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Rapeseed Oil-based Biodiesel as Lubricant: Frictional Force and Tribological Analysis

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Abstract
Lubrication is necessary to minimise the frictional impact created during the running of a vehicle since it increases wear and friction among the parts in contact. Wear and friction shorten the component's life, decrease its dependability, and raise maintenance costs. The current study uses a tribo tester to examine the friction and wear properties of rapeseed biodiesel at fixed parameters. The investigated lubricants included B0 (diesel), B100 (biodiesel), and four distinct blends of biodiesel: B15, B30, B45, and B60. Analysis was done for one hour at ambient temperature with a standard load of 140 N at a speed of 1000 rpm. The outcome showed that as the concentration of biodiesel augmented, friction and wear scar get reduced. The aluminium pin wear in B100 appeared 16% less than that in diesel. Also, the presence of esters and fatty acids during Fourier transform infrared analysis of biodiesel contributes more to its possibilities as a lubricant.

Keywords- Biodiesel, Rapeseed oil, Friction, Wear, Load.

1. Introduction

The need has pushed the effective operation of petroleum refinery products for industrial and home use for energy. For day-to-day operation, all alternative energy sources that are produced from renewable sources still need a source from petroleum-based products (Xiao et al., 2019; Vimali et al., 2022). However, the constant need for the products coupled with the scarcity of traditional fuel has forced investigators to devise a process of producing fuel products available as and when required. This can be accomplished by looking for alternative fuel sources to replace conventional fuel because the byproducts of refineries have a problem with having greenhouse effects (Singh et al., 2021; 2021b). One of the promising alternative fuels and sustainable options for addressing these energy challenges is biodiesel, produced from renewable sources such as vegetable oils and/or waste cooking oil. It is made up of various fatty acids (Singh et al., 2020).

Regarding the attributes of the fuel and how it burns, biodiesel and petroleum diesel are identical. However, there are some technical advantages over petroleum diesel and some limits because of chemical variations. The biodegradability, higher flash point, high cetane number, etc., are among biodiesel's most frequently cited benefits over petroleum diesel (Cardone et al., 2002; Arumugam and Sriram, 2012). According to reports, clean biodiesel has more lubricity by nature than petroleum diesel. Due to these advantages, biodiesel is becoming more and more popular, yet several substantial disadvantages have restricted its commercial application. Among the main issues are injector coking, filter clogging, and reactivity of unsaturated hydrocarbon chains. Many of these issues may also affect the friction and wear of various engine parts that come into contact with biodiesel while sliding (Ghobadian et al., 2009; Gupta and Agarwal, 2021).

A recent study has examined biodiesels' wear characteristics utilizing various tribometer methods. Fazal et al. (2013) used a four-ball wear test, several diesel-biodiesel blends, and speed adjustments to evaluate palm biodiesel's friction and wear properties. A chrome alloy steel with a hardness rockwell C (HRC) of 62 was used in this study. It was determined that biodiesel outperformed diesel in terms of surface protection. The performance was attributed to the presence of ester molecules in biodiesel. Using four-ball tribometers and biodiesel made from Calophyllum Inophyllum that was added to diesel at various quantities, Habibbullah et al. (2015) attained similar results. The best outcome was found for pure biodiesel when testing a carbon-chromium bearing steel at a fixed speed of 1800 rpm. Farias et al. (2014) used the high-frequency reciprocating test rig to examine the lubricity of various diesel and biodiesel mixes. They claimed that when compared to diesel fuel, pure biodiesel (B100) and diesel-biodiesel blends had improved lubricity, most likely because interfacial lubricant films formed more effectively.

