Chapter 11
Potential of Bio-lubricants in Automotive Tribology

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Abstract Lubricants are used as anti-friction and heat absorbing media and therefore lead to smooth and reliable functions/operations, and therefore reduces the risks of frequent failures and thus enhance the durability/life-cycle of vehicle. At present, due to worldwide concern in protecting the environment from pollution and the increased prices and depletion of reserve crude oil, there has been growing interest to formulate and apply an alternative solution with the research and development in environment-friendly bio-lubricants from natural resources. A bio-lubricant is renewable and sustainable lubricants which is biodegradable, non-toxic, and emits net zero greenhouse gas. This chapter deals the potential of vegetable oil-based bio-lubricant for automotive application. In this chapter, the source, properties, as well as advantages and disadvantages of the bio-lubricant has been detailed. Further, the future prospects and challenges of bio-lubricants as potential alternative of conventional lubricants has been elucidated.

Keywords Biolubricant · Automotive application · Tribology · Friction · Wear

11.1 Introduction

In recent years, researchers all around the world endeavored to make a product which is environment friendly, durable, reliable and effective for energy utilization in automotive applications (Singh et al. 2019). Innovation in technological resolutions such as introduction of material having light weight, fuels which are harmless, fuel combustion in controlled way, and more efficient gas at exhaust after treatment, are the possible ways to minimize the problems encountered to the environment through industrial machines and vehicles (Gerbig et al. 2004). During the combustion process

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in internal combustion (IC) engine, involvement of high temperature and pressure conditions, result in direct force to the engine components such as pistons, to move it by a certain distance, for achieving the mechanical energy by the transformation of chemical energy (Singer and Williams 1954). In every engineering equipment, the irregularities present in the surface of moving/working components result in the loss of material due to abrasion wear. The possible ways of minimizing the wear in the moving/working components are either by surface properties modification through surface engineering processes or by the application of lubricants (Panchal et al. 2017). At the desired operating conditions, the effective lubrication of moving components of an engine permits them to slide over other components smoothly, for the safe and reliable automobile operation. Reduction of friction and wear during the tribological interaction of automobile components helps in minimizing the energy losses (Mobarak et al. 2014).

The process employed for reducing the wear between the surfaces moving relative to each other is well known as lubrication. The major objectives of lubrication during any application are: (i) to minimize the wear of contacting surfaces moving relative to each other and along with reducing the wear it also helps in preventing the heat loss, (ii) to create the environment which helps surfaces to become corrosion free and oxidation resistant, (iii) to create the environment as an insulator for applications such as transformer applications, (iv) to create the shielding environment for the surfaces against the water, dust and dirt. Heat and wear both the terms are linked to the friction occurred between the moving surfaces and can be minimized up to the significant levels by minimizing the coefficient of friction between the moving surfaces with the application of lubricants found in the solid, liquid and gaseous form. Among all categories of available lubricants, the liquid, solid or semi-solid form of lubricants are most widely used forms in the various applications (Panchal et al. 2017; Ahmed and Nassar 2013; Iqbal 2014).

In an automobile application, at desired operational conditions the effective and efficient lubrication of working/moving parts is the mandatory requirement for safe as well as reliable operation of an automotive vehicle which results in reducing the wear and friction for drive-trains and engines (Singh et al. 2017a, 2019). The lubricants obtained by mineral oils has been extensively used in automotive applications for a very long time. Mineral oils are the byproduct of crude oil and is obtained by the distillation process but the use of mineral oils is limited due to the limited availability of reserves for crude oil. In addition to this, the disposing of mineral oils causes the pollution in the aquatic as well as in the terrestrial ecosystems especially the aquatic system (Ssempebwa and Carpenter 2009). Moreover, the use of mineral oils in engine combustion as a lubricant lead to degradation of environment by emitting the metal traces such as magnesium, phosphorous, zinc, iron nano-particles and calcium (Miller et al. 2007). Furthermore, the current as well as the future prospects of mineral oils in automotive engine applications as a lubricant were analyzed by Tung and McMillan (Tung and McMillan 2004) and they predicted it as bleak for future prospects. Therefore, there is a necessity for identifying the alternative resources to mineral oils which are suitable for use as lubricant in automotive engines (Singh et al. 2019).

