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Review Article

Development and Performance Evaluation of Vegetable Oils as Bio-Lubricant: A Review

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Abstract *- Presently, mineral oil is used as a commercial lubricant in various applications because it is easily available, its good overall performance and is low cost. However, the petroleum base stock is non-renewable, and mineral oil causes adverse environmental effects, which are increasing day by day; therefore, these elements couldn't maintained in the future. Researchers are currently focusing on bio-lubricants as a substitute for MO as a source of lubricants. Bio-lubricants are formulated from vegetable oils and esters, which are renewable base stocks. Bio-lubricants are clearly biodegradable and more environmentally friendly as they are less toxic. As a lubricant, vegetable oil has some limitations, like poor thermal and oxidative stability, that might have an effect on their tribological performance. This paper presents an overview of the development, features, characterisation, benefits, and applications of vegetable oil-based lubricants. Raw vegetable oils have poor thermal and oxidative stability, so they need chemical modification. The research focuses on the necessary chemical modification techniques to improve the characteristics of bio-lubricants, as well as the tribological analysis of bio-lubricants with Nano-additives. The drawbacks of bio-lubricants, as well as their future potential, have been noted.*

Keywords *- Bio-Lubricants, Epoxidation, Nano- additives, Thermal stability, Transesterification.*

1. Introduction

Lubrication can be defined as a strategy to control friction and wear between interacting surfaces in relative motion under load through a solid, liquid or gaseous media. Lubricants smooth out work, lower the frequently occurring breakdowns and safeguard genuine machine operations by acting as an antifriction substance. In machinery, lubricants are essential for a variety of reasons, including corrosion resistance, heat transfer, and power transmission. [5]

Mineral oil is currently used as an engine lubricant and they are formulated from petroleum oil. Mineral oils are toxic and non-biodegradable; therefore, they are not environment-friendly. Due to the depletion of mineral oil sources, its high prices and the environmental relevance of pollution, researchers are focusing on the development of environmentally friendly lubricants as a replacement for mineral oil in industrial applications and engines. [4]

1.1. Bio-Lubricant

Bio-lubricants are lubricants made from renewable and biodegradable base materials. This definition, however, is not universally accepted. In certain cases, the word simply refers to biodegradability. For present applications, biolubricants are biodegradable and renewable materials. Biolubricants do not have to be fully composed of vegetable oils. These are natural oil-derived compounds, such as fat-derived fatty acids, that combine with synthetic alcohols or polyols to form biolubricant esters. Natural vegetable oils may also be treated to create more biodegradable and sustainable products. [5]

1.1.1. Alternative Lubricants: Vegetable Oil

Compared to synthetic and mineral oils, vegetable oil-based lubricants have the most significant qualities, such as high lubricity, high flash point, high loading capacity, high viscosity index, low toxicity, and low environmental emission. [15, 29]

However, vegetable oils have low oxidative and thermal stability, poor cold flow characteristics and poor corrosion prevention. [3] Edible oils and non-edible oils are the two primary categories of vegetable oils.

Producing both edible and inedible vegetable oil seeds has enormous potential in India. The greatest potential for application in the production of lubricants based on vegetable oil is demonstrated by these oil seeds. Vegetable oils include castor oil, crumb oil, sunflower oil, capia oil, olive oil, jojoba oil, coconut oil, canola oil, palm oil, safflower oil, linseed oil, rapeseed oil, and soybean oil.

Table 1. Vegetable oil advantages and limitations [15, 3]

Advantages	Limitations
Quick biodegradation	Poor corrosion protection
Renewable and environmentally friendly	Low oxidation and thermal stability
High VI	Operating temperature restrictions
Higher flash points	
Higher lubricity	
Excellent boundary lubrication	
Engine emissions have been reduced.	
Low-cost disposal	
Less toxic	
Low volatility	

1.1.2. Physiochemical Properties [18]

Biolubricants offer several beneficial physicochemical properties. They provide technological benefits over standard petroleum-based lubricants.

Viscosity

That is oil's most important feature. It is defined as internal resistance to deformation, and it changes with pressure and temperature. A good lubricant generally possesses high viscosity properties.

Viscosity Index

It is a unit less quantity, which measures changes in viscosity with respect to temperature. VI is inversely proportional to temperature changes.

Because vegetable oils have a higher VI compared to mineral oils, they can function effectively at high temperatures as they maintain the oil film thickness. As a result, biolubricants work across a wide temperature range.

Pour Point

The minimum temperature at which oil flows or pours is known as the pour point. It is a significant element. Vegetable-based biolubricants have lower pour points compared with mineral oils, which makes them ideal for cold starts.

Flash Point

The flash point is the minimum temperature at which a lubricant must be heated before it vaporizing. With a greater flash point than mineral oils, biolubricants derived from vegetable oils reduce the chance of a lubricant leak, therefore guaranteeing safety on the shop floor.

Fire Point

The fire point is the lowest temperature at which continuous ignition, rather than instantaneous ignition. A good lubricant should have a higher fire point and flash point.

Cloud Point

The temperature at which solid-forming components begin to separate from the oil and crystallize is called the cloud point. It demonstrates the usefulness of the lubricant in cold weather.

Oxidation Stability

It is defined as the capacity to resist the formation of oxides, which increases with temperature. Metal surfaces, temperature, impurities, pressure, agitation, and water are the leading causes of oxidation. Poor oxidative stability suggests that if left untreated, oil oxidizes quickly during usage, thickening and polymerising to a plastic-like consistency.

Rust and Corrosion Prevention

In contrast to corrosion, which happens when chemicals react with metal, rust is an iron oxide that is created by the chemical interaction of oxygen and ferrous metals in the presence of atmospheric moisture. Compared to mineral oils, biolubricants based on vegetable oils are less reactive to chemicals, water, and ferrous metals.

Anti-Wear Properties

The lubricant’s anti wear properties can be enhanced by adding additives which reduce friction, wear, scoring and scuffing. Anti-wear additives form a protective covering at the interfaces to prevent wear. Standard laboratory procedures are used to identify anti-wear properties.

