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*Research Paper*

# Castor Biodiesel Improves Lubricity of Low Sulphur Petro-Diesel Fuels

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**ABSTRACT**

Demand for fossil fuels has been continually increasing. The combustion of fossil fuels has a negative impact on air quality and human health and contributes to global warming. To reduce exhaust emissions from internal combustion engines, the sulfur content of fossil fuels should be lowered. The low sulfur content in petrodiesel reduces the lubrication properties of diesel fuels and thus causes wearing of the diesel engine fuel systems. In this study, biodiesel was added into petrodiesel and a ball-on-ring (BOR) wear tester was used to determine the optimal concentration of the blend. An optical microscope was employed to measure the average wear diameter of a steel ball and the lubricating efficiencies of the fuels were estimated. The experimental results verified that lubricating the steel ball using either the pure petrodiesel or castor biodiesel yielded a wear diameter of 1.13 or 0.94 mm, respectively. The results revealed that low-concentration biodiesel additives served as an effective lubricant. The biodiesel was composed of fatty acids with molecular layers thicker than those of the mineral-type petrodiesel; hence, the wear observed on the metal lubricated using the biodiesel was reduced. Therefore, the proposed biodiesel can be employed to effectively enhance the lubricity of a fuel under the condition of boundary lubrication.

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**Key words:** Biodiesel, diesel engine, lubrication, wear testing.

## INTRODUCTION

Fossil fuels are crucial to a nation's industry and economy. Demand for fossil fuels has been continually increasing. Therefore, identifying alternative fuels that are technically feasible, economically competitive, environmentally friendly and easy to obtain is imperative. Biofuel is a renewable form of energy that has a low environmental impact and is a viable substitute for fossil fuels. Using biofuels can meet vehicle exhaust emission standards, thus, facilitating environmental conservation and protecting human health (Ghobadian et al., 2009). Because diesel engines have high compression ratios, high thermal efficiency and low fuel costs, they are frequently used in large units such as vessels, heavy-duty trucks, construction machines, and generators (Gokalp et al., 2011).

Fuel injector performance in diesel engines generally depends on the lubricity of the fuel. Abrasion generally occurs when moving components of the fuel injectors are exposed to friction. The sulfur content of diesel must be reduced to 50 parts per million (ppm) for now and 10 ppm in near future to ensure environmental conservation and human health. Due to a reduction in the sulfur content of diesel fuels that lowers the lubricity, additives must be used to resist abrasion. Alternatively, using biodiesel also improves the lubricity of petrodiesel, particularly for ultra-low-sulfur diesel (Buyukkaya, 2010).

Because biodiesel does not contain sulfur, using biodiesel for diesel engines reduces sulfate and smoke emissions. Moreover, using biodiesel as a transportation fuel prevents inducing acid rain. Biodiesel exhibits physical and chemical properties that are similar to those of fossil fuels; hence, using biodiesel in diesel engines does not result in engine failure or damage. According to Puppan

(2002), the advantages of using biofuels over fossil fuels are that it is 1) a renewable form of energy; 2) environmentally friendly; 3) biodegradable and 4) sustainable.

Biodiesel contains no petroleum products, but is compatible with conventional diesel and can be mixed with fossil fuels at any ratios for stability; thus, it has become the most common biofuel in the world. Biodiesel is refined from vegetable oil (edible or inedible) or animal fat (methyl or ethyl esters) (Cao, 2003). There are more than 300 oil-bearing crops identified, among which only palm, soybean, safflower, sunflower, rapeseed cottonseed and peanut oils are considered as potential alternative fuels (Hamamci et al., 2011). Initial concerns over biodiesel production are production costs and how it competes with food production for edible raw materials. Due to the increasing demand for biodiesel, some inedible animal and vegetable oils are gradually receiving attention. Several non-edible oils like castor oil, Jatropha, karanja, Karanja, Neem, Tobacco, Waste edible oil, Moringa-seed oils and grease (Agarwal, 2007).

*Ricinus communis* belongs to the Eurphorbiaceae family and also called castor beans. It is non-edible oil seed crop that is easily grown and resistant to drought. The tree is grown in many countries such as United States, India, China, Central Africa, Brazil and Australia with different cultivation cultures. Its oil is viscous, slightly odor, pale yellow, non-volatile and non-drying oil with a bland taste and is sometimes used as a purgative. On the average, the seeds contain about 40 to 60% oil (Atadashi et al., 2008). Castor oil is a vegetable oil with excellent properties, particularly, the heat value and cetane number, both of which are relatively higher than those of other types of biodiesel.

