Vol. 45, No. 4 (2023) 591-603, DOI: 10.24874/ti.1472.04.23.07

Tribology in Industry

www.tribology.rs

RESEARCH

Experimental Investigations on Thermophysical, Tribological and Rheological Properties of MoS_2 and WS_2 Based Nanolubricants with Castor Oil as Base Lubricant

Jyoti Srivastava[a,b,*], Tandra Nandi[a], Rakesh Kumar Trivedi[b]

[a]*Defence Materials and Stores Research and Development Establishment, Kanpur-208013, India,*
[b]*Department of Oil Technology, Harcourt Butler Technical University, Kanpur-208002, India.*

Keywords:

Vegetable oil
Nanoparticles
Nanolubricants

* Corresponding author:

Jyoti Srivastava
E-mail: jyotisri69@rediffmail.com

Received: 20 April 2023
Revised: 16 June 2023
Accepted: 27 July 2023

A B S T R A C T

Molybdenum disulfide (MoS_2) and Tungsten disulfide (WS_2) nanoparticles addition to castor oil produce nano lubricants of novel properties. These nanomaterial additives are dispersed thoroughly in the liquid phase and are intended to boost the base fluid's thermo-physical, rheological, and tribological properties. All these properties have been studied by varying concentrations of nanoparticles from 0.05 to 2.5%. The size of both nanoparticles are in the range of <20nm. The density of nano lubricants was found to change with respect to nanoparticle concentration and temperature. The density increases from 0.06 to 0.6% with respect to the increase in concentration and decreases by 4%, for increasing temperature from 25 to 100 ° C. A significant (15 %) increase in thermal conductivity with MoS_2 nanoparticles in lubricants could be observed while with WS_2 nanoparticles only 8 % enhancement was observed. The rheological study suggests that nano lubricants have better dynamic viscosity and shear stress than neat castor oil. A tribology study showed improved lubrication properties of the nanolubricants as compared with base castor oil. The addition of MoS_2 and WS_2 nanoparticles in castor oil decreased the friction coefficient by 53 % and 42 %, respectively, and reduced the wear scar diameter by 24% and 20 %, respectively, as compared to base castor oil. This study was done to develop nonedible vegetable oil based nanolubricants exploring their potential as emerging lubricants.

1. INTRODUCTION

Castor oil is a vegetable-based nonedible oil have a better viscosity index, lubricity, fire resistance, and lower lubricity than mineral oil, hence, a good candidate for bio-degradable lubricants [1]. Castor oil-based lubricants also found application in grinding and turning [2-4]. The main use of castor oil is in heavy loads happening in the bearings. The reason behind this is its high density and viscosity. Castor oil is non-drying, viscous and non-volatile oil [5]. W.M.L.B. Naranpanawe et al. [6] investigated the effect of castor with coconut and sesame oil for transformer oil substitution. A. Suhane et al. [7] compared servo gear oil with castor oil base lubricant for automotive use. K.M. Talkit et al. [8] studied castor oil and soybean blends as substitutes for mineral oil. M.A. Delgado et al. [9] added ethyl cellulose in castor oil and found antiwear properties increase. K.K.S Pathmasiri et al. [10] investigated castor with palm oil in industrial applications. A. K. Singh [11] investigated castor oil as a smoke pollution reducer. H.Y. Shrirame et al. [12] examined the advantage of castor with jatropha and Pongamia oil. According to Z.L.A García et al. [13] it is a beneficial non-edible lubricant source because of easy derivatization. D.K. Karupannasamy et.al [14] stated that in comparison to palm, mahua, and mineral oil generally used in machining applications, castor oil exhibited superior lubrication properties. The lubrication performance of 60 NiTi bearings with castor oil and mineral oil has been studied and found that with castor oil super lubricity has been achieved. [15]. Castor oil exhibited better load-carrying capacity antifriction, and antiwear properties than commercial ones [16]. The nano-material addition in base fluids/lubricants for enhancement of their rheological and thermal behavior is a recent trend since 1995 [17]. CuO and MoS_2 have been used in base Chemically Modified Palm Oil (CMPO) and it has been observed that about 50% enhancement in antiwear and extreme pressure properties were achieved [18]. The tribological characteristics of rapeseed oil were improved by MoS_2 nano-vesicles [19]. When MoS_2 nanoparticle was incorporated into coconut oil, base oil made the surface smoother [20]. MoS_2 was used in Soybean oil based nano lubricants having improved antiwear and antifriction properties [21]. Sesame and coconut oil used Boric acid nanoparticles and reduction in cutting force [22]. The incorporation of MoS_2 nanoparticles in Coconut, Sesame and Canola oil exhibited better machining performance [23], Similarly when different nanoparticles in base castor oil have been added following results have been achieved. Hexagonal boron nitride nanoparticles were used and wear property was improved [24]. Surface-modified CuO nanoparticles were used when in castor oil coefficient of friction, wear reduction has been achieved along with remarkable improvement in the weld load of nano lubricants [25]. Graphite, multi-walled carbon nanotubes, and multi-layered graphene graphite nanoparticles in castor oil have exhibited better wear reduction and extreme pressure properties [26]. MoS_2 and CuO hybrid combination of nanoparticles led to a reduction in COF and wear value [27]. Castor oil with ZnO showed a lesser value of COF and wear rate [28]. CeO_2 and Polytetrafluroethylene CeO_2 nanoparticles in castor oil exhibited significant improvement in the load-carrying and antifriction properties of nanolubricants [29]. The addition of WS_2 nanorods showed the best antifriction and antiwear properties, in comparison with the base oil and 2H-WS_2 [30]. The IF nanoparticles showed the best tribological properties in comparison to pure paraffin oil [31]. Tungsten disulfide-based motor oil has better antiwear, antifriction, and extreme pressure properties than Shell helix and Great Wall motor oils [32]. The addition of hybrid nanoparticles hBN/WS_2 to palm oil improves tribological properties [33]. The worn wear scar value of chemically modified rapeseed oil CMRO having nano CuO is reduced than synthetic lubricant and CMRO with nano WS_2 and nano TiO2 respectively [34]. When modified canola oil was added with Molybdenum disulphide and Tungsten disulphide nanoparticles the rheological and tribological properties were enhanced as compared with base oil [35].

Mineral and synthetic oils are generally used as a base oil for lubricants but they are not biodegradable and moreover, the scarcity of petroleum products is increasing day by day. Lubricants from plant origin can meet the challenge of future demand for petroleum products in future.

Castor oil is nonedible vegetable oil having a functional polar group beneficial in boundary lubrication because of lubricating film formation tendency. To enhance lubricity and other properties various additives are also added to base castor oil. Molybdenum disulfide and tungsten disulfide are widely used nanomaterials as antifriction and antiwear additives but are mostly studied on mineral and other base oils. These nanoparticles have not been much studied in non-edible vegetable oil, especially in castor oil. Although there is a lot of scope for castor oil as an engine lubricant because of vegetable origin and nonedible oil. Another advantage is its abundant availability in India. very few reports/ literature are available for castor oil-based nano lubricants based on Molybdenum disulfide and tungsten disulfide nanoparticles [36,37]. Authors reported [36] only tribological studies of MoS_2 based nanolubricants with bigger particle size (60 nm) while with WS_2 [37] only tribological studies were done at 300 rpm speed and 5 N load conditions with 80-200 nm particle size.

The present investigation is focused on analyzing the possibilities of castor oil as a lubricant with the addition of MoS_2 and WS_2 nanoparticles. The nanoparticles used here are in a smaller size (10-20nm) and tribological properties of the base castor and its MoS_2 and WS2-based nanolubricants have been studied at a higher load of 294 N and a higher speed of 1200rpm. All these parameters along with details of the thermophysical rheological, and tribological properties of both nanolubricants have been studied for the first time.