To complete the feedstock requirement for biodiesel production, non-edible plant-based oil has been the main cutting edge in terms of suitability, cost efficiency, accessibility, and environmentally responsive fuel (Al-Zuhair, 2007; Bhale et al., 2008). More than 350 crops have the capabilities of producing oil and have been identified as prospective sources for the generation of biodiesel, according to Singh et al. (2021). For the manufacturing of biodiesel, a variety of feedstocks have been assessed, including waste cooking oil, vegetable oil, and algal oil. Additionally, a limited supply of terrestrial plants can be used to make biodiesel. Vegetable oils and other food-based crops are considered the primary source for biodiesel production. Palm oil and rapeseed oil are examples of edible oils. Non-edible oils are those that are not suitable for human consumption (e.g., Polanga and mahua oil) (Thirugnanasambantham et al., 2020; Singh et al., 2021a; Tasneem et al., 2022; Opia et al., 2022; Shahabuddin et al., 2022). Akintunde et al. (2021) transesterified sandbox oil into biodiesel and studied the impact on diesel engine performance and combustion and came to the conclusion that it's a realistic solution for lowering emissions. Rapeseed oil-based biodiesel and bio-based lubricant were subjected to a 150-hour endurance test as a substitute for diesel and synthetic lubricant, and Arumugam and Sriram (2012) found that the combination of the two lowered the concentration of metal after wear. Pathak et al. (2019) looked into the performance of Karanja oil as a fuel and lubricant in diesel engines; they found that the engines performed better and lost less power to friction. The lack of thermo-oxidative stability and fluidity deterioration was attained at minimum temperatures by making bio-based lubricants unsuitable for general usage as lubricants, according to Arumugam and Sriram (2012) and Karmakar et al. (2017). These flaws can be corrected through the chemical manipulation of plant seed oils. According to the literature, the methyl ester extraction of non-edible feedstocks requires two steps of catalytic processing because they have a maximum free fatty acid (FFA) quantity. The following are some benefits of chemically treated vegetable oil that investigators have looked into: (a) Oil extraction from non-edible sources has no impact on the availability of food or the condition of the land i.e., it can be barren; (b) It is sustainable, makes countries that import fossil fuels more reliant on their own markets, promotes employment opportunities in rural parts, and supports in boosting of economy; (c) improved viscosity index; (d) better friction coefficient.

The approaches used by various researchers to examine the lubricity of biodiesel or its blends vary across a large variety of parameters in addition to inside a specific window. However, it appears that more work needs to be done to ensure long-term success in enhancing lubricity using various methods. To the author's best knowledge, rapeseed-based biodiesel's friction and wear characteristics have not been reported at various parameters. Using a tribo tester, the current study evaluates the lubricity properties of rapeseed oil blends on mild steel surfaces with three different loads.

2. Materials and Methods

2.1 Material and Process Applied

Shive Enterprises, Pune, India, provided the pure biodiesel (B100) used in this investigation, made from rapeseed oil. Additionally, the 100% Petro diesel used in this study came from a nearby Bharat Petroleum gas station. In this study, blend samples were created and tribologically evaluated with various volume concentrations of biodiesel at 0% (B0), 15% (B15), 30% (B30), 45% (B45), 60% (B60), and 100% (B100), respectively. To stop the diesel oil from degrading, 10 ml of the combination was created prior to the tribological experiment. The experiment used a mild steel disc and aluminium silicon alloy pin. The disc and pin were made available through the local vendor of the city of Roorkee, Uttarakhand, India. Fourier-transform infrared spectroscopy (FT-IR) analysis was used to evaluate changes in the biodiesel and diesel functional groups. The equipment was supplied by Bruker having invenio model version. FTIR was run in the wavelength range of 4000 cm^{-1} to 500 cm^{-1}. Additionally, tests on the diesel sample's density, viscosity, and flash point were performed. A viscometer was used to measure the viscosity (SICBEV-01, Engler viscometer apparatus). The density was measured using a rheometer (VTD 50 Hz, Vinsyst), and the flash point was checked through the automatic apparatus (VT684, Nunes Instruments, Coimbatore, Tamil Nadu, India).

