

An Experimental Investigation on Tribological Behaviour of Tire-Derived Pyrolysis Oil Blended with Biodiesel Fuel

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Abstract: The demand for alternative fuels has risen in recent years due to the economic and environmental consequences of conventional fuels. In addition to engine characteristics, i.e., performance, combustion, and emission the lubricity of the considered fuel is an important parameter for its selection. This experimental study shows the tribological performance of the tire pyrolysis oil by using the four-ball tester. Waste tire pyrolysis oil was purified by using the distillation process. The experiment was conducted over 300 s at 40, 50, 63, and 80 kg load, 1800 rpm constant speed, and 27 °C temperature of all fuels on the ASTM D2266 standard. The tribological performance of the tire pyrolysis oil was compared with the BT10 (biodiesel 90%–tire pyrolysis oil 10%) and BT20 (biodiesel 80%–tire pyrolysis oil 20%) and biodiesel. The optical microscope is used to measure the wear scar diameter and then it is examined through a scanning electron microscope. In terms of greater load-carrying capacity, tire pyrolysis oil shows better anti-wear behaviour compared to biodiesel fuel. The wear scar diameter of BT10, BT20, and tire pyrolysis oil was 23.99%, 8.37%, and 32.62%, respectively, lower than the biodiesel fuel at 80 kg load. The SEM micrographs revealed that tire pyrolysis oil and BT10 displayed lower wear as compared to counterparts. Finally, it is concluded that BT10 is the most suitable fuel in terms of tribological performance.

Keywords: renewable; tire pyrolysis oil; sustainable fuels; tribology; four-ball tester and biodiesel

1. Introduction

The extinction of fossil fuels, climate change, economic recession, surges in population growth, increasing demand, and declining supply of fuel have highlighted the significance of alternative fuels [1,2]. Two main forms of alternative renewable fuels are food and waste based. Food-based fuels include sunflower, palm oil, and rapeseed, etc. These could result in global issues like deforestation and food shortages worldwide and thus received a lot of criticism [3]. Waste-based fuels and microalgae biodiesel are non-food-based fuels and have very potential as an alternative fuel [4]. However, waste-based fuels are the most potent alternative fuels that can replace conventional fossil fuels [5]. On the other hand, the dumping of solid waste tires results in a plethora of environmental

issues [6,7]. According to a report by the European Automotive Manufacturers Association (EAMA), there are ~1.35 billion automobiles on the roads [8] and this amount will increase to 2 billion in the next 15 years [9]. The dumping of waste tires has created huge health and environmental issue around the world. Every year, almost 1 billion tons of tires are discarded worldwide [10]. At present, an estimation is that ~4 billion waste tires are in stockpiles and landfills globally [6]. A total of 5.26 million tons of tire pyrolysis oil (TPO) can be generated from the 1 billion waste tires [11].

Converting this waste to fuel would not only reduce the problems of waste dumping but can also reduce the pressure on conventional fuels and thus can be an ideal alternative renewable fuel. These waste tires can be processed in a static stirred batch pyrolysis reactor and therefore converted into 44% char, 49% oil, and 7% pyrolytic gases [12]. Accordingly, an estimate shows 44.5% tire pyrolysis oil can be purified in the form of fuel [13]. TPO is one of the main products of waste automobile tires. Its use as a waste-based alternative fuel in compression ignition engines [14–17], furnaces [18], and boilers [19] has been a topic of interest for researchers. Even though the sulphur content of TPO is notably higher than diesel fuel, however, its calorific value, kinematic viscosity, and density are roughly equivalent [20]. The sulphur content in the fuel tends to increase the lubricity of the fuel [21]. Due to the 0.55–3.95% sulphur contents, the TPO is desulphurised and distilled [22] to control its permissible limit in the diesel engines.

Biodiesel is among the world's most effective renewable fuels for coping with energy needs. It is derived from various animal fats and vegetable oils [23,24]. Compared to diesel fuel, biodiesel offers technological advantages such as biodegradability, better flash point, cetane number, and lower exhaust emission [25–27]. Biodiesel offers a fundamentally higher lubricity than diesel fuel [28]. The fuel with higher oxygen content leads to more wear. The chemical reaction between unsaturated fatty acids and oxygen comes into contact with metal surfaces [29]. Mujtaba et al., reported that BD30 (30% biodiesel–70% diesel) + TiO₂ additive showed 6.72% reduction in coefficient of friction (COF) and 38.4% reduction in wear scar diameter (WSD) as compared to BD30 fuel [30]. In the experimental study, the average palm-sesame oil blend P50S50 (50:50 wt%) biodiesel friction coefficient was 2.29% and 12.37% lower than palm biodiesel and commercial diesel, respectively [31]. With advancements in technology and rapid rejuvenation in the industrial world, the fuels do not only supply energy but is also an essential lubricant [32]. The life of an engine is dependent on its lubricity. Lubricity tends to reduce the consumption of energy and power by reducing the frictional force between moving parts and lubricating the injectors and fuel pumps [33].

