Investigation of the Effects of ZNO-CU Nano Particles on the Physiochemical and Tribological Characteristics of a Biolubricant Derived from Vegetable Oil

Ababu Girma Teshome
Mattu University; Mattu, Ethiopia

Abstract:
In this investigation, nine distinct vegetable oil-based blends were made from jatropha, sunflower, and soybean, by mixing them with commercial-grade engine oil of SAE20W40 and 1%, 2% weight percentage of Zno-Cu nanoparticles. Under the ASTM D4172B standard, four ball lubricant tests were used to examine the physiochemical characteristics: density, viscosity, viscosity index, and flash point as well as the tribological characteristics. A higher percentage (2%) of nanoparticle addition produced superior effects, according to the data. However, the pour point of the bio-based lubricant is also decreased at nano-particles the pour point should be increased due to wax crystal formation as nanoparticles act as nucleating site. When compared to SAE20-W40 commercial lubricant, the J102 and Su202 blends in particular have demonstrated decreased wear scar diameter (57.3% and 51.6%, respectively).

Keywords:
Flashpoint, Four ball tester, Jatropha, Pour point, Soybean oil, Sunflower oil, Viscosity, Wear.

1. Introduction

Fossil fuels are mostly utilized as energy sources, especially in the current manufaact-uring and automobile industries. Lubricants, which rely on crude oil supply, are frequently utilized to prevent equipment wear and tear damage.Crude oil-based lubricants' poorbiode-gradability endangers anthropogenic climate change by contaminating natural resources. It is necessary to use different techniques and materials for the same objective because of its toxicity, poor disposal, and quick degradation (Attia et al., 2020). However, because of deforestation, urbanization, and the expansion of infrastructure, plant-based resources which have immense potential to address these problems have lost significance. In order to get around this problem, efforts are being made to employ mineral oil lubrication in conjunction with vegetable oil-based lubricant, which may reduce usage and be a superior substitute. However, that is hardly a novel concept in our culture. Ancient people utilized plant and animal fats to reduce wear and friction (Dehghani Soufi et al., 2019). Additionally, studies and research in this rapidly growing field may also be conducted. In the same the same direction, but lubricants derived from vegetable oils are becoming more and more significant in industrial settings. Their high viscosity index, high flash and fire points, biodegradability, and ability to regenerate are some of their special advantages (Zhang et al., 2020). As a result, they have several drawbacks, including poor cold flow characteristics, weak oxidation, and poor thermal stability. Chemical treatments such as transesterification (Nogales-Delgado et al., 2021) and epoxidation (Barbosa et al., 2021)can be used to get around these problems. Many researchers looked at the tribological characteristics of oils derived from vegetables, including neem (Al-Arafi et al., 2022), pogamia (Shah et al., 2021), rice bran (Pindit et al., 2021), palm (Álvarez et al., 2025), sunflwer (De Feo et al., 2023), jatropha (Muthurathinam & Perumal, 2022), sesame (Melo Neta et al., 2023), and coconut(Muhammad et al., 2016). To cut down on the use of lubricants based on mineral oils, these modified oils can be used as bio additives to base stocks. Because of this, eco-friendly lubricants are crucial in the current crude oil crisis. By adding suitable nanoparticles, their lubricating properties can be improved to match or surpass those of their commercial counterparts. It contributes to longer lubrication life and better quality,

DOI: https://doi.org/10.5281/zenodo.20604611

which lowers energy usage. Nanoparticles' excellent anti-wear and heat-dissipating qualities make this very likely (Tulashie & Kotoka, 2020). In particular, the nanoparticles are employed as anti-wear (Sabarinath et al., 2019) and severe pressure (Mahara & Singh, 2020) additions to improve the tribological properties. The nanoparticles' size and quantity are crucial since an increase in volume could result in subpar tribological performance. Since the spherical shape of the nanoparticles covers the gaps between the surface's rough asperities, it is essential in lowering wear and friction (Panchal et al., 2017). Numerous additives made of nanoparticles are compatible with lubricants.Worldwide, studies are being conducted on nanoparticles, including graphene [24], SiO_2 (Kotturu et al., 2020) CuO (Jagatheesan & Babu, 2020), TiO_2 (Cursaru et al., 2019), Al_2O_3 (Sheikholeslami, 2018), and other nanoparticles (Kotia et al., 2019). An investigation on the dispersion of Al_2O_3, TiO_2, and hybrid particles in SAE5W30 oil under sliding contact friction and wear analysis was conducted by Sheikholeslami, (2018). They found that the commercial lubricant's dispersion of nanoparticles contributed to a decrease in fuel usage. Similarly, using Al_2O_3 and SiO_2 nanoparticles, (Farfan-Cabrera et al., 2020) discovered the mechanism of wear and friction in gear oils. In contrast to SiO_2 nano lubricant, they discovered that Al_2O_3 nano lubricant effectively reduced friction and wear of SS 304 material pins, demonstrating the good anti-wear properties of Al_2O_3 nanoparticles. The viscosity and density changes in pololester-based lubricants with different Al_2O_3 dispersion combinations were examined by Mark A. Kedzierski [(Sabarinath et al., 2019). He developed a model for the correlation of several characteristics, including the mass fraction of nanoparticles, their diameter, temperature, viscosity, and surfactant mass fraction, based on his research. He came to the conclusion that temperature and the mass fraction of surfactants affect the viscosity of nano-lubricants. To determine the effective dispersion percentage, Jagatheesan & Babu, (2020) investigated the dispersion of CuO particles in SAE20W50 motor oil. The best sample was determined to be 0.2% wt of CuO in oil because it had the best fire point and flash point readings with minimal viscosity change. Viscosity, thermal conductivity, and particle volume fraction were found to correlate with CuO nanoparticles and SAE 68 hydraulic oil by Kotia et al., (2019). The behavior of CCTO and ZDDP nanoparticles in castor oil lubricant was investigated by Zhang et al., (2020) using a four-ball wear tester. They discovered that adding 0.25% and 1% of both additives increased wear resistance and friction. The COF was found to be 30% lower when 2% cellulose nanocrystals were added to polyalphaolefin biolubricant by Álvarez et al., (2025). Nogales-Delgado et al., (2021) also saw a decrease in wear scar diameter (11%) and friction coefficient (15%) when TiO_2 nanoparticles were added to palm oil-based TMP ester. According to the findings of Shah et al., (2021), the inclusion of rod-shaped ZnO nanoparticles in sesame oil biolubricant decreased the wear scar diameter by 13.74%. Blends of methyl ester based on vegetable oil would benefit greatly from the addition of nanoparticles in terms of lubrication. The mixes are significantly affected by the addition of Zno-Cu nanoparticles in two different amounts. For the first time, this study examines how nano Zno-Cu particles affect the physiochemical and tribological characteristics of nine distinct biolubricant blends.

