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Potential Vegetable Oil-based Lubricants: A Review

Steven Odi-Owei, John Ameh, Sylvanus Alibi, Akobuche Chikezie
Department of Mechanical Engineering, Rivers State University, Nkpolu-Oroworukwo, Port Harcourt, Rivers State, Nigeria
([1]steveodiowei252@gmail.com, [2]Ikowad@yahoo.com, [3]linksylvanus01@yahoo.com, [4]chikezieakobuche@yahoo.com

ABSTRACT

A comprehensive review of the research in vegetable oil-based lubricants and their applications was carried out in this study. The materials used in this review were from 38 research publications on vegetable oil-based lubricants as environmental friendly alternatives to petroleum-based lubricants. The methods used for gathering the materials were searched through the databases of publishers such as Google Scholar, Reseachgate, Sciencedirect, and multiple search engines. This was followed by sorting out the relevant ones for detailed review. The review showed research results on oils from various vegetable seeds, namely, groundnut, avocado, jatropha, water melon, star apple, sand box, nicker nut, Barbados nut, mango, black date, yellow oleander, calabash, castor, palm fruit syrup, neem, palm, mustard, cotton, soyabean, jojoba, olive, melon coconut, shea butter, palm kernel, african bean, and african elemi. The research areas were mainly on analysis of their physicochemical properties, experimental investigation of their tribological performance, and their industrial application. It is expected that the outcome of this review would constitute a repository of knowledge on the potentials in vegetable-based lubricants, particularly in their friction and wear behaviour.

KEYWORDS: Vegetable oil, Lubricant, Friction, Wear, Physicochemical.

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1. INTRODUCTION

The need for lubrication has existed over the centuries. Scientists and engineers have sought for means to meet this need at various times in the past even to the present day. The use of bio-based lubricants derived from natural fats and oils of animals and plants on axles of chariots and on the rolling building stones were common during the Egyptian and Roman era. Vegetable oil-based lubricants are derived from plant seed oils. Castor seed oil was a major vegetable oil used as standard lubricating oil alongside animal fats before petroleum-based oil gradually started taking over by 1890 (Kerley, 1981). It is the long chain fatty acid structures in vegetable oil that influences its lubricity (Adhvaryu *et al*., 2005; Syahir *et al*., 2017). Jakab (2002) reported that triacylglycerols, the main compound in vegetable oil, constitutes 95-98% of this property. The common fatty acid constituents in triacylglycerol compound oils are palmitic, stearic, oleic, linoleic and linolenic acids. These 5 moieties combine in different ways to form different types of triacylglycerol. This means that one type of triacylglycerol may not contain all these 5 moieties in its form. Minor compounds in vegetable oils, constituting 2-5% are tocopherols, carotenoids, wax esters, tocotrienols and hydrocarbon.

Vegetable oil-based lubricants are 90-98 percent biodegradable and hence, environmentally friendly, compared to petroleum-based lubricants, which are hazardous and contaminate the environment. Depletion of petroleum reserves is a major challenge to the world and hence, an alternative source of energy is required. However, the main limitation of vegetable oil is its susceptibility to thermal degradation and low oxidative stability (Thottackkad *et al*., 2012). This limitation can be reduced by the treatment with anti-oxidant as additives to the base stock or by chemical modification of the oil (Shafi *et al*., 2018). Anti-oxidant compounds interrupt the process of oxidation of vegetable oil by preferentially associating with the radicals in the fat to form another stable radical which has very slow or little reaction with oxygen or moisture (Aluyor & Ori-Jesu, 2008).

The key physicochemical properties of vegetable oils that influence their tribological performance are viscosity, free fatty acid, relative density, saponification number, acid value, peroxide value, iodine value, pH value, refractive index, pour point, flash point, etc. These properties or a combination of these properties at the right levels enable the vegetable oils to perform their primary lubrication functions of reduction of friction and wear of tribo-pairs, heat removal, transmission of power and corrosion prevention. The oils should also be able to exist as liquid under varying temperatures while performing these functions. The physicochemical properties of vegetable oil-based stock can be modified chemically or by the introduction of additives to improve their performance; the base stock provides viscosity for the control of wear and friction between surfaces in tribological contacts (Odi-Owei *et al.*, 1987; Moser *et al.*, 2011).