The friction and wear mechanism of the fuel engine is hence an essential topic to conduct a study on. The literature lacks studies on the investigation of TPO's tribological characteristics the way there are on engine characteristics, i.e., performance, combustion, and emission in diesel engines [14–18,34–37]. A few examinations have been researched on the wear attributes of the various biodiesel and their mixes with diesel fuel that are presented in Table 1. To focus on this gap, the current study looks at the contact and wear attributes of TPO and their blend with biodiesel fuel at various test boundaries. The tire pyrolysis oil (TPO), palm biodiesel fuel (BD), and their blends BT10 (Biodiesel 90%, TPO 10%) and BT20 (Biodiesel 80%, TPO 20%) were investigated. Furthermore, the test investigation of contact and wear attributes of TPO is analysed by utilizing the four-ball tribometer (FBT).

Table 1. A summary of the literature review of tribological characteristics of different tested fuels using fourball tester or other equipment.

Tested Samples	Apparatus	Ball Material	Working Conditions	Tribological Characteristics Comparison with Diesel	References
CIB10, CIB20, CIB30, CIB50, CIB100, DF (Calophyllum inophyllum (CI))	FBT	Carbon–chromium steel	27 °C, the normal load of 40, 50, 63, and 80 kg for 300 s at 1800 rpm speed	Friction and wear ▼ with the ▲ of concentration of biodiesel and friction and wear ▼ with ▲ of load.	[38]
PB10, PB20, PB100, CIB10, CIB20, CIB100, DF (Palm oil biodiesel (PB), Calophyllum inophyllum (CI)),	FBT	Carbon–chromium steel	27 °C, 45 °C, 60 °C, and 75 °C, normal load of 40 and 80 kg for 300 s at 1800 rpm speed	Friction and wear ▼ with the ▲ of concentration of biodiesel and friction and wear ▼ with ▲ load and temperature.	[39]
B0, B10, B20, B50, B100 (Sunflower, Soybean)	FBT	Carbon–chromium steel	75 °C, load 40 kg for 300 s and 3600 s at 600, 900, 1200, and 1800 rpm	Friction and wear ▼ with the ▲ of concentration of biodiesel and friction and wear ▲ with ▲ of speed.	[40]
MO5, MO8, MO12 Mongongo-oil biodiesel MO5 (5% Mongongo oil-95% SAE 20W-40)	pin-on-disc tribometer	aluminium-silicon alloy	27 °C, the normal load of 40, 80, and 120 N, for 300 s and 3600 s at 600, 900, 1200, and 1800 rpm varying speed	Friction ▼ with the ▲ load and wear ▲ with ▲ of load.	[41]
B0, B5, B20, B100 (Soybean)	High-frequency reciprocating rig	AISI 52100 steel	60 °C, 1.96 N for 75 min at 50 Hz frequency	Friction ▲ with the ▲ of concentration of biodiesel.	[42]

2. Materials and Methods

2.1. Tire Pyrolysis Oil Production and Purification

The pyrolysis process is used to convert the waste tires to tire pyrolysis oil (49%), solid char (44%), and pyrolytic gas (7%) respectively. The waste tires were condensed and their flow rate differed from 5.5 to 14.5 kg/h [12]. The physicochemical properties of raw tire pyrolysis oil are listed in Table 2. It is reported that the viscosity, density, flash point, and calorific value of waste TPO is similar to automotive diesel, but the amount of sulphur is substantially higher than the diesel [20]. The presence of an excess quantity of oxygen content (0.10–3.96%) in TPO [7] and 10.79% in biodiesel [43] can minimize friction and wear as compared to diesel [44].

Table 2. The physicochemical properties of raw tire pyrolysis oil.

