Friction and Wear Characteristics of Calophyllum Inophyllum and Moringa Oleifera Biodiesel Blends

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Abstract: This study is conducted to investigate the friction and wear characteristics of Calophyllum inophyllum and Moringa oleifera biodiesel-blends using a four-ball triborheometer. The tests were conducted at different loads (40, 50, 70, and 80 kg) at a constant speed of 1800 rpm and room temperature of 27 °C over a 300-s period. The average coefficient of friction of diesel is 24.93% higher than that for the blend containing 10 vol% of Moringa oleifera biodiesel (MB10). Moringa oleifera biodiesel contains 74% of oleic acid, which can reduce friction from metal contacting surfaces. The biodiesels result in lower frictional energy loss and minimum wear on the metal surfaces. The blends containing 20 vol% of Calophyllum inophyllum biodiesel and Moringa oleifera biodiesel (CIB20 and MB10) show the best results with the lowest coefficient of friction, offering excellent lubricating properties.

1 INTRODUCTION

Friction is a phenomenon that occurs when two contacting surfaces are in relative motion, which has a significant effect on fuel efficiency. Friction is of interest to vehicle and engine manufacturers as well as lubricant manufacturers because friction leads to wear, where the minute surface asperities of the two contacting surfaces become locked and grind against one another, resulting in the removal of material. Wear can also occur due to the electromagnetic forces between the molecules of the two contacting surfaces, as well as chemical reactions between the contacting surfaces and the environment. Many studies have been carried out to reduce friction and thus, minimize wear of contacting surfaces such as the development of surface coatings (Arslan et al., 2015), modifications of the surface textures (Ahmed et al., 2016; Arslan et al., 2016), the use of lightweight materials (Quazi et al., 2016), and the improvement of lubrication formulations.

Lubricant is a substance (which can be solid, liquid, or gas) used to form a barrier between the asperities of the contacting surfaces in order to minimize friction and wear. Various additives have been used to (1) maintain the temperature sensitivity of the lubricant viscosity, (2) protect the contacting surfaces from friction and wear by the formation of a protective film, (3) reduce solid-to-solid friction by making the surfaces more slippery, (4) keep the contacting surfaces clean and free from debris, and (5) maintain the properties of the lubricant within acceptable levels. In recent years, lubricant additives derived from ash in the exhaust stream have become important in the field of advanced diesel engines equipped with emission aftertreatment control systems (Priest and Taylor, 2000).

Friction in internal combustion engines arises from

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the shearing of oil films between the various working surfaces such as fuel pumps, reciprocating pistons, piston cylinders, piston liners, fuel injectors, fuel depositors, and piston rings. Therefore, lubrication plays an important role to minimize friction and wear of engine components (Taylor, 1998). Lubrication protects the engine components from damage caused by friction and wear. The frictional energy losses caused by the moving engine components will eventually increase the fuel consumption of the engine and reduce engine life, which indicates the importance of lubrication (Tung and McMillan, 2004). However, the presence of a lubricant may lead to undesirable changes in the fuel properties such as an increase in the fuel kinematic viscosity and density, which in turn, leads to an increase in the absorbency of water and corrosion of the engine components. In addition, lubricant carries solid contaminants from combustion, some of which cannot be filtered, and this leads to plugging of the filters (i.e., the contaminants adhere to and clog the filters) and coking of the fuel injectors (i.e., the chemically degraded lubricant components and combustion products adhere to the surface of the fuel injectors) (Fazal et al., 2011).

Nowadays, there is great interest in investigating the lubricity of biodiesels, and not just the potential of biodiesels as a fossil fuel alternative, which helps eliminate the use of a lubricant. According to Serrano et al. (2012), biodiesels provide lubrication to the fuel pumps and injectors. Dharma et al. (2016) and Silitonga et al. (2019) found that biodiesels have good fuel lubricity in addition to good engine perfromance and lower exhaust emissions compared with diesel. Likewise, Hu et al. (2005) found that biodiesels have good lubricity, which helps in ensuring smooth movement of engine parts. Van Gerpen et al. (1999) compared the lubrication characteristics of soybean oil and soybean biodiesel and found that the soybean biodiesel has favourable tribological characteristics.