Even though vegetable oils have been shown to have good lubricating qualities, there has been no strong proof to date which attests to their wide applications at a large scale industrial level based on the previous laboratory tests. Hence, there is a need for more research in vegetable oil-based lubricants to overcome any existing deficiencies and improve their areas of application. This study is aimed at reviewing, comprehensively, the research in vegetable oil-based lubricants and their applications by engineers and scientists The outcome of this review is expected to constitute a repository of knowledge in related research, particularly in their friction and wear behaviour.

2. MATERIALS AND METHODS

The materials used for this study are the research publications by scientists and engineers in the universities, research institutions, public and private organizations across the nations. The methods used for gathering the materials were in stages. The first stage was to search through the databases of publishers such as Google Scholar, Reseachgate, Sciencedirect, and other multiple search engines. The second stage involve sorting out the materials into these related groups of studies; analysis of the physicochemical properties, investigation of triboogical performance, and the areas of application of the vegetable oils. The oil types cut across each of this grouping. The third and final stage was the review proper under “Results and Discussion”.

3. RESULTS AND DISCUSSION

Different types of vegetable oils were involved in this review. The review was grouped into the analysis of vegetable oil-based lubricant molecular structures, the physicochemical properties, investigation of the tribological performance, and the areas of applications of the vegetable oils as shown in Sections 3.1 to 3.3.

3.1 Molecular Components and Structures of Vegetable Oils

Fatty acid compositions in vegetable oils play major roles in their tribological performances. These performance results are supported by related research by Murakami & Sakamoto (2003), who confirmed the lubrication effectiveness of fatty acid, especially, linolenic acid, as the most effective at increased temperature. Anastopoulos *et al.* (2017) asserted that increasing the concentration of fatty acid, especially saturated fatty acid additives in marine gas oil, increased the lubricity of the gas oil. Odi-Owei (1989) concluded that the anti-wear performance of fatty acid (lauric acid) was comparable to that of the reference oil (HD90). Martin *et al.* (2013) tested and confirmed that both saturated fatty acid (stearic acid) and unsaturated fatty acids (oleic, linoleic and linolenic acids) effected reduction of friction between steel-steel contact pair. The result was also collaborated by Porcayo-Calderon *et al.* (2015), who demonstrated that the unsaturation present in fatty acid contributed to its corrosion inhibition ability by adsorption on the metal surface to form a monolayer of protective oxides. The type and molecular structures of fatty acids; saturated or unsaturated, long chain or short chain, linear or branched chain, polar group at the end or at other points, etc., play influencing roles in their lubricity. Table 1 shows a typical fatty acid analysis of oils of castor seed, coconut seed, melon seed, mango seed and commercial engine oil (SAE20W50).

Table 1 Fatty Acid Analysis of Oils of Castor Seed, Coconut Seed, Melon Seed, Mango Seed and Engine oil (SAE20W50)

	Castor seed oil		Coconut kernel oil		Melon seed oil		Mango kernel oil		SAE20W50	
Fatty Acid [%]	Saturated	Unsaturated	Saturated	Unsaturated	Saturated	Unsaturated	Saturated	Unsaturated	Saturated	Unsaturated
Caproic acid	3		8.53		2.86				2.85	
Myristic acid	0.3		12.99		14.01		0.08		4.67	
Myristoleic acid		0.2		9.24		0.06		0.02		0.16
Palmitic acid	1.81		56		2.37		2.7		0.28	
Palmitoleic acid		0.04		0.02		0.27		0.22		0.28
Stearic acid	5.01		2.72		20.46		25.4		3.2	
Oleic acid		0.13				0.23		0.23		3.13
Linoleic acid		0.01		0.29		0.12		0.14		2
Y-linolenic acid		20.89		2.6		51.71		0.28		6.17
Arachidic acid	0.13								9.32	
Paullinic acid		0.01				0.07		66.94		3.94
Eicosadienoic acid		0.02				0.42		0.26		2.96
Dihomo-y-linolenic acid		18.73		2.02		6.64		0.02		6.37
Arachidonic acid		0.02		0.16		0.45		0.32		21.85
Behenic acid	23.71		3.98		0.06		3.05		11.8	
Erucic acid		25.54				0.17		0.04		15.02
Cervonic acid				0.33				0.04		3.24
Lignoceric acid	0.03		0.37		0.11		0.16		1.5	
Nervonic acid				0.75				0.1		1.26
Total Saturated	**33.99**		**84.59**		**39.87**		**31.39**		**33.62**	
Total Unsaturated		**65.59**		**15.41**		**60.14**		**68.61**		**66.38**

3.2 Physicochemical Properties

The physicochemical properties of vegetable oils play important roles in their tribological behaviour. The vegetable oil-based stock provides viscosity for low friction and wear (Odi-Owei *et al*., 1987), controls oxidation, corrosion and provides sufficient surface for the transfer of heat. Some of the other desirable physicochemical properties of vegetable oils are shown in Table 2.