Parameters	ASTM Standard	Raw TPO
Calorific value (MJ/Kg)	ASTM D240	43.09
Kinematic viscosity @ 40 °C (cSt)	ASTM D7042	4.74
Density @ 15 °C (kg/m ³)	ASTM D4052	927
Flashpoint (°C)	ASTM D93	<40
Pour point (°C)	ASTM D97	<40
Sulphur (mass, %)	ASTM D4294	0.77
Ash (mass, %)	ASTM D462	0.009
Carbon residue (m/m, %)	ASTM D4530	1.07
Acid number (mg KOH/g)	ASTM D664	1.03
Water by distillation (V/V, %)	ASTM D95	0.10
Sediment by extraction (m/m, %)	ASTM D473	0.097

The purification of waste TPO was completed in the research facility. Towards the beginning, waste TPO was warmed at 110 °C to eliminate its water content. At this point, 8% H₂SO₄ was added to the waste TPO for the hydro sulfuric acid treatment at 70 °C and mixed with a magnetic stirrer for 4 h. After this cycle, the blend was left for 48 h. At last, the blend was run through a distillation unit. The biodiesel fuel was acquired from a local organization. BT10 and BT20 blends were made by utilizing the magnetic stirrer. The physical properties of biodiesel fuel, BT10, BT20, and tire pyrolysis oil (TPO) are presented in Table 3. The apparatuses utilized in this work are recorded in Table 4.

Table 3. Different properties of tire pyrolysis oil-biodiesel blended fuels used in the present study.

Fuel	Density (kg/m ³)	Kinematic Viscosity (cSt)	Calorific Value (MJ/kg)
	15 °C	40 °C	
Biodiesel	875.5	4.45	38.89
BT10	886	4.21	39.26
BT20	896	4.13	39.37
TPO	946	2.23	41.81

Table 4. A detailed list of the equipment and instruments used in the present study.

	Standard	Apparatus	Made	Model	Accuracy
Calorific value	ASTM D240	Bomb calorimeter	IKA, UK	C2000	±0.1% MJ/kg
Kinematic viscosity	ASTM D7042	Stabinger viscometer	Anton Paar, UK	SVM 3000	±0.35%
Density	ASTM D4052	Stabinger viscometer	Anton Paar, UK	SVM 3000	±0.1 kg/m ³
Friction and wear	ASTM D2266	Four ball testers	DUCOM, India	TR-30L- IAS	-
Wear scar diameter	ASTM D4172	Optical microscope	IKA, UK	C2000	±0.01 mm
Scanning electron microscope (SEM)	X30/X2000	SEM	Hitachi	S3400N	3.0 nm at 30 kV

2.2. Test Setup

Four ball tribometer (TR-30L-IAS, DUCOM, Bengaluru, Karnataka, India) was utilized during the examination that aided in the research and development of tribology of new oils (shown in Figure 1). It utilized four balls to test the sample however three of those were fixed in the fuel sample bath and one ball was turning that was held by the motor spindle. The schematic diagram of the four-ball tester and the exploratory setup appears in Figure 2. The fuel/oil bath was loaded up with the tested fuel. The highlights of the fourball tester are recorded in Table 5.

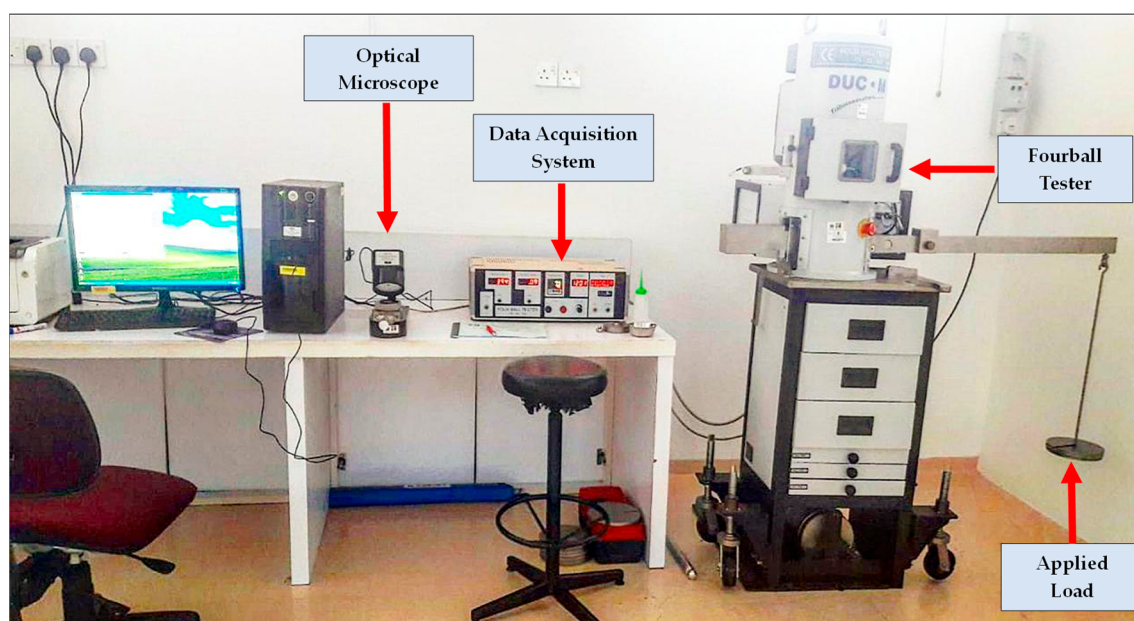


Figure 1. The experimental setup used in the current study.