Several studies have been carried out to evaluate the lubricating properties of the biodiesel blends, and there is a decrease in the coefficient of friction, depending on the type of biodiesel. Better tribological characteristics have been observed for blends with different percentages of additive (Silitonga et al., 2013). Fazal et al. (2013) investigated the tribological characteristics of palm biodiesel and its blends (B10, B20, B50, and B100) at a constant load of 40 kg, temperature of 75 ℃, and different rotational speeds (600, 900, 1200, and 1500 rpm). They found that both friction and wear were reduced with a higher concentration of biodiesel in the fuel blend. Much effort has been made to investigate the potential of using Calophyllum inophyllum biodiesel as a lubricant despite its higher unsaturated fatty acid content (Milano et al., 2018), higher viscosity and density (Ong et al., 2019), lower oxidation stability, higher acid value, and higher flash point compared with biodiesels produced from other non-edible plant-based oils (Mosarof et al., 2016). Calophyllum inophyllum and Moringa oleifera biodiesels have been proven to have a higher viscosity, flash point, and acid value, and better lubricity than diesel and other biodiesels (Silitonga et al., 2013).

Previous studies (Fazal et al., 2013; Habibullah et al., 2015) have been carried out to investigate the tribological characteristics of palm and Calophyllum inophyllum biodiesel blends. However, to date, there are no studies focused on the friction and wear characteristics of Calophyllum inophyllum and Moringa oleifera biodiesel blends, which is worthy of investigation. Therefore, the objective of this study is to investigate the friction and wear characteristics of Calophyllum inophyllum and Moringa oleifera biodiesel blends. It is believed that this study will provide insight on the potential of Calophyllum inophyllum and Moringa oleifera biodiesel blends as a lubricant, thereby eliminating the need for an additional lubricant in diesel engines.

2 MATERIALS AND METHODS

2.1 Biodiesel Production

The crude Callophyllum inophyllum and Moringa oleifera oils were initially heated in a vessel at ~100℃ for approximately 15 min order to remove moisture, which can reduce the biodiesel yield. The crude Calophyllum inophyllum and Moringa oleifera oils were then left to cool to below 60 ℃ before adding a catalyst-alcohol solution, which was prepared by dissolving 1 wt% of potassium hydroxide into 25 vol% methanol for the transesterification reaction. The transesterification reaction was conducted for 2 h at a stirring speed of 1000 rpm. After the transesterification reaction, the mixture was poured into a separatory funnel. Two layers eventually formed in the separatory funnel, where the top layer was biodiesel and the bottom layer was a mixture of glycerine and other impurities. The bottom layer was removed by opening the stopcock of the separatory funnel. The biodiesel was then collected and washed with distilled water several times to remove the remaining impurities. The purified biodiesel was then dried using a rotary evaporator and then filtered with filter paper. The Calophyllum inophyllum biodiesel

Table 1: Physicochemical properties of diesel, calophyllum inophyllum biodiesel, moringa oleifera biodiesel, and calophyllum inophyllum and moringa oleifera biodiesel blends.

Property	Unit	Standard	Diesel	CIB10	CIB20	CIB100	MB10	MB20	MB100
Kinematic viscosity at 40 ℃	mm2/s	D445	34.926	37.318	37.986	49.762	35.611	36.924	51.338
Density at 15 ℃	kg/m3	D4052	857.6	859.5	860.4	887.2	859.1	860.3	877.6
Acid value	mg KOH/g	D664	0.072	0.22	0.24	0.41	0.19	0.20	0.287
Oxidation stability	h	EN 15751	35	27.70	25.19	2.53	108.6	91.4	26.4
Flash point	℃	D93	68.5	72.3	73.1	92.6	79.5	82.1	150.6
Calorific value	MJ/kg	D240	45.6	44.48	43.86	39.17	44.3	43.6	39.8

(CIB100) and Moringa oleifera biodiesel (MIB100) were then blended with diesel to produce biodiesel blends. The following blends were prepared: (1) CIB10 (10 vol% of Calophyllum inophyllum biodiesel + 90 vol% of diesel), (2) CIB20 (20 vol% of Calophyllum inophyllum biodiesel + 80 vol% of diesel), (3) MB10 (10 vol% of Moringa oleifera biodiesel + 90 vol% of diesel), and (4) MB20 (20 vol% of Moringa oleifera biodiesel + 80 vol% of diesel).

