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Lubricity of bio-based lubricant derived from chemically modified jatropha methyl ester

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HIGHLIGHTS

- *TMP ester (Jatropha) has better lubricity in compared to paraffin oil under extreme pressure conditions.*
- *It has similar characteristics to fully formulated lubricant (FFL) in terms of the CoF.*
- *It also has the lowest CoF and high wear scar diameter.*

ABSTRACT

Many studies have been undertaken with a view to using chemically modified vegetable oil as a bio-based lubricant. This research focused on tribological properties of trimethylolpropane (TMP) ester, which is derived from renewable resource. This TMP ester was produced from jatropha methyl ester; it is biodegradable and has high lubricity properties. Two different conditions of lubrication are being investigated: extreme pressure and anti-wear. It was found that the TMP ester (Jatropha) has better lubricity in terms of wear and friction compared to paraffin oil under extreme pressure conditions. TMP ester (Jatropha) has similar characteristics to fully formulated lubricant (FFL), in terms of the coefficient of friction (CoF). In terms of the anti-wear condition, TMP ester (Jatropha) has the lowest CoF; however it also has the high wear scar diameter. This is due to corrosion and chemical attack.

Keywords:
| Synthetic lubricant | Bio-based lubricant | Jatropha |

NOMENCLATURE

h_{min}	Minimum film thickness
H_{min}	Dimensionless minimum film thickness
η_0	Dynamic viscosity at atmospheric pressure
1	Rotational ball
2	Stationary ball
E	Modulus elasticity of the solids
E'	Modulus elasticity of the interacting solids
F	The applied load
k	Elipticity ratio
r	Distance from the center of the contact surface on the lower balls to the axis of rotation
R	Radius of the ball
R'	Reduced radius
T	Friction torque
u	Mean speed of contacts
U	Dimensionless speed parameter
W	Load
α	Dynamic viscosity
μ	Coefficient of friction
σ	Surface roughness of the two contacting surfaces
AW	Anti-Wear
EP	Extreme Pressure
FFL	Fully formulated lubricant
ISL	Initial Seizure Load
SDL	Seizure Delay Load
TMP	Trimethylolpropane
CoF	Coefficient of friction
SEM	Scanning electron microscopy
EHL	Elastrohydrodynamic
CPO	Crude Palm Oil
POME	Palm Oil Methyl Ester
WSD	Wear Scar Diameter
RPM	Rotational per minute
WL	Weld Load

1.0 INTRODUCTION

It has been reported in "World Lubricants to 2017", that lubricant consumption was expected to increase 2.4 percent per year to 43.6 million metric tons in 2017 (World Lubricants to 2017, 2013). This is due to a strong growth in vehicle ownership and ongoing industrialization in the developing countries of Asia. However, in recent years, the concern has been to focus on the issues related to the large proportion of lubricants lost in the environment. The breakdown products are potentially harmful to the environment. Volatile lubricants and lubrication haze will affect the air, while loss from lubrication systems will directly contaminate the water and soil. Increased environmental awareness is a primary driving force for the new technological developments, and there has been much interest in using vegetable oil as a substitute for mineral oil.

Engine oil plays an important role as lubricant for moving parts such as piston rings and cylinder liners, and it also cleans, inhibits corrosion, improves sealing, and acts as a coolant by carrying heat away. Mineral, synthetic, and semi-synthetic engine oils are not directly involved in the ecological cycle of air and soil. However leakage, human error, or blown pipes may occur and the disposable of engine oil, with its toxicity, may effect and damage the ecosystem. Knowledge and concern over the use of petroleum-based products has created the opportunity to produce environmentally friendly lubricants from biodegradable feedstock (Kodali, 2002).

Natural oils present an attractive substitute to conventional lubricants especially in environmentally sensitive areas such as agriculture, forestry, and mining, since they have a low toxicity, high biodegradability (Bockish, 1998; Erhan & Asadauskas, 2000; Havet et al., 2001; Lathi & Mattiasson, 2007), low friction and wear characteristics (Padgurskas et al., 2013; Sarhan et al., 2012) and improved the surface finish (Lawal et al., 2013). However, natural triglycerides have some drawbacks, including a low pour point (Erhan et al., 2006; Fox & Stachowiak, 2007; Hwang & Erhan, 2001) and thermal stability (Erhan et al., 2006; Hamblin, 1999). In general, it has been widely understood that the hydrogen atoms on the β-carbon atom of the alcohol fragment in ester molecule leads to poor oxidative and thermal stability(Gryglewicz et al., 2003). The presence of the hydrogen atoms causes a corrosion mechanism that produces acid and alkenes, and hence increases viscosity and acidity. These problems can only be partially solved with additives (He et al., 2005; He et al., 2004; Hwang & Erhan, 2001; Lathi & Mattiasson, 2007). Consequently, vegetable oil has to be chemically modified, such as through transesterification (Bokade & Yadav, 2007; Uosukainen et al., 1998) and epoxidation of vegetable oil (Hwang & Erhan, 2001; Lathi & Mattiasson, 2007), to eliminate vulnerable sites for oxidation and to interrupt the formation of crystals at low temperatures.

It is assumed that natural triglycerides could enhance lubricity as they can provide an effective boundary layer due to the presence of a polar structure, which disperses non-polar molecules or base lubricant and can act as an anti-wear additive and friction modifier for commercial mineral-based lubricating oil. Erhan et al. (2008) found that the 5% addition of chemically-modified soybean oil (CMSO) products caused a ~50% reduction in wear in hexadecane-based oil. The coefficient of friction obtained for hexadecane (0.095) was reduced to 0.031 upon the addition of CSMO products under these experimental conditions. In another study, Maleque et al. (2000) found that viscosity test results showed that 5% of palm oil methyl esters (POME) can improve the viscosity index (VI) of mineral-based lubricant up to a load of 500 N. However, corrosive wear and the formation of pits on the damaged surface are the dominant modes of wear at higher temperatures. It is believed that corrosive wear occurs in situations where the POME additive reacts with the metal surface at higher temperature, and the reaction products are worn away from the surface, leading to greater wear and friction. , Goodrum and Geller (2005) also found that castor methyl ester and lesquerella oil methyl ester also enhanced lubricity to acceptable levels at concentrations below 1%. It is believed that the high concentration of the unique fatty acid methyl ester, methyl ricinolate could be responsible for the lubricity enhancing properties of castor oil methyl ester.

Several studies have found that oxidation stability and thermal stability could be tackled by replacing glycerol with alcohol, which does not contain β-hydrogen atoms such as neopentyl glycol or trimethylolpropane (TMP) (Gryglewicz et al., 2013; Hamid et al., 2012). However the mechanism, and understanding of the tribological properties, of TMP ester is still vague. This research has therefore been conducted in order to improve understanding of the tribological properties of TMP ester (Jatropha) and development of TMP ester (Jatropha) as a bio-based lubricant. This research will investigate the effects of TMP ester (Jatropha) on two different conditions (extreme pressure and anti-wear).

