Chapter 5
Biolubricants and the Potential of Waste Cooking Oil

J.G. Alotaibi and B.F. Yousif

Abstract In the current decade, development of recycle, renewable, and sustainable products to replace fossil products is an essential and important matter from industrial, environment, and academic point of views. The excessive usage of Petroleum-based oils significantly contributes to the pollution of the environment and had caused environmental pollution and awareness from the environmental sectors. Researchers start exploring an alternative oil from natural resource aiming to replace the fossil oil and this becomes the main ambitious of many researchers, environmental, and government bodies. In this chapter, a comprehensive literature review is introduced and several issues are addressed with regards of the usage of newly developed lubricants that are based on vegetable oils. Furthermore, it is exploring the potential of using waste cooking oil as lubricant for tribological applications.

1 Introduction

Later in the 1800s, petroleum had been discovered and that led to the replacement of animal fats, vegetable oils, and mineral oils with synthetic oils. Petroleum oil had gradually started to be the main lubricant base stocks, and that was because of their low cost and superior performance. Lubricants are being used widely in all fields of manufacturing and industrial applications. Studies showed that more than thirty eight million metric tons of oils were used in lubrication techniques in 2005 for different industrial applications in the United States (USA). Lubricants are

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commonly used to reduce overheating and friction in a variety of engines, machinery, turbines, and gear. The excessive usage of petroleum-based oils significantly contributes to the pollution of the environment [1] and had caused environmental pollution and awareness from the environmental sectors. Besides that, the demand for fossil fuel and oil products is increasing in numerous areas. From the reported works, alternative oil should increase to cover about 36 billion gallons in 2022 [2]. The literature showed that bio-oil becomes the most successful candidate for biofuel since, in the current decade, there are few attempts aiming to study the potential of using bio-oil such as sunflower oil [3, 4], castor oil [5, 6], soybean oil [7, 8], etc. as biofuels for diesel engines. Most of the works showed good and promising results. However, there is a tribological issue raised by most of the researchers in which biofuels deteriorate the engine components.

Besides the usage of the bio-oil as fuel, there is an effort that is currently put to use bio-oil as lubricant for several tribological applications [9–11], e.g., soybean oil (USA and South America) [12], rapeseed oil (Europe) [13], and palm oil (Asia) [14–16]. The studies are still in the initial stage and there are many issues and limitations need to be addressed [17, 18]. Moreover, the literature highly recommends deep investigation to study the performance and the potential of using biolubricants [19–21].

Lubricants are being divided into solid, semisolid, gas, or fluid. Lubricants are classified into two major groups: (i) automotive lubricants and (ii) industrial lubricants. Automotive lubricants have to perform in different types of vehicles both petrol and diesel under a variety of operating conditions. Quality requirements of such lubricants are established by the Society of Automotive Engineering (SAE) and are specified in its classification system [22]. Industrial oils are used for protecting internal elements from intensive cycles of operation. Viscosity of industrial oils is an essential factor to maintain operating at an optimal condition over a wide range of temperature and working conditions. Industrial lubricants are classified by the International Standards Organization (ISO) from the American Society for Testing and Materials (ASTM) D2422. The ISO classification is based solely on viscosity ranges at 40 °C. In the light of the above, the current paper is motivated to cover the recent literature on the biolubricants and explore the potential of using waste cooking oil as lubricant for tribological applications.

2 Lubricants and Biolubricants

Tribology science covers friction, wear, and lubricant branches. The science of tribology starts long time ago about 4500 BC when the first wheel has been developed [23]. This followed by animal fat to ease the rock movements in building Egyptian pyramids. A lubricant is used to be a protector between devices. When two devices are in contact with each other, a contacting pressure will be created between them causing surface damage if there was not any protector between them. Lubricant is used to reduce and lower the wear between the components of any mechanical devices [24]. 100 years ago, water was mainly used to cool cutting tools due to its high availability and thermal capacity. Lubrication and cooling in machines are vital to reduce the effect of any cutting process at the interface of a cutting tool–workpiece. The main drawbacks in the coolant are the poor lubrication and corrosion of the machines. On the other hand, mineral oils were used at that time due to their higher lubricity, but the high costs and low cooling ability of them had led to only using them in "low cutting speed machining operations" [25]. Any lubricant can also be used to remove and reduce the heat from a device during its operation. Lubricants are commonly used to reduce overheating and friction in a variety of engines, machinery, turbines, and gear [26, 27]. The development of tribology science continues since that time until now. With the discovery of fossil oil, new areas of research have been developed owing to discover the synthetic lubricants for various tribological applications. Lubricants are being used widely in all fields of manufacturing for lubricating their materials and machines. From economical point of view, more than thirty eight million metric tons of oils were used for lubrication techniques. In the current era, petroleum-based lubricants are mostly used in industries. However, the excessive usage of such lubricants is effecting the environment leading to numerous issues related to environments such as groundwater and surface water contamination, soil contamination, and air pollution [1, 28, 29]. Specifically, synthetic lubricants can be emitted into the environment through cleaning activities and accidental leakage. Further to this, wastewater lubricants include free oil and emulsified oil, created by a mixture of oil with a wastewater and washing agent. Several techniques have been developed to overcome such problems such as corrugated plate interception [30] or gravitational oil separation [31].

