Tribological analysis of automotive material under wet lubrication condition using diesel, biodiesel and their blend

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Abstract. Biodiesel made from vegetable oil can be considered the best alternative fuel for a partial or complete diesel replacement. Earlier studies on biodiesel and its blends have proven that biofuels in the existing engine can be favorable for partial eradication of diesel from C.I. engines. Therefore, this study investigates the tribological impact of various biodiesels and diesel and their optimum blend at normal room conditions. The tribological analysis is performed on a pin-on-disc tribometer. During the tests, the coefficient of friction, friction force and wear of pins (Aluminium, Copper and Iron) were examined; apart from this, weight & volume loss of the metal pins were also investigated. The pin surfaces were characterized by surface microscopic analysis. Fuel constituents and fatty acid content were analysed by GC-MS and FT-IR tests to understand the cause of tribological wear better. Castor and Rapeseed biodiesel show the lowest weight of pin in comparison to diesel. The wear rate of metals with diesel shows extreme rises in wear as the sliding distance increase. The coefficient of friction, friction force of pins was found to be highest in diesel, followed by biodiesel and their blend in almost every case.

1. Introduction
Although ample research has been done on biodiesel as a lubricant, very few researchers have compared and analysed the combined effect of two different biodiesel as a lubricant fuel on C.I. engine actual components materials. Keeping this in mind, an in-depth understanding of their tribological behaviour with engine component material is needed. Tribology can be defined as the branch of science & engineering that deals with the contacts of two surfaces in relative motion. The tribological study includes the deep study of wear, lubrication and friction at the surface of the material; therefore, this is chosen as the prime method for selecting a suitable lubricant for a particular application. For discovering a requirement of lubrication one has to understand the consequences of parameters related to tribology [1]. Therefore the lubricants are very essential for every moving component of the engine. The lubricants are those substances in solid or liquid state used to lubricate the surfaces that are in mutual contact with each other so that the material wear and friction between moving parts can be minimized. In most vehicles, the lubricating oil helps transfer power, clean, cool, and lubricate the engine components. The fuel used to run C.I. engine must have an excellent lubricating capability to minimise the wear and various tribological complications that are usually found in fuel lines and pumps. The good lubricating property of fuel is very important for fuel
injection systems because fuel pumps are dependent on fuel for their rotational parts lubrication and cooling. Nowadays, the oil refineries have to produce a low sulphur content diesel because of stringent emission rules and regulations, which ultimately reduces its lubricating properties. The problems like high corrosion, extreme wear, erosion of fuel injector nozzle, difficulty in engine starting, high engine emission and reduction in engine power can be easily noticed in the engines using low sulphur fuel. The life of fuel distributor pumps is reduced by 94.8% with the continuous use of low sulphur diesel [2]. Another kind of lubricity like boundary lubricity, is formed because of mutual contact between two solid surfaces and diesel fuel impurities that stick on the metal surface. Surfactants (Polar), nitrogen, sulphur and heterocyclic aromatics are some of the most popular types of impurities found in diesel fuel. These impurities react or get themselves absorbed on rubbing metal surface, which minimizes the friction and wear by reducing the bond between mutual contact surfaces.

