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RESEARCH

Effect of Nano-Additives on Tribological Behaviour of Hazelnut Oil and Sunflower Oil

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A B S T R A C T

The performance loss in industrial equipment due to friction and wear is one of the critical concerns among researchers. This drives the need to develop lubrication fluids that reduce friction to provide extended performance. The global sustainability movement drives the research towards novel bio-based oils to aid in lubrication. This study analyses the dispersion stability, tribological behaviour and antiwear properties of zinc oxide (ZnO), titanium dioxide (TiO_2) and molybdenum di sulphide (MoS_2) nanoparticles as an additive in hazelnut and sunflower oils. The viscosity index and flash point of the prepared nano lubricants were analyzed. The tribological test conducted on four ball tester resulted in a 12.6% and 35.8% reduction in coefficient of friction (COF) for 0.5% ZnO in hazelnut oil and 1% MoS_2 in sunflower oil. The corresponding wear scar images were analysed. The extreme pressure (EP) test resulted that 1% MoS_2 in sunflower oil exhibiting improved performance as it sustained a 1800N load. The kinematic viscosity of the 0.5% ZnO in hazelnut oil and 1% MoS_2 in sunflower oil had an improvement against others. Therefore, infusion of nano additives in bio-oils offers enhanced tribological properties foreseeing sustainability in applications.

1. INTRODUCTION

Amongst the conspicuous research areas connected with mechanical components, the study related to the tribological properties stands out as a result of it being the most heeded factor concerned with the performance of the system. The immense cost of tribological inadequacies is mainly due to a large amount of material and energy loss that occurs in the mechanical system at the operational stage [1]. The energy loss by friction and wear cannot be overlooked with the expanding automation of machinery [2,3]. The energy loss from wear and friction accounts for 33% of total annual energy consumption and the energy crisis has turned into a critical matter [4]. Mineral oil and synthetic-based lubricants were the largely utilized lubricants for industrial applications. However, the global trend towards sustainability and the growing concern in the development of environmentally friendly and biodegradable products has promoted extensive research on bio-based lubricants [5,6]. The biodegradability rate of mineral oil is 30-60% when compared to bio-oil at 95% [7]. The polar nature of fatty acids benefits in bond formation with a metallic surface and developing a thin film that assists in lowering friction and wear [8]. Though bio-oil-based lubricants expedite sustainability, they do possess some limitations like thermal oxidative stability, gumming effect and non-negative pour point [9,10]. The usage of nanofluids was introduced in various applications that needed improved thermal conductivity, viscosity etc., where the property of base oils was enhanced by dispersing suitable nanoparticles. The CuO nanofluid exhibited improved thermal conductivity with an increase in particle concentration [11]. Similar results were obtained for Al_2O_3-water nanofluids exhibiting improved thermal conductivity and heat transfer coefficient having potential application in shell and tube heat exchangers [12]. CNT-based nanofluids exhibited a significant increment in the critical heat flux having potential applications in cooling high heat flux [13]. Similarly, the limitations of bio-lubricants are outweighed by the application of nano-lubrication. Nano lubrication involves dispersing nanosized particles in the lubricant. The nanoparticles exhibit better mechanical properties that will improve the thermal physio properties of the base lubricant [14,15]. The nanoparticles sometimes structure a bond with a metallic surface and sometimes turn sliding into rolling friction [16,17]. The addition of 0.25% CuO and TiO_2 in palm oil based cutting fluid aided in a significant reduction of spindle speed vibration, surface roughness and material removal rate [18,19].

Several research concerning the tribological behaviour of diversified blends of bio-oils and nano additives have been accomplished [20]. The study of Shaari et al. on the tribological analysis of palm oil with 0.05, 0.1 and 0.2 wt% of TiO_2 nanoparticle in a four-ball tribo-tester resulted in a reduction of COF for 0.1 wt% and lower wear scar diameter (WSD) for 0.2 wt% of nanoparticle [21]. Ionescu et al. conducted the tribological characterisation of rapeseed oil added with ZnO and TiO_2 as nano additives of 0.25, 0.5 and 1 wt% in a four-ball tester that resulted in reduced COF with TiO_2 nanoparticles and reduced WSD with ZnO nanoparticles and both the values raise with increasing load [22]. Saravanakumar et al. studied the tribological characteristics of palm oil and sunflower oil having 0.1 & 0.2 wt% of copper oxide (CuO) and titanium oxide(TiO) against conventional oil in a pin on disc tester and resulted that 0.2 wt% of TiO with sunflower oil and 0.2 wt% of CuO with sunflower oil revealed 51% and 48% lower COF respectively as the sunflower oil forms a comparatively thick film than palm oil and overall, the bio-oil outperforms the conventional oil [23]. Shafi et al. conducted the friction & wear behaviour test of hazelnut oil blended with 0.5 and 1 wt% concentration of copper nanoparticles in a pin-on-disc tester and concluded that hazelnut oil with 0.5 wt% of copper nanoparticles improved COF by 80% and specific wear rate by 99% in comparison with a base oil and stated that the improved performance is the result of copper nanoparticle's film formation capability [24]. Cortes et al. examined the tribological behaviour of sunflower oil with 0.25-1.25 wt% concentrations of silica and TiO nanoparticles on a custom-made block on ring tribo tester that resulted in a reduction of COF by 93.7% and 77.7% with the addition of TiO and silica [25]. Xu et al. experimented with the tribological behaviour of rapeseed oil blended with 0.5, 1, 1.5 & 2 wt% of MoS_2 nano additives in a four-ball tester and concluded that the 1 wt% and 2 wt% of MoS_2 nano additive in rapeseed oil offered the lowest COF and lower WSD amongst the other [26]. Koshy et al. carried out the tribological characterisation of coconut oil against the paraffin oil with 0.25, 0.5, 0.75 and 1 wt% of MoS_2 nanoparticles in a four-ball tester and concluded that 0.5 wt% was the optimal concentration with less COF at 0.049 [27]. The investigative work by Ramakrishnan et al. on the tribological performance of ZnO and copper ZnO mixture with a concentration of 0.01 to 0.05 wt% in engine oil on a four-ball tester resulted in reduced COF and WSD of 18.75% and 50.8% for ZnO nanoparticle than copper ZnO mixture for 0.02 wt% concentration [28]. The bio-oils containing monounsaturated fatty acids are meant to provide an improved lubricating effect and oxidation stability. The use of nano-additive in oils is appreciated due to improved thermomechanical properties and the influence in improving lubrication. The influence of ZnO, TiO_2 and MoS_2 nano additive in improving the lubricating effect of hazelnut oil and sunflower oil to suit potential applications has not been assessed so far.

