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(Review Article)

Palm oil as an alternative bio lubricant: A review

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Abstract

Lubrication in mechanical operations involving relative motions of machine elements have been known to facilitate longer techno-economic life span of machine and its components. Lubrication reduces wear and tear of contacting surfaces in relative motion by creating a lubricous layered gap of fluid, powder or semi-solid like grease. Lubricant has also been proven to move heat away from rubbing surfaces to enhance thermal stability of their operations. Various methods, substances and technologies have been adopted to achieve the desired smooth running, minimize frictional losses and improve the thermal stability in the machine members. Mineral oils of long chain hydrocarbon as base oil have really gained ground as an extremely popular choice either in liquid or semi-solid state as lubricant. Recent research has however revealed that mineral oils are non-biodegradable, prone to pollution and hence constitute enormous risks to the environment. This observation and the need for a friendly environment have aroused the curiosity of researchers in the field of tribology and material engineering to the onerous challenge of finding alternative lubricants that will be harmless to the ecosystem and easy disposal of after use. Chief amongst the suggestions made towards the discovery of an environmentally friendly lubricant is the use of vegetable oils of distinct species. The identification of the potential available in vegetable oils has been demonstrated in certain classical operations requiring moderate temperature such as machining and few other cold working operations. This review examines the previous studies regarding the discovery of an alternative machine lubricant from the available vegetative seed oils, particularly palm oil, and suggests ways to improve previous findings and potentials.

Keywords: Vegetable oil lubricants; Palm oil; Bio lubricants; Wear; Friction; Mineral oil lubricants

1. Introduction

Wear constitutes losses in most engineering applications because it brings about wastage and adverse cost implications. Wear is the loss of materials, usually due to sliding and relative motion resistance. Typically wear is undesirable as it can lead to increased friction and ultimately to component failure. Like friction, wear is typically minimized by using a lubricant to separate the two bodies so that they do not directly touch one another. The two most common types of wear are abrasive, in which a harder material removes material from a softer one, and adhesive, in which two bodies adhere to one another locally, so that material is transferred from one to the other. Booser (1983) described wear as dislocation in the grain boundaries of materials surfaces because of high degree of strain leading to large amounts of defects and lattice distortion at the material surface or subsurface. Worn surfaces generally must have undergone initial dislocations causing reduction in strength, performance and wastage of material layers. Repeated actions leading to this phenomenon will continue to deplete the performance and functionality of the equipment. According to Sripada et al. (2013) wear also leads to poor performance of machine and equipment. Zhang et al. (2020) stated that wear is frequently encountered in rubbing parts where traditional resistance of motion is dominant. Although various heat treatment and use of synthetic lubricants have been found to mitigate against wear rate in rubbing mechanical

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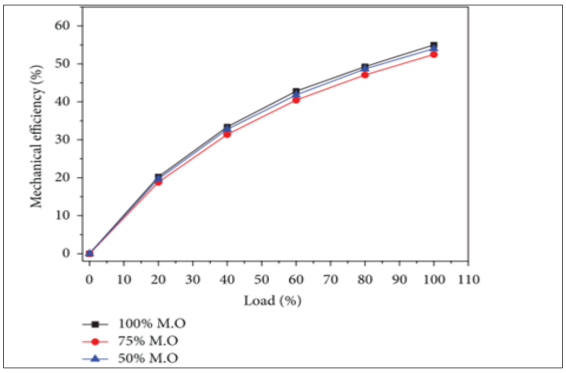
components. Distaso et al. (2020) stated that lubrication is the use of a fluid, or in some cases a solid, to minimize friction and wear. Chaurasia et al. (2020) also mentioned that even though developments in seed oils have demonstrated significant relevance in the quest for an environmentally friendly and biodegradable lubricant. Distaso et al. (2020; Kumar et al. (2020); Singh & Abd Rahim (2020) and Zhang et al. 2020) have all agreed that researchers are still being inundated with enormous challenges in confirming a specific seed oil for lubrication against the common non-degradable mineral oils.