Compared to mineral oils, biolubricants derived from vegetable oils have higher wear resistance. The physicochemical properties of vegetable oils are listed above. But the main question is whether vegetable oil can be used in pure form, mixed with other essential oils or added micro or nano additives. [20]

2. Need of Chemical Modification

Vegetable oils have outstanding lubricating features such as viscosity index, resistance to friction and wear, good flash point, pour point and high load-bearing capacity. However, its use is limited due to poor corrosion resistance, oxidation resistance, and thermal stability. Plenty of research has been done to enhance thermal oxidation characteristics and make them compatible with petroleum-based lubricants. [1] Vegetable oils are made up of fatty acids produced from triglyceride molecules that, include glycerol. A tertiary β-hydrogen (secondary hydrogen) is formed in natural oils due to the presence of glycerol, and it is linked to the β-carbon (secondary carbon) of the functional hydroxyl group. The quick oxidation of natural oils is caused by unsaturated fatty acids that include β-hydrogen, which is known to have oxidative instability. Therefore, it is necessary to modify the physiochemical characteristics of vegetable oils through various chemical processes in order to enhance critical properties for use in various applications. Chemical modification methods include the following:

Table 2. Physiochemical properties of edible oils [18]

Properties → Vegetable Oils ↓	Kinematic Viscosity (at 40° c) mm^2/s	Oxidation Stability 110 °c, h	Cloud point (°c)	Flash point (°c)	Density (kg/m^3)
Palm oil	5.72	4.0	13.0	165	875
Sunflower oil	4.45	0.9	3.42	185	878
Coconut oil	2.75	35.4	0	112	805
Soya bean oil	4.05	2.1	1.0	176	885
Linseed oil	3.74	0.2	-3.8	178	890
Olive oil	4.52	3.4	-	179	892
Peanut oil	4.92	2.1	5.0	177	882
Rapeseed oil	4.45	7.5	-3.3	62	880
Rice bran oil	4.95	0.5	0.3	-	886

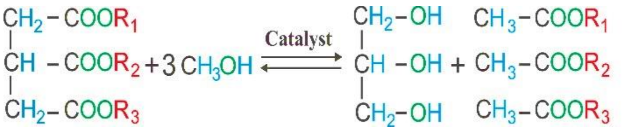
Table 3. Physiochemical properties of non-edible oils [18]

Properties → Vegetable Oils ↓	Kinematic Viscosity (at 40° c) mm^2/s	Oxidation Stability 110 °c, h	Cloud point (°c)	Flash point (°c)	Density (kg/m^3)
Jatropha oil	4.82	2.3	2.75	136	878
Karanja oil	4.80	6.0	9.0	150	918
Mahua oil	3.40	-	-	210	850
Neem oil	5.20	7.2	14.5	44	885
Castor oil	15.25	1.2	-13.5	260	898
Tobacco oil	4.25	0.8	-	166	887

2.1. Transesterification of Vegetable Oils

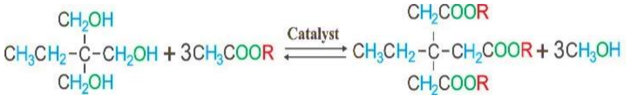
Transesterification is a chemical process that converts one ester into another by changing an alkyl group. Transesterification of vegetable oil produces alkyl esters of different fatty acids when vegetable oils react with short and long-chain-length alcohols in the presence of a catalyst, i.e., acid or basic. Fatty acid alkyl esters generated from this process can be utilized as lubricants as a finished product. Triglyceride and alcohol are required in 1:3 mole ratios for a stoichiometric reaction. Excess alcohol, on the other hand, is utilized to enhance the production of the alkyl ester and separate it from the produced glycerol.

The molar ratio (alcohol: oil), reaction temperature, reactant purity, free fatty acid content, type of catalyst (alkaline or acidic), and its concentration are the factors which must be considered during the transesterification reaction. They are significant elements influencing transesterification. [15] In a two-stage transesterification process, the first step is vegetable oil triglyceride, in the presence of a catalyst, reacts with methanol to form methyl ester and glycerol. The second step involves the methyl ester reacting with polyols like TMP, NPG and PE to remove the β-hydrogen atom from the triglyceride and stabilize the bio-lubricant. [1]



$$\begin{array}{l} CH_2-COOR_1 \\ | \\ CH-COOR_2 \\ | \\ CH_2-COOR_3 \end{array} + 3\,CH_3OH \xrightleftharpoons{Catalyst} \begin{array}{l} CH_2-OH \\ | \\ CH-OH \\ | \\ CH_2-OH \end{array} + \begin{array}{l} CH_3-COOR_1 \\ CH_3-COOR_2 \\ CH_3-COOR_3 \end{array} \quad (1)$$

Triglyceride Methanol Glycerol Methyl Ester



$$CH_3CH_2-\overset{\displaystyle CH_2OH}{\underset{\displaystyle CH_2OH}{C}}-CH_2OH + 3CH_3COOR \xrightleftharpoons{Catalyst} CH_3CH_2-\overset{\displaystyle CH_2COOR}{\underset{\displaystyle CH_2COOR}{C}}-CH_2COOR + 3CH_3OH \quad (2)$$

TMP Methyl Ester TMP- Ester Methanol

2.2. Epoxidation

A cyclic ether made up of three parts in the epoxide ring is referred to as an epoxide. For unsaturated fatty acids, epoxidation is a vital process that often takes place in situ. Epoxidation can also be used to activate vegetable oil double bonds, which serve as reactive sites in coatings. Vegetable oils have several drawbacks, including unsaturation, which limits the applications for which it is suitable as a lubricant at high temperatures. In recent years, the usage of epoxidized vegetable oils has grown in popularity. Furthermore, vegetable oil-based PVC polymer plasticizers and additives have been demonstrated to be more resistant to extreme heat and light. Epoxide groups or oxirane rings are present in epoxidized oils. The epoxide reaction, in which alkenes react with organic peroxy acids, is a typical method for producing epoxide groups. Epoxidation procedures differ based on the type of reactants and catalysts utilized in the process. Acid or enzyme-catalyzed percarboxylic acid epoxidation is a technique for producing epoxides from olefin-type compounds. In situ epoxidation processes usually involve two steps: (1) the production of a peroxy acid and (2) the peroxy acid's interaction with an unsaturated double bond. The transformation of ethylene unsaturation into epoxide is influenced by a variety of factors, including ethylenic unsaturation: carboxylic acids ratio, catalyst, catalyst concentration, temperature, rpm and H2O2 addition time. To avoid regions of high peroxide concentration that might result in the creation of explosive combinations, H2O2 is progressively added. [15]

3. Nanoparticle Additive

Nanoparticles are mixed into lubricants to increase the service life of mechanical components. It also contributes to environmental protection by minimizing friction, wear, and energy loss. [10] Nano additives are added to lubricants to improve their tribological characteristics.

It is critical to understand nanoparticle lubricating mechanisms. There are two types of mechanisms: direct mechanisms and indirect mechanisms. The rolling mechanism and protective film mechanism are direct mechanisms, while the repair mechanism and polishing mechanism are indirect mechanisms. [10]

3.1. Rolling Mechanism

If the nanoparticles are spherical, they roll between the mating surfaces like bearings. This mechanism is widely utilized to improve lubricant tribological characteristics in low-load applications.

3.2. Mending Mechanism

Nanoparticles are deposited and accumulated in the grooves of the friction surface to reduce wear.

3.3. Polishing Mechanism

In this mechanism, surface smoothness increases by the polishing effect of nanoparticles due to rubbing surfaces. Nanoparticles accumulate in the gaps of rough asperities; thus, they reduce friction and wear.

3.4. Protective Film Mechanism

Nanoparticles produce an amorphous layer into interacting surfaces to reduce the contact area. The interaction between the nanoparticles and the substrate resulted in the creation of a protective layer known as tribo-film. [10]

4. Sample Preparation

4.1. Natural Oils

Various techniques of extraction and distillation are employed to produce the corresponding oils from vegetables, fruits, or seeds. To enhance its characteristics, these natural oils can be added with additives or used in pure form.