2.0 EXPERIMENTAL

2.1 Lubricant

Paraffin oil is a colorless, odorless, and light mixture of alkanes in the C15 to C40 range from a non-renewable source, particularly a distillate of petroleum. It is saturated hydrocarbon based oil. Paraffin oil without any additive was used in this study as a baseline oil to compare with TMP ester (Jatropha). The fully formulated lubricant (FFL) that usually contains 80% of base oil (paraffin oil) and 20% of additives was also used for a comparison. FFL was one of the available commercial engine oils with grade SAE40. TMP ester (Jatropha) was from a sample given by University Putra Malaysia. Details of the physical properties of the lubricant used in this study are presented in Table 1. The TMP ester utilized were synthesized by the transesterification of methyl esters prepared from jatropha (JME) and TMP, as shown in Figure 1 (Hamid et al., 2012).

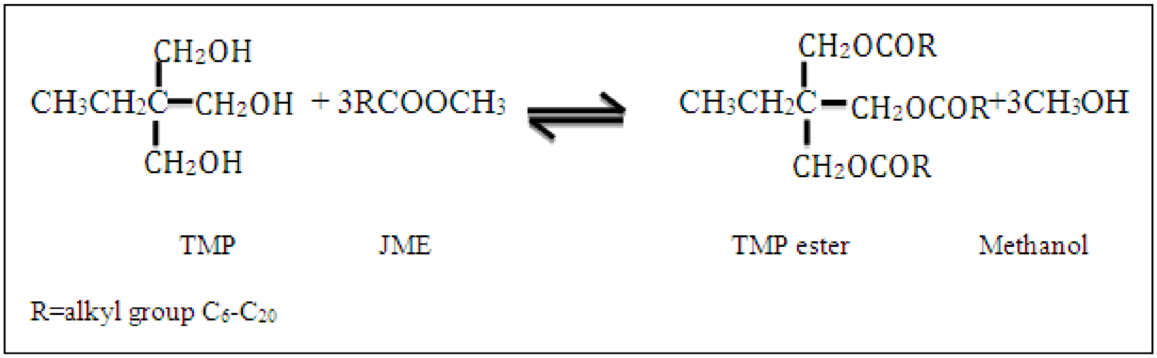

Figure1 Synthesis of TMP ester

Density, Viscosity and VI

Density and dynamic viscosity at various temperatures were measured on a Stabinger SVM3000 viscosmeter. The instrument automatically calculates and displays kinematic viscosity from the density and dynamic viscosity data. A viscosity index was calculated from kinematic viscosity data at 40°C and 100°C.

Pour point and flash point

The methods and apparatus for PP measurements were based on automatic analysis using a ASTM D5949. The flash point test was conducted according to ASTM D93, using a Petrotest Flash Point Meter. This closed cup method requires the heating of a 75 ml sample at a predetermined temperature rate.

Oxidation stability

The oxidation performance of lubricant was tested using a modified Baader test according to DIN 51 554, Part 3. Test oils were aged for six days in a glass vessel at a constant temperature of 95°C. The condition of the oil was monitored by measurements of kinematic viscosity at 40°C for 72 and 144 hours periods.

2.2 Four-ball wear test

A four-ball machine was used to investigate the effect of TMP ester (Jatropha)under boundary and extreme pressure conditions. The four-ball wear tester is the predominant wear tester used by the oil industry to study lubricant chemistry. The four-ball wear tester consists of three balls held stationary in a ball pot plus a fourth ball held in a rotating spindle, as shown in Figure 2. The balls used in this study were steel balls, AISI 52-100, 12.7 mm in diameter, with a hardness of 64–66 HRC. The balls were thoroughly cleaned with toluene before each experiment. The sample volume required for each test is approximately 10 ml.

2.2.1 Calculation for lubrication regime

During testing, the upper ball was lubricated from contact with the lower three balls by a thin film of lubricant. The minimum film thickness for a circular point contact, as formed in the four-ball rotating machine, was calculated using the EHL in the following equation which is developed by Hamrock and Dowson (1981) :

$$H_{\min} = 3.63U^{0.68}G^{0.49}W^{-0.073}\left(1-e^{-1.68k}\right) \tag{1}$$

$$H_{\min} = 3.63\left(\frac{u\eta_0}{E'R'}\right)^{0.68}(\alpha E')^{0.49}\left(\frac{F}{E'R'^2}\right)^{-0.073}\left(1-e^{-1.68k}\right) \tag{2}$$

where H_{min} is the dimensionless minimum film thickness, U is the dimensionless speed parameter and equal to $\left(\frac{u\eta_0}{E'R'}\right)$, where u is the mean speed of contacts in $\left(\frac{u_1+u_2}{2}\right)$, η_0 is the coefficient of dynamic viscosity, E' which is equal to $\left(\frac{1-v_1^2}{E_1}+\frac{1-v_2^2}{E_1}\right)$ is the modulus of elasticity of the interacting solids and R' is the reduced radii which is equal to $\left(\frac{1}{R_1}+\frac{1}{R_2}\right)^{-1}$. G is the dimensionless material parameter and equivalent to $\alpha E'$, where α is the pressure viscosity coefficient. W is the dimensionless load parameter which is equivalent to $\left(\frac{F}{E'R'^2}\right)$, where F is the applied load and k is the elipticity ratio $\left(\frac{R_y}{R_x}\right)$, equaling 1 for point contact. The minimum film thickness, h_{min} was calculated using the following equation,

$$h_{\min} = H_{\min}\cdot R' \tag{3}$$

The lambda factor was ratio calculated using the following equation,

$$\lambda = \frac{h_{\min}}{\left(\sigma_1^2+\sigma_2^2\right)^2} \tag{4}$$

λ is the film thickness ratio, σ is the average surface roughness of the contacting surfaces. According to EHL theory, the relationship is between λ and the lubrication regime is given in Table 1.

Table 1 Regime lubrication

λ	$\lambda \geq 3$	$3 > \lambda > 1$	$\lambda \leq 1$
Lubrication regime	Full fluid film	Mixed film	Boundary lubrication

2.2.2 Anti wear test

For anti-wear characteristics, the standard test IP 239. The test conditions are 392 N load, an operating temperature of room temperature, rotational speed of 1200 rpm and operation time of 60 min. The wear produced on the three stationary balls is measured under a calibrated microscope and reported as the scar (WSD) or calculated volume.

2.2.3 Extreme pressure test

For the extreme pressure conditions the test standard is ASTM 2783. In the machine, a vertical driving spindle rotated a chuck with a speed of 1770 rpm. The load was increased by 196 N for every 10 seconds until the ball is welded. Seizure is indicated by a sharp rise in the coefficient of friction. A number of tribological parameters were determined by using the standard procedures prescribed by the manufacturers (Hwang & Erhan, 2006). For the purpose of illustration a wear–load curve ABCD is shown diagrammatically in Figure 3. Each test was carried out three times to observe any errors which needed to be analyzed. The error measurements specified in this experiment were based on the maximum deviation between three measurements.