The factors such as the limitation on availability of crude oil resources worldwide, the increasing prices of oil, and most importantly the necessity of environment protection against the pollution caused due to the use of lubricating oils focused the attention of researchers towards the development as well as use of alternative lubricants which can protect environment deterioration by replacing lubricating oils (Mobarak et al. 2014; Ruggiero et al. 2017). The certain physico-chemical properties of bio-based lubricant (Bio-lubricant) and their biodegradable properties has shown great potential to use bio-lubricant as an alternative lubricant to mineral oils for automotive application without causing any harm to the environment (Syahir et al. 2017). The bio-lubricant possesses the improved properties such as high flash point, high viscosity index, high lubricity and low evaporative losses in comparison to mineral oils (Asadauskas et al. 1996; Erhan and Asadauskas 2000; Jayadas et al. 2007; Alves et al. 2013; Nagendramma and Kaul 2012). The existence of polar groups and extended fatty-acid chain structure of plant-based oil-lubricant makes them suitable for hydrodynamic and boundary lubrication based automotive sector applications (Jayadas et al. 2007; Alves et al. 2013). The sources of plant-based oil-lubricants are the seeds containing oil and are available in different forms through-out worldwide (Nagendramma and Kaul 2012; Lathi and Mattiasson 2007). As per the available literature, worldwide about 350 distinct crops are identified with oil bearing properties (Mobarak et al. 2014; No 2011; Agarwal 2007). Edible and non-edible are two categories of plant-based oil resources (Mobarak et al. 2014). In the available literature, it is observed that non-edible plant-based oils are preferred to be employed as lubricant in automotive applications specifically in CI engines over the edible plant-based oil resources due to its effect on ecological systems by cultivating crops (Atabani et al. 2013; Adhvaryu et al. 2004). The sources of non-edible plant oils are jojoba, mongongo, polanga, neem, castor, Jatropha curcas, mahua, karanja, coriander and hingan (Singh and Singh 2010a; Singh et al. 2017b, 2018). In addition to this, the sources of inedible oil include Sapindus mukorossi, linseed oil, Acrocomia aculeata, nahor oil, Nicotiana tabacum, rubber seed oil, Crambe abyssinica, Sapium sebiferum, and Euphorbia tirucalli (Hasni et al. 2017). In available literature, most of the researchers reported use of plant-based oil as an engine fuel, only few researchers reported use of plant-based oils as lubricant in automotive applications (Mobarak et al. 2014).

The main aim of this chapter is to provide specific information to readers, industrialists, policy makers, researchers and engineers who are focused in bio-lubricant based studies in automotive tribology. This study presents the comprehensive review on potential use of bio-lubricants for automotive applications and this review includes the studies from the extremely observed publications and most recent available publications.

11.2 Lubrication and Lubricants

Lubrication is the process of imposing the lubricant between the contacting interfaces of moving or working components. Lubrication helps in, reducing the wear, friction, heat loss, oxidation, provides the corrosion prevention environment, provides the insulator environment, and also provides the protection of parts against moisture, dirt and dust (Panchal et al. 2017; Mobarak et al. 2014). A good lubricant must possess the properties such as its higher oxidation resistant environment, capability of providing corrosion prevention environment, lower value of freezing point, higher value of viscosity index, higher thermal stability, and higher boiling point values (Mobarak et al. 2014). Lubricants can be classified on the basis of physical appearance, resources of base oil and applications.

