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Review

Vegetable Oil Based Lubricants: Challenges and Prospects

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Abstract

Lubricants are very important consumables in all industries as failure in machine parts due to absence or wrong choice of lubricants carries enormous cost. The base oil used for the formulation of most lubricants is environmentally hostile mineral oil and 30% of lubricants consumed ends up in the ecosystem. However, mineral oil reserve is depleting and the environmental concern about the damaging impact of mineral oil is growing. The search for environment friendly substitutes to mineral oils as base oils in lubricants has become a frontier area of research in the lubricant industry. Vegetable oils are perceived to be alternatives to mineral oils for lubricant base oils due to certain inherent technical properties and their ability to be biodegradable. This paper is an overview of recent research on vegetable oils as base oil for lubricant production with focus on the prospects, challenges and efforts to overcome the challenges of using vegetable oils as base oil for the production of industrial lubricants. Compared to mineral oils, vegetable oils in general possess high flash point, high viscosity index, high lubricity, low evaporative loss, are renewable, and are environmentally friendly. Poor oxidative and hydrolytic stability, high cost, food versus energy debate, high temperature sensitivity of tribological behaviour and poor cold flow properties are reckoned to be the limitations of vegetable oils for their use as base oils for industrial lubricants. The current effort to overcome these limitations includes the use of non edible oils, additives, chemical modifications and thermal modifications. More research and legislation in favour of the use of vegetable oil lubricants is recommended.

Keywords

vegetable oil, biolubricants, environmentally-friendly, wear, friction, tribometers

1 Introduction

Friction is generated when mechanical components come in contact and when there is a relative motion between them. Friction causes wear and wear is the major cause of material and energy wastage in industrial machines. Wear results to loss of mechanical performance therefore any reduction in wear can give rise to considerable savings [1]. Lubrication is one of the efficient ways of reducing friction and wear between two contacting surfaces that are in relative motion.

A lubricant is a substance introduced between two moving surfaces to reduce friction, minimize wear, distribute heat, remove contaminants, and improve efficiency [2]. The state of the art industrial lubricant consists of base oil and an additive package. Different kinds of additives are used to improve the performance and longevity of lubricants. Depending on the specific demands and performance level requirements, several different classes of additives may be used. These include detergents, dispersants, extreme pressure (EP), anti-wear (AW), viscosity index improvers (VII), and corrosion inhibitors [3].

Within the lubrication market, there are a vast number of applications which require specifically formulated lubricants that have given rise to the upwards of 10,000 different lubricants that satisfy more than 90% of all lubricant applications worldwide [4]. Figure 1 shows the global lubrication market as of 2004, which consumed roughly 37.4 million tons of lubricant [4]. This figure illustrates how automotive and industrial lubricants are the most prevalent. Industrial lubricants amount to 32% and were composed of 12% hydraulic oils, 10% other industrial oils, 5% metalworking fluids, 3% greases, and 2% industrial gear oils [5, 6]. The 10% of other industrial oils within the industrial lubricants section consist of a wide range of lubricants such as air and gas compressor oils, bearing and circulating system oils, refrigerator compressor oils, and steam and gas turbine oils. In the automotive lubricants section, the most commonly used liquid lubricants were engine oils (petrol

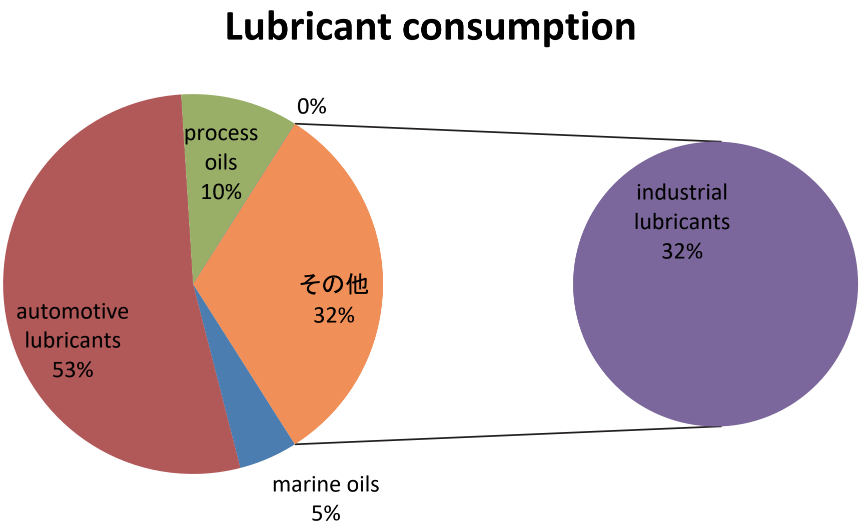

Fig. 1 Worldwide lubrication consumption in 2004 [4]

and diesel engine oils), automatic transmission fluids, gearbox fluids, brake fluids, and hydraulic fluids.

Lubricants are very important consumables in virtually every industry, within the last decade the annual worldwide consumption of lubricants is over 40 million metric tonnes. According to Ajithkumar [7] a lubricant consists of over 90% base oil and less than 10% additive package. The base oil used for the formulation of most lubricants is environmentally hostile mineral oil and 30% of lubricants consumed ends up in the ecosystem [7, 8]. The physical and to some extent chemical properties of mineral oil based lubricants have been studied for long time. Lubricant manufacturers have, over the years, gathered know-how and the necessary technologies to blend lubricants to give the required performance.

However, mineral oil reserve is depleting and the environmental concern about the damaging impact of mineral oil is growing. The search for environment friendly substitutes to mineral oils as base oils in lubricants has become a frontier area of research in the lubricant industry [7, 9-11]. Vegetable oils are perceived to be alternatives to mineral oils for lubricant base oils due to certain inherent technical properties and their ability to be biodegradable. This paper is an overview of vegetable oil as lubricant with emphasis on its prospects and challenges as well as recent research efforts directed at mitigating the challenges of using vegetable oil as lubricants.