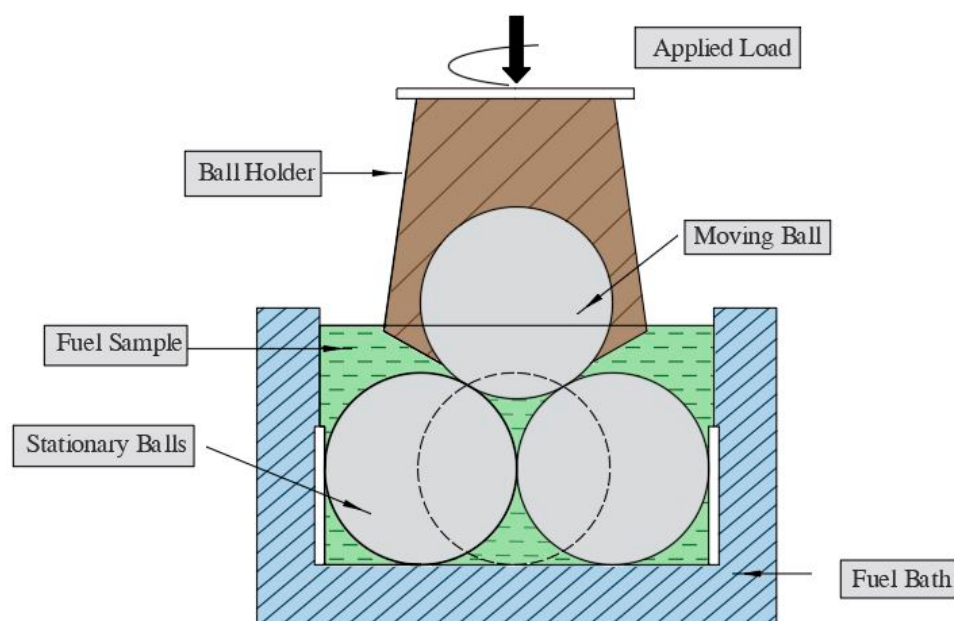


Figure 2. The schematic representation of four-ball tribometer geometry.

The lever arm was utilized to apply loads on the balls fixed at the bottom and frictional torque was determined by the balanced arm utilizing a spring connected to a friction recording apparatus. The carbon-chromium steel balls were utilized in this investigation and the details of the balls are recorded in Table 5. Four new balls were cleaned with acetone and dried using air and tissue paper.

Table 5. The key features of four-ball tester, data acquisition system and optical microscope.

Specification	Units	Detail	Accuracy
Model	-	Make: DUCOM TR-30L-IAS	
Speed	RPM	300–3000	1
Oil Temperature	°C	Ambient temperature to 100	0.5
Maximum axial load	N	10,000	0.5
Range of scar	μm	100–4000	0.5

Diameter of ball	mm	12.7
Image measuring system	Optical microscope	
Image acquisition system	Make: Radical instrument, 220 V, 50 Hz	
Software	Web camera, 12 megapixels	
	Winducom 2010	

2.3. Test Procedure

Acetone was used to clean the four steel balls and oil cups to remove the dust particles and oil before each experiment. In accordance with the recommended torque, the 03 steel balls were locked in the cup, and then test oil was poured into the oil cup until the 03 steel balls were completely covered. 01 ball clutched and then fixed within the apparatus. The oil cup was placed inside the apparatus and the controller cable was attached to it. ASTM standard D2266 was used for these experiments. The duration was 300 s at 1800 rpm constant spindle speed with 40, 50, 63, and 80 kg loads at an oil temperature of 27 °C. The software (Winducom 2010) was used to measure and evaluate the readings at the decided varying parameters. Table 6 shows the experimental requirements for four-ball experiments. The three steel balls in the oil cup were acquired at the end of the experiment to measure the wear scar's diameter using an optical microscope and for SEM study.

Table 6. The experimental conditions and parameters for four-ball test used in the study.