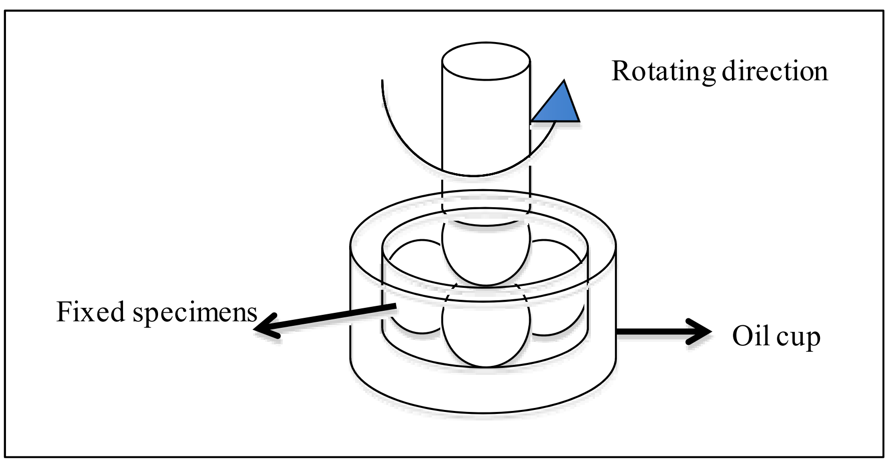

Figure 2 Schematic of four-ball test machine

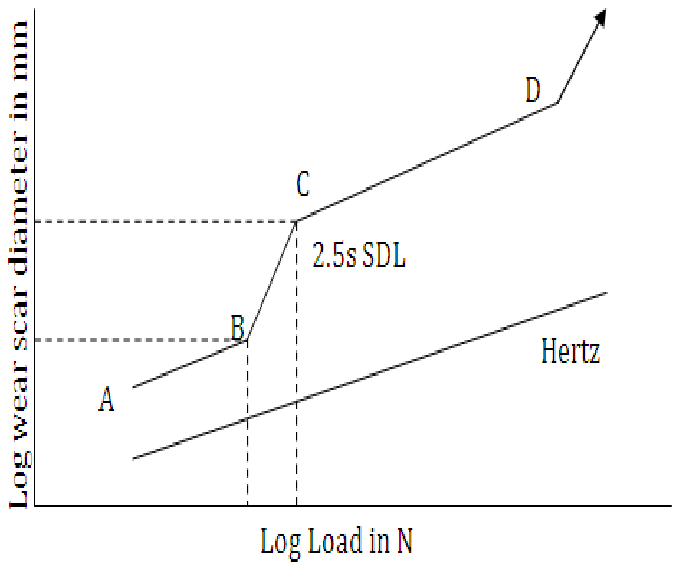

Figure 3 Illustration of a wear load graph

Initial seizure load

The initial seizure load (ISL) is the load at which the wear–load line deviates from the Hertz line. It shows the commencement of the plastic deformation of the balls.

Weld load

Weld load (WL) is the load at which the lubricant completely fails and at which so much heat is generated that the fusion of metal occurs between the rubbing surfaces. It is detected by the apparent fusion of the rubbing surfaces of the steel balls. It is identified by Point D in Figure 3.

Second seizure delay load of 2.5s

The load for which the seizure delay is 2.5 second provides a reliable method for testing the protection against seizure afforded by the lubricant used in gears. This load corresponds with the second discontinuity at C in the wear–load curve.

2.2.4 Friction evaluation

The coefficient of friction is a dimensionless number, which describes the ratio between the friction force between two bodies and the normal force that pressing them together. In lubricated condition, CoF plays important role in determining the transmission efficiency, less CoF means less friction that contributes to higher efficiency. The frictional forces were monitored real-time by recording the shaft torque continuously. The coefficient of frictions in these experiment were calculated using IP-239 standards as shown in below as in Eq.5.

$$\mu = \frac{T\sqrt{6}}{3Wr} \tag{5}$$

where μ, is the CoF, T is the frictional force (Nm), where W is applied load (N), and r is the distance from the center of the contact surface on the lower balls to the axis of rotation which was determined to be 3.67mm. These methods were also used by Husnawan et al. (2007) and Ing et al., 2012.

3.0 RESULTS AND DISCUSSION

3.1 Physical properties

Table 2 compares some of the physical properties of TMP ester (Jatropha) with paraffin oil and ordinary lubricant. As shown in Table 2, TMP ester (Jatropha) has a slightly higher density than paraffin and FFL. This is because of the long carbon chain length in TMP ester. The kinematic viscosity of TMP was higher than that of paraffin oil, however much lower than that of FFL. It is important to understand the viscosity since it plays an important role in the tribological process. FFL has higher viscosity because of the several additive packages such as viscosity improver, anti-wear additives, and corrosion inhibitor already added to the lubricant. Methyl ester has a very low viscosity and it is not suitable as a lubricant. The modification of methyl ester makes it suitable as a lubricant since the viscosity of modified ester does not vary much compared to crude vegetable oil.

Table 2 Major physical properties of different lubricants

Sample \ Properties	Specific gravity at 15.6°C (g/ml)	Viscosity (cSt) at		VI	Pour point (°C)	Flash point (°C)
		40°C	100°C			
Paraffin oil	0.8283	14.85	3.47	110	6	130
FFL	0.8549	101.86	14.46	146	-30	220
TMP (Jatropha)	0.9120	60.83	10.21	156	-35	290
JME (Pramanik, 2003)	0.8800	4.4	-	-	2	135
Jatropha Oil (Pramanik, 2003)	0.9400	52.76	-	-	4	225

The higher the VI of oil, the smaller the decrease in its viscosity with increasing temperature. Thus oil with a higher VI is desirable, since lubrication performance is affected by changes in temperature. The chemical modification showed that VI improved compared to the crude oil, as can be seen in Table 2. Flash point is the lowest temperature at which it can vaporize to form an ignitable mixture in air. TMP (Jatropha) showed the highest flash point as high as 290˚C. In this study, TMP (Jatropha) has better flash point compared to FFL. The number of carbon contained in a structure influences flash point. The more the number of carbon, the higher the flash point. The higher of flash point indicate the resulting ester TMP has a great potential for the production of lubricants (Arbain and Salimon, 2011).

3.2 Oxidation and cold flow properties

It is well known that ester based oils may have problems with oxidation stability and thermal stability. Vegetable oil has a long chain fatty acid triesters of glycerol. The rate of oxidation is relative to the degree of unsaturation of a fatty acid chain and the "β-CH" of the glycerol. As can be seen in Figure 4, jatropha oil has the highest increase in kinematic viscosity change after 144 hours, which relates to their poor oxidation stability. The "β-CH" group exists in jatropha oil. This group is easily removed from the molecular structure that weakens the middle carbon-oxygen bond and results in the formation of a carboxylic acid. Furthermore, the formation of carboxylic acid will further degrade the lubricant.