The cumulative literature on bio-oil-based lubricants with nanoparticle additives proposes improved tribological characteristics of bio-lubricants with the inclusion of nanoparticles like metal oxides and sulphides. The current study focuses on improving the tribological behaviour of the bio-oils with the inclusion of ZnO, TiO_2 and MoS_2 nano additives as minimal studies have been reported on the analysis of tribological behaviour of hazelnut oil and sunflower oil with the selected nanoparticles. The current study intends to assess the tribological behaviour of hazelnut oil and sunflower oil blended with ZnO, TiO_2, MoS_2 and nanoparticles of varied weight percentages utilizing a four-ball tester. The oil-nano additive blends exhibiting improved wear resistance were further subjected to EP and viscosity analysis.

2. MATERIALS

The oils chosen as the base in this work are hazelnut and sunflower oil, and the additives added were ZnO, TiO_2, and MoS_2. Hazelnut oil has a major component of monounsaturated fatty acids which provides effective lubricant performance at both high and low temperatures [29]. Sunflower oil contains unsaturated fatty acids that combine with the metallic surface to create a thin film-like layer which provides better lubricating features. The metal oxides aid in wear resistance as a result of the compaction of nanoparticles under heat and pressure or film formation between the surfaces or rolling in between sliding surfaces, while the sulphides produce a protective film mechanism formed due to the heat generated as a result of friction [30,31]. Due to their tiny size and huge surface area, the nanoparticles are more reactive and more able to cling to surfaces. With less wear and friction between moving elements, the equipment may operate more effectively and last longer. However, overdosing on nanoparticles can also harm the lubricant by making it more viscous and decreasing its flowability. When nanoparticles are added in large quantities, they tend to aggregate and form clusters that impair lubricant effectiveness. The compatibility and stability of the lubricant can be impacted by the interaction between the nanoparticles and the lubricant base oil and additives, which could have an impact on performance and dependability [32–35]. Thus, the lubricants were prepared with 0.25% - 1.0% nano-additive weight fractions in hazelnut oil and sunflower oil. The composition and the properties of the chosen oils and additives are given in Table 1&2 respectively.

Table 1. Lubricant oils used and their properties

Oil	Fatty acid compositions	Density	Viscosity Index	Flash Point
Hazelnut Oil	Unsaturated (mono): 77-83%	0.905 g/cm³	259.7	320 °C
	Unsaturated (poly): 10-14%			
	Saturated: 7-8%			
Sunflower Oil	Unsaturated (mono): 23%	0.91 g/cm³	206	252 °C
	Unsaturated (poly): 65%			
	Saturated: 12%			

Table 2. Properties of nano additives.

Material	Purity	Avg. particle size	Molecular weight	Melting point	Morphology
ZnO	99.9%	20-25 nm	81.408g/mol	1,975°C	Spherical
TiO_2	99.9%	25-35 nm	79.9 g/mol	1,843°C	Spherical
MoS_2	99.9%	85-90 nm	160.07 g/mol	2,375°C	Lamellar

3. EXPERIMENTAL SETUP

The nano lubricants were made by blending 0.25, 0.5, 0.75 and 1 wt% of nanoparticles in hazelnut oil and sunflower oil. The prepared nano lubricants were subjected to dispersion analysis and wear study. The best result-yielding combination was chosen for kinematic viscosity and EP analysis. The UV-1900 UV-VIS spectrophotometer was used to gauge the stability of the nano lubricants. Before the light reaches the sample, it is split into two beams in a double-beam UV-Vis spectroscopy. The liquid sample is illuminated by one beam, while the other beam serves as a reference. The test was conducted by adding around 3 ml of the base oils to the quartz cuvettes and measuring the oils' baseline. After measuring the baseline, the nano lubricant sample is inserted into the cuvette's base oil, and the sample's absorbance is calculated. For a range of wavelengths between 200 and 800 nm, the absorbance of the nano lubricant samples is determined. The flash point of the prepared nano lubricants was evaluated based on the ASTM D92 standard.

The friction and wear test was conducted using a Ducom four-ball tribometer as per the ASTM standard D4172. The four-ball tribometer equipped with a mobile ball bearing rotates in constant contact with three ball bearings that are fixed and as shown in fig. 1, is immersed in the prepared lubricant. The test balls used were chrome alloy steel (AISI E52100) measuring 12.7 mm in diameter and 64-66 HRC. For the wear test, the load applied was 392 N at a constant speed of 1200 rpm. The prepared oils were heated up to 75 °C and were run for 60 minutes. The balls were subjected to wear scar analysis after the test to identify the effect of bio-lubricants in the reduction of wear. The EP test was conducted in a Ducom four-ball tribometer with loads ranging from 1000N to 2000N at a constant speed of 1770 rpm at ambient temperature for 10 seconds and the load at seizure was noted.

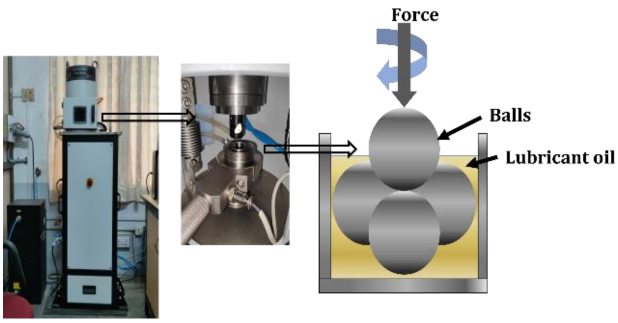


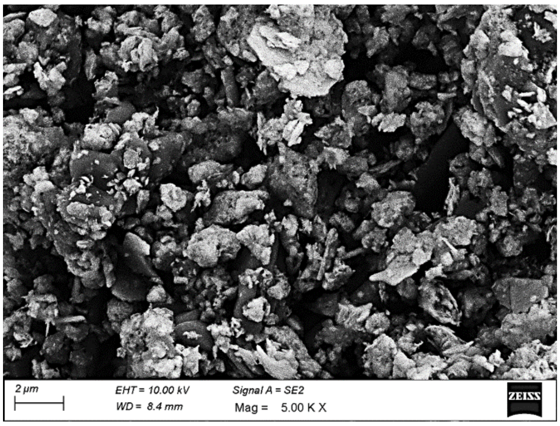
Fig. 1. Schematics of four-ball test apparatus.

The kinematic viscosity of the nano additive blended oils was measured using a redwood viscometer and the procedure was represented by IP 70/62. The blended oils were filled in the inner cylinder and 50cm^3 oil flows through the outlet to a standard flask the time taken is noted. The test was carried out at a temperature of 30°C with an increment of 10°C. The viscosity index of the nano lubricants was evaluated based on ASTM D-2270 utilising the kinematic viscosity of nano lubricants at 40°C and 100°C.

4. RESULTS AND DISCUSSIONS

4.1 Particle Characterisation

The size and shape of the nanoparticles are characterised by Scanning Electron Microscope (SEM), the constituents are verified by Energy Dispersive Spectroscopy (EDS) analysis and the phases formed were analysed using X-Ray Diffraction (XRD). The SEM characterisation of the acquired nanoparticles at different magnifications is depicted in fig. 2. The EDS analysis of the additives is shown in fig. 3. The SEM micrograph revealed ZnO (fig 2 a,d) and TiO_2 (fig 2 b,e) nanoparticles to be spherical and MoS_2 exhibited a lamellar structure as shown in fig 2c,f. The EDS images shown in fig 3a-c confirm the presence and purity of the nanoparticle elements. The XRD analysis confirms the phases in the nano additives, no impurity peaks or other phases were observed (fig 3d). The corresponding elemental mapping of nano additives is depicted in fig 4.



