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COMPARATIVE ANALYSIS OF TRIBOLOGICAL PERFORMANCE OF NANO-ENHANCED HYBRID BIO-LUBRICANT WITH CONVENTIONAL SYNTHETIC OIL

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ABSTRACT

The need to have environmentally friendly lubricants has triggered a lot of research on the development of biodegradable and renewable alternatives to petroleum-based oils. The intrinsic lubricity of vegetable oils like cottonseed oil (CSO) and palm oil (PO) is due to the polar ester structures in them; however, limitations in wear properties and load-carrying capacity restrict their direct application in industries. This experiment compares the tribological behavior of CSO, PO, and a hybrid CSO-PO mixture with nano-additives (MoS₂, TiO₂, and SiO₂) at 1, 1.5 and 2 wt.% and compares these formulations with a commercial synthetic lubricant (SAE 20W50). Nano-enhanced bio-lubricants were made through the controlled dispersion method and evaluated with a four-ball tribotester under the ASTM D4172 conditions. Wear scar diameter (WSD) and coefficient of friction (COF) were the main performance indicators. The data show that the addition of nanoparticles significantly enhances tribological behavior, and 1.5 wt% is the most optimal loading. The hybrid CSO-PO + 1.5 wt% MoS₂ had the lowest WSD (509 μm) and COF (0.061). Compared to the synthetic oil (WSD = 530 μm and 0.088), the optimized nano-bio lubricant had a 3.96% wear reduction and a 30.68% friction reduction. These results indicate that nano-enhanced hybrid vegetable oil formulations, particularly those containing MoS₂, have the potential to provide better friction reduction and competitive wear resistance, and thus have a high potential as sustainable, high-performance alternatives to traditional synthetic lubricants.



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I. INTRODUCTION

The increase in the rate of industrialization and the growth of global energy demand have enhanced the use of petroleum-based lubricants in transportation and manufacturing industries, thus increasing the sustainability issues [1] [2]. Traditional lubricants that are based on petroleum are mostly non-biodegradable, and their lifecycle, including production, utilization, and disposal, has a great impact on the environment, such as soil and water pollution, greenhouse gas emissions, and long-term ecological damage [3] [4]. Lubricants that are based on minerals release toxic substances into the environment when improperly disposed of or accidentally spilled, thus becoming hazardous to ecosystems and human health [5] [6]. Due to the growing environmental effects and the growing regulatory systems that favor sustainability, there has been an increasing pressure to substitute mineral lubricants with renewable, biodegradable, and low-toxicity lubricants [7] [8]. Modern studies emphasize the fact that it is high time to switch to eco-friendly, renewable, and bio-based lubricants in order to reduce the impact on the environment and maintain tribological properties [9] [10]. Vegetable oils have received a lot of interest as bio-lubricant base stocks due to their natural high lubricity, high viscosity index, biodegradability, and low volatility compared to mineral oils; therefore, they are promising sustainable alternatives in tribological applications [11] [12]. However, the inherent characteristics of unmodified vegetable oils are not as good as they have poor oxidation stability, limited thermal resistance, and inadequate cold-flow properties, which restrict their direct use in high- or low-temperature operating environments [13] [14].

CSO and PO are among the most appealing vegetable oils because of their triglyceride structures, which have a high concentration of long-chain fatty acids (e.g., oleic, linoleic and palmitic acids), which significantly determine the viscosity behavior and oxidative properties [15] [16]. The presence of polar ester functional groups in these fatty acid chains increases surface adsorption and boundary-film formation, which, in turn, improves the friction reduction and wear resistance; this is the key to the high lubrication potential of CSO and PO in tribological systems that are sustainable [17] [18]. To address the challenges of the contemporary tribosystems, the introduction of nano-additives into lubricants has become a necessity to increase the load-carrying capacity, reduce surface damages, and satisfy the requirements of the modern tribosystems [19] [20]. High surface activity and contact interface interaction are the characteristics of nanoparticles that enhance tribological performance by drastically lowering friction and wear [21] [22]. The main improvement processes are the rolling effect, which involves the use of nanoparticles as nano-bearings; tribo-film formation, which creates a protective layer of the surface; the mending effect when the nanoparticles fill the surface asperities; and the polishing effect when the nanoparticles smooth worn surfaces during sliding [23] [24]. In particular, molybdenum disulfide (MoS₂) is well-known as an effective layered solid lubricant, as it has low interlayer shear strength; titanium dioxide (TiO₂) nanoparticles have high anti-wear and protective film-forming properties; and silicon dioxide (SiO₂) nanoparticles provide nano-bearing and surface smoothing effects, which makes these materials highly promising in the development of advanced nano-lubricant formulations [25] [26].