2 Vegetable oils as lubricants

Vegetable oils have been used as lubricating oils from ancient days [12]. They are easily obtained from natural sources; therefore they had been the main ingredient of lubricating oils until the 19th century. The requirement of lubricants became very high thereafter because of rapid industrialisation, putting pressure on the price and availability of lubricants from vegetable and animal sources. Mineral oils were started being used as lubricating oils after the successful prospecting and extraction of mineral oils during the second half of 19th century which made available large quantities of cheap replacement for lubricants of vegetable and animal origin. Mineral oils provide various fluids which have desirable properties as lubricating oils at a reasonable cost. For that reason, most of the lubricating oils are supplied from petroleum-based materials.

Recently, demand for environmentally friendly lubricants are increasing because of the high concern for environmental protection. Vegetable oils are natural products and, in addition, they are recognized as fast biodegradable fluids. Therefore, they are promising candidates for the base oils of the environmentally friendly lubricating oils [13]. Lubricants based on mineral oils have been used in all kinds of applications since the beginning of industrialization including industrial gears, automotive engines, metalworking applications transmission and hydraulic systems. But soon it was found that mineral oil with the same viscosity as that of the vegetable or animal based oils was not as effective as a lubricant as the latter. This was attributed to a property of the vegetable or animal oils and fats called “oiliness” or “lubricity” [14]. Lubricity or oiliness of vegetable oils is attributed to their ability to adsorb to the metallic surfaces and to form a tenacious monolayer, with the polar head adhering to the metallic surfaces and the hydrocarbon chains orienting in near normal directions to the surface [15].

Many countries including Austria, Canada, Hungary, Japan, Poland, Scandinavia, Switzerland, the USA, and EU are either in the process of formulating or have already passed legislation to regulate the use of mineral oil based lubricants in environmentally sensitive areas [8, 16]. The U.S. market for all lubricants is 8,250,000 tons/year and only 25,000 tons/year were based on vegetable oils [17]. In the USA, executive order 12873 (EQ 12873) encourages the use of environmentally compatible oils where it is possible to meet the requirements. Similarly, the Great Lakes Water Quality Initiative (GLWQI) in the USA is intended to maintain, protect, and restore the unique Great Lakes resource (e.g. water quality). Within GLWQI, there are proposals to encourage use of fast biodegradable lubricating oils and limiting the use of potentially toxic (to aquatic life) additives to very low levels. In Austria use of mineral-based lubricants, in particular applications like chain saw oils are banned. Recently the European Community (EU) has released the Dangerous Substances Directive. It establishes criteria for a product’s potential hazards to aquatic environment. This hazard potential is determined through assessment of aquatic toxicity, biodegradability, and bioaccumulation potential. The other countries mentioned above have at least established regulations to evaluate the lubricant caused impairment to the environment.

From a technical point of view, it is accepted that more than 90% of all present-day lubricants could be formulated to be rapidly biodegradable [18]. On the other hand, a great deal of development work still needs to be done and present costs are high [19, 20]. Vegetable products as well as modified vegetable oil esters can be used as a base stock for preparation of environmentally friendly, rapidly biodegradable lubricants. The production of environment friendly, rapidly biodegradable fluids for lubricants based on petrochemicals such as polyalphaolefins, polyglycols, polyalkylene glycols and synthetic esters are also discussed in literature [19, 21]. However, vegetable oils are preferred over these synthetic fluids because they are from renewable resources and cheaper [22].

Some of the rapidly biodegradable lubricants are based on pure, unmodified vegetable oils. In Europe, predominantly rapeseed oil and sunflower oil are used [18]. Chemically, these are esters of glycerine and long-chain fatty acids (triglycerides) as shown in Fig. 2, which have molecular structure with three long chain fatty acids attached at the hydroxyl groups via ester linkages [23]. The alcohol component (glycerine) is the same in almost all vegetable oils. The fatty acid components are plant-specific and therefore variable. The fatty acids found in natural vegetable oils differ in chain length and number of double bonds. Besides, functional groups like hydroxyl groups as in castor oil may be present. Natural triglycerides are very rapidly biodegradable and are highly effective lubricants. However, their thermal, oxidative and hydrolytic stabilities are limited. Therefore, pure vegetable oils are only used in applications with low thermal stress [24]. These include total loss applications like mold release and chain saw oils. The following subsections contain a thorough overview of some of the lubricants based on pure unmodified vegetable oils.

2.1 Cotton seed oil

Kalhapure et al. [25] investigated the tribological performance of cotton seed oil as a lubricant for application in multi-cylinder engine by evaluating the anti-wear characteristics of cottonseed oil. The study used four ball testing machine (according to ASTM D 4172 standard) to measure the coefficient of friction and wear scar diameter of cotton seed oil and compared it with commercial mineral oil lubricants SAE 20W50 and SAE 20W40. The test balls were made of chrome alloy steel from AISI standard steel E-52100, having diameter of 12.7 mm [0.5 in.] and Grade 25 EP (Extra Polish), and has hardness of steel ball in the range of 64 to 66 RC. It was found that though coefficient of friction for cottonseed oil was 0.0636 which is lower compared to the commercial lubricants: SAE 20W50 which had friction coefficient of 0.1121 and SAE 20W40 had friction coefficient of 0.086, the wear scar diameter for cotton seed oil was larger than that of the commercial mineral oils as seen in Table 1. Hence it was concluded that though coefficient of friction for cottonseed oil is lower compared to commercial lubricants, the wear scar diameter is larger, therefore cotton seed oil cannot be used as a lubricant in the unmodified form. The antiwear characteristic might be improved by chemical modification of oil or adding suitable anti-wear additives in the oil.