4.2. Chemically Modified Vegetable Oils

Plant-based oils undergo chemical modification to create synthetic esters. A variety of catalytic techniques and chemical modification techniques can enhance vegetable oils' physiochemical characteristics.

4.3. Blending with Mineral Oils

Lubricant samples are prepared by blend formulated by mixing vegetable oil with mineral oil. It combines the advantages of both vegetable oil as well as mineral oil and also reduces dependability on the mineral oil to some extent.

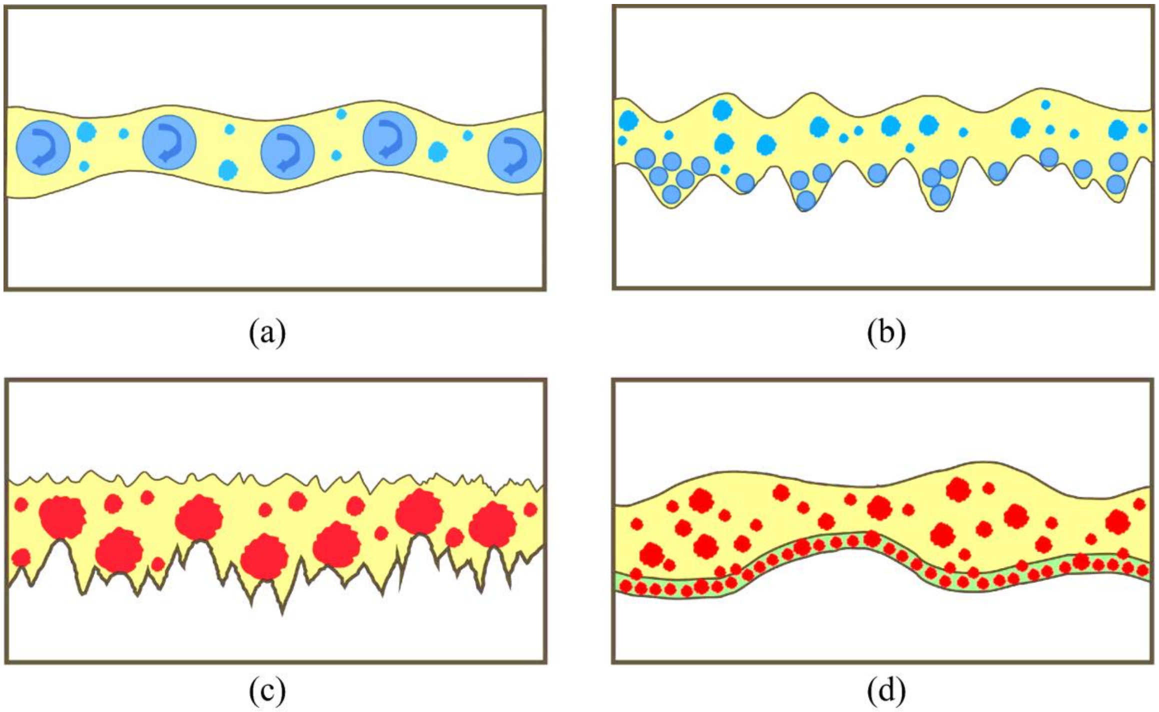


Fig. 1 Various nanoparticle-based mechanisms for enhancing tribological performance (a) Rolling mechanism; (b) Mending mechanism; (c) Polishing mechanism; (d) Protective film [10]

4.4. Use of Additives to Improve Lubricant Properties

Additives can be used to enhance lubricant's tribological characteristics. When non-toxic inorganic oxide nanoparticles, like CuO, ZnO or TiO2, are added, asperity contact and wear are reduced because the sheets align in the same direction, which promotes sliding and enhances the final biolubricant's friction and wear characteristics. Molybdenum, tungsten sulfides, graphene, boron nitride, and other layered materials are also included in these applications.

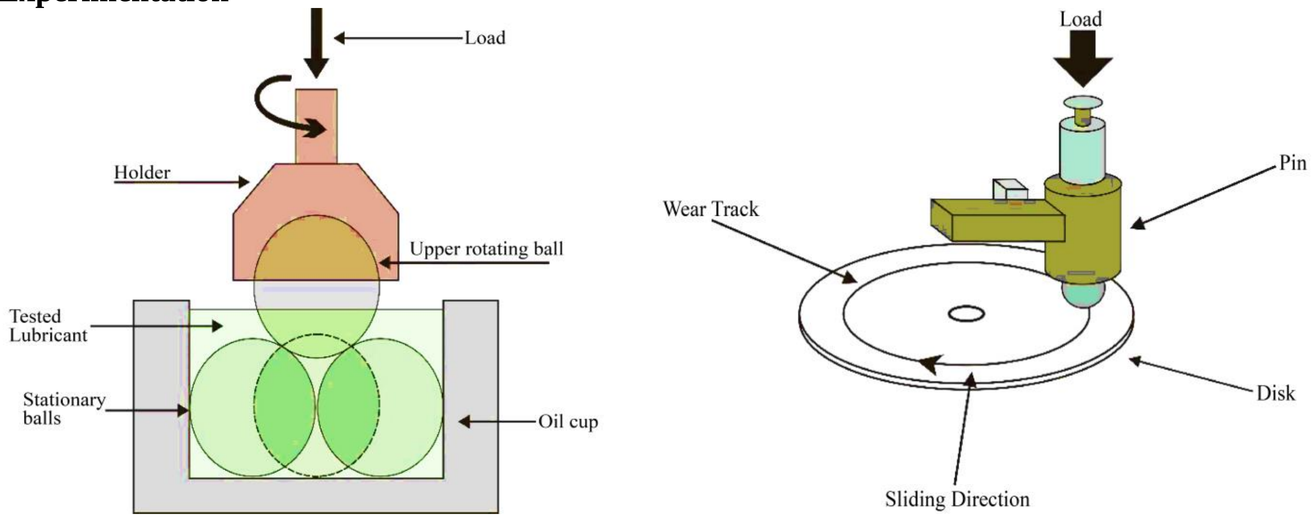
Because of their high refractory nature, these inorganic compounds may be used at higher pressures and temperatures when "powder lubricants" are added.

