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Experimental Analysis of Engine Performance and Exhaust Pollutant on a Single-Cylinder Diesel Engine Operated Using Moringa Oleifera Biodiesel

Manzoore Elahi M. Soudagar [1], Haris Mahmood Khan [2], T. M. Yunus Khan [3,4], Luqman Razzaq [5], Tahir Asif [5], M. A. Mujtaba [5], Abrar Hussain [6], Muhammad Farooq [5], Waqar Ahmed [7,8], Kiran Shahapurkar [9], Azham Alwi [10], T. M. Ibrahim [10], Usama Ishtiaq [5], Ashraf Elfasakhany [11], Maughal Ahmed Ali Baig [12], Mohammad Shahab Goodarzi [13] and Mohammad Reza Safaei [14,15,16,*]

1 Department of Mechanical Engineering, School of Technology, Glocal University, Delhi-Yamunotri Marg, SH-57, Mirzapur Pole, Saharanpur District, Uttar Pradesh 247121, India; me.soudagar@gmail.com
2 Department of Chemical, Polymer and Composite Materials Engineering, University of Engineering & Technology, Lahore 54890, Pakistan; hariskhan@uet.edu.pk
3 Research Center for Advanced Materials Science (RCAMS), King Khalid University, P.O. Box 9004, Abha 61413, Saudi Arabia; yunus.tatagar@gmail.com
4 Department of Mechanical Engineering, College of Engineering, King Khalid University, Abha 61421, Saudi Arabia
5 Department of Mechanical Engineering, University of Engineering and Technology, New Campus Lahore 54890, Pakistan; Luqmanrazzaq@uet.edu.pk (L.R.); tahir.asif@hotmail.com (T.A.); m.mujtaba@uet.edu.pk (M.A.M.); engr.farooq@uet.edu.pk (M.F.); 2018me302@student.uet.edu.pk (U.I.)
6 Department of Mechanical and Industrial Engineering, Tallinn University of Technology, Ehitajate Tee 5, 12616 Tallinn, Estonia; Abhuss@taltech.ee
7 Malaysia-Japan International Institute of Technology (Mjiit), UTM Kuala Lumpur, Jalan Sultan Yahya Petra, Kuala Lumpur 54100, Malaysia; waqarum.ah@gmail.com
8 Institute for Advanced Studies, Univerity of Malaya, Kuala Lumpur 50603, Malaysia
9 School of Mechanical, Chemical and Materials Engineering, Adama Science and Technology University, Adama 1888, Ethiopia; kiranhs1588@astu.edu.et
10 Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia; azham.alwi@outlook.com (A.A.); ymtmis@um.edu.my (T.M.I.)
11 Mechanical Engineering Department, College of Engineering, Taif University, P.O. Box 11099, Taif 21944, Saudi Arabia; ashr12000@yahoo.com or a.taha@tu.edu.sa
12 Department of Mechanical Engineering, CMR Technical Campus, Hyderabad 501401, India; mabaig09@gmail.com
13 Institute of Research and Development, Duy Tan University, Da Nang 550000, Vietnam; mohammadshahabgoodarzi@duytan.edu.vn
14 Mechanical Engineering Department, Faculty of Engineering, King Abdulaziz University, Jeddah 21589, Saudi Arabia
15 Department of Medical Research, China Medical University Hospital, China Medical University, Taichung 40402, Taiwan
16 Department of Civil and Environmental Engineering, Florida International University, Miami, FL 33174, USA
* Correspondence: msafaei@fiu.edu; Tel.: +1-502-657-9981

Abstract: In this investigation, biodiesel was produced from Moringa oleifera oil through a transesterification process at operating conditions including a reaction temperature of 60 °C, catalyst concentration of 1% wt., reaction time of 2 h, stirring speed of 1000 rpm and methanol to oil ratio of 8.50:1. Biodiesel blends, B10 and B20, were tested in a compression ignition engine, and the performance and emission characteristics were analyzed and compared with high-speed diesel. The engine was operated at full load conditions with engine speeds varying from 1000 rpm to 2400 rpm. All the performance and exhaust pollutants results were collected and analyzed. It was found that MOB10 produced lower BP (7.44%), BSFC (7.51%), and CO_2 (7.7%). The MOB10 also reduced smoke opacity (24%) and HC (10.27%). Compared to diesel, MOB10 also increased CO (2.5%) and NO_x (9%) emissions.