1.1. Tribology with hydrodynamic lubrication conditions
Baskar S & Sriram G conducted an experiment using a pin-on-disc tribometer for characteristics of the metal wear and friction of a bearing material using 20W40 synthetic oil and chemically improved Rapeseed methyl ester under hydrodynamic lubrication condition. The rotating disc is made from EN31 hardened steel and the pin is made from brass. They have kept 200N load constant for this tribology testing and a varying sliding distance from 2-10 m/s. It has been found that the friction coefficient of chemically improved Rapeseed methyl ester is lower and it also has wear-resistant properties [3]. Jain A K & Suhane A conducted a similar type of tribology testing by using pin-on-disc tribometer. They have chosen Castor, mahua oil and their blends for investigating its tribological behaviour as a bio-based lubricant. For this test mild steel rotating disc and carbon steel pin were chosen. Their results claim that with the use of bio lubricant, the mechanical operational efficiency and life of design application increases. The bio-based lubricant also reduces friction coefficient and lowers wear up to 63% [4]. The capability of mahua methyl ester towards lubricity for the applications like maintenance was investigated by Suhane et al. They created a blend of 90T gear oil with mahua methyl ester in various proportions. For this, they have also used pin-on-disc tribometer. This time, the test was conducted on hydrodynamic or wet lubrication conditions by using a blend of 90T gear oil with mahua methyl ester. Carbon steel and mild steel are used for the manufacturing of pin and rotating discs. The rotating disc’s speed was kept in between 100 to 500 RPM with an interval of 100 RPM. Results show that the blend of 90T gear oil with mahua methyl ester has very good wear-reducing properties apart from this it also shows ecological benefits [5]. A similar kind of work was performed by Shanta et al. for studying the effect of mixing canola, soybean and peanut methyl ester with 15W40 lubricating oil on its tribological behaviour by using a pin-on-disc tribometer. The test was conducted on pin made from AISI 316 stainless steel and disc made from AISI 1018 under hydrodynamic or wet lubricating conditions. They find that biodiesel’s dilution in any proportion degrades the lubricating properties of 15W40 conventional oil [6]. Shahabuddin et al. conducted an experiment by using a blend of jatropha methyl ester with SEA 40 lubricating oil on a pin-on-disc tribometer under a constant load of 30N and 2000 RPM of a disc rotating speed for one hour to find its lubricating properties. For this experiment, the lubricating condition was kept as hydrodynamic and the pin and rotating disc were fabrication from aluminium and cast-iron. According to their claimed results, the accumulation of 10% of jatropha methyl ester in SEA 40 shows optimum results for an application like automobile. That blend shows best results with respect to viscosity, friction coefficient increment in temperature, wear, etc. [7].

2. Experimental methodology and materials

2.1. Selection of biodiesel
Although it has been recognized that biodiesel may be the superlative replacement of diesel and having the capability to fulfill the need of current diesel engines however deciding on superior biodiesel is a chunk of a tough challenge. For the current experiment, two biodiesels (Castor and
Rapeseed) and their optimum blend (15CA15R) are selected based on their availability, lubricating, performance, combustion, and emission properties are directly connected to the physical, chemical and fatty acid concentration of the biodiesel. The seeds of Castor and Rapeseed are found in abundant quantity in India and they are also non-edible. These plants does not require any additional care during their growth. Amongst the non-edible biodiesels, Castor and Rapeseed have been widely explored as useful sources of biodiesel. Various researchers have performed an experiment on single biodiesel and their biodiesel-diesel blend and found some pros and cons of every biodiesel after that, they suggested that combining two biodiesel together can improve their physical, chemical and lubricating properties. Retaining this as an initial objective for identifying the tribological behaviour of biodiesel two biodiesels and their blend were chosen. The Castor biodiesel has a high concentration of acid value, highest viscosity, density, lower cetane number and worst cold flow properties on the other hand, the Rapeseed biodiesel has lower acid concentration, lower viscosity, density, cetane number, flash point, improved cold flow properties. Because of the reasons mentioned above, they together can counter each other’s properties. Therefore Rapeseed biodiesel is the suitable choice for making a dual biodiesel blend with Castor biodiesel.

This biodiesel was made via transesterification process by mixing raw Castor and Rapeseed oil with methanol separately at 60°C. Potassium hydroxide is used as a catalyst to enhance the reaction in both cases. The mixture of raw oil and methanol with potassium hydroxide is kept for 12 hours for a proper reaction; after that, the glycerine and biodiesel were separated. Fatty acid composition present in biodiesel, physical and chemical properties of biodiesels are shown in Table 1.