Table 4. Summary of the works done on biolubricant alternatives for Mineral oils in various applications

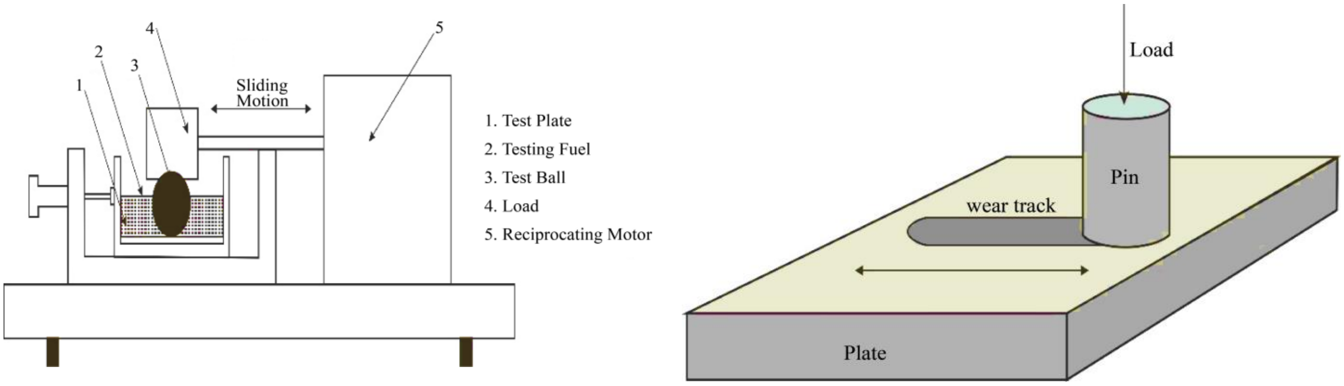
Biolubricant	Chemical Modifications and Additives	Reference Lubricant	Sample Preparation	Tribosystem	Ref.
Palm - Sesame oil	TiO2 & CNT (Carbon Nano Tubes) additives	SAE 40	Palm - Sesame oil mixed into SAE 40	Four ball tribotester	[2]
Cottonseed oil	Transesterification	SAE 40	TMP Cottonseed oil mixed into SAE 40	HFRR & Four ball tribotester	[3]
Jatropha Methyl Ester (JME)		SAE 15W40	JME blended into SAE 15W40 from 2.5 to 12. 5 %	Four ball tribo tester	[4]
Castor Oil, Mahua oil & Sunflower oil			Castor oil + Sunflower oil & Mahua oil + Sunflower oil (1:3 ratio by volume)	Pin on Disc tribotester	[5]
Neem oil	SiO2		Nanoparticles are added in various concentrations.	Pin on Disc tribotester	[7]
Jojoba oil	TiO2		Nanoparticles are added in various concentrations.	Pin on Disc tribotester	[8]
Sunflower oil		SAE 40	Pure vegetable oil	Four ball tribotester	[11]
Waste Cooking Oil (WCO)	Transesterification	SAE 20W40	Waste cooking oil is blended into SAE 20W40.	HFRR & Pin on Disc tribotester	[13]
Castor & Karanja oils			Refined karanja oil is blended into Refined castor oil in the ratio of 10% to 25%.	Four ball tribotester	[16]
Castor oil		Commercial mineral oil (372cSt)	Pure vegetable oil	Pin on Disc tribo tester & Four ball tribotester	[20]
Palmolien oil, Mustard oil, Sesame oil, Rice bran oil, Groundnut oil			Pure vegetable oil	Four ball tribotester	[21]
Jatropha curcas L. oil			Pure vegetable oil	Reciprocating pin on flat tribometer	[22]
Modified Jatropha oil (MJO)	Transesterification	Commercial Synthetic Ester (SE)		Four ball tribotester	[23]
Jatropha oil		SAE 20W40	Jatropha oil blended into SAE 20W40 in various ratios.	Pin on Disc tribotester	[26]
Refined Castor oil & Refined Mahua oil		Servo Gear Oil 90 (T)	Refined mahua oil is blended into Refined	Pin on Disc tribotester	[30]

			castor oil in various ratios.		
Soybean oil, Jatropha Oil, Palm Oil		Commercial stamping oil and commercial hydraulic oil	Pure vegetable oil	Four ball tribotester	[32]
Jatropha oil		SAE 40	Jatropha oil blended into SAE 20W40 in various ratios.	Four ball tribotester	[33]
Cottonseed oil		SAE 40	Pure vegetable oil	Pin on Disc tribotester	[34]
RBD Palm Olein (PO), Palm Fatty Acid Distillate (PFAD), Jatropha oil		Commercial hydraulic oil and stamping oil		Four ball tribotester	[36]
Palm Fatty Acid Distllate (PFAD)		Commercial Metal Forming Oil (CMFO)	PFAD blended with CMFO at various ratios.	Four ball tribotester	[37]
Jatropha oil		SAE 40	Jatropha oil blended into SAE 40 at various ratios.	Cygnus friction and wear testing machine, Four ball tribotester	[38]
Conventional soybean oil, Epoxidied soybean oil, High oleic soybean oil	Epoxidation, genetic modification to obtain High oleic soybean oil. ZDDP		Addition of nanoparticles	Four ball wear tester	[39]
Palm oil		Commercial mineral oil	Pure vegetable oil	Modified single-ball tribometer	[40]
RBD Palm Olein (PO)		Hydraulic mineral oil		Pin on Disc tribometer	[42]
TMP Palm oil	Transesterification TiO2		Addition of nanoparticles	Four ball tribometer	[44]
RBD Palm Olein (PO)		paraffinic mineral oil (Additive free)		Four ball tribometer	[46]

5. Experimentation



(a) Four ball tribotester [2] **(b) Pin on Disc tribotester [13]**



(c) High frequency reciprocating tribotester (HFRR) [13] **(d) Reciprocating pin on flat tribotester [22]**

Fig. 2 Schematic diagrams of tribological testing

5.1. Four Ball Tribotester

The chrome alloy steel balls in the four ball tribo tester have the ability to spin and slide. One ball is positioned at the top of the oil cup, and three balls are positioned at the bottom. The bottom three balls are placed in an oil cup filled with lubricating oil for the test. The three lower balls press down on the higher ball, which rotates at the selected speed and load. The tested lubricant is identified by the wear marks that appear on the ball surface. An image acquisition system is used to measure this wear scar. It operates according to specific standards commonly referred to as ASTM D-2266 and ASTM D-4172. In a Four-ball tribotester, these standards are used to analyze the characteristics of grease and oil, respectively. [4]

5.2. Pin on Disc Tribotester

In a pin-on-disc tribo-machine, the pin remains stationary, and the disc rotates at the desired speed. LVDT is used to determine wear, and a sensor is installed to detect changes in the COF. Lubricating oil is used on the wear track to investigate its tribological characteristics. ASTM G99 standard is used to perform experimentation. [26]

5.3. High Frequency Reciprocating Tribotester (HFRR)

Lubricity in HFRR is measured in the form of the COF between the disc and ball in lubrication. This equipment investigated COF, wear resistance, frictional force of the tested samples with different lubricants or specific wear, applied load, temp., frequency, stroke length, etc. In HFRR disc is stationary within the machine groove, the ball reciprocates on it, and data is acquired in the Data acquisition system. The angle of oscillation of the servomotor is used to regulate the stroke of the top specimen while a load is exerted on it, according to a value specified in the computer. [13]

5.4. Reciprocating Pin on Flat Tribometer

In this tribometer, the pin is held in contact with a flat specimen and lubricant is applied at the interface. In this setup stepper motor is used to give reciprocating movement to the pin holder. Due to this, it swings a portion completely around back and forward. Then, Rocker's arm converts spinning motion into linear movement. The load cell is used to acquire the frictional force, and COF is noted during the test. The sliding velocities are obtained by varying the oscillation frequency, and other parameters are kept constant. [22]

6. Literature Regarding the Development and Tribological Investigation of Vegetable Oil-based Bio-Lubricants

Gul et al. [1] performed RSM to investigate and optimize response conditions of the transesterification system for cotton bio-lubricant production. Their anticipated effects have been effectively demonstrated experimentally with the help of artificial neural networking. After purification near about 90% to 94%, CSO was obtained, and its lubricity, tribological and physiochemical characteristics were investigated and then compared with SAE 40 and ISO VG-46 lubricant. From the results, it is concluded that cottonseed oil has a potential source as a bio-lubricant in industrial applications.