Table 2 Physicochemical Properties of Some Vegetable Oils

Constituents	Jatropha	Castor	Watermelon	Mango	Olive	Jojoba	Calabash seed oil
Acid value		2.24	-	40.33	-	-	-
Specific Gravity	0.91	-	-	-	-	-	-
Free Fatty acid (mgKOH/g)	29.06	1.12	1.55	20.16	-	-	1.55
Saponification Value mgKOH/g	209	64.52	-	179.52	-	-	-
Relative density			-	0.9	-	-	-
Viscosity 40^0C (cSt)	55.22	-	38.60	99.09	24.94	39.10	53
Viscosity 100^0C (cSt)		-	7.90	-	6.67	8.43	9.30
Viscosity index	195.22	-	146	-	238	200	167
Pour point (^{o}C)	7	-	12	-	-	-	28
Cloud point (^{0}C)	-8	-	-	-	-	-	
Flash point (^{0}C)	178	-	162	-	-	-	240
Peroxide value (mg/g)	5.98	0.60	-	0.47	-	-	-
Corrosion value	0	-	-	-	-	-	-

Bilal *et al*. (2013), Ameh *et al* (2021), Menkiti *et al*. (2017), Woma *et al*. (2019), Owuna *et al*. (2018), Ossia, *et al*. (2010), Odi-Owei *et al*. (2021)

Woma *et al*. (2019) investigated the suitability of jatropha oil as base stock for lubricant production. The physicochemical, rheological, temperature, thermo-oxidative stability and the corrosion properties of jatropha oil were studied and reported in Table 2. These properties of the vegetable oil were compared with those of SAE 20W50 commercial lubricant. It was concluded that the Jatropha oil has a better viscosity index compared to the SAE 20W50, whereas the SAE 20W50 is better than the Jatropha oil in other measured properties.

Jayeoye *et al*. (2014) extracted oil from the following oilseeds; tamanu, watermelon, star apple, sandbox, nicker nut, barbados nut and mango for application as potential cutting fluids in turning operation. The physicochemical parameters and biodegradability of the extracts were assessed. Further research on watermelon seed oil was carried out by Odi-Owei *et al*. (2021). Table 2 presents the range of the various physicochemical properties of the vegetable oils that were analyzed.

Awoyale (2011) used the solvent extraction method to extract oil from the black-date seed. The mixture of the extracted base oil, calcium hydroxide thickener, stearic acid and additives was hydrolysed to form solid grease. The grease produced was tested to determine its biodegradability. Other tests carried out were the grease's workability and dropping point following the ASTM D217-IP50 standard. Oando conventional grease was used as control. The Biochemical Oxygen Demand (BOD) test result was within the acceptable range.

Owuna *et al*. (2018) formulated a lubricant using calabash seed oil. An experimental design using the mixture design method in Minitab 17 was used in the formulation of the oil. The calabash seed oil was 28.75%, signal to noise ratio was 500 (68.75%), and the additive was 2.50% to enable the production of lubricant with improved physicochemical parameters. It was concluded that the blend of lubricant obtained in the research had quality parameters that are comparable to those of synthesized engine oils, and are within the standards for engine oils.

Menkiti *et al*. (2017) transesterified jatropha oil into jatropha methyl ester with trimethylolpropane (TMP) using a calcium hydroxide catalyst. The gas chromatography, Fourier transforms infrared spectroscopy, and ASTM standards were used to examine the physicochemical properties. Table 1 presents the physicochemical properties of the oil. It was concluded that the jatropha bio-lubricant properties followed the International Standards Organization Viscosity Grade (ISO VG 32) and could be used as a lubricating base oil.

3.3 Tribological Performance of Vegetable Oil-Based Lubricant

The real contact points between two surfaces in motion are the asperities, consisting of protuberances upon protuberances (Greenwood & Wu, 2002). The ploughing force of the asperities of the harder surface ploughs into the softer surface while the adhesive force shears the contact points. The product of the sheared softer surfaces is the wear of the material while the resistance to the sharing force is the friction. A typical measure of the friction performance of castor seed and mango seed oils compared with commercial engine oil (SAE 20W50) is shown in Figure 3.1.