2. MATERIALS AND METHOD

Castor oil was obtained from Jayant Agro organics limited (Mumbai, Maharashtra, India). Castor oil contains 90% ricinoleic acid which is monounsaturated, 18- carbons fatty acid other acids are 3% oleic, 4% linoleic, 1% stearic, and less than 1% linolenic fatty acids [38].

Table 1 shows the physiochemical properties of MoS_2 and WS_2 nanoparticles. MoS_2 has been synthesized according to the patent [44] and tungsten di sulfide nanoparticle (WS2) was procured from mK Nano, which was treated in a ball mill for further size reduction. The average particle size (APS) was calculated from TEM Figure no 1(a,b), and thermal conductivity by (40, 41)

Table 1. Physical properties of MoS_2 and WS_2 nanoparticles.

Physical parameters	Molybdenum di sulfide (MoS_2)	Tungsten di sulfide (WS_2)
Purity (%)	99	99
Density (Kg/m3)	5.6	7.8
APS (nm)	5	10
Thermal conductivity (W/m°K) 25 °C	35*[40]	32*[41]

2.1 Instrumentation

The particle size of both materials was evaluated with Transmission Electron Microscopy (TEM) investigations, make: Tecnai G2 20. XRD analysis was performed in an X-Ray diffractometer instrument (Bruker Model No-D8 Advance). Zeta potential studies were carried out with a dynamic light scattering (DLS) instrument (make: Malvern Instruments (Malvern, UK), model: Zetasizer Nano series ZS 90) A thermal gravimetric analyzer (make: TA Instruments, model: SDTQ-600) was used under an inert at a heating rate of 10 °C/min to examine the thermal stability of all samples. Decagon devices, KD2 pro instrument was used to measure The thermal conductivity of all nanolubricants which functions on the principle of transient hot-wire method. Tribological tests were executed on a Ducom four-ball tester, model TR-30L-PNU-IAS according to the standard method. The COF and wear scar diameter tests were accomplished for both castor oil and its MoS_2 and WS_2-based nanolubricants at atmospheric pressure, a load of 294N and 75 °C temperature with a constant speed of 1200 rpm according to IP-239. Steel balls of chrome steel alloy, made from AISI E-52100, with a diameter of 12.7mm and Rockwell C hardness of 64 to 66 were used during testing. The worn surface analysis and EDAX of base three balls in base oil and nano lubricants have been studied by FESEM at a magnification of 250×. Make Carl Zeiss model No. sigma 500. Rheology of all samples has been done with rheometer model Anton Par, model MCR702. Sonics VCX130 ultrasonic processor was used for sonication and dispersion of nanoparticles in base oil. It was operating at 20 kHz frequency and 750 watts.

2.2 Preparation of nano lubricants

Nanolubricants were prepared by dispersing different concentrations of MoS_2 and WS_2 Nanoparticles (0.05-1%) in base castor oil. All the nanoparticles (MoS_2 and WS_2) were weighed according to volume concentration (0.05-2.5%) then mixed with base castor oil and stirred completely with a magnetic stirrer make IKA –RCT Basic at 1400 rpm for 15 minutes for complete mixing. After that the samples were sonicated further for 30-45 min in Sonics VCX 130) to enhance stability and ensure that all nanoparticles were uniformly mixed in the base oil without agglomeration. It has been observed that the beyond this concentration of both nanoparticles, nanolubricants of castor oil become highly viscous and unstable. The volume fraction φ is calculated by Kole and Dey method [42].

$$\varphi = (w_p / \rho_p) \div (w_p / \rho_p + w_m / \rho_m)$$

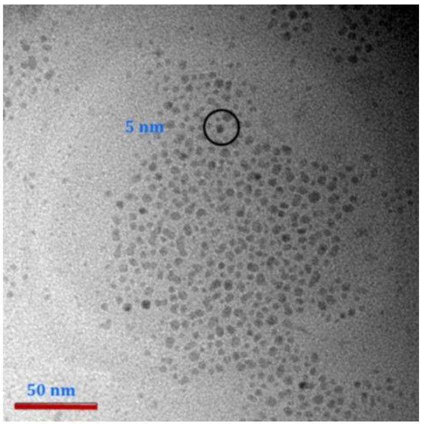
Where, w_p = weight fraction of nanoparticles w_m = weight fraction of base oil, ρ_p and ρ_m are the density of nanoparticles and base oil respectively.

3. RESULTS AND DISCUSSION

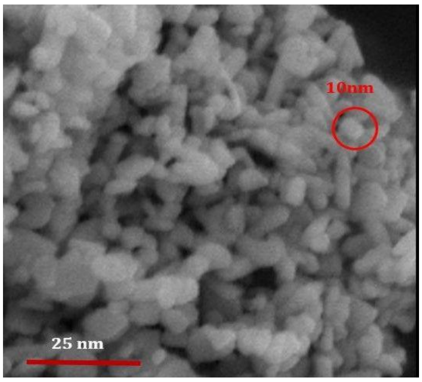
In the present work, MoS_2 and WS_2 were added as nano additives to castor oil. Their physiochemical, thermal, tribological, and rheological properties have been evaluated.

3.1 Characterization of nanoparticles by TEM

The size and morphology of both nanomaterials were done by TEM analysis. The samples were prepared by drop-casting on the copper grid, followed by drying. In Fig. 1(a) and Fig. (b), the TEM of both MoS_2 and WS_2 shows spherical to unsymmetrical MoS_2 and WS_2 nanoparticles with sizes ranging from 5 to 10 nm.



(a)

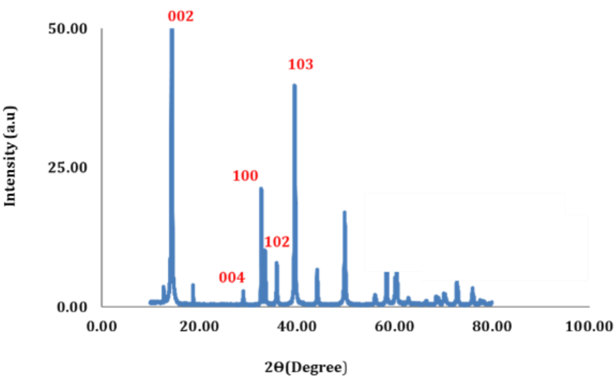


(b)

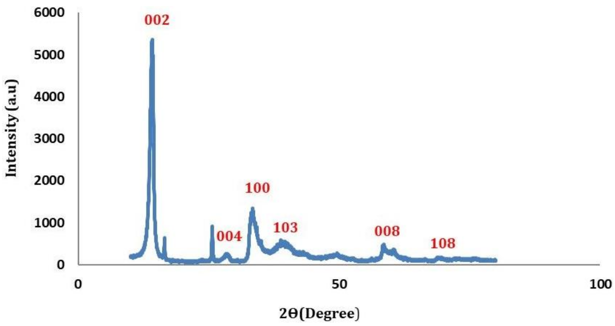
Fig. 1. (a) TEM of MoS2 nanoparticle, (b) TEM of WS_2 nanoparticle.