2. Materials and Methods

According to earlier studies, the three biolubricant blend samples were shortlisted. In order to prepare the oils samples, the biolubricant mixes jatropha, sunflower, and soya bean methyl ester. jatropha, soyabean, and Sunflower oils were transesterified to produce methyl ester and methyl esters of Zno-Cu composite nanoparticles were introduced to the biolubricant samples in two weight percentages (1% and 2%, respectively) after they had been prepared, and they were vigorously mixed. Figure 1(a,) illustrates the morphology and size distribution of Zno-Cu composite nanoparticles as determined by SEM imaging. The six nano-biolubricant samples were made as indicated in Table 1. In order to examine the performance of nano-bio lubricants, SAE20W40 oil was selected as a reference sample in addition to those samples. In this investigation, the four-ball lubricant tester, seen in figures 2(a) and 2(b), was manufactured by Ducom Instruments. A steel collet keeps the top ball in place, and a cup containing the lubricant holds the other three

DOI: https://doi.org/10.5281/zenodo.20604611

balls firmly in place. The balls have a diameter of 12.7 mm and are composed of AISI 52100 Chrome alloy steel. Its hardness falls between 64 and 66 HRC. A data gathering device and a computer are connected to the tribotester. Using Ducom's Tribodata software, the testing data is captured in real time. The apparatus uses a force sensor, load cell, and speed sensor to supply data to the data gathering system. The tribotester can manage loads of up to 10,000 N and revolve at up to 3000 rpm.

The test standards ASTM D2783
IP239, DIN51350-02, ASTM D4172, ASTM D5183,
and DIN51350-03 can all be used; however, ASTM D4172 B is the recommended research standard for this assessment. The table below (2) lists the test parameters.

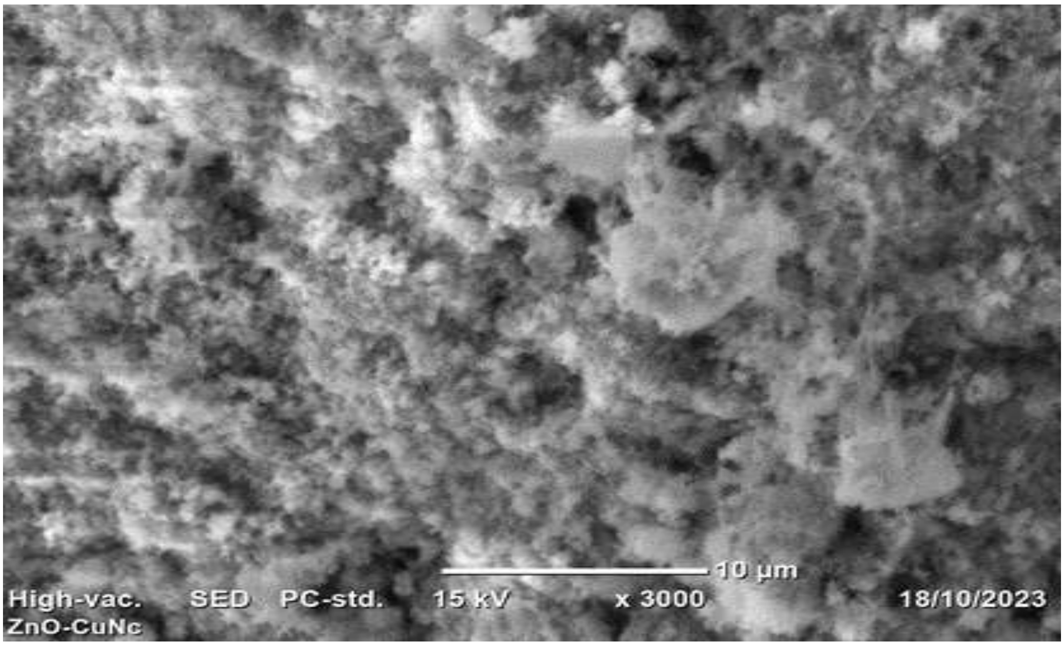


Figure.1. (a) Nano Particles (Zno-Cu) 3000X times Magnification.