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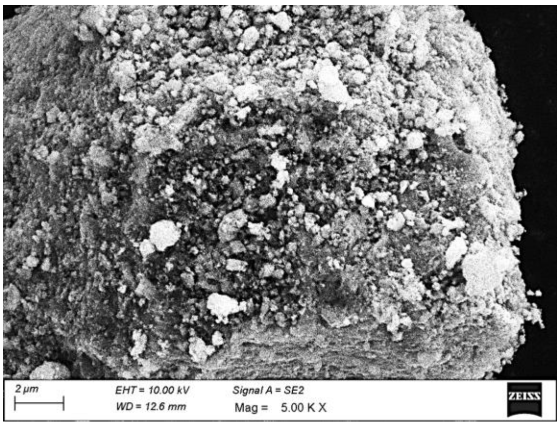

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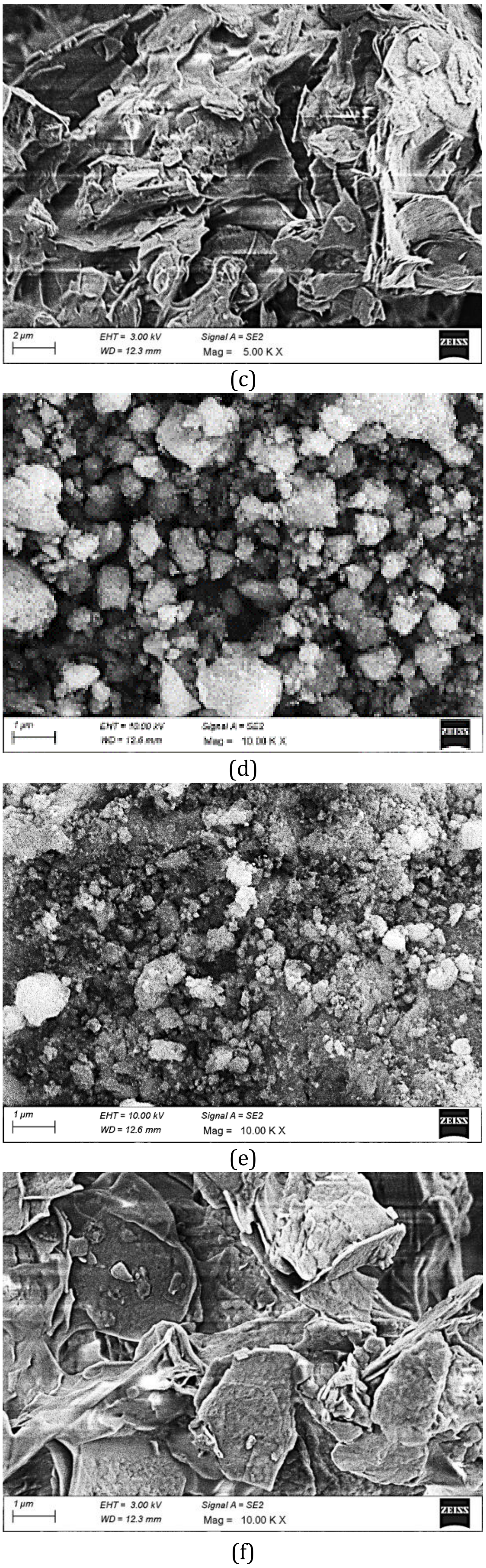


Fig. 2. SEM micrographs of (a,d) ZnO, (b,e) TiO_2, (c,f) MoS_2 nano additives.

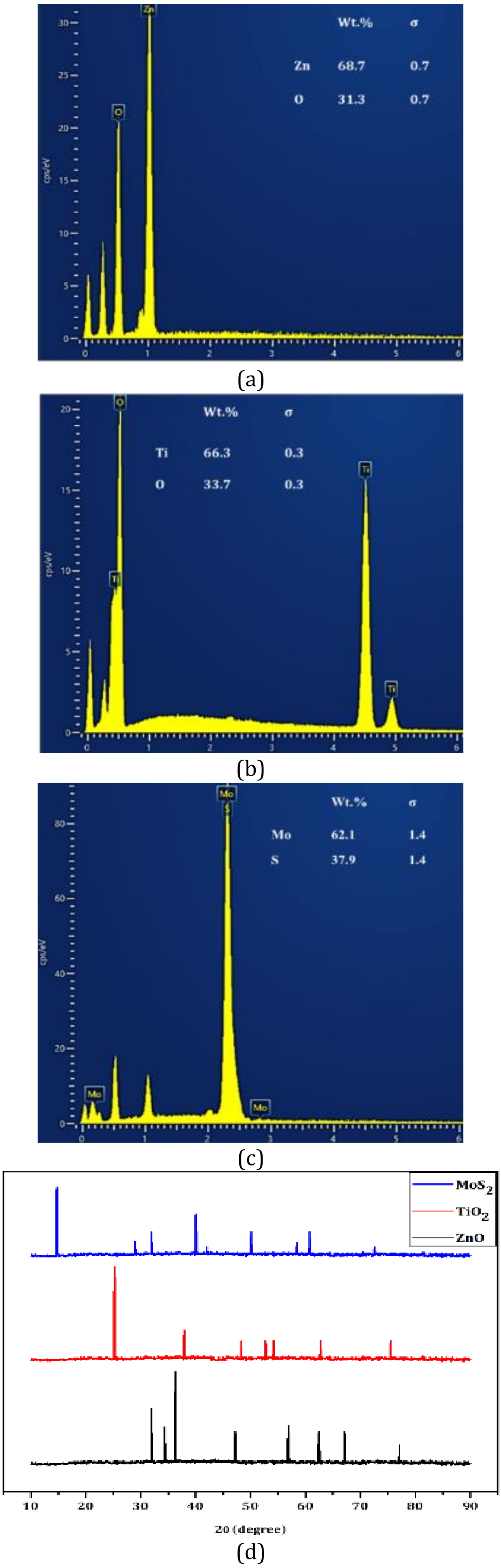


Fig. 3. EDS analysis of (a) ZnO, (b) TiO_2, (c) MoS_2 nano additives (d) XRD analysis of nano additives.