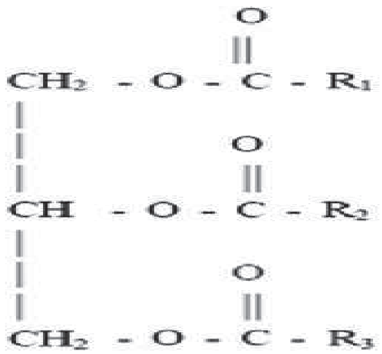

Fig. 2 Chemical structure of triglyceride of a typical vegetable oil [23]

2.2 Sesame, coconut and sunflower oils

Nair et al. [26], carried out detailed study on the evaluation of physicochemical, thermal and tribological properties of sesame oil (Sesamum indicum L.) as a potential agricultural crop base stock for eco-friendly industrial lubricants. The physicochemical, rheological, thermal, oxidative, and tribological properties of sesame oil (SESO) were studied and compared with coconut oil (CO), sunflower oil (SUO) and a commercially available mineral oil, SAE 20W40 using standard ASTM methods. The sesame oil was extracted from sesame seeds collected from Hooghly, East Midnapore and West Midnapore districts of West Bengal, India. The fatty acid profiles of vegetable oils were evaluated using gas chromatography, the thermal stability was evaluated using Perkin Elmer, Diamond TG/DTA thermogravimetric analyser with a temperature range of 0–400°C. Mettler Toledo Differential Scanning Calorimetry (DSC) 822e was used to determine the pour point; the testing was done at a temperature varying from −50°C to 80°C and sample weight ranging from 6 mg to 9 mg. The conventional ASTM D97-96a method was also performed to evaluate pour points of the selected oils and to verify the results obtained from DSC. Rheological properties of the sesame oil, coconut oil, sunflower oil and the mineral oil SAE 20W40 were determined by evaluating their viscosities. Kinematic viscosities at 100°C and 40°C were estimated using Redwood viscometer, from these results viscosity index (VI) for the oils were calculated per ASTM D 2270.

The tribological properties of the oils were evaluated by measuring the wear scar diameter (WSD) and coefficient of friction (COF), using a four-ball tester according to the ASTM D 5183-05 standard for coefficient of friction. The load, speed, run-time and the temperature for the COF test are 40 kg, 600 RPM, 60 minutes and 75°C respectively. ASTM D 4172-94 standard was used to conduct wear test. The load, speed and run-time and the temperature for the wear test are 40 kg, 1200 RPM, 60 minutes and 75°C respectively. The wear scar diameter was analysed using an optical microscope and a Hitachi SU6600 Scanning Electron Microscope (SEM). The balls used for the tests were of diameter 12.7 mm and made from chrome alloy steel with a Rockwell hardness of 61 HRC. It was found that from the flash and fire point data that the sesame oil was more thermally stable than commercially available mineral lubricant SAE 20W40. Also pour point of the sesame oil was better than that of the coconut oil; which was attributed to the coconut oil having a higher level of saturated fatty acids than the sesame oil [27].

Table 1 Average values of coefficient of friction and wear scar diameter for tested oils [25]

Oil	Coefficient of friction (μ)	Wear scar diameter (micron)
SAE 20W50	0.1121	523.55
SAE 20W40	0.086	401.44
Cotton seed oil	0.0636	653.44

Thus, raw sesame oil (without using any pour point depressant additives) has pour point comparable to commercially available mineral oil SAE 20W40. The result of the thermal properties is shown in Table 2 and the tribological and rheological properties for the vegetable (crop) oils studied are shown in Table 3. All vegetable oils had high VI since the change in viscosities with temperature was less. Among the selected vegetable oils, sesame oil possessed the highest viscosity index. However, its viscosity index was much lower than that of the mineral oil SAE 20W40. Therefore sesame oil can be employed as a commercial lubricant if its viscosity index is improved further by the addition of proper viscosity improvers.

The result of the tribological studies shows that the coefficient of friction of the sesame oil was much lower than that of coconut oil and mineral oil SAE 20W40. Conversely the wear scar diameter obtained for SAE 20W40 was less than that of vegetable oils. However, among the vegetable oils, wear scar diameter obtained for the sesame oil was less than that of coconut oil and sunflower oils. By adding proper anti-wear additives to sesame oil, wear can further be brought down. It was concluded that, in general, sesame has excellent thermal and tribological properties, but the enhancements of its oxidative and rheological properties are essential. Sesame oil can be considered as a potential agricultural crop base stock for industrial lubricants which can become an eco-friendly substitute for its mineral oil counterparts in near future.

2.3 Date palm syrup

Mohammed [28], preliminarily evaluated the tribological properties of date palm fruit syrup as a potential environmental-friendly lubricant using a ball on disc to conduct wear tests on mild steel samples. Different concentrations (50, 75, and 100 vol%) of the syrup in water were tested at a normal load of 50 N and a sliding linear speed of 0.1 m/s. Scanning electron microscopy and optical profilometry were used to characterize the wear tracks and estimate the wear rate. 100 vol% date syrup with a viscosity of 16.95 mPa·s showed excellent results by reducing the coefficient of friction of steel-on-steel from 0.6 (dry conditions) to a value of ~0.1. The depth of the wear track reduced from ~152 μm (dry conditions) to ~11 μm, signifying a considerable reduction in wear. The coefficient of friction of 100% date palm syrup was at par with a commercial lubricant, also the depth of the wear track was slightly lower for the 100% syrup as compared to the case of industrial lubricant. Even the wear track width was lower for the 100% syrup (~316 μm) as compared to that of the industrial lubricant (~328 μm). However, the thermal-oxidative as well as other temperature properties of the syrup were not investigated and are likely not to be good.