The tribological analyses play a critical role in assessing the frictional behaviour, the wear resistance, and the load-carrying capacity of lubricants under simulated contact conditions, thus allowing the reliable examination of their ability to perform in the real-life mechanical systems [27] [28]. The four-ball tribometer under ASTM D4172 is one of the most commonly used methods of testing the anti-wear and friction-reducing properties of lubricants in a controlled load, speed, and temperature environment [29] [30]. The four-ball testing provides the key performance indicators WSD and COF as the former measures the material loss and surface damage, and the latter measures the capacity of the lubricant to reduce resistance between sliding surfaces [31] [32]. The recent developments in nano-enhanced biodiesel lubricants highlight their increasing potential as the alternative to the traditional mineral oils due to the significant enhancement of their viscosity, thermal stability, and tribological properties. Initial studies with metallic and metal-oxide nanoparticles proved their usefulness in improving the lubrication properties of vegetable oils. Singh et al. [33] found that the addition of 0.9% copper nanoparticles to modified desert date oil significantly lowered the COF, wear rate, and surface damage, whereas Singh et al. [34] found that 0.6% SiO₂ nanoparticles enhanced the surface morphology and the overall tribological performance of the *Balanites aegyptiaca* oil. In the same way, Chinnachamy et al. [35] showed that the addition of silver nanoparticles into the *Jatropha* and *Pongamia* oils increased the viscosity, thermal conductivity, and wear resistance, thus indicating the positive effect of noble metal additives. Adding to these results, Prabhakaran et al. [36] demonstrated that addition of 0.240.4 wt.% of the CuO nanoparticles to modified Kusum oil enhanced viscosity, flash point, and tribological properties, which confirmed its suitability in industry.

Similar progress on iron-oxide systems has yielded encouraging outcomes. The castor-oil-based bio-lubricant with Fe₃O₄ nanoparticles and ethylene glycol developed by Ahmad et al. [37] had a production yield of 94% and achieved a 50% decrease in friction and a 40% decrease in wear. Aithal et al. [38] have found that PEG-coated Fe₃O₄ nanoparticles showed a maximum of 70% wear reduction in the presence of neem oil, which greatly improved the viscosity retention and thermal conductivity. Similarly, Sadiq et al. [39] showed that maghemite nanoparticles enhanced viscosity, thermal conductivity, and anti-wear properties of vegetable oil, and Sadiq et al. [40] went a step further to add graphene and maghemite nanoparticles to coconut oil, which enhanced oxidation stability, thermal degradation, and friction and wear behavior, which could be used in high-temperature machining.

Carbon based nano-additives have also become very effective reinforcement material in bio-lubricant systems. Kumar et al. [41] have indicated that palm-oil-commercial oil blends that incorporated 0.1 wt% functionalized multi-wall carbon nanotubes (FMWCNTs) reduced the wear-scar diameter and wear volume by 38 and 35%, respectively. Applying this study to bearing applications, Kamarapu et al. [42] showed better tribological and vibration characteristics with FMWCNT-blended palm oil, which retained its lubrication capacity during 80% of the working time. Nugroho et al. [17] also used carbon and oxide nanoparticles in the lubrication of electric-vehicles and demonstrated that palm-oil-based lubricants with additives of graphene, TiO₂, and Al₂O₃ decreased the COF by up to 34% and enhanced wear resistance.

Complementary research by Ravikiran et al. [43] found that TiO₂ and SiO₂ nanoparticles increased viscosity, flash point, and wear resistance of canola-wheat germ oil mixtures, whereas Madhwesh et al. [44] found that TiO₂-enhanced jojoba bio-lubricants increased engine efficiency and lowered emissions. Even though Katpatal et al. [45] found that the CuO nanoparticles did not have a significant effect on the pressure distribution in journal bearings, their experiment proved that the bio-lubricant formulations could reach the same frictional performance as ISO VG46 mineral oil. These studies, together, highlight the transformative nature of nanoparticles, metallic, metal-oxide, and carbon-based, in increasing the tribological performance of bio-lubricants, as well as their thermal stability, which would enhance their efficacy as viable, sustainable substitutes to industrial and automotive applications. Although a lot of literature has been done on nano-enhanced bio-lubricants, very little research has been done to compare the various types of nanoparticles and their concentrations in a hybrid vegetable oil system and compare their performance with commercial synthetic lubricants under the same operating conditions. Moreover, the blending effect of base-oil (CSO-PO) and layered MoS₂ reinforcement has not been sufficiently investigated. The current paper fills this gap by performing an extensive comparative study of MoS₂, TiO₂, and SiO₂ at optimal concentrations in a hybrid bio-lubricant system and finding an optimum formulation with much better friction reduction and competitive wear resistance compared to synthetic oil.

II. MATERIALS AND METHODS

This section outlines the materials used and the experimental methods used in the synthesis and testing of nano-enhanced bioderived lubricants. The methodology includes the choice of base oil, nanoparticle dispersion plans, and tribological evaluation in the conditions of four-ball tests.

II.1 BASE OILS

The three vegetable-based oils and one commercial synthetic lubricant were used as base fluids in the present study to conduct tribological assessment. Refined CSO was purchased at a local agricultural supplier and used without any further chemical treatment. Refined edible grade PO, also sourced through a local supplier, was chosen due to its desirable fatty acid profile and established lubrication properties. A hybrid oil (CSO-PO) was made by mixing cotton seed oil and palm oil in a constant volume ratio of 50:50 (v/v). The blending was done by continuous mechanical stirring at ambient temperature to achieve uniformity and homogeneity of the resulting hybrid formulation. Besides the vegetable oils, a commercially available fully synthetic engine oil (SAE 20W50 grade) was used as a reference lubricant to be compared. All base oils were filtered before experimentation to remove suspended impurities and kept in airtight and dark glass containers in ambient laboratory conditions to reduce oxidation and moisture uptake.