Mujtaba et al. [2] have investigated SAE-40 lubricant samples infected with recognized percentages of fuels. They form fuels from the blend of diesel palm-sesame biodiesel, i.e. B30. They mixed B30 with dimethyl carbonate, ethanol, titanium oxide and carbon nanotubes. They found out the influence of these fuels on tribological characteristics of lubricant by using a 4-ball tribotester, and SEM of worn surfaces was investigated to find out wear types. The results show that biodiesel blends (B30) + nanoparticles reduce the degradation of lubricants as compared to alcoholic fuel additives and commercial diesel. Gul et al. [3] have studied the tribological performance of cottonseed oil mixed into SAE40 by using HFRR and Four ball tribometer. 10% cottonseed biolubricant addition with SAE 40 shows the lowest COF and wear with respect to SAE 40, But when the volume % of cottonseed oil in SAE 40 increases above 10 %, friction and wear also increase. Therefore, the addition of 10% TMP cottonseed oil can be utilized as a lubricant additive to minimize partial dependability on commercial mineral oil. Shahabuddin et al. [4] have performed extreme pressure and anti-wear characteristic tests to investigate the tribological performance of JME-based bio-lubricants. They performed experimentation by using a fourball tribotester according to ASTM D 2783 and ASTM D 4172 standards, respectively. Then, they compared the characteristics of JME-based bio-lubricants with the SAE 15W-40 lubricant.

From investigation, they concluded that 10 % JME bio-lubricant (BL10) was the most favorable, and it fulfils all the standard ISO requirements without pour point. Gemsprim et al. [5] have investigated Castor, Mahua and sunflower oils as biolubricant POD tribotesters, and that could be a top-class source of bio-lubricants which will benefit the rural and urban economies. Experimental results showed Mahua + sunflower oil mixture plays a better role in each category with respect to the castor + sunflower oil mixture. Owuna et al. [6] have reviewed research work on vegetable oils' thermal-oxidative stability So that they can analyze their potential sources as lubricants to replace mineral oils because of their adverse effect on the environment. Mahara et al. [7] have carried out experimental work on neem oil to suggest alternative sources for tribological applications. They used SiO2 nanoparticles to improve the lubricity property of the oil. They conducted experimentation with the help of a DUCOM tribometer at different loads. When they added 0.3 % nanoparticles minimum COF was obtained. But when they added more amounts of nanoparticles, disc wear was also increased. Experimental results showed that when they added 0.3 % of nanoparticles, it improved its tribological properties as compared with raw neem oil.

Zaid et al. [8] have added TiO2 nanoparticles in the oil for the improvement of its lubricity property. They performed experimentation with the help of a DUCOM tribometer at various loads at constant temperature. As per previous research, they added nanoparticles in various concentrations. When they added nanoparticles, up to 0.3 % minimum COF was obtained. But, when they added more amounts of nanoparticles, it increased disc wear. Experimental results showed that when they added 0.3 % of nanoparticles, it improved its tribological properties as compared with raw jojoba oil. Mahadi et al. [9] have carried out a study on vegetable oil formulating green machining lubricant by considering present issues, challenges, and its future for sustainable machining. They formulated vegetable oil lubricant and its output performance compared to conventional MO lubricant. From experimentation, they concluded that, when they use vegetable oil lubricant, it performs better compared to commercial MO lubricant from a surface finish view. Though VO has some issues and challenges as a lubricant in machining, it has the potential to replace mineral oil lubricants. Singh et al. [10] have presented a review of the literature on lubricants mixed nanoparticles. With this, they analyzed the effect of adding nanoparticles on different performance properties. Also, it reviewed that different nanoparticles at various load conditions, concentrations and running at various RPMs showed that when they were added at optimum conditions, it increased load carrying capacity, viscosity and pressure distribution. Also, it lowers wear scar diameter and COF. They also discussed nanoparticle constraints.

For this study, they consider various nanoparticles like Al2O3, CuO, TiO2, ZnO, etc. Jabal et al. [11] investigated sunflower oil with the help of a four-ball tribometer to understand its lubricant characteristics at various loads and tested exhaust emissions with the single-cylinder four-stroke diesel engine. Sunflower oil showed better tribological characteristics than petroleum oil at low loads. Experimental results conclude that at various test conditions SO, based lubricant performed better in the reduction of exhaust gas emission. Therefore, SO-based lubricant proves its possibility to be used as a lubricant at contacting surfaces. Puttaswamy et al. [12] have performed experimental work by using the MQL method for the investigation of VO as a cutting fluid in the AISI 304L SS drilling application. Then, they compared the performance of two Vegetable oils, Neem (Azadirachtaindica) and Mahua (Madhucaindica), with commercial Mineral oil (Servocut 945), which they used as cutting fluid. From Experimental results and statistical analysis, they concluded that Mahua and Neem oils can replace commercial Mineral oil as cutting fluids.

Singh et al. [13], Due to economical sources, they blended Waste Cooking Oil (WCO) with lubricating oil for biodiesel production. They studied tribological characteristics of piston-cylinder liner and cam-tappet in valve train in the wet lubrication condition with the help of HFRR & POD tester. Additionally, they analyze wear particles present in the lubricants by using the analytical ferrography method. As per experimental results shown in Figures 3 and 4, when they blended 10% WCO biodiesel with SAE20W40, then COF and WSD showed better results. Gunjal et al. [14] have investigated coconut oil, canola oil and soyabean oil as cutting fluids in hardened AISI 4340 SS turning applications to find surface roughness and tool life. In this experiment depth of cut and feed rate were kept constant, and vary the cutting speed was in the higher range. This work showed that canola oil has a better performance compared with the remaining two oils.

