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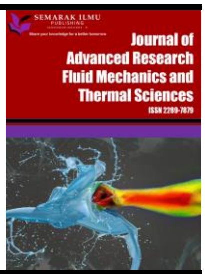

Experimental Study of the Effect of Plastic Pyrolysis Oil on the Physical-Chemical Properties of Rubber Seed Biodiesel and Diesel Engine Performance using a Mixture of Plastic Pyrolysis Oil-Rubber Seed Biodiesel-Diesel Fuel

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ABSTRACT

Rubber seed oil is a potential source of biodiesel, but its utilization is still limited. From previous research studies, the addition of Rubber Seed Biodiesel (RSB) to diesel will reduce engine performance and increase BSFC but can increase emissions. At the same time, plastic waste has posed a very serious environmental challenge due to its large quantity and suboptimal processing problems. Pyrolysis is considered to be an efficient solution for handling plastic waste, because it operates at low pressure and produces Plastic Pyrolysis Oil (PPO) as fuel. The success of research on converting plastic waste into fuel can be a solution to limited biodiesel raw materials, as well as a solution for handling plastic waste. From various previous studies it is known that PPO has a higher heating value than biodiesel, but biodiesel has a higher centane number. Based on these various symptoms, it is interesting to research the use of a mixture of RSB and PPO fuels, because they are thought to complement each other. In this research, PPO was added to RSB starting at 10%, 20%, 30% and 40%, then the physicochemical properties of each mixture were examined, it was found that PPO could increase the heating value, reduce viscosity, density and acid number, reduce the cetane number and reduces the oxidation stability of RSB. To test on a diesel engine, PPO was added to the diesel-RSB mixture. The diesel portion is set at 60%, while the RSB and PPO portions are varied starting from 40% RSB 0% PPO, 30% RSB 10% PPO, 20% RSB 20% PPO and 10% RSB 30% PPO. Diesel engine performance and emissions were investigated when PPO was added to the fuel mixture. The search results show that BTE decreased by 4% when using B10P30 compared to using pure diesel, but increased by around 30% compared to using RSB40 at full load. The addition of PPO to the Diesel-RSB mixture increases CO, HC and smoke emissions, but is still lower than pure diesel emissions.

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1. Introduction

Because of its superior thermal efficiency and ease of access and handling, diesel is widely used in a variety of industries, including the power generation, automotive, and agricultural sectors [1].

Meanwhile, the requirement for fuel oil industrial growth has increased over the past 40 years along with the usage of motorized vehicles and the growth of industry [2]. The depletion of fossil energy supplies during the same decades has led to an increase in the economic worth of fossil fuels [3]. Air pollution from burning fossil fuels is increasing, along with the demand for alternative fuels for ICE to address environmental issues and provide energy security [4].

Because vegetable oil is renewable and ecologically beneficial, its usage in diesel engines is increasing in an effort to limit the use of fossil fuels [5]. Vegetable oils of various kinds, such as pongamia, peanut, rapeseed, jatropha, palm, rubber seed, and sunflower oil, are used as raw materials in the manufacturing of diesel engines [6]. Because single vegetable oil has a greater viscosity and a lower calorific value, it performs less well in diesel engines [7].

Rubber seed oil is the potential raw material used in the esterification and transesterification procedures to produce biodiesel from a variety of non-edible oil sources [8]. Rubber seed utilization as a biodiesel source material is regarded as a recent innovation, because to obtain rubber seeds as raw material you don't need to plant rubber trees specifically, you just need to take them from existing plantations [9]. So far, rubber seeds have not been utilized optimally, only a small portion is used for seedlings, the rest is simply thrown away [10]. Around 12 million hectares of world rubber plantations are spread across Southeast Asia and sub-Saharan Africa which can produce 17.2 million tons of rubber seeds per year. Up to 89.4% of rubber seeds are made up of oil, of which 80.5% is made up of unsaturated fatty acids, so from 17.2 million tons of rubber seeds can produce 8.72 million tons of vegetable oil which can be converted into 7.76 million tons of biodiesel [11].

However, the majority of earlier research indicates that adding RSB to diesel reduces engine performance [12]. The engine's torque and brake power are lower than diesel engines by around 5% and consume more fuel on average around 10% [13]. This results from biodiesel's 8-12% decreased calorific value [14]. When the BSFC is greater, more mix and biodiesel are needed to generate the same engine power as diesel fuel [14]. RSB and all of its mixes have lower BP, BTE, and engine torque when compared to diesel because of RSB's reduced energy content [12]. With an increase in the amount of RSB in the mixture, NOx emissions rose somewhat and almost linearly. The oxygen content of the biodiesel and the high temperature of the combustion chamber are the main causes of this, which promote almost flawless combustion [12].

When compared to diesel, RSB and its mixes dramatically lower other emissions including CO, UHC, and smoke [15]. This behavior is assumed to be caused by RSB's reduced carbon content, elevated O_2 concentration, and lack of aromatic chemicals [12].