II.2 NANOPARTICLE ADDITIVES

Three different nanoparticle species were added to the tribological properties of the chosen base oils as lubricant additives: molybdenum disulfide (MoS₂), titanium dioxide (TiO₂), and silicon dioxide (SiO₂). All nanoparticles were obtained through certified chemical vendors with reported purities of over 99% and average particle diameter of 30-50nm. The particles were kept in hermetically sealed containers in a desiccated environment before their deployment to reduce the uptake of moisture and agglomeration. Molybdenum disulfide (MoS₂) nanoparticles have a highly layered lamellar crystal structure that allows interlayer slippage during shear and, therefore, decreases friction and increases load-bearing capacity. Titanium dioxide (TiO₂) nanoparticles have strong thermal stability and surface interaction characteristics, which enhance the anti-wear properties and the development of protective films in sliding. Silicon dioxide (SiO₂) nanoparticles, which are usually in the form of a sphere or amorphous, are known to facilitate rolling and polishing activities at the interface of contact, resulting in less wear and better surface smoothness. In the current study, the different classes of nanoparticles were added to the base oils at three different weight percentages of 1, 1.5, and 2% to determine the effect of additive loading on the reduction of friction and wear resistance at otherwise the same test conditions.

II.3 PREPARATION OF NANO-ENHANCED LUBRICANTS

The nano-enhanced lubricants were prepared by dispersing molybdenum disulfide (MoS₂), titanium dioxide (TiO₂), and silicon dioxide (SiO₂) nanoparticles in the chosen base oils (Cotton Seed Oil (CSO), PO, a mixture of CSO and PO, and a synthetic oil) at a fixed mass fraction of 1 wt%, 1.5 wt%, and 2 wt%. The amount of nanoparticles to be used in each sample was determined by the total mass of the lubricant system and then measured with a precision digital balance with a calibration error of ± 0.001 g. The dispersion process was developed as a two-step process to obtain homogeneous distribution of the particles with a minimum agglomeration. The weighed nanoparticles were added to the base oil in the first stage under constant mechanical stirring at about 600 rpm and a period of 30 minutes at room temperature. This pre-mixing step helped to wet the nanoparticles in the oil matrix and pre-mix them. The partially mixed slurry was then ultrasonicated using a probe-type sonicator over 45 minutes, which disperse any remaining aggregates and enhances the stability of the suspension. During ultrasonication, the temperature was constantly checked and kept at a constant level in order to avoid thermal degradation of the oil. No surfactants or chemical dispersants were added so as to maintain the inherent physicochemical characteristics of the base oils. After the preparation, the nano-enhanced lubricants were placed in opaque glass containers with no air and left to stabilize over 24 hours under the laboratory ambient conditions before tribological testing was initiated. This stabilization phase guaranteed the formation of dispersion equilibrium and minimized the tendency towards sedimentation in the further experimental assessment.

II.4 EXPERIMENTAL TEST SETUP

The prepared lubricants were evaluated in terms of tribological performance by a four-ball tribotester in compliance with ASTM D4172 standards. Before testing, the AISI 52100 chrome steel balls (12.7 mm diameter, approximately 64 HRC) were carefully washed with acetone to remove any contaminants and then dried to create equal contact conditions. The three stationary balls were clamped in the test cup and completely immersed in the lubricant sample, and the fourth ball was placed on the rotating spindle and contacted with the stationary balls under a given load. All experiments were performed at a constant load of 60 minutes at a fixed temperature. A continuous measurement and recording of COF was done through integrated data acquisition system which was linked to a computer interface. After the test was completed, the balls were thoroughly removed, washed and under a high-resolution optical microscope to measure the wear scar diameter (WSD). Each wear scar was measured twice perpendicularly and averaged to obtain the final WSD. The WSD of each lubricant is the average of the values of the three stationary balls. Table 1 summarizes all the operating parameters that were kept in the course of the experiments. The experiments were conducted in the same conditions and repeated thrice to guarantee the repeatability and reliability of the experimental results.

Table 1: Key Specifications of Tribological Test Conditions.

Parameter	Specification
Test Standard	ASTM D4172
Load	40 kg (392 N)
Rotational Speed	1200 rpm
Test Duration	60 minutes
Test Temperature	75 $\pm$ 2 °C
Ball Material	AISI 52100 steel
Ball Diameter	12.7 mm (½ inch)
Ball Hardness	~64 HRC
Measured Parameters	COF, WSD

Source: Authors, (2026).

II.5 MEASUREMENT OF PERFORMANCE PARAMETERS

The tribological behavior of the lubricants prepared was measured on two main parameters: WSD and COF. These parameters were chosen to determine the anti-wear properties and the friction-reducing property of the lubricant formulations in the conditions of boundary lubrication. The tribotester integrated load cell and data acquisition system were used to continuously measure the COF during every test. The data of the frictional forces were measured in real time and the mean steady-state value of COF was obtained during the stable operation of the test. This value is the capacity of the lubricant to reduce the resistance between the moving surfaces of contact. After each experiment was completed, the three stationary balls were washed and observed under a high-resolution optical microscope to identify the WSD. Each wear scar was measured and averaged in two perpendicular diameters to get the average wear scar diameter of each ball. The WSD that is finally reported on a lubricant sample is the average of three stationary balls. The COF and WSD measurements were done three times and under the same operating conditions and the mean values were compared to compare the various lubricant formulations.