Some scholars concluded that biodiesel and aliphatic compounds are more lubricative than conventional petrodiesel, particularly, petrodiesel fuels with low sulfur content. Researchers also concluded that biodiesel is more effective than petrodiesel for lowering exhaust emissions (Dwivedi et al., 2006; Fazal et al., 2011). Diesel engines using biodiesel emit 20% less CO, 30% less hydrocarbons, 50% less smoke and dust and 40% less particulate matter (PM) than those using petrodiesel as engine fuels. Liaquat et al. (2010) added blends of biodiesel in 25, 50 and 70% concentrations to conventional petrodiesel, respectively. The study results revealed that the mixed fuels reduced PM emissions considerably. However, Liaquat did not provide any convincing explanations about how this reduction occurred. Canakci and Van Gerpen (2001) investigated how two types of biodiesel (cooking oil and soybean oil) and conventional petrodiesel affect diesel engine exhaust emissions. The study results revealed that using both types of biodiesel were substantially more effective than conventional petrodiesel for reducing PM emissions, but there was no significant difference in PM emissions between the two types of biodiesel.

Bettis et al. (1982) reported that diesel engines that use biodiesels exhibited slightly reduced brake power and slightly increase fuel consumption. The exhaust emissions from biodiesels are lower than those of petrodiesels because biodiesels are composed of compounds with oxygen atoms. Moreover, biodiesels are environmental friendly because they neither generate $SO_x$ nor contribute to the global carbon dioxide emissions.

Demirbas (2008) reported that the structural oxygen content of a fuel enhances its combustion efficiency because of an increase in the homogeneity of oxygen with the fuel during combustion. Therefore, the combustion efficiency of biodiesel is higher than that of petrodiesel. Sulex et al. (2010) reported that adding 5% of biodiesel into petrodiesel can reduce the coefficient of friction and wear scar diameter by 10 and 50%, respectively. Syed et al. (2009) researched the properties of exhaust gases emitted from diesel engines when biodiesel fuels were added, reporting that biodiesel fuels can substantially reduce exhaust gas emissions.

Studies in the past decade identified a direct relationship between the deterioration in human health and the emission of diesel engine exhaust gases. Such studies also concluded that biodiesel exhibits relatively high combustion efficiency and low noxious gas emissions (Jeno et al., 2008; Kalam et al., 2011). Biodiesel has substantial potential as a replacement for conventional petrodiesel for diesel engines. However, related studies have overlooked the tribological properties of biodiesel. Therefore, the present study investigated the tribological properties of conventional petrodiesel mixed with castor oil.

## EXPERIMENTAL PROCEDURE

Different types of fuels (that is, pure petrodiesel fuel and castor oil blends) were tested. A castor oil biodiesel–petrodiesel fuel blend is referred to as CXX, with XX referring to the proportion of castor oil biodiesel. For example, $C_{20}$ refers to a fuel blended with 20% of castor oil biodiesel and 80% of petrodiesel (Goodrum and Geller,2005). A series of castor oil biodiesel–petrodiesel fuel blends with different concentrations were investigated. Table 1 shows the essential fuel properties. Each of the tested fuel blend was mixed by a mechanical mixer for 30 min with none of the fuel blends exhibiting phase separation phenomena. After each experimental test was executed, all of the test-related components were washed using ethanol. This experiment was conducted to simulate the wear conditions of an automobile fuel injection pump and nozzle. The testing specimens were immersed in a castor oil biodiesel fuel blends to conduct a series of wear tests. The tribology wear tests used the ball-on-ring contact method with five different fuels forcing a stationary ball against a rotating ring, forming the tribocontact (Figure 1).

The ring was made of bearing steel (AISI 52100 steel with HRc of 60 to 62, of composition: 0.95 to 1.05% C, 0.15

**Table 1:** Base fuel properties.

| Property | Petrodiesel | Castor biodiesel |
|---|---|---|
| Density at 27°C, (kg/m$^3$) | 840 | 925 |
| Viscosity (40°C, Cst) | 2.62 | 15.82 |
| Flash point (°C) | 88 | 172 |
| Sulphur content (%) | 0.01 | <0.01 |
| Water content (ppm) | 50.2 | <500 |
| Cetane number | 52.3 | 58 |