In addition, the massive amounts of plastic garbage combined with issues with processing and disposal have made it a particularly major environmental burden [16]. More than 381 million tons of plastic garbage were created worldwide in 2015; only 18% of this debris was appropriately managed; the remainder was disposed of recklessly, polluting the environment [17]. Because of its benefits, which include a high conversion efficiency of around 84%, low pressure operation, abundant raw materials, and the least amount of residue generated, pyrolysis is a superior technique for turning plastic waste into plastic oil [18].

Research on producing waste plastic oil from plastic waste has recently become one of the research trends among energy and environmental researchers recently [19]. It is hoped that the success of research in this field can be a solution to the limitations of biodiesel raw materials, as well as a solution in handling plastic waste [20]. A review of several earlier research shows that while comparison to biodiesel, WPO has a lower cetane number, it has a greater total heating value [21].

In order to optimise the physicochemical characteristics of rubber seed biodiesel, several researchers have made various efforts, such as mixing several types of feedstocks, changing the catalyst and reaction method in the biodiesel manufacturing process, and mixing biodiesel with biodiesel from other raw materials [22]. Some catalysts used are sulfuric acid, hydrochloric acid, phosphoric acid, sodium hydroxide, potassium hydroxide, calcium oxide, zeolite, silica-alumina, magnesium oxide, lipase enzymes, and several heterogeneous catalysts [23]. In general, the price of catalysts is costly, so the use of catalysts is considered uneconomical [24]. Several methods are used: two-stage, one-stage, enzymatic, and microalgae reactions [25]. Some fuels mixed with biodiesel are diesel oil, ethanol, methanol, or biodiesel from different feedstocks [26]. These efforts aim to increase calorific value, reduce acid levels, viscosity, and density, increase oxidation stability, and ultimately improve the performance of diesel engines when using them.

One of the easiest and most efficient methods to raise the calorific value of biodiesel is to add additives [27]. Additives are substances added to biodiesel in small quantities to improve its properties and performance [28]. Some additives that have been used to increase the heating value of biodiesel are ethanol, methanol, acetone, glycerol, and others [29]. These additives can also reduce biodiesel's viscosity and free fatty acid content, which is essential for engine performance [27].

The use of waste plastic pyrolysis oil mixed with diesel fuel has been studied in the past. The suitability of WPO oil and its mixes for use in single-cylinder diesel engines was investigated by Kumar *et al.,* [22]. Different mixes with volume proportions of WPO of 10%, 20%, 30%, and 100% were made. According to the research findings, the optimal fuel combination exhibits better overall performance and emission characteristics when compared to diesel and contains 10% plastic waste oil and 90% diesel fuel. Among all fuel mixes, pure WPO also had the lowest BSFC and the greatest BTE. Exhaust emissions, however, are also the greatest Das *et al.,* [30] conducted a similar experiment on WPO and its combinations and found that the best fuel mixture for producing improved efficiency and lower fuel consumption is one that has 20% WPO dose. But with greater loads, NOx and HC emissions rise noticeably.

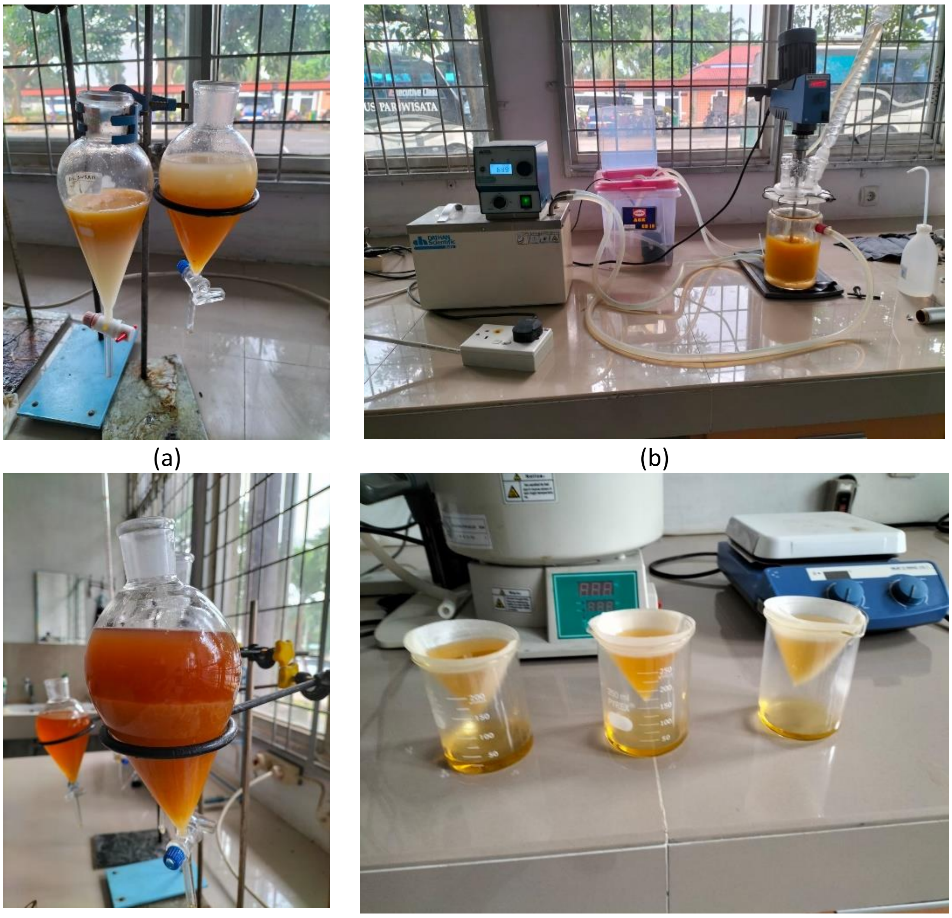
Studies in the literature indicate that while biodiesel has a higher cetane number, WPO fuel has a higher calorific value. This metric has the potential to be significant, particularly when it comes to lowering fuel consumption while using diesel-biodiesel blends in CI engines. Thus, engine tests at various loads were used in this study to assess RSB and WPO as well as their mixes with diesel. Following the addition of WPO to the diesel-RSB blended fuel, the test fuel's performance and emission characteristics were measured and contrasted with those of the mix and pure diesel.