Keywords: biodiesel; moringa oleifera methyl ester; compression ignition engine; transesterification; performance and emission characteristics

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1. Introduction

The growth of the human population and a higher quality of living have increased global energy consumption. One of the most significant consumers of energy is the transportation field [1,2]. Transportation is heavily dependent on gasoline and diesel engines. Nevertheless, compared to gasoline, diesel engines are more cost-effective and energy-efficient [3,4]. Diesel has also become preferable because of its higher fuel efficiency, energy density, and lower carbon dioxide (CO_2) emissions [5,6]. Thus, diesel engines provide higher mileage [7]. However, factors such as the increasing price of world crude oil, the decline in fossil fuel, and the increase in greenhouse gas emissions have forced researchers and scientists to find renewable and sustainable energy resources [8–10].

Furthermore, the health issues resulting from the exhaust of fossil fuel engines are causing alarm across the world [11,12]. Therefore, scientists and researchers are now searching for more renewable, sustainable and cleaner alternatives to replace fossil fuels [13,14]. Scientists and researchers are looking for ways to develop alternative fuels to deal with escalating energy demands [15–17].

In this regard, biodiesel or fatty acid methyl ester (FAME) is a potential substitute for petroleum-derived diesel in vehicles [18,19]. Biodiesel is usually produced by transesterification of edible oil or animal fats [20,21]. However, nowadays, biodiesels are also produced from the transesterification of non-edible oils, waste cooking oil, macroalgae, animal fats, and microalgae [22]. Thus, the sources used to produce biodiesel are sustainable and renewable [23]. Moreover, the biodiesel feedstock can be replenished by cultivating crops and rearing livestock.

In contrast, the sources of fossil fuel are non-renewable [24]. Biodiesel blends have been used without making any significant modifications to diesel engines. Biodiesels are potential alternatives for diesel because of their chemical and physical properties [25,26]. Biodiesel utilization in unmodified diesel engines slightly increases brake-specific fuel consumption and NO_x emissions. However, biodiesel consumption significantly decreases CO, unburned hydrocarbon (HC), and particulate emissions due to more oxygen and the lack of aromatic content in biodiesels [27,28]. Various research studies have been performed on engines to examine the performance and emission characteristics of *Calophyllum inophyllum* and palm biodiesel blends [29].

A number of experimental studies have also been performed on the production of *MOB* and its physicochemical properties. However, there are no comparative studies to date regarding engine performance and the emission characteristics of *MOB* and its blends of 10% and 20% with diesel in an SCD. This provided the motivation and purpose of this study, which may also potentially assist in the future generation of alternative fuel. Therefore, the engine performance and emission characteristics resulting from regular fossil diesel and all *Moringa oleifera* methyl ester blended fuels were investigated.

Liaquat, Masjuki [30] experimentally examined exhaust gas emissions from a compression ignition engine fueled with palm biodiesel. A Bosch gas analyzer was used to analyze the engine exhaust emission parameters for 250 h at a 2000 rpm engine speed. A significant reduction in CO and CO_2 emissions was recorded as the biodiesel concentration increased in blends. This was due to an excess amount of oxygen, which results in complete combustion occurring in the combustion chamber. Ozsezen and Canakci [31] examined the performance and emission characteristics of the CI engine palm oil methyl ester (biodiesel) blended with pure diesel. As a result, BSFC and brake power (BP) increased by 7.5 and 2.5%, respectively. A significant reduction of 86.89% in CO, 14.29% in HC, and 67.65% in smoke opacity were observed for palm biodiesel. However, the palm oil methyl ester enhanced NO_x emissions by 22.1%. Sharon, Karuppasamy [32] used different palm biodiesel concentrations in diesel using a KIRLOSKAR TV-1 diesel engine. During the test, the engine's load was changed from 20% to 100% at a constant engine speed of 800 rpm. The BSFC for palm biodiesel and pure diesel was found to be

0.315 and 0.2755 kg/kWh, respectively, at full load conditions. Biodiesel blends, B25, B50 and B75, showed a slightly higher BSFC of 2.6%, 8.9% and 9.3%, respectively, than pure diesel. Ong, Masjuki [33] used *Calophyllum inophyllum* biodiesel in their study to examine engine performance and the emission characteristics of a CI engine. According to their experimental results, the B10 blend showed a slight improvement in BTE as compared to diesel. However, EGT and BSFC were lower for this blend. Shehata and Razek [34] reported on the performance and emission characteristics of neat SOME at different engine speeds and loads. Resultantly, BSFC increased while BP, BTE, and torque were decreased as compared to diesel. For emissions, NO_x was reduced, but CO and CO_2 were increased. Roy, Wang [35] experimented using COME to monitor the performance and emission characteristics of a four-stroke two cylinders CI engine. The results suggested that BSFC of 10% COME blended fuel showed no significant increment, but further increasing biodiesel concentration in diesel fuel caused a slight increase in the BSFC, up to 2.3% compared to pure diesel. For emissions, CO emission was reduced for all percentage ratios of blended fuels, while similar trends were observed for NO_x emission from the B10 blend and pure diesel. However, an increasing percentage of COME in blended fuel increased the NO_x emission. Agarwal and Dhar [36] explored the performance, combustion and emission characteristics of Karanja oil methyl ester blended fuel (10%, 20%, and 50%). With regard to the engine performance, BSFC and EGT increased while BTE decreased as compared to diesel fuel. A significant reduction in HC and smoke opacity was observed with a slightly escalation in NO_x emissions as compared to high-speed diesel. Both B10 and B20 blends delivered almost the same performance and emission characteristics.