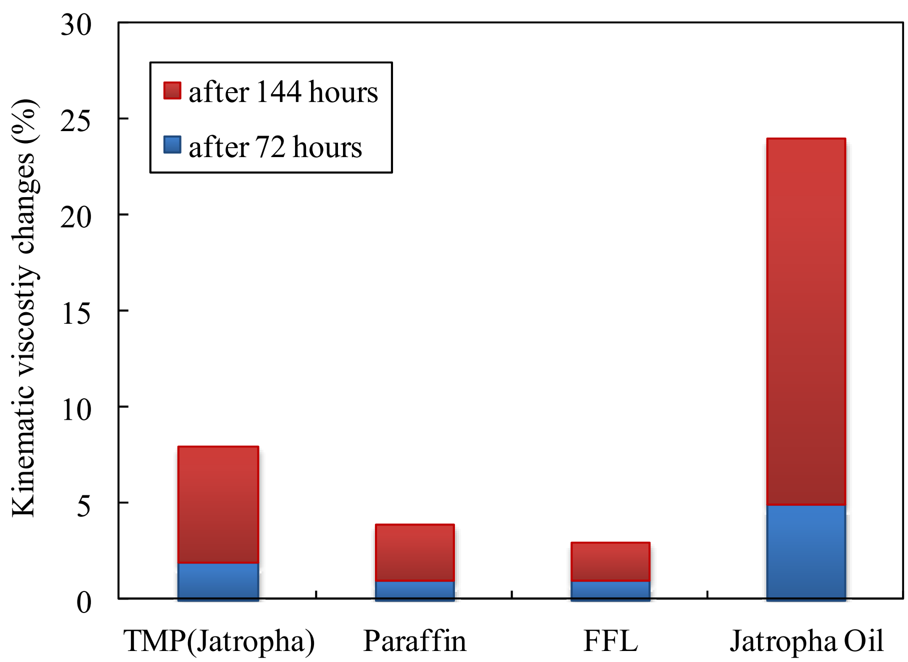

Figure 4 Oxidation analysis of different lubricant sample

TMP ester (Jatropha) produced better oxidation stability to compare with the jatropha oil since the process of transesterification eliminates the "β-CH". The oxidation stability of the TMP ester (Jatropha) improved by 100% compared to the jatropha oil. However the oxidation stability of TMP ester (Jatropha) is still high compared to FFL and paraffin oil.

The cold flow properties of lubricant are evaluated using a pour point. A lower pour point indicates that the oil will flow even at low temperatures and not become solid, which is a good property for lubricant to be used in colder climates. The data in Table 2 indicates that the pour point for TMP ester (Jatropha)was significantly lower compared to other lubricants. This is caused by two-stage of transesterification. Triglycerides, which are from vegetable oil, are subjected to alcoholysis with methanol to obtain fatty acid methyl esters (FAME) and then subsequently transesterified with a polyhydric alcohol(Schuchardt et al., 1998). The branching introduced into methyl ester by transesterification will therefore disrupt the alignment and stacking of hydrocarbon chains, which allow oil to solidify at lower temperatures.

3.3 Tribological properties

The results will be divided into three sections. The first section reports on the calculated film thickness using the well-established equation. The second section reports on the experimental extreme pressure condition and the final section reports on the mixed lubrication condition.

3.3.1 Calculated film thickness

The pressure-viscosity coefficient is calculated from measured film thickness using the EHL film thickness equation. The pressure-viscosity coefficient is approximately constant in each group of lubricants. In the present study, the pressure-viscosity coefficients of different lubricants, as shown in Table 3, are used in calculation. The dynamic viscosity used in this calculation was approximately 25°C. The calculated minimum film thickness and lubricant regime ratio for each lubricant are presented in Table 4.

Based on Eq.1, if the geometry, elastic properties of the balls and speed for the test are fixed, EHL film thickness varies with the pressure viscosity coefficient (α), dynamic viscosity (η), and the applied load (F). In general, as the load increased, the film thickness also decreased hence the lubrication regime changed from mixed lubrication to boundary conditions as can be seen in Table 6. At high contact loading, the stress intensity produced will lead to localized plastic deformation followed by initiation and the steep propagation of crack resulting in spall formation (Al-Bukhaiti et al., 2011).

Table 3 Calculated film thickness at load varying from 196.2N to 1177.2N

Sample	Contact Load (N)	Min film thickness (µm)	Film thickness ratio	Lubrication regime
Paraffin oil	196.2	0.0287	1.0151	Mixed lubrication
	392.4	0.0273	0.9650	Boundary
	588.6	0.0265	0.9368	Boundary
	784.8	0.0259	0.9174	Boundary
	981.0	0.0255	0.9025	Boundary
	1177.2	0.0252	0.8906	Boundary
FFL	196.2	0.0378	1.3367	Mixed lubrication
	392.4	0.0359	1.2707	Mixed lubrication
	588.6	0.0349	1.2336	Mixed lubrication
	784.8	0.0342	1.2080	Mixed lubrication
	981.0	0.0336	1.1885	Mixed lubrication
	1177.2	0.0332	1.1728	Mixed lubrication
TMP (Jatropha)	196.2	0.0504	1.7807	Mixed lubrication
	392.4	0.0479	1.6928	Mixed lubrication
	588.6	0.0465	1.6434	Mixed lubrication
	784.8	0.0455	1.6093	Mixed lubrication
	981.0	0.0448	1.5833	Mixed lubrication
	1177.2	0.0442	1.5623	Mixed lubrication

Since the increased load will increase friction, the temperature also increases, and thus the dynamic viscosity decreases. The minimum film thickness will therefore decrease. On the other hand, the increase of viscosity will increase the film thickness. TMP ester (Jatropha) therefore has the highest film thickness around 0.05 µm, and paraffin has the lowest film thickness around 0.028 µm. This makes steel ball life greater with TMP ester (Jatropha) than with paraffin ball. Even though, FFL has low film thickness compared to TMP ester, additive packages in the lubricant will help to protect the surfaces.

3.3.2 Anti-wear condition

3.3.2.1 Effect of different lubricant on WSD and CoF

The CoF for the different samples at a constant load is shown in Figure 5. A significant improvement in CoF was found for the TMP ester (Jatropha) compared to paraffin oil, of around 40%. Jatropha oil based TMP showed a better CoF compared to the other sources. This finding is similar to the findings reported by Yunus et al. (2004) who found a lower WSD using palm oil based TMP ester compared to commercial hydraulic fluid. In addition, Masjuki et al. (1999) also found that palm-based lubricating oil had better wear performance compared to mineral oil. Fernández Rico et al. (2002) reported that the addition of a synthetic ester (TMP) to a low viscosity polyalphaolefin acted as a wear reducer.