Zhang et al. (2020) believed that increased environmental knowledge is a motivation for technological advancement towards ameliorating the hazards of non-degradable fuels and lubricants by replacing mineral lubricant base-oils with the new generation lubricant. (Heikal et al., 2017) however suggested that the use of petroleum base lubricant inclined the environment to dangerous geopolitical strategies concerning unrefined petroleum manipulation and untold consequence on the environmental balance. In most of these findings, researchers have clearly demonstrated the need to gradually eliminate the harsh effects of the petroleum-based lubricants to protect the environment from continuous degradation.

1.1. Potentials and limitations of vegetable oil

The need to abate the increasing concerns over environmental pollution and degradation because of continued usage of non-degradable mineral oils for lubrication in transportation, industrial and engineering applications. Finding a suitable lubricant for these applications and so many others have remained a big challenge for researchers in last one decade. Reddy et al. (2014) in varying proportions by percentage volume of palm oil blended with base mineral oil SAE20W recorded appreciable emission performance of a 4 -stroke Contact Ignition (CI) engine. Their study showed that, compared to mineral-based commercial oil, the palm oil-based lubricant showed superior tribological properties but offers no significant advantage on engine and emission performance. Masjuki & Maleque (1997) carried out a comparative study of wear, friction, viscosity, lubricant degradation, and exhaust emissions with palm oil and commercial lubricating oil. Their results revealed that the palm oil-based lubricating oil exhibited better performance in terms of wear and that the commercial oil exhibited better performance in terms of friction. However, the palm oil-based lubricant was more effective in reducing the emission levels of CO and hydrocarbon. Beyond this, many other researchers have worked on palm oil and some other vegetable oils in prospecting biodegradable lubricants. Dandan & Syahrullail (2017) demonstrated that palm oil can be applied for lubrication in sensitive operations due to their non-toxicity. Distinct lubricity of palm oil at low temperature is a potential for its preference upon other vegetative seed oils. Unfortunately, the problem of low flow property of palm oil at low temperature operations such as in pasteurizing operation in the food industry negates the potential in the advocacy for palm oil as lubricant. This menace in its properties has necessitated intensified research towards improving the viscosity index by modifications in the structure and reactivity. Figure 1 shows variation of mechanical efficiency with respect to percentage loads for SAE 20W40 and different palm oil blends as presented by Reddy et al. (2014). Most of the modifications that have been done include but are not limited to esterification, transesterification, fractionation, pre-fractionation, addition of additives, addition of antioxidant, addition of surfactants, polymerization etc. Another method that has been applied is improvement in the properties of the materials requiring lubrication. Both tribological properties of the materials as well as the mechanical and physiological properties which are fortified by different methods ranging from heat treatment, reinforcement and nano addition. The motive is to increase the load bearing capabilities of the materials against wear, attrition, corrosion and other forms of surface depletion.



(Reddy et al., 2014)

Figure 1 Mechanical efficiency versus load

Maximum mechanical efficiency is 54.92% with 100% mineral oil, 52.45% for 25% palm oil, and 54% for 50% palm oil. With the increase in palm oil percentage, the mechanical efficiency is like when the engine is operating with mineral oil alone. The decrease in mechanical efficiency can be observed initially due to increase in friction power as the palm oil percentage is less compared to mineral oil. Many other researchers have shown the amazing ways in which palm oil can functionally substitute mineral oils in engineering as well as in industrial operations. Although poor oxidation stability is still a course of concern. Whereas tribologists are intensifying efforts to overcome these concerns, material scientists as well are not left behind in the quest to modify the materials adequately. Several standardized experiments and materials modifications that have so far been done have indicated that

Lubricant is a material that is used to reduce the friction between surfaces in contact, it can also have the role of carrying foreign or worn-out particles away (Singh et al., 2018, 2020; Syahrullail et al., 2011). Approximately 85% of lubricants being used around the world are petroleum-based oils. According to Kamalarkar et al. (2013); Padmaja et al. (2012) and Cavalanti et al. (2018) a good lubricant has the following characteristics: high boiling point, high viscosity index, prevention of corrosion, low freezing point, thermal stability, and high oxidation resistance. Shomchoam & Yoosuk (2014) agreed that most lubricants applications are in form of oils in line with recent findings that lubricants usually contain 90% base oil (most commonly mineral oils) fractions of petroleum and less than 10% of additives (Beheshti et al., 2020). Palm oil maybe fractionated into a liquid fraction (palm olein: PO) and a more solid fraction (palm stearin). PO has higher levels of oleic acids (39–45%) and linoleic acids (10–13%) clearer at ambient temperature of 25 °C with respect to palm oil (Soareset al., 2009).