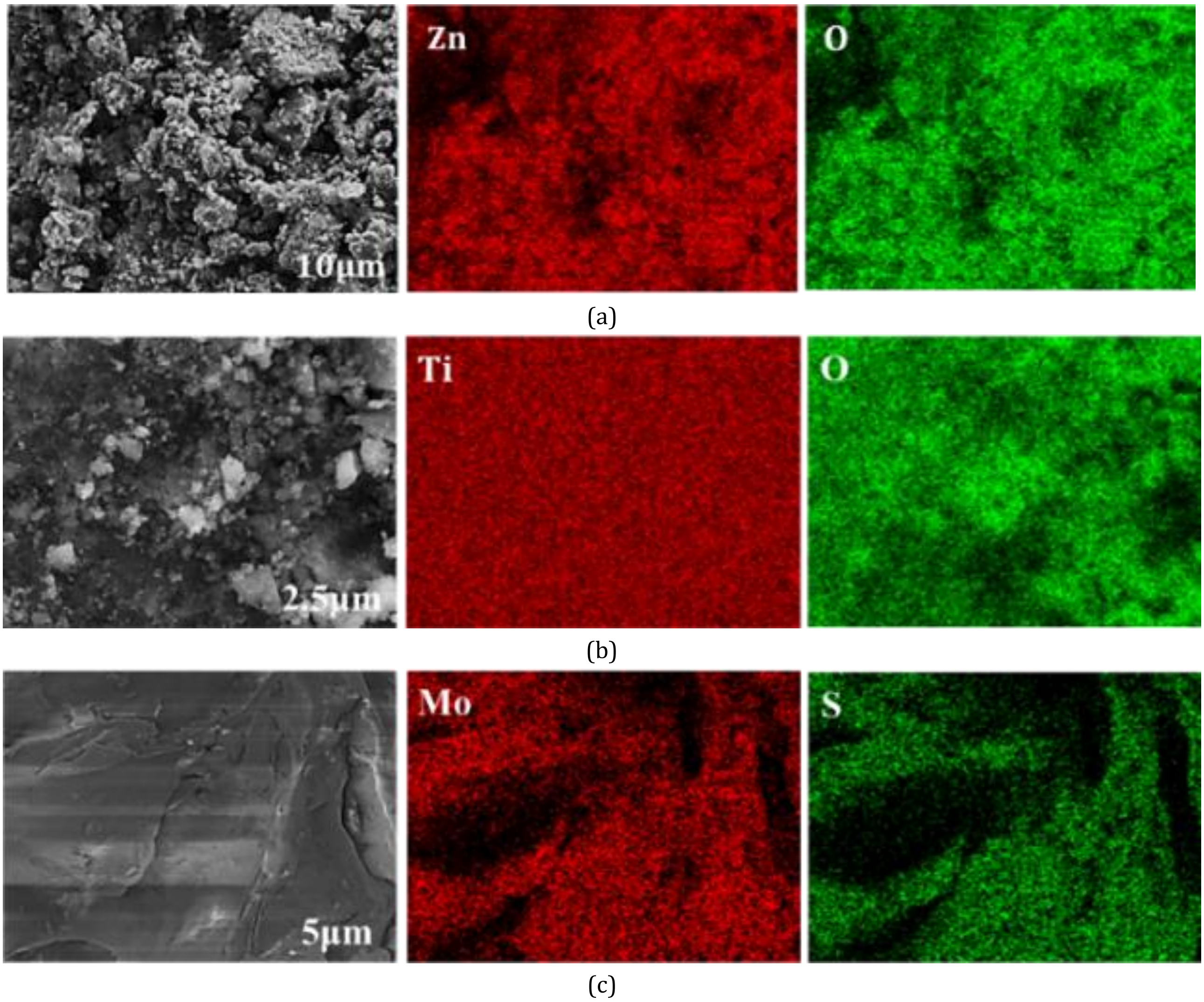


Fig. 4. Elemental mapping of (a) ZnO, (b) TiO_2, (c) MoS_2 nano additives.

4.2 Dispersion study

Figure 5a-f shows the stability of nano lubricants made from hazelnut and sunflower oils and having additives with various concentrations of ZnO, TiO_2, and MoS_2. With an increment in the concentration of ZnO in both hazelnut and sunflower oils, the absorbance was found to reduce after 0.5wt% and 0.25wt.% respectively. Hazelnut oil + 0.5%ZnO and sunflower oil +0.25% ZnO had the highest absorbance of 4.025 and 3.235 at 358 and 361nm respectively. Similarly, an increment in the concentration of TiO_2 greater than 0.25 wt.% in both hazelnut and sunflower oils resulted in the reduction of the absorbance. Hazelnut oil + 0.25% TiO_2 and sunflower oil +0.25% TiO_2 had the highest absorbance of 4.281 and 4.395 at 371 and 365nm respectively. The reduced absorbance at higher concentrations of additives can be accounted for by the aggregation of the nanoparticles as the repulsive forces are superseded by Brownian motion and Van-der-Walls force that degrades the properties of the nano lubricants [36,37]. While for the addition of MoS_2 in bio-oils, it has been found that for all samples, the absorbance of the nano lubricant samples rises with the concentration of nanoparticles. Further observation reveals that the peak value is shifted to higher wavelengths by the nanoparticle concentration. Hazelnut oil had the highest peak absorbance values for 1% MoS_2 at 3.353 which correspond to a wavelength of 363 nm. Similarly, sunflower oil had the highest peak absorbance values for 1% MoS_2 at 3.588 which correspond to a wavelength of 333 nm. The increased absorbance of the nano lubricant samples indicates that the oil is stable revealing that the nanoparticles are suspended in the oil [38–40].