Recently, the excessive world consumption of crude oil has several impacts to the world in term of economic since there is a huge increase in the price of the fuel products. Moreover, there is a huge impact on the environment since there are challenges from global and environmental sectors. This encourages the researchers in the area of oil and fuel products to find alternative friendly product to replace the synthetic product for several applications [32]. In addition to that, this alerts the reconsideration of using friendly lubricants with renewable properties and sources, like nonedible vegetable oils [33]. The high interest in the research area of the biolubricants is evidence in the increase of number of publications related to the area in sciencedirect database Fig. 1. Due to the increase interest in the research area of biolubricants, the following sections will focus and discuss the recent issues raised by the reported works to cover the potential biolubricants and the required characteristics of the lubricants.

2.1 *Biolubricants in the Recent Era*

Most of the lubricants used in rotary machine elements are based on mineral and synthetic oils combined with different additives to meet the requirements of the

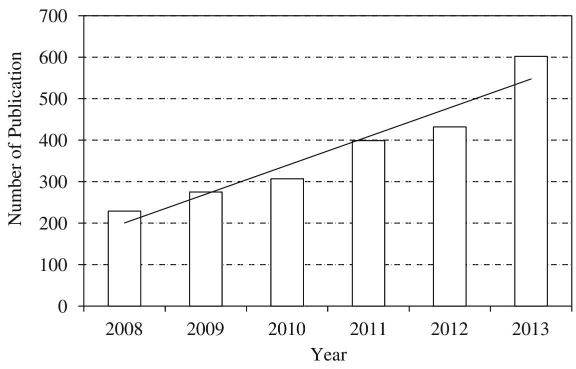

Fig. 1 Extracted data from international database (www.sciencedirect.com) showing the number of publications in the area of biolubricants

intended applications [34]. The main disadvantages and limitations of mineral oils are the poor biodegradability, high cost, and limited resources [35], i.e., there is a need for substitutions of friendly environmental lubricants [36] due to strict government and environmental regulations as reported by recent work [19, 37]. Petroleum-based lubricants are toxic to environment and difficult to dispose, and many lubricant manufacturers have reconsidered vegetable oils over synthetic fluids due to a combination of renewability, biodegradability, excellent lubrication performance, and low cost [38, 39].

Bio-oil can be divided based on its resources into vegetable and animal. Vegetable oil is more popular and common compared to the animal due to its availability, ease in extraction, and low cost [40, 41]. Vegetable oils are promising candidates as base fluid for eco-friendly lubricants. From the reported works, vegetable oils as lubricants have numerous advantages such as good contact lubrication [42], excellent lubricity [40], biodegradability, viscosity–temperature characteristics [43, 44], very low volatility high viscosity indices as minimum changes in viscosity with temperature [45], and high flash point due to the high molecular weight of the triglyceride molecule and excellent temperature–viscosity properties [46].

Despite of the above advantages, vegetable oils can be edible or nonedible oil. Edible oils are more common and available compared to the nonedible oils. However, since most of the vegetable oils are edible, a limitation can be found in using such oil in tribological applications. Therefore, it is not highly recommended to use edible oil as lubricant and/or either fuel [37, 47, 48]. In this scenario, there are two demands that need to be considered in developing a new oil which should have less impact on the environment and be nonedible. The researcher of this project finds that waste cooking oil is a potential candidate as alternative to the synthetic and edible oils. From fuel point of view, there are several researches that are going on in the current year aiming to convert waste cooking oil into biofuels using different techniques as reported by [49, 50]. In the next section, a summary of the current works on waste cooking oil that is introduced.