2.2 Experimental Set Up

A tribo tester was utilised to carry out tribological analysis having pin and disc as essential parts (Novus Wear Tribotester), as schematically depicted in Figure 1. Before the examination, all samples were cleaned with ethanol in an ultrasonicator for 15 minutes. In the experiment, mild steel was rotated against the pin under lubricants. Throughout the action, the coefficient of friction (COF) was gauged. 5 mL of the blend was applied to the contact until it was inundated, following the ASTM G99 standard, which was developed for evaluating diesel lubricity. During the initial usage, a constant load of 140 N was applied. The rotating motion with 1000 rpm speed (0.52 m/s sliding velocity) lasted 60 minutes in each trial. At least three trials of each experiment were performed. The coefficient of friction was calculated based on equation (1). The wear scar diameter was calculated based on the images obtained through view 7 software equipped with a 3D microscope. The pin was made 10 mm in diameter and 30 mm in length, having a tip of thickness of 2 mm.

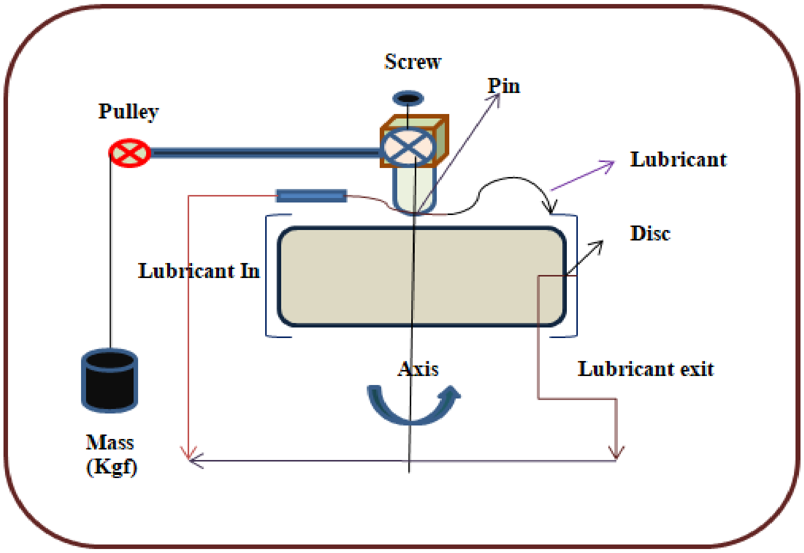

Figure 1. Schematic image of the set up used for analysis.

$$\mu = \frac{FF}{N} \quad (1)$$

where, μ = Coefficient of friction
FF = Frictional force
N = Applied load.

3. Results and Discussion

3.1 Physicochemical Characterization

Table 1 shows the physicochemical characteristics of the biodiesel, diesel and mixtures of biodiesel. It is observed that viscosity of pure biodiesel is more as compared to the diesel. When biodiesel is blended with diesel, its viscosity is reduced. This is due to the presence of saturated fatty acids in the biodiesel that makes it viscous as compared to the diesel (Xiao et al., 2019; Tamilvanan et al., 2022). The same effect has also been observed with respect to the density. Biodiesel and its blends are having more density as compared to the diesel. The flash point of biodiesel in comparison to diesel, which is a going indication for its suitability as a lubricant (Dwivedi et al., 2011; Dharma et al., 2017).

Table 1. Properties of the biodiesel, diesel and their blends.

Properties	Unit	B0	B100	B15	B30	B45	B60
Dynamic viscosity @ 40ºC	mPa.s	5.37	12.7	6.39	6.89	8.32	9.24
Density @ 20ºC	g/cm^3	0.8342	0.8934	0.8432	0.8572	0.8612	0.8719
Flash point	(ºC)	67.3	176.2	71.5	79.8	95.6	118.4