2.4 Castor oil lubricants

Castor oil is gotten from the castor bean tree (Ricinus communis), the castor bean is shown in Fig. 3. It belongs to the family Euphorbiaceae, a drought resistant non-edible oil seed crop widely distributed throughout tropical and subtropical regions, but also in many of the temperate countries of the globe. Castor oil is regarded as one of the most valuable laxatives in medicine and its annual production in India is 271 MT. Its seed contain 46 to 55% oil that is viscous, non-volatile, non- drying, pale yellow in colour with slight odour and a bland taste.

Binfa et al, [10] carried out a study to compare the lubricant properties of castor oil and commercial engine oil 20W50 using a steel ball (comparable to EN 31, 64–66 HRC type), 12.7 mm in diameter four ball tribo-tester. The test for friction coefficient and wear scar diameter was carried out based on ASTM D4172 method, while the extreme pressure test was based on IP 239 method, similar to ASTM D 2783. The result showed that castor oil has a lower coefficient of friction of 0.0607 compared to the commercial mineral oil with a coefficient of friction of 0.0763; however the wear scar diameter of the commercial mineral (0.40322) was lower than that of the castor oil (0.68625). Also in the extreme pressure test, Castor oil demonstrated a higher weld load (2158 N) compare to engine oil (1766 N). It was concluded that Castor oil can reduce friction and improve fuel conservation and mechanical efficiency in engines more than the commercial mineral-based oil because unrefined castor oil possesses better "oiliness" and higher weld load, than formulated foreign commercial 20W-50 crankcase oil.

2.5 Jatropha oil lubricants

Golshokouh et al. [29] carried out a comparative study between jatropha oil and engine oil-based commercial lubricating oil by measuring friction, wear and viscosity on a four ball tribotester fitted with a CCD camera according to the

Table 2 Thermal properties of sesame oil, coconut oil, sunflower oil and SAE 20W40 oils [26]

Oils	Thermal Properties (°C)		
	Flash Point	Fire Point	Pour Point
Sesame oil	315	319	-15
Coconut oil	320	325	22
Sunflower oil	332	337	-18
SAE 20W40	204	209	-20

Fig. 3 Castor bean

Table 3 Rheological and tribological properties for sesame oil, coconut oil, sunflower oil and SAE 20W40 oils [26]

Oils	Viscosity at 40°C (cst)	Viscosity at 100°C (cst)	Viscosity Index	Coefficient of friction	Wear scar diameter (mm)
Sesame oil	31.86	7.46	213.5	0.0862	0.650
Coconut oil	27.8	6.1	176	0.0901	0.836
Sunflower oil	29	6	159	0.0742	0.685
SAE 20W40	112.6	14.8	135.57	0.107	0.470

American Society for Testing and Materials (ASTM) standard, speed (1200 rpm), load (392 N) and temperature 75°C. The results showed that viscosity for jatropha was 16 mPa·s was lower than that for commercial engine oil which was 18.8 mPa·s, however, the average for the wear scar area for jatropha oils was 0.160 mm^2, which was lower than that of mineral base engine oil which was 1.124 mm^2. Also the friction torque for jatropha oil (0.01392 Nm) was less than half of that of engine oil (0.06089 Nm) while the coefficient of friction for engine oil (0.07977) was more than Jatropha oil which had coefficient of friction of 0.0346. From the result of the study it was concluded that the jatropha oil performed better than the mineral oil in terms of wear and friction while the mineral oil has a better viscosity.

2.6 Rapeseed, soybean and sunflower oils as universal tractor transmission lubricant

Stojilković and Kolb [30] carried out a study on the tribological properties of biodegradable universal tractor transmission oil by using three vegetable oils: rapeseed oil (RE), soybean (SO) oil and sunflower oil (SU), by comparing their properties with a commercial mineral oil based universal tractor transmission oil (MN). Tribological tests for all four samples were conducted on annealed alloy steel 16MnCr5 (Č4320) having the hardness of 35 HRC block on disc tribometer TPD-93, with a sliding speed in the contact zone of 0.8 m/s and contact duration of 60 minutes.

Results obtained showed that the coefficient of friction of tested vegetable oils samples was lower than that of the reference mineral oil universal tractor transmission oil, especially at higher loads. Also sunflower oil had the lowest wear scar width of 1.345 millimetres while the mineral based oil had the highest wear scar width of 1.585 millimetres as shown in Fig. 4. From the study it was concluded that rapeseed oil had the best performance with regards to coefficient of friction while sunflower oil performed best in terms of wear scar width, thus all the vegetable oils are better in tribological performance compared to the universal tractor transmission oil. The properties of the studied oils are shown in Table 4 for the purpose of comparison.

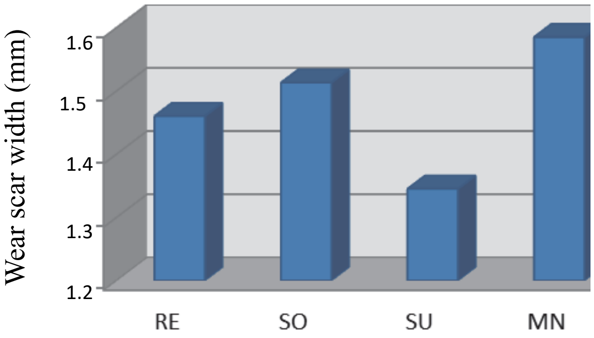

Fig. 4 Measured width of the scar wear on block [30]

3 Vegetable oils as additive to mineral oil based lubricants

To impart “oiliness” to mineral oil based lubricants, a small percentage of vegetable or animal oil started being added to it as “oiliness” additive [7]. Later many organic, inorganic and polymer additives for mineral oil based lubricants were developed to meet the more and more severe operating requirements made on the lubricants used in various applications such as high speed and high performance internal combustion engines. A review of some of the blends of vegetable oil in mineral oil base lubricants is carried out in the following subsections.