i. On the basis of physical appearance, the lubricants can be categorized as solid, semisolid and liquid lubricants: Manmade oils, animal oils, petroleum oils and vegetable oils all comes in the category of liquid lubricants; the solid lubricants are the lubricants which are composed of layers of organic and inorganic compound like cadmium di-sulphide, molybdenum di-sulphide, and graphite; the semisolid lubricants are the lubricants in which the liquid is floated in solid matrix of thickener as well as the additives like grease (Mobarak et al. 2014).
ii. On the basis of resources of base oil, the lubricants can be categorized as refined oil, natural oil (also known as natural esters) and synthetic oil (also known as synthetic esters): oil extracted from the petroleum as well as crude oil reserves are comes under the category of refined oils like aromatic, naphthenic and paraffinic oils; oil which is the outcome of crop driven as well as the animal driven is comes under the category of natural oils; oil which is the outcome of the end product of reactions as per the requirement comes under the category of synthetic oils and the examples are polyalphaolefines, synthetic esters, diesters, silicones, polyglycols, ionic liquids, perfluoroalkylethers, genetically modified organisms or any other man-made lubricant comprising chemical compounds (Mobarak et al. 2014; Reeves et al. 2017).
iii. On the basis of applications, the lubricants can be categorized as automotive oils, industrial oils and special oils: oil used in transportation and automobile sector comes under the category of automotive oils like hydraulic as well as brake fluids, gear box oils, transmission oils and engine oils; oil used for industrial purpose comes under the category of industrial oils like hydraulic oils, metal working fluid, compressor oils and machine oils; oil used for specific operation with special purpose comes under the category of special oils like instrumental oils white oils and process oils (Mobarak et al. 2014).

11.3 Bio-lubricants

The lubricants which are having the constituents or base which is based on bio-based raw materials like animal fat, vegetable oils or any other environmentally benign hydrocarbons is termed to be bio-lubricant (Reeves et al. 2017). Biodegradability and non-toxicity of bio-lubricants to the human beings and to the other living organisms is mainly due to its base constituents (Salimon et al. 2010). Globally, the demand of bio-lubricants is rising due to its environmentally friendliness factor and the economic factors such as prevention of toxic substances to the environment; depletion of reservoirs of crude oil; hike in the prices of crude oil and the strict regulations

Table 11.1 Statics of oil-content in some non-edible and edible oil species (Reeves et al. 2017; Usta et al. 2011; Singh and Singh 2010b; Mofijur et al. 2012; Wang et al. 2012; Li et al. 2012; Kumar and Sharma 2011; Sharma and Singh 2010; Karaosmanoglu et al. 1999; Wang et al. 2011)

S. No.	Non-edible species	Oil content (% of volume)	Edible species	Oil content (% of volume)
1.	Moringa	20–36	Coconut	63–65
2.	Linseed	35–45	Corn	48
3.	Mahua	35–50	Olive	45–70
4.	Castor	45–60	Peanut	45–55
5.	Karanja	30–50	Palm	30–60b
6.	Neem	30–50	Rapeseed	38–46
7.	Jatropha	40–60	–	–
8.	Desert date	37–48	–	–
9.	Niger	43–50	–	–

of government from time to time for the operation, use and disposal of petroleum based oils (Deffeyes 2008; Goodstein 2005). In current scenario, the potential of bio-lubricants in automobile sector makes them the best economical alternative to the traditional petroleum-based lubricants.

Production of bio-lubricants is necessary for alternative energy applications due to their numerous worldwide source availability. While looking from country to country the type of feedstock for bio-lubricants may differ due to the different geographical locations. In the literature, it is reported that number of oil-bearing crops are known to be more than 350 among which only peanut oil, cottonseed, rapeseed, safflower, coconut, sunflower, soybean, and palm oils are considered as alternative lubricants which have the potential (Mobarak et al. 2014). Oil content statics of some edible and non-edible seeds are shown in Table 11.1 (Usta et al. 2011; Singh and Singh 2010b; Mofijur et al. 2012; Wang et al. 2012; Li et al. 2012; Kumar and Sharma 2011; Sharma and Singh 2010; Karaosmanoglu et al. 1999; Wang et al. 2011). Oil extracted from non-edible seeds such as karanja, neem and jatropha has received the interest worldwide (Mofijur et al. 2012).