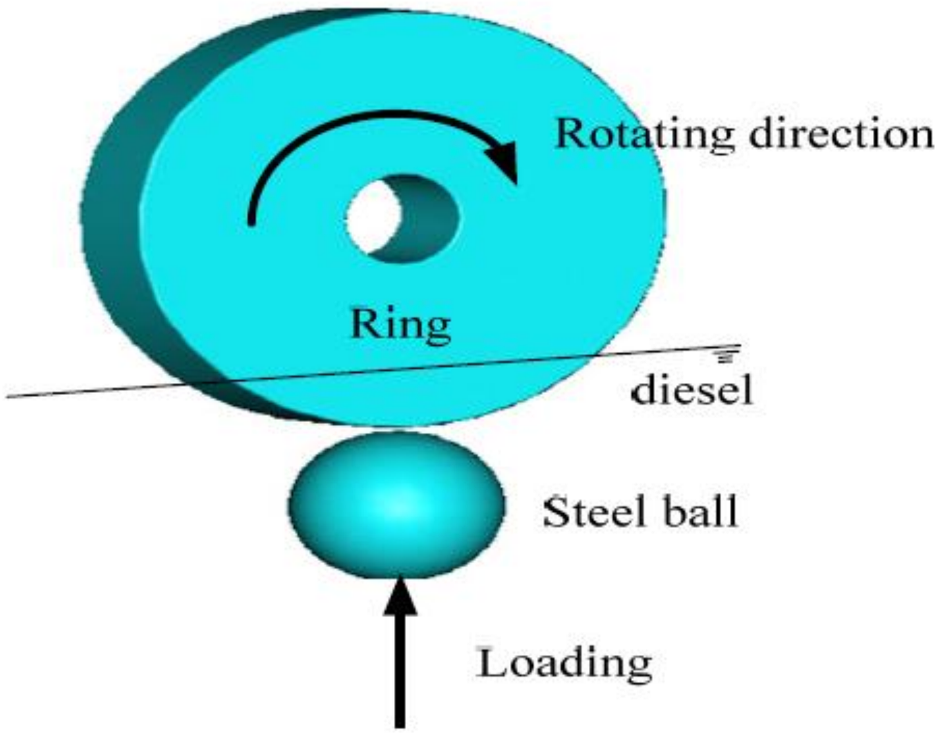


**Figure 1.** A schematic drawing of the ball-on-ring apparatus.

to 0.35% Si, 0.2 to 0.4% Mn, <0.027% P, <0.020% S, 1.3 to 1.65% Cr, <0.3% Ni and<0.25% Cu) with 70 mm diameter and thickness of 7 mm. The ball used in this study was made of bearing steel GCr15 (composition: 0.95 to 1.05% C, 0.15 to 0.35% Si, 0.25 to 0.45% Mn, 1.40 to 1.65% Cr, ≤0.10% Mo, ≤0.025% P, ≤0.025% S, ≤0.30% Ni, ≤0.25% Cu and ≤0.50% Ni+Cu) with hardness of HRc 59 to 61 and diameter of 12.7 mm. Both surfaces were polished to roughness Ra= 0.05 µm for ball and Ra= 0.20 µm for ring. During the test, the ball and ring was fully submerged in the tested fuels at a sliding speed of 0.06 m/s lasting 2 h (Figure 2). Table 2 lists the wear test conditions. The mean diameter of wear scar on the ball was then measured from five identical tests using a digital-reading microscope with accuracy of 0.01 mm. The friction forces were measured by performing sliding tests on an identical tester and recorded using the strain gauge in the tester. A data acquisition system with an AD converter was used for continuous monitoring and measurement of frictional force (Peng et al., 2010; Peng, 2015). The steel balls were rinsed in ethanol immediately and the topography of the scar surfaces after the wear test was observed by OM (Kimberly et al., 2005).

## RESULTS AND DISCUSSION

### Blend stability

Fuel blend stability tests were conducted to evaluate whether phase separation of the fuel blends occurred. The test was performed using 0, 2, 5, 10, 20 and 50% castor oil biodiesel by weight in petrodiesel fuel, respectively. The blended fuels were maintained in a temperature controlled atmosphere at 30°C and stability was tested every 2 h for the first 24 h and every day thereafter for one month (Figure 3). During the experiment, no precipitation or turbidity of the fuel blends was observed, indicating that