To ascertain the chemical compositions and presence of fatty acids in biodiesel, biodiesel and diesel were subjected to FTIR analysis. The outcomes are displayed in Figure 2. The biodiesel and diesel have distinctive absorption peaks that are visible in the FTIR spectrum. From rapeseed oil, the presence of oxygenate organic groups can be observed. The findings also showed the presence of ester (-C=O) at 1435 cm^{-1} peak and vibrational bending at 1012 cm^{-1} (Azizi et al., 2018). Asymmetric bending absorption peaks of the -O-CH_3 carbon-hydrogen bond are available at 1423 cm^{-1} (Xiao et al., 2019). In addition, the bending of bonds and a carbon-hydrogen bond were also visible at 2734 cm^{-1} and 2893 cm^{-1} peaks, respectively (Lazzari et al., 2018). Two prominent peaks at 1156 cm^{-1} and 1228 cm^{-1} show the appearance of the fatty acid-based esters. The spectrum range at 650 to 712 cm^{-1} showed that the biodiesel consists of several methyl esters of fatty acids (Ong et al., 2020). The investigation ultimately showed that fatty substances were the primary constituents of biodiesel. The peak available at biodiesel fuel at 1435 cm^{-1} is absent in the diesel fuel that indicated the presence of oxygen in the biodiesel. Also, the peaks presenting fatty acid profile at biodiesel are absent in the diesel fuel profile.

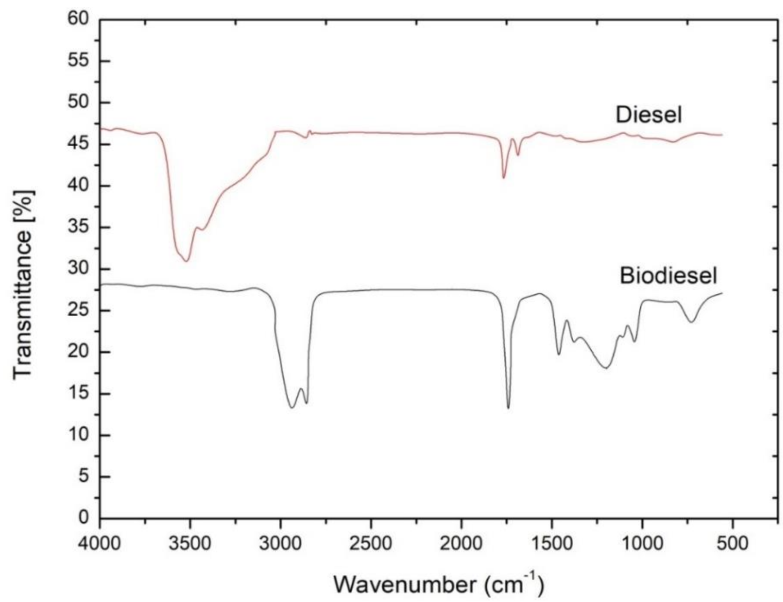

Figure 2. FTIR spectra of biodiesel and diesel.

3.2 Wear Scar and Coefficient of Friction

According to Table 1, wear preventative experiments have been carried out using biodiesel blends and diesel at various ratios. The wear-preventive tests were carried out for 60 minutes with a continuous load of 140 N (14 kg), running at 70 °C, and a rotating speed of 1000 rpm. Figures 3 and 4 display the plots of CoF and wear scar diameter (WSD) of blends. For all of the blended combinations, it can be observed that the CoF has significantly improved. The biodiesel has the lowest CoF (0.057) of the different combinations with all blended biodiesel or diesel. WSDs of 0.94 g. 0.77 g, 0.58 g, 0.33, 0.21 g and 0.16 g were obtained for respective samples i.e., 0%, 15%, 30%, 45%, 60% and 100%. The WSD decreases as biodiesel, and biodiesel-diesel content is added in phases from 15% to 100%, as seen in Figure 4. According to the observation, adding biodiesel to diesel enhanced lubricity and decreased WSD, indicating that it might be employed as a wear reducer. The findings demonstrated that biodiesel, which has a ratio of 45% and 60%, performs roughly better as a lubricity enhancer than 15% and 30% blends. Biodiesel is not ideal when the blending ratio is low, such as 15%, since it wears down machinery more quickly than other mixed lubricants. At lower mix ratios, biodiesel has superior lubricity qualities to other blends. Free fatty acids and glycerol, according to Sarin et al. (2007), improve the lubricity qualities of biodiesel. The polarity of biodiesel, one of its natural features, aids in lubricating the disc metal surfaces (Bhan et al., 2021). Not only the presence of free fatty acids and glycerol but the viscosity also plays an essential role in determining the lubricity behaviour of oil. It was observed from Table 1 that viscosity increases concerning the blending of fuel. The reduction in coefficient of friction was also observed in Figure 5 concerning sliding speed regarding biodiesel. Biodiesel has more viscosity than diesel, which helps maintain a stable film on the surfaces during their interaction. Wain et al. (2005) found that biodiesel with more oxygen can minimise friction. According to a different study (Xu, 2007), the primary process in lowering friction may be the production of a number of compounds on the frictional surface of steel, including FeSO4, as well as organic compounds. The presence of aliphatic fatty acids in biodiesel with high oxygen content (O) can also lessen wear and friction between contact surfaces. By creating lubricating sheets, this fatty acid improves lubrication properties. According to Havet et al. (2001), the area of the protected surface rises as a result of the film's thickness due to the length of the fatty acid chain. These protective layers can increase lubricity and decrease thermal energy in sliding contact (Knothe and Steidley, 2005).