Parameter	Values
Standard	ASTM D2266
Speed (rpm)	1800
Load (kg)	40, 50, 63 and 80
Temperature of Fuel (°C)	27
Time (s)	300
Material of Ball	Carbon–chromium steel (SKF)
Composition	85.06% Fe ;10.2% C; 0.07% S; 0.45% Si; 0.42% Mn; 0.06% Ni; 1.46% Cr; 0.12% P; 2.15% Zn
Ball Diameter (mm)	12.7
Ball Hardness (HRc)	62
Ball Surface roughness (µm)	0.1 C.L.A

2.3.1. Friction Evaluation

The software (Winducom 2010) used in the measurement of the value of friction's mean coefficient by using the Equations (1) and (2) [38]. Frictional torque is measured by using a load cell in the apparatus.

$$T = \frac{\mu \times r \times 3W}{\sqrt{6}} \quad (1)$$

$$\mu = \frac{T \times \sqrt{6}}{r \times 3W} \quad (2)$$

where μ is the friction coefficient, T is the frictional torque (N.m), W is the applied load (N) and r is the distance defined to be 3.67 mm from the middle of the contact surface on the lower balls to the rotation axis.

2.3.2. Flash Temperature Parameter

The flash temperature parameter (*FTP*) of all fuels were measured using Equation (3) [38]. It is an important parameter for the lubricants to portray the critical flash temperature under the input conditions of the four-ball test.

$$FTP = \frac{F}{D^{1.4}} \quad (3)$$

where *F* is the applied load (kg) and *D* is the average WSD (mm).

2.3.3. Wear Evaluation

As per standard ASTM D4172, the optical microscope was used to measure the wear scar diameter of the steel balls at a resolution of 0.01 mm. [38]. The optical microscope used the computer's software (Scar View 2005) to capture the wear scar image. In addition, the wear scar diameter using this Scar View 2005 was measured.

3. Results and Discussion

3.1. Friction Behaviour

The frictional performance was unstable due to the run-in period of the testing at the start of the experiment. The balanced friction behaviour was reported after a couple of seconds and it is called the steady-state condition. The steady-state point is reached over time. This result is due to the fact that, at the start, the surface layer is scratchy. The surface of the tested balls is smoothed a few minutes later by eliminating prominent asperity. The run-in period coefficient of friction was shown in the first 10 s, and the mean steady-state coefficient of friction for the last 100 s was recorded and presented in Figure 3.

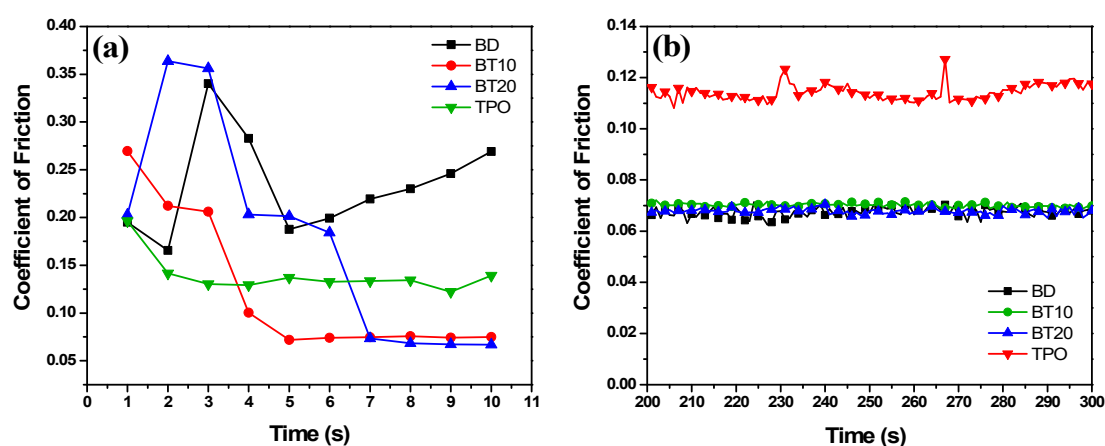


Figure 3. The friction coefficient performance of tire pyrolysis oil-biodiesel blended fuel with time; (a) Run-in period and (b) Steady-state condition.

Biodiesel is shown to have a relatively higher run-in period friction coefficient over a longer period of time than the other fuel samples. TPO produces better friction protection performance than biodiesel and blended fuel samples. Mello et al. reported [21] that the higher sulphur content tends to increase the lubricity. Therefore, TPO performs better lubricity performance due to higher sulphur content as compared to biodiesel fuel that is why TPO, BT10, and BT20 shown an unsteady friction coefficient of 41, 49.66, and 28.63% respectively, lower than biodiesel fuel. In contrast to biodiesel TPO, BT10 and BT20 displayed a smooth mechanism of the steady-state coefficient of friction that confirms a fluctuating pattern.