2. Materials and Methods

2.1 Biodiesel Production

Smallholder farms in Indonesia's North Sumatra province are the source of rubber seeds. To extract the kernel from the shell, rubber seeds are shattered. To extract the sap, rubber seed kernels are cooked for two hours. The kernels are boiled, rinsed, and then sun-dried for two days in bright weather, or until they take on an oily appearance. RSO is obtained by kernel extraction using the press method at the Workshop Metal machining and fabrication, Universitas Negeri Medan, Indonesia. RSO is processed into biodiesel through the degumming, esterification and transesterification stages at the New and Renewable Energy Laboratory of the Politeknik Negeri Medan, Indonesia.

At the deguming stage, 1 liter of rubber seed oil is put into a double glass jacket mixed with 5% (50 ml) H_3PO_4, the mixture was strained at a temperature of 60^{o}C, 1000 rpm for 1.5 hours, then settled for 5 hours (Figure 1(a)), then the sap was discarded. In the Esterification stage, 500 ml of degumming RSO is put into a double tube jacket mixed with methanol in a ratio of 1: 1.25 (V methanol = 1.25 x 500 ml = 400 ml) plus 1% (5 ml) H_2SO_4. The mixture is stirred in double jacket at a temperature of 60^{o}C, rotation of 1000 rpm for 1.5 hours (Figure 1(b)), then evaporated at a temperature of 90^{o}C rotation of 70 rpm, pressure - 0.7 bar. In trans- esterification, 250 ml of esterified oil is put into a double tube jacket added with 0.5% solid KOH (KOH mass = 0.5% x 250 ml = 1.25 gr), before being put into a double tube jacket, solid KOH is first melted with 200 ml of methanol. Next, the mixture is adjusted into a double tube jacket for 30 minutes, then settle and remove the sap/dirt, then spray it with distilled water at a temperature of 50^{o}C, settle until it looks separated (Figure 1(c)), after the sediment is removed, the biodiesel is evaporated to remove the water content, then filtered using filter paper (Figure 1(d)).



(a) (b) (c) (d)

Fig. 1. RSB production process; (a) Degumming, (b) Esterificatio-Transesterification in Double jacket reactor, (c) deposition, (d) filtering

2.2 PPO Production

Plastic pyrolysis oil (PPO) mineral water gallon caps (HDPE) are produced in the energy conversion laboratory of Universitas Negeri Medan, Indonesia, using a pyrolysis reactor Figure 2(a). This PPO has been distilled to separate the diesel-like fraction and the gasoline-like fraction based on the evaporation point and specific gravity. The PPO used in this research is the diesel-like fraction (Figure 2(b)).

(a) (b)

Fig. 2. (a) PPO, (b) Mixed fuel samples

2.3 Fuel Mixture for Physicochemical Properties Test

To investigate the effect of adding PPO on changes in the physico-chemical properties of RSB, RSB and PPO were mixed at volume percentage ratios of 90:10, 80:20, 70:30, and 60:40 (Figure 3(a)). Each mixture was then tested for its physicochemical properties, and the changes in physicochemical properties that occurred in each mixed fuel were observed. The equipment used in testing physicochemical properties is shown in Table 1.