11.3.1 Bio-lubricant Properties

Bio-lubricants driven by vegetable oils reveals the suitable properties (Willing 2001). Bio-lubricants possesses various practically preferable capabilities relative to the petroleum driven lubricants (Munoz et al. 2012) or in other words we can say that bio-lubricants possesses many useful and valuable physicochemical properties. Bio-lubricants have high viscosity index, elevated lubricity, high flash point and evaporative conditions which are minimum (Raj and Sahayaraj 2010; Usta et al. 2011; Willing 2001; Asadauskas et al. 1996; Erhan and Perez 2002; Munoz et al. 2012; Das

Table 11.2 Comparative study of properties of vegetable and mineral oils (Mobarak et al. 2014; Johnson and Miller 2010)

Properties	Vegetable oils	Mineral oils
Viscosity index (VI)	100–200	100
Pour point, 1 °C	−20 to +10	−15
Miscibility with mineral oils	Good	–
Density @20 °C (kg/m^3)	890–970 (kg/m^3)	840–920 (kg/m^3)
Flash point	Higher	Lower
Fire point	Higher	Lower
Hydrolytic stability	Poor	Good
Cold flow behavior	Poor	Good
Oxidation stability	Moderate	Good
Biodegradability (%)	80–100 (%)	10–30 (%)
Sludge forming tendency	Poor	Good
Seal swelling tendency	Slight	Slight
Shear stability	Good	Good
Solubility in water	Non-miscible	Non-miscible
Specific gravity	More	Less

et al. 2012). Overall vegetable oil-based lubricants possess exhibits the superior properties than the mineral oil-based lubricants. Table 11.2 represents the comparative analysis of properties of vegetable oil and mineral oil-based lubricants.

11.3.1.1 Viscosity

The most important property of oils is Viscosity which indicates the resistance to the flow. The higher value of viscosity indicates the higher resistance to flow while the lower value indicates the lower resistance to flow. Viscosity of oils directly dependent on pressure, temperature and formation of film (Mobarak et al. 2014).

11.3.1.2 Viscosity Index (VI)

VI represents the measure in change of viscosity with the variation of temperature. The higher value of VI represents the lower variation in the temperature while the lower value of VI indicates the higher variation in temperature. This is the most important property of bio-lubricants which ensures bio-lubricant to be more effective at higher temperature ranges by maintaining the thickness of oil film to be thick when compared with the mineral oils. This property of bio-lubricants makes them most suitable lubricants for wide variety of temperature ranges (Mobarak et al. 2014).

11.3.1.3 Pour point

The lowest temperature at which oil start to flow or pours is known to be the pour point of oils. This is one of the most important property of lubricants. The vegetable-based oils are having the low value of pour point while comparing with the mineral oils, which enables bio-lubricants as excellent lubricants for cold start applications (Mobarak et al. 2014).

11.3.1.4 Flash Point and Fire Point

The minimum temperature at which lubricant must be heated before its vaporization is known as the flash point of the lubricant. While mixing of air with lubricant enables it to ignite but not to burn. Fire point is the temperature at which the combustion of lubricant continues. Lubricants volatility and fire resistance properties are identified on the basis of its flash point and fire point. These two factors play vital role during the transportation of lubricants. The bio-lubricants generally have the higher value of flash point in comparison to mineral oils which reduces the risk of fire due to the leaked lubricant and provides the safety on shop floors (Mobarak et al. 2014).

11.3.1.5 Cloud Point

The temperature at which solid dissolves in oil is known as the cloud point. While dropping of the temperature wax is crystallized and became visible. The prevention of filter clogging can be ensured by maintaining the temperature above the cloud point (Mobarak et al. 2014).

11.3.1.6 Acid or Neutralization Number

The amount of base content or acid required by a lubricant for neutralization can be termed as neutralization number or acid number (Mobarak et al. 2014).

11.3.1.7 Oxidation Stability

Ability of lubricant to resist the oxidation forming tendency is known as oxidation stability. With the rise of the temperature oxidation stability of lubricant increases. The noteworthy contributors to oxidation comprise agitation, pressure, contaminants, temperature, metal surfaces and water. The lower value of oxidation stability shows that the oxidation of oil take place rapidly during the use if it is untreated, becomes thick and polymerizes to a plastic-like consistency (Mobarak et al. 2014).