| Table 1. Fatty acid composition and physical-chemical properties of Castor and Rapeseed biodiesel. |
|---|---|---|
| Fatty acid composition (%) | Biodiesel | Castor | Rapeseed |
| Caprylic (C8:0) | - | - | - |
| Capric (C10:0) | - | - | - |
| Lauric (C12:0) | - | - | - |
| Myristic (C14:0) | - | - | - |
| Palmitic (C16:0) | 2.64 | 4.9 | |
| Palmitoleic (16:1) | - | - | - |
| Stearic (C18:0) | 1.52 | 2 | |
| Oleic (C18:1) | 4.69 | 62.8 | |
| Linoleic (C18:2) | 8.4 | 19.4 | |
| Linolenic (C18:3) | - | 8.9 | |
| Ricinoleic (C18:1:OH) | 81.9 | - | |
| Arachidic (C20:0) | - | 1.9 | |
| Gondoic (C20:1) | - | - | |
| Behenic (C22:0) | - | - | |
| Erucic (C22:1) | - | 1.2 | |
| Lignoceric (C24:0) | - | - | |
| Physical-Chemical properties | | | |
| Viscosity at 40 °C (mm²/s) | 280 | 34.7 | |
| Density (x10³kg/m³) | 0.961 | 0.92 | |
| Flash Point (°C) | 240 | 321 | |
| Pour Point (°C) | 2.7 | -14.8 | |
| Cold filter plugging point(°C) | 7.1 | -12.8 | |
| Cetane number | 39.48 | 54.21 | |
| Calorific value (MJ/kg) | 38.6 | 36.8 | |
2.2. Functional group & chemical composition analysis
The chemical functional group of diesel, biodiesels and their blend have been obtained by using G-FTIR. The spectra were obtained using a Fourier transform infrared spectrometer (Perkin-Elmer, model Frontier, USA), standard temperature LiTaO3 MIR detector, and an SNR value of 9,300:1, high-performance DTGS MIR detector with an SNR value of 14,500:1, temperature-stabilized. Optical system with windows of KBr for collecting data over a 8,300 – 350 cm⁻¹ spectral range at a resolution of 0.5 cm⁻¹ and the composition of biodiesel was analyzed by Gas chromatography-mass spectroscopy (GC-MS) in Shimadzu GC-2010 and using a Fused Silica capillary column having 30 m x 0.25 μm film thickness RTX-5. N-pentadecane (NC15) was used as an internal standard. A stock solution of acetone with a known amount of N-pentadecane was prepared a priori and used for analysis.

2.3. Selection of metal for pin preparation
A diesel fuel system's role is to spray a precise amount of atomized and pressurized fuel inside every engine's cylinder at the demarcated time. The diesel engine's essential parts are the fuel system, which comes in direct contact with diesel/biodiesel, i.e., injection nozzles, injection pump, fuel transfer pump, fuel tank, and fuel filters. Ferrous and non-ferrous materials, i.e., cast irons, steel, copper and aluminium alloys, come in direct contact with fuel. Rubber is the common non-metallic ingredients of the components used in the fuel systems [8-9]. Fuel gets transferred and gets in touch with these materials under different situations and these are the sources for deterioration and degrades of fuel supplying components diversely. The lift pump, fuel filter, plunger pump, injection pump, priming pump, diesel fuel tank, and injection nozzles are the fuel system's key components that directly contact diesel/biodiesel. Based on this concept, an elementary has been conducted on the existing engine parts (Make: Kirloskar, Model: TV1) and from that test, pins are prepared, pin composition is as shown in Table 2.

| Elements (%) | Components of CI Engine |
|--------------|-------------------------|
|              | Connecting Rod Bearing | Piston | Piston Ring | Exhaust Valve | Inlet Valve | Cylinder Liner |
| S 0.023       | -                       | 0.03   | 0.074       | 0.074         | 0.028       |
| Sn -          | 0.016                   | -      | -           | -             | -           |
| Cr 16.94      | 0.016                   | 19.11  | 0.043       | 0.043         | 17.02       |
| Ni 10.95      | 0.66                    | 9.06   | 0.046       | 0.046         | 11.05       |
| Fe 68.99      | 0.93                    | 68.77  | 93.651      | 93.651        | 68.74       |
| Mg 0.013      | 0.49                    | 0.0083 | -           | -             | 0.02        |
| Pb 0.019      | 0.047                   | 0.0025 | -           | -             | 0.012       |
| Ti -          | 0.027                   | -      | -           | -             | -           |
| Zn 0.014      | 0.63                    | 0.014  | -           | -             | 0.015       |
| Si 0.89       | 13.25                   | 0.75   | 1.53        | 1.53          | 0.74        |
| Mn 1.85       | 0.11                    | 2      | 0.57        | 0.57          | 2.03        |
| C 0.082       | -                       | 0.08   | 3.38        | 3.38          | 0.088       |
| Al 0.02       | 82.23                   | 0.0016 | -           | -             | 0.023       |
| Co 0.02       | -                       | 0.0032 | -           | -             | 0.018       |
| Cu 0.018      | 1.58                    | 0.0119 | 0.46        | 0.46          | 0.013       |
| P 0.03        | -                       | 0.045  | 0.14        | 0.14          | 0.032       |