3.2 XRD analysis of nanoparticles

Different types of lattice planes were observed in XRD analysis and (2θ) diffraction peaks were analyzed.Fig.2(a) and (2b) shows the XRD diffractrograms of both MoS_2 and WS_2 nanoparticles between 10° - 80°. It was seen that the sample mainly consists of MoS_2 with a small amount of Mo_2S_2. At (002)/(004) lattice plane (2θ) peaks were observed at 14.39°/29.02°, similarly for (100)/ (102)/ (103) lattice planes (2θ) peaks were seen at 32.68°/35.88°/ 39.55°, which indicates crystalline MoS_2 (JCPDS card No. 65-0160) [43]. In a similar way, Fig. 2(b) shows latticeplanes(004)/(100)/(101)/(102)/(103)/(006)/(105)/ (106)/(008) corresponds to 2θ peaks28.76/32.663/3.42/35.26/39.57/44.28/4 9.65/55.53 / 60.31 of structure of WS_2. The notable peak located at 2θ = 14.38◦ corresponds to the (002) plane of 2H-WS_2 (JCPDS file no. 08-0237) [44].



(a)

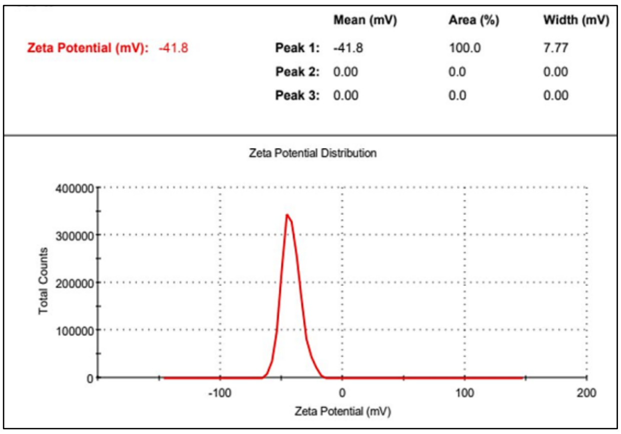


(b)

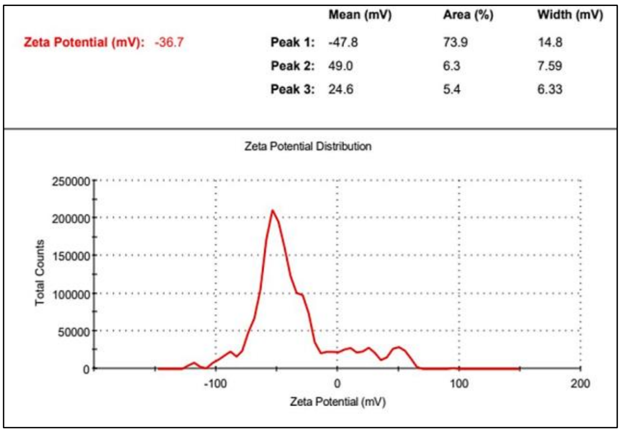
Fig. 2. (a) XRD of MoS2 nanoparticle, (b) XRD of WS_2 nanoparticle.

3.3 Zeta potential measurement results

It is a crucial and important parameter to examine the stability of any nano lubricant. It measures electrostatic or charge repulsion/attraction amongst nanoparticles. By evaluating zeta potential details about internal molecular interaction inside nano lubricants are examined. The reasons for aggregation, stable/unstable dispersions, etc are thoroughly investigated. In the present study, the zeta potential of nano lubricants of 0.05% MoS_2 and WS_2 has been measured by the DLS technique. Figure 3(a,b) show the value of zeta potential MoS_2 and WS_2 respectively. The value observed were -41.8 mv and -36.7 mv for MoS_2 and WS_2 based nano lubricants respectively. Better results have been obtained with MoS_2 based lubricant as compared with WS_2 based nano lubricant. The higher stability of MoS_2 based nano lubricant was attributed to the higher dispersion stability of MoS_2 nanoparticles.



(a)



(b)

Fig. 3. (a) Zeta potential measurement result of MoS_2 based nanolubricants, (b), Zeta potential measurement result of WS_2 based nanolubricants.

3.4 Physiochemical properties of nanolubricants

Density: The density of nanofluids is an important parameter as it affects Reynold's number and Nusselt's number. A Pycnometre is used to measure the density of nano lubricants according to IP-249. The values are compared with those obtained from calculated density by equation no. 1. It has been noted that the density of nano lubricants increases with the dispersion of nanoparticles. The theoretical value of density is calculated by the equation

$$\rho_{nf} = (1-\varphi)\rho_f + \varphi\rho_s \quad [45] \qquad (1)$$

The values of φ different concentration of MoS_2 and WS_2 in base castor oil has been obtained by a volumetric fraction and shown in Table-2. The values are compared with those obtained from the correlation shown in equation no.1, where ρ_{nf} : nanofluid density (g/cm^3), ρ_s and ρ_f : densities of the solid particles and base fluid, respectively and φ is volume fractions. Tables -3 and 4 represent variations in the density of base castor oil and its MoS_2 and WS_2 based nanolubricants concerning temperature and concentration. Effective density of MoS_2 in castor oil at 0.05 % and 0.1% is found to be approximately the same because the difference between respective base fluids densities is very small in both experimental and theoretical values, while density at 0.25% MoS_2 is found to increase by 0.6% as compared with the base value. Table-5 shows the error values obtained from the experimental and by equation-1. As can be seen, error in the density of the studied nanolubricants within the acceptable range of accuracy. The density decreases with increasing temperature which is due to the weaker viscous force of all nanolubricants. It has been observed that there is a 0.62% increase in density of nanolubricant with 2.5% MoS_2 based nanolubricant as compared with neat castor oil at 25 °C and a similar trend has been observed at 100 °C. In the case of castor oil, the density decreases by 4% when the temperature increases from 25 to 100 °C. An almost similar trend has been observed with 2.5% based nanolubricants.

Table 2. Calculation of φ different concentrations of MoS_2 and WS_2.

Concentration	φ (MoS_2)	φ (WS_2)
0.05	0.000098	0.000064
0.1	0.00019	0.00012
0.25	0.00048	0.00032

Table 3. Variation of density concerning concentration and temperature for base castor oil and its MoS_2 based nanolubricants.

Temp (° C)	Neat Castor (Kg/m³)	Castor + 0.05 % MoS_2 (Kg/m³)		Castor+ 0.1 % MoS_2 (Kg/m³)		Castor+ 0.25 % MoS_2 (Kg/m³)	
		Exp.	Cal.	Exp.	Cal.	Exp.	Cal.
25	964	964.0	963.4	967	964.7	970	966.0
30	959	959.0	958.4	961	959.7	963	961.2
40	954	955.0	954.4	956	954.7	958	955.4
50	952	952.5	952.4	953	952.7	954	953.4
60	940	940.8	940.4	950	940.0	952	941.5
75	937	937.5	937.4	943	937.0	945	938.5
90	930	930.7	930.4	932	930.0	934	931.5
100	926	926.8	926.4	928	926.0	932	927.5

Table 4. Variation of density concerning concentration and temperature for base castor oil and its WS_2 based nanolubricants.

Temp (° C)	Neat Castor (Kg/m³)	Castor + 0.05% WS_2 (Kg/m³)		Castor+ 0.1% WS_2 (Kg/m³)		Castor+ 0.25 % WS_2 (Kg/m³)	
		Exp.	Cal.	Exp.	Cal.	Exp.	Cal.
25	964	965	964.4	969	964.7	972	966.1
30	959	960	959.3	963	959.7	965	960.4
40	954	956	954.3	955	954.7	960	955.4
50	952	952	952.4	954	952.7	956	951.0
60	940	941	940.4	952	940.0	954	942.0
75	937	938	937.4	945	937.0	946	939.0
90	930	931	929.1	933	930.0	935	932.1
100	926	927	926.4	929	926.0	933	928.1

Table 5. Error values (%) in density of MoS_2 and WS_2 based nanolubricants.