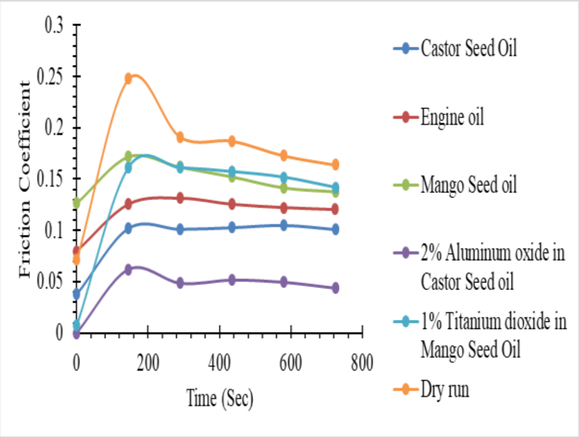

Figure 1: Friction Coefficient Against Time for Mango and Castor Seed Oils (Ameh, *et al*., 2021)

Chikezie *et al*. (2021) modified avocado seed oil and palm oil with the organic additives of mustard seed and ginger extracts. The adsorption of these oils on AISI 8620 steel surfaces was investigated under elevated conditions (120 - 300 N) at 35 °C. The Gibbs adsorption values of the modified oils were measured. It was concluded that the palm oil lubricant in the unmodified state performed better than the avocado seed oil, while the avocado seed oil in the modified states presented better adsorption phenomena on steel surfaces than the modified palm oil.

Olorunnishola and Anjorin (2015) studied the effects of seed oils on wear using a pin-on-disc experimental set-up. Parameters investigated were loading, sliding speed, sliding duration under lubricating oils of castor, cotton, soya, palm, groundnut, and mineral oil (SAE 20W/50). The results showed that the volume of wear increased with the load. It was observed that the groundnut, soya, cotton, and palm oils lubricated discs showed higher rates of wear compared to the mineral oil and the castor oil.

Odi-Owei (1989) investigated some fats and vegetable oils to determine their extreme pressure, fatigue resistance and anti-wear properties. A four-ball, and ball-cylinder sliding test set-ups were used. Groundnut oil, coconut oil, soya bean oil, hydrogenated palm oil fats and reference petroleum oil-based lubricant (HD90) were all tested. The results obtained showed that coconut oil and groundnut oil performed better in fatigue endurance test than the reference mineral oil. The anti-wear characteristics of the palm oil distilled fatty acid was comparable to that of the reference oil. Hydrogenated fats of palm oil and soya bean had superior anti-wear properties compared to that of reference oil. Fats had better extreme pressure properties than HD 90 mineral oil while vegetable oil had inferior values.

Ameh *et al*. (2021) investigated the effects of mango seed oil and castor seed oil-based lubricants on friction and wear performance of steel-steel surface contacts. The oils were extracted using the Soxhlet extraction method. The pure oils were blended with nanoparticle of copper II oxide, aluminum oxide and titanium dioxide. A pin-on-disc apparatus was used for the friction and wear performance tests. The coefficient of friction of pure mango seed oil and castor seed oil improved by 21%, and 41%, respectively due to the addition of the nanoparticles. These blends performed well compared to the control engine oil (SAE20W50). The wear test results indicated that pure mango seed oil and pure castor seed oil, and 1% titanium dioxide nanoparticle in mango seed oil have 23%,7% and 36% better total wear performance than the reference commercial engine oil (SAE20W50), respectively.

Odi-Owei *et al*. (2021) investigated the tribological response of the watermelon seed oil in the friction and wear simulation on an AISI 1045 steel disc in contact with an AISI 52100 steel ball on a tribometer. The steel surface with the watermelon seed oil had a lower friction coefficient and wear rate compared to the steel surface that was lubricated with the mineral oil. They concluded that the watermelon seed oil has the potential to be used as raw material for the formulation of vegetable oil lubricants.

Ossia, *et al*. (2010) evaluated the tribological properties of some unmodified vegetable oils: castor, jojoba, olive, and sunflower oils as substitutes for an unmodified petroleum mineral oil. Several tests were carried out on the oils, namely, anti-wear, lubricity, and load-carrying capacity, oxidation induction, thermal stability, and viscosity and viscosity indices of the oils. The result obtained showed that the wear scar of the oil measured increased with the oil bulk temperature except for the jojoba oil. The biodegradable oils had a lower friction coefficient compared to the mineral oil.