11.3.1.8 Rust and Corrosion Prevention

Chemical reaction between ferrous metals and water is known as rust while the chemical reaction between metals and chemicals is known as corrosion. Bio-lubricants are non-toxic in nature and does not react with ferrous metals, water and chemicals when comparing with the mineral oils (Mobarak et al. 2014).

11.3.1.9 Anti-wear Properties

Vegetable oil-based bio-lubricants indicates the improved anti-wear properties than mineral oils. At low pressure and low speed applications lubricants performs satisfactorily. In case of boundary lubrication, when the oil viscosity is not sufficient to provide the surface contact prevention, the inclusion of additives with anti-wear property provides the defensive film at surfaces on contact to minimize the wear (Mobarak et al. 2014).

11.3.1.10 Hydrolytic Stability

The ability of lubricant to offer the resistance to cleavage or attack of water molecule or vapor of water is known as the hydrostatic stability. This property of a lubricant strongly depends on the synthetic ester and the fatty acid ester structure of bio-based fluids due to the reason that the chemical reaction for these molecules is an equilibrium reaction. In hydrolysis process the bio-based fluids cleave into their acid and alcohol components and influences the ester bond directly. This is known to be hydrolytic splitting process which takes place until the restoration of chemical equilibrium (Totten et al. 2019). Chemical structure is the key factor which influences the hydrostatic stability of an ester. Bio-lubricants have the high degree of hydrostatic stability which are derived from saturated esters with straight chain components in comparison to the branched or unsaturated esters.

11.3.2 Biodegradability

Now a days, the industries as well as the automotive sectors are moving towards the use of green lubricants, which prerequisites the two major properties to be within the bio-lubricants: (i) highly biodegradable and (ii) lower ecotoxicity. The major advantage involved with the use of bio-lubricant is their inherent biodegradable property and the lower toxicity towards the environment. The chemical dissolution process through which the organic materials/substances are broken down with the help of enzymes originated from the living organisms is known as the biodegradation process. In other words, we can say that the bio-lubricants based on raw materials which are renewable and derived from H_2O and CO_2 via. process of photosynthesis,

Table 11.3 Biodegradability of some bio-lubricants base stocks (Singh et al. 2019)

Base-stock types	Bio-degradability range (% loss at 21 days)
Non-edible vegetable oils	70–100
Diesters	55–95
Polyethylene glycols	10–75
Polyols	5–95
Aromatic esters	0–90
Alkyl benzenes	5–20
Mineral oils	15–75

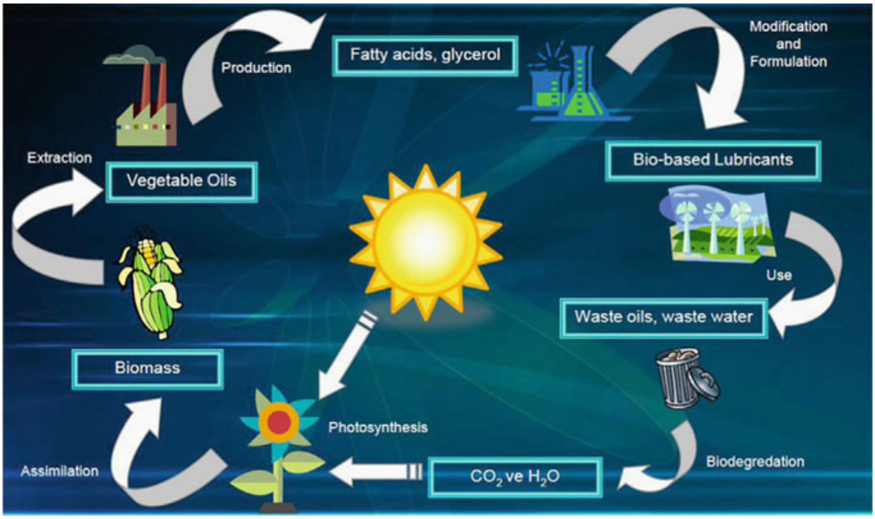

Fig. 11.1 Life cycle of bio-based lubricants (Mobarak et al. 2014). Copyright (2014) Elsevier Ltd

after the application, at the end returns to environment in the form of H_2O and CO_2 by the process of biodegradation (Johansson and Lundin 1979). Table 11.3 represents the bio-degradability of some bio-lubricant base stocks (Singh et al. 2019). Figure 11.1 shows the life cycle of the bio-lubricants.