Also used as base oils are seed oils or synthetic liquids, such as hydrogenated polyolefin, esters, silicones. However, most of the petroleum-based oils are highly toxic to the environment and difficult to dispose of after use (Syahrullail et al., 2011). Therefore, more concerns to the environmental issues drive the lubricant industry to increase the ecological friendliness of its products by exploring the potentials of vegetative seed oils. Even though vegetable oils have disadvantages such as their low thermal and oxidative stability. (Rios et al., 2019) found that they can be overcome through various chemical modifications, such as the use of polyols without hydrogen and other nano additives (Cavalcante et al., 2019; Cavalcanti et al., 2018; Kamalakar et al., 2013; Padmaja et al., 2012; Yasa et al., 2017). Good lubricity has economic advantages in that it reduces fuel consumption and lengthens the life of the machinery. Less often occurring downtime reduces production losses. It has been demonstrated experimentally that adding nanoparticles to different oils or lubricants has good tribological properties, which have environmental benefits such as increased fuel efficiency and a decrease in emissions and particulate matter (Chia et al., 2022).

Vegetative seed oils are generally most popular over artificial fluids, because of their renewable resources and cheaper in cost (Bahari, 2017). Furthermore, in contrast to the standard mineral-based oils, vegetable-oil lubricants are perishable, non-toxic and are easily disposed (Koh et al., 2014). Palm oil possesses the potential to fulfill the demand for seed oil-based lubricants, however, confirmation of its suitability for this purpose is still subject to further investigations (Syahrullail et al., 2011). (Syahrullail et al., 2011) showed that palm oil has satisfactory lubrication performances, as compared to paraffinic mineral oil, and has advantages in reducing extrusion load.

2. Materials and Methods

Seed oils such as palm oil, palm kernel, coconut oil, soya beans oil, castor seed oil, cotton seed oil, melon seed oil, and groundnut oil have been found to possess significant potential for wear reduction. Palm oil has also been singly identified for lubrication against wear and tribological decay of engineering materials (Farfan-Cabrera et al., 2020; Martín-Alfonso et al., 2020; Sen et al., 2020; Syahrullail et al., 2011; Xu et al., 2019; J. Zhang et al., 2019; M. Zhang et al., 2020; Zheng et al., 2020). Dandan et al. (2018) reviewed the potential of saturated and unsaturated vegetable oils to suggest future use of palm oil for lubricant. In a similar review, Dandan and Syahrullail (2017) suggested the replacement of mineral oil with palm oil as alternative automotive lubricant to arrest the scourge of mineral oils toxic consequences on the environment. Table 1 shows the comparison of the properties of saturated and unsaturated oils with transformer oil while Table 2 shows the advantages the properties of palm oil in the review. The advantages

Table 1 Typical Properties of conventional transformer oil and vegetable oils (Dandan et al., 2018)

Properties	**Conventional mineral transformer oil**	**Vegetable oil with saturated fatty acid ≥ 80%**	**Vegetable oil with unsaturated fatty acid ≥80%**
Viscosity (cSt) at 40 °C	13	29	37.6
Density (kg/m^3) at 20 °C	895	917	886
Pour point (°C)	−40	20	-22
Flash point (°C)	154	225	260
Oxidation onset temp (°C)	207	282	192
Conductivity (S/m) at 20 °C	13^{-13}	10^{-11}	10^{-10}
Breakdown strength (kv)	45	60	56

Table 2 Advantages of palm oil as a lubricant (Dandan and Syarullail, 2017)

Properties	**Advantage**
Higher lubricity	Lower friction losses, better fuel economy
Lower volatility	Decrease in exhaust emissions
Rapid biodegradation	Reduced environmental hazards
Better skin compatibility	High cleanliness and less dermatological at workplace
Higher flash points	Provide higher safety
Higher boiling temperatures	Less emission

In his investigation of anti-wear characteristics of palm oil methyl ester, Masjuki & Maleque (1997) used the Four-ball tester to verify that the characteristics performance improvement of mineral oils SAE 10 and SAE 30 by contaminating it with palm oil methyl ester POME as additive under predetermined loads and tribological conditions. The result indicated a remarkable increase in the lubricant performance with increasing POME up to 5% wt/vol. of the mineral oils.