Table 1. Composition of Nano-biolubricant samples.

Samples	**Vol. of Base oil for 1 litre (in ml) (SAE20W40)**	**Biolubricant additive**	**Volume of Biolubricant additive (ml)**	**Nanoparticle % weight**
J101	**900**	**JOME**	**100**	**1**
J101	**900**	**JOME**	**100**	**2**
SO201	**800**	**So-OME**	**200**	**1**
SO202	**800**	**So-OME**	**200**	**2**
SU301	**700**	**Su-OME**	**300**	**1**
SU302	**700**	**Su-OME**	**300**	**2**
SAE20W40	**1000**	**_____**		

Table 2. Wear test parameters (ASTM 4172B)

Test Parameters	Load (N)	Speed (RPM)	Duration (Mins)	Temperature (^{o}C)
Range / values	40	1200	60	75

DOI: https://doi.org/10.5281/zenodo.20604611

Figure. 2. (a). Four ball tester
(b). Four ball tester sample desk.

3. Results and Discussion

3.1. Physiochemical properties

Nano-biolubricant samples have been investigated for a number of physiochemical characteristics, including cloud point, pour point, density, viscosity, viscosity index, flash point, and fire point. It compares the outcomes.

3.1.1. Density

The density of a biolubricant is crucial since any equipment must pump lubrication to stop wear and tear in moving parts. The density of oil is affected by temperature. Additionally, wear debris that contaminates oil gradually lowers the oil's density, which impacts the effectiveness of the lubricant (Dehghani Soufi et al., 2019,Kotia et al., 2019). SAE20W40 oil, which is shown to be advantageous in reducing wear and friction at higher temperatures, has higher density values than ASTM D792 requirements. This is because vegetable oils-based samples had higher values than SAE20W40 because of the additional mass density of nano Zno-Cu particles. It was discovered that the J102 and So302 samples in particular had almost 12.5% more than the mineral oil lubricant.

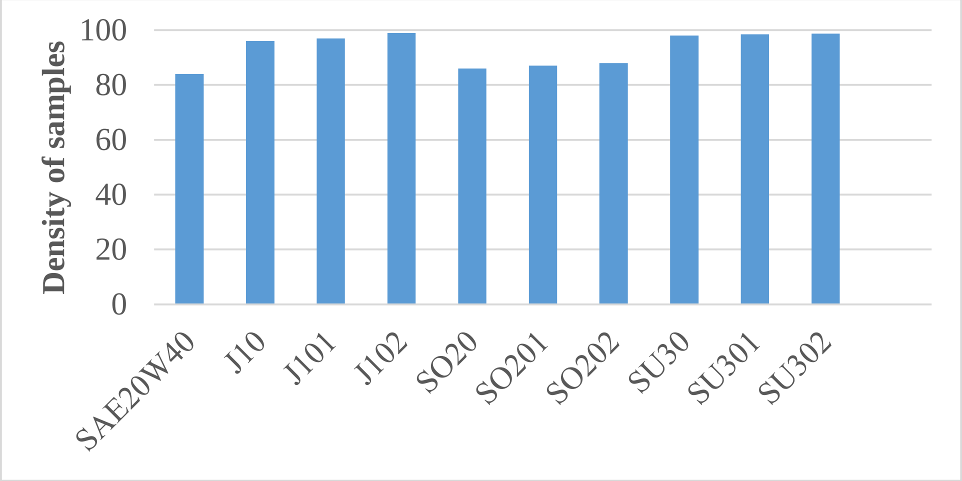


Figure. 3.1. Density of oil samples

3.1.2. Viscosity

Viscosity is a measure of a fluid's resistance to shear load. It is a crucial characteristic of all liquids, especially lubricants, that establishes their fitness for use in preventing wear and friction (Farfan-Cabrera et al., 2020, Cursaru et al., 2019). Using the ASTM D455 standard, the viscosity is measured at 40°C and 100°C.

DOI: https://doi.org/10.5281/zenodo.20604611

All of the nano-biolubricant samples' viscosities at 40°C slightly increase as the concentration of nano Zno-Cu particles rises. Mahara & Singh, (2020) discovered the identical behavior. Therefore, at 100^{o}C, almost all oils have viscosities comparable to SAE20W40 oil.