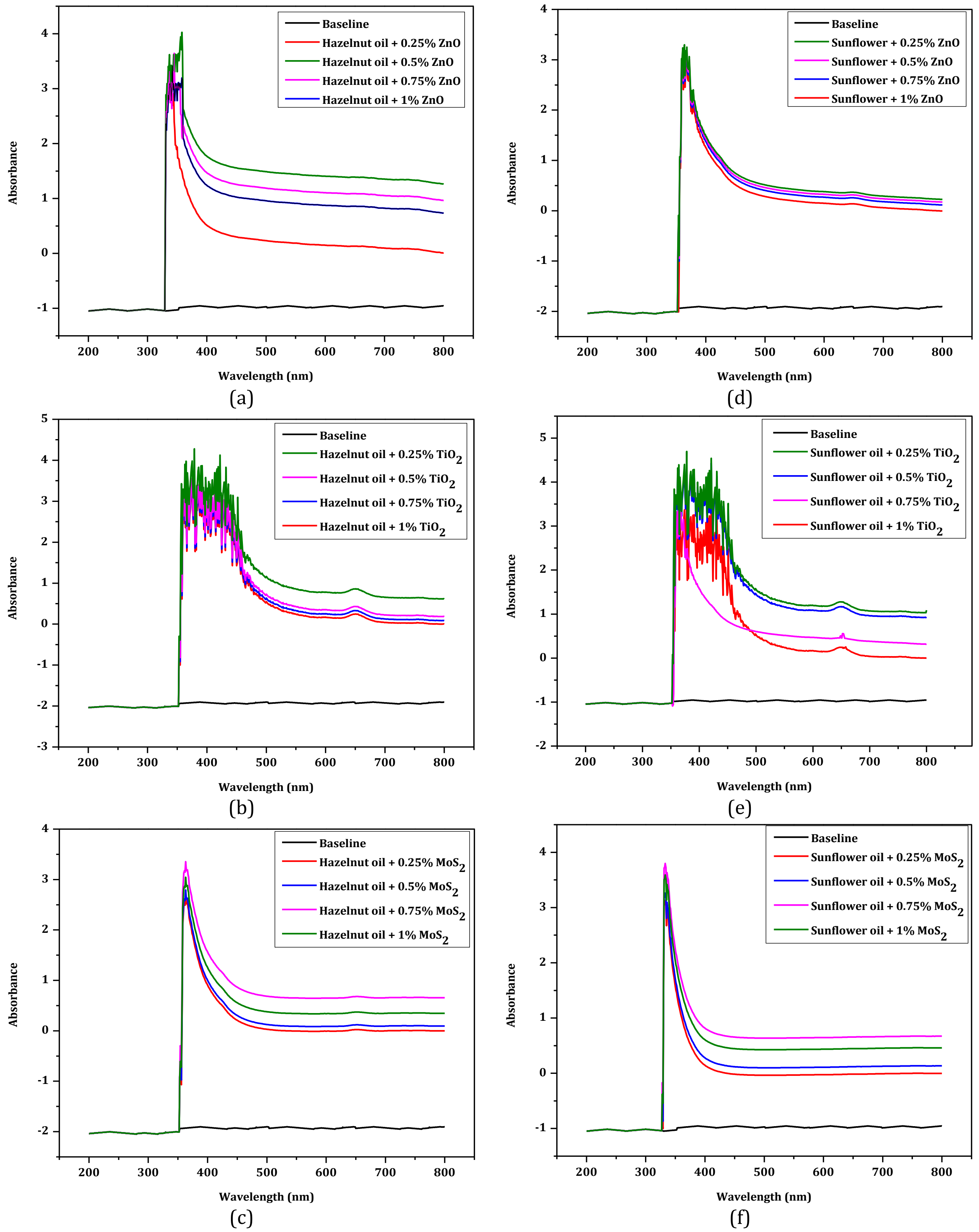
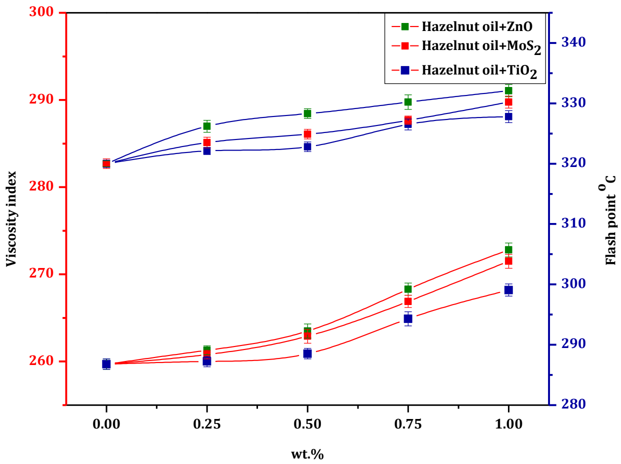


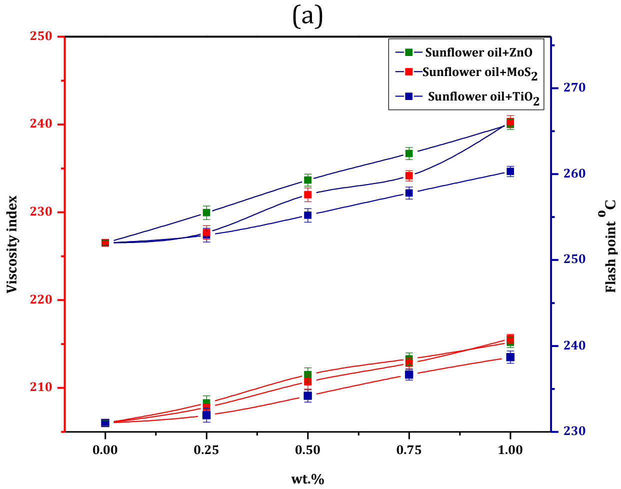
Fig. 5. Spectral absorbance of nano-lubricants with various fractions of nano additives.

4.3 Viscosity Index and flash point

The viscosity index, which is based on the kinematic viscosity of the samples, is a significant metric that determines lubricity. The flash point is the lowest temperature at which the fluid can form a combustible mixture with air. Fig. 6a, b illustrates the difference in viscosity index and flash point of nano lubricants prepared at different nanoparticle concentrations in hazelnut oil and sunflower oil respectively. With an increase in the nanoparticle concentration, both the viscosity index and flash point were observed to increase. Due to the higher accumulation of ZnO nanoparticles and the proximity of nanoparticles compared to MoS_2 and TiO_2, which makes the ZnO nanoparticles more coherent. The ZnO nanoparticles had higher viscosity values than both MoS_2 and TiO_2 nano lubricant [41]. At higher wt%, MoS_2 and ZnO had viscosity close in range. A similar trend was observed in the flash point evaluation of nano lubricants. The flash point study revealed that the ZnO and MoS_2 nano lubricants operating temperatures were equivalent at greater particle loading levels, with ZnO showing slightly better results in hazelnut oil, which is because ZnO nanoparticles are more stable and have better thermophysical properties than MoS_2 nanoparticles. In general, the presence of the nanoparticles increases the thermal conductivity of the nano lubricants, which accounts for their increased flammable resistance. Therefore, the increased flash point can be seen as a benefit with the increased lubricity properties of pure oil [42].



(a)

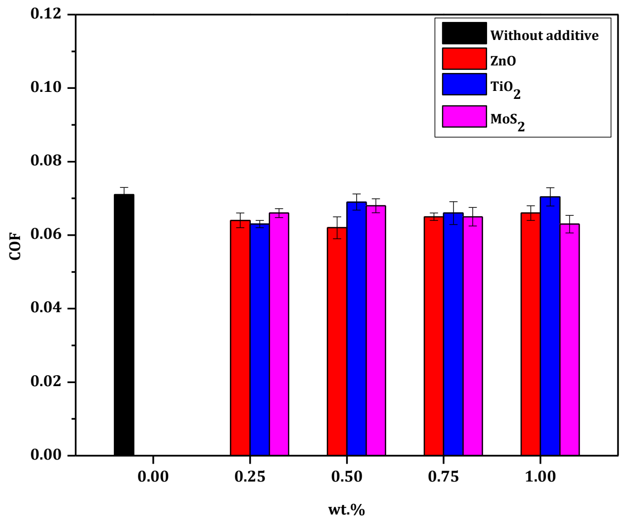


(b)

Fig. 6. Viscosity index and flash point of nano lubricants prepared with (a) hazelnut oil, (b) sunflower oil.