3.1 Palm and soybean oils blends in commercial mineral oil SAE 15W40

Bahari et al. [31] studied the friction and wear of palm and soybean blends with commercial mineral engine oil SAE 15W40 for high temperature and severe contact conditions application using a linear reciprocating rig. Four samples were prepared: palm oil (PO), soybean oil (SBO), 50% mineral oil+50% palm oil and 50% mineral oil +50% soybean oil and tested for friction, wear, viscosity, and oxidation stability. Results obtained showed that mineral oil had the lowest coefficient of friction (0.093) while the soybean oil had the highest (0.112). Also the wear performance of the mineral oil was the best as only 0.65 mg mass loss was observed; palm oil had the worst wear performance of 45.76 mg mass loss. The blends of palm oil with mineral engine oil showed 25% improvement in wear compared to raw palm oil while soybean oil with mineral oil blend showed 27% improvement. It was concluded that there is no simple relationship between friction and wear, the palm and soybean oils performed below the commercial mineral oil and are therefore not suitable as severe contact engine oil or ubricity additive.

3.2 Jatropha oil blend in commercial mineral oil SAE 40

Shahabuddin et al. [32] studied the development of eco-friendly biodegradable biolubricant based on jatropha oil blends in mineral based oil SAE 40 using a tri-pin-on-disc machine. Aluminum was used to build three pin and cast

Table 4 Comparison of the tribological properties of mineral and vegetable oils

Oil	Viscosity (cSt)	Viscosity Index	Coefficient of friction	Wear scar diameter (mm)	Weld load (N)
Cotton seed oil	-	-	0.0636	0.65344	-
Sesame oil	31.86	213.5	0.0862	0.650	-
Coconut oil	27.8	176	0.0901	0.836	-
Sunflower oil	29	159	0.0742	0.685	-
Castor oil			0.0607	0.68625	2158
Jatropha oil	16	-	0.0346	-	-
Soybean oil	-	-	0.112	-	-
SAE 20W50			0.1121	0.52355	1766
SAE 20W40	112.6	135.57	0.086	0.40144	
SAE 15W40	-	-	0.093	-	-

iron was used for disc specimen while lubricant samples were prepared by homogeneously mixing of 10%, 20%, 30%, 40% and 50% Jatropha oil in SAE 40. Friction, wear and Viscosity were measured for both 40°C and 100°C. Also a multi-element oil analyzer (MOA) was used to determine the kinds and amount of metals contained in the lubricating oil at the end of the experiments. The results showed that the wear rate for 10% Jatropha oil added to the lubricant was almost identical with base lubricant. From the elemental analysis of the biolubricants, it was found that amount of Iron and Aluminum was increased after the test due to the wear of material from the pin and the disc. In terms of viscosity, almost all biolubricants met the ISO viscosity grade requirement whereas, 40% and 50% addition of Jatropha oil did not meet the ISO VG 100 requirement at 40°C. Though impressive results were obtained, yet the biodegradability and environmental friendliness of the lubricant developed cannot be ascertain as the use of hazardous mineral oil persists.

In furtherance to the research, Shahabuddin et al. [33] also carried out a comparative tribological investigation of bio-lubricant formulated from a non-edible oil source (Jatropha oil) using cygnus wear and four-ball tribo testing machines. To formulate the bio-lubricants, 10–50% by volume of jatropha oil were blended with the base lubricant SAE 40. Experimental results showed that the lubrication regime that occurred during the test was boundary lubrication while the main wear mechanisms were abrasive and adhesive wear. During Cygnus wear testing, the lowest wear was found with the addition of 10% jatropha oil, and above 20% contamination, the wear rate was increased considerably. The addition of Jatropha oil in the base lubricant acted as a very good lubricant additive which reduced the friction and wear scar diameter by maximum of 34%. The addition of 10% Jatropha oil in the base lubricant is the optimum for automotive application as it showed best overall performance in terms of wear, coefficient of friction, viscosity, rise in temperature, wear scar diameter and flash temperature parameter (FTP).

Also the Effect of bio-lubricant on tribological characteristics of IP 239 standard steel was investigated by contaminating SAE 40 with a various amount (1%, 2%, 3%, 4%, 5% by volume) of jatropha oil. The friction torque and wear were studied using four ball tribotester. It was found that wear scar diameter increased with the increase of load for lube oil and reduced by addition of percentage of jatropha oil. Friction torque analyzed in the experiment showed that 5% contamination with jatropha oil had dominant performance at 40 kg load. The 5% of jatropha oil contaminated with the base lubricant showed better performance in terms of viscosity index, wear and friction characteristics and can be the alternative lubricant for the automotive application especially for steel [34]. This study did not consider the thermal oxidative stability of the formulated lubricant and the environmentally unfriendly mineral oil is still the base oil.

3.3 Blends of various vegetable oil as lubricant

Talkit et al. [35] carried out an analytical study on lubrication properties of different vegetable oils blends at different temperatures by testing soybean oil, olive oil, almond oil, amla oil, castor oil, groundnut oil, cottonseed oil, coconut oil, sesame oil, sunflower oil and mustard oil and their blends in different proportion for lubrication properties like cloud point, pour point, flash point, fire point and percentage carbon residues. It was found that soybean almond oil blend possessed the lowest pour point which was attributed to increasing cis-unsaturation or low molecular weight fatty acid while soybean amla oil blend possessed the highest pour point due to increasing high molecular weight fatty acid. Also, soybean castor oil blend possessed lowest cloud point while soybean sesame oil blend possessed highest cloud point; soybean groundnut oil blend had highest flash point while soybean castor oil blend had the lowest flash point. Similarly, it was found that soybean olive oil blend had the highest fire point while soybean almond oil blend possessed the lowest fire point; the percentage carbon residue of soybean amla oil blend was lower while soybean castor oil blend was higher than other vegetable oil blends. The study is useful for development of biolubricants from blends of soya bean and other vegetable oil however it is limited in that it did not study the effect of the blending on friction and wear.