Table 1
Equipment test for physicochemical properties

Property	Equipment
Calorific value (J/g)	SVM 3000 viscometer cold properties (Anton Paar, Austria)
Cetane Index	Koehler K88620-1 Cetane Indeks (USA)
Kinematic viscosity (mm^2/s) at 40°C	SVM 3000 viscometer cold properties (Anton Paar, Austria)
Density (kg/m^3) at 40°C	SVM 3000 viscometer cold properties (Anton Paar, Austria)
Oxidation stability (hours at 110°C)	rapidOxy 100 fuel (oxidation stability tester (Anton Paar, Germany)
Acid number (mg KOH/g oil)	ECH 7000 Titrator Type TAN/TBN Titrator (ECH Germany)

2.4 Fuel Mixture for Physicochemical Properties Test

Before testing on a diesel engine, pure diesel, RSB and PPO is mixed with the volume ratio as in Table 2, the mixture is stirred in a double tube jacket for 5 minutes, each mixture is put into a bottle as shown in Figure 3(b).

Table 2
Fuel composition and initials

Diesel (% vol.)	RSB (% vol.)	PPO (% vol.)	Initials
100	0	0	D100
60	40	0	B40
60	30	10	B30P10
60	20	20	B20P20
60	10	30	B10P30

(a) (b)

Fig. 3. Fuel samples for testing (a) physico-chemical properties, (b) Engine Performance

2.5 Engine Performance Test

Test engine of the diesel engine at the Universitas Sumatera Utara, Internal Combustion Engine Laboratory is used to operate the test fuel. The engine performance testing installation is shown in Figure 4. A single cylinder diesel engine is connected via a clutch to a water meter dynamo as shown in Figure 4. Diesel engine specifications are explained in Table 4. The TecQuipment TD114 IC Engine Instrumentation measuring instrument panel contains engine speed, torque, exhaust gas temperature, cylinder inlet air flow speed and burette. With the use of a timer, the burette is used to calculate the rate of gasoline consumption. To monitor emissions, an opacity tester and gas analyzer are attached in the exhaust pipe. The engine is run using a fuel mixture as in Table 3 at medium speed (2200 rpm) and varying loads of 25%, 50%, 75% and 100%.

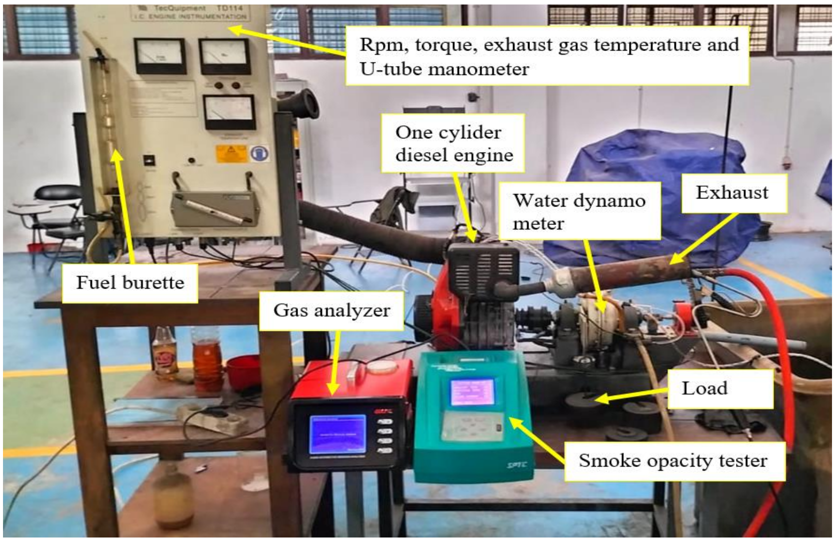


Fig. 4. Diesel engine performance testing installation

Table 3
Physico-chemical properties of mixed fuels

No.	Fuel Properties	Test Method	D100	B40	B30P10	B20P20	B10P30
1	Calorific Value (kJ /kg)	ASTM D-4809-06	44.99	36.93	37.87	38.33	39.74
2	Density (gr/ml)	ASTM D-2638-10	0.846	0.807	0.791	0.784	0.768
3	Viscosity (mm^2/s)	ASTM D-445	4.24	8.7	6.75	5.05	4.11
4	Cetane number	ASTM - D 2699	48	62.9	54.9	53.9	51.1

From the torque data measured on the tool panel, the brake power BP is calculated using Eq. (1).

$$BP = \frac{2\pi NT}{60000}\ (kWh) \tag{1}$$

Where N is the engine speed and T shows the measured torque.