Wain et al. [44] stated that biodiesel containing more oxygen can minimize friction and wear. The coefficient of friction performance of BT10 and BT20 is relatively similar to biodiesel fuel in the case of a steady-state condition. According to the test conditions adopted at the boundary, the viscosity of lubricating oils is the key parameter that affects the film thickness separating the surfaces and therefore determines the friction behaviour [45]. In view of the importance of the viscosity of the lubricating oil considered, higher temperatures were observed in the fourball contact geometry, resulting in a reduction in the viscosity of the oil and a higher average coefficient of friction. The comparison of friction profiles therefore showed poor TPO friction activity.

3.2. Wear Behaviour

The metal to metal contact contributes to the battering of the collaborating tribo-pair under minimal grease conditions. Figure 4 demonstrates the wearing actions of all of the tested fuel considered. The investigation clearly shows that a bad anti-wear mechanism has been demonstrated by TPO at low loads such as 40, 50, and 63 kg. However, better wear prevention is noticed by TPO at a higher load of 80 kg. This pattern has shown the high load carrying limit of TPO. The potential rises in contact temperatures at higher loads resulted in low viscous oils that enhanced the chances of tribo-pair surface contact. As compared with BD, TPO, and BT20 at both low and high loads, BT10 demonstrated a better anti-wear mechanism. The WSD of BT10, BT20, and TPO was 23.99, 8.37, and 32.62% respectively that was lower than the biodiesel fuel at the 80 kg load. High sulphur content in TPO reduces the wear behaviour and their blend with biodiesel helps to increase the lubricating properties [46]. Biodiesel has no sulphur content that caused the problems in the lubricity, but Mello et al. also reported [21] that the higher sulphur content tends to increase the lubricity.

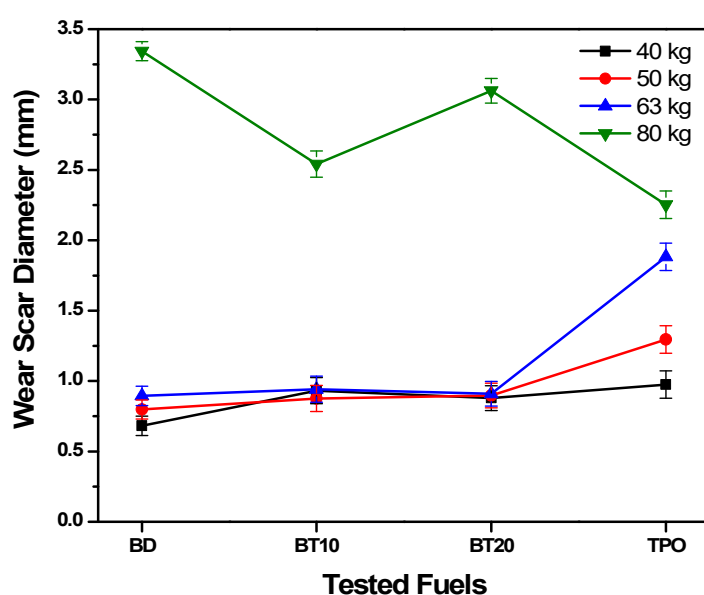


Figure 4. Wear scar diameter of tire pyrolysis oil-biodiesel blended fuels at varying loads.

3.3. Flash Temperature Parameter

The result of tested fuels on the flash temperature parameter (FTP) is presented in Figure 5. Strong lubricating efficiency and a low chance of lubricant layer breakdown lead to a high FTP value. The temperature at which a lubricating layer can be formed to enhance lubricity is flash temperature. A higher FTP value leads to better lubricating performance and reduced risks of lubricant film breakdown [47]. The FTP value for each tested fuel rises with a reduction in the wear load. The findings show that the load increase appears to increase the worn surface's WSD as well and FTP is

inversely proportional to wear scar diameter [48]. Compared to other fuels, TPO displayed the highest FTP of 25.67 °C at 80 kg load. The better FTP results are shown by BT10 and BT20 and that is similar to biodiesel fuel. However, biodiesel fuel (14.77 °C) has been credited with the lowest FTP rating at 80 kg, because of the biodiesel deterioration. Hence, the contact surfaces surround each other and enhance the surface of the contact [49].