4 Challenges of vegetable oil as lubricant

Though vegetable oils exhibit excellent tribological properties like lubricity at low temperatures and has good prospect to replace mineral oil for lubricant production, they have considerable challenges that limits their wide use as lubricant base stock. The performance limitations of vegetable-based lubricants stem from inherent properties of the vegetable oil base stocks rather than composition of additive package. Base stocks usually comprise more than 90% of the lubricants and nearly entirely pre-define properties such as high biodegradability, low volatility, ideal cleanliness, high solvency for lubricant additives, miscibility with other types of system fluids, negligible effects on seals and elastomers, and other less significant properties (e.g. density or heat conductivity) [36]. Base stocks are also a major factor in determining oxidative stability, deposit forming tendencies, low temperature solidification, hydrolytic stability, and viscometric properties.

On the other hand, parameters like lubricity, wear protection, load carrying capacity, corrosion (rust) prevention, acidity, ash content, colour, foaming, de-emulsification (so called demulsibility), water rejection, and a number of others are mostly dependent on the additives or impurities/contaminants [36]. Therefore, when a given fluid is considered for its suitability as a lubricant, first of all, the base stock dependent parameters are evaluated. In addition to biodegradability, the following characteristics must be given attention: cleanliness (particle count), compatibility with mineral oil lubricants, homogeneity during long term storage, water content and acidity, viscosity, viscosity index, pour point, cloud point, cold storage, volatility, oxidative stability, elastomer compatibility and possibly other properties, depending on intended application. Water rejection, demulsibility, corrosion protection, ash content and foaming could also be tested if contamination of the additive-free oil is suspected. Some of the most important challenges or limitations of vegetable oils as lubricants is reviewed in the following subsections.

4.1 High wear at high temperatures under sliding

Vegetable oils are known to cause increased wear at high temperatures and under sliding conditions. Choi et al. [37] showed that olive oil and soybean oil exhibit high amount of wear when tested at 150°C above a sliding speed of 0.4 m/s. Also fatty acid constituents of vegetable oils show increased wear above certain transition temperatures [38]. The transition temperature depends on individual fatty acids, the nature of the lubricated metals, and on the load and speed of sliding.

4.2 Poor oxidative and thermal stability

Oxidation stability is the resistance of a lubricant to molecular disintegration or rearrangement at high temperatures in the presence of oxygen while thermal stability is the resistance to molecular breakdown at high temperature in the absence of oxygen [2]. A lubricant that oxidizes quickly is said to have poor oxidative stability and will require frequent maintenance or replacement resulting in higher operating cost.

Vegetable oils especially poly-unsaturated oils are known to possess low oxidative stability [22, 39]. The reason for the thermal and oxidative instability of vegetable oils is attributed to the structural “double bond” elements in the fatty acid part and the “β-CH group” of the alcoholic (glycerine) components [18]. Also a high content of linoleic/linolenic acid decreases thermal and oxidative stabilities [7]. In particular, multiple double bonds are a hindrance for technical application. The bis-allylic protons present in alkenyl chains with multiple bonds are highly susceptible to radical attack and subsequently undergo oxidative degradation and form polar oxy compounds [40]. This phenomenon produces insoluble deposits and increase in oil acidity and viscosity which in turn brings about higher corrosion attacks of the parts lubricated.

4.3 Poor hydrolytic stability

Further weakness of vegetable oils is their tendency to hydrolyze in the presence of water [41]. The presence of ester functionality groups renders these oils susceptible to hydrolytic breakdown [42], therefore, contamination with water in the form of emulsion must be prevented at every stage. Vegetable oils also show poor corrosion protection especially when moisture is present [43]. The β-hydrogen atom is easily eliminated from the molecular structure in the presence of oxygen in moisture which leads to the cleavage of the esters into acid and olefin [7].

4.4 Poor low temperature (cold flow) properties

Poor low-temperature properties include cloudiness, precipitation, poor flowability, and solidification at relatively high temperatures [13]. Low-temperature studies have shown that most vegetable oils undergo cloudiness, precipitation, poor flow, and solidification much above the pour point upon long term cold storage [40, 44].

4.5 High cost, food versus lubricant competition

Another major challenge is the cost of the bio-lubricants. Bio-lubricant costs somewhere between 30–40% more compared to a conventional lubricant [45]. Lubricant formulations for more environmentally benign applications are, therefore, being developed based on their benefits and limitations.

There is also a food versus energy (lubricants and biofuel) debate concerning the use of vegetable oils for bio-lubricant production. Most countries are unable to produce the quantity of edible oil they need, for example India has 16.6 million tonnes annual edible oil consumption and is the largest importer of edible oil [46]. Therefore it becomes very challenging to use scarce edible oil for lubricant production; due to the high demand on vegetable oil the price is also high.

5 Current research efforts to mitigate challenges of vegetable oil as lubricant

While poor oxidative and hydrolytic stability, high temperature sensitivity of tribological behaviour, high cost, competition between the food and industrial lubricants sectors and poor cold flow properties are reckoned to be the limitations of vegetable oils for their use as base oils for industrial lubricants [10, 36, 40], there are current effort to overcome these limitations including the use of non-edible oils, additives, chemical modifications and thermal modifications [47]. Some of the current research and development efforts to mitigate these challenges are reviewed below.