Eq. (2) is then used to get the brake thermal efficiency (BTE) based on the acquired BP value.

$$BTE = \frac{BP}{\dot{m}f\ x\ Q_{LHV}}\ (\%) \tag{2}$$

where Q_{LHV} is the fuel's calorific value (kJ/kg) and $\dot{m}f$ is the fuel consumption rate (kg/h). In the meanwhile, Eq. (3) was used to compute specific fuel consumption (BSFC).

$$BTE = \frac{BP}{\dot{m}f\ x\ Q_{LHV}}\ (\%) \tag{3}$$

Table 4
Main engine test parameters

Parameter	Specifications
Brand-type	ROBIN-FUJI DY23D
Valve position	0.10mm
Valve rockers clearance	0.10mm
Cylinder volume	230 cm^3
Bore	70mm
Stroke	60mm
Compression ratio	21
Number of cylinder	1
Maximum power	4.2 kW on 3750 rpm
Maximum torque	11.2 Nm on 3500 rpm
Injection time	23^o BTDC

To ascertain the measurement device's accuracy, error analysis is performed. Numerous elements, such as the test design, instruments, calibration, observations, and ambient circumstances, might lead to errors. Instrument and percentage uncertainty of load, engine speed, fuel consumption, CO, HC, opacity, time meter are presented in Table 5.

Table 5
Uncertainly instruments

Measurements	Accuracy	% Uncertainly
Load	± 0.1 kg	± 0.2
Engine speed	± 10 rpm	± 0.3
Fuel consumption	± 0.1 ml	± 1
CO	± 0.02%	± 0.1
HC	± 5%	± 0.2
Opacity	±0.1%	± 1
Time (stopwatch)	± 0.2 s	± 0.2

3. Results

3.1 The Effect of PPO Mixing on the Physicochemical Properties of RSB

After mixing RSB with PPO, each mixture's physicochemical properties were checked. The results of examining the physicochemical properties of the mixture of RSB and PPO are shown in Table 6.

A higher calorific value is one of the most important criteria for raw materials as biofuels [4]. Table 6 show that the heating value of PPO (46.55 J/g) is much higher than RSB (39.95 J/g) and slightly higher than diesel fuel (46.22 J/g). Even though the heating value of RSB is at the ASTM standard (37.27 J/g), this value is still far below the heating value of diesel fuel (46.22 J/g) [16-18]. After RSB is mixed with PPO, As the proportion of PPO in the blended fuel rises, so does the fuel's calorific value.

Table 6
Physico-chemical properties of RSB, PPO, and their mixtures

Physico-chemical properties	Test method	%RSB+%PPO (v/v)						ASTM Biodiesel, [31-33]	Diesel [31,34]
		100% RSB	100% PPO	90+10	80+20	70+30	60+40		
Calorific value (J/g)	ASTM D-4809-06	39.95	46.55	40.86	41.11	41.93	42.35	37.270	46.22
Cetane Index	ASTM D-976/D-2699	56.9	53.8	57.1	56.8	56.2	55.9	47 minimum	53.1
Kinematic viscosity (mm^2/s) at 40°C	ASTM D-445	4.9	2.98	4.72	4.44	4.42	4.24	1.9 to 6	3.25
Density (kg/m^3) at 40°C	ASTM D-2638-10	887	814	884	882	872	869	860 to 900	831
Oxidation stability (hours at 110°C)	ASTM D-7525 / EN 15751	1.2	0.98	0.91	0.9	0.9	0.88	3	
Acid number (mg KOH/g oil)	ASTM D-664	0.53	0.31	0.4	0.39	0.39	0.39	0.5	0.35

In contrast to the heating value, in Table 6 it can be seen that the PPO Cetane Index (53.8) is slightly lower than the RSB Cetane Index (56.9) but is still higher than the Solar Cetane Index, overall, the addition of PPO to RSB is slightly decreases the Cetane index value, but a very interesting finding is that in the 90:10 mixtures the cetane index increases to 57.1. The decrease in the cetane index due to the addition of PPO is not very significant; the lowest value is found in the 60:40 mixture (55.9), which is still far above the ASTM minimum standard for biodiesel (47) and petroleum diesel (53.1).

The viscosity of biodiesel is related to its flowability [18]. In Table 6, it can be seen the viscosity of the mixed fuel decreases as with increasing percentage of PPO in mixed fuel. This means that adding PPO to RSB can reduce its viscosity.

Density is an illustration of the density of fuel molecules. Table 6 show adding PPO to RSB reduces the density. Density is related to the air-fuel mixing capacity of fuel. The smaller the density, the easier it is for a fuel to mix with air [21]. So, it can be concluded that adding PPO to RSB can improve the RSB density value.

The oxidation stability of RSB (1.2 hours) is higher than PPO (0.98 hours); the addition of PPO to RSB also reduces the oxidation stability of RSB; this is certainly not good because higher oxidation stability is needed so that the fuel is not oxidized with itself when exposed to air [18]. An interesting finding in Table 6 is that a significant decrease in oxidation stability occurred with adding 10% PPO. However, adding 20% or more only provided a very small decrease.