Temp (° C)	Castor + 0.05 % (Kg/m3)	Castor + 0.1 % (Kg/m3)	Castor + 0.25 % (Kg/m3)
	MoS_2	WS_2	MoS_2
25	0.06	0.06	0.23
30	0.06	0.07	0.13
40	0.06	0.17	0.13
50	0.01	0.04	0.03
60	0.04	0.06	1.0
75	0.01	0.06	0.64
90	0.03	0.20	0.21
100	0.04	0.06	0.21

Viscosity: The effectiveness of lubricants can be controlled by another important parameter, i.e. viscosity.Einstein [46] first suggested equation-2 given below for nanofluid viscosity determination however there was an assumption that nanoparticle concentration (volume fraction) was <0.02. From Table 2 it has been concluded values φ lie in this range. Referring to Fig 4(a,b), it was found that kinematic viscosity decreases with an increase in temperature while it increases with an increase in the concentration of MoS_2 and WS_2. In the case of both MoS_2 and WS_2 nanoparticles, viscosity is found to increase marginally, 0.2% as the nanoparticle concentration varies from 0.05% to 0.25% at all temperatures, i.e. from 25 to 100 °C but it decreases 3.8 and 3.9% respectively at 0.05 to 2.5 % of MoS_2 and WS_2 based nanolubricants. The intermolecular forces of attraction are reduced at high temperatures resulting decrease viscosity. It is a normal trend observed both in base castor oil and its nanolubricants. High viscosity increases the ability of nanolubricants to form stable films between contacting surfaces.

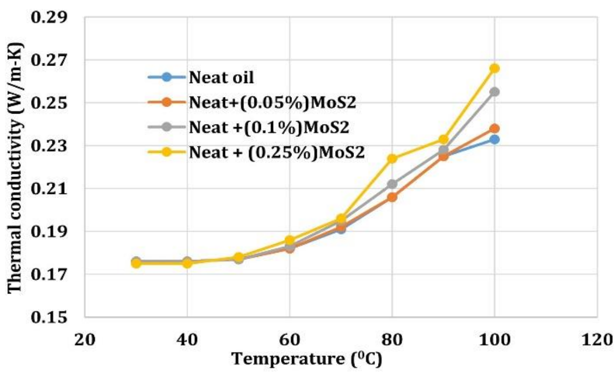
$$\mu_{nf} = \mu_{bf}(1+2.5\varphi) \quad [46] \qquad (2)$$

3.5 Thermal properties of Castor oil and its nanolubricants

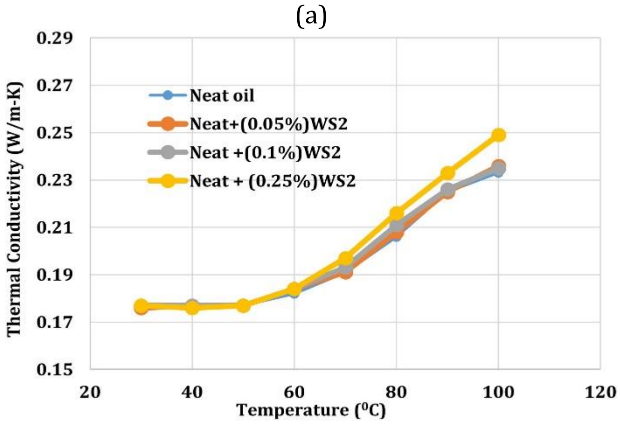
The KD2 instrument evaluates thermal conductivity and thermal resistivity and the equation for the calculation of thermal conductivity is shown below.

$$k = q/4\pi(T2 - T1)\ell nt2/t1 \text{ [47]} \quad (3)$$

The thermal conductivity results are presented in Fig. 4(a, b), the lowest thermal conductivity was calculated for base castor oil. The effect of variation of thermal conductivity with volume concentration for different nanolubricants has also been studied and is shown in Fig. 4(a) and, 4b), the data shows that there is a greater enhancement in thermal conductivity by 15% for 0.25% MoS_2 based nanolubricants [at 100 °C] as compared to the base oil.



(a)



(b)

Fig. 4. (a) Thermal conductivity of MoS2 Nanoparticles based nanolubricants (b), Thermal conductivity of WS_2 Nanoparticles based nanolubricants.

Similarly, with WS_2 based nanolubricants the enhancement of 8% in thermal conductivity (at 100 °C) was observed as compared with base oil. while increasing the volume concentration from 0.05% to 0.25%, the marginal change is observed upto 90 °C. The enhancement in thermal conductivity of base castor oil by incorporating nanoparticles was observed due to the Brownian motion of nanoparticles. The increase in temperature and decrease in particle size boost the Brownian motion providing higher thermal conductivity. This study is useful in developing a new class of heat transfer fluids based on vegetable oil possessing higher thermal conductivity as compared with base oil [48].

Thermogravimetric analysis: Thermograms were obtained at a heating rate of 10 °C·min^{-1} from 25 °C to 400 °C under N2 atmosphere. Fig. 5 shows the thermogravimetry curves of base castor oil and its MoS_2 and WS_2 based nanolubricants. Base castor oil and its nanolubricants are thermally stable until approximately 250 °C. The onset degradation temperature of castor oil is 312 °C and upto 375 °C weight loss is 40%. In the case of Castor+ 0.1 WS_2 onset temperature is 316 °C and upto 375 °C weight loss is 38%. Similarly with Castor+0.25 WS_2 onset temperature is 325 °C and upto 375 °C weight loss is 30%. The value of onset temperature was 327 and 330 °C with Castor +0.1MoS_2 and Castor +0.25 MoS_2 respectively. Similarly, weight loss decreases to 25% and 17.5%. The weight loss decreases maximum with Castor+0.25 MoS_2 nanolubricant.

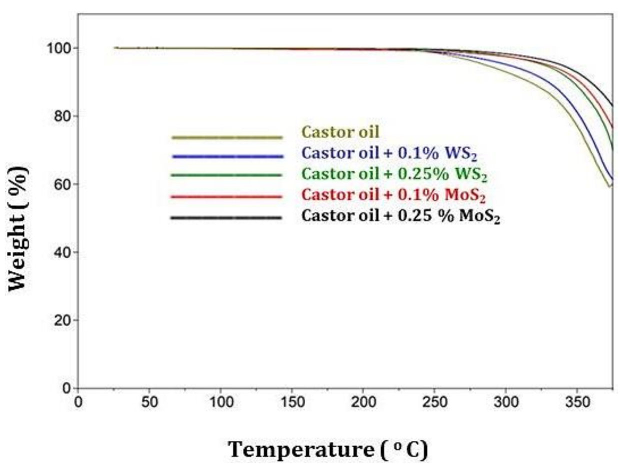


Fig. 5. TGA of MoS_2 and WS_2 nanoparticles based nanolubricants.

3.6 Rheological study of base oils and their nanolubricants

The solid volume fraction is a very important parameter that affects the rheological behaviour of nanolubricants. The dynamic viscosity of developed nanolubricants concerning solid particles(nanomaterials) at different temperatures (40 °C and 100 °C) and shear rates have been studied.