Ossia *et al*. (2008) examined the tribological and oxidation stability properties of unmodified castor oil and jojoba oil. 0, 2, and 4%wt of zinc dialkyl dithiophosphate (ZDTP), eicosanoic acid and octadecanoic acid were used as an additive in the base materials. The resulting formulations were tested in a four-ball tribosystem, differential pressure calorimetry, optical photomicrographs, and electron probe microanalysis. From the results, it was concluded that eicosanoic and octadecanoic acids had better antiwear and lubricating properties compared to ZDTP in the formulated lubricant.

Bahari *et al.* (2018) studied the friction and wear response of vegetable oil lubricants blended with mineral oil subjected to high temperature and pressure contact conditions. Commercial mineral oil was mixed with palm oil and soybean-based vegetable oils at a ratio of 50-50 by volume. Soybean oil showed a coefficient of friction higher than that of pure palm oil. The overall result showed that the palm oil and soybean oil components in the blend influenced the performance of the resultant lubricant. They concluded that the tribological characteristics of vegetable oils dominated that of the mineral oil.

Vardhaman *et al.* (2018) analyzed the tribological impacts of coconut oil, as bio-lubricant, on the performance of carbide cutting tool while in cutting operation. The coefficient of friction, tool wear, chipping morphology and surface quality during cutting operation of steel with tungsten carbide were measured under wet and dry cutting conditions. The results compared well with those of conventional cutting fluids.

Nair *et al.* (2018) observed that sesame oil was characterized with low pour point and a reasonable oxidation ability, which limited its application as a bio-based lubricant. The study improved the characteristics of sesame oil by the addition of micro- and nano-particles of titanium dioxide, zinc oxide and micro-particle of molybdenum disulphide with the aim of enhancing its tribological properties. The results of the study showed that zinc oxide reduced the coefficient of friction and wear scar diameter.

Azhary *et al.* (2017) studied the tribological behaviour of refined bleached and deodorized palm stearin, and palm fatty acid distillate. ASTM 2783 and D4172B standards were applied. The speed (1200 rev/min) and temperature (75 degrees Celsius) were held constant for 10 minutes and the load was increased until failure. The mineral oil was used as a benchmark for the test results. The anti-wear results showed that palm fatty acid and distillate showed the least surface roughness, wear scar diameter and friction coefficient. On the other hand, the extreme pressure test results showed that the earliest failure first occurred with Refined Bleached Deodorized Palm Stearin at a lower loading condition, followed with Fatty Acid Distillate at a higher load, and the mineral oil at the highest load.

Zuan *et al.* (2017) investigated the tribological behaviour of Palm Fatty Acid Distillate (PFAD), Refined Bleached and Deodorized (RBD) Palm stearin. A four-ball tribometer was used to measure their extreme pressure and anti-wear performance. The friction coefficient, wear scar diameters and surface roughness of the contacts were determined. The results obtained were compared with those of mineral oil lubricant. The friction coefficient of the Palm Fatty Acid Distillate and Palm stearin was better than that of the mineral oil at the initial stage of loading. As the load was increased, the mineral oil performed better. Similar results were obtained for the anti-wear test. It was inferred that the addition of appropriate additives, bio-based oil has potential for use as an alternative to the mineral oil.

Zulhanafi and Samion (2018) compounded double fraction palm olein oil and tertiary eutyl-hydroquinone (anti-oxidant agent) to reduce the oxidation of palm olein oil. The formulated lubricant was tested in a four-ball tribometer to measure surface roughness, the diameter of wear scar and coefficient of friction. The result showed that the anti-oxidant agent improved the coefficient of friction and helped to smoothen the surface. However, it could not sustain the surface protection over time as a result of the development of the film of soap on the metal, thereby causing the exhibition of large wear scar diameter.

Afifah *et al.* (2017) studied the impact of additives to vegetable oil (palm seed oil) to improve its tribological properties as a bio-lubricant. The study used copper oxide as the nanoparticle additive. The tests were carried out using a four-ball tribometer on nanoparticles of copper oxide additive plus palm seed oil. Synthetic oil (SAE15W50) and fossil oil (SAE40) were also used as sample lubricants at standard loads and extreme pressure conditions. The results showed that the additive (copper oxide) to palm seed oil improved tribological performance in terms of wear and friction reduction as well. This also improved its load bearing capacity by 15 percent.