In Table 6, it can be seen that the addition of PPO to RSB reduces the acid value. Mixing 10% PPO into RSB makes the fuel acid value drop drastically from 0.53 to 0.4 mg KOH/g oil, but the addition of

20% to 40% PPO no longer reduces the fuel acid value mixture. This decrease in acid value is good, as the acid content in the fuel affects the durability of the exposed components [22]. Acid is corrosive, so, it can reduce component life and is related to engine durability [30]. From the results of this research, it appears that PPO can be used as an additive to reduce the acid value of RSB. This section discusses the results obtained from the surface pressure measurement study.

3.2 The Effect of Adding PPO to RSB on Engine Performance

3.2.1 Torque

Torque variations with engine load for pure diesel and each blended fuel are shown in Figure 5(a). The torque of all fuels tested increases with increasing engine load. Diesel fuel (D100) has the greatest torque of all the fuels tested, 4.50 Nm and 9.30 Nm respectively at 25% load and maximum load. The lowest of all the fuels tested is 8.50 Nm for the diesel and RSB mixture (B40), but the full load values for the diesel, RSB, and PPO mixtures (B30P10, B20P20, and B10P30) are 8.70 Nm, 8.80 Nm, and 8.90%, respectively. The torque of pure diesel fuel is higher than all the fuels tested at all loads. This is due to the viscosity, density of the mixed fuel being higher than petro diesel fuel. Fuels with higher viscosity and density cause poor atomization [24]. Furthermore, mixed fuel has a lower calorific value than petro-diesel fuel. When PPO is added to the Diesel-RSB combination, torque may be increased at all loads.

3.2.2 Brake power (BP)

Braking power for all fuels tested is shown in Figure 5(b). It can be seen that BP is proportional to torque, because BP is obtained from the torque variable using Eq. (1). BP of all fuels tested increases with increasing engine load.

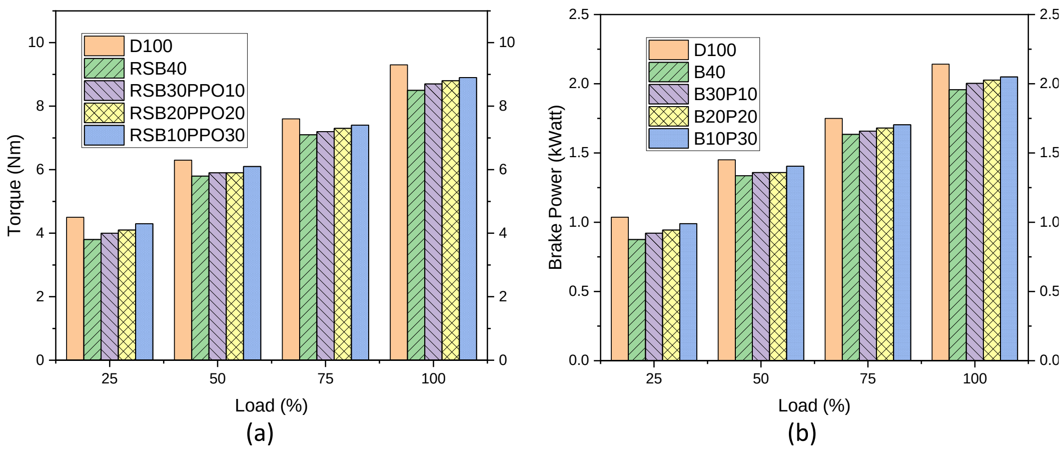


Fig. 5. (a) Torque (b) Brake Power at each load

3.2.3 Brake specific fuel consumption (BSFC)

The load-BSFC curve is depicted in Figure 6(a). According to these numbers, at full load, diesel has a BSFC of 0.23 kg/kWh and 0.50 kg/kWh at 25% load. At 25% load, the diesel-biodiesel combination produces 0.89 kg/kWh, and at full load, 0.37 kg/kWh. At full load and 25% load, the B30P10's BSFC is 0.32 kg/kWh and 0.77 kg/kWh, respectively. At 25% and full load, respectively, the B20P20's BSFC is 0.70 kg/kWh and 0.32 kg/kWh. At 25% and full load, the B10P30's BSFC is 0.59 and 0.26, respectively.

For various fuels, the change in BSFC with load indicates a decline with increasing load. Because the blended fuel has a lower calorific value than diesel, the blend's overall BSFC is higher than diesel's over the whole load range. The BSFC, however, decreases when PPO is added to the diesel-biodiesel combination because, as Table 6 indicates, the calorific value of the fuel in the PPO mixture is larger than that of the diesel-RSB mixture.