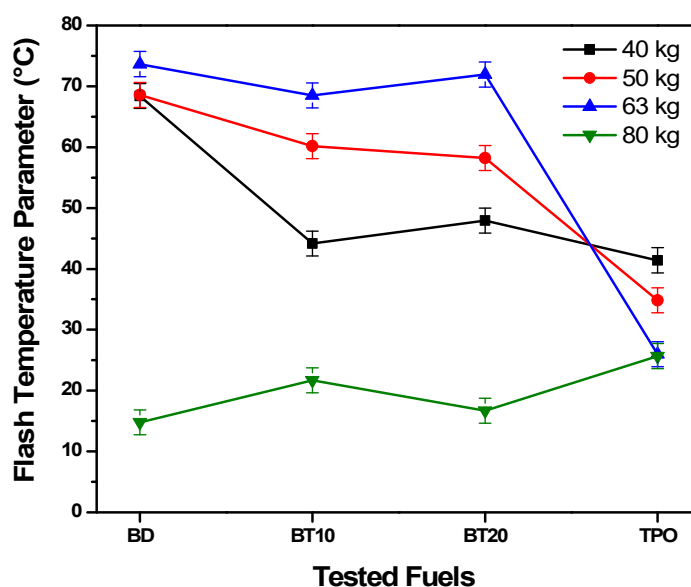


Figure 5. The effect of tire pyrolysis oil-biodiesel blended fuels on flash temperature parameter at varying loads.

3.4. Morphological Analysis

Tested ball worn surfaces were characterized by scanning electron microscopy (SEM) to understand the anti-wear behaviour of considered fuel samples. The related worn surfaces were also analysed using SEM, TPO showed better wear prevention at higher loads (80 kg). For the fuel samples tested, Figure 6a–l displays the SEM micrographs of the worn surfaces of the tested balls under 80 kg. The micrographs of the biodiesel showing adhesive wear and rough surface area as clear in Figure 6a–c above the TPO blended samples Figure 6d–l. Similarly, the least material removal is presented in Figure 6d–f relative to Figure 6g–l. For all tested fuels, the surface wear is greater than 20 µm, thus representing adhesive wear [50]. As the TPO blend ratio increases, the wear scar diameter leads to an increase. The SEM images also demonstrate that the metal layers are separated from the surfaces in the direction in which the spinning ball rotates. Wain et al. reported that [44] the alternative fuels that have oxygen content may contribute to lower diesel engine emissions but compared to higher sulphur fuels, they may also have lower anti-wear properties.