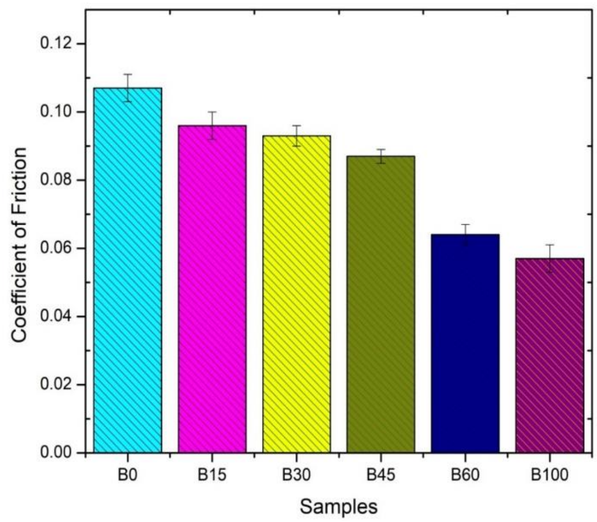

Figure 3. Coefficient of friction for different biodiesel samples.

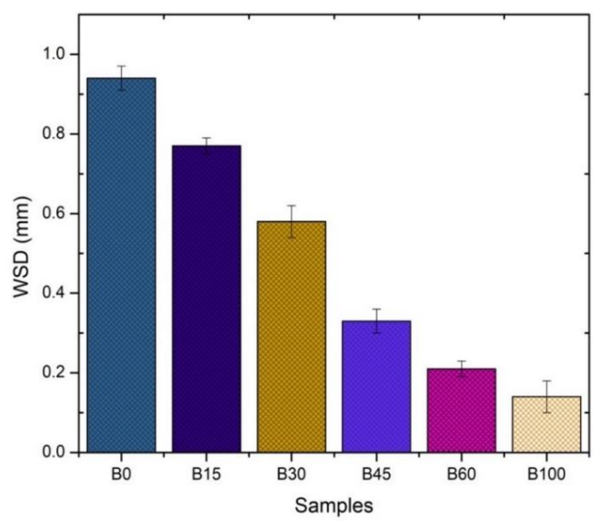

Figure 4. Wear scar diameter for different biodiesel samples.