3.2.4 Brake thermal efficiency (BTE)

Figure 6(b) illustrates how BTE varies with engine load for both pure diesel and the corresponding mixed fuels. The highest BTE of all tested fuels is 37.07% for diesel (D100) at full load. For a mixture of diesel and RSB (B40) it is 27.08% which is the lowest of all the fuels tested, while for a mixture of diesel, RSB and PPO namely B30P10, B20P20 and B10P30 respectively at full load it is 30.16%, 32.14% and 35.47%. As engine load increases, so does the BTE of diesel, diesel mixture RSB, and combination of diesel, RSB, and PPO. The heat produced in the combustion chamber increases with engine load, increasing thermal efficiency as a result. At maximum load, the thermal efficiency of a diesel mixture containing plastic waste oil is better than that of a combination of biodiesel, but it is lower than that of pure diesel. This might be because, as Table 6 shows, PPO has a larger calorific value than RSB, meaning that for a given fuel mass, PPO releases more energy [24].

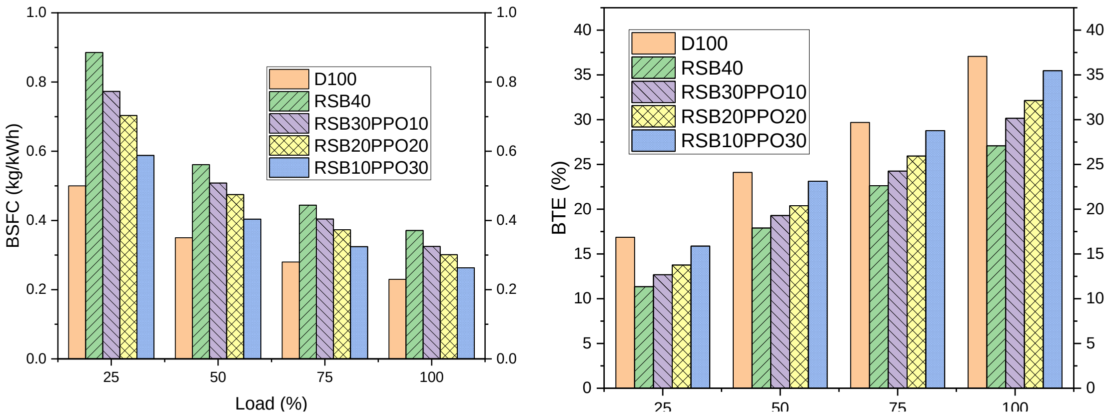


Fig. 6. (a) Fuel specific brake consumption, (b) Brake thermal efficiency

3.3 Emission

3.3.1 CO (carbon monoxide)

The production of carbon monoxide, a hazardous gas, occurs when there is insufficient oxygen in the air, inadequate airflow, inadequate mixture preparation, and incomplete combustion [35]. The two biggest factors for CO emissions from engines are low ignition temperatures and excessive fuel-to-air ratios [36]. Increased CO emissions cause the engine to lose power [36]. Its creation can have a variety of origins; among the reasons are inadequate residence times and excessively high or low equivalency ratios [17]. The CO emission trend for each fuel tested at different engine loads is displayed in Figure 7(a). CI engines typically run on a lean mixture. As a result, it was discovered that CO emissions were lower than those of SI engines. Diesel emits different amounts of CO, ranging from 0.08% at 75% load to 0.17% at full load. For diesel-biodiesel blends, it ranges from 0.04% at 75% load to 0.08% at full load. The figure for the B30P10 is 0.1% at full load and 0.07% at 25% load. At 25% load, the readings for B20P20 and B10P30 are, respectively, 0.08% and 0.09%; at full load, the values are 0.13% and 0.15%. The quantity of CO rises with increasing load for all test fuels. The addition of PPO to the Diesel-RSB mixture raises the CO emissions at all engine loads; this might be because the additional oxygen in RSO is helpful for improved combustion. The CO emissions of the entire mixed fuel are lower than those of pure diesel at all loads [36].

3.3.2 UHC (unburned hydrocarbon)

Unburned hydrocarbons consist of incompletely burned fuel [23]. An organic component in gaseous form is referred to as a hydrocarbon, whereas a solid hydrocarbon is a particulate matter [25]. Incomplete combustion of the fuel and air combination results in UHC emissions [26]. Figure 7(b) illustrates how UHC emissions for diesel, diesel-RSB mixture, and PPO vary with engine load. For pure diesel, it ranges from 36 ppm at 25% load to 40 ppm at full load. The value for Diesel-RSB is 27 ppm at 25% load and 30 ppm at full load, respectively. The result for the B30P10 is 34 ppm at full load and 29 ppm at 25% load. At 25% load, the readings for B20P20 and B20P20 are 32 and 30 ppm, while at full load, they are 36 and 38 ppm. Diesel with RSB added lowers its hydrocarbon emissions, whereas diesel with PPO added raises its hydrocarbon emissions. The hydrocarbon nature of PPO may be the culprit; if it burns partially, UHC will be released into the exhaust.