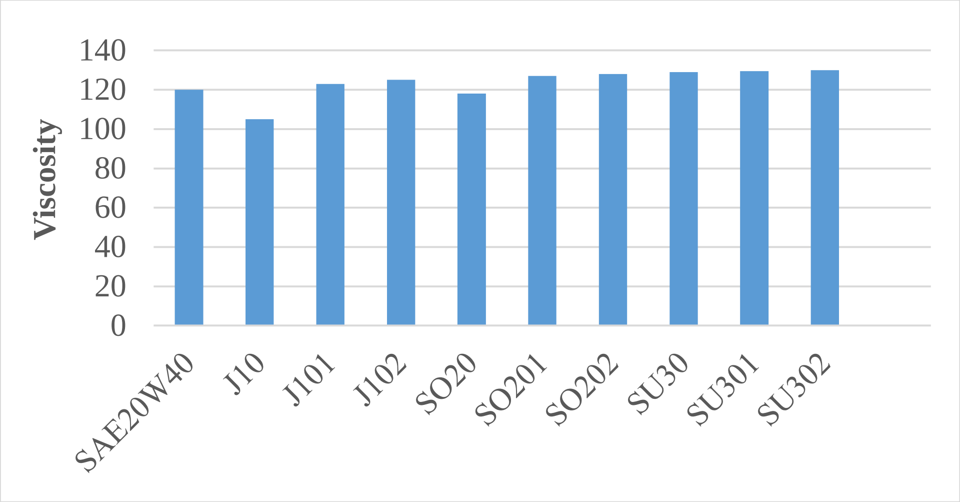
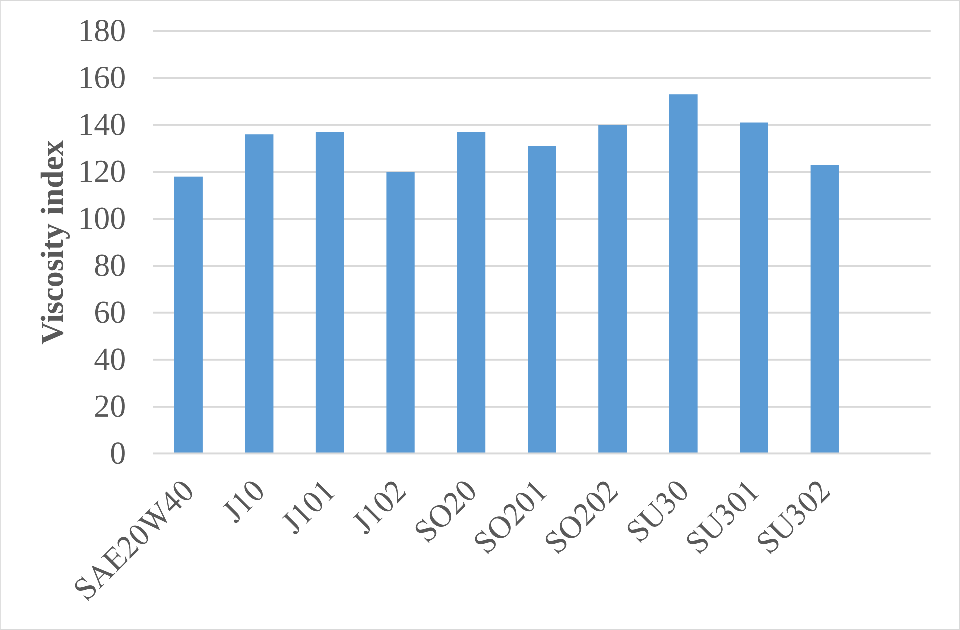


Figure. 3.2. Viscosity of oil samples (at 40^{o}C and 100^{o}C)

3.1.3. Viscosity Index

One essential metric for lubricating liquids that forecasts how viscosity will change with temperature is the viscosity index. This is an extremely important and desired feature of lubricants since friction produces heat and lubricants are used to lessen wear and friction. Consequently, it should be able to keep its lubricating properties at greater temperatures. Research has shown that the viscosity index values of nano-biolubricant blends are higher than those of SAE20W40 oil, a crucial characteristic of vegetable oils (Sheikholeslami, 2018,Li et al., 2019). Particularly, Su301 and So201 oils have a viscosity index that is 28% higher than that of regular SAE20W40 oil.



DOI: https://doi.org/10.5281/zenodo.20604611

Figure. 3.3. Viscosity Index of oil samples.

3.1.4. Flash point

A lubricant's flash point is the amount of heat it may withstand before turning into an ignitable mixture. In compliance with ASTM D92, it is performed using a Cleveland open cup tester (Panchal et al., 2017,J agatheesan & Babu, 2020). Zno-Cu nanoparticles have been found to increase the flash point values of J10, So20, and Su30 oils, which is very desirable as it is a reliable indicator of lubrication suitability. Zno-Cu 's enhanced thermal properties are ascribed to the methyl ester-based blends of vegetable oils' improved flash point characteristics. The flash point value of Su302 was comparable to that of commercial SAE20W40 oil out of all the mixes.

3.1.5. Pour point and Cloud point

The "pour point" of a lubricant, is the lowest temperature at which it will still flow under specified test conditions, essentially indicating its cold-temperature fluidity. The pour point is the temperature at which a liquid loses its ability to flow, or "pour," under defined test conditions. It's a crucial property for lubricants and other fluids, as it determines how they will behave in cold environments, ensuring proper lubrication and functionality. In compliance with ASTM D97, it is performed using automatic pour point and cloud point analyzer (KOEHLER instrument) (Mahara & Singh, 2020). The Zno-Cu can decrease the pour point of J10 and J101, then it should be increased at J102. Because, as the nanoparticle concentration increases, the nanoparticles acting as nucleation sites for wax crystal formation. This means that crystals start forming at slightly higher temperatures (increasing the cloud point) and the fluid solidifies at a higher temperature (increasing the pour point).