11.3.3 Merits and Demerits of Bio-lubricant

Bio-lubricants can be used in their natural form as a lubricant. They have various merits and demerits while considered for industrial, automotive and any other applications.

Table 11.4 Benefits of bio-lubricants (Mobarak et al. 2014)

Higher viscosity index	Wide range of temperature
Higher boiling temperatures	Lower emissions
Lower volatility	Decreased exhaust emissions
Higher lubricity	Lower friction losses, better fuel economy
Higher flashpoints	Higher safety on shop floor
Higher detergency	Eliminating the requirement of detergent additives
Oil-mist and oil-vapor reduction	Helps in preventing the oil-mist into lungs during breathing
Rapid biodegradation	Reduced toxicological and environmental hazards
Better skin compatibility	High cleanliness and less dermatological at worplace

The merits of bio-lubricants that they have an excellent lubricity while comparing with the mineral oils and they have high viscosity index, high flash point. The properties such as biodegradability, less-toxic nature and renewable nature makes them more attractive for industrial and automotive applications. The increased viscosity also helps in reducing the operational temperature which contributes in saving the energy for automotive applications. The above-mentioned properties make it as the better alternative for industrial and automotive applications as compared to the petroleum-based oils. Benefits of few bio-lubricants are shown in Table 11.4.

The negative side of bio-lubricants is its low oxidation stability which requires the treatment of bio-lubricant before the use for better performance. Bio-lubricants are having the low temperature limitations such as its unpleasant smell, lower compatibility with sealants and paints, filter clogging tendency and flushing propensity due to the low viscosity.

11.3.4 Bio-lubricants in Automotive Tribology

The best alternative available to the mineral oil-based lubricant is the bio-based lubricants in industrial as well as in the automotive sector due to the excellent inherent qualities of bio-lubricants. The advantages involved with the use of bio-lubricants are their environmentally friendliness property towards the sensitive environments which helps in the preventing the pollution. Now a days, bio-lubricants applications can be seen in the industrial as well as in the automobile sector. The most important applications of bio-lubricants are: automotive oils like engine oils, gear box oils, transmission fluids, brake and hydraulic fluids; industrial oils such as machine oils, hydraulic fluids, metal working fluids, compressor fluids; and special oils like instrumental oils, white oils and process oils. Figure 11.2 shows the major benefits involved with the application of bio-lubricants (Mobarak et al. 2014) whereas

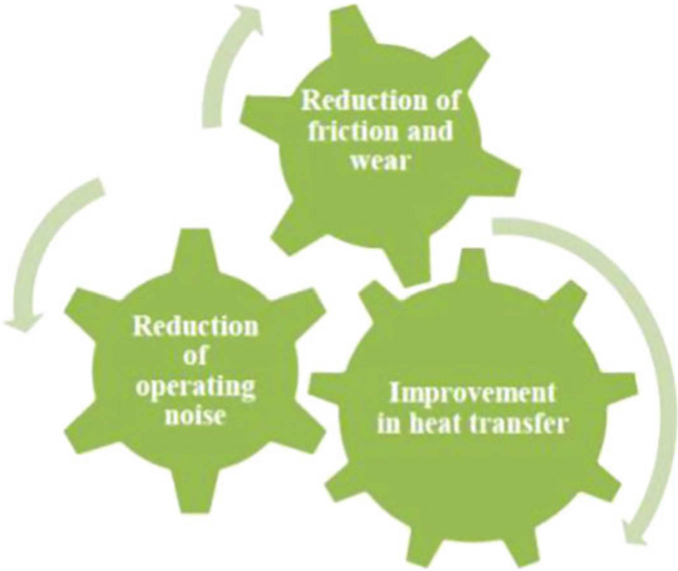

Fig. 11.2 Major benefits involved with the application of bio-lubricants in an industry (Mobarak et al. 2014). Copyright (2014) Elsevier Ltd