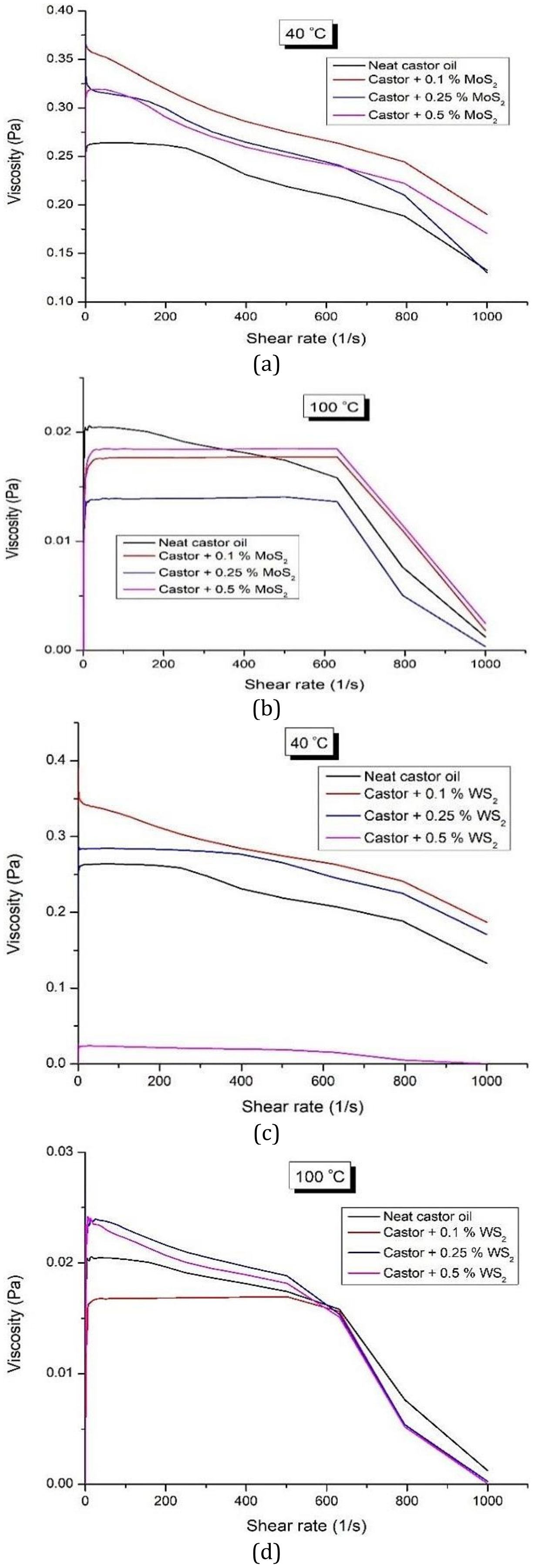


Fig. 6. (a, b, c, d) dynamic viscosity Vs shear rate of Castor oil and its MoS_2 and WS_2 based nanolubricants.

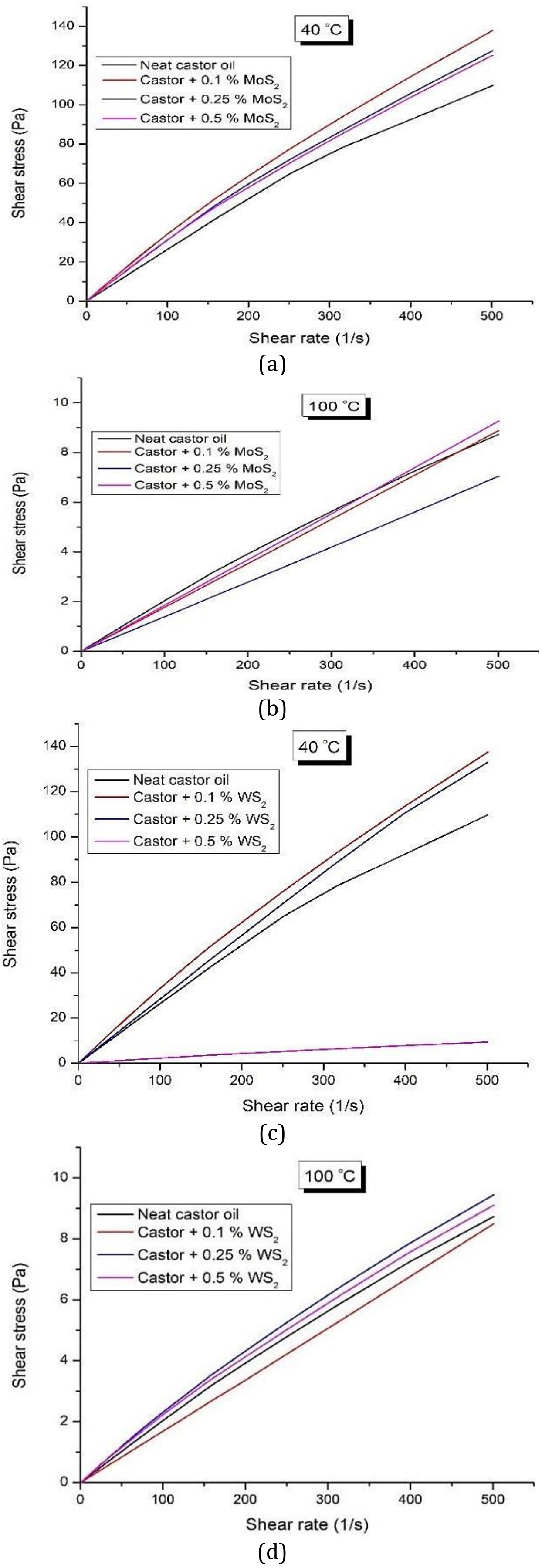
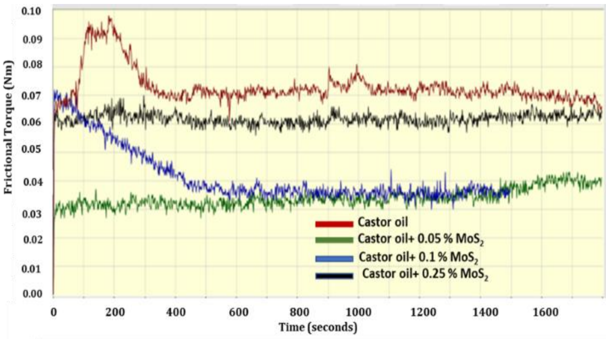


Fig. 7. (a, b, c, d) shear stress Vs shear rate of Castor oil and its MoS_2 and WS_2 based nanolubricants.

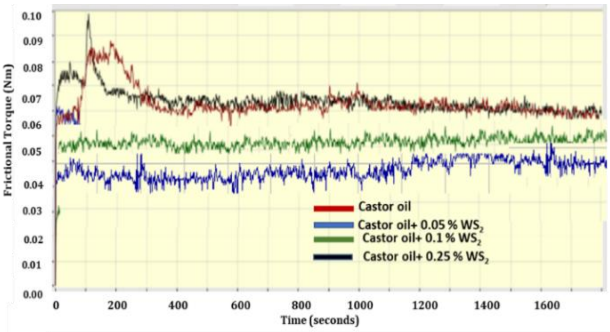
These tests were performed for the rheological behavior of base castor oil and its nanolubricants with molybdenum di sulfide (MoS_2) and tungsten di sulfide (WS_2) nanoparticles at different concentrations (0.1 to 0.5%). The rheological results are shown in Fig. 6(a,b,c,d) and Fig. 7(a,b,c,d) representing shear rate at constant temperature (40 °C and 100 °C) and impact of viscosity on nanolubricants. Study with MoS_2 based nanolubricants the variation of viscosity was with in 2-3% suggesting that the behaviour of nanolubricants was identical and they can be treated as Newtonian. The trend was a non Newtonian type with a higher concentration (0.5%) WS_2 based nanolubricants. The results also show a general trend according to which the dynamic viscosity decreased when temperature increased for all nanolubricants.