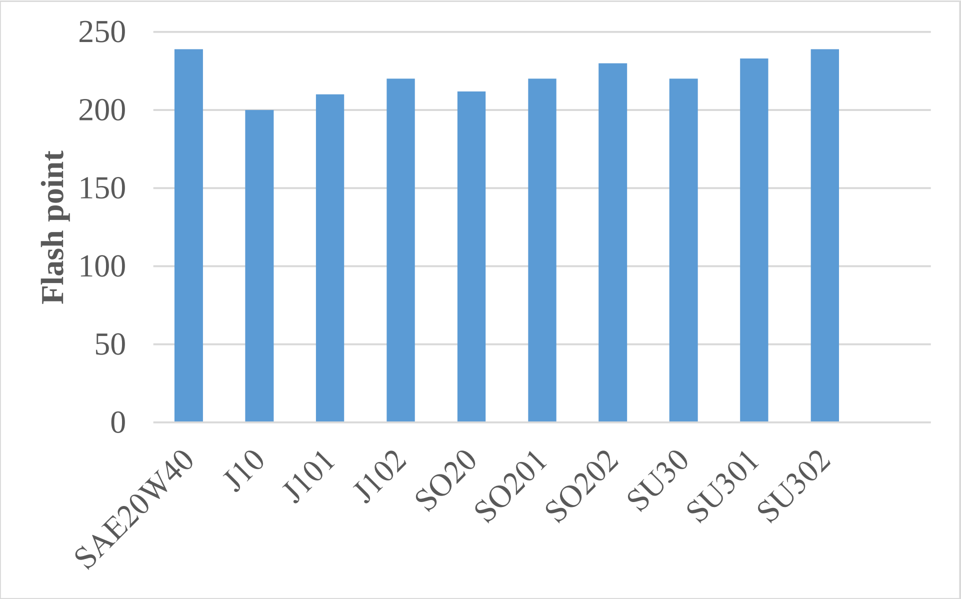


Figure. 3.4. Flash point of oil samples.

DOI: https://doi.org/10.5281/zenodo.20604611

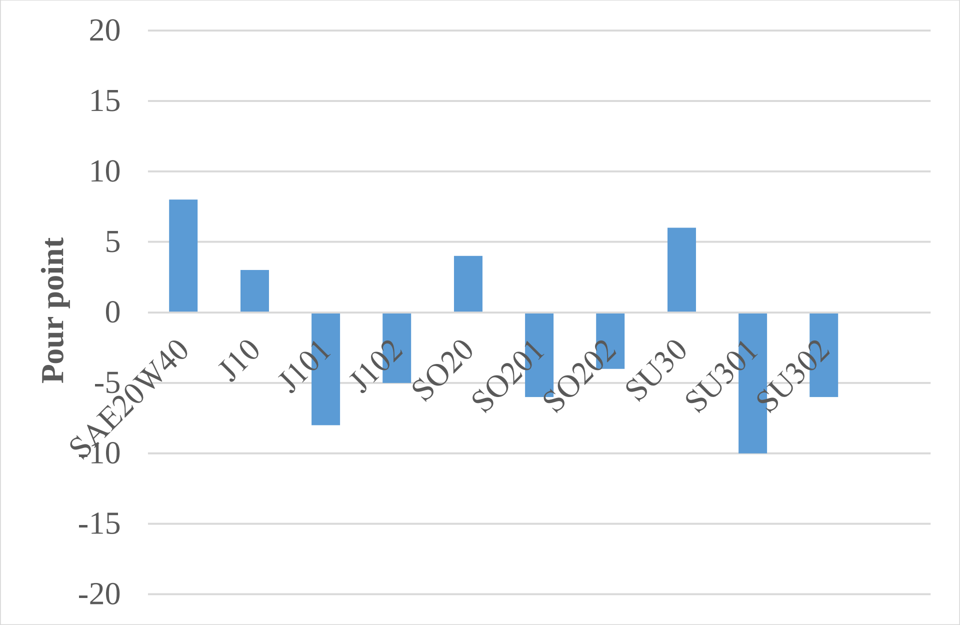


Figure. 3.5. Pour point of oil samples

3.1.11. Wear scar diameter

Figure 3.9 illustrates the wear scar diameters of all the lubricant samples. Based on observation, it is clear that the addition of nanoparticles has reduced the wear scar diameter, which is a positive result as predicted by the literature (Cursaru et al., 2019,Kotia et al., 2019, De Feo et al., 2023). Wear scar diameters have decreased for all biolubricant mixes and blends including nanoparticles. In particular, the J10, J101, and J102 samples have wear scar diameters of 715.2 µm, 626.7 µm, and 377.4 µm, which are 13.62%, 24.43%, and 54.2% smaller, respectively, than the SAE20W40 oil's wear scar diameter of 836.9 µm. This is because the addition of nanoparticles accelerated the rate of density growth, increasing the wear protection film's thickness through lubricant penetration across contact surfaces (Li et al., 2019). The So20, So201, and So202 samples show a similar pattern, with the wear scar diameter decreasing as the nanoparticle concentration is increased. So20, So201, and So202 have shown 17.6%, 26.9%, and 51.6% smaller wear scar widths at 673.2 µm, 591.3 µm, and 413.7 µm, respectively, in contrast to SAE oil. So-OME oil exhibits less wear scar than blends based on JOME because, although having a lower density than NOME oil, it contains a higher percentage of unsaturated fatty acids than the other two methyl esters (Sabarinath et al., 2019). In comparison, the Su-OME blends exhibit a growing rate of wear scar diameter; nonetheless, the values remain below those of the commercial lubricant SAE20W40. Su30 exhibits 47% (436.5 µm), 36% (532.3 µm), and 19.3% (671.7 µm) lower wear scar sizes than SAE20W40. The fact that there is more stearic acid (18.5%) present than So-OME (6.8%) and JOME (14.4%) makes it possible. It is well known that saturated acids interact with other molecules and that esters are polar, which aids in surface preservation (Farfan-Cabrera et al., 2020,Attia et al., 2020, Barbosa et al., 2021). More stearic acid in oils also improved their resistance to oxidation, which enhances their ability to lower friction.