II.6 REPEATABILITY AND STATISTICAL ANALYSIS

In order to be sure that the experimental results were reliable and consistent, repeatability tests were carried out on each lubricant formulation under the same operating conditions. Every tribological experiment was conducted thrice and the value of WSD and COF were noted in each trial. The average of the three measurements was taken as the representative outcome of each sample. To determine the dispersion and reproducibility of the data, statistical analysis was performed by determining the standard deviation (σ) and the coefficient of variation (CV). The variation of repeated measurements about the mean value was measured using the standard deviation and the coefficient of variation gave a normalized measure of variability expressed as a percentage. The coefficient of variation was calculated using the following expression:

$$CV = \frac{\sigma}{\mu} \times 100 \quad (1)$$

Where σ represents the standard deviation and μ denotes the mean of the measured parameter (WSD or COF). A CV value below 5% was considered acceptable, indicating good repeatability and consistency of the experimental procedure. All statistical calculations were performed using standard spreadsheet-based analytical tools.

III. RESULTS AND DISCUSSIONS

The tribological behavior of the bio-lubricants that were prepared was systematically defined and described through the measurement of wear-scar diameter (WSD) and COF in a controlled four-ball testing regime. This section provides a comparative analysis of base oils and nano-enhanced formulations and their performance against a commercial synthetic lubricant in detail.

III.1 TRIBOLOGICAL PERFORMANCE OF BASE OILS

Figure 1(a) and Figure 1(b) in the current study show the relative wear and friction properties of plain CSO, PO, hybrid CSO-PO, and SAE20W50 when subjected to the same four-ball test conditions. With regard to wear performance, PO had the best Wear-Scar Diameter (WSD = 594 μm), followed by CSO (574 μm) and the hybrid CSO-PO blend had a significantly lower Wear Scar Diameter (WSD = 542 μm). This amalgamated formulation reflected an 8.75% decrease in WSD compared to PO and a 5.57% decrease compared to CSO, which was a strong synergistic effect that could be attributed to the blending process. The synthetic oil had slightly lower wear (530 μm), but the WSD of the hybrid oil was higher than that of the synthetic by just 2.26 μm , thus, validating similar anti-wear behavior. Similar observations have been made with vegetable-oil blends, where increased lubricity is due to equal viscosity and increased surface-adsorption properties highlighting the inherent high lubricity and viscosity index of vegetable oils. Besides, palm-oil blends studies under four-ball testing have shown wear behaviour to be either comparable or better than mineral oils, which can be explained by the prevailing tribological characteristics of vegetable components. The data on friction also indicates a clear benefit of the hybrid oil. The hybrid CSO-PO had the lowest coefficient of friction (COF = 0.068), which is 21.84% lower than SAE20W50 (0.0884), 18.07% lower than PO (0.083), and 21.84% lower than CSO (0.087). Although the synthetic oil had slightly less wear, it had the highest COF of all the samples. This counter-intuitive effect can be explained by the fact that the ester functional groups in vegetable oils are highly polar and therefore adsorb onto metallic surfaces to create a stable boundary-lubricating film and thus reducing interfacial shear stress. Other friction-reduction effects related to vegetable-derived esters have been reported where the presence of the ester reduced significantly friction and wear compared to diesel fuel. Moreover, lubricants made of cottonseed oil have demonstrated a greater reduction of friction compared to mineral oils due to the better formation of boundary-films. All the data together prove that, despite the fact that synthetic oil provides slightly worse wear in the given conditions, the hybrid vegetable-oil mixture provides significantly lower friction with the same wear resistance. This hybrid formulation is, therefore, a possible, environmentally friendly alternative lubricant that can be used in boundary-lubrication regimes.