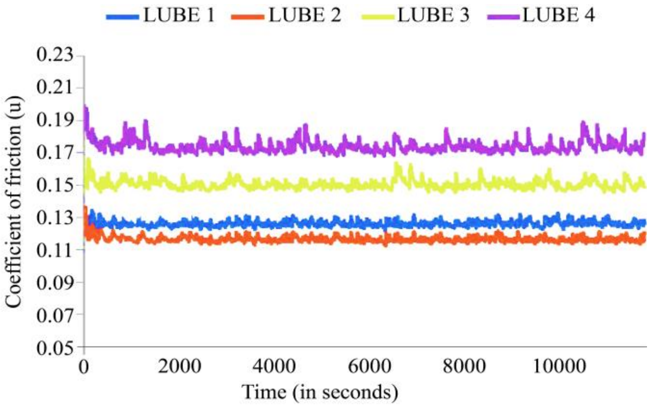


Fig. 3 Variation in COF of different lubricants with time in HFRR test [13]

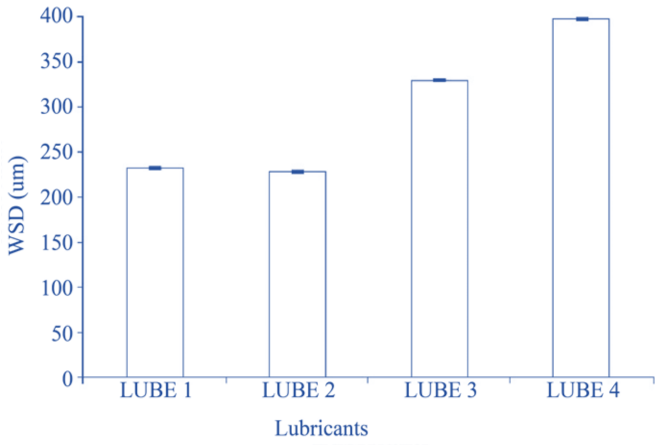


Fig. 4 Variation in WSD for different lubricant samples [13]

Traditional oil has maximum tool life as compared to VO-based cutting fluids at high operational speed with the MQL method. They also examined surface roughness for dry cutting. They kept the feed rate constant during the experiment and varied the cutting speed in the higher range, but it didn't show any remarkable effect on surface roughness. Also, they observed tool wear continuously after each operational cut from average flank wear. Panchal et al. [15] have investigated vegetable oil-based lubricants as well as greases. Also, they take a review of the literature and newly published data about vegetable-based bio-lubricant production by chemical modifications. Suhane et al. [16] have carried out experimentation to characterize the performance of castor oil lubricant from a wear point of view on low-speed application.

In this experimental work, Taguchi's L16 orthogonal array was used with the effect of factors like blending ratio, load and speed. Taguchi optimization technique was used for these three factors' optimum combination. Taguchi technique was used for the preparation of the experimental design, and a four-ball testing machine was used to analyse tribological characteristics of castor oil lubricant at different blending ratios. Heikal et al. [17] used a two-stage transesterification process to create biolubricants from Jatropha oil and palm oil. Products were evaluated by ASTM analysis and confirmed by FTIR.

The trimethylolpropane esters derived from Jatropha oil have moderate thermal stabilities, low pour point temperature and high viscosity indices, and they are competitive with ISO VG46 grade commercial oil. Trimethylolpropane esters (5°C) of palm oil have a high pour point, which necessitates the use of pour point depressants, but other lubricating qualities such as flash point, viscosity, and viscosity index are equivalent to commercial VG46 and ISO VG32 industrial oils. Mobarak et al. [18] explored the potential of biolubricants derived from vegetables as a substitute for conventional lubricants, drawing from prior research. In this literature survey, they present sources, characteristics, advantages and limitations of the biolubricants, their potential as an alternative lubricant in automobile applications and at the end, they overviewed the global biolubricant market and its future potential.

Paleu et al. [19] have carried out standard tests to investigate the load-carrying potential of cutting fluids with the use of four ball tribometer machine. They compared the obtained results with standard requirements by measuring WSD on bottom balls from four balls. They found addition of 10% Sulphur additive with base oil shows minimum friction torque and optimum surface quality. But from an economical point of view minimum of 4% additive content was acceptable as per actual standards test results. Bhaumik et al. [20] have analyzed the wear resistance and extreme pressure characteristics of MO and castor oil as per ASTM G 99 & D-2783 standards. Also, they used SEM images for ball surface and pin analysis after performing tribo testing.

Experimental results show that commercial mineral oil performs better compared with neat castor oil as per antiwear and extreme pressure property analysis, due to the presence of additives in it. So, we can improve the performance of castor oil by the addition of additives in it. Kumar et al. [21] investigated vegetable-based oils like mustard, palm olien, sesame, groundnut, and rice bran and compared them with non-biodegradable mineral oils. They used a four-ball tribotester to evaluate the impact of vegetable oils on wear performance during metal-cutting operations. Results show mustard oil performs better compared with remaining oils. Ruggiero et al. [22] have investigated Jatropha oil for tribological performance with the help of a ball-on-flat reciprocating machine at various frequencies. They selected AISI 52100 steel and X210Cr12 as contacting surfaces and monitored COF for 40 minutes in all tests at 12N load.

Also, they analyzed Jatropha oil for its physical and chemical properties. From the results, they conclude that as frequency increases, COF decreases, and the range of the final value is between 0.04-0.122. Talib et al. [23] have carried out the orthogonal cutting process and supplied lubricants by using the MQL technique. They used modified jatropha oils to replace petroleum-based oils as a metalworking fluid. Experimental results showed that MJO5 perform better compared with commercial Synthetic Ester (SE) from COF and WSD points of view, and it also reduces cutting force by 5 to 12% and cutting temperature by 6 to 11%. Therefore, MJO5 has the potential to replace SE as a machining lubricant. Verma et al. [24] have improved the cold flow characteristics of palm oil-based biodiesel by blending it with a cold flow improver.

The results showed that PE80 is suggested for use as engine fuel in low-temperature zones, and cold flow property improver is the optimum method for achieving the appropriate degree of cold flow property. Sapawe et al. [25] have carried out experimentation to investigate the thermal-oxidative stability of phenolic antioxidant added palm oil and their results compared with superior mineral engine oil. Studies found that a uniform blend of tertiary-butyl-hydroquinone and palm achieved acceptable antioxidant properties. This mixture also reduces wear and friction. Singh [26] has carried out experimentation to investigate the tribological properties of Al-7% Si alloy when Jatropha oil is mixed with lube oil. This work shows that when they added 15% Jatropha oil into the base lubricant, it performed better as well as improved in its anti-wear characteristics. Inkerd et al. [27] have discussed the potential of palm oil-based biolubricant and its properties. The manufacturing processes of biolubricant products were compared with three types of products: A, B and C. They carried out experimental work at an ambient pressure at room temperature with a batch reactor system.

From this work, they analyzed various properties of bilolubricant and observed that biolubricant has a similar property with lubricating base oil standards. Wan et al. [28] have investigated tribological characteristics of lubricating oil added with boron nitride additive. They investigate the rheological action of lubricating oil by rheometer and anti-frictional and anti-wear chracteristics with tribo-tester. They conclude that lubricating oil performs excellent when it is added with the minimum amount of boron nitride additives. Krishna Reddy et al. [29] have investigated vegetable oil without adding any additive for the replacement of mineral oil in a CI engine application. They conducted emission tests and engine performance tests with a water-cooled, single-cylinder, four-stroke CI engine. Comparing results, they conclude palm oil-based lubricants perform better in engines and reduce exhaust gas emissions. Jain et al. [30] have investigated the tribological performance of refined castor oil blended with mahua oil at different blending ratios like 10%, 20 and 30 % as biolubricants. They analyzed tribological characteristics with the help of a POD machine at different parameters.