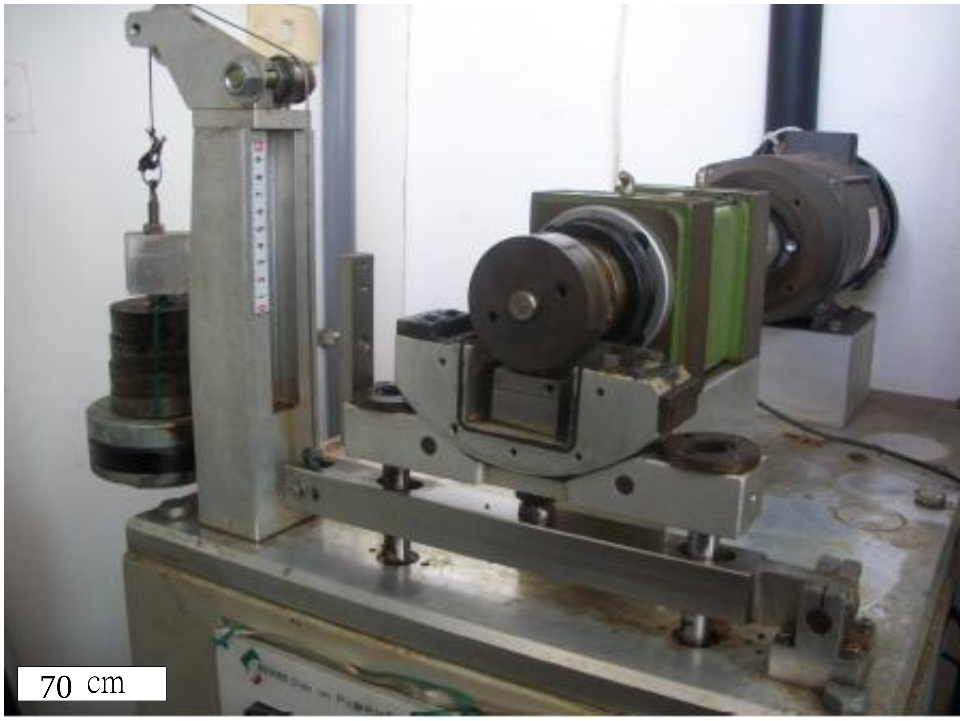


**Figure 2.** TE-53 wear test rig.

**Table 2.** Wear test conditions.

| Variable | Mean diameter |
|---|---|
| Apparent load (N) | 30-50-70-90 |
| Sliding speed (m/s) | 0.06 |
| Sliding distance (m) | 432 |
| Temperature (°C) | 28 |

the stability and blend ability of these two types of fuels were excellent.

## Friction properties

Figure 4 shows the results of the tribological test using a tribological wear and friction testing machine. Biodiesel mixed fuel with 10% castor oil reduced the wear scar diameter of the steel shots from 1.36 to 1.05 mm (approximately, 22.79%). The biodiesel substantially enhanced the lubricity of the mixed fuels. The higher the castor oil content, the lower the magnitude of the wear scar diameter reduction. However, the wear scar diameter was increased when the castor oil content exceeded 20%. The optimal castor oil ratio to achieve optimal lubricity was 10%. The tribological test results revealed that castor oil exhibited the optimal lubricity for protecting the sliding surfaces of the fuel injectors. This is because the mixture of oxygen compounds and fatty acid methyl esters were adsorbed onto the sliding surfaces, thereby reducing the friction and enhancing the oil film thickness of the boundary lubrication. Accelerating the formation of chemical thin films through catalytic reaction of the biodiesel protected parts that come into direct contact with sliding surfaces. Accelerating the growth of the chemical thin films enhanced the wear resistance. However, tribochemical wear occurred when the biodiesel exceeded a certain concentration.

As shown in Figure 5, examining the various concentrations of castor oil revealed that the castor oil methyl esters expressed similar lubricating behaviors. Adding biodiesel enhanced the lubricity of the fuels. When 10% biodiesel was added to the primary reference fuel, the tribological test results revealed that the friction coefficient was substantially reduced. When the castor oil concentration was slightly higher than 5%, the extent of enhancement in the lubricity of the castor oil methyl esters became stable. The most effective concentration of castor oil methyl esters for lubricating enhancements was 5 to 20%. The main reason for this reduction was possibly because the biodiesel contains polar compounds, thus, enhancing the stability of the lubricating films.

Figure 6 shows the variations of the wear scar diameter

**Figure 3.** The sedimentation of biodiesel in petro-diesel of pure petro-diesel (left), 5% biodiesel, 10% biodiesel, 20% biodiesel, 50% biodiesel and 100% biodiesel (right).