Aiman *et al.* (2017) studied the tribological behaviour of palm oil modified with varied percentages of pour point depressant additives in a four-ball tribometer under different load and temperature conditions. The experiment was in compliance to ASTM D4172 standard. The research results showed that at a low temperature of 15 deg, the sample with a higher concentration of pour point depressant withstood the temperature and performed better, in terms of friction coefficient, than those with lower pour point depressant concentrations. The diameter of the wear scar was not affected by the treatment with pour point depressant.

Hassan and Khalefa (2018) studied the tribological behaviour of mustard seed-SAE40 mineral oil blend in a four-ball tribometer. ASTM D4172B standard was adopted. The results showed that the mustard seed-mineral oil blend performed better with lower wear scar diameter, friction coefficient and higher flashpoint compared to mineral oil only or natural mustard seed oil only.

Hassan *et al.* (2019) studied the lubrication characteristics and the exhaust emission performance of sunflower oil under different loading conditions in a four-ball tribometer and a four-stroke single-cylinder diesel internal combustion engine. The ASTM 4172-B standard was used. The anti-wear and anti-friction performance was high in the sunflower oil compared to the mineral oil-based lubricant. In the emission test, the sunflower produced a low level of carbon monoxide and carbon dioxide, compared to the mineral-based oil at different running conditions.

Hassan *et al*. (2018) studied the characteristics of mustard seed oil-based lubricant under different loading conditions using a pin-on-disc tribometer, in line with the ASTM G99 standard. These results, which were compared to those of commercial lubricant (SAE40), showed that the mustard seed oil had a better anti-wear and anti-friction performance than those of the commercial petroleum oils.

Azman *et al.* (2018) measured the effect of nano-particles of copper (II) oxide in palm oil-based lubricant. The formulated oil was tested in a pin-on-disc tribometer. The tribometer speed was adjusted to 0.2ms^{-1}, and a 9.8N load was applied for a duration of 60 minutes. The results obtained showed that the addition of nano-particles of copper (II) oxide improved the tribological properties of palm oil-based lubricant. Coefficient of friction and wear scar diameter were reduced by 56 and 48 per cent, respectively. The roughness of the surfaces was reduced by 43.7 percent. The results compared well with the results obtained from the mineral based-oil (SAE40).

Ruggiero *et al.* (2017) analyzed the tribological characteristics of hydrogenated rapeseed oil, rapeseed methyl ester oil and jatropha curcas oil in an AISI 52100 and X210Cr12 steel lubricated contact. A ball-on-flat tribometer was used under normal loads and frequencies. The friction coefficient of the oils increased in this order; hydrogenated rapeseed oil, rapeseed methyl ester oil and jatropha curcas oil. The hydrogenated rapeseed oil had the least wear volume and the highest surface roughness.

Shankar *et al.* (2018) investigated the tribological behaviour of kapok (Ceibapentandra) oil-based lubricant on a pin-on-disc tribometer on ~~a~~ steel to steel contacts at varying loads and speeds. The steel surfaces were studied in an optical microscope. The stability of the lubricant with respect to the lubricant corrosion and oxidation were also studied. The results obtained were compared to those of SAE 20W40 mineral oil and palm oil lubricants. Kapok oil had a lower friction coefficient and wear rate compared to the mineral oil and palm oil. Thus, kapok oil was recommended as a potential vegetable oil-based lubricant.

Shafi *et al.* (2018) studied the tribological performance of avocado oil modified with copper particles on a pin-on-disc tribometer. Stribeck curves for the base oil and that of the modified lubricant with different additive concentration were obtained. The lubricants with high copper concentration showed lower friction coefficient with high wear rate. At lower copper concentration, the wear rate was low. The ability of copper particle to form film immensely contributed to the high tribological performance. The overall result confirmed that avocado oil has potential for use as alternative base-oil lubricant for industrial use

Nathe *et al.* (2016) studied the effects of castor seed oil used as bio-lubricants on the tribological properties of steel. The study analyzed the wear and friction of steel using SAE40 lubricating oil and a pin/ball on a disc testing machine. Applied load, rotational speed and time were varied. The result showed that rate of wear, coefficient of friction and frictional force increased with the applied normal load.

3.4 Areas of Application of Vegetable Oil-Based Lubricants

The physicochemical properties of the vegetable oils greatly influence the areas of application of the oils as lubricant-based stock. Table 3 shows the vegetable oils and the areas these are used as lubricant-based stock.