Table 1 Different types of vegetable oils and their applications

Vegetable oils	Applications
Canola oil [51]	Hydraulic oils, metalworking fluids, "food grade lubes," penetrating oils, "chain bar lubes tractor transmission fluids"
Castor oil [33]	Greases, gear lubricants
Coconut oil [52]	"Gas engine oils"
Crambe oil [53]	Intermediate chemicals, grease, surfactants
Cuphea oil	Motor and cosmetic oils
Jojoba oil	Cosmetic industry, grease, lubricant applications
Linseed oil	Paints, coating, lacquers, stains, varnishes,
Olive oil [51]	Automotive lubricants
Palm oil [54]	Grease, steel industry, rolling lubricant,
Rapeseed oil [33]	"Air compressor-farm equipment," "chain saw bar lubricants," biodegradable greases

Vegetable oils are promising candidates as base fluid for eco-friendly lubricants because of possession of some excellent properties for their potential use as a base stock for lubricants and functional fluids such as good contact lubrication, excellent lubricity, biodegradability, viscosity–temperature characteristics, very low volatility high viscosity indices (VI) (i.e., minimum changes in viscosity with temperature), and high flash point due to the high molecular weight of the triglyceride molecule and excellent temperature–viscosity properties. On the other hand, VOs in its natural form cannot fully meet the performance criteria for the most lubricants due to their drawbacks including poor low-temperature properties such as opacity, precipitation, and poor flowability at relatively moderate temperature. Table 1 demonstrates possible applications for different vegetable oils.

With regard of the vegetable oils, most of the works have been studying the wear and frictional performance of the oil without any chemical additives as reported recently by Madankar et al. [55] on castor seed oil. Castro et al. [56] studied the wear properties of different modified neat soybean oils without any additives. In that work, the test has been performed using tribological setup at fixed speed of 700 rpm. There is no remarkable effect of the different oils on the wear and frictional performance of the soybean oil. Table 2 summaries the recent works on

Table 2 Main physical properties of vegetable oils [54]

Vegetable oils	Palmitic (16:0)	Stearic (18:0)	Oleic (18:1)	Linoleic (18:2)	Linolenic (18:3)	Linolenic (18:3)	Unsaturated/saturated ratio
Castor oil	2.63	1.51	4.74	8.36	–	82.80	23.20
Soybean oil	11.28	2.70	24.39	56.28	5.34	–	6.15
Rapeseed oil	4.56	–	65.99	21.13	8.16	–	20.90
Sunflower oil	6.18	2.16	26.13	65.52	–	–	11.00
High-oleic sunflower oil	3.84	4.42	83.66	8.08	–	–	11.10

vegetable oil as lubricant and their findings. In general, there is interest and high attention from the researchers to focus their studies on the possibility of using vegetable oil as lubricant for several applications. However, there is no clear direction on the application of vegetable oil yet since such oil is new and need deep investigation.

In [12], mixtures of the original soybean oil, the epoxidized soybean oil, and the hydrogenated soybean oil as the base oils have been examined to determine the viscosity and working efficiency of the oils. The applications of those mixtures of oils have focused for internal combustion engines. The results showed that the epoxidized soybean oil has extremely large viscosity in comparison with the engine lubricants as well as the original soybean oil, whereas the hydrogenated soybean oil is clearly opposite. This viscosity analysis offers good information to fit viscosity of the engine lubricants by mixing the three soybean oils as base oils. For the two-stroke engines, castor oil-based lubricants have been used owing to reduce the smoke and emission level, in comparison with the conventional oil used for two-stroke engines (*2T-Lubricant*, [57]).

2.2 Characteristics of Biolubricant Oils

Low resistance to oxidative degradation and poor low-temperature properties are the main performance issues accounted in using vegetable oils as lubricant oils. Therefore, there are different methods to solve these problems such as reformulation of additives, chemical modification of vegetable-based oils, and genetic modification of the seed oil crop. Triethanolamine oleate, triethanolamine, and oleic acid are the main additives of the base oils which are used as lubricant oils. These additives affect the thermal stability of rapeseed and tribological behavior of base oils. The additives demonstrated significantly better thermal stability and tribological behavior. Also, the thermal stability of vegetable oils can be enhanced by chemical modification techniques. Modifications of the “carboxyl group” and modifications of the “fatty acid chain” are the two main chemical modification techniques. Modifications of the carboxyl group include Esterification/Trans esterification techniques and modifications of the fatty acid chain include selective hydrogenation (Dimerization/oligomerisation), formation of C–C and C–O bonds, metathesis, and oxidation techniques. The different methods under genetic engineering are used and new vegetable oil types are being used. Sunflower and “high oleic soybean oils” are some good examples. These oils have higher “thermo-oxidative stability” and higher load transportation capacity. These oils need less adjustment to be used as “base oil lubricants,” compared to conformist plant based [33].