DOI: https://doi.org/10.5281/zenodo.20604611

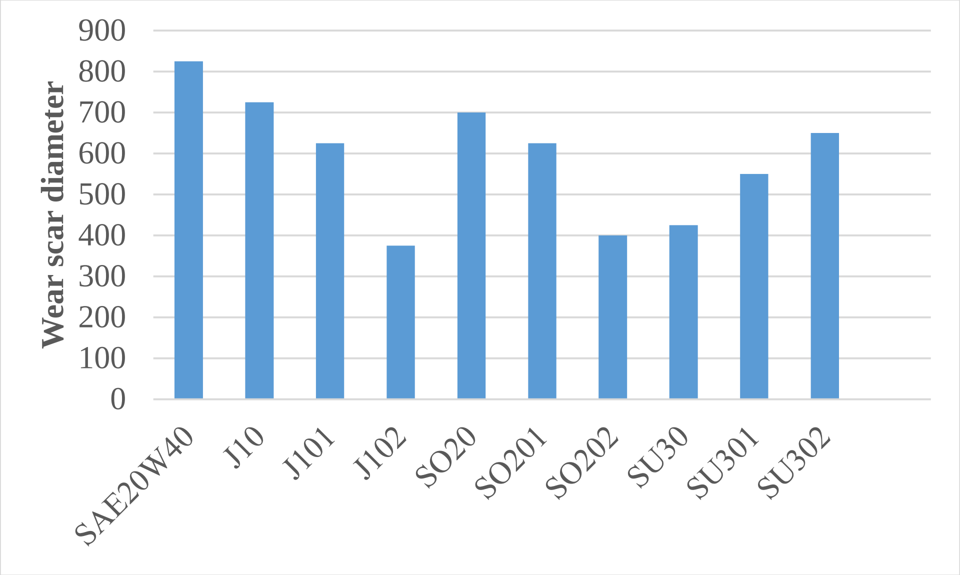


Figure. 3.6. WSD comparison of all oil samples

3.1.12. Anti-wear and Anti friction mechanism of Zno-Cu nanoparticles

The hexagon-shaped, densely packed crystal substance Zno-Cu has good wear, heat, and hardness resistance. It performs better than other materials in terms of resistance to wear as a result.

Due to their small size, modified Zno-Cu nanoparticles can readily make sliding contact without interfering with the hydrodynamic regime(Nogales-Delgado et al., 2021,Álvarez et al., 2025, Muthurathinam & Perumal, 2022). Zno-Cu nanoparticles can work similarly to ball bearings since they are typically spherical, eliminating direct contact between friction pairs and transforming sliding friction into rolling friction (Al-Arafi et al., 2022, Álvarez et al., 2025). Under severe strain, this enhances anti-wear qualities. When combined with lubricating oil, Zno-Cu nanoparticles aid to withstand compressive stress by taking up space in the worn-out area. Additionally, because of the high temperature produced by friction, the nanoparticles are chemically adsorbed and sintered on the metal friction surface.

3.1.13. SEM Imaging (Wear Scar Measurement)

Figure 3.7. exhibits the worn scar diameter SEM pictures. The wear pattern clearly has less grooves, and the inclusion of Zno-Cu nanoparticles works well with both JOME (J101 and J102) and POME (So201 and So202) blends. This is due to the Zno-Cu nanoparticles' smoothing effect in the boundary lubrication regime (Muthurathinam & Perumal, 2022). The higher density and higher viscosity values have an adverse effect with nanoparticles, which causes plowing of metals due to the higher hardness of the Zno-Cu nanoparticles (Tulashie & Kotoka, 2020). In contrast, the addition of nanoparticles had a negative effect with Su301 and Su302 oil blends.