Table 3 Industrial Applications of Some Vegetable Oils (Panchal *et al*., 2017)

Vegetable Oil	Area of Application
Canola oil	Hydraulic oils, tractor transmission fluids, metal working fluids, penetrating oils, chain bar lubes
Castor oil	Gear lubricants, greases
Coconut oil	Gas engine oils
Olive oil	Automotive lubricants
Palm oil	Rolling lubricant, grease
Rapeseed oil	Chain saw lubricants, air compressor-farm equipment
Soybean oil	Metal casting/working, hydraulic oil
Jojoba oil	Grease, liquid lubricants
Crambe oil	Grease,
Sunflower oil	Grease
Cuphea oil	Motor oil
Tallow oil	Steam cylinder oils

Ipilakyaa *et al*. (2021) developed an emulsion oil-in-water cutting fluid for application in a turning operation in a lathe machine. Yellow oleander seed oil, castor seed oil and jatropha seed oil were used as the base oils. The oils were formulated with water, additives sodium petroleum sulphate emulsifier, lemon fruit juice antioxidant, triazine biocide and banana sap corrosion inhibitor. In the Analysis of Variance (ANOVA), there was a 95% significance difference between jatropha and castor oil when compared with the mineral oil cutting fluid at various input parameters. However, cooling properties and surface roughness between yellow oleander oil and mineral oil had no significant difference.

Bello *et al*. (2019) also developed a cutting fluid from yellow oleander seeds. The physicochemical properties and performance rating of the fluid were determined. The physicochemical properties of specific gravity, viscosity index, pH value, flash point and pour point of the oil were low compared to conventional castor oil. The flashpoint of the yellow oleander seeds was 98 ° C, which showed that its danger to the operator and the environment was very low. However, the pour point of the oil was -1°C, which was high compared to castor oil, -43°C. As a result, it was concluded that the yellow oleander is only suitable for tropical countries like Nigeria.

Ibeh *et al*. (2017) performed a qualitative and comparative study of several locally sourced oils; namely, melon oil, African elemi oil and African bean oil to assess their suitability as ~~a~~ substitute quenching media to mineral-based oils. The cooling capacity of the oil was investigated using AISI 1034 medium carbon steel. The influence of the heat transfer coefficient on the severity of quenching and the mechanical properties of the quenched samples was investigated during the study. The results showed that the maximum heat extraction ratio of melon oil, African bean oil and African elemi oil was higher than that of the mineral oil. It was concluded that the selected oils can be used as hardeners for medium carbon steels as they exhibited better cooling and mechanical properties than the mineral oils.

Onuh, *et al*. (2017) highlighted the benefits of chemical modification of non-edible vegetable oil through transesterification for practical applications as vegetable oil-based drilling mud. The chemically modified vegetable oil improved its physicochemical properties and its effects on drilling mud. Used as additives in drilling mud, vegetable oil increased the lubricity of the mud and hence minimized high drag and torque, sticking of drilling string and bits. The vegetable oil-based mud also carries drilling cuttings to the surface for ease of disposal, and reduces corrosion of drilling equipment. The study concluded that the chemical modification reduced the challenges in high viscosity of the mud and also the rate of oxygen absorption and hence stabilized the oxidation process.

Odi-Owei *et al.* (2021) carried out an experimental investigation on melon seed oil and coconut seed oil and their application as lubricants in hydrodynamic journal bearing performance. In this study, pressure distribution, load carrying capacity and eccentricity ratio at varying loading and speed conditions were investigated. The oils were extracted using the soxhlet extraction method and then subjected through standard laboratory analyses to determine their basic tribological properties. The experiment was conducted with a journal bearing test apparatus. The results showed that the average hydrodynamic pressures generated with melon seed oil and coconut seed oil were 21.56% and 6.28%, respectively, lower than that of the SAE20W50 oil. Similarly, the load carrying capacities were 24.45% and 6.97% lower while the eccentricity ratios were 96% and 103% higher, respectively. The experimental results were numerically validated.

Khasbage *et al.* (2016) experimentally investigated the tribological properties of jatropha oil and its performance in hydrodynamic journal bearing in comparison to synthetic lubricant, SAE -40 oil. Computational Fluid Dynamics (CFD) software was used to validate the experimental results. Pure Jatropha oil showed similar properties with that of the SAE-40 oil. The load carrying capacity and the pressure distribution of the oils were higher in the SAE-40 oil compared to the bio-lubricants.

3.5 Strengths, Weaknesses, Opportunities and Threats

Vegetable oil-based lubricants, alternative to mineral-based lubricants, have their inherent characteristic good qualities (strengths), as well as their limitations (weaknesses). However, when considered comparatively to mineral oil-based lubricants and their impact on the environment, vegetable oils have significant advantages (opportunities). The only major snag (threat) posed by large scale industrial use of vegetable oils is the competition between their use as food and as industrial input for lubricant production.