Table 3 Advantages and disadvantages of vegetable oils as lubricants

S/N	**Pros**	**Cons**
1	Biodegradability is high (as they are free of aromatics)	Poor oxidation stability of pyrolysis bio-oils.
2	High boiling point (lower emissions)	Vegetable oils have higher melting points.
3	High viscosity index	Higher extent of upgradation required for thermochemically derived base stocks.
4	Lesser number of contaminants	High acidity of pyrolysis bio-oils.
5	Longer tool life	High cost.
6	High lubricity	Several vegetable oils are edible

This however remains a challenge for the environmental considerations for the non-degradability of mineral base oil. The four-ball tester has shown remarkable potency in its usage for detecting lubricant potentials. In another development, Aiman and Syahrullail (2017) adopted the Four-ball tester to evaluate the performance of sample lubricants using ASTM D4172 standard. From the results, it showed that the sample lubricants for engine oil mixing with RBD Palm Olein reduce by 38% of coefficient of friction compared to pure engine oil. From the overall results, the performance of lubricants in terms of friction was improved in RBD Palm Olein. Notwithstanding. Performance at raised temperature suggests that RBD palm olein would require oxidation stability to be to acclaim such status as suggested. To suggest that RBD Palm Olein could match the performance of SAE10-SAE40 as lubricants, it must maintain remarkable oxidation stability.

3. Results and Discussion

Many antioxidants as additives have been suggested for oxidation stability in vegetable oils. Lubricant additives are natural or inorganic compounds dissolved or suspended as solid residue from liquid solutions in oil. They typically range between 0.1 to 30 percent of the lubricant volume, contingent upon the apparatus.

Additives have three fundamental parts, they enhance existing base oil properties with antioxidants, corrosion inhibitors, anti-foam agents and demulsifying powers.

Additives reduce undesirable base oil properties accompanying pour-point depressants and viscosity index (VI) improvers. They also impart new properties to base oils with extreme pressure (EP) additives, detergents, metal de-stimulator and tackiness.

Sliding wear had been noted for machine damage and shortage of life span because of improper lubricity, irregular speeds and material selection to guide against wear and attrition in machine members (Beheshti et al., 2020; Feng et al., 2019; Singh et al., 2018). Since surface interaction of machine members is a common phenomenon in various mechanical contraptions, finding suitable machines lubricant within the available seed oils against synthetic petroleum oil products that are environmentally friendly, affordable and sustainable has tremendously engaged researchers in the last one decade (Almasi et al., 2021; Heikal et al., 2017; Khoirunnisa Ismail et al., 2020). To enhance the capacity of vegetative seed oil with potential for engine lubrication, palm oil has been studied under different additives for improved lubricity (Shomchoam & Yoosuk, 2014; Syahrullail et al., 2011). Carbon nanotubes of fly ash integrated with ultrathin copper oxide CuO, silica, pentaerythritol rosin ester, sepiolite, silicon oxide SiO_2 and zinc oxide ZnO have all been studied as nano additives with seed oils (Martín-Alfonso et al., 2020; Salah et al., 2017; Xu et al., 2019).

3.1. Effect of additives and non-polar agents

Additive polarity is the natural directional attraction of molecules to other polar materials in contact with it. Generally, it is water soluble. All polar materials like metal surface, water, sponge, wood pulp etc., are known as polar materials. Non-polar substances include wax, Teflon, mineral base stock, water repellents. This is the reason why special consideration should be given to the environment of application and other substances in the direction which could act as contaminants. Contaminants such as water, silica, dirt, might get attached to the additive and cling to it thereby settling at the bottom to be filtered out or depleted

3.2. Polar Mechanism

Some polar mechanisms are particles enveloping, some water emulsifying and some metal wetting. Particles enveloping means that the additive will cling to the particle surface and envelope it. Such additives are metal deactivators, detergents and dispersants. They are essential for dispersing soot particles to prevent agglomeration and settling down at the bottom as deposits at reduced temperature.