The results show that refined castor oil and mahua oil with a 20% blending ratio have the potential to be used in maintenance applications, mainly in gear applications. Refined mahua oil can be used as an environment-friendly friction modifier additive. Ahmed et al. [31] have formulated a new bio lubricant to replace industrial lubricant according to its viscosity. They developed nine different samples, and from that, the blend has a mixture of 40.55 % MO, 52.70 % SO, and 6.75 (%) additives performed better and its viscosity fitted with the viscosity of the industrial lubricant. They also tested the physio-chemical properties of that blend.

From the results, they conclude that the selected blend indicates positive properties in safer transportation, wider temperature change and cold weather application as per result of the viscosity index, pour point, and flash point test. Degradation tests also indicate positive characteristics. Syahrullail et al. [32] have carried out experimentation on plant oils like palm oil, jatropha oil and soyabean oil according to ASTM D 2783 and ASTM D 4172 on four-ball tribotester equipment. They focused on the use of plant oil as a lubricant and its wear behavior.

The results showed that soybean oil, jatropha and RBD palm oil had the same performance as commercially available hydraulic fluids in terms of wear resistance and extreme pressure conditions. Habibullah et al. [33] have carried out experimental work on four ball tribometer considering various parameters to explore the impact of JO mixed with SAE40 on tribological properties. From experimental work, they conclude that the addition of 5% JO into SAE40 performs better and shows positive anti-wear properties. Therefore, due to the environment-friendly nature of the 5% JO mixed SAE40 blend, It might be used in automobiles as a substitute lubricant. Agrawal et al. [34] have investigated the effect of lubrication on the tribological characteristics of the M2 HSS tool on the POD tester. They consider cottonseed oil as a biolubricant to analyze its effect on tribological properties and compare it in both lubrication conditions.

From the results, they conclude that cottonseed oil has superior performance compared with the other two conditions in reducing wear and COF. Singh et al. [35] have carried investigation with the MQL technique to reduce problems with the conventional lubrication method. EN-31 steel surface roughness value obtained during turning operation with MQL of VO & MO was compared.

From the results, they conclude that the surface roughness of VO was nearly similar to MO. Syahrullail et al. [36] have performed experimentation on four ball tribometers according to ASTM D2783 on vegetable oils like Jatropha oil, RBD palm olein and PFAD under extreme pressure conditions.

From the results shown in Figures 5 and 6, it was clear that VO has high COF and steel ball WSD were slightly larger compared with commercial stamping oil. However, this issue might be fixed with the addition of suitable additives. Therefore, they conclude that VO has the potential to replace MO in industrial applications.

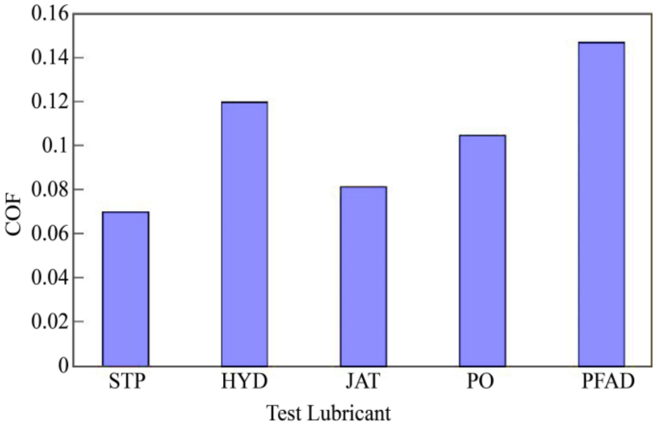


Fig. 5 COF for all types of test lubricants at steady state conditions [36]

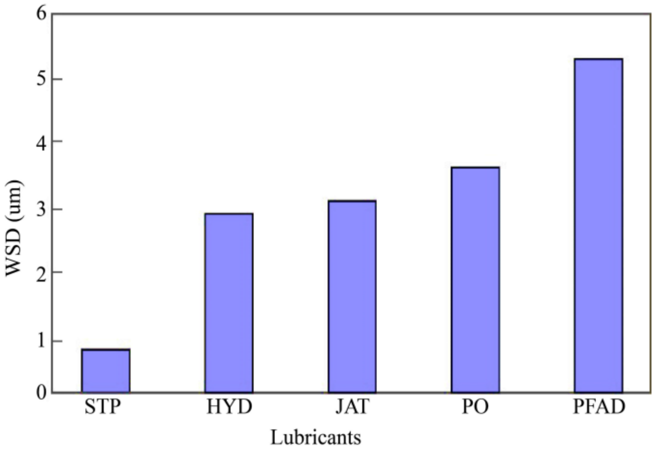


Fig. 6 WSD on ball bearing lubricated with test lubricants [36]

Syahrullail et al [37] have carried investigation of PFAD mixed with mineral oil at different percentages from 5% to 25% of the total mass for its lubricating properties. They performed experimentation with the help of a four-ball tribometer as per ASTM 4172 standard. Experimental results show that the addition of 20% palm oil by its mass into mineral oil shows a lower value of COF as well as wear scar dia. This mix has an acceptable value with respect to other conditions. Therefore, they conclude that if the blending ratio is determined properly then the addition of VO will improve the performance of MO. Shahabuddin et al. [38] have investigated tribological properties of JO-infected bio-lubricant with the help of Cygnus wear and a four-ball tribometer. They formulated biolubricants by mixing 10 to 50 % JO into SAE 40 by its volume. Experimental work showed that a blend of 10% JO with SAE40 oil performs as a good lubricant in terms of COF, WSD, viscosity, temperature rise and FTP. Cheenkachorn [39] have carried out experimentation on four ball tribometers to investigate the effect of additive, temperature and speed on COF and WSD of SBO, ESBO and HOSBO at a load of 25 lbs. They conclude that ZDDP and speed notably affect the WSD of conventional SBO. Whereas WSD of ESBO & HOSBO were affected by speed, ZDDP and temperature as well as the interconnection between them. Razak et al. [40] have carried out experimentation to find the effect of PO and commercial MO lubricant on ABS curve surface structure sliding on ball bearing by using a modified standard fourball tester. They found the minimum value of COF using PO compared to MO. Shahabuddin et al. [41] have performed experimentation on a Cygnus Wear test machine to find tribological properties of JO-based biolubricants at 2000 rpm rotating speed, 30N load, rotating for one hour. They formulated biolubricants by mixing 10 to 50 % JO into SAE 40 mineral oil. From the experimentation, they concluded that the boundary lubrication regime of lubricant was observed. The wear mechanism occurred in the test mainly adhesive and the abrasive wear. The results also show that adding 10% JO to SAE 40 oil is ideal for automotive applications with improvement in the overall performance of COF, wear, viscosity and temperature rise. Syahrullail et al. [42] carried out the experiment on a POD tester as per ASTM G99 standard at a normal load of 10 N and at speeds of 4 m/s and 0.4 m/s to examine the performance of hydraulic oil and RBD palm olein. For this, they used the direct lubricant flow method.