Moringa oleifera Lamarck is a member of the Moringaceae family, a tropical plant that is easy to disseminate and grows to a height of around 5 m–10 m. It is widely grown in tropical countries and is mainly distributed in India, Bangladesh, Pakistan, Africa, South America, Arabic countries, the Philippines, Thailand, and Malaysia. The seeds of *Moringa oleifera* contain 40% of oil by weight, and the oil produced is a golden yellow color [37]. Several researchers have reported that *Moringa oleifera* oil contains a high oleic acid volume, that is, approximately 70% of the total fatty acid summary [38]. Compared to other feedstocks, *Moringa oleifera* oil is from a non-edible source, which gives it good potential for conversion into biodiesel without affecting food industries [39].

Rajaraman et al. [40] have discussed blended Moringa oleifera methyl ester (B20 and B100) and analyzed the engine performance and emission characteristics using a direct injection CI engine at full load conditions. The performance results show that the brake thermal efficiency of Moringa oleifera blended fuel decreased compared to standard diesel fuel due to its high viscosity and density, as well as the lower calorific value of the blended fuel. The emission results show that Moringa oleifera blended fuel produces lower CO, HC NOx, and PM than regular diesel fuel.

The current energy emergency has negatively affected the worldwide economy. The economies of numerous non-industrial nations have become uncompetitive because of the lack of usable energy. The present study is an effort to reduce the consumption of conventional fossil fuels. Moringa oil is derived from the seeds of Moringa oleifera, a small tree local to the mountains that can be used to prepare biodiesel via the transesterification process.

2. Materials and Methods

2.1. Biodiesel Preparation

The *Moringa oleifera* biodiesels were produced through an alkaline-catalyzed transesterification process. Firstly, the *Moringa oleifera* crude oil was mixed with 25% vol. of methanol and 1% wt. of KOH. A temperature of 60 °C and a stirring speed of 1000 rpm were maintained for 2 h. These conditions, were used to ensure that a homogenous mixture of Moringa oleifera oil, methanol, and potassium hydroxide was obtained, and so that the transesterification process would produce a desirable yield rate. Once the transesterification process was finished, the biodiesel was separated via a separating funnel. After 12 h, the product was transformed into two layers. Two immiscible layers of liquid formed in the separating funnel, the top layer was the methyl ester (biodiesel), and the bottom layer consisted of impurities and glycerin. The bottom layer was drained from the separating funnel, and following this, 50% vol. of distilled water at a temperature of 60 °C was used to spray and wash each methyl ester. Next, the methyl ester was rinsed with hot DW until *Moringa oleifera* methyl ester was cleaned of all impurities. Then, by using a rotary evaporator, methyl ester was dried and then purified via filter paper. After the purification process, MOME was mixed with diesel at various ratios to produce the biodiesel blends. The blends prepared in this study were as follows: MOB10, MOB20, and diesel. A total of three samples were prepared for the study, comprising two samples of biodiesel blends and one sample of pure diesel.

2.2. Composition of Biodiesel

The FAC of the MOME was analyzed using a gas chromatography (GC) system, Agilent 7890 series, USA. Specifications and operating mode of GC system are summarized in Table 1. The FAC of the MOME is presented in Table 2. The amount of esters, methyl linoleate, monoglycerides, diglycerides, triglycerides, and free and total glycerin was measured according to the EN14103 standard.

Table 1. Operating parameters of gas chromatography.

Parameters	Specifications
Injector	Split type
Injection volume	1 μL
Oven temperature	210 °C, isothermal
Split flow	100 mL/min
Carrier gas	Helium, 83 kPa
Column	60 °C for the initial time
Column 2 flow	The constant flow of helium at 1 L/min
Temperature	Rise from 60 °C to 200 °C at an interval of 10 °C
Detector	250 °C, flame ionization detector with electronic flow control

Table 2. Composition of moringa oleifera methyl ester.