3.3. Mechanism and Quantity of Additive

Adding more and more quantities of additive to a lubricant has many implications. Sometimes there is more benefit gained as a result of the addition and at times the performance actually deteriorates (Ojaomo et al., 2023). There are cases when the performance does not improve but significant increment is seen in the duration of service,

3.4. Concentration

In essence, increasing the percentage of certain additives may improve one property of an oil and may also degrade another one at the same time. This brings the idea of acceptable optimum concentration. The acceptable optimum concentration of an additive should balance the otherwise overall quality of the oil to be affected. It must measurably influence the desired property optimally for an operational standard.

3.5. Surface interaction

Some additives compete for same space on a metal surface. A situation where a high concentration of anti-wear agents is added to the oil. It was reported as agglomeration of the grit particles according to Ojaomo et al. (2023). The corrosion inhibitors may become less effective. The consequences may lead to undesirable corrosion tendencies.

3.6. Water emulsifying

This happens when the polar head of an additive clings to a microdroplet of moisture. The phenomenon depletes the health of any additive remaining in the oil. A proper oil analysis will indicate the additive left in the oil.

3.7. Metal Wetting

When additives anchor to metal surfaces which is their requirement in service. Additives like these are found to be attached to gear teeth, bearings, shafts, gear casing materials etc. Additives functioning in this manner are rust inhibitors, anti-wear and extreme pressure, oiliness agents and corrosion inhibitors. Anti-wear additives work majorly to secure metal surfaces at boundary conditions. They are a ductile ash-like film at moderate to high contact temperature (150 F-320 F)

4. Conclusion

This review showed that the wear reduction capacity of palm oil when used as lubricant can be enhanced and improved upon to serve as replacement for the non-degradable mineral oils. Various methods of enhancement enumerated in the review suggest the potential inherent in vegetable oils for exploration. In addition to the positive environmental impact of vegetable oils, the renewability potential of bio lubricants was evident as they can be grown and regenerated unlike the fossil products of mineral lubricants which studies have predicted exhaustion over time. The review is a pointer to the fact that further study is required in enhancement of palm oil bio lubricants for future substitution of the non-degradable toxic mineral-based lubricants. Research conducted in this direction will improve the lubrication of machines with the use of biodegradable palm oil to secure the ecosystem from hazardous and difficult to dispose of mineral lubricants. Fortunately, palm oil has gained sufficient attention in the research to confirm its usage for machine lubrication. Other limitations against this laudable potential are its loss of friction bearing capacity and susceptibility to shear at moderate thermal conditions. This calls for further investigation into the ways to further improve its properties to be adequately suited for machine lubrication.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Almasi, S., Ghobadian, B., Najafi, G., & Dehghani Soufi, M. (2021). A novel approach for bio-lubricant production from rapeseed oil-based biodiesel using ultrasound irradiation: multi-objective optimization. Sustainable Energy Technologies and Assessments, 43(April 2020), 100960.

[2] Aiman, Y. and Syarullail, S. (2017). Development of Palm Oil Blended with Semi-Synthetic Lubricant using Four-ball Tester. Journal of Tribology (13) 1-20

[3] Bahari, A. (2017). Investigation into Tribological Performance of Vegetable Oils as Biolubricants at Severe Contact Conditions. Thesis University of Sheffield. 292.

[4] Beheshti, A., Huang, Y., Ohno, K., Blakey, I., & Stokes, J. R. (2020). Improving tribological properties of oil-based lubricants using hybrid colloidal additives. Tribology International, 144, 106-130.

[5] Cavalcante, I.M., Rocha, N.R.D.C., De Brito, D.H.A., Schuller, A.P.D., Cˆ amara Neto, J.F., De Morais, S.M., Luna, F.M.T., Schanz, M.T.G.F., Maier, M.E., Ricardo, N.M.P.S., (2019). Synthesis and characterization of novel polyol esters of undecylenic acid as ecofriendly lubricants. J. Am. Oil Chem. Soc. 96 (1), 75–82.