From experimentation they conclude that RBD palm oil has shown lower wear compared to hydraulic oil. Also, at low speed, the COF and WSD of the lubricated specimen with RBD palm olein were significantly lower and at high speed, it is roughly similar to hydraulic oil. Nazri et al. [43] have performed experimentation with the help of mineral oil and biolubricant to explore the elastohydrodynamic flow of lubrication at elliptical conjunctions. They determine the effect of lubricants with the help of CFD software and also confirm the deformation at the conjunctions due to the pressure distribution. From this work they conclude that MO shows higher dynamic pressure compared to bio-lubricant at constant speed. Also, they found MO has a higher load-carrying capacity than bio-lubricant. However, bio-lubricant protects surfaces from wear and damage due to its significant property of lower dynamic pressure compared to MO. Zulkifli et al. [44] have investigated paraffin oil and biolubricant mixed with TiO2 additives for their tribological characteristics by using a four-ball tribometer. They perform experiments under 40 kg to 160 kg load at 1200 rpm for 10 minutes. From the results shown in Figures 7 and 8, they conclude that TiO2 added TMP shows good friction reduction. At 160 Kg, TiO2 added in TMP reduces COF by 15% and WSD by 11% with respect to pure TMP. Therefore, TMP added TiO2 has the potential to replace mineral oil as an automobile lubricant. Sutaria et al. [45] have investigated base stock oil for its shear stability and extreme pressure properties and the impact of low-viscosity oil blended with based oil. They perform experimentation by using four ball tribometers at different loads and taking different oil samples under consideration. From the results, they conclude that COF and oil viscosity reduce as the mixing ratio of oil increases in the case of increasing temperature.

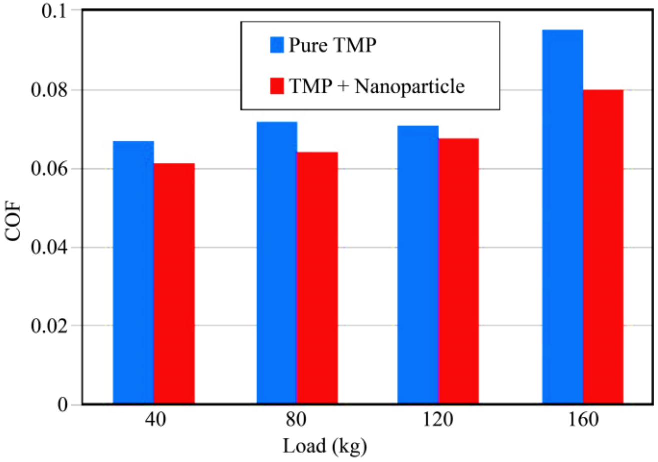


Fig. 7 COF vs Load for biolubricant [44]

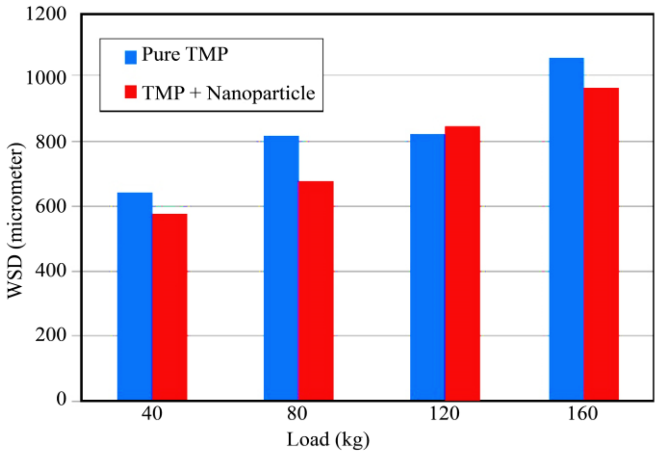


Fig. 8 WSD vs Load for biolubricant [44]

Also, when the blending ratio of oil increases, it increases WSD. Chiong Ing et al. [46] have performed experimentation on four ball tribometer according to ASTM D 4172 to find the effect of normal load (30 to 60 kg) on tribological characteristics of paraffinic mineral oil and RBD palm olein. From the results, they conclude that the RBD palm olein performs better than paraffinic MO with respect to the ability of friction reduction. Shahabuddin et al. [47] have performed experimentation to investigate BP, BSFC, exhaust temperature, and emission characteristics and compare biodiesel fuel with ordinary diesel fuel. From this, they conclude that biodiesel formulated with a 20% blending ratio and 1 % additive performs best and also reduces exhaust gas emission. Mannekote et al. [48] have investigated a few VO by using four-ball tribometers to analyze boundary lubrication properties.

From this work, they conclude that as peroxides formed, they increased wear with respect to ageing time and temperature for all the oil samples. Also, soft iron soap was formed, and it resulted in low COF for oxidized oil samples. Syahrullail et al. [49] investigated palm oil as a lubricant for cold working applications by using a plane strain extrusion apparatus on an aligned aluminum A1100 workpiece at room temperature, and then they compared the performance of PO with plain paraffinic MO. From the results, they conclude that palm oil performs satisfactorily with respect to paraffinic mineral oil. Also, it has the potential to reduce the extrusion load. Adhvaryu et al. [50] have investigated ESBO, SBO and HOSBO as lubricants for their performance to utilize at high temperatures. They used micro-oxidation as well as different calorimetry techniques to confirm the results of thermal and deposit-forming tendencies of the entire samples. From this work, they conclude that ESBO has the potential to be used as a lubricant in high-temperature applications. In boundary lubrication, HOSBO, SBO, and ESBO form stable polymeric film on the metal surface; therefore, it shows outstanding COF-reducing properties.

7. Conclusion

This paper presents the latest technology related to the tribological behavior of biolubricants in addition to nano-additives, nanoparticle performance as additives, and nanoparticle additive lubrication mechanisms. In conducted investigation, it was found that nanoparticles as an additive in bio-lubricants improve their performance.The mechanisms of nanoparticle lubrication reported in the literature are difficult to understand due to the enormous number of nanoparticles available, and the performance of each nanoparticle is different in each application. Also, maintaining dispersion stability is an important parameter to improve lubricant performance. There are various dispersion methods, surface modification techniques, and surfactants to be used to disperse nanoparticles in biolubricants fully. Biodegradability is an essential concern, and the worldwide demand for biolubricants is included in publications concentrating on the creation of biodegradable lubricants as substitutes for mineral oils. Future studies should concentrate on creating novel nanoadditives and chemically modified biolubricants for various tribological uses. They must investigate different lubrication mechanisms and performance factors that influence the tribological characteristics of biolubricants.

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