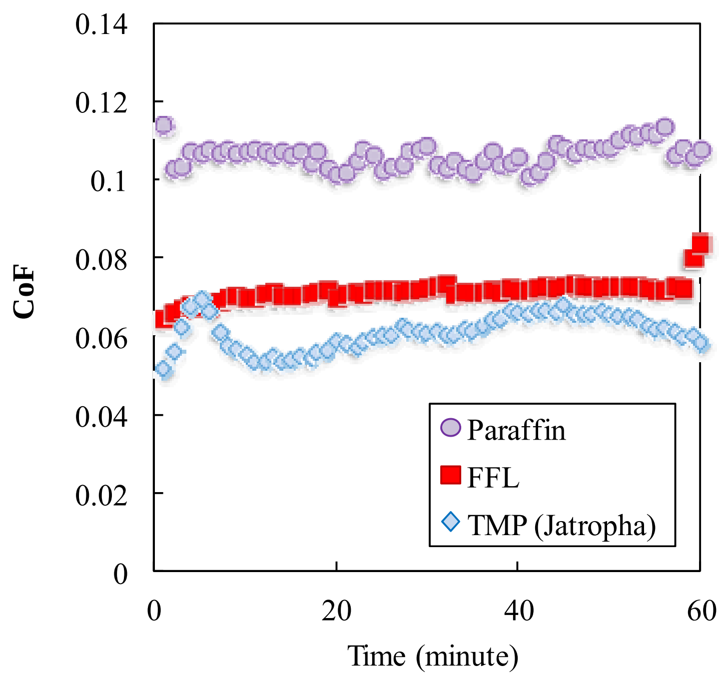

Figure 5 Relationship between COF for different lubricant (Conditions: Load: 40kg, Duration: 1 hour, rpm: 1200)

According to Havet et al. (2001), the length of the fatty acid chains tends to increase the adsorbed film thickness, therefore increasing length of fatty acid, and increasing the surface that area protected. In addition, an increase in the number of ester groups leads to greater binding of the molecules and therefore a greater resistance to shear forces. Figure 6 shows the correlation of WSD and different lubricants. The WSD for paraffin oil is relative to the CoF; the higher the CoF the higher the WSD. In contrast with TMP (Jatropha), it has the lowest CoF, however it has the highest WSD. This unique phenomenon is probably due to the decomposition of the TMP ester release the acid. As a result corrosion occurred and increased the rate of wear. As well as this, at high temperature, the lubricant formed by fatty acids tended to be less stable or more likely to break down (Ing et al., 2012).

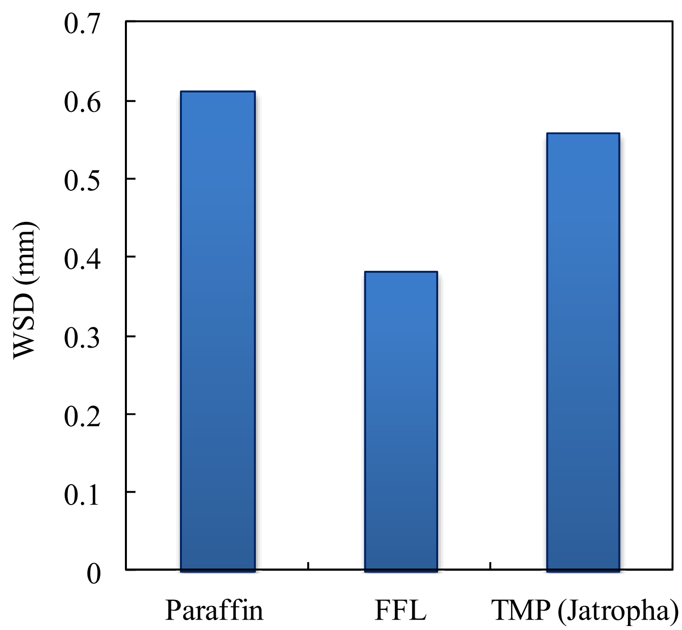

Figure 6 Relationship between WSD for different lubricant lubricant (Conditions: Load: 40kg, Duration: 1 hour, rpm:1200)

3.3.2.2 Surface characteristics

From Figure 7 (a) it can be seen that under FFL lubricant wear is minimal. The WSD is the smallest compared to the others, at around 0.35 mm. The lubricant protected the surface area. In addition, EDX results show that anti-wear additives such as Zn, P, S, and Ca actively protect the surface. According to Figure 7 (b), boundary lubrication occurred here. The paraffin oil did not manage to create an oil film. The rupture of the oil film causes metallic contact. This metallic contact caused the adhesion of micro asperities. Plastic deformation of the surface occurred. The large amounts of friction increased the temperature and caused wear and seizure. In Figure 7(c) it can be seen that severe adhesive wear only occurred in the middle of the WSD. The lubricant failed to provide enough support in the highly pressurized contact area and caused plastic deformation.