3.7 Tribology study of base oils and their nanolubricants

The frictional torque and coefficient of friction (COF) were studied and the frictional characteristics of both base castor oil and its MoS_2 and WS_2 based nano lubricants are shown in Fig. 8 (a) and 8(b). For castor oil COF was observed 0.0552. The reduction in coefficient of friction (COF) was found to be lowest with both nanoparticles at 0.05% concentration. It was 53.0% and 42% respectively for both MoS_2 and WS_2 based nanolubricants, shown in Fig. 8 (a) and Fig 8(b). The efficiency of reduction in friction of castor oil was found better with nano addition. The phenomena behind this reduction were the creation of a thin lubricating film between contacting surfaces of moving mechanical parts that cause a reduction in COF. In the four-ball instrument, the scars presented on the bottom three balls were seen by an optical microscope to access the wear characteristics of the base castor oil and its nano lubricants. The wear patterns were investigated by wear scars formed on the balls. In the case of castor oil, a smaller wear scar diameter was 445μm present on the surface shown in Fig. 9 (a). The analysis of the worn surfaces of bottom balls has been investigated by FESEM at a magnification of 250×. Fig. 9 (b), Fig 9(c) and 9(d) show the scars of Castor oil with MoS_2 based lubricants at different concentrations (0.05,0.1 and 0.25%). There was a maximum 24% reduction in wear scar diameter with 0.1% MoS_2 concentration as compared with neat castor oil. Similarly, Fig. 9 (e), Fig 9(f) and Fig 9(g) show the scars of castor oil with WS_2 based lubricants at different concentrations (0.05, 0.1, and 0.25%). There was a maximum 20% reduction in wear scar diameter with 0.1% WS_2 concentration as compared with neat castor oil. The lamellar structure of both MoS_2 and WS_2 nanoparticles was the reason for the reduction in COF. Both nanoparticles formed tribofilm between sliding surfaces when added with base castor oil into the surfaces. The best results have been obtained at the optimum 0.1% concentration of nanoparticles and after that increasing the concentration agglomeration of nanoparticles occurs that causing a decrease in friction coefficient. The surface of the scar present in Fig 9(a) was almost roughen and a bigger wear scar diameter was found with base castor oil, however, when both nanoparticles were added in castor oil scar surface became smoothen and the scar diameter reduced shown in Fig 9 (b) and Fig 9(c). The presence of nanoparticles in base oil may level the grooves present on the rubbing surface due to their adhesive nature.



(a)



(b)

Fig. 8. (a) COF of Castor oil and its MoS_2 based nanolubricants at different concentrations, (b) Castor oil and its WS_2 based nanolubricants at different concentrations.

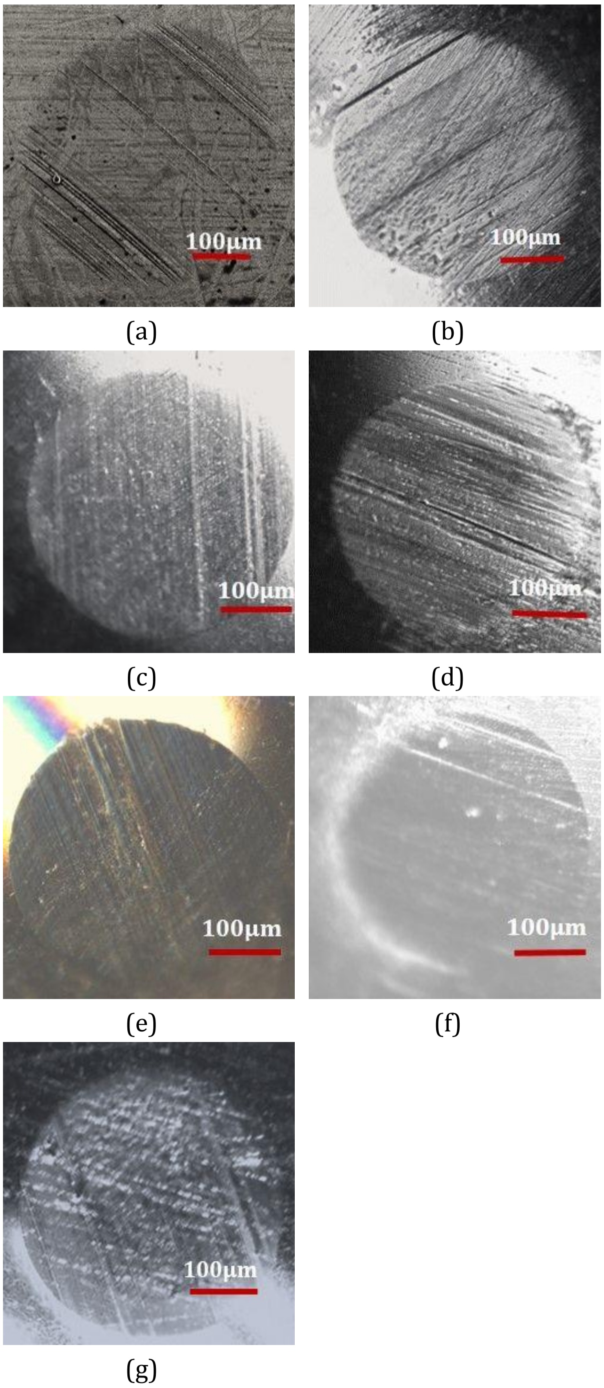


Fig. 9. (a) Wear scar image of Castor oil (445μm), (b) MoS_2 nanoparticle based NLF at (0.05% Conc.) (356μm), (c) MoS_2 nanoparticle based NLF at (0.1% Conc.) (338μm), (d) MoS2 nanoparticle based NLF at (0.25% Conc.) (421μm), (e) WS_2 nanoparticle based NLF at (0.05% Conc.) (386μm), (f) WS_2 nanoparticle based NLF at (0.1% Conc.) (365μm), (g) WS_2 nanoparticle based NLF at (0.25% Conc.) (424μm).

3.8 EDAX analysis

This sample analysis was performed to find out the chemical content of worn surfaces. Fig. 10(a) and Fig 10(b) shows the EDAX of both MoS_2 and WS_2 based nano lubricants in castor oil at 0.1% concentration. Results showed that MoS_2 nanoparticles present 0.49% on the surface as compared with WS_2 0.95%.

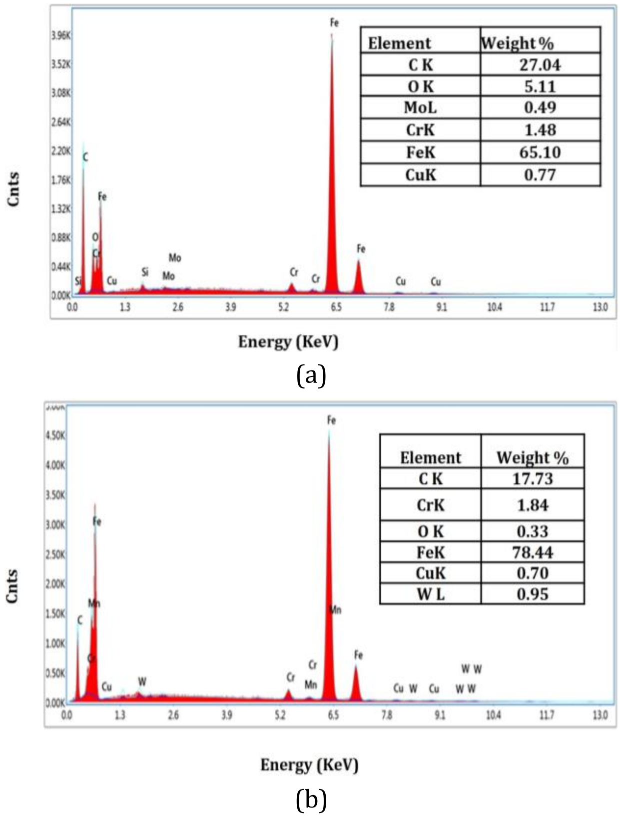


Fig. 10. EDAX of (a) Castor oil with MoS_2 (at 0.01% Concentration), (b) Castor oil with WS_2 (at 0.01% Concentration).

