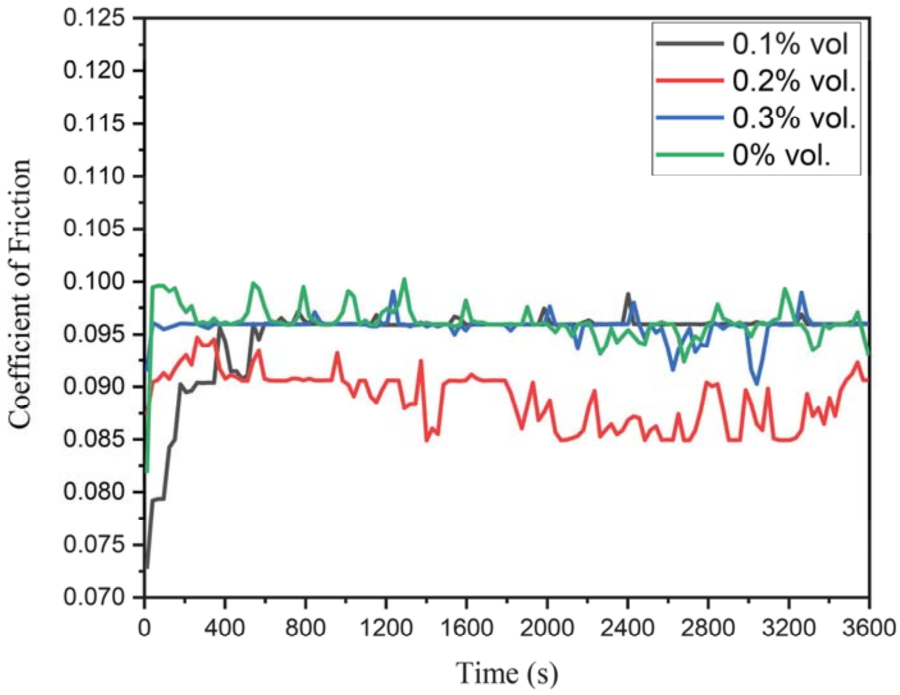

FIGURE 3. Variation of Coefficient of friction for tested lubricants using a four-ball friction tester.

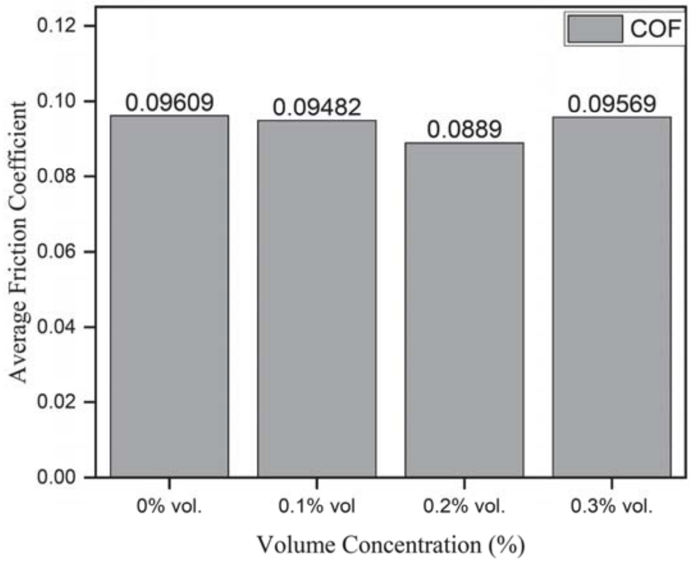

FIGURE 4. Average Friction coefficient indicating performance of all the tested lubricants

Anti-Wear Properties and Friction Torque

The anti-wear properties of a lubricant are determined by measuring the wear scar diameter (WSD) of lubricant. The ability of lubricants to withstand wear is evaluated by this measurement. Lower wear scar diameter symbolises better lubricant performance. In this study, the WSD and COF are functions of additives in vegetable oil. Figure 5 shows that WSD decreases with the increase of concentration of nanoparticles but increases slightly at the highest level of concentration. The reduction of WSD at the lowest and mid-level concentrations when compared to the base coconut oil is 4.31% and 5.92%, respectively. Alves et al [13] observed that lower concentration are effiicient in reducing wear of contacting surfaces thereby reducing cost associated with lubricant development. The lower WSD at lower concentrations is an indication of improved anti-wear property of the enhanced nanolubricants. Similarly, lower friction torque implies better performance as the lubricant film offers enough resistance from being oxidised or broken down. Higher friction torque leads to an increase of WSD and COF.

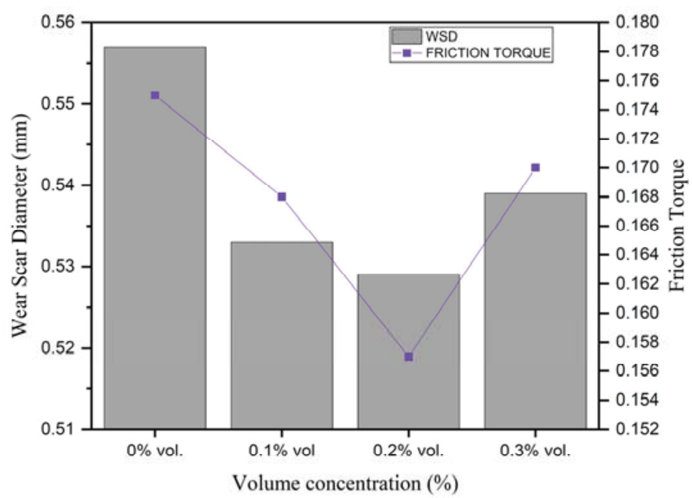

FIGURE 5. Wear Scar Diameter (WSD) and Friction torque of tested lubricants showing their anti-wear property for each lubricant.

CONCLUSION

The properties of enhanced vegetable oil with nanoparticle have been evaluated in terms of thermal conductivity, viscosity, and tribological properties. The dispersion of maghemite nanoparticles in coconut oil has shown enhancement of its performance. Therefore, maghemite enhanced nanolubricant is a promising candidate for sustainable lubrication and heat dissipation when applied in manufacturing processes and other areas of application where efficient lubrication and heat transfer may be required. From the analysis, the following conclusions can be reached.

i. The thermal conductivity of nanolubricants increased with nanoparticle addition, which will aid the thermal and oxidative stability of the nanolubricants. Thermal conductivity enhancement of 7.33% over base fluid was achieved.
ii. The nanolubricants indicated good tribological properties as it shows a reduced wear scar diameter and coefficient of friction. The nanolubricants indicated a lower friction coefficient and wear scar diameter compared to the pure coconut oil. However, the coefficient of friction and wear scar diameter increases at the highest concentration but lower than the pure coconut oil. Thus, optimum concentration at which improved friction and wear reduction was achieved can be used as basis for developing nanolubricants for sustainable application.
iii. The viscosity of lubricant improved significantly with nanoparticle addition, thus making it stable under high operation temperature with evaporating easily like pure vegetable oil. At the highest concentration level, the viscosity of nanolubricants improved significantly by 12.55% and 30.68%, respectively, over pure vegetable oil at 30°C and 80°C.

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