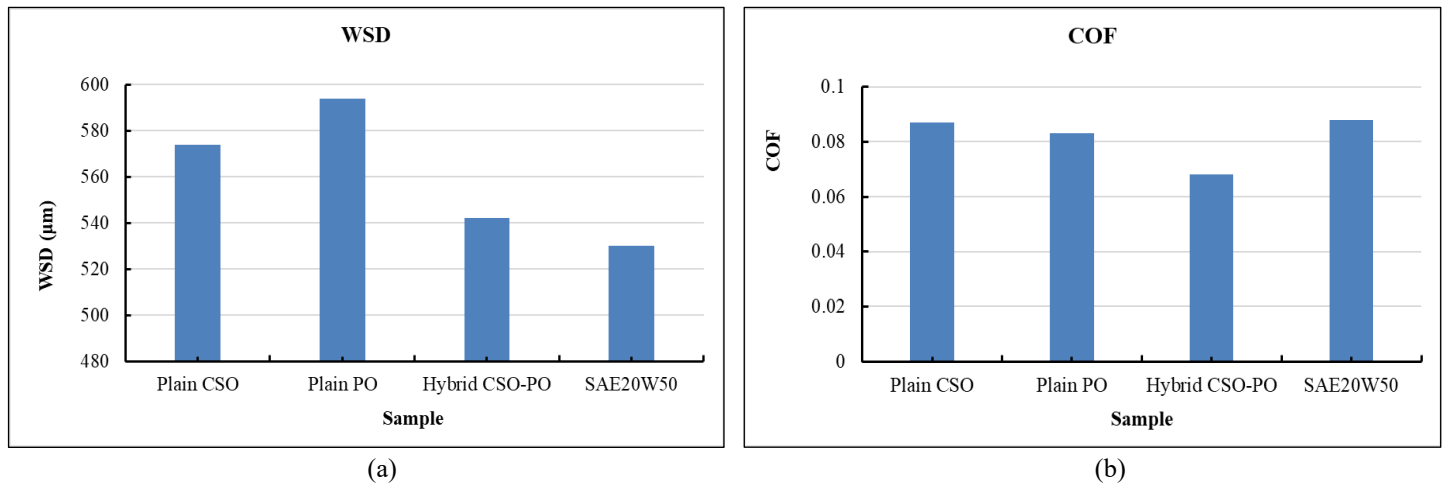


Figure 1: Comparison of tribological performance of plain CSO, PO and Hybrid CSO-PO with synthetic SAE20W50 oil (a) WSD (b) COF.

Source: Authors, (2026).

III.2 EFFECT OF NANOPARTICLE TYPE ON WEAR AND FRICTION

Figures 2(a) and 2(b) illustrate how the type of nanoparticle affects the average WSD and COF of all the base oils and concentrations studied. MoS₂ has the lowest mean WSD (541.33 µm), then TiO₂ (555.33 µm) and SiO₂ (570.89 µm). Compared to SiO₂, MoS₂ has an average wear reduction of about 5.18%, but it is 2.52% lower than TiO₂. On the other hand, TiO₂ has a lower WSD by 2.72% as compared to SiO₂. These data determine the hierarchy MoS₂ TiO₂ SiO₂, meaning that MoS₂ has better anti-wear properties in the conditions of the tested boundary-lubrication. The increased wear resistance of MoS₂ can be explained by the fact that the crystal structure of the material is lamellar, which allows interlayer sliding and the creation of a low-shear-strength tribofilm on the contact surface. These mechanisms are also extensively reported in tribological literature, where the MoS₂ nanoparticles significantly enhance load-bearing capacity and reduce surface damage due to their solid-lubricant property. Conversely, TiO₂ plays a major role in terms of tribofilm reinforcement and mild polishing, hence, moderate wear reduction is attained, whereas SiO₂, though showing rolling and mending effects, exhibits relatively high wear, probably because of lower load-bearing capacity at high contact stresses. The same tendency can be observed in the friction behavior where MoS₂ has the lowest mean COF (0.0698), then TiO₂ (0.0747), and finally SiO₂ (0.0791). MoS₂ has an average COF reduction of 11.80% compared to SiO₂ and 6.55% compared to TiO₂. Also, TiO₂ has a lower COF by 5.63% compared to SiO₂. The high friction reduction of MoS₂ can be attributed to its low shear strength and high adsorption capacity on metallic surfaces, which reduce interfacial resistance in the course of sliding. Similar decreases in friction have been demonstrated with MoS₂ nanoparticles, in which the lamellar structure of MoS₂ reduced COF by a large margin compared to oxide nanoparticles. Additives that work by forming protective films and micro-polishing, including TiO₂ and SiO₂ (Oxides) are applicable; they are generally more efficient through lower friction, but their greater shear resistance compared to layered sulfides also restricts their friction-reduction ability, as discussed. On the whole, the findings validate the hypothesis that, out of the studied nanoparticles, MoS₂ offers the best enhancement in wear resistance and friction reduction, followed by TiO₂, and SiO₂ has a relatively lower tribological enhancement in the current operating conditions.

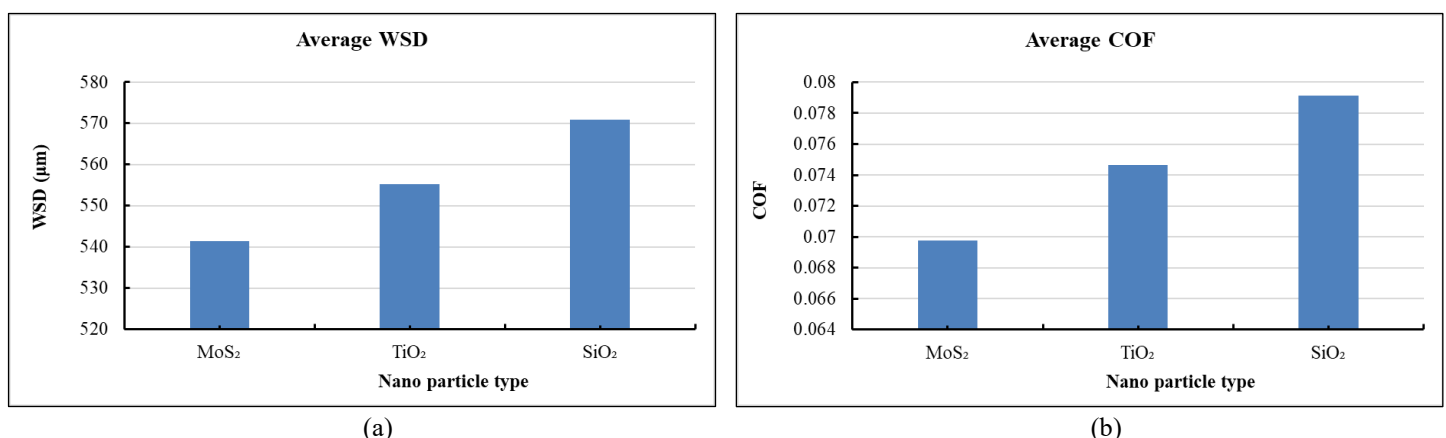


Figure 2: Comparison of nanoparticle type on (a) WSD (Average) and (b) COF (Average)

Source: Authors, (2026).