2.2 Physicochemical Properties of Biodiesel

The physicochemical properties (kinematic viscosity at 40 °C, density at 15 °C, flash point, acid value, oxidation stability, flash point, and calorific value) of the CIB10, CIB20, MB10, and MB20 blends were determined according to standard methods and the results were compared with those for diesel, CIB100, and MB100, as shown in Table 1.

2.3 Test Procedure

The test fuels were then tested for both sliding and rolling contacts. The sliding contact tests were conducted using a four-ball triborheometer (Model: TR-30H), as shown in Fig. 1. The test balls were cleaned with toluene to remove oil stains and impurities and then dried with a clean paper towel. For each test, 10 mL of the test fuel was poured into a steel cup to cover the stationary balls and then the steel cup was placed into the four-ball triborheometer. The upper steel ball was rotated against the three lower stationary balls, forming a tetrahedron. The frictional data were collected using software installed in a desktop computer. Four loads were used for the tests: 40, 50, 70, and 80 kg. The speed of the rotating ball was set at a constant speed of 1800 rpm at room temperature (27 °C) for 5 min. The operating conditions were carried out according to ASTM D2596 and ASTM D2783 standards, as tabulated in Table 2. The data were used to calculate the coefficient of friction (CoF) using Eq. 1 (Liaquat et al., 2013).

Coefficient of friction, μ =

$$\frac{\text{Friction torque (kg·mm)} \times \sqrt{6}}{3 \times \text{Applied load (kg)} \times \text{Distance (mm)}} = \frac{T\sqrt{6}}{3Wr} \quad (1)$$

where T is the frictional torque in kilogramme millimetres (kg-mm), W is the applied load in kilogrammes (kg) and r is the distance measured from the centre of the lower ball's surface to the rotation axis in millimetres (mm). Here, r is 3.67 mm.

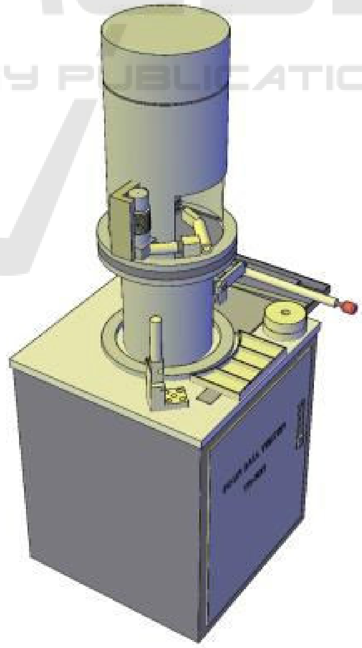

Figure 1: Four-ball triborheometer.

Table 2: Operating conditions for the four-ball triborheometer.

Machine operating conditions	
Parameter	Value
Load	40, 50, 70 and 80 kg
Speed	1800 rpm
Temperature	Ambient (27 °C)
Test duration	5 min
Specifications of the test balls	
Materials	Carbon-chromium steel (SKF)
Size (ϕ)	12.7 mm
Hardness	62 HRc
Elemental composition	85.06% Fe, 10.2% C, 0.12% P, 0.45% Si, 1.46% Cr, 0.07% S, 0.42% Mn, 2.15% Zn, 0.06% Ni,
Surface roughness	0.1 µm (centre line average)

2.4 Wear Evaluation

The four-ball triborheometer was used to assess the lubricity of the Calophyllum inophyllum and Moringa oleifera biodiesel blends. An optical microscope (Model: C200, IKA, UK) with a resolution of 0.01 mm was used to measure the wear scar diameter of the test balls. The wear scar images of the test balls were captured, and the wear scar diameter was measured using the computer software. After each test, the average wear scar diameters of all the test balls were determined. Calculating total magnification of microscope requires knowing the magnification of the ocular (eyepiece) and of the objective lens being used. The wear was evaluated for all of the test balls in this study. The wear scar diameters of the three stationary balls were measured, and the average value was determined.