Fig. 11.3 shows the wide areas of application of bio-lubricant in automotive sectors (Mobarak et al. 2014). These oils fruitfully take the place of mineral oils as compressor oils, hydraulic oils, engine oils, aviation oils, metal working oils, insulating oils, general/multi-purpose oils, grease and lubricants for tractors, gears, pump sets generators etc. Table 11.5 shows the work done by various researchers on vegetable oil-based bio-lubricant in different applications.

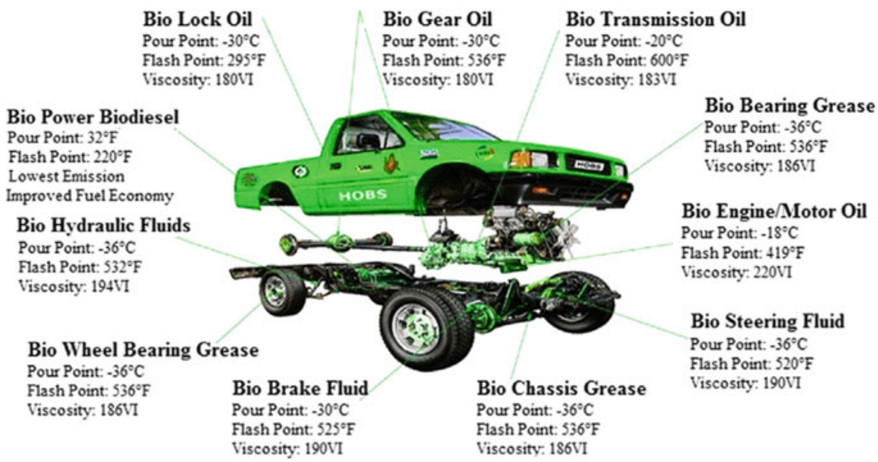

Fig. 11.3 Requirements of lubrication for a pick-up truck in an automotive sector (Mobarak et al. 2014). Copyright (2014) Elsevier Ltd

Table 11.5 Previous research summary by researchers on vegetable oil-based bio-lubricant (Singh et al. 2019; Mobarak et al. 2014)

Bio-lubricants	Lubricant taken for reference	Testing method/condition	Result	Reference
Palm oil	SAE20W50	High-frequency reciprocating test rig (ball-on-flat) steel–steel pair contacts	Stronger lubricant film stability Unsaturated hydrocarbon chain reactivity Better anti-corrosion and oxidation properties Lower friction coefficient Low corrosive nature	Haseeb et al. (2010), Lebedevas et al. (2013), Fazal et al. (2011, 2012), Sulek et al. (2010), Anastopoulos et al. (2001), Maleque et al. (2000), Maleque (1997)
Coconut oil	SAE20W50	4-ball tester	Enhanced lubricity properties Higher anti-wear properties Lower friction coefficient	Jayadas et al. (2007)
Waste palm oil	SAE40	4-ball tribo-testing unit with standard method of testing	Viscosity is higher Lower friction coefficient	Kalam et al. (2011)
Vegetable oils (sunflower, mahua, olive, castor, coconut, palm, soybean, karanja, neem, jatropha etc.)	Mineral oils (petroleum based)	Various tribo-testers with standard method of testing	Eco-friendly and cheaper Less expensive Better performance Minimum evaporative losses Enhanced lubricity properties High viscosity and flash point	Singh (2011), Singh et al. (2011, 2014), Singh and Chamoli (2013), Thames and Yu (1999), Suhane et al. (2012), Ting and Chen (2011), Chauhan and Chibber (2013)
Castor oil	Mineral oil (super refined)	4-ball wear testing unit	Antioxidant concentration is higher Low volatility Lower deposit formation tendency Higher viscosity index	Singh et al. (2010)