4.4 Friction and Wear Test

The COF obtained is depicted in fig. 7(a, b). It adduces the infusion of nano additives in the base oil and enhances the wear and friction properties of the bio lubricant. Suspension of 0.5% of ZnO in hazelnut oil and 1% MoS_2 in sunflower oil offered a better reduction in COF when compared to others. The inclusion of TiO_2 also reduced the COF, 0.25% TiO_2 exhibited lower COF as compared to the base oils as TiO_2 induces a shear thickening effect when dispersed in oil [25]. The blend of nano additive dispersed oils that exhibited improved tribological performance was further analysed in detail. The COF value for 0.5% ZnO in hazelnut oil was 0.062 as observed in fig. 8a and COF for 1% of MoS_2 in sunflower oil was 0.050 as indicated in fig. 8b. The inclusion of nano additives in the hazelnut oil and sunflower oil aided in the reduction of COF by 12.6% and 35.8% respectively.



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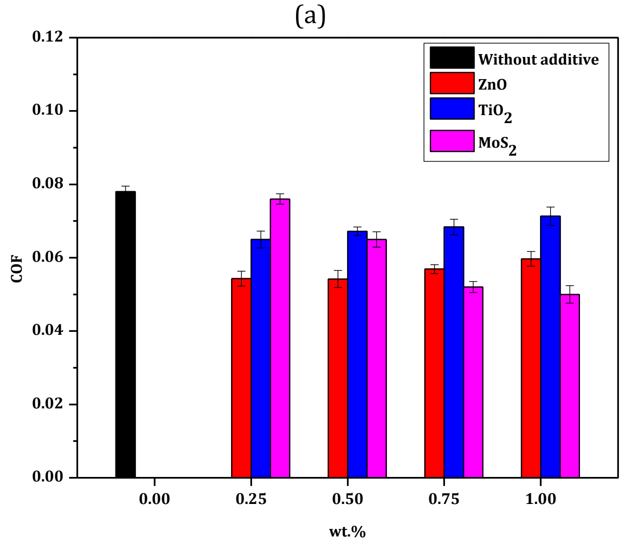
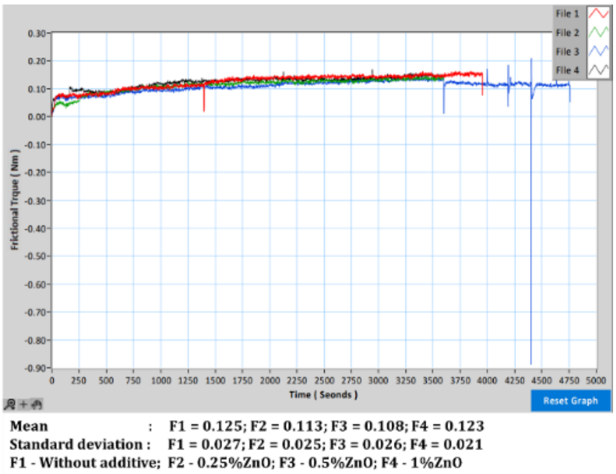


(b)

Fig. 7. COF of (a) Hazelnut oil and (b) Sunflower oil.



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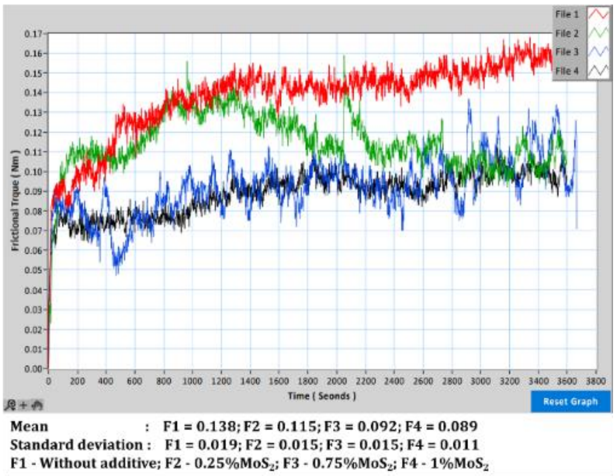
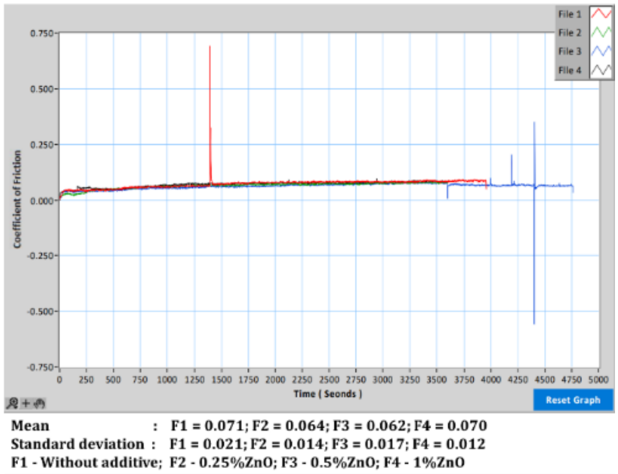


(b)

Fig. 8. COF for various concentrations of (a) ZnO in hazelnut oil, (b)MoS_2 in sunflower oil.

The frictional torque of hazelnut oil with various concentrations of ZnO is shown in fig. 9a reveals that the addition of 0.5% of ZnO in hazelnut oil showed reduced frictional torque to 0.108 Nm having a 13.6% reduction compared to that of oil without additives. The frictional torque of sunflower oil with various concentrations of MoS_2 is depicted in fig. 9b shows that the addition of 1% of MoS_2 in sunflower oil gave reduced frictional torque of 0.089 Nm having a 35.5% reduction compared to that of oil without additives. Metal oxides perform well under heat and pressure by the rolling mechanism that is supported by its spherical microstructure. With an increase in lubricant temperature from normal (25^0C) to working temperature (75^0C), the nanoparticles begin to diffuse and decrease in volume. The nanoparticles increasingly aggregate and disperse into rather tight clusters as the oil temperature rises. The second significant factor for the lower frictional coefficient is that the spherical profile of ZnO nanoparticles continued throughout the diffusion and particles were deemed combined due to ZnO nanoparticles with the increase in melting point and density than TiO_2 in the bulk form [43]. Higher concentrations of both nano additives (ZnO, TiO_2) added to each oil demonstrate an escalating trend in wear from agglomeration and abrasion [44].



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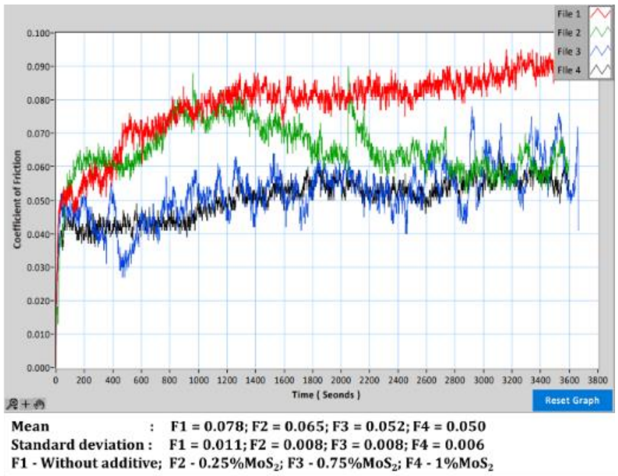


(b)

Fig. 9. Frictional torque for various concentrations of (a) ZnO in hazelnut oil, (b) MoS_2 in sunflower oil.