III.3 EFFECT OF NANOPARTICLE CONCENTRATION

Figure 1(a-c) and 2(a-c) show how the concentration of nanoparticles (1 wt/l, 1.5 wt/l, and 2 wt/l) affects the WSD and COF of coconut-derived oil (CSO), peanut-derived oil (PO), and Hybrid CSO-PO base oils. In all three base oils, a similar pattern can be observed: nanoparticles addition significantly enhances tribological performance at 1.5 wt, but performance declines at 2 wt. In the case of CSO, the addition of MoS₂ decreases WSD by 539 -1 wt -1 to 520 -1 wt -1 (a 3.53 -1 decrease), and then increases to 542 -1 wt -1.

The same pattern is observed with TiO₂, where a 5.66% decrease in WSD is observed between 1 wt% (565 μm) and 1.5 wt% (533 μm), compared to a relatively small 0.89% decrease in SiO₂ over the same concentration range. At 1.5 wt%, MoS₂ reduces WSD by 573 to 559 (2.44% decrease) compared to 2.91 and 4.45 (TiO₂ and SiO₂, respectively). Nevertheless, at 2 wt%, all nanoparticles exhibit higher wear, especially TiO₂ in PO, which increases drastically to 603 μm (a 6.16 percentage increase compared to 1.5 wt% percentage). The Hybrid CSO-PO shows the strongest improvement, particularly with MoS₂, where WSD is reduced to 509 -1.5 wt -1 (3.78 wt -1) and then again to 529 at 2 wt -1. These results show that 1.5 wt% is the best concentration to reduce wear in all types of nanoparticles and base oils. Similar behaviour with concentration is seen with friction characteristics. In the case of CSO, MoS₂ decreases COF by 0.076 at 1 wt.% to 0.067 at 1.5 wt.% (an 11.84% decrease), compared to a 10.13 wt -1 and 9.41 wt -1 decrease with TiO₂ and SiO₂, respectively. MoS₂ in PO attains 8.45% COF reduction at 1.5 wt and SiO₂ reduces COF by 7.89%. The hybrid oil once again shows the greatest reduction in friction, especially with MoS₂, in which COF is reduced to 0.061 (12.86% reduction). All types of nanoparticles show increased COF at 2 wt, which means reduced efficiency at high loadings. This tendency can be explained by the agglomeration of nanoparticles and enhanced third-body abrasion at high concentrations that interfere with the formation of uniform tribofilms and increase interfacial shear resistance. This is also observed in nanolubricant literature, where overloading of nanoparticles causes clustering and unstable dispersion of the nanoparticles, which are detrimental to wear and friction performance, as noted in (Jiang et al., 2024) and (Aher & Pandey, 2023). The excellent performance of MoS₂ in all the oils and concentrations is explained by its lamellar structure that is layered, which promotes low-shear sliding and stable formation of tribofilms, whereas TiO₂ is mainly involved in the reinforcement of protective oxide films and SiO₂ in rolling and polishing processes. In general, the findings prove that the concentration of nanoparticles is a critical factor in determining tribological performance, and 1.5 wt.% is the best balance between effective surface coverage and dispersion stability of the studied bio-lubricant systems.