4. CONCLUSIONS

1. The density of castor oil based nanolubricants increases with nanoparticle volume fraction and decreases with temperature. Calculated and experimental values are almost similar in all nanolubricants.
2. Viscosity behavior with nanoparticles concentration is non-linear and it increases with concentration and the results are compared with the theoretical equation.
3. The thermal conductivity of both nanolubricants is found higher than the neat castor oil.
4. MoS_2 based nanolubricants show better thermal stability as compared with base castor oil and WS_2 based nanolubricants

5. Enhancement in rheological properties with the addition of MoS_2 and WS_2 nanoparticles was experimentally investigated. In the case of both types of nanolubricants, MoS_2 based nanolubricants are better because of their high viscosity and shear stability.

6. Tribology (COF & wear scar diameter) study showed improved lubrication properties of the nanolubricants. There is a reduction in COF for both MoS_2 & WS_2 based nano lubricants compared to neat castor oil and also a reduction in wear and scar diameter. The MoS_2 based nanolubricants have better properties as compared WS_2 based nanolubricants. This study of castor oil based MoS_2 and WS_2 nano lubricant will add some insight into the field of nano lubrication/ nano additives and tribology and certainly help the researchers in this field.

Acknowledgment

The authors thank Director, DMSRDE, Kanpur, India for his constant motivation and encouragement.

REFERENCES

[1] X. Wu, G. Zhao, X. Wang, and W. Liu, "Preparation of High-Temperature Lubricants by Blending Castor Oil with Lithium Bis(trifluoromethylsulfonyl)imide," *Tribology Letters*, vol. 65, no. 2, Mar. 2017, doi: 10.1007/s11249-017-0833-9.

[2] S. Guo *et al.*, "Experimental evaluation of the lubrication performance of mixtures of castor oil with other vegetable oils in MQL grinding of nickel-based alloy," *Journal of Cleaner Production*, vol. 140, pp. 1060–1076, Jan. 2017, doi: 10.1016/j.jclepro.2016.10.073.

[3] H. J. Pei, Z. Wen, G. C. Wang, and H. Q. Wang, "Application of biodegradable cutting fluids in high speed turning," *Advanced Materials Research*, vol. 381, pp. 20–24, Nov. 2011, doi: 10.4028/www.scientific.net/amr.381.20.

[4] H. J. Pei, Y. Shen, C. Shen, and G. C. Wang, "Application of castor Oil-Based cutting fluids in precision turning," *Applied Mechanics and Materials*, vol. 130–134, pp. 3830–3834, Oct. 2011, doi: 10.4028/www.scientific.net/amm.130-134.3830.

[5] J. Salimon, D.A.M. Noor, A.T. Nazrizawati, M. Y. M. Firdaus, A. Noraishah, "Fatty Acid Composition and Physicochemical Properties of Malaysian Castor Bean (Ricinus Communis) Seed Oil," *Sains Malaysiana*, vol. 39, no. 5, pp. 761-764, May 2010.

[6] W.M.L.B. Naranpanawe, M.A.R.M. Fernando, J.R.S.S. Kumara, E.M.S.N. Naramapanawa, "Performance Analysis of Natural Esters as Transformer Liquid Insulation Coconut, Castor and Sesame Oils," *IEEE 8th International Conference on Industrial and Information Systems*, pp. 105-109, Dec. 2013, doi: 10.1109/ICIInfS.2013.6731964

[7] A. Suhane, R.M. Sarviya, A. Rehman, H.K. Khaira, "Effect of additive addition in base oil of a lubricant – A Review," *International Research Journal of Engineering and Technology*, vol. 3, iss. 4, Apr. 2016.

[8] K.M. Talkit, D.T. Mahajan, V.H. Masand, "Study on physicochemical properties of vegetable oils and their blends use as possible ecological lubricant," *Journal of Chemical and Pharmaceutical Research*, vol. 4, no. 12, pp. 5139-5144, 2012.

[9] M. Delgado, L. A. Quinchia, H. A. Spikes, and C. Gallegos, "Suitability of ethyl cellulose as multifunctional additive for blends of vegetable oil-based lubricants," *Journal of Cleaner Production*, vol. 151, pp. 1–9, May 2017, doi: 10.1016/j.jclepro.2017.03.023.

[10] T. K. K. S. Pathmasiri, G. I. P. Perera, and R. Gallage, "Investigation of palm-castor oil blends as base stocks of bio-lubricants for industrial applications," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 44, no. 1, pp. 1354–1374, Jul. 2019, doi: 10.1080/15567036.2019.1643425.

[11] A. Singh, "Castor oil-based lubricant reduces smoke emission in two-stroke engines," *Industrial Crops and Products*, vol. 33, no. 2, pp. 287–295, Mar. 2011, doi: 10.1016/j.indcrop.2010.12.014.

[12] H. Y. Shrirame, N. L. Panwar, and B. R. Bamniya, "Bio Diesel from Castor Oil – A Green Energy Option," *Low Carbon Economy*, vol. 02, no. 01, pp. 1–6, Jan. 2011, doi: 10.4236/lce.2011.21001.

[13] L. A. García-Zapateiro, J. M. Franco, C. Valencia, M. Delgado, C. Gallegos, and M. V. R. Méndez, "Viscosity modification of high-oleic sunflower and castor oils with acid oils-derived estolides for lubricant applications," *European Journal of Lipid Science and Technology*, vol. 115, no. 10, pp. 1173–1182, Aug. 2013, doi: 10.1002/ejlt.201300066.

[14] D. K. Karupannasamy and R. Ruthuraraj, "Synthesis of Eco-Friendly machining lubricants and its tribological characteristics," *International Journal of Recent Technology and Engineering*, vol. 8, no. 3, pp. 1902–1906, Sep. 2019, doi: 10.35940/ijrte.c4466.098319.

[15] Q. Zeng and G. Dong, "Superlubricity behaviors of Nitinol 60 alloy under oil lubrication," *Transactions of Nonferrous Metals Society of China*, vol. 24, no. 2, pp. 354–359, Feb. 2014, doi: 10.1016/s1003-6326(14)63068-5.

[16] B. Bongfa, P.A. Atabor, A. Barnabas, M.O. Adeoti, "Comparison of lubricant properties of castor oil and commercial engine oil, Comparison of lubricant properties of Castor oil and commercial engine oil," *Journal of Tribology*, vol. 5, pp. 1-11, Jun. 2015.

[17] S.U.S. Choi, J.A. Eastman, "Enhancing thermal conductivity of fluids with nanoparticles," *International mechanical engineering congress and exhibition*, Nov. 1995.

[18] A. A. S. Noori, H. A. Hussein, and N. S. M. Namer, "Influence of adding CUO and MOS_2 nano-particles to castor oil and moulding oil on tribological properties," *IOP Conference Series*, vol. 518, no. 3, p. 032040, May 2019, doi: 10.1088/1757-899x/518/3/032040.

[19] S. Bhaumik, R. Maggirwar, S. Datta, and D. S. Pathak, "Analyses of anti-wear and extreme pressure properties of castor oil with zinc oxide nano friction modifiers," *Applied Surface Science*, vol. 449, pp. 277–286, Aug. 2018, doi: 10.1016/j.apsusc.2017.12.131.

[20] R. Gupta and A. P. Harsha, "Antiwear and extreme pressure performance of castor oil with nano-additives," *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, vol. 232, no. 9, pp. 1055–1067, Oct. 2017, doi: 10.1177/1350650117739159.

[21] K. N. Thakkar, S. Mhatre, and R. Y. Parikh, "Biological synthesis of metallic nanoparticles," *Nanomedicine: Nanotechnology, Biology and Medicine*, vol. 6, no. 2, pp. 257–262, Apr. 2010, doi: 10.1016/j.nano.2009.07.002.