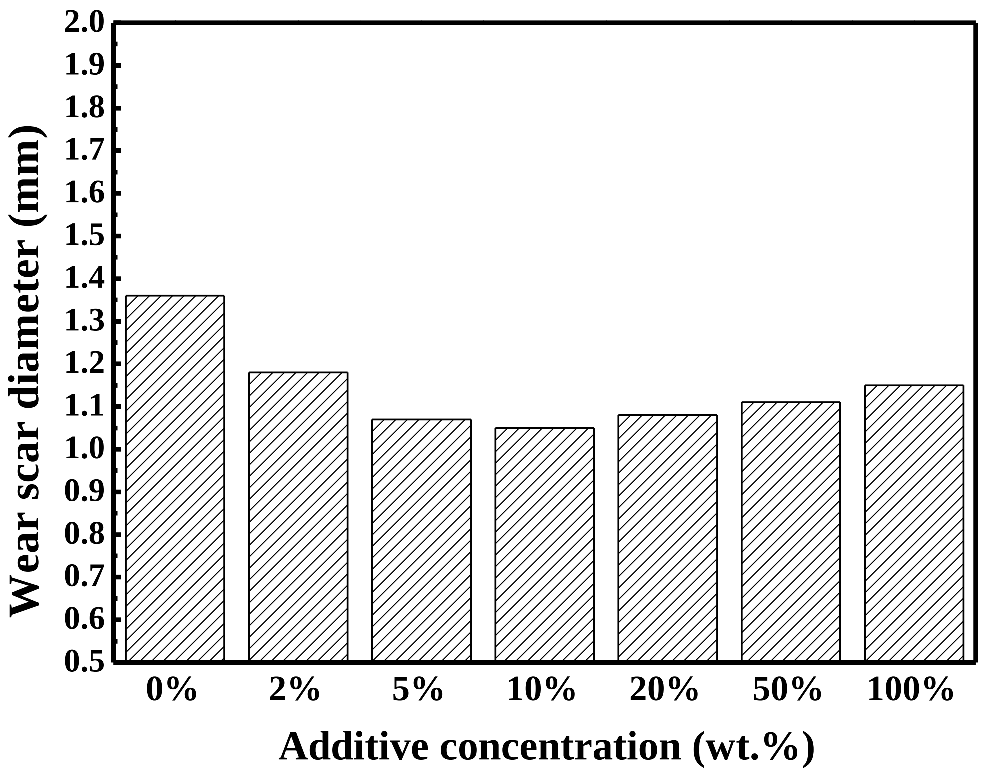


**Figure 4.** Wear scar diameter related to the additive concentration of biodiesel in pure petroleum diesel at room temperature (ball-on-ring, 500 rpm, Ra: 0.20 μm, 50 N, 120 min).

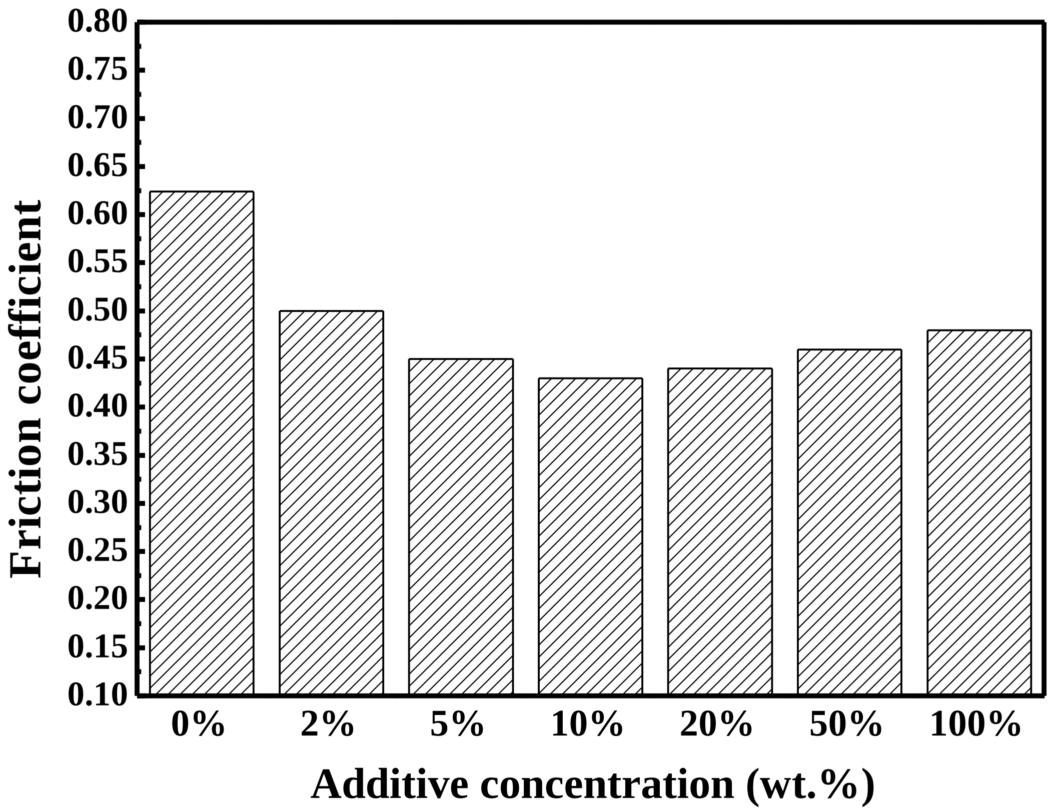


**Figure 5.** Friction coefficient related to the additive concentration of biodiesel in pure petroleum diesel at room temperature (ball-on-ring, 500 rpm, Ra: 0.20 μm, 50 N, 120 min).