[6] Cavalcanti, E.D., Aguieiras, E.C., ´ da Silva, P.R., Duarte, J.G., Cipolatti, E.P., Fernandez L. R., da Silva, J.A.C., Freire, D.M.G., (2018). Improved production of biolubricants from soybean oil and different polyols via esterification reaction catalyzed by immobilized lipase from Candida rugosa. Fuel 215, 705–713

[7] Chia, S. R., Nomanbhay, S., Ong, M. Y., Chew, K. W., & Show, P. L. (2022). Renewable diesel as fossil fuel substitution in Malaysia: A review. Fuel, 314, 123137.

[8] Distaso, E., Amirante, R., Calò, G., de Palma, P., Tamburrano, P., & Reitz, R. D. (2020). Predicting lubricant oil induced pre-ignition phenomena in modern gasoline engines: The reduced GasLube reaction mechanism. Fuel, 281(May), 118709.

[9] Dandan, A. & Syahrullail,. (2017). Palm oil as an alternative lubricant oil: A brief review. The Colloquium, UTM, 11, 17–19.

[10] Dandan, M. A., Yahaya, A. W., Samion, S., & Musa, M. N. (2018). A comprehensive review on palm oil and the challenges using vegetable oil as lubricant base-stock. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 52(2), 182–197.

[11] Farfan-Cabrera, L. I., Gallardo-Hernández, E. A., Gómez-Guarneros, M., Pérez-González, J., & Godínez-Salcedo, J. G. (2020). Alteration of lubricity of Jatropha oil used as bio-lubricant for engines due to thermal ageing. Renewable Energy, 149, 1197–1204.

[12] Feng, Y. qiang, Hung, T. C., He, Y. L., Wang, Q., Chen, S. C., Wu, S. L., & Lin, C. H. (2019). Experimental investigation of lubricant oil on a 3-kW organic Rankine cycle (ORC) using R123. Energy Conversion and Management, 182(December 2018), 340–350.

[13] Heikal, E. K., Elmelawy, M. S., Khalil, S. A., & Elbasuny, N. M. (2017). Manufacturing of environment friendly biolubricants from vegetable oils. Egyptian Journal of Petroleum, 26(1), 53–59.

[14] Kamalakar, K., Rajak, A.K., Prasad, R.B.N., Karuna, M.S.L., 2013. Rubber seed oil-based biolubricant base stocks: a potential source for hydraulic oils. Ind. Crops Prod. 51, 249–257.

[15] Khoirunnisa Ismail, N. I., Abdul Sani, A. S., & Rosli, N. (2020). Study of oil flow rates effects on lubricant oil behaviour during minimum quantity lubrication milling process. Materials Today: Proceedings, 12th July 2020.

[16] Kumar Chaurasia, S., Kumar Singh, N., & Kumar Singh, L. (2020). Friction and wear behavior of chemically modified Sal (Shorea Robusta) oil for bio based lubricant application with effect of CuO nanoparticles. Fuel, 282(May), 118762.

[17] Martín-Alfonso, J. E., Martín-Alfonso, M. J., & Franco, J. M. (2020). Tunable rheological-tribological performance of "green" gel-like dispersions based on sepiolite and castor oil for lubricant applications. Applied Clay Science, 192(April), 105632.

[18] Masjuki, H. H. and Maleque, M.A. (1997). Investigation of the anti-wear characteristics of palm oil ethyl ester POME using a four-ball tribometer tester. 2069(1-2) 179-186.

[19] Ojaomo, K. E., Syahrullail, S., Zawawi, F. M., & Yusop, M. Z. (2023). Potential of palm oil with tert-Butylhydroquinone in place of mineral oil lubricant for reducing environmental degradation. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 237(6), 1342-1352.

[20] Padmaja, K.V., Rao, B.V., Reddy, R.K., Bhaskar, P.S., Singh, A.K., Prasad, R.B., (2012). 10- Undecenoic acid-based polyol esters as potential lubricant base stocks. Ind. Crops Prod. 35 (1), 237–240.

[21] Reddy, K. S. V. K., Kabra, N., Kunchum, U., & Vijayakumar, T. (2014). Experimental Investigation on Usage of Palm Oil as a Lubricant to Substitute Mineral Oil in CI Engines. Chinese Journal of Engineering, 2014, 1–5.