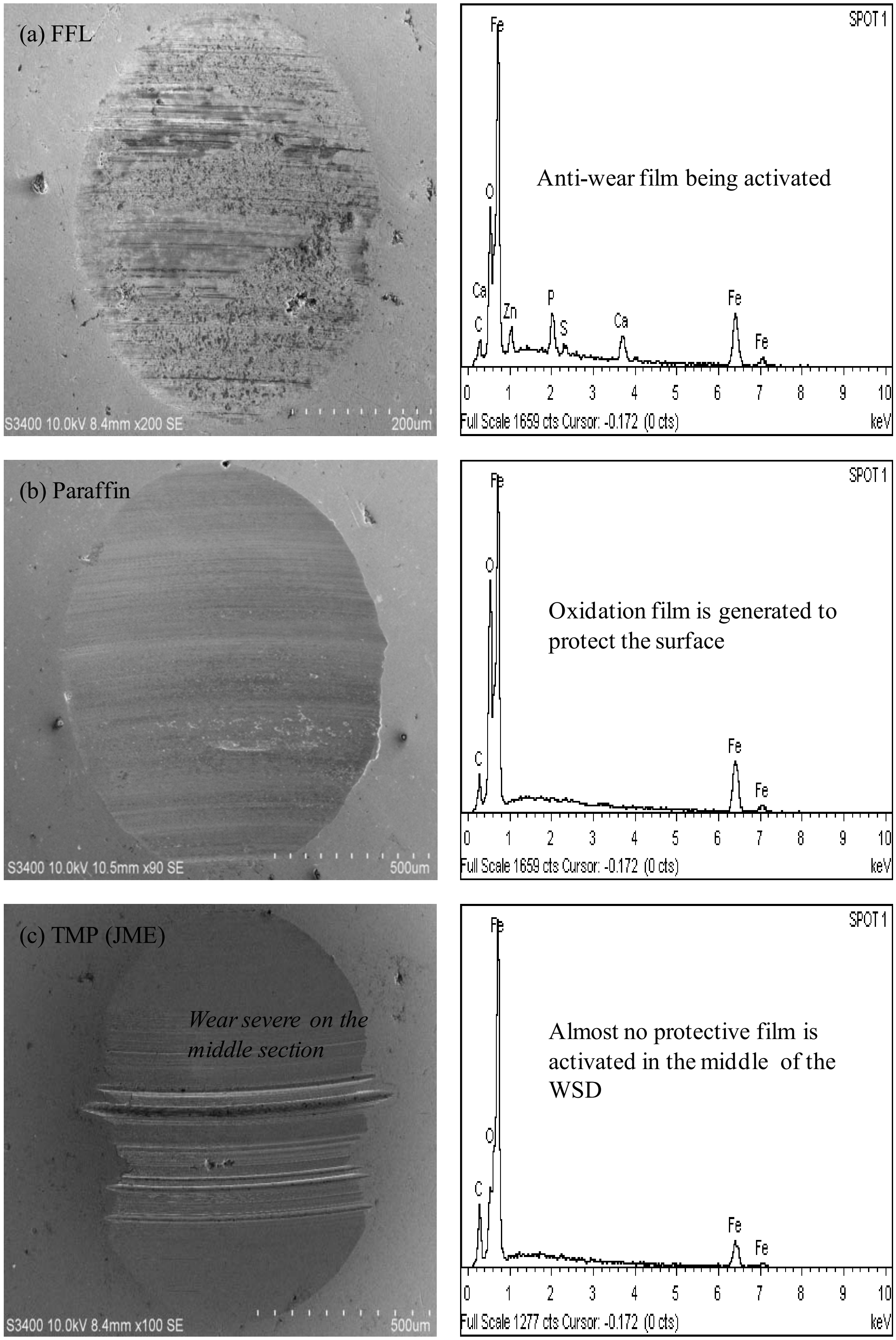

Figure 7 Wear micrograph and EDX of bottom ball for different lubricant (Conditions: Load: 40kg, Duration: 1 hour, Temperature: 75°C, rpm: 1200)

3.3.3 Extreme pressure condition

3.3.3.1 The effect of applied load on coefficient friction

Table 4 shows the extreme pressure condition of different lubricants. Based on these, it can be seen that, paraffin oil has the lowest ISL at 392N followed by TMP (Jatropha) at 981N and FFL at 1177N. A higher ISL indicates that the lubricant can sustain at higher load. The weld load for paraffin was 1177N, followed by TMP (Jatropha) at 1569N and FFL at 1981N. FFL has the highest WL, because it has additive packages such Zn, sulfur, and molybdenum to protect the surface. TMP (Jatropha) has a lower COF compared to FFL is because of a higher triester content of the lubricant will increase the polarity; and thus will better protect the surface (Yunus et al., 2004).

Table 4 Extreme Pressure conditions

	Paraffin	FFL	TMP(Jatropha)
ISL(N)	392	1177	981
Weld load (N)	1172	1981	1569
CoF at 981N	0.6	0.08	0.070
WSD at 981 N(mm)	4.3	0.54	0.504

Figure 8 shows the correlation of CoF with different loads using lubricant. For Figure 8 (a), at low loads (below 392 N) the CoF of paraffin oil is almost at the same low value. This shows that the thin film that is formed can still sustain the load. However, as the load was increased to 490 N the thin film started to break down and the CoF increased. As the load increased to 785 N, the CoF increased sharply at the beginning and then decreased. This is possibly due to the "running-in" effect. In running in, the thickness of the oil film is too thin, so that contact begins at the peak of the asperities, thus increasing both the CoF and wear. This regime is known as boundary lubrication (Nogueira et al., 2002). In this regime the contacting regions increase the local pressures, which may lead to noise, fatigue damage, and high-wear rates (Lugt et al., 2001). The rubbing surfaces are thus smoothed and at this latter stage their wear rate is low and constant. At 981 N, the CoF continues increasing until the ball is welded. This is due to the high pressure and high temperature; the lubricant evaporates and causes the balls to weld together.

Figure 8 (b) shows the correlation of CoF with different loads using FFL. Even at 981 N, the lubricant still did not encounter the initial seizure load. It shows that this lubricant has better extreme pressure characteristics than paraffin oil. It is believed that the extreme pressure additive package acted to maintain the low CoF value. From Figure 8 (c) it can be seen that as the load is increased, the CoF increased. In addition, the thin film formed by the TMP (Jatropha) still did not encounter the initial seizure load at 981 N. No obvious peak occurred here. It almost has a similar pattern to FFL, however it has a lower CoF compared to FFL.