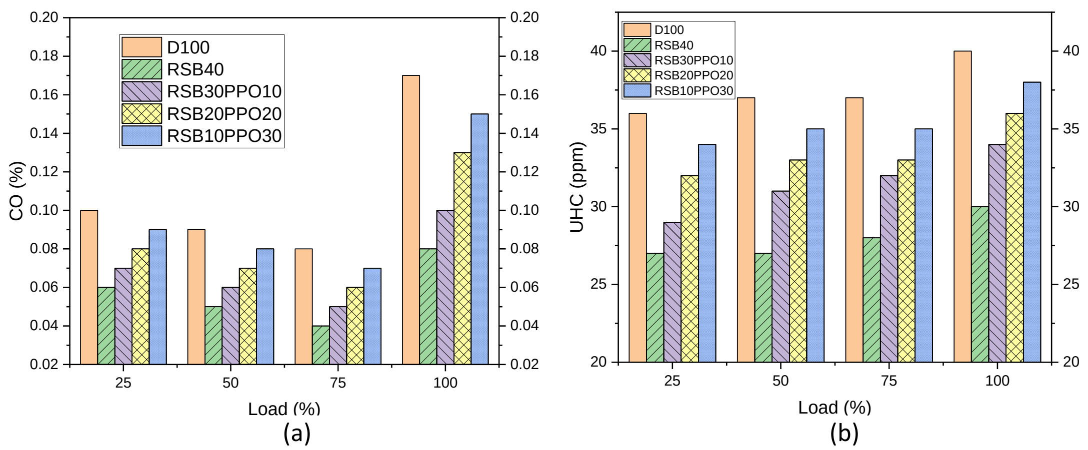


Fig. 7. (a) CO emission, (b) HC emission

3.3.3 Smoke opacity

As engine load increases, fuel smoke becomes more opaque. Higher engine load causes the air-fuel ratio to drop as fuel injection volume rises, increasing smoke emission [27]. The change in smoke emissions with engine load for all tested fuels is displayed in Figure 8. Diesel smoke has an opacity level of 22.4% at 25% load and 51.3% at full load. The figures for the Diesel-RSB combination are 40.1% at full load and 13.7% at 25% load. At 25% load, the smoke opacity for B30P20, B20P20, and B10P30 is 15.1%, 17.10%, and 19.10%, respectively; at maximum load, it is 45.30%, 48.50%, and 49.40%. Diesel's smoke opacity decreases when RSB is added; however, when PPO is added to the diesel-RSB combination, smoke opacity increases, but it still remains lower than that of pure diesel. This is because RSB's increased oxygen concentration promotes the creation of a lean mixture and an oxygen-containing fuel mixture [28]. When the mixture is rich, incomplete combustion occurs in the combustion chamber and produces smoke [29]. However, if PPO smoke emissions increase, this is due to the ignition delay time and longer burning duration which may cause higher smoke [37].

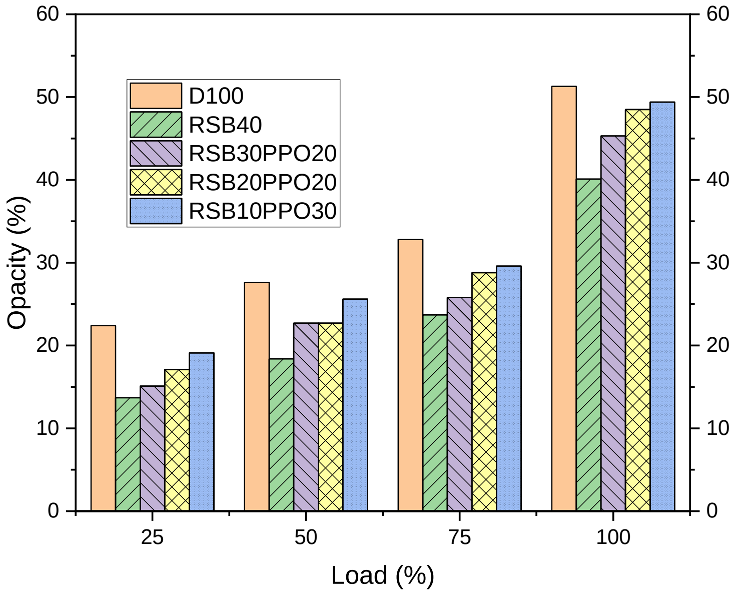


Fig. 8. Opacity emission

4. Conclusions

Mixing PPO into RSB can improve several physical and chemical properties of RSB, including increasing heating value, reducing viscosity, density and acid number. On the other hand, PPO also worsens the physicochemical properties of RSB, including reducing the cetane number and reducing oxidation stability.

Overall engine performance using pure diesel (D100) was higher than all the mixed fuels tested, but when compared with using RSB 40, the addition of PPO to the diesel-RSB mixed fuel improved engine performance. Brake thermal efficiency decreases by 4% when using B10P30 compared to using pure diesel, but increases by around 30% compared to using RSB40 at full load. When using RSB40, CO, HC, and smoke emissions are at their lowest. When PPO is added to the Diesel-RSB combination fuel, these emissions rise, but they are still less than those of pure diesel.

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