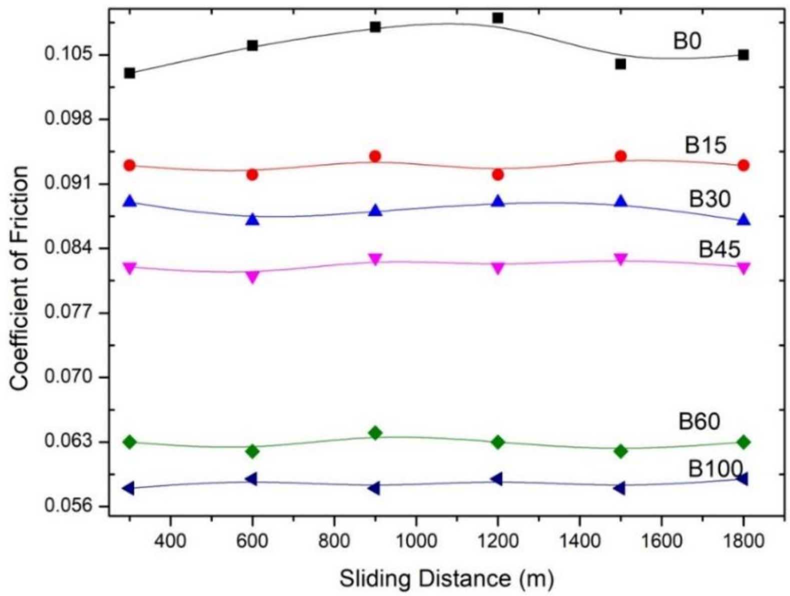

Figure 5. Coefficient of friction with sliding distance.

4. Conclusions

The study explored the possibilities of rapeseed oil-based biodiesel as a lubricant. Six samples were analysed and investigated at fixed parameters for their tribological characteristics during the study. The following are the conclusion obtained based on the analysis:

- From rapeseed oil, the presence of oxygenate organic groups can be observed. The findings also showed the availability of esters and fatty acids, making it more prone to its application as lubricant.
- For all of the blended combinations, it can be observed that the CoF has significantly improved. The biodiesel has the lowest CoF (0.057) of the different combinations with all blended biodiesel or diesel. Free fatty acids and glycerol improve the quality of the lubricity of biodiesel.
- The minimum CoF was also observed for biodiesel in comparison to other blends during the achievement of the sliding distance defined.
- WSDs of 0.94 g. 0.77 g, 0.58 g, 0.33, 0.21 g and 0.16 g were obtained for respective samples, i.e., 0%, 15%, 30%, 45%, 60% and 100%. The WSD decreases as biodiesel and biodiesel-diesel content are added in phases from 15% to 100%. The scar formation on the samples tested with biodiesel gets reduced due to the availability of a strong protective film on the surface.
- According to the observation, adding biodiesel to diesel enhanced lubricity and decreased WSD, indicating that it might be employed as a wear reducer. The findings demonstrated that biodiesel, which has a ratio of 45% and 60%, performs roughly better as a lubricity enhancer than 15% and 30% blends.

Conflict of Interest
There is no conflict of interest.

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References

Akintunde, S.B., Obayopo, S.O., Adekunle, A.S., Obisesan, O.R., & Olaoye, O.S. (2021). Combustion and emission study of sandbox seed oil biodiesel performance in a compression ignition (CI) engine. *Energy Reports*, *7*, 3869-3876.

Al-Zuhair, S. (2007). Production of biodiesel: Possibilities and challenges. *Biofuels, Bioproducts and Biorefining: Innovation for a Sustainable Economy*, *1*(1), 57-66.

Arumugam, S., & Sriram, G. (2012). Effect of bio-lubricant and biodiesel-contaminated lubricant on tribological behavior of cylinder liner–piston ring combination. *Tribology Transactions*, *55*(4), 438-445.

Azizi, K., Moraveji, M.K., & Najafabadi, H.A. (2018). A review on bio-fuel production from microalgal biomass by using pyrolysis method. *Renewable and Sustainable Energy Reviews*, *82*, 3046-3059. https://doi.org/10.1016/j.rser.2017.10.033.

Bhale, P.V., Deshpande, N., & Thombre, S. (2008). Simulation of wear characteristics of cylinder liner ring combination with diesel and biodiesel. *Society of Automotive Engineers*. NUMBER 2008280107.

Bhan, U., Singh, D., & Ranganathan, A. (2021). Effect of different loads on the friction and wear characteristics of material lubricated with neem oil. *Materials Today: Proceedings*, *46*, 10113-10116. https://doi.org/10.1016/j.matpr.2020.09.378.

Cardone, M., Prati, M.V., Rocco, V., Seggiani, M., Senatore, A., & Vitolo, S. (2002). Brassica carinata as an alternative oil crop for the production of biodiesel in Italy: Engine performance and regulated and unregulated exhaust emissions. *Environmental Science & Technology*, *36*(21), 4656-4662.