The test balls were collected, cleaned and subjected to an image acquisition device to capture the WSD (fig. 10). The wear scar analysis revealed a critical decrement in wear upon nano additives being blended. While comparing the Mean Wear Scar Diameter (MWSD), there is a reduction of 4.74% in Hazelnut oil with 0.5% ZnO and 17.17% in sunflower oil with 1% MoS_2 compared to that of oils without additives. While analysing the MWSD of TiO_2 in both the oil blends, it was found that 0.25% exhibited lower MWSD. A reduction of 2.29% and 5.31% in MSWD was observed for hazelnut oil and sunflower oil blended with 0.25% TiO_2. The interaction between lubricant and friction modifier blended determines how a lubricant's anti-wear qualities will change in the presence of a friction modifier. ZnO has demonstrated improved anti-wear characteristics at lower concentrations. Higher ZnO concentrations did not affect the COF. Along with the increase in ZnO concentration, the wear scar also grew [45]. The three-body abrasion effect of the nanoparticle is what causes the WSD to increase at increased concentrations of nanoparticles [46]. Analysing the MWSD, the 1% MoS_2 in sunflower oil revealed the lowest WSD. That is because of the protective film/layer formation. MoS_2 offered overall better COF that proves its protective layer mechanism formed under heat which significantly improves the lubricant performance [47]. The addition of 1% MoS_2 in sunflower oil exhibited much lower WSD compared to that of CuO and ZrO_2 nanoparticles dispersed in sunflower oil [48].

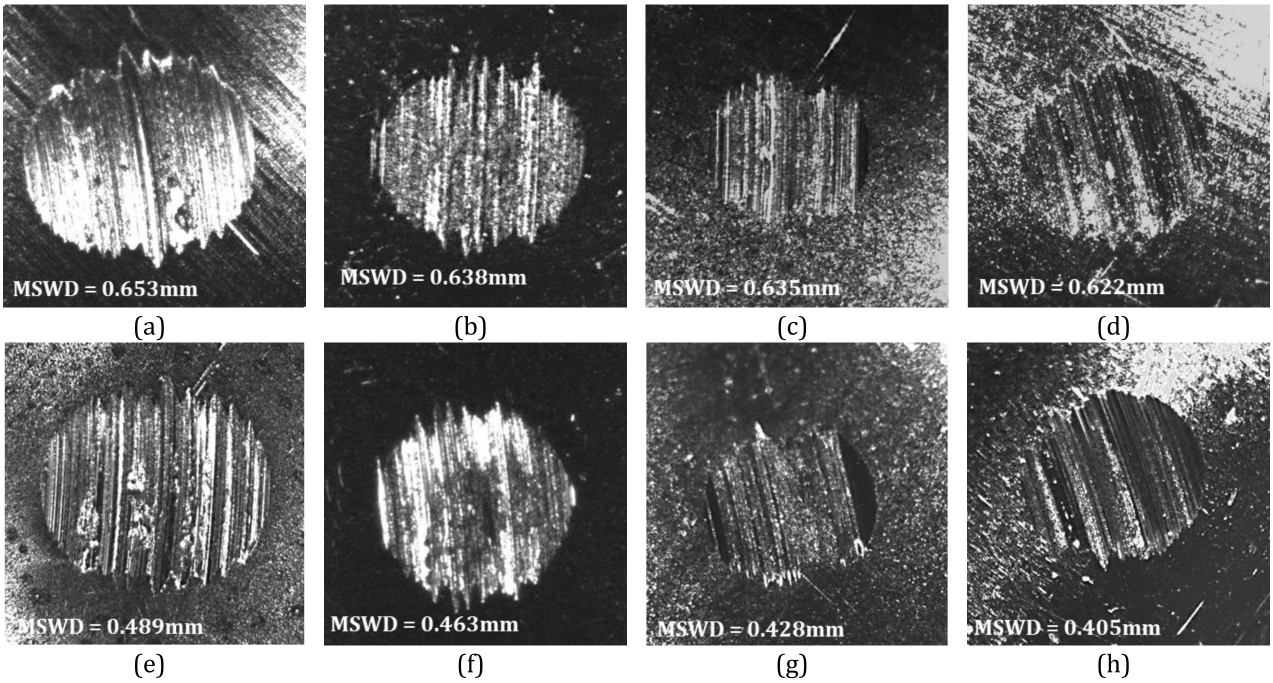


Fig. 10. WSD of the balls a) Hazelnut oil, b) Hazelnut oil with 0.25%TiO_2, c) Hazelnut oil with 1%MoS_2, d) Hazelnut oil with 0.5% ZnO, e) Sunflower oil, f) Sunflower oil with 0.25%TiO_2, g) Sunflower oil with 0.5% ZnO, h) Sunflower oil with 1% MoS_2

4.5 Extreme pressure

The EP behaviour of the produced nano lubricants was evaluated using a four-ball tribometer using ASTM D 2783 standard. Since Hazelnut oil with 0.5% ZnO and sunflower oil with 1% MoS_2 exhibited better wear properties, these oil blends were subjected to EP analysis. The conducted EP test revealed that the seizure load for Hazelnut oil with 0.5% ZnO was found to be 1250N while for sunflower oil with 1% MoS_2, it was 2000N where the balls got cold welded as shown in fig. 11. The balls are forced against one another as a result of friction, the ZnO particles are also crushed in the surface grooves created by this process. The asperities' interaction raised the contact pressure, which then raised the local contact temperature.

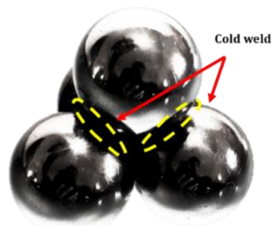
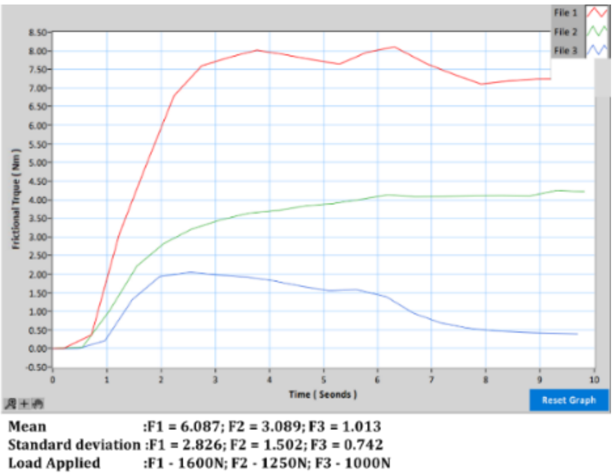


Fig. 11. Cold welded balls at seizure load.