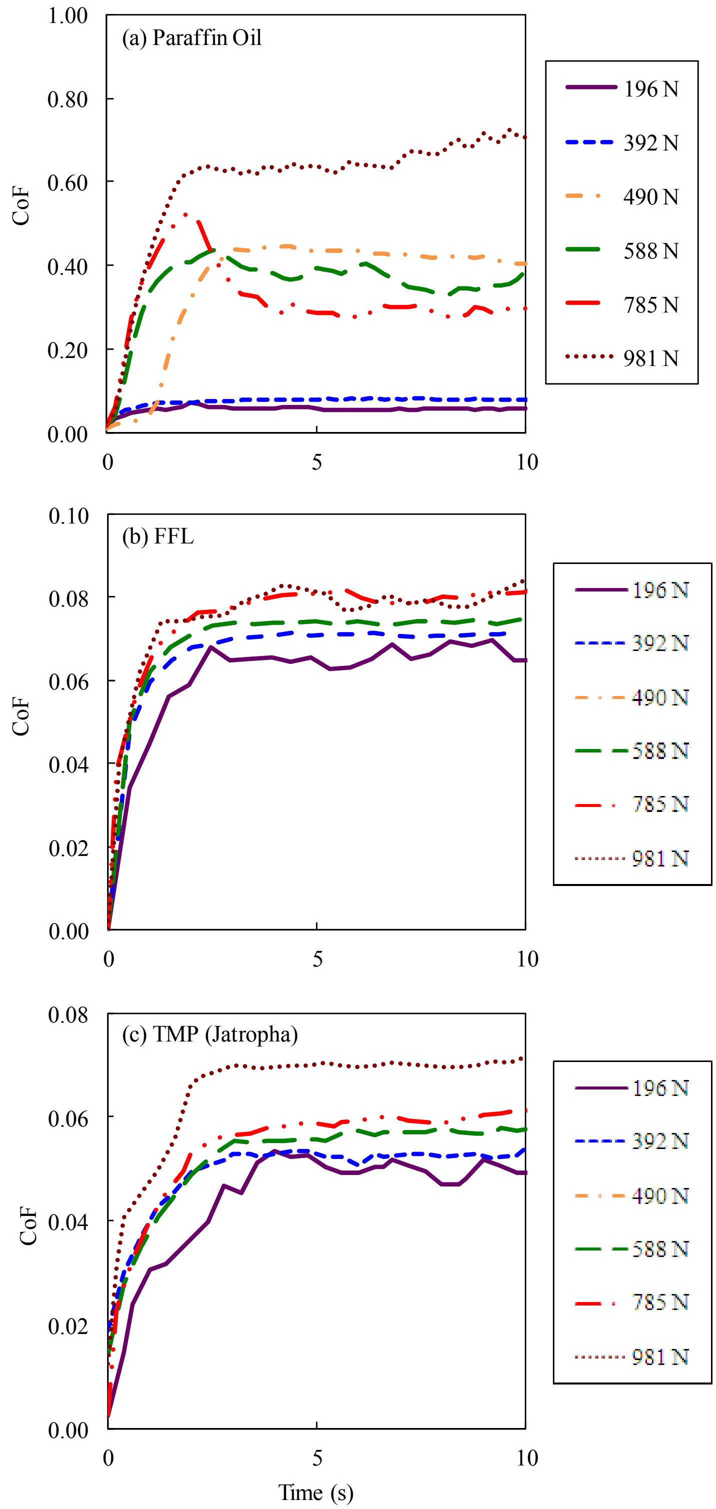

Figure 8 Variation of COF with load from 196 N to 981 N in 10 second for (a) paraffin oil (b) FFL (c) TMP (Jatropha)

3.3.3.2 The effect of applied load on the wear scar diameter

The WSD can be defined as two different regions in Figure 9. The first region is the anti-wear region, which is before the ISL. The WSD is similar to the elastically deformed area of contact under static loading. The second region is the EP, which is after the ISL. The WSDs here are much larger than in the previous region. Figure 9 shows that the WSD increases gradually in the anti-wear region. However it increases abruptly up to a 2.5 s seizure delay load after the ISL, followed by a slow increase up to the WL. The slow increase of the WSD before the ISL is reached may be attributed to the formation of a thin film of lubricant and the adsorption of additive on the sliding surfaces. The sudden increase in the WSD is due to the rise in temperature and consequent partial desorption of the adsorbed thin layer of lubricant (Singh et al., 1992). After a 2.5 s seizure delay load, the WSD increases slowly due to the formation of a combined layer of additive and the reaction of the TMP ester. This combined layer prevents metallic contact between the balls, even at higher loads.

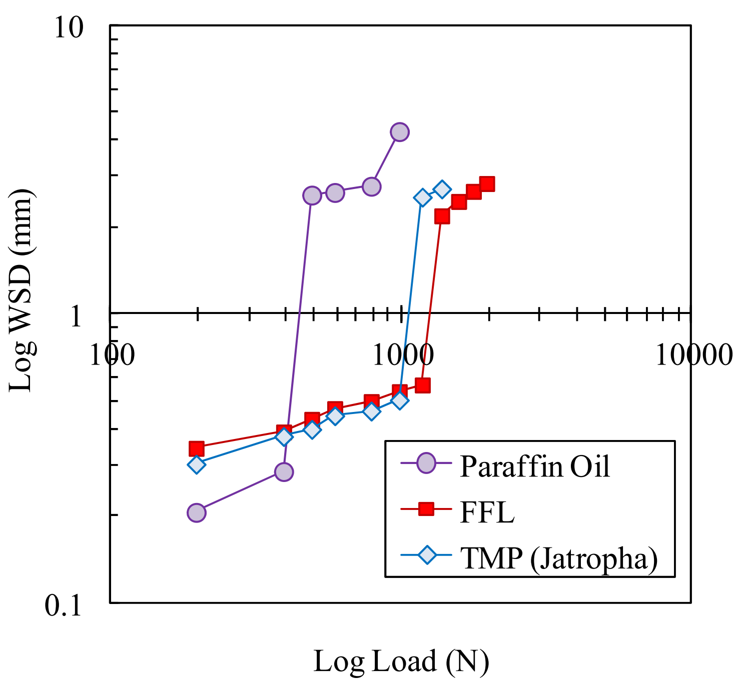

Figure 9 Relationship between load and wear scar diameter (WSD) at load varies from 20 kg-180 kg

In addition, Figure 9 shows that the TMP ester improves the load-carrying capacity and function of the lubricant in high loads. It can also be seen that at low loads there is no significant difference between the TMP ester (Jatropha) and FFL except for the paraffin oil. However as the load increased to over 490 N, paraffin oil greatly increased the WSD. Paraffin oil could not sustain a load of more than 785 N and the ball was welded at 981 N.

The Jatropha TMP has an almost similar trend to that of FFL. Figure 6 shows that TMP (Jatropha) has a slightly lower WSD compared to FFL. However, at higher loads it seems that FFL shows better extreme pressure properties because it can sustain loads of up to 1961 N and has the lowest ISL of around 1177 N.

CONCLUSIONS

The experiment results show that TMP (Jatropha) lubricant improves wear preventive lubrication properties in terms of CoF. Under extreme pressure conditions the maximum load bearing capacity of 1373 N was found to be using TMP (Jatropha) respectively by retaining its quality without breakdown compared to paraffin at around 788 N. Under the fluid film lubrication, TMP (Jatropha) with a higher content of fatty acid triester shows the lowest CoF around 0.05 even compared to fully formulated lubricant of around 0.07. In order to utilize TMP ester (Jatropha) as engine oil, many other properties including oxidative, thermal and hydrolytic stabilities need to be examined. TMP ester (Jatropha) is environmentally desirable as a mineral oil based lubricant, and research to investigate the properties of TMP ester (Jatropha) to make it technologically competitive as an automobile lubricant should be encouraged.

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REFERENCES

AL-Bukhaiti, M. A., Al-Hatab, K. A, & Gabbert, Ulrich, 2011. The Influence af High Contact Stresses and Lubricant Type an the Rolling Contact Fatigue Life and Failure Mode of Aisi 52100 Steel Balls. Emirates Journal for Engineering Research, 16(1), 9-22.

Arbain, Noor Hafizah, & Salimon, Jumat, 2011. Synthesis and characterization of ester trimethylolpropane based Jatropha curcas oil as biolubricant base stocks. Journal of Science and Technology, 2(2).

Bockish, M., 1998. Fats and Oils Handbook,Champaign, IL,838

Bokade, V. V., & Yadav, G. D., 2007. Synthesis of Bio-Diesel and Bio-Lubricant by Transesterification of Vegetable Oil with Lower and Higher Alcohols Over

Heteropolyacids Supported by Clay (K-10). Process Safety and Environmental Protection, 85(5), 372-377.

Erhan, S. Z., & Asadauskas, S., 2000. Lubricant basestocks from vegetable oils. Industrial Crops and Products, 11(2), 277-282.

Erhan, S. Z., Sharma, B. K., & Perez, J. M., 2006. Oxidation and low temperature stability of vegetable oil-based lubricants. Industrial Crops and Products, 24(3), 292-299.