Dharma, S., Hassan, M.H., Ong, H.C., Sebayang, A.H., Silitonga, A.S., Kusumo, F., & Milano, J. (2017). Experimental study and prediction of the performance and exhaust emissions of mixed Jatropha curcas-Ceiba pentandra biodiesel blends in diesel engine using artificial neural networks. *Journal of Cleaner Production*, *164*, 618-633.

Dwivedi, G., Jain, S., & Sharma, M. (2011). Impact analysis of biodiesel on engine performance—A review. *Renewable and Sustainable Energy Reviews*, *15*(9), 4633-4641.

Farias, A.C.M.D., Medeiros, J.T.N.D., & Alves, S.M. (2014). Micro and nanometric wear evaluation of metal discs used on determination of biodiesel fuel lubricity. *Materials Research*, *17*, 89-99.

Fazal, M., Haseeb, A., & Masjuki, H.H. (2013). Investigation of friction and wear characteristics of palm biodiesel. *Energy Conversion and Management*, *67*, 251-256.

Ghobadian, B., Rahimi, H., Nikbakht, A., Najafi, G., & Yusaf, T. (2009). Diesel engine performance and exhaust emission analysis using waste cooking biodiesel fuel with an artificial neural network. *Renewable Energy*, *34*(4), 976-982.

Gupta, J.G., & Agarwal, A.K. (2021). Engine durability and lubricating oil tribology study of a biodiesel fuelled common rail direct injection medium-duty transportation diesel engine. *Wear*, *486*, 204104. https://doi.org/10.1016/j.wear.2021.204104.

Habibullah, M., Masjuki, H.H., Kalam, M., Zulkifli, N., Masum, B., Arslan, A., & Gulzar, M. (2015). Friction and wear characteristics of Calophyllum inophyllum biodiesel. *Industrial Crops and Products*, *76*, 188-197.

Havet, L., Blouet, J., Valloire, F.R., Brasseur, E., & Slomka, D. (2001). Tribological characteristics of some environmentally friendly lubricants. *Wear, 248*(1-2), 140-146.

Karmakar, G., Ghosh, P., & Sharma, B.K. (2017). Chemically modifying vegetable oils to prepare green lubricants. *Lubricants*, *5*(4), 44. https://doi.org/10.3390/lubricants5040044.

Knothe, G., & Steidley, K.R. (2005). Kinematic viscosity of biodiesel fuel components and related compounds. Influence of compound structure and comparison to petrodiesel fuel components. *Fuel*, *84*(9), 1059-1065.

Lazzari, E., Schena, T., Marcelo, M.C.A., Primaz, C.T., Silva, A.N., Ferrao, M.F., Bjerk, T., Caramao, E.B. (2018). Classification of biomass through their pyrolytic bio-oil composition using FTIR and PCA analysis. *Industrial Crops and Products*, *111*, 856-864.

Ong, H.C., Chen, W.H., Singh, Y., Gan, Y.Y., Chen, C.Y., & Show, P.L. (2020). A state-of-the-art review on thermochemical conversion of biomass for biofuel production: A TG-FTIR approach. *Energy Conversion and Management*, *209*, 112634. https://doi.org/10.1016/j.enconman.2020.112634.

Opia, A.C., Hamid, M.K.A., Syahrullail, S., Johnson, C.A., Mamah, S.C., Hilmi, C.D.Z., Rahim, A.B.A., Ali, A. I. (2022). Improving tribological properties and shear stability of base lubricant using Eichhornia crassipes carboxylmethyl cellulose polymer under different conditions. *Industrial Crops and Products*, *180*, 114741. https://doi.org/10.1016/j.indcrop.2022.114741.

Pathak, M.K., Joshi, A., Mer, K.K.S., Katiyar, J.K., Patel, V.K. (2019). Potential of Bio-lubricants in Automotive Tribology. In: Katiyar, J., Bhattacharya, S., Patel, V., Kumar, V. (eds) *Automotive Tribology. Energy, Environment, and Sustainability* (pp.197-214). Springer, Singapore. https://doi.org/10.1007/978-981-15-0434-1_11.