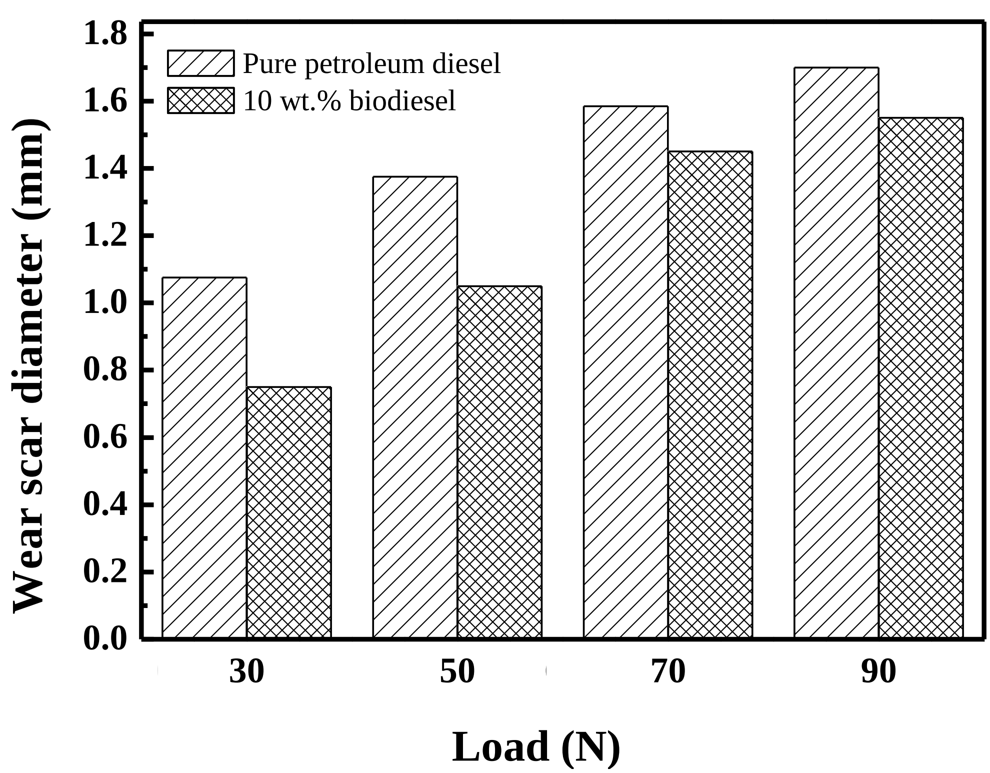


**Figure 6.** Comparison of wear scar diameter related to applied load for pure petroleum diesel and petroleum diesel containing biodiesel (ball-on-ring, 500 rpm, Ra: 0.20 μm, 120 min).