Vegetable oils have excellent lubricity performance, which leads to lower friction and wear, improved power and better fuel economy. Vegetable oils have lower volatility resulting in decreased exhaust emissions. The other tribological qualities of vegetable oils are high viscosity index, high shear stability, high detergency, ability to disperse, biodegradable, leading to decreased environmental contamination. The limitations of vegetable oils are poor thermo-oxidative stability, high temperature induced wear rate, poor hydrolytic stability as they easily hydrolyze in the presence of water, and poor cold flow properties (Table 4).

In order to harnessed the opportunities availed by vegetable oils, researchers are working on overcoming the characteristic limitations of the oils with a view to taking advantage of their friendly impact on the environment compared to mineral oils. Some of these improvement actions are, namely, chemical modification of pure vegetable oils by transesterification or hydrogenation, application of anti-friction and anti-wear additives, viscosity modifiers, nanoparticle additives, thermos-oxidative staility additives, etc. Relevant government policies in support of increased production of vegetable oils, especially the non-edible oils will mitigate competition between their use as food and as industrial input for lubricant production.

Table 4 Advantages and Disadvantages of Vegetable Oil-Based Lubricant (Panchal *et al.*, 2017; Syahir *et al.*, 2017)

Advantage	Disadvantage
1. Biodegradable	1. Low thermo-oxidative stability
2. Low toxicity level towards both terrestrial and aquatic lives	2. High pour point
	3. Short service life

3. High flash point, high viscosity, low evaporative losses	4. Not available in large volume
4. Strong affinity with metal surfaces	5. Poor viscosity index
5. Low volatility	6. Poor corrosion protection
6. A renewable product	7. Susceptible to hydrolytic breakdown

3.6 Methods for improvement of tribological properties of vegetable oil-based lubricant (Soni & Agarwal, 2014) are:

i. **Esterification / Transesterification**

The properties of the vegetable oil-based lubricant can be changed by modification of the carboxyl group of the fatty acid chain of its molecules. Transesterification causes the cleavage of esters. The features of the substrates directly influence the properties of the ester.

ii. **Hydrogenation**

Hydrogenation is the modification of the physical characteristics of the vegetable oil for specific applications and to improve its oxidative stability and minimize the rate of decomposition. Hydrogenation transforms unsaturated fatty acids into single unsaturated fatty acids without increasing the saturated part of the oil. Pure and natural vegetable oils contain unsaturated fatty acids; linoleic and linolenic acids. Hydrogenation transforms them into a more stable components and improves their lubricity performance.

iii. **Oligomerisation / estoloides**

Oligomerisation reaction process modifies the double bonds of unsaturated fatty acid by linking the carboxylic acid functionality of one fatty acid to the site of unsaturation of another fatty acid to form oligomeric esters. The ester linkages formed are more stable than the triglycerides in natural vegetable oils. This improves the physical properties of the vegetable oil-based lubricant.

iv. **Epoxidation**

Epoxidation process is by reacting acetic or formic acid with hydrogen peroxide in the presence of strong mineral acids, for example, sulfuric acid, to generate peracid. This improves the lubricity and the oxidative stability of the vegetable oils.

v. **Chemical, thermal and structural modification**

Structural modification of vegetable oils utilizing thermal and chemical processes can greatly influence its anti-wear and load carrying capacity properties under boundary lubrication regimes. The triacylglycerol structures will have a better temperature range stability.

vi. **Additives**

Additives are used to enhance the tribological performance of the base oil. Additives improve the quality of the base oil and enable it to overcome its limitations in such areas as viscosity index, corrosion inhibition, rusts inhibition, anti-oxidation, anti-wear, extreme-pressure and anti-friction

4 CONCLUSION

Researchers have carried out investigations on oils from various vegetable seeds, namely, groundnut, avocado, jatropha, water melon, star apple, sand box, nicker nut, Barbados nut, mango, black date, yellow oleander, calabash, castor, palm fruit syrup, neem, palm, mustard, cotton, soya, coconut, shea butter, palm kernel, african bean, and african elemi. Research areas were mainly on the analysis of their physicochemical properties, experimental investigation of their tribological performance, and their industrial applications. It is expected that the current global targets for carbon emission and sustainable environments will be greatly supported by results of the ongoing research in vegetable oil as renewable alternatives to mineral-based oils.

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