“Low temperature performance” is one of the main limitations for the usage of vegetable oils as lubricants, more than synthetic oil-based or mineral lubricants. [54] studied the low-temperature behaviors of different types of vegetable oils which are used in lubricating applications. Also, [54] studied vegetable oils’ behaviors after blending them with “pour point additives.” Blends are prepared by rotating the samples at 300 rpm at 100–150 °C for 5–10 h, depending on concentration of additives and types of them. This thermal process is required to make sure that the additives are completely soluble in vegetable oils. After that, samples are cooled at room temperature. Different vegetable oils are used as base stocks such as castor (CO), soybean (SYO), rapeseed (RO), sunflower (SO), and high-oleic sunflower (HOSO). CO oils are received from Spain; SYO, RO, and HOSO oils are supplied by Germany and Spain; and SO oils are obtained from local supermarket. Main physical properties of vegetable oils are demonstrated in Table 2.

Thermal analysis by "Differential scanning calorimetry" (DSC), "Pour point temperature measurement," "Viscosity measurements at low temperature," and Statistical analysis are the main methods used to study the behavior of vegetable oils. Thermal analysis by "Differential scanning calorimetry" (DSC) can be defined as the analysis of cooling curves (heat flow (W/g) vs. temperature) and their blends with cold flow and viscosity improver additives which are obtained using a differential scanning calorimeter (Q-100). In this method, samples are heated in hermetic aluminum tubes at 25 °C, and directly cooled with a cooling rate of 5 °C/min to −80 °C. Also, samples are cleaned with nitrogen which has a flow rate of 50 mL/min and then to determine freezing temperature and wax appearance, the cooling curve for each sample is analyzed. The pour point can be defined as the lowest temperature for vegetable oil when it is cooled. The pour point of vegetable oils and their blends with additives are determined by (Standard Test Method for Pour Point of Petroleum Products (ASTM D97-02)). In viscosity measurements at low-temperature method, the dynamic viscosities for vegetable oils will be measured using coaxial cylinder in "rotational controlled-strain rheometer" [54].

"Differential Scanning Calorimetry" (DSC) is a method used to determine the crystallization for "vegetable-based lubricants." Also, DSC method is more accurate and faster than viscosity measurements and pour point temperature at low-temperature methods. In all tests, castor oil demonstrates a better behavior at low temperature, because it has low content of saturated fatty acids and it has hydroxyl groups in the fatty acid chain which can obstruct the crystal packing system of triacylglycerols (TAG) molecules. Vegetable oils which have lower ratio of "unsaturated/saturated fatty acids" crystallize at higher temperatures. Additionally, the concentrations of "Polyunsaturated Fatty Acids" (PUFAs) in vegetable oils have more impact on low-temperature properties than the concentration of "saturated fatty acids." Therefore, the "rapeseed oil" has better behaviors at low temperatures compared with other types of oils which have similar molecular structure such as HOSO, SO, and SYO oils. Generally, "The Pour Point Depressant" (PPD) additives are used to improve the low-temperature behaviors of vegetable oils. PPD additives increase the low-temperature performance and decrease the pour point for vegetable oils which depend on fatty acid composition in vegetable oils. The results demonstrate that the blend of sunflower and the pour point depressant (SO/PPD) has lower pour point than neat oil (HOSO/PPD) [54].

Biodegradability investigation of lubricants using standardized tests used to provide valuable information for regulation assessment and purposes of how chemical structure of lubricants influences biodegradability. Poor solubility of lubricating base oils in water is the major problem which obstructs the biodegradability analysis. Ultimate and primary biodegradability are the two phases of biodegradability which are used for analyzing different chemical structure oils such “syntheticpolyolester” oils, rapeseed oil, conventional mineral oils, and poly (a-olefin) oils. “Co-coordinating European council for the development of performance tests for lubricants and engine fuels” (CEC L-33-A-93 test) is used to evaluate primary biodegradability of lubricants. “Organization for Economic Cooperation and Development Guidelines for Testing of Chemicals” and “301B Ready biodegradability” (OECD 301 B and OECD 310 tests) are used to evaluate ultimate biodegradability of lubricants. Primary biodegradability is evaluated according to the CEC L-33-A-93 test using triplicate flasks containing “Di-IsotridecylAdipate” (DITA) as the reference material, and triplicate flasks contain the test oils, “duplicate neutral flasks” and “duplicate poisoned flasks,” which are prepared for various durations of time (0, 7, 14, and 21 days) during the test [55]. Despite the low-temperature properties and oxidative stability of vegetable oil-based lubricants compared with petroleum-based lubricants, it is used in many countries. For example, in USA people use corn oil and soybean oil, while in Europe and North America rapeseed oil is used [9].