Initially, before starting the tribo-wear test based on the elementary analysis of actual engine components, three metals each for pin has been selected for the pins preparation and disc EN31 is
chosen as per ASTM G99-95a, the pins are having a size of 30 mm in length & 10 mm in diameter and disc having diameter and thickness of 175 mm & 10 mm. After fabrication and polishing, the grease was removed using a mixture of xylene–isopropanol in equal quantity v/v %. Before the test weight of each pin was recorded up to an accuracy of 0.1 mg [10].

2.4. Wear test parameters

Friction tests were carried out for the selected biodiesels to characterize their frictional properties under wet lubrication and pure sliding motion according to ASTM: G 99-95a standard using a pin-on-disc tribometer. Test fuels are diesel, two biodiesel (Castor and Rapeseed and their optimum blend 15CA15R (70% Diesel + 15% Castor + 15% Rapeseed). The test is performed using a tribometer configured for a pin-on-disc (Make: Ducom Instruments, Model: Micro POD). In this study, the metal disc is rotated against a stationary metal pin, the dimension and elemental composition have been selected as per ASTM: G 99-95a. To simulate the actual sliding condition the sliding speed and load were selected as 5.5 m/s and 70 N because as the engine used in our previous research was a constant speed CI engine (Make: Kirloskar oil engine ltd. Model: TV1) which runs at 1500 RPM and the full rated load of the engine was 12 kg as it is well known that the engine is not continuously running on its rated full load in real life. So as per the load factor provided by SCC-2270005055 of US EPA document titled as ‘Median life, annual activity, and load factor values for non-road engine emissions modeling NR-005b’ for the current engine load factor is provided as 0.59 or can be said as 59% [11]. That’s why the sliding speed and load were selected as 5.5 m/s and 70 N others operating parameters are shown in Table 3.

2.5. Weight loss and volume loss analysis

To recognize weight reduction and volume loss because of wear, before and after the tribo-wear test the metal pins were appropriately cleaned so that all debris of metal, lubricant and dirt can be distant and after the cleaning, metal pins were investigated to get their weight with a precision of three digits after decimal so a minor variation in weight can likewise be noted down and this test is led with weighing machine-accessible at NABL licensed research laboratory. Using the weight loss and density of metal, one can quickly identify the volume loss. For this, the below-mentioned equation was used which is given by ASTM G 99-95a. Other details i.e., Density of metal, are mentioned in Table 3. The volume loss has been obtained by equation 1, provided by the ASTM standard.

\[
Volume\ Loss\ (mm^3) = \frac{Before\ weight\ (g)-After\ weight\ (g)}{Alloy\ Density\ (\frac{g}{cm^3})}
\]  

(1)

| Track Diameter | RPM | Tip Velocity (m/s) | Lubricant Flow Rate Litre/Min | Pin Metal | Metal Density Kg/m³ | Pin Length (L&D) | Load (N) | Sliding Distance (m) |
|----------------|-----|------------------|-------------------------------|-----------|---------------------|------------------|----------|---------------------|
| 95 ± 0.01 mm   | 1105| ± 1              | 0.333 ± 0.02 Max flow         | Aluminium | 2700 ± 1           | 30 ± 0.01       | 70 ± 1   | 10000 ± 1           |
| 125 ± 0.01 mm  | 840 | ± 1              | 5.5 ± 0.01 Max flow           | Copper    | 8940 ± 1           | 0.01 mm         | ± 0.01   | ± 1                 |
| 135 ± 0.01 mm  | 778 | ± 1              |                               | Iron      | 7870 ± 1           | 0.01 mm         | 10 ±     | ± 0.01              |