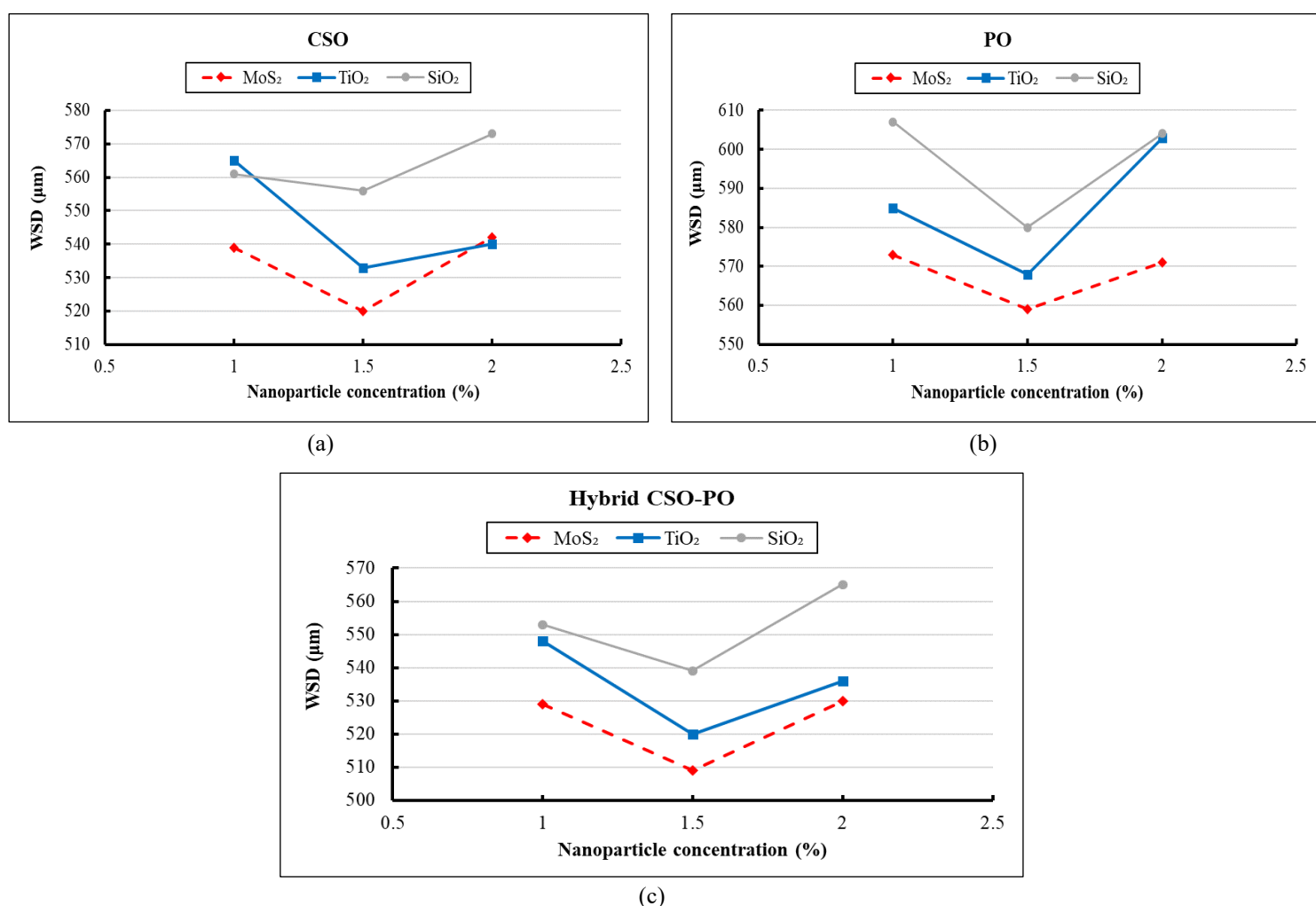


Figure 3 Effect of nanoparticle concentration on WSD for (a) CSO, (b) PO and (c) Hybrid CSO-PO
Source: Authors, (2026).

IV. COMPARATIVE PERFORMANCE AND OPTIMUM FORMULATION

An overall analysis of all the tested formulations shows clearly that Hybrid CSO-PO reinforced with 1.5 wt% MoS₂ is the best lubricant system in the current operating conditions. This formulation had the smallest wear scar diameter (509 μm) and the smallest coefficient of friction (0.061) of all 31 experimental runs. The optimized hybrid nano-lubricant has a 3.96% wear reduction and a significant 30.68% friction reduction when compared to the commercial synthetic oil (WSD=530 μm ; COF=0.088). These findings suggest that the synthetic oil has a moderately competitive anti-wear performance, but it has a much higher interfacial friction in the conditions of boundary lubrication.

Compared to the plain hybrid oil (WSD= 542 μm ; COF= 0.068), the 1.5 wt% MoS_2 addition causes a 6.09% wear reduction and a 10.29% friction reduction, which validates the high level of synergistic interaction between the blended vegetable oil matrix and the layered MoS_2 nanoparticles. This formulation is superior because of several reinforcing mechanisms such as the creation of a low-shear lamellar tribofilm, increased surface coverage because of the polarity of the ester groups in the hybrid oil, and the increased load-carrying capacity through the entrainment of nanoparticles at the asperity interface. Moreover, compared to other nanoparticle systems at the same concentration, Hybrid + MoS_2 (1.5 wt%) exhibits 2.12% less wear than Hybrid + TiO_2 (520 μm) and 5.57% less wear than Hybrid + SiO_2 (539 μm) and 10.29% and 16.44% lower friction, respectively. In all the base oils, the findings are always similar that MoS_2 is better than TiO_2 and SiO_2 and 1.5 wt% is the best concentration of nanoparticles. Both WSD and COF are higher at 2 wt.% and this indicates that agglomeration effects are present and dispersion stability is lower at higher loadings. The overall impact of the optimized nanoparticle concentration and hybrid base oil blending is the improved formation of the boundary film and the reduction of interfacial shear stress. In general, the Hybrid CSO-PO + 1.5 wt% MoS_2 formulation exhibits better friction reduction and competitive wear resistance than the commercial SAE20W50 lubricant, which validates its high potential as a high-performance bio-based alternative lubricant.