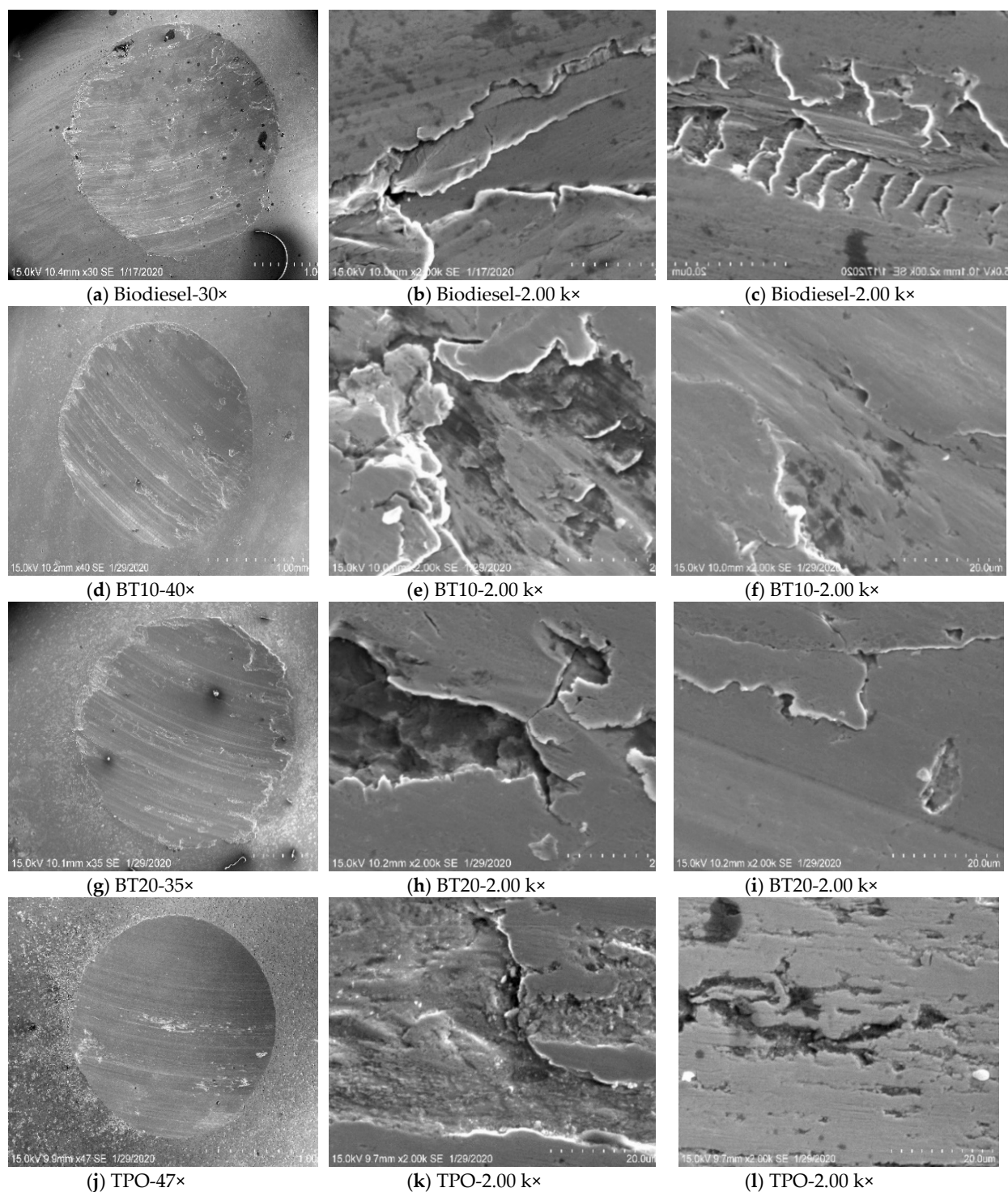


Figure 6. The micrograph of the wear scar and distribution of Biodiesel, BT10, BT20 and TPO (a) Biodiesel wear scar (30×), (b) Biodiesel distribution (2 k×), (c) Biodiesel distribution (2 k×), (d) BT10 wear scar (40×), (e) BT10 distribution (2 k×), (f) BT10 distribution (2 k×), (g) BT20 wear scar (35×), (h) BT20 distribution (2 k×), (i) BT20 distribution (2 k×), (j) TPO wear scar (47×), (k) TPO distribution (2 k×) and (l) TPO distribution (2 k×).

4. Conclusions

This experimental study identifies the tribological performance of the tire-derived pyrolysis oil blended with biodiesel fuel by using a fourball tester. The experiment was conducted over 300 s at 40, 50, 63, and 80 kg load, 1800 rpm constant speed, and 27 °C temperature of all fuels on the ASTM D2266 standard. The tribological performance of the TPO was compared with the BT10 (Biodiesel 90%, TPO 10%) and BT20 (Biodiesel 80%, TPO 20%) and biodiesel. Fourball tester is a basic test rig that is generally used in the lubricant industry to assist with new lubricant or grease research and growth. Therefore, it is used to study the tribological performance of the TPO blended with biodiesel fuel. The major findings of this experimental study are as follows:

1. BT10, BT20, and TPO have 49.66%, 28.63%, and 41% lower unsteady coefficient of friction, respectively, than biodiesel. In contrast to the variable performance of biodiesel fuel, the BT10 and TPO showed a smooth behaviour of the unsteady friction coefficient.
2. In comparison to biodiesel fuel, at low and high loads, TPO and BT10 exhibit better wear patterns. The WSD of TPO, BT10, and BT20 were as 32.62%, 23.99% and 8.37%, respectively, lower than the biodiesel fuel at 80 kg load. The higher sulphur content in the TPO shows better anti-wear behaviour.
3. TPO demonstrates a higher load-carrying capacity that reflects its ability to be used in higher loads and extreme situations of pressure.
4. The wear behaviour of fuel blends tested suggests that for a particular application, moderate friction behaviour, as well as higher load-carrying capacity, can be achieved.
5. Compared to other fuels, TPO has a maximum FTP of 25.67 °C at 80 kg load. The FTP results shown by BT10 and BT20 are similar to biodiesel fuel at low loads but a better performance of BT10 and BT20 at high loads. However, biodiesel fuel (14.77 °C) was rated with the lowest FTP value.
6. The SEM micrographs revealed that BT10 and BT20 showed lower metal extrusion compared to biodiesel fuel. Morphology showed that biodiesel fuel particles are broad and are shortened with the rise in the percentage of TPO.

The result of the study suggests that in terms of friction and wear BT10 showed favourable tribological performance. Therefore, it can be used to enhance an engine's life. In addition, tire pyrolysis oil blended with various oils (Fat oil biodiesel, jatropha biodiesel, microalgae biodiesel, and plastic oil etc.) could be used in future work to reduce engine wear. To increase the tribological efficiency, various additives and nanoparticles may be added to increase the desired properties in the TPO blended fuel.

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