2.3 Edible and Inedible Oils

Recently, there is a big concern about using edible vegetable oil or the feedstock first generation, because it may cause starvation in poor and developing countries, the other problem appears in utilizing the available “arable land,” and it can create ecological imbalances when countries start cutting forests. Hence, these feedstock cause deforestation and wildlife damage. Therefore, second-generation feedstock or “non-edible vegetable oils” will be attractive to produce biodiesel, besides for the “sustainable production of biodiesel” the second-generation feedstock is very promising. There are examples of nonedible seed crop oils like jatrophacurcas, tobacco, deccan hemp, castor, jojoba, sea mango, coriander, salmon oil, desert date, cardoon, milkweed, tung, and lucky bean tree. Microalgae oils are considered to be “inexhaustible source of biodiesel.” They are very economical when compared with edible oils. Microalgae give the highest oil yield, and its yield is “25 times higher than the yield of traditional biodiesel crops.” Waste of cooked vegetable oils is another biodiesel feedstock with cheap price relatively for production of biodiesel from fresh vegetable. As an economical source biodiesel production from cooked vegetation oil is good option, global consumption of biodiesel feedstock should rely on multiple sources since expiring one source will bring harmful effects on the long term, and biodiesel feedstock should be as diversified as possible, depending on geographical locations in the world [7].

Using noneditable vegetables will not contradict with countries demands for food. Vegetable oil lubricants cover a small market segment and rise slowly and steadily in open applications such as chainsaws, forestry, two-stroke engines, etc. More efforts had been taken to change the global laws and policies to ensure environmental safety, and all cases of lubricants interference environmental compatibility must be checked. Nonedible vegetable oils have the potential to divert the agricultural practices and strengthen the economics [5].

Biomass like edible, nonedible crops, microorganisms, algae, recycled cooking greases, wood (lignocelluloses), and animal waste are used to derive bio-oils. The most popular virgin crops used for the production of bio-oil are canola, corn, soybean, rapeseed, mahua, mustard, jatropha, safflower, sunflower, and palm. For bio-ethanol production, sweet sorghum, straw, sugarcane/beet and, rice, wheat, and corn can be used. The debate of fuel versus food and the environmental impacts concerned about conversion and cultivation will limit using food crops to produce fuel. Converting residues from lignocellulose material or wood into biofuels is difficult; in the next decades advanced technology is expected to "reach their commercial stage," which does not require lands to produce algae, fungi, yeast, and bacteria to reach 70 %. However, production of large scale of oil from microorganisms and microalgae can be a challenge [8].

3 Waste Cooking Oil

In using edible bio-oils as fuels, several feedstock have been proven impractical or infeasible because of their extremely high cost due to their usage primarily as food resources as reported recently by Yaakob et al. [50]. Waste cooking oil (WCO) can be considered the most promising bio-oil feedstock despite its drawbacks, such as its high free fatty acid (FFA) and water contents [50, 58]. Waste cooking oil (WCO) can be produced from different sources and its base materials are plant-based lipids (sunflower, corn, margarine, coconut, palm, olive, soybean, oil, and canola) or animal-based lipids (butter, ghee). It can be freely collected from food production industries, restaurants, and houses using a special "recycle bin," this requires public awareness, [50]. WCO and fats produce significant disposal problems in many parts of the world and the growing problem of wastes affects the daily lives of millions of people, [59, 60] who reported that the estimated amount of WCO collected in Europe is about 700,000–100,000 tons/year. In United States, there is about 11 billion liters (2.9 billion gallons) of recycled vegetable oil produced yearly which is mainly from industries of deep fryers, snack food, and fast food [61].

To make use of such waste oil, several studies have been conducted aiming to convert the oil into biofuels especially in the current era as reported by [49, 62]. Table 3 lists waste cooking oil applications in the recent era. As reported by many researchers, biofuels produced from waste cooking oils have numerous advantages such as low pollution (CO2, CO, and NOx), low cost, and acceptable brake-specific fuel consumption. Moreover, biodiesel produced from waste cooking oil may improve the pump plunger lubrication conditions [63]. However, it has been

Table 3 Waste cooking oil application in the recent era

References	Oil type	Applications	Remarks
Bio-oil from the pyrolysis of palm and Jatropha wastes in a fluidized bed [67]	Palm kernel shell		The finding indicates that they were similar to palm fatty acid distillate from palm oil and could be used as alternative feedstocks for biodiesel production using hydrotreating process
Bio-oils from microwave pyrolysis of agricultural wastes [68]	Sago wastes		The bio-oils have a potential as valuable source for fuel or chemical feedstocks
Performance, emission, and combustion characteristics of a variable compression ratio engine using methyl esters of waste cooking oil and diesel blends [69]	Waste cooking oil methyl ester	Single cylinder four-stroke engine	The blends when used as fuel results in reduction of carbon monoxide, hydrocarbon, and increase in nitrogen oxides emissions
[58]	Waste cooking oil (sunflower oil)	As fuel for diesel engine	Showed promising results with some optimization
[70]	Collected from fish restaurant	As fuel for diesel engine	In this comparative study, conversion of waste cooking oil to methyl esters was carried out using the ferric sulfate and the supercritical methanol processes. This process resulted in a feedstock to biodiesel conversion yield of about 85–96 % using a ferric sulfate catalyst