Erhan, Sevim Z., Sharma, Brajendra K., Liu, Zengshe, & Adhvaryu, Atanu, 2008. Lubricant Base Stock Potential of Chemically Modified Vegetable Oils. Journal of Agricultural and Food Chemistry, 56(19), 8919-8925.

Fernández Rico, J. E., Hernández Battez, A., & García Cuervo, D., 2002. Wear prevention characteristics of binary oil mixtures. Wear, 253(7–8), 827-831.

Fox, N.J., & Stachowiak, G.W., (2007). Vegetable oil-based lubricants—a review of oxidation. Tribology International 40(7), 1035-1046.

Goodrum, J.W., & Geller, D.P., 2005. Influence of fatty acid methyl esters from hydroxylated vegetable oils on diesel fuel lubricity. Bioresource Technology 96(7), 851-855.

Gryglewicz, S., Muszyński, M., & Nowicki, J., 2013. Enzymatic synthesis of rapeseed oil-based lubricants. Industrial Crops and Products 45, 25-29.

Gryglewicz, S., Piechocki, W., & Gryglewicz, G., 2003. Preparation of polyol esters based on vegetable and animal fats. Bioresource Technology, 87(1), 35-39.

Hamblin, P., (1999). Oxidative stabilisation of synthetic fluids and vegetable oils. Journal of Synthetic Lubrication, 16(2), 157-181.

Hamid, H. A., Yunus, R., Rashid, U., Choong, T. S. Y., & Al-Muhtaseb, A. H., 2012. Synthesis of palm oil-based trimethylolpropane ester as potential biolubricant: Chemical kinetics modeling. Chemical Engineering Journal, 200–202(0), 532-540.

Hamrock, Bernard J, & Dowson, Duncan, 1981. Ball bearing lubrication: the elastohydrodynamics of elliptical contacts.

Havet, L., Blouet, J., Robbe Valloire, F., Brasseur, E., & Slomka, D., 2001. Tribological characteristics of some environmentally friendly lubricants. Wear, 248(1-2), 140-146.

He, Z. Y., Song, Y. P., Shao, H. Y., Zhan, W. Q., & Ren, T. H., 2005. A study of the synergistic effect of a triazine-dithiocarbamate derivative with tcp in vegetable oil. Journal of Synthetic Lubrication, 21(4), 287-297.

He, Zhongyi, Lu, Jinliang, Zeng, Xiangqiong, Shao, Heyang, Ren, Tianhui, & Liu, Weimin, 2004. Study of the tribological behaviors of S, P-containing triazine derivatives as additives in rapeseed oil. Wear, 257(3–4), 389-394.

Husnawan, M., Saifullah, M. G., & Masjuki, H. H., 2007. Development of friction force model for mineral oil basestock containing palm olein and antiwear additive. Tribology International, 40(1), 74-81.

Hwang, Hong-Sik, & Erhan, Sevim, 2001. Modification of epoxidized soybean oil for lubricant formulations with improved oxidative stability and low pour point. Journal of the American Oil Chemists' Society, 78(12), 1179-1184.

Hwang, Hong-Sik, & Erhan, Sevim Z., 2006. Synthetic lubricant basestocks from epoxidized soybean oil and Guerbet alcohols. Industrial Crops and Products, 23(3), 311-317.

Ing, Tiong Chiong, Mohammed Rafiq, A. K., Azli, Y., & Syahrullail, S., 2012. The Effect of Temperature on the Tribological Behavior of RBD Palm Stearin. Tribology Transactions, 55(5), 539-548.

Kodali, D. R., 2002. High performance ester lubricants from natural oils. Industrial Lubrication and Tribology, 54(4), 165-170.

Lathi, Piyush S., & Mattiasson, Bo, 2007. Green approach for the preparation of biodegradable lubricant base stock from epoxidized vegetable oil. Applied Catalysis B: Environmental, 69(3–4), 207-212.

Lawal, Sunday Albert, Choudhury, Imtiaz Ahmed, & Nukman, Yusoff, 2013. A critical assessment of lubrication techniques in machining processes: a case for minimum quantity lubrication using vegetable oil-based lubricant. Journal of Cleaner Production, 41(0), 210-221.

Lugt, P. M., Severt, R. W. M., Fogelströ, J, & Tripp, J. H., 2001. Influence of surface topography on friction, film breakdown and running-in in the mixed lubrication regime. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 215(6), 519-533.

Maleque, M. A., Masjuki, H. H., & Haseeb, A. S. M. A., 2000. Effect of mechanical factors on tribological properties of palm oil methyl ester blended lubricant. Wear, 239(1), 117-125.

Maleque, MA, Masjuki, HH, & Sapuan, SM, 2003. Vegetable-based biodegradable lubricating oil additives. Industrial Lubrication and Tribology, 55(3), 137-143.

Masjuki, H. H., Maleque, M. A., Kubo, A., & Nonaka, T., 1999. Palm oil and mineral oil based lubricants—their tribological and emission performance. Tribology International, 32(6), 305-314.

Nogueira, I., Dias, A. M., Gras, R., & Progri, R., 2002. An experimental model for mixed friction during running-in. Wear, 253(5–6), 541-549.

Padgurskas, Juozas, Rukuiza, Raimundas, Prosyčevas, Igoris, & Kreivaitis, Raimondas, 2013. Tribological properties of lubricant additives of Fe, Cu and Co nanoparticles. Tribology International, 60(0), 224-232.

Pramanik, K., 2003. Properties and use of jatropha curcas oil and diesel fuel blends in compression ignition engine. Renewable Energy, 28(2), 239-248.

Sarhan, Ahmed AD, Sayuti, M, & Hamdi, M., 2012. Reduction of power and lubricant oil consumption in milling process using a new SiO 2 nanolubrication system. The International Journal of Advanced Manufacturing Technology, 1-8.

Schuchardt, Ulf, Sercheli, Ricardo, & Vargas, Rogério Matheus, 1998. Transesterification of vegetable oils: a review. Journal of the Brazilian Chemical Society, 9, 199-210.

Singh, T., Bhattacharya, A., & Verma, V. K., 1992. A study in EP activity evaluation of some new oil-soluble Mo-S complexes. Tribology International, 25(6), 381-385.

Uosukainen, Esa, Linko, Yu-Yen, Lämsä, Merja, Tervakangas, Tommi, & Linko, Pekka, 1998. Transesterification of trimethylolpropane and rapeseed oil methyl ester to environmentally acceptable lubricants. Journal of the American Oil Chemists' Society, 75(11), 1557-1563.

Freedonia Group, 2013.World Lubricants to 2017, Preston Road, Dallas.

Yunus, Robiah, Fakhru'l-Razi, Ahmadun, Ooi, Tian Lye, Iyuke, Sunny E., & Perez, Joseph M., 2004. Lubrication properties of trimethylolpropane esters based on palm oil and palm kernel oils. European Journal of Lipid Science and Technology, 106(1), 52-60.