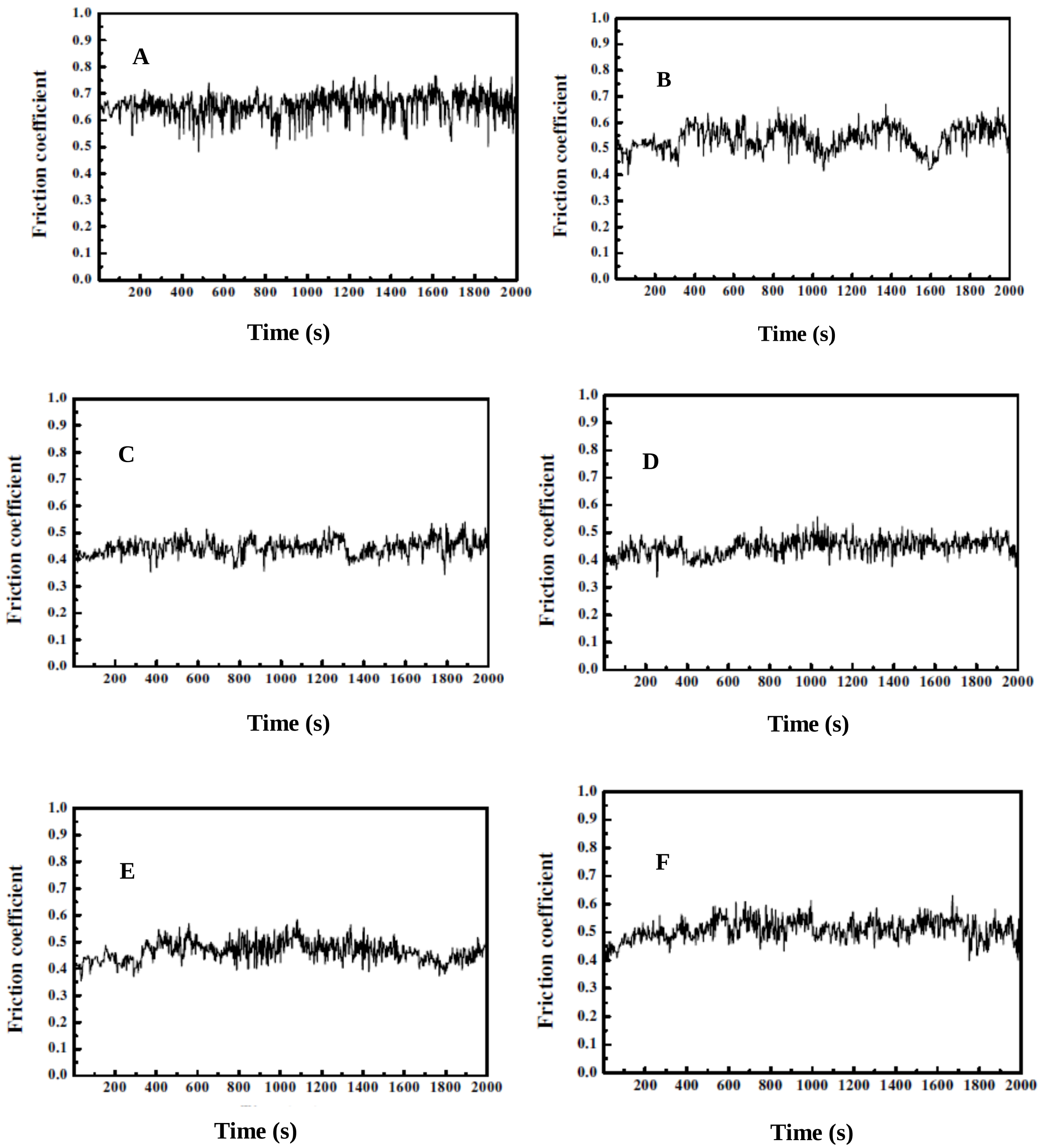


**Figure 7.** Typical friction behavior of ball-on-ring tested in the various oils (ball-on-ring, 500 rpm, Ra: 0.20 µm, 50 N); (a)$C_0$, (b)$C_2$, (c) $C_5$, (d) $C_{10}$, (e) $C_{20}$ and (f) $C_{100}$.

for various loads for pure petroleum diesel and petroleum diesel adding 10 wt.% castor biodiesel. This figure indicates that the wear scar diameter of the ball increases with the applied load for both fuels. In using pure petroleum diesel, the diameter of wear scar increases sharply as applied load increases. However, for the usage of petroleum diesel adding 10 wt.% castor biodiesel the wear scar diameter of the ball subjected to the same applied load has the stable increasing. A slight wt% of castor biodiesel exhibits improved load capacity wear resistance. Compared to pure petroleum diesel, petroleum diesel adding slight castor biodiesel has better tribological properties in terms of load-carrying capacity, antiwear and friction-reduction.

Figure 7a shows the typical frictional behaviors of the BOR wear tests for petrodiesel. To determine how to elevate the castor biodiesel lubricity, the tribological properties of the biodiesel fuel blends were examined (Figure 7b to f). The magnitude of the friction coefficient confirmed that lubrication mode involved boundary lubrication. The properties of the boundary film dominated the wear behaviors. The results revealed that