reported that biodiesel produced from waste cooking oil highly damages the engine components [64]. In general, biodiesels have significant effects on the engine from tribological point of view, i.e., some biodiesel properties such as higher viscosity, lower volatility, and the reactivity of unsaturated hydrocarbon chains which causes injector coking and trumpet formation on the injectors, more carbon deposits, oil ring sticking and thickening, and gelling of the engine lubricant oil [63]. Many biodiesel investigations are related to wear of engine components such as piston, piston ring, cylinder liner, bearing, crankshaft, cam tappet, valves, and injectors [65, 66].

Besides the above needs to make use of waste cooking oil and its influence on the engine life, an interest can be drawn to use waste cooking oil as lubricant. Based on the knowledge of recent publications, there is no research work that has been attempted in using waste cooking oil as lubricant. However, there are several articles and industrial applications which have been reported on using vegetable oils as lubricants. The edibility of vegetable oil is the main limitation in using it as lubricants. Therefore, waste cooking oil can be used as lubricant for better application compared to biofuels and/or using virgin vegetable oils as lubricants.

3.1 Operating Parameters Effects on Wear and Frictional Behavior of Wet Contact Surfaces

There are several works that have been reported in studying the frictional and wear behavior of metals under neat biolubricant conditions. Up to the recent time, most of the works focused on specific application in which the sliding speed, sliding distance, environmental temperature, and applied load are fixed, this can be found in the work reported recently by Sharma et al. [71] and Luo et al. [18]. However, it is well known that the operating parameters have significant influence on the wear and frictional behavior of metal contact under dry and/or lubricant conditions as reported by [72–74]. For example, in [73], friction and wear behavior of gray cast iron has been investigated under different test parameters, i.e., applied load, sliding speed, and test environment. He found the followings:

1. The wear loss increased with increasing sliding speed and load. However, the presence of the oil lubricant caused a reduction in the wear loss.
2. Temperature near the specimen surface increased with test duration. The rate of increase was high initially followed by a reduction in the rate of increase. Friction coefficient also followed an identical trend in general.
3. Increasing applied load and sliding speed brought about higher frictional heating while the severity of heating reduced in the presence of the oil lubricant.
4. The friction coefficient decreased with increasing load, wherein the rate of reduction was high initially followed by the attainment of a steady-state value. Also, increasing sliding speed caused the friction coefficient to decrease during dry sliding while it produced a mixed effect on the property in the presence of the oil lubricant.

In other words, the operating parameters should be considered in testing a new lubricant. This motivates the current study to focus on the influence of the operating parameters on the newly developed bio-oil from waste cooking oil.

3.2 Effect of Lubricant Temperature on the Wear and Frictional Behavior of Metals

With regard of the biolubricants, several works that have been conducted to study the influence of the oil temperature on the viscosity of the bio-oil in which the oil was heated up and the viscosity was determined. For instance, Ting and Chen [12] studied the viscosity of soybean oil-based biolubricants at different temperatures and they found that increasing the temperature drops, the viscosity of the oil which in turn affects the friction and wear characteristics of the rubbed surfaces. Although vegetable oils have some excellent properties for their potential use as lubricants, some inconveniences should be technologically improved, i.e., limited range of viscosities available. Quinchia et al. [45] used ethylene–vinyl acetate copolymer as viscosity modifier for sunflower oil (SO), high-oleic sunflower oil (HOSO), and soybean oil (SYO). The viscosity experiments have been conducted at moderated temperature (below 40 °C) and the copolymer found to be very effective since it highly improves the viscosity of the oil. Similar works have been reported by many researchers such as [22, 39, 55]. Those works focused on the influence of the temperature on the oil viscosity only where in practical application, the oil will be in the rubbing area and the interface temperature associated with the environmental temperature may have combine effect on the friction and the wear behavior. In this work, the research focuses on the combination of both the environmental and the interface temperatures since a new tribology machine will be developed to conduct such experiments, see the new tribology machine section.