Quinchia et al. [48] studied the tribological potential of vegetable oil-based lubricants containing environmentally friendly viscosity modifiers. High oleic sunflower (HOSO), soybean (SYO) and castor (CO) oils were blended with 4% (w/w) of ethylene–vinyl acetate copolymer (EVA) and 1% (w/w) of ethyl cellulose (EC). The viscosity over a temperature range of 25 – 100°C were measured as well as the film thickness and friction measurements were carried out. It was found that castor oil showed the best lubricant properties in comparison with the high oleic sunflower (HOSO) and soybean (SYO) oils. The ethyl cellulose performed better than the ethylene-ninyl acetate copolymer as a viscosity modifier with the best viscosity increaments (125% at 40°C) corresponding to castor oil- ethyl cellulose blend.

Similarly, Alves et al. [49] investigated the tribological behaviour of vegetable oil based lubricants with nano particles of oxides in boundary lubrication conditions. Sunflower and soybean oils were epoxidized and analysed in terms of viscosity, density and iodine value. Copper oxide and zinc oxide nano particles were prepared by an alcothermal method and added to the vegetable oils, mineral oil and synthetic oil that were used as control. Friction and wear tests were conducted using steel ball on disc. Results showed that tribological properties of the mineral oils were improved significantly by the addition of the nano particles of zinc and copper oxides, however, nano particles addition did not improve the tribological properties of vegetable oils. Thus, copper oxide and zinc oxide nano particles do not show good anti wear ability when combined with epoxidized vegetable oils.

Erhan et al. [50] studied the oxidation and low temperature stability of vegetable oil based lubricants by adding Zinc diakyldithiocarbamate (ZDDC) and Antimony diakyldithiocarbamate (ADDC) to five vegetable oils (refined soya bean oil, mild oleic soya bean oil, high oleic soyabean oil, high oleic safflower oil and high oleic sunflower oil) then evaluating their pour point as per ASTM D97 method, oxidation and low temperature stability using differential scanning calorimetry (DSC) and rotary bomb oxidation tests (RBOT) as per ASTM D-2272 standard and comparing the result to that of a commercial biodegradable hydraulic fluid. The results showed that the vegetable oils formulated according to the above methods exhibited superior oxidative stability and improved low temperature properties compared to the commercial hydraulic fluid and compared at par with petroleum based lubricants.

Also, Azhari et al. [51] studied the modification of corn and canola oils using Zinc Dialkyldithiophosphate (ZDDP) as anti-wear agent. Samples with addition of 0 mass%, 2 mass% and 5 mass% ZDDP were prepared and tested using rotating disc electrode atomic emission spectroscopy (RDE-AES) which is automatically monitored by spectroil software, and a heated viscometer. The samples were then characterized using a pin-on-disc tribometer. Corn oil had a lower kinematic viscosity value compared to canola oil and gave a lower kinematic viscosity value of 36.3 cSt with the addition of 2 mass% ZDDP. The addition of 2 mass% ZDDP in corn oil and canola oil lowered the coefficient of friction for both type of oil. The results showed that 5% addition of ZDDP will not lead to further improvement of lubricant properties in corn and canola oils.

The other possible way to control these obstacles is structural modification of the oils by chemical reaction [52]. Vegetable oils are mostly split into their oleochemical components such as fatty acids or fatty acid methylesters and glycerine before they are modified. Fatty alcohols can be formed out of fatty acid methylesters. However, the vegetable oil can be directly modified, for example, by direct transesterification or selective hydrogenation. The most important modifications concern the carboxyl group of the fatty acids. They account for about 90% of the oleochemical reactions, whereas reactions of the fatty acid chain only account for less than 10% [44, 53].

Heikal et al. [54] studied the manufacturing of environment friendly biolubricants from palm oil and jatropha oil. The biolubricants were produced through a two stage transestrification, confirmed by Fourier Transform Infrared (FTIR) spectroscopy and analysed for viscosity, pour point and thermal stability according to ASTM standard methods. It was found that the jatropha oil based biolubricant exhibited high viscosity index (140), low pour point (-3°C) and moderate thermal stability and thereby meet the requirement for commercial industrial oil ISO VG46 grade. The palm oil based biolubricant however, had high pour point (5°C) which is undesirable and therefore need improvement, but its viscosity, viscosity index and flash point are comparable to commercial industrial oil ISO VG32 and VG46.

Also Singh and Chhibber [55] studied the chemical modification in karanja oil for biolubricant industrial applications. Karanja oil was extracted from dry karanja seeds and study of its composition and physico-chemical properties were carried out; further its modification into trimesters to improve the oxidation and cold flow behaviour were also done. The oxirane ring opening of epoxidized karanja oil using behenic acid and p-toluene sulfonic acid (PTSA) as catalyst followed by esterification reaction with octanol and 2-ethyl hexanol to form diesters was achieved. The remaining free hydroxyl group was reacted with oleic and stearic acid to give triesters. The oil before modification had viscosity index, pour point and flash point of 172, -9°C and 212°C respectively and after modification it was 194cp, -36°C and 307°C respectively. The structures of the products were confirmed by FTIR, 1H- and 13C-NMR. From the results it was concluded that the modified karanja oil can be easily used as metal working lubricant, hydraulic fluid turbine oil, refrigeration oil and food processing lubricant.

To mitigate the competition between food and biolubricant industry, non edible oil is gaining consideration for bio-lubricant and bio-diesel development. According to Ioan [56] and Erhan et al. [50] non edible vegetable oils besides being cheaper offer better or at least the same performance as mineral oil base in lubricant products. For example Jatropha is a perennial tree, which has a life span of 40-50 years and can bear fruits for 25 years [46]. It can grow in marginal lands, and does not compete for the food production with human or for land with food.