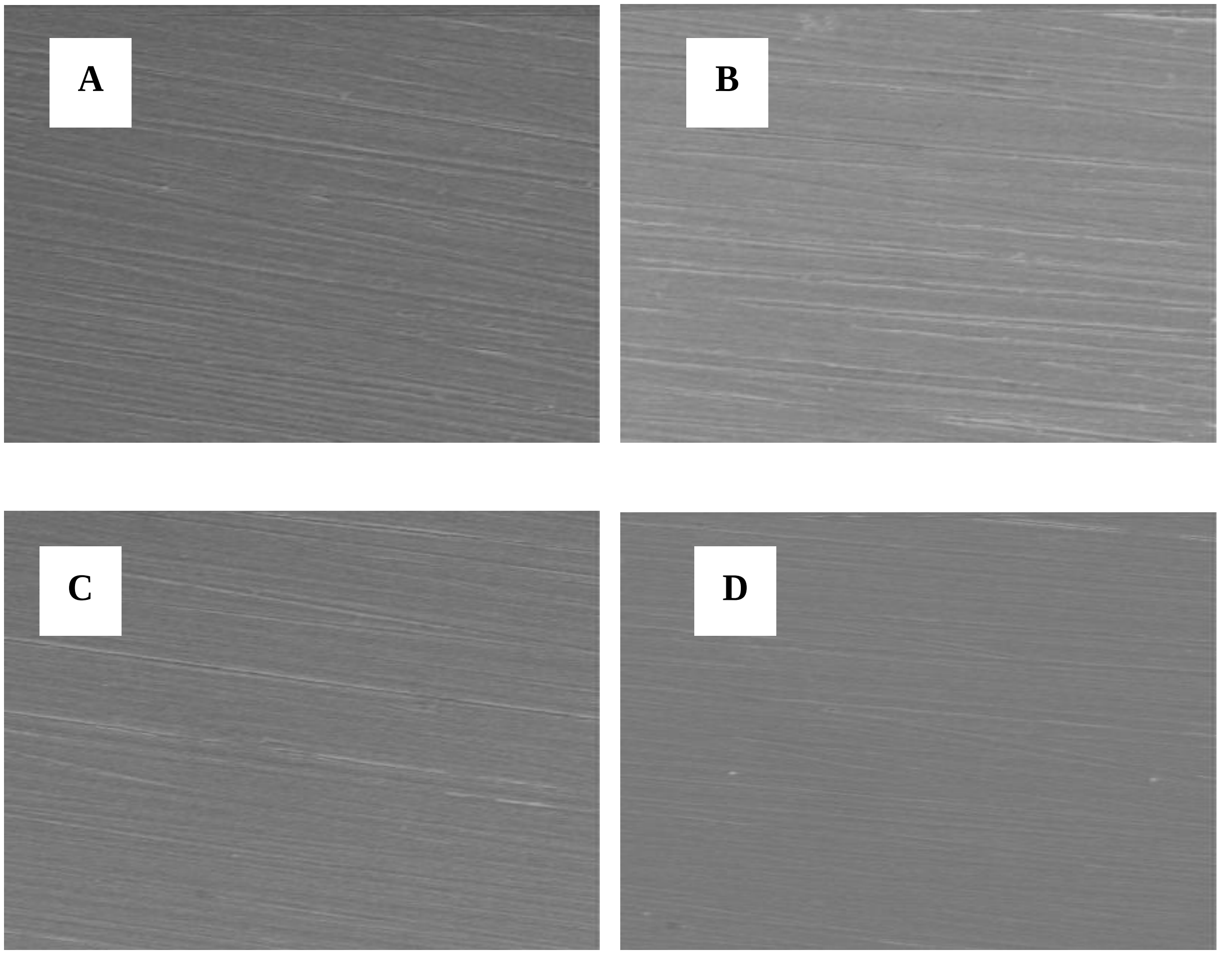


**Figure 8.** SEM micrographs of worn surfaces (ball-on-ring, 500 rpm, Ra: 0.20 µm, 50 N, 120 min); (A) Pure petroleum diesel, (B) Petroleum diesel added by 2 wt.% biodiesel, (C) Petroleum diesel added by 5 wt. % biodiesel and (D) Petroleum diesel added by 10 wt. % biodiesel.

the castor biodiesel yielded the lower friction coefficient. The largest decrease was observed earlier when the additive concentration was 2 to 10%. Minimal friction was observed when castor biodiesel concentration achieved 10%. The percentage share of the lubricant film covering the surface under friction conditions increases as concentration increases. The blending of biodiesel into pure petrodiesel appeared to reduce the negative effects on wear resistance, thus, reducing the friction coefficient.

The results from these studies concluded that hydroxylated fatty acid methyl esters exhibit properties to enhance lubrication. Studies revealed that because the hydroxyl group provides hydroxylated fatty acid methyl esters with unique chemical properties to form oil films, their applicability in plastics, inks and binders is high since they enhance the plasticity and adhesiveness of such products. Although the $C_{10}$ quickly formed a physical adsorption film on the sliding surface during the run-in process, the anti-abrasion properties of $C_{100}$ was not as effective as that of $C_{10}$. The possible cause for this difference was chemical corrosion.

**Analysis of worn surface**

Figure 8a to d displays the wear surface of the steel ball lubricated with either the petrodiesel or castor biodiesel blends at the room temperature. The worn surfaces of the ball specimens tested in pure petrodiesel showed wear mechanisms, including abrasive wear and delamination Figure 8a. Comparing Figure 8a and d revealed that the wear surface lubricated with the castor biodiesel blends was smoother than that lubricated with the petrodiesel. Similar wear patterns were also observed in the steel ball lubricated with the castor biodiesel blends, but the primary wear pattern of the ball was minor abrasive wear; hence, the antiwear property of the castor biodiesel blends was more favorable than that of the petrodiesel. Castor biodiesel are oxygenated compounds containing several types of fatty acid methyl ester, which adsorb to the wear surface, thereby decreasing friction and increasing the film thickness of boundary lubrication.

The oxygen content of the castor biodiesel used in this study was high, which may have caused some corrosion wear. However, the oxygen content may accelerate the formation of inorganic oxides, such as iron (II, III) oxides ($Fe_3O_4$) and the lubricating film forms more easily on the contact interface. Previous studies revealed that castor oil is more effective than other types of biodiesel in enhancing lubricity. The hydroxylated fatty acids of ricinoleic acid in castor oil enhance the lubricity more effectively than do other conventional vegetable oils and fats.

## Conclusions

The ball-on-ring test results revealed that using methyl ricinoleate as a lubricant improves the wear resistance of low-sulfur petrodiesel. The increased content (2 to 10%) of methyl ricinoleate enhance the lubricity of the mixed fuels. The wear test revealed that the wear diameter of the steel ball lubricated with either the pure petrodiesel or 10 wt.% castor biodiesel blends was 1.36 or 1.05 mm, respectively. This was attributed to the presence of methyl ricinoleate in castor biodiesel blends. Methyl ricinoleate has a strong affinity for metal surfaces; therefore, a chemical coating was formed between the two motion surfaces to protect the two contacted surfaces from wear. Therefore, the proposed biodiesel can be employed to effectively enhance the lubricity of a petrodiesel under the condition of boundary lubrication.

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