4 The Potential of Using Waste Cooking Oils as Lubricants

Viscosity is one of the most important properties used to determine and choose the suitable lubricant. In the case that the viscosity of any lubricant is high, the lubricant requires a larger force to overcome its intermolecular forces. When viscosity of the lubricant is very low, then the surfaces between the devices are rubbed leading to damage to the components. In this article, the main focus is to determine the potential of using waste cooking oil from viscosity point of view. In the following sections, the experimental procedure with the preliminary results will be presented.

4.1 Oil Collections and Experimental Procedure

There are different resources for bio-oil. In the current study, waste cooking oil was collected from a restaurant in Toowoomba city which is used for fish and chips production. In the preparation and cleaning process of the lubricant, the collected waste cooking oil was first filtered using sieves to remove the big undesired materials. This is followed by heating up the oil to a temperature of about 80 °C and then filtered using microfilter, which was supplied by Sefara PLY filter. Different blends of lubricants were prepared by mixing the prepared waste cooking oil with fully industrial synthetic oil (10 W-40). Viscosity of the oil was tested using ISL Viscometer at. In the current study, the viscosity of the oil is compared with the fully syntactic oil. Kinematic and dynamic viscosities of the prepared oils were measured according to the ASTM D 445 (ASTM Standards, 1991b) and were carried out at 40–100 °C.

4.2 Initial Results

Dynamic viscosity of the collected oil and its blends against different temperatures is plotted in Fig. 2a, b in two forms. It has been found that some of the data in the literature are presented in log form, [12] and for comparison purposes, the current values are presented in these two forms. The general trend of the viscosity is decreasing with the increase of the temperature since this is expected for all the types of oils. For the 0 % blend of waste cooking oil (fully synthetic), there is about 900 % drop in the viscosity when the temperature increased from 10 to 80 °C.

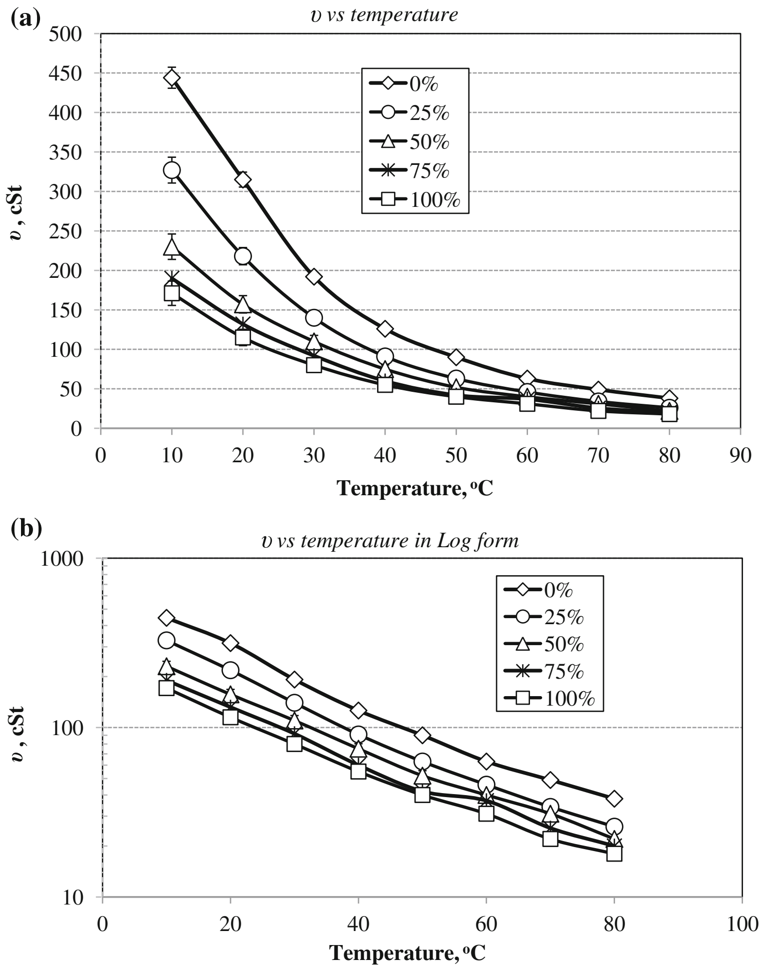

Fig. 2 Viscosity versus temperature of different blends of waste cooking and synthetic oils