3 RESULTS AND DISCUSSION

3.1 Kinematic Viscosity

The kinematic viscosity of a lubricant is strongly dependent on its composition, with higher kinematic viscosity being associated with higher molecular weight. The lubrication effect on metal contacting surfaces is determined by the viscosity of the lubricant. Kinematic viscosity can increase or decrease during engine operation, which determines the properties of the lubricant. The products of condensation and polymerization reactions, which take place under high thermal stress of the lubricant, as well as the presence of oxidation products contributes to the increase in kinematic viscosity. It shall be noted that high engine speeds enhance fuel dilution, which leads to a significant decrease in the kinematic viscosity, resulting in more wear. However, friction is slightly reduced, which is probably due to the drop in kinematic viscosity (Kalam et al., 2012). The wear caused by soot occurs through abrasive wear mechanism, where the soot antagonistically interacts with the protective tribofilms formed by the anti-wear additives and worsens the wear of engine components. The kinematic viscosities of the Calophyllum inophyllum and Moringa oleifera biodiesel blends and diesel at 40 and 100 °C are shown in Fig. 2. The MB100 biodiesel has a higher kinematic viscosity than diesel and CIB100 biodiesel. Viscosity and frictional forces can develop by the shearing of the viscous lubricant. Corrosive wear can occur on the bearing surfaces due to the presence of lubrication. Adhesive wear is possible at the initial and end processes. Corrosive wear can be reduced through lubricant precipitation and formation of films on the bearing surface (Serrato et al., 2007). Therefore, a lower kinematic viscosity leads to more wear on the sliding surface, whereas a higher kinematic viscosity causes frictional losses during sliding of the metal components. From Table 1, the MB100 biodiesel has a higher kinematic viscosity compared to diesel and other biodiesel blends. A higher viscosity index indicates less viscosity variation with respect to changes in temperature, whereas a lower viscosity index indicates high changes in viscosity with respect to temperature. These results can be attributed to the triglyceride compounds in the vegetable oils while sustaining stronger intermolecular interactions when the temperature is rising (Ahmed et al., 2014). Hence, the Moringa oleifera biodiesel blends in this study are found to reduce more wear on the metal contacting surfaces than Calophyllum inophyllum biodiesel blends. The results indicate that the Moringa oleifera biodiesel blend is suitable for boundary lubrication applications.

3.2 Friction

Friction is the force resisting the relative motion of two mating surfaces in contact with a fluid. The two sliding surfaces move relative to each other, and the friction between the mating surfaces converts the kinetic energy into heat or thermal energy. In this study, the CoF values are presented with respect to the running-in period and steady-state condition. The running-in period is the period where the test balls are first brought into contact and slid over one another, and it is a transient event. The CoF values

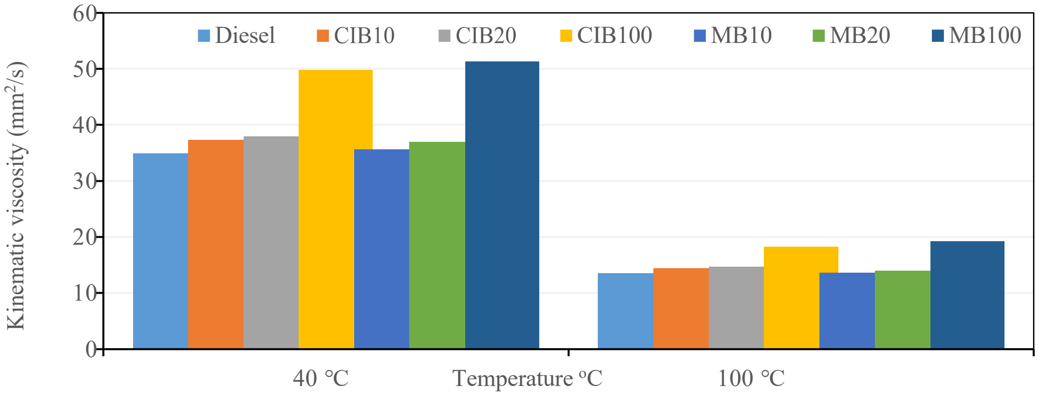

Figure 2: Kinematic viscosities of diesel, Calophyllum inophyllum biodiesel, Moringa oleifera biodiesel, Calophyllum inophyllum and Moringa oleifera biodiesel blends at a temperature of 40 and 100 °C.