DOI: https://doi.org/10.5281/zenodo.20604611

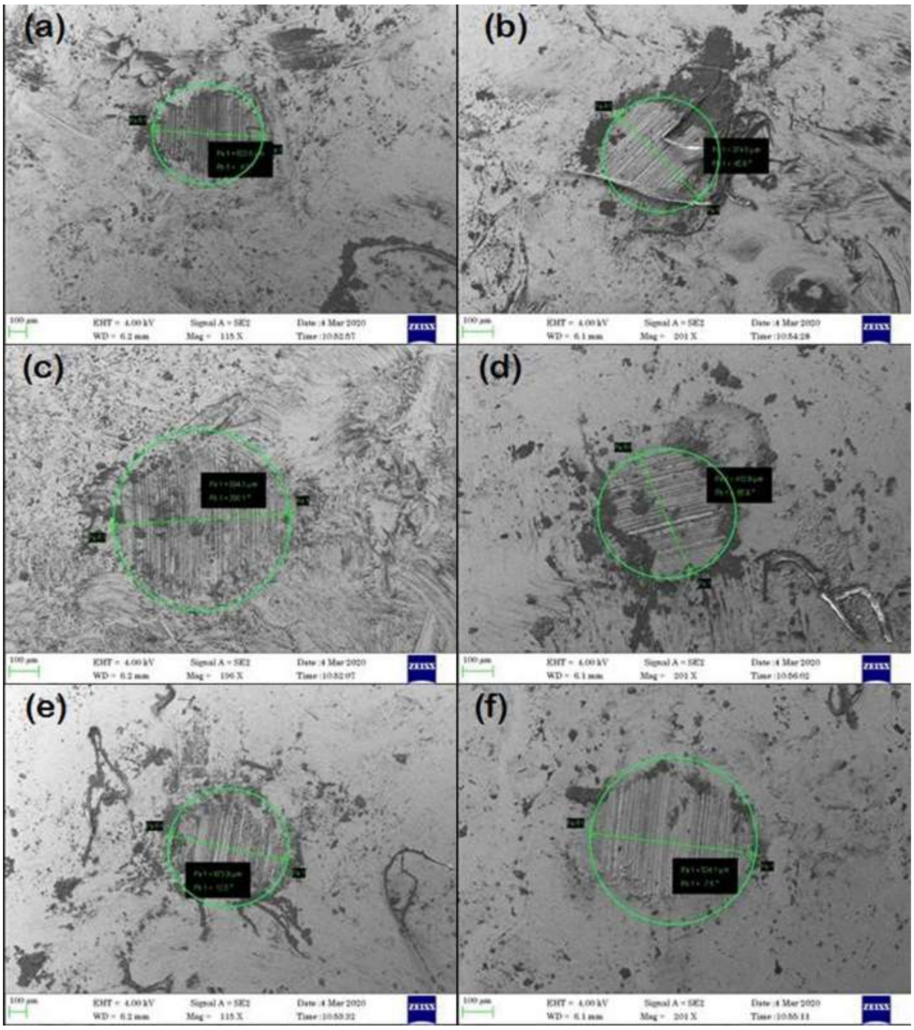


Figure. 3.7. Comparison of Wear scar diameters (a) J101, (b) J102, (c) So201, (d) So202, (e) Su301, (f) Su302.

4. Conclusion

The physiochemical and tribological characteristics of the various oil blends based on vegetable oil methyl esters containing 1% and 2% Zno-Cu nanoparticles were investigated. The findings led to the following observations: In JOME and JOME-based oil blends, the addition of nano Zno-Cu particles has demonstrated positive effects on physiochemical properties such as density, viscosity, and viscosity index. Since the values are better than those of the commercial lubricant SAE20W40, it is strongly advised to use the appropriate quantity of nano Zno-Cu with these blends. Notably, the property has enhanced once nano Zno-Cu was added to the flash point. The pour point of the base oil is also decrease due to the addition of Zno-Cu. Analyses of wear scars also revealed a similar pattern. In proportion to the quantity of nano Zno-Cu, the wear scar diameter decreased. In particular, J102 and So202 displayed the smallest wear scar diameters when compared to SAE20W40 oil, measuring 375 (55.2% smaller) and 413.9 (51.6% smaller). This indicates that the best combination of bio-nano additives and commercial lubricants will help reduce wear on contacting surfaces. Other mixes similarly decreased the WSD by roughly 17 to 53%. According to the study, adding nanoparticles to Sunflower oil methyl ester-based blends has negative effects on their behavior (apart from density and flash point) because the two substances are incompatible, which means that the combination should not be used in any anti-wear or anti-friction applications. Overall, the results demonstrate that the concentration of nano Zno-Cu

DOI: https://doi.org/10.5281/zenodo.20604611

particles had a significant impact on the wear and friction properties of the four ball wear test.

References

Al-Arafi, N., Salih, N., & Salimon, J. (2022). Synthesis, Characterization, Tribological and Rheological Properties of Oleyl Oleate Based Biolubricant. Egyptian Journal of Chemistry, 65(5), 419–433. https://doi.org/10.21608/ejchem.2021.77715.3797

Álvarez, P. M., Collado Contreras, J., & Nogales-Delgado, S. (2025). Biodiesel and Biolubricant Production from Waste Cooking Oil: Transesterification Reactor Modeling. Applied Sciences (Switzerland), 15(2). https://doi.org/10.3390/app15020575

Attia, N. K., El-Mekkawi, S. A., Elardy, O. A., & Abdelkader, E. A. (2020). Chemical and rheological assessment of produced biolubricants from different vegetable oils. Fuel, 271(March), 117578. https://doi.org/10.1016/j.fuel.2020.117578

Barbosa, M. S., Freire, C. C. C., Brandão, L. M. S., Pereira, E. B., Mendes, A. A., Pereira, M. M., Lima, Á. S., & Soares, C. M. F. (2021). Biolubricant production under zero-waste Moringa oleifera Lam biorefinery approach for boosting circular economy. Industrial Crops and Products, 167(November 2020). https://doi.org/10.1016/j.indcrop.2021.113542

Cursaru, D. L., Giagkasa, N., Vizireanu, S., Mihai, S., Matei, D., Biţă, B., Stancu, C., Manta, A. M., & Ramadan, I. (2019). Improvement of antiwear properties by coating the steel surfaces and by lubricant additivation. Digest Journal of Nanomaterials and Biostructures, 14(4), 907–915.