(continued)

Table 11.5 (continued)

Bio-lubricants	Lubricant taken for reference	Testing method/condition	Result	Reference
Soybean oil	Mineral oils (petroleum based)	4-ball tribo-testing unit	Eco-friendly and cheaper Non-toxic Enhanced lubricity properties Lower friction coefficient	Asadauskas et al. (1997), Adhvaryu et al. (2005)
TMP ester (palm oil based)	SAE40	High-frequency reciprocating machine	Better wear preventing characteristics in terms of wear-scar diameter and friction coefficient	Erhan et al. (2006)
Palm oil and castor oil	SAE20W40	Pin-on-disc machine	Lower friction coefficient, force of friction and wear Enhanced lubricity properties Lower volatility Eco-friendly, renewable and biodegradable	Zulkifli et al. (2013), Arumugum and Sriram (2012)
Pongamia oil	SAE20W40	Pin-on-disc machine	At all applied loads minimum degradation of lubricant Lower surface wear	Singh et al. (2017b, 2018)
Mongongo oil	SAE20W40	4-ball wear testing unit	Lower deposit forming tendencies Higher viscosity index Lower friction coefficient	Singh et al. (2017b, 2018)
Pongamia oil	SAE20W40	4-stroke, single-cylinder, water-cooled, direct-injection, compression ignition engine	Completely eliminate emission Improved efficiency Frictional losses lower Highest BTE and minimum BSEC at high and medium load conditions	Maleque et al. (1998), Bekal and Bhat (2012)

(continued)

Table 11.5 (continued)

Bio-lubricants	Lubricant taken for reference	Testing method/condition	Result	Reference
Jatropha oil	SAE20W40	Pin-on-disc machine	Lower friction coefficient Chemically modified Lower cumulative weight loss Lower wear loss	Bekal and Bhat (2012)
Rapeseed oil (bio-lubricant)	SAE20W40	High-frequency reciprocating machine	Good performance in terms of friction coefficient and force of friction Better cold flow characteristics Better oxidative stability	Jaina and Suhanea (2013)
Commercial soybean oil	synthetic lubricant	High-frequency reciprocating machine	Viscosity extremely large	Arumugum and Sriram (2013)
Cottonseed oil	SAE 40	Pin-on-disc machine	Biodegradable and eco-friendly Lower friction coefficient Enhanced lubricity properties Low wear at high speeds	Agrawal et al. (2014)

11.4 Conclusion

The bio-lubricants based on non-edible oils are biodegradable and eco-friendly. Biodegradability of bio-lubricant makes them most suitable lubricant alternative for the automotive sector applications. Alternative to mineral oil-based lubricants in the form of bio-based lubricants in an automobile sector offers a reasonable solution for obtaining the renewable and environment friendly lubricants with respect to the environmental concern. The non-edible oil-based bio-lubricants are the potential contender for the automotive sector applications. Their inherent characteristics of bio-lubricants such as increased equipment service life, elevated lubricity, high ignition temperature, viscosity, good anti-wear property, high load carrying ability, elevated viscosity index, lower emission of metal trace to atmosphere, higher biodegradability, excellent coefficient of friction and lower evaporation rates makes them better alternative to the mineral-oil based lubricants. But in current scenario, bio-lubricants have not substituted the petroleum-based lubricants completely due to the inappropriate chemical configuration of bio-lubricants, which does not allow them to use in different odd situations. The problems researchers facing in this area is to improve certain characteristics of vegetable oils without damaging the environmentally as well as the tribologically significant properties. Chemical alteration can help to change the chemical configuration of vegetable-oil to make them suitable for automotive sector applications. This area needs to be focused by the researchers to find the solution to the problems associated with non-edible oil-based lubricants to be used as bio-lubricant. This work only explores the potential of bio-lubricants as an alternative to mineral oil-based lubricants in the automotive tribological applications.

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