[22] Rios, ́I.C., Cordeiro, J.P., Arruda, T.B.M.G., Rodrigues, F.E.A., Uchoa, A.F.U., Luna, F.M. T., Cavalcante Jr., C.L., Ricardo, N.M.P.S., (2019). Chemical modification of castor oil fatty acids (Ricinus communis) for biolubricant applications: an alternative for Brazil's green market. Ind. Crops Prod., 112000

[23] Salah, N., Alshahrie, A., Abdel-wahab, M. S., Alharbi, N. D., & Khan, Z. H. (2017). Carbon nanotubes of oil fly ash integrated with ultrathin CuO nanosheets as effective lubricant additives. Diamond and Related Materials, 78, 97–104.

[24] Sen, B., Mia, M., Mandal, U. K., & Mondal, S. P. (2020). Synergistic effect of silica and pure palm oil on the machining performances of Inconel 690: A study for promoting minimum quantity nano doped-green lubricants. Journal of Cleaner Production, 258, 120755.

[25] Shomchoam, B., & Yoosuk, B. (2014). Eco-friendly lubricant by partial hydrogenation of palm oil over Pd/γ-Al2O3 catalyst. Industrial Crops and Products, 62, 395–399.

[26] Singh, Y., & Abd Rahim, E. (2020). Michelia Champaca: Sustainable novel non-edible oil as nano based bio-lubricant with tribological investigation. Fuel, 282(April), 118830.

[27] Singh, Y., Sharma, A., Singh, N. K., & Chen, W. H. (2020). Development of bio-based lubricant from modified desert date oil (balanites aegyptiaca) with copper nanoparticles addition and their tribological analysis. Fuel, 259(May 2019), 116259.

[28] Singh, Y., Singh, P., Sharma, A., Choudhary, P., Singla, A., & Singh, N. K. (2018). Optimization of wear and friction characteristics of Phyllanthus Emblica seed oil-based lubricant using response surface methodology. Egyptian Journal of Petroleum, 27(4), 1145–1155.

[29] Sripada, P. K., Sharma, R. v., & Dalai, A. K. (2013). Comparative study of tribological properties of trimethylolpropane-based biolubricants derived from methyl oleate and canola biodiesel. Industrial Crops and Products, 50, 95–103.

[30] Su, Y., Gong, L., & Chen, D. (2015). An investigation on tribological properties and lubrication mechanism of graphite nanoparticles as vegetable-based oil additive. Journal of Nanomaterials, 2015.

[31] Syahrullail, S., Zubil, B. M., Azwadi, C. S. N., & Ridzuan, M. J. M. (2011). Experimental evaluation of palm oil as lubricant in cold forward extrusion process. International Journal of Mechanical Sciences, 53(7), 549–555.

[32] Wang, W., Zhang, G., & Xie, G. (2019). Ultralow concentration of graphene oxide nanosheets as oil-based lubricant additives. Applied Surface Science, 498(August), 143683.

[33] Xu, Z., Lou, W., Zhao, G., Zhang, M., Hao, J., & Wang, X. (2019). Pentaerythritol rosin ester as an environmentally friendly multifunctional additive in vegetable oil-based lubricant. Tribology International, 135, 213–218

[34] Yasa, S.R., Krishnasamy, S., Singh, R.K., Penumarthy, V., 2017. Synthesis and characterization of iso-undecenoic and iso-undecanoic acids-based polyol esters. Ind. Eng. Chem. Res. 56 (26), 7423–7433.

[35] Zhang, J., Li, P., Zhang, Z., Wang, X., Tang, J., Liu, H., Shao, Q., Ding, T., Umar, A., & Guo, Z. (2019). Solvent-free graphene liquids: Promising candidates for lubricants without the base oil. Journal of Colloid and Interface Science, 542, 159–167.

[36] Zhang, M., Ge, Y., Wang, X., Peng, Z., Tan, J., Hao, L., Lv, L., & Wang, C. (2020). An investigation into the impact of burning diesel/lubricant oil mixtures on the nature of particulate emissions: Implications for DPF ash-loading acceleration method. Journal of the Energy Institute, 93(3), 1207–1215.

[37] Zheng, L., Zhu, H., Zhu, J., & Deng, Y. (2020). Effects of oil film thickness and viscosity on the performance of misaligned journal bearings with couple stress lubricants. Tribology International, 146(January), 106229.