De Feo, G., Ferrara, C., Giordano, L., & Ossèo, L. S. (2023). Assessment of Three Recycling Pathways for Waste Cooking Oil as Feedstock in the Production of Biodiesel, Biolubricant, and Biosurfactant: A Multi-Criteria Decision Analysis Approach. Recycling, 8(4). https://doi.org/10.3390/recycling8040064

Dehghani Soufi, M., Ghobadian, B., Atashgaran, M., Mousavi, S. M., & Najafi, G. (2019). Biolubricant production from edible and novel indigenous vegetable oils: mainstream methodology, and prospects and challenges in Iran. Biofuels, Bioproducts and Biorefining, 13(3), 838–849. https://doi.org/10.1002/bbb.1953

Farfan-Cabrera, L. I., Gallardo-Hernández, E. A., Gómez-Guarneros, M., Pérez-González, J., & Godínez-Salcedo, J. G. (2020). Alteration of lubricity of Jatropha oil used as bio-lubricant for engines due to thermal ageing. Renewable Energy, 149, 1197–1204. https://doi.org/10.1016/j.renene.2019.10.116

Jagatheesan, K., & Babu, K. (2020). Experimental investigation of minimum quantity lubrication effects in turning process with nano fluids using aisi 4320. Digest Journal of Nanomaterials and Biostructures, 15(3), 809–814. https://doi.org/10.15251/djnb.2020.153.809

Kotia, A., Ghosh, G. K., Srivastava, I., Deval, P., & Ghosh, S. K. (2019). Mechanism for improvement of friction/wear by using Al2O3 and SiO2/Gear oil nanolubricants. Journal of Alloys and Compounds, 782, 592–599. https://doi.org/10.1016/j.jallcom.2018.12.215

Kotturu, C. M. V., Srinivas, V., Vandana, V., Chebattina, K. R. R., & Seetha Rama Rao, Y. (2020). Investigation of tribological properties and engine performance of polyol ester–based bio-lubricant: Commercial motorbike engine oil blends. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 234(5), 1304–1317. https://doi.org/10.1177/0954407019878359

Li, K., Zhang, X., Du, C., Yang, J., Wu, B., Guo, Z., Dong, C., Lin, N., & Yuan, C. (2019). Friction reduction and viscosity modification of cellulose nanocrystals as biolubricant additives in polyalphaolefin oil. Carbohydrate Polymers, 220(May), 228–235. https://doi.org/10.1016/j.carbpol.2019.05.072

Mahara, M., & Singh, Y. (2020). Tribological analysis of the neem oil during the addition of SiO2 nanoparticles at different loads. Materials Today: Proceedings, 28(xxxx), 1412–1415. https://doi.org/10.1016/j.matpr.2020.04.813

Melo Neta, M. M. F., Lima, G. R. R., Tavares, P. de O., Figueredo, I. de M., Rocha, W. da S., Ribeiro Filho, P. R. C. F., Cavalcante, C. L., & Luna, F. M. T. (2023). Thermo-Oxidative Stability and Tribological Properties of Biolubricants Obtained from Castor Oil Fatty Acids and Isoamyl Alcohol. Lubricants, 11(11). https://doi.org/10.3390/lubricants11110490

Muhammad, M., Dauda, M., & Bongfa, B. (2016). Influence of formulated neem seed oil and jatropha curcas seed oil on wire drawing of mild steel and medium carbon steel at

DOI: https://doi.org/10.5281/zenodo.20604611

elevated temperatures. Jurnal Tribologi, 10(August), 16–27.

Muthurathinam, S. G., & Perumal, A. V. (2022). Experimental study on effect of nano Al2 O3 in physiochemical and tribological properties of vegetable oil sourced biolubricant blends. Digest Journal of Nanomaterials and Biostructures, 17(1), 47–58. https://doi.org/10.15251/djnb.2022.171.47

Nogales-Delgado, S., Encinar, J. M., & González Cortés, Á. (2021). High oleic safflower oil as a feedstock for stable biodiesel and biolubricant production. Industrial Crops and Products, 170. https://doi.org/10.1016/j.indcrop.2021.113701

Panchal, T. M., Patel, A., Chauhan, D. D., Thomas, M., & Patel, J. V. (2017). A methodological review on bio-lubricants from vegetable oil based resources. Renewable and Sustainable Energy Reviews, 70(November 2016), 65–70. https://doi.org/10.1016/j.rser.2016.11.105

Pindit, K., Thanapimmetha, A., Saisriyoot, M., & Srinopakun, P. (2021). Biolubricant basestocks synthesis using 5-step reaction from jatropha oil, soybean oil, and palm fatty acid distillate. Industrial Crops and Products, 166(October 2020), 113484. https://doi.org/10.1016/j.indcrop.2021.113484

Sabarinath, S., Rajendrakumar, P. K., & Prabhakaran Nair, K. (2019). Evaluation of tribological properties of sesame oil as biolubricant with SiO2 nanoparticles and imidazolium-based ionic liquid as hybrid additives. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 233(9), 1306–1317. https://doi.org/10.1177/1350650119837831

Shah, R., Woydt, M., & Zhang, S. (2021). The economic and environmental significance of sustainable lubricants. Lubricants, 9(2), 1–11. https://doi.org/10.3390/lubricants9020021

Sheikholeslami, M. (2018). Influence of magnetic field on Al2O3-H2O nanofluid forced convection heat transfer in a porous lid driven cavity with hot sphere obstacle by means of LBM. Journal of Molecular Liquids, 263, 472–488. https://doi.org/10.1016/j.molliq.2018.04.111

Tulashie, S. K., & Kotoka, F. (2020). The potential of castor, palm kernel, and coconut oils as biolubricant base oil via chemical modification and formulation. Thermal Science and Engineering Progress, 16(January). https://doi.org/10.1016/j.tsep.2020.100480

Zhang, W., Wu, J., Yu, S., Shen, Y., Wu, Y., Chen, B., Nie, K., & Zhang, X. (2020). Modification and synthesis of low pour point plant-based lubricants with ionic liquid catalysis. Renewable Energy, 153, 1320–1329. https://doi.org/10.1016/j.renene.2020.02.067

DOI: https://doi.org/10.5281/zenodo.20604611