of diesel and Calophyllum inophyllum and Moringa oleifera biodiesel blends during the running- in period of 10 s under a load of 80 kg are shown in Fig. 3. The CoF is one of the key parameters to analyse the tribological characteristics of the test fuels. It can be seen that within the 10-s period, the CoF is unstable and exhibits a higher magnitude. The maximum CoF values are found to be 0.5454, 0.4933, 0.5126, and 0.4959 for the CIB10, CIB20, MB10, and MB20 blends, respectively. The CoF of the diesel fuel is 0.5316 and the highest CoF is obtained for the CIB10 blend, with a value of 0.5454. The CoF values of the characteristics of test fuels for steady-state condition under a load of 80 kg load is shown in Fig. 4. In steady-state condition, diesel has a higher CoF and the value eventually stabilizes after 292 s. The CIB20 blend shows a similar CoF trend as diesel. The CoF trends are similar for the CIB10, MB10, and MB20 blends. In general, the Moringa oleifera blends have a lower CoF compared with diesel and Calophyllum inophyllum blends in steady-state condition. The Calophyllum inophyllum and Moringa oleifera blends have a lower CoF than diesel. Diesel has a slightly higher CoF than the CIB10, CIB20, MB10, and MB20 blends by 13.47, 4.21, 24.93, and 23.48%, respectively. The MB10 blend has the lowest CoF compared with the other fuel blends. The lubricating ability of the fuels due to their very low viscosity is mostly dependent on their boundary film forming properties. At the same time, the sensitivity of biodiesel towards oxidation may vary and is mainly dependent on the feedstock and presence of natural antioxidants (Zulkifli et al., 2013). The high oleic acid content of Moringa oleifera biodiesel is the main reason for the lower friction characteristics of the Moringa oleifera blends. The CIB20 blend results in more friction, especially at a high applied load. Therefore, biodiesel (which has fatty compounds) possesses better lubricity than hydrocarbons and the lubricity somewhat improve with the chain length and presence of double bonds (Knothe and Steidley, 2005; Kumar et al., 2014). The Moringa oleifera biodiesel and its blends reduce the friction caused by two metal contacting surfaces compared with the diesel and Calophyllum inophyllum blends. The lubrication performance of Moringa oleifera biodiesel blends decreases with an increase in the load applied to the contacting surfaces. Therefore, Moringa oleifera biodiesel has lower friction characteristics in running-in period and steady-state condition under a high applied load. For longer periods, oxidation may occur, which causes fuel debasement and results in a higher steady-state CoF. Biodiesel is susceptible to oxidation due to the presence of unsaturated fatty acids in its moiety. These reactions are accelerated in the presence of oxygen and high temperatures, which may alter the lubrication characteristics (Agarwal, 1999; Kumar et al., 2014).

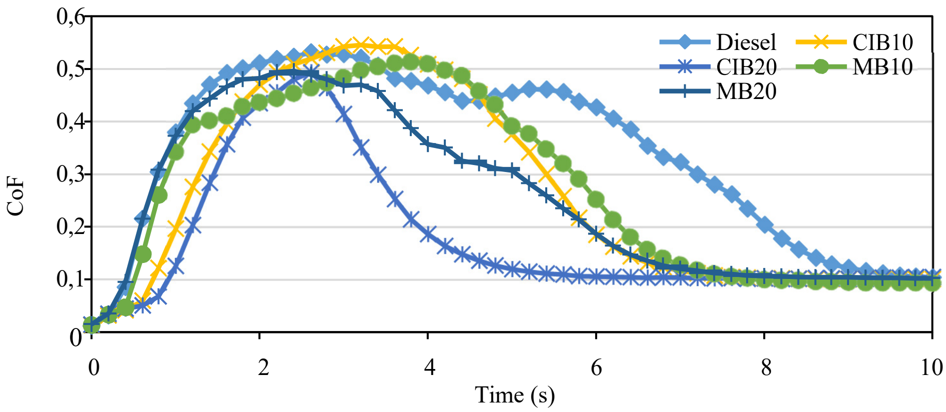

Figure 3: Friction characteristics of diesel and Calophyllum inophyllum and Moringa oleifera biodiesel blends during the running-in-period.