Fig. 5 Jatropha plant

Jatropha oil, a non-edible vegetable oil produced from the seeds of jatropha curcas seed plant shown in Fig. 5 is one of the largely investigated oils for industrial and automotive lubrication. Its high viscosity due to the dominant ricinoleic acids, around 90% [57], and high oleic acid (43%) suggests the possibility of its application as lubricating oils. The bio-lubricant produced from Jatropha curcas oil have a more preferable cooling characteristics than that from palm oil, better viscosity than that from castor oil and higher oxidative stability and lower acidity than that from soybean oil [58]. The world production of jatropha plant is around 1.5Mt. Africa has a contribution of around 1.08Mt. The yield of jatropha curcas seed in Nigeria is rated at between 9,901,700 kg/ha [59], and virtually every part of the country is suitable for jatropha plantation. The average oil content of a jatropha seed on the basis of dry weight is 58% [60].

6 Practical applications of vegetable oils as lubricants

While most of the reported work on vegetable oil lubricants are laboratory level tests, there are actual engine performance data reported and more will become available as commercial bio-based lubricants are beginning to enter the market. Typically a formulation is subjected to a number of screen tests to evaluate its efficacy in a particular application before being tested in the actual end-use equipment [61]. Vegetable oils are mostly used in applications where leakage of equipment is inevitable or where a system is designed to function by loss lubrications such as; two stroke engine oils, chain saw oils, mould release oils, farming, mining and forestry equipment, open gear lubricants, greases and fuels.

Grease produced from Thevetia Peruviana and Jatropha Curcas seed oils were applied on the bearing of a grinding engine and the counting gears of a fuel dispensing machine. No wear, visible defect, rust nor oil leakage were observed in the grinding engine or counting gears of the fuel dispensing machine after two weeks of operation, the texture of the grease were also found to be normal [62].

Also vegetable oil has extensively been used as a metal working fluid in the machining industry [63]. Talib et al. [63] formulated a vegetable oil based metal cutting fluid called MJO5a. This metal cutting fluid was made using Jatropha methyl oil (JME) modified by transestrification with trimethylolpropane (TMP) at JME/TMP molar ratio of 3.5:1 added with 0.05% hexagonal boron nitride. MJO5a was successfully used to cut AISI 1045 and it was found to give excellent machining performances by reducing the cutting force, cutting temperature, chip thickness, tool chip contact length and specific energy. It was concluded that MJO5a exemplified its potential on the lubricant market place with regard to the environmental concern and energy saving.

Blended sunflower and canola oil with extreme pressure additive have been employed for machining of Al 7075-T6, it was found to have 38% improvement in cutting force and achieved a lower nose and flank wear compared to the commercial petroleum-based oil [64]. Ojolo et al. [65] used ground nut oil, coconut oil,shea butter oil and palm kernel oil as metal working fluids for turning of mild steel. The vegetable based metal working fluids improved the product quality significantly by reducing the cutting force. Ground nut oil exhibited the best performance.

Mamuda et al. [66] investigated the suitability of bio-based lubricants for wire drawing. The biobased lubricant was formulated using neem seed and jatropha seed oil as lubricants, using antimony dialkyl dithiocarbamates (ADTC) as an additive. A Tungsten Carbide die and the formulated lubricants were used to draw mild steel and medium carbon steel rod (6 and 8 mm diameter respectively) at temperatures from 20°C to 750°C, on a drawing bench. Up to 45% of reductions in area, without wire fracture, were achieved on the drawing of the medium carbon steel. It was concluded that the formulated oils can be good non-toxic, biodegradable, renewable alternative lubricant for high temperature wire drawing operations.

One of the profound practical applications of vegetable oil based lubricants is found in the elevator of the Statue of Liberty in New York Harbor, USA. The elevator now runs on a biodegradable hydraulic fluid made from soy oil. This soy oil based hydraulic fluid was developed by seasoned vegetable oil based lubricant researches lead by Sevim Erhan and Atanu Adhvaryu in the National Center for Agricultural Utilization Research at the request of the National Park service of the USA [67].

7 Conclusion

Lubricants are important consumables in all industries as they reduce friction, minimize/ prevent wear, provide cooling and transport debris away from the interface of contacting machine parts. The base oil used for the formulation of most lubricants is environmentally hostile mineral oil and 30% of lubricants consumed ends up in the ecosystem [7, 8]. However, mineral oil reserve is depleting and the environmental concern about the damaging impact of mineral oil is growing. The search for environmentally friendly substitutes to mineral oils as base oils in lubricants has become a frontier area of research in the lubricant industry. Vegetable oils are perceived to be alternatives to mineral oils for lubricant base oils due to certain inherent technical properties and their ability to be biodegradable. This work reviewed recent research on vegetable oils as base oil for lubricant production. The overview focuses on the prospects, challenges and current research efforts to overcome the challenges of using vegetable oils as base oil for the production of industrial lubricants.

Compared to mineral oils, vegetable oils have good prospects as lubricants because vegetable oil in general possesses high flash point, high viscosity index, high lubricity and low evaporative loss [22, 36, 68]. Vegetable oils have been found to be a renewable resources, less dangerous to the soil, water, flora and fauna during disposal or accidental spillage compared to mineral oil [11, 61, 69]. The challenges of vegetable oil as lubricant base oil includes high cost, competition between food and lubricant industries for vegetable oil, poor oxidative and hydrolytic stability, high temperature sensitivity of tribological behaviour and poor cold flow properties. The current efforts to overcome these challenges includes the use of additives, chemical modifications, thermal modifications [47] use of non-edible vegetable oils and government commitment through legislation to encourage the use of vegetable base oil lubricants.

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