Sarin, R., Arora, A.K., Ranjan, R., Gupta, A.A., & Malhotra, R.K. (2007). Bio-diesel lubricity: correlation study with residual acidity. *Lubrication Science*, *19*(2), 151-157.

Shahabuddin, M., Mofijur, M., Rizwanul Fattah, I.M., Kalam, M.A., Masjuki, H.H., Chowdhury, M.A., & Hossain, N. (2022). Study on the tribological characteristics of plant oil-based bio-lubricant with automotive liner-piston ring materials. *Current Research in Green and Sustainable Chemistry*, *5*, 100262. https://doi.org/10.1016/j.crgsc.2022.100262.

Singh, N.K., Singh, Y., Sharma, A., & Kumar, S. (2020). Diesel engine performance and emission analysis running on jojoba biodiesel using intelligent hybrid prediction techniques. *Fuel*, *279*, 118571. https://doi.org/10.1016/j.fuel.2020.118571.

Singh, Y., Negi, P., Yadav, A., & Tripathi, R. (2021a). Michelia Champaca based bio lubricant and its application during tribological behaviour analysis. *Materials Today: Proceedings*, *46*, 10510-10512. https://doi.org/10.1016/j.matpr.2020.12.1235

Singh, Y., Negi, P., Yadav, A., & Tripathi, R. (2021b). Raphnus raphanistrum L: A novel feedstock for bio based lubricant application. *Materials Today: Proceedings*, *46*, 10482-10484. https://doi.org/10.1016/j.matpr.2020.12.1189.

Singh, Y., Singh, N.K., Sharma, A., Singla, A., Singh, D., & Rahim, E.A. (2021). Effect of ZnO nanoparticles concentration as additives to the epoxidized Euphorbia Lathyris oil and their tribological characterization. *Fuel*, *285*, 119148. https://doi.org/10.1016/j.fuel.2020.119148.

Tamilvanan, A., Jeyalakshmi, P., Mohanraj, M., & Deepanraj, B. (2022). Feasibility study on raw Simarouba glauca oil as an alternate fuel in a diesel engine and comparative assessment with its esterified oil. *Fuel*, *327*, 125168. https://doi.org/10.1016/j.fuel.2022.125168.

Tasneem, H.R.A., Ravikumar, K. P., & Ramakrishna, H. V. (2022). Performance and wear debris characteristics of karanja biodiesel and biolubricant as a substitute in a compression ignition engine. *Fuel*, *319*, 123870. https://doi.org/10.1016/j.fuel.2022.123870.

Thirugnanasambantham, R., Elango, T., & Elangovan, K. (2020). Wear and friction characterization of chlorella sp. microalgae oil based blended lubricant on pin on disc tribometer. *Materials Today: Proceedings, 33*, 3063-3067. https://doi.org/10.1016/j.matpr.2020.03.512.

Vimali, E., Gunaseelan, S., Devi, V.C., Mothil, S., Arumugam, M., Ashokkumar, B., Moorthy, I.M.G., Pugazhendhi, A., Varalakshmi, P. (2022). Comparative study of different catalysts mediated FAME conversion from macroalga Padina tetrastromatica biomass and hydrothermal liquefaction facilitated bio-oil production. *Chemosphere, 292*, 133485. https://doi.org/10.1016/j.chemosphere.2021.133485.

Wain, K.S., Perez, J.M., Chapman, E., & Boehman, A.L. (2005). Alternative and low sulfur fuel options: Boundary lubrication performance and potential problems. *Tribology International*, *38*(3), 313-319.

Xiao, H., Zou, H., Liu, S., & Li, C. (2019). An investigation of the friction and wear behavior of soybean biodiesel. *Tribology International, 131*, 377-385. https://doi.org/10.1016/j.triboint.2018.10.037.

Xu, Y., Wang, Q., Hu, X., & Chen, J. (2007). Preliminary study on tribological performance of straw based bio-fuel. In *International Joint Tribology Conference* (Vol. 48108, pp. 81-83). San Diego, California, USA. https://doi.org/10.1115/IJTC2007-44098.

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