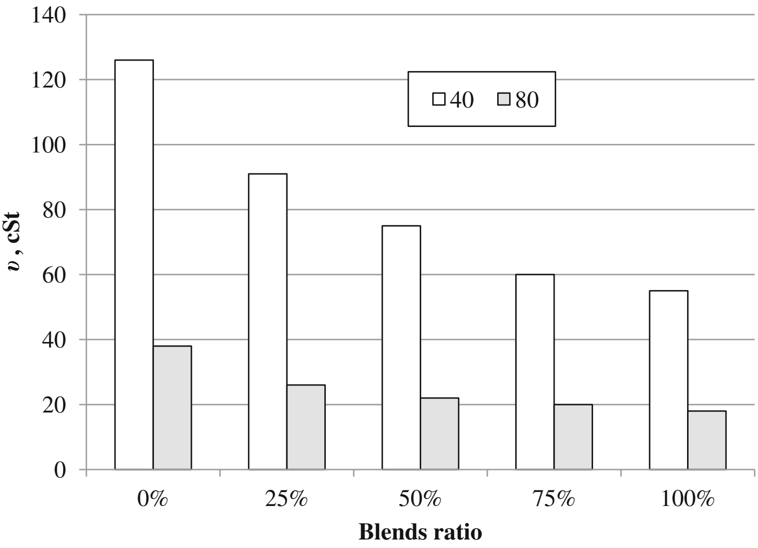

Fig. 3 Viscosity of the blends at 40 and 80 °C

Meanwhile, the drop in the viscosity of the pure waste cooking oil is about 600 %. This introduces promising results for waste cooking oil in term of stability and less sensitivity to the temperature compare to the synthetic fibers. Similar trend can be noticed in Fig. 2b.

It is well known that the determination of the oil application and performance is based on the viscosities at 40 and 80 °C. Therefore, the viscosities of the blends at those temperatures are extracted from Fig. 2 and represented in Fig. 3. It is obvious that the synthetic oil has higher viscosity values compared to its blends. Moreover, the increase in the addition of the waste cooking oil drops the viscosity of the blends for both selected temperatures as can be seen in Fig. 3.

From [75–77], the ISO viscosity grade requirements are listed in Table 4. For the current blends, it can be seen that the pure waste cooking can fit with the ISo VG 68 which can be used for crankcase oil Grades 20 W [78, 79]. However, further study is required to determine. However, further study is required to determine the degradability of the oil and the degradability of the oil and the tribological performance of the components under this lubrication condition.

Table 4 ISO viscosity grade requirement extracted from [75–77]

Kinematic viscosity	ISO VG32	ISO VG46	ISO VG68	ISO VG100	Pure waste cooking oil
@40 °C	>28.8	>41.4	>61.4	>90	65.5
@100 °C	>4.1	>4.1	>4.1	>4.1	9.5

Table 5 Compared with previous works and standards

	υ (cSt) at 40 °C	υ (cSt) 80 ° C
0	126	38
25	94	26
50	75	22
75	60	20
100	55	18
Original soybean [12]	≈175	≈29
Jatropha oil [81]	≈172	≈23
Soybean oil (SYO) [36, 45]	33.6 ± 0.9	12.3 ± 0.5
Sunflower oil (SO) [36, 45]	32.9 ± 2.3	12.7 ± 0.8
Castor oil (CO) [36, 45]	242.5 ± 21.7	37.1 ± 1.7
Castor seeds [55]	248.8	NA
Diluent (polyalphaolefin), and high-oleic vegetable oils [22]	42.33	
BIO-H01 is a mixture of 83.5 % high-oleic sunflower oil and 13.5 % ditridecyl adipate [80]	37.41	11.42
BIO-H02 blend of high-oleic sunflower oil at 73 and 24 % of diisooctyl adipate [80]	27.67	9.08

From the literature, some potential vegetable oils have been investigated to find the possibility of using them as lubricant. The most recent works are summarized in Table 5 showing the viscosity of vegetable oils at 40 and 80 °C. One can see that there are different ranges of viscosities for the oil and there is no pronounce comparable can be drawn. However, there could be comparable values for the pure waste cooking oil with soybean, [36, 45] and sunflower oil [36, 45], despite waste cooking oil exhibits better value of viscosity. In some work [80], modifier can be used to improve the viscosity performance of vegetable oil and this can be considered in the future work for waste cooking oil.

5 Conclusions

This work covers about 80 international articles published in the area of biolubricant aiming to address the most recent issues and explore the potential of suing waste cooking oil lubricant. Some important points can be drawn as conclusion from this work as follows:

1. There is a concern from environmental point of view to find alternative lubricants and an attention is paid by the researchers and vast work is focusing on the

possibility of using vegetable oils. It is highly recommended to use nonedible oils rather than edible oils.

2. There is an issue with disposing waste cooking oil. The potential of using it has been explored to be used as alternative fuel for diesel engines. However, there is a limitation of using the waste cooking oil as fuel since they highly impact on the engine performance from tribological point of view.
3. The potential of using waste cooking oil as alternative lubricant was investigated in the current study. From viscosity point of view, there is promising results to use such oil as lubricant. However, further study is recommended.

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