*Note: L: Pin length, D: Pin diameter

2.6. Microscopic Surface Analysis
After the tribo-wear test led by tribo-tester instrument, adequate data was found, but for the complete analysis, a detailed qualitative analysis has to perform for that an image was taken from scanning electron microscope (SEM), Make: Hitachi, Resolution SE: 3.0nm at 30kV (vacuum mode), Hitachi patented Quad Blass function instead of expensive LaB6-tips, Motorized: 5 axes in standard) at a magnification of 500X so that a detailed surface analysis can be done and along with this, the detection of wear type can also be recognized.

3. Result and Discussion

3.1. Weight loss analysis
Weight loss analysis can be defined as the reduction from the initial to the final weight of the pin due to rubbing on the disc. A very minute reduction in weight can be observed with the biodiesel, as shown in figure 1, their weight losses are gradually increasing as we move towards the 15CA15R and diesel. The probable reason might be due to the presence of fatty acid and also due to the high viscosity of biodiesel. It has good lubricating properties in comparison to diesel, which results in a reduction of pin weight. As with the government, new emission norms the diesel fuel has been more refined and the quantity of sulphur has to be reduced to 10ppm (BS-VI; nationwide), which ultimately leads to reducing the emission, but along with that the diesel fuel will lose its lubricating properties which can be seen from figure 1 there is 37, 369 and 150 mg reduction in weight by use of diesel with aluminium, copper and iron pin. With the use of other biodiesels, pins are showing variation marginally in their weight. The blend of diesel, Castor and Rapeseed biodiesel has shown relatively good results compared to pure diesel. This blend can fulfill the demand of the modern automotive society for metal wear and regulatory emission norms.

3.2. Effect of biodiesel on the coefficient of friction

![Figure 1. Weight analysis of metal pins (Aluminium, Copper & Iron) with fuels (Diesel, Castor, Rapeseed and 15CA15R).](image)

Lubricated friction can be classified into three regimes: (BL – Boundary layer), (ML- Mixed layer) and (EHL- Elasto hydrodynamic). In contrast with the lubricated wet friction based on operating
conditions such as the temperature, lubricant viscosity, sliding speed, etc., shown in Table 1 and 3. The trend of the coefficient of friction (CoF) follows the trend shown in figure 2. For the current case, all the operating parameters are kept constant and from the result, it has been identified that with every test fuel, the value of CoF till 1000 m is quite high. From figure 2 it has been identified that in comparison to aluminium and copper pins, the iron pins have more CoF the reason behind this is that the CoF depends on the materials used, i.e., the disc is also made from an iron alloy (EN31) and the pin is also having similar kind of composition due to that the CoF increases. Another finding is related to the drastic difference between the CoF value of pins with diesel in comparison to biodiesel and 15CA15R; the probable reason is due to the higher content of viscosity, which helps to reduce the friction in between the pin and disc, the lubricating film is found to be stable in biodiesel in compare to diesel which also leads to a reduction in CoF [12].

3.3. Effect of biodiesel on the friction force

The friction force is generated due to the opposite movement between the fixed pin and rotating disc surfaces. As no surface is perfectly smooth, which is the main cause of friction. In lubricated wet friction, a fuel separates two surfaces of pin and disc. The graph of friction force between pin and disc with each test fuel is shown in figure 3. Figure 3 shows that similar to CoF, the friction force also follows the same trend and the probable causes are already discussed above. During the experiment, it has been observed that scratching sound generated due to friction between pin and disc was found to be highest in the iron pins because of more friction force. The friction force trend remains more or less constant in the case of pins that are in contact with Castor, Rapeseed and 15CA15R after 2000 m till the last phase of the experiment. But pins with diesel have shown drastic fluctuation in their results from the beginning to end of the experiment. The probable reason for this is due to the low viscosity of diesel in comparison to other fuels. Oxygen bonds in biodiesel are superior lubricity providers in comparison to sulfur present in diesel.