[22] J. N. Tiwari, R. N. Tiwari, and K. S. Kim, "Zero-dimensional, one-dimensional, two-dimensional and three-dimensional nanostructured materials for advanced electrochemical energy devices," *Progress in Materials Science*, vol. 57, no. 4, pp. 724–803, May 2012, doi: 10.1016/j.pmatsci.2011.08.003.

[23] S.U.S. Choi, D.A. Signer, H.P. Wang, "Developments and Applications of Non-Newtonian Flows," *ASME International Mechanical Engineering Congress and Exposition*, Nov. 1995.

[24] Y. Wang, Z. Wan, L. Lu, Z. Zhang, and Y. Tang, "Friction and wear mechanisms of castor oil with addition of hexagonal boron nitride nanoparticles," *Tribology International*, vol. 124, pp. 10–22, Aug. 2018, doi: 10.1016/j.triboint.2018.03.035.

[25] R. Gupta and A. P. Harsha, "Tribological study of castor oil with surface-modified CuO nanoparticles in boundary lubrication," *Industrial Lubrication and Tribology*, vol. 70, no. 4, pp. 700–710, May 2018, doi: 10.1108/ilt-02-2017-0030.

[26] S. Bhaumik, S. Datta, and D. S. Pathak, "Analyses of tribological properties of castor oil with various carbonaceous Micro- and Nano-Friction modifiers," *Journal of Tribology*, vol. 139, no. 6, Jun. 2017, doi: 10.1115/1.4036379.

[27] M. Gulzar *et al.*, "Improving the AW/EP ability of chemically modified palm oil by adding CuO and MoS_2 nanoparticles," *Tribology International*, vol. 88, pp. 271–279, Aug. 2015, doi: 10.1016/j.triboint.2015.03.035.

[28] Z. Y. Xu, K. Hu, C. Han, X. Hu, and X. Yu, "Morphological influence of molybdenum disulfide on the tribological properties of rapeseed oil," *Tribology Letters*, vol. 49, no. 3, pp. 513–524, Jan. 2013, doi: 10.1007/s11249-012-0092-8.

[29] C. P. Koshy, P. K. Rajendrakumar, and M. V. Thottackkad, "Evaluation of the tribological and thermo-physical properties of coconut oil added with MoS_2 nanoparticles at elevated temperatures," *Wear*, vol. 330–331, pp. 288–308, May 2015, doi: 10.1016/j.wear.2014.12.044.

[30] L. L. Zhang, J. P. Tu, H. Wu, and Y. Yang, "WS_2 nanorods prepared by self-transformation process and their tribological properties as additive in base oil," *Materials Science and Engineering: A*, vol. 454–455, pp. 487–491, Apr. 2007, doi: 10.1016/j.msea.2006.11.072.

[31] L. Rapoport *et al.*, "Tribological properties of WS_2 nanoparticles under mixed lubrication," *Wear*, vol. 255, no. 7–12, pp. 785–793, Aug. 2003, doi: 10.1016/s0043-1648(03)00044-9.

[32] S. Chen, D. Mao, and H. Feng, "Preparation of tungsten disulfide motor oil and its tribological characteristics," *Journal of Central South University of Technology*, vol. 14, no. 5, pp. 673–678, Oct. 2007, doi: 10.1007/s11771-007-0129-6.

[33] A.M. Sabri , N. Talib, A.S.A Sani, "A study on tribological performances of hBN/WS_2 and hBN/TiO_2 hybrid vegetable based nanofluids for metalworking fluid," *Proceedings of Mechanical Engineering*, pp. 248-249, Avg. 2022.

[34] S. Baskar, G. Sriram, S. Arumuga, "Experimental Analysis on Tribological Behavior of Nano Based Bio-Lubricants using Four-Ball Tribometer," *Tribology in Industry*, vol. 37, no. 4, pp. 449-454, 2015.

[35] G. Gupta, M. I. U. Haq, A. Raina, and W. K. Shafi, “Effect of epoxidation and nanoparticle addition on the rheological and tribological properties of canola oil,” *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, vol. 236, no. 9, pp. 1837–1845, May 2021, doi: 10.1177/13506501211016181.

[36] R. Yu, J. Liu, and Y. Zhou, “Experimental study on tribological property of MOS_2 nanoparticle in castor oil,” *Journal of Tribology*, vol. 141, no. 10, Aug. 2019, doi: 10.1115/1.4044294.

[37] T. Ouyang, W. Lei, W. Tang, Y. Shen, and C. Mo, “Experimental investigation of the effect of IF-WS_2 as an additive in castor oil on tribological property,” *Wear*, vol. 486–487, p. 204070, Dec. 2021, doi: 10.1016/j.wear.2021.204070.

[38] V. R. Patel, G. G. Dumancas, L. C. K. Viswanath, R. Maples, and B. J. J. Subong, “Castor Oil: Properties, uses, and optimization of processing parameters in commercial production,” *Lipid Insights*, vol. 9, p. LPI.S40233, Jan. 2016, doi: 10.4137/lpi.s40233.

[39] J. Srivastava, P.K.B. Pathak, J.P. Singh, T. Nandi, N.E. Prasad, *A process for synthesis of ultrafine MoS2 particles*, Indian Patent granted, No. 361165

[40] R. Yan *et al.*, “Thermal Conductivity of Monolayer Molybdenum Disulfide Obtained from Temperature-Dependent Raman Spectroscopy,” *ACS Nano*, vol. 8, no. 1, pp. 986–993, Jan. 2014, doi: 10.1021/nn405826k.

[41] Y. Zhang *et al.*, “Reduction in thermal conductivity of monolayer WS_2 caused by substrate effect,” *Nano Research*, vol. 15, no. 10, pp. 9578–9587, Jul. 2022, doi: 10.1007/s12274-022-4560-7.

[42] M. Kole and T. K. Dey, “Effect of aggregation on the viscosity of copper oxide–gear oil nanofluids,” *International Journal of Thermal Sciences*, vol. 50, no. 9, pp. 1741–1747, Sep. 2011, doi: 10.1016/j.ijthermalsci.2011.03.027.

[43] K. C. Lalithambika, K. Shanmugapriya, and S. Sriram, “Photocatalytic activity of MoS_2 nanoparticles: an experimental and DFT analysis,” *Applied Physics A*, vol. 125, no. 12, Nov. 2019, doi: 10.1007/s00339-019-3120-9.

[44] X. Zhang *et al.*, “Synthesis of ultrathin WS_2 nanosheets and their tribological properties as lubricant additives,” *Nanoscale Research Letters*, vol. 11, no. 1, Oct. 2016, doi: 10.1186/s11671-016-1659-3.

[45] B. C. Pak and Y. I. Cho, “Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles,” *Experimental Heat Transfer*, vol. 11, no. 2, pp. 151–170, Apr. 1998, doi: 10.1080/08916159808946559.

[46] A. Einstein, *A new method for determination of themolecular dimensions*, Annalen der Physik, vol. 19, pp. 289-305, 1906.

[47] A. Katiyar, P. Dhar, T. Nandi, and S. K. Das, “Magnetic field induced augmented thermal conduction phenomenon in magneto-nanocolloids,” *Journal of Magnetism and Magnetic Materials*, vol. 419, pp. 588–599, Dec. 2016, doi: 10.1016/j.jmmm.2016.06.065.

[48] F. Marquis and L. P. F. Chibante, “Improving the heat transfer of nanofluids and nanolubricants with carbon nanotubes,” *JOM*, vol. 57, no. 12, pp. 32–43, Dec. 2005, doi: 10.1007/s11837-005-0180-4.