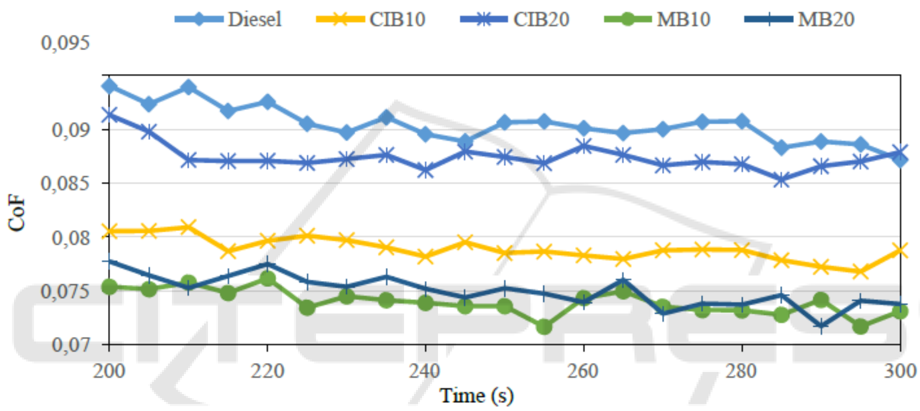

Figure 4: Friction characteristics of diesel and Calophyllum inophyllum and Moringa oleifera biodiesel blends during steady-state condition.

3.3 Wear Scar Diameter (WSD)

The wear scar diameter (WSD) was measured by an optical microscope. The morphologies of the worn surface reveal that the nanoparticle concentrations improve the friction and wear properties of liquid paraffin. The WSDs of the surfaces lubricated with the test fuels are shown in Fig. 5. The average WSDs of the CIB10, CIB20, MB10, and MB20 blends are higher by approximately 9.38, 39.30, 3.36, and 2.27%, respectively, relative to that for diesel. The smallest WSD is obtained for the CIB20 blend regardless of load, and the WSD is significantly lower compared with those for the CIB10, MB10, and MB20 blends. The result indicates that diesel results in the largest WSD for all load conditions. In general, the larger the WSD, the more severe the wear (Syahrullail et al., 2013). The WSD is determined by the applied load. The scar will be larger as the load pressurizing the metal contacting surfaces increases, resulting in more wear. Biodiesels also have a high oxygen content, which helps to reduce friction and wear of the steel contacting surfaces. The susceptibility of biodiesel to oxidation upon exposure to oxygen is due to its unsaturated fatty acid chains, especially those with bis-allylic methylene moieties. The bis-allylic protons are highly susceptible to radical attacks and subsequently, the molecules undergo oxidation. It can be deduced that the biodiesels enhance the lubrication property through the development of lubricating films. The efficiency of the lubricant and the film formed is dependent on the fatty acid chain length (Havet et al., 2001).

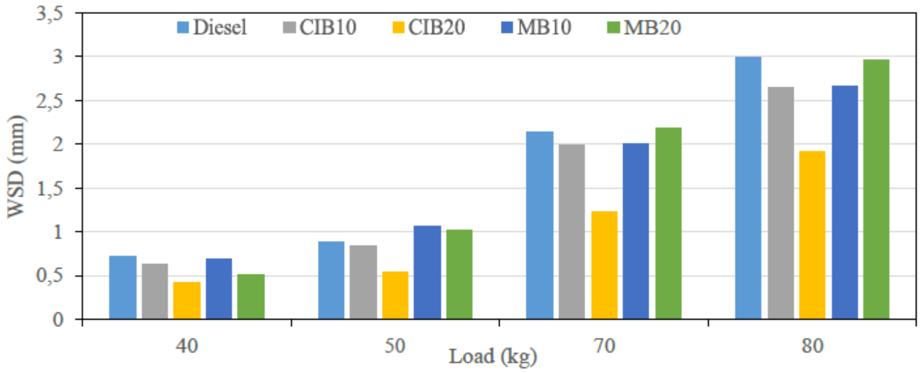

Figure 5: WSD of biodiesel blends with the variations of load.

4 CONCLUSIONS

Biodiesels can be used as a lubricity enhancer, hydraulic fluid, cutting fluid, drilling fluid, viscosifier, and chain oil at moderate temperatures. A four-ball tribometer is a common research rig used in the lubricant industry to assist in manufacturing new lubricants and greases. This study was conducted to investigate the friction and wear characteristics of Calophyllum inophyllum and Moringa oleifera biodiesel blends. The findings of this study raise a serious question on the utilization of biodiesel blends in compression-ignition engine parts, especially for long-term applications. In this regard, it is imperative to add environmentally friendly modifiers into biodiesels to mitigate the effect of oxidative instability. Moreover, the biodiesel blends produce more abrasive wear whereas diesel produce adhesive wear. Powertrain manufacturers and additive suppliers can make use of the findings of this study to improve powertrain system efficiency, product performance, and fuel economy. Biodiesels can improve engine efficiency, powertrain durability, and vehicle performance in the engine life due to their lower friction and wear characteristics.

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