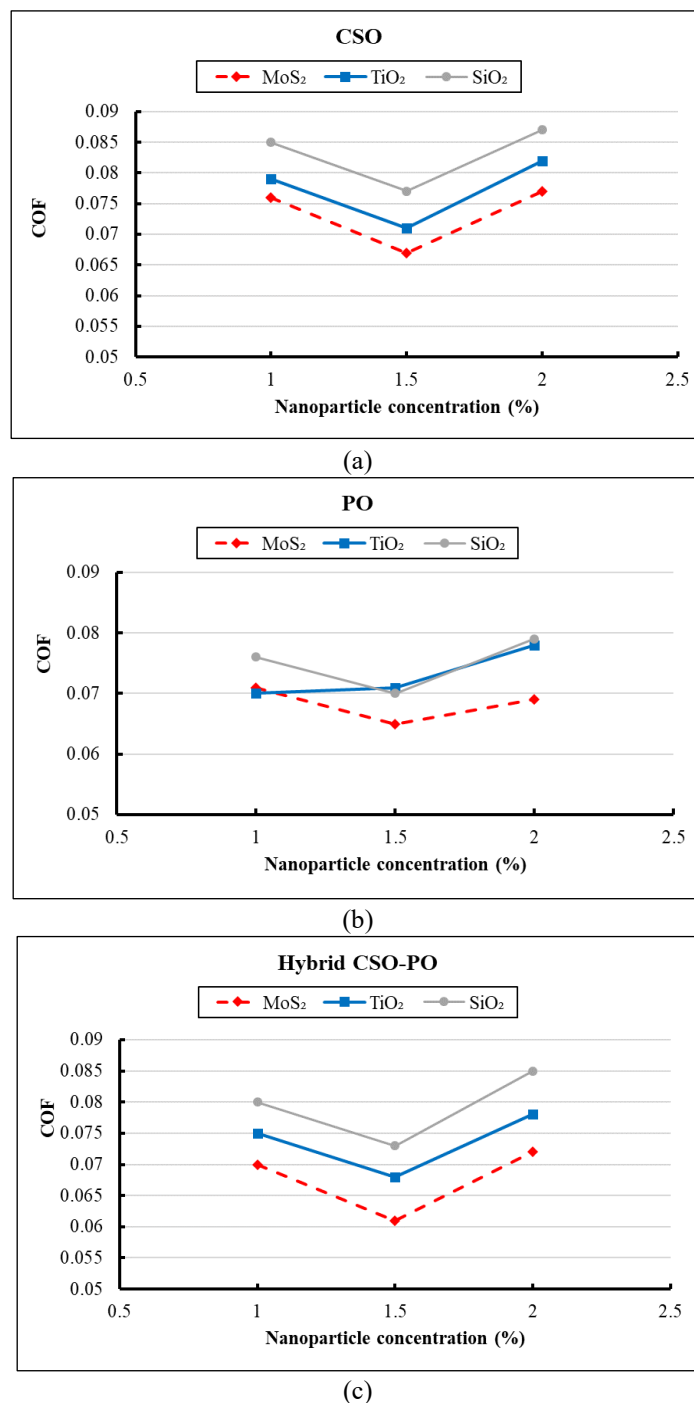


Figure 4 Effect of nanoparticle concentration on COF for (a) CSO, (b) PO and (c) Hybrid CSO-PO
Source: Authors, (2026).

IV. CONCLUSIONS

The current study investigated the tribological performance of CSO, PO, and a hybrid CSO-PO bio-lubricant that was supplemented with MoS₂, TiO₂ and SiO₂ nanoparticles at concentrations of 12 wt% using a four-ball tribotester and the results were compared systematically with those of a commercial synthetic lubricant (SAE 20W 50) to determine their viability as sustainable alternatives.

- The baseline tribological performance of Hybrid CSO-PO was better compared to that of the CSO and PO base oils, which showed a synergistic blending effect.
- Among the nanoparticle additives tested, MoS₂ exhibited the greatest anti-wear and friction-reducing properties in all base oils.
- The optimal loading of nanoparticles was identified to be 1.5 wt% above which wear and friction scores began to rise, probably because of nanoparticle agglomeration.
- The best-performing formulation, Hybrid CSO-PO with 1.5 wt.% MoS₂, had the least wear-scar diameter of 509 µm and a coefficient of friction of 0.061.
- Compared to the commercial SAE 20W50 reference, the optimized nano-bio lubricant had a 3.96% wear reduction and a 30.68% friction reduction, thus showing a better frictional performance with a competitive wear resistance.
- The enhanced tribological properties can be explained by the synergistic formation of the boundary film that is mediated by polar ester groups and the lamellar sliding mechanism that MoS₂ nanoparticles confer.

Future research must focus on the long-term oxidation stability, thermal stability, optimization of dispersion stability, and validation of nano-enhanced hybrid bio-lubricants in the real engine to advance the industrial applicability of nano-enhanced hybrid bio-lubricants.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Gaurav Pendbhaje, Mohammed Ali and Dipak Bajaj.

Methodology: Gaurav Pendbhaje, Mohammed Ali and Dipak Bajaj.

Investigation: Gaurav Pendbhaje, Mohammed Ali and Dipak Bajaj.

Discussion of results: Gaurav Pendbhaje, Mohammed Ali and Dipak Bajaj.

Writing – Original Draft: Gaurav Pendbhaje, Mohammed Ali and Dipak Bajaj.

Writing – Review and Editing: Gaurav Pendbhaje, Mohammed Ali and Dipak Bajaj.

Resources: Gaurav Pendbhaje, Mohammed Ali and Dipak Bajaj.

Supervision: Gaurav Pendbhaje, Mohammed Ali and Dipak Bajaj.

Approval of the final text: Gaurav Pendbhaje, Mohammed Ali and Dipak Bajaj.

VIII. REFERENCES

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