As a result of the localised heating of asperities brought on by the friction between the tribo pairs, ZnO particles were diffused. ZnO nanoparticle deposition caused the asperities to be covered, minimising interaction among tribo pairs and enhancing load-bearing capacity [49]. The safe operating loads for Hazelnut oil with 0.5% ZnO and sunflower oil with 1% MoS_2 were found to be 1000N and 1800N. The frictional torque at a safe load was 1.013Nm for Hazelnut oil with 0.5% ZnO above which the balls got cold when a load of 1250 N was applied (fig. 12a), while it was 0.438Nm for sunflower oil with 1% MoS_2, where the oil could provide effective lubrication even at an elevated load of 1800N (fig. 12b). The portrayed improvement in MoS_2-based nano lubricant was due to the solid covalent bonding keeping the molybdenum and sulphur intact. Van der Waals bond and numerous layers were sheared effectively along the sulphur bond, offering lubrication. The seizure of reaching layers was avoided by the sheared MoS_2 particles [31].



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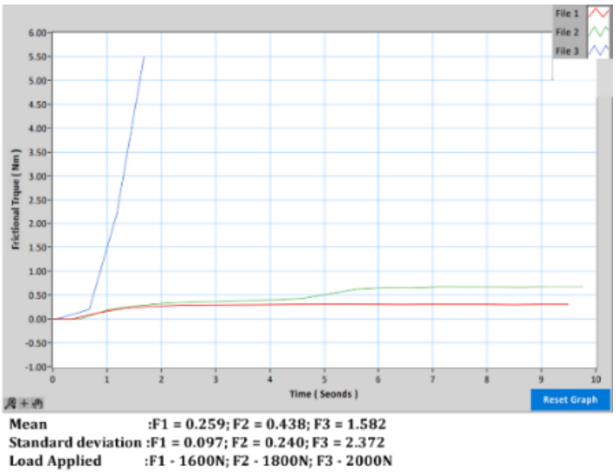

(b)

Fig. 12. Frictional torque of various loads for (a) Hazelnut oil with 0.5% ZnO, (b) sunflower oil with 1% MoS_2.

4.6 Kinematic viscosity

Viscosity, one of the key elements in choosing the right lubricating oil for moving parts in machinery, is the measure of a fluid's resistance to flow. The kinematic viscosity of the oil blends those offered improved wear characteristics was analysed from room temperature to 80°C. The bend of hazelnut oil+0.5%ZnO and sunflower oil+1%MoS_2 which provided better reduction in wear along with base oils were subjected to kinematic viscosity analysis.

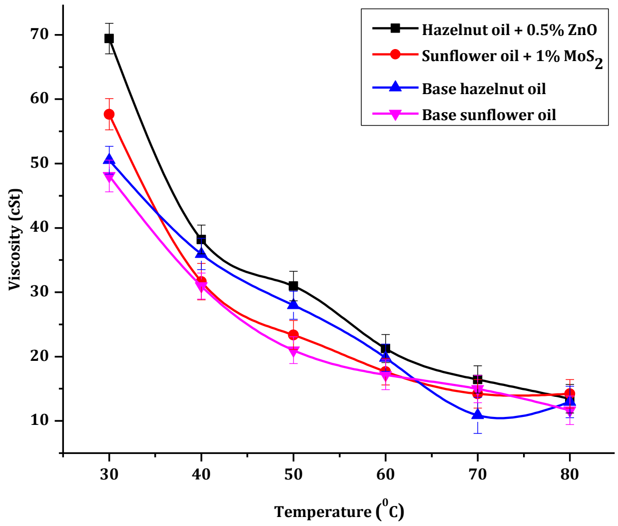

Fig. 13. Kinematic viscosity of nano lubricants exhibiting improved lubricating effect compared to base oils.

It can be observed from fig. 13 that at 80°C, the viscosities of hazelnut oil and sunflower oil were 12.95 centistokes (cSt) and 11.66 cSt respectively. The viscosity of the two oils decreased with an expansion in temperature when additives were integrated into the oil, they were situated between the oil layers and escorted to facilitate the liquid layer development on one another [50]. Thus, the viscosity reduced marginally, and the reducing pattern should have been visible for 0.5% ZnO in hazelnut oil. As the added substance concentration expanded, particles agglomerate and make greater and deviated particles, which forestall the development of liquid layers on one another; consequently, the viscosity expanded for a higher convergence of nanoparticles as in sunflower oil with 1% MoS_2. The addition of nano additives has increased the kinematic viscosity of the oils, the comparison of the viscosities at 80°C for both oil and oil with additive showed that there is an increment in viscosity of 16.6% for sunflower oil with 1% MoS_2 and 9.81% for Hazelnut oil with 0.5% ZnO.

5. CONCLUSION

The friction and wear behaviour of the bio lubricant with nano additives has been evaluated. The present industrial trend in global sustainability bolsters the usage of bio-based lubrications replacing conventional synthetic lubrication. This work focuses on the wear and friction behaviour of hazelnut oil and sunflower oil with a blend of selected additives. There was a considerable enhancement in the anti-wear behaviour of the base oil over the inclusion of nanoparticles.

- Hazelnut oil with 0.5% of ZnO and sunflower oil with 1% MoS_2 offered superior wear and friction properties.
- The COF decreased by about 12.6% and 35.8% upon adding the nano additives in hazelnut oil and sunflower oil.
- The MWSD reduced by about 4.74% and 17.17% in Hazelnut oil with 0.5% ZnO and sunflower oil with 1% MoS_2 compared to that of oils without additives.
- The kinematic viscosity of sunflower oil with 1% MoS_2 and Hazelnut oil with 0.5% ZnO was increased by 16.6% and 9.81% respectively at 80°C.
- The EP test revealed that a maximum load of 1000N was sustained by hazelnut oil with 0.5% of ZnO and 1800N for sunflower oil with 1% MoS_2.
- Sunflower oil with 1% MoS_2 exhibited overall improvement in tribological behaviour and can be chosen as the best option for appropriate applications.

Therefore, bio-lubricants with the inclusion of optimum nano additives exhibit extended advantages over conventional lubrication and have the potential to be employed in a vast range of applications also reducing the chances of pollution due to synthetic lubricants. The improvement in the tribological performance of nano lubricants also has some hidden demerits. The performance of the lubricant may be impacted if nanoparticles are unable to mix uniformly with lubricating oil due to a lack of a dispersion agent. This could cause agglomeration. Even though the presence of nanoparticle additives may help with film formation, improved wear properties, and load-carrying capacity, operating with a high load for a prolonged period still presents many difficulties. Because there are numerous nanoparticles that operate differently for various applications, lubrication is linked to a variety of mechanisms that are challenging to understand. The sustainability and biodegradability of the produced nano lubricants still pause a problem due to the non-biodegradable nature of additives. Future studies may be directed at improving the tribological properties by analysing the effect of a mixture of two or more nano additives in bio-oils and also the creation of organic, chemically modified, and hybridised nano additives for tribological use.

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