3.4. Effect of biodiesel on wear

![Figure 2. Coefficient of friction analysis of metal pins (Aluminium, Copper & Iron) with fuels (Diesel, Castor, Rapeseed and 15CA15R).](image)

Wear can be defined as damaging, slow removal and distortion of material from surfaces. There are various causes of wear, but in the current case, due to sliding motion, fatigue, and creep, mechanical
wear occurs between pin and disc. These types of study are also known as tribology as material wear has greater economic significance, as discussed by Jost Report [13]. Figure 4 shows that with diesel, the wear in aluminium, copper and iron pin is found to be approx. 150 μm, which is not even come closer to its blend 15CA15R.

Similarly, in almost all the cases, in the case of copper pins, after covering 2000 m of sliding distance, the wear has gradually reduced. An approx. of 290 μm of wear can be clearly seen with diesel fuel with iron; due to high CoF and FF, the fatigue, surface removal, or distortion occurred, which results in more wear in comparison to biodiesel and their blends. The absence of fatty acid composites which provide better lubricity against friction than hydrocarbons, due to the presence of polarity-impacting O radicals, free fatty acids, monoacylglycerols provides superior lubricity than pure esters and the presence of free OH groups, presence of double bonds and chain length are can be the probable reasons of the improved lubricating property of biodiesel in compare to diesel [14].

3.5. Microscopic Surface Analysis
Microscopic analysis can be defined as the in-depth study at the micro-level of the interface between two surfaces, from physics, chemistry and mechanical engineering, and material science. Figure 5 a detailed study of pin surface analysis, which shows the compound layer removal and deep grooved on the surface of aluminium and iron pin with diesel fuel. Secondly, with 15CA15R blend of Castor and Rapeseed, abrasive and plastic deformation can be seen at some point of pin surface. Due to the presence of free fatty acid and dissolved oxygen in biodiesel, the lubricity properties enhance, resulting in very fine surface removal and abrasion of metal from the surface. Compared to Castor and Rapeseed biodiesel, Castor biodiesel has better lubricity property, which is visible in figure 5. Due to the high presence of dissolved oxygen in Castor and Rapeseed biodiesel, the surface also gets some oxide film layer.

![Figure 3](image-url)  
**Figure 3.** Friction force analysis of metal pins (Aluminium, Copper & Iron) with fuel (Diesel, Castor, Rapeseed and 15CA15R).
Figure 4. Wear analysis of metal pins (Aluminium, Copper & Iron) with fuel (Diesel, Castor, Rapeseed and 15CA15R).

| Scanning electron microscope analysis (S3400 15.0kV  X 500 SE) after wear test |
|-------------------------------|
| Diesel | Castor | Rapeseed | 15CA15R |
| Aluminium | ![Aluminium Diesel](image1) | ![Aluminium Castor](image2) | ![Aluminium Rapeseed](image3) | ![Aluminium 15CA15R](image4) |
| Copper | ![Copper Diesel](image5) | ![Copper Castor](image6) | ![Copper Rapeseed](image7) | ![Copper 15CA15R](image8) |
| Iron | ![Iron Diesel](image9) | ![Iron Castor](image10) | ![Iron Rapeseed](image11) | ![Iron 15CA15R](image12) |

Figure 5. Microscopic analysis of metal pins (Aluminium, Copper & Iron) with fuel (Diesel, Castor, Rapeseed and 15CA15R).
4. Conclusion
The final consequence of the present experimental analysis has led to the following conclusion:

- The tribological behavior includes friction force, coefficient of friction, wear and from the results, it has been proven that biodiesel is the best substitute for diesel.
- SEM results show lower surface wear and tear in biodiesel in comparison to diesel.
- 15CA15R has a nearly similar calorific value and better lubricating properties in comparison to pure diesel.
- B30 (15CA15R) blend can be considered as the best-compromised fuel for the existing diesel engines.

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