Fatty Acids	Chemical Structure	Molecular Mass (g/mol)	Composition of MOME (*w*/*w* %)
Laurate	C12:0	214.34	
Myristate	C14:0	242.4	0.1
Palmitate	C16:0	270.45	8.1
Palmitoleate	C16:1	268.43	1.6
Stearate	C18:0	298.5	5.4
Oleate	C18:1	296.49	74.3
Linoleate	C18:2	294.47	4.1
Linolenate	C18:3	292.46	0.2
Arachidate	C20:0	326.56	2.3
Eicosenoate	C20:1	324.24	1.5
Behenate	C22:0	354.61	2.6
Saturated			18.7
Monounsaturated			76.9
Polyunsaturated			4.4

2.3. Physiochemical Characteristics of Biodiesel

It was imperative to measure Moringa oleifera biodiesel (MOME) characteristics and their blends (MOB10 and MOB20) to assess the quality and suitability of these fuels for diesel engines. Each biodiesel has different physicochemical properties depending on feedstock type and biodiesel production process, post-production treatment, and fatty acid composition of the biodiesel. Hence, different biodiesel and biodiesel blends shows different effects on the CIDE's performance and exhaust emissions. In this study, the physicochemical properties (i.e., density, viscosity index, flash point, acid number, oxidation stability, pour point, cloud point, and CFPP and kinematic viscosity) of MOME and the blends were measured using ASTM standards. Results of the measured properties are summarized in Table 3. A Stabinger viscometer (Model: SVM 3000, Anton Paar, UK) was utilized to measure density (at 15 and 40 °C) and kinematic viscosity (at 40 and 100 °C). A bomb calorimeter (Model: C2000 Basic, IKA, UK) was utilized for calorific value measurement.

$$\begin{aligned} CCI = 0.0892(T_{10N}) \quad & +45.2 + [0.131 + 0.901\ (B)][T_{50N}] \\ & +[0.0523 - 0.420(B)][T_{90N}] + 107(B) + 60B^2 \\ & +[0.00049]\left[{T_{10N}}^2 - {T_{90N}}^2\right] \end{aligned}$$

where,

CCI = calculated cetane index, D = density at 15 °C (g/mL), B = $[e^{(-3.5)(DN)}] - 1$, DN = D − 0.85, $T_{10N} = T_{10} - 215$, $T_{50N} = T_{50} - 260$, and $T_{90N} = T90 - 310$.

Table 3. Physicochemical characteristics of *Moringa oleifera* biodiesel and their blends.

Property	Unit	ASTM Standards	Diesel	MOB10	MOB20	MOB100
Density at 15 °C	kg/m^3	D4052	856.9	860.1	861.7	877.6
Density at 40 °C	kg/m^3	D4052	828.4	831.2	834.6	860.7
Kinematic viscosity at 40 °C	mm^2/s	D445	3.2525	3.5572	3.6772	4.8338
Viscosity index	–	–	91	101.5	112.1	185.2
Oxidation stability	h	EN ISO 14112	35	33.5	32.7	26.4
Cetane index	–	D4737	48.9	48.3	49.6	58.5
Flashpoint	°C	D93	68.7	80.1	82.9	151.2
Cloud point	°C	D2500	8	7	8	18
Pour point	°C	D97	0	3	6	18
Cold filter plugging point	°C	D6371	5	6	6	18
Calorific value	MJ/kg	D240	45.86	44.18	43.61	39.98

The cetane index of MOME and the blends was calculated based on the recovered temperature values at 10%, 50%, and 90% (T_{10}, T_{50}, and T_{90}) and the fuel density at 15 °C (D) according to ASTM D4737 standard test methods, which is given by the equation in [41].

2.4. Engine Setup

A naturally aspirated, single-cylinder, four-stroke, direct injection diesel engine with an eddy current dynamometer was used in this study. Technical specifications for the tested engine are listed in Table 4. The experimental layout of the test engine is displayed in Figure 1. Engine tests were carried out in full load conditions in triplicates, and the engine speed varied from 1000 to 2400 RPM with an interval of 200 rpm. The exhaust emission parameters (smoke opacity, NO_x, HC, and CO) were analyzed using an AVL exhaust gas analyzer (Model: DiCom 4000, AVL Ditest, Austria). In Table 5, the technical specifications of the used gas analyzer (AVL exhaust gas analyzer) are listed. First, the neat diesel fuel was utilized to bring the engine to a stable operating condition. Once this condition was reached, the biodiesel blended fuel was used for investigation. The engine was run for a few minutes, and then the residual diesel was drained. Data acquisition was performed after the drainage of residual diesel. This practice was repeated for each biodiesel blend. After one test was completed for the biodiesel blend, the engine was operated via diesel. This practice helped to drain the residual biodiesel blend used in the previous test from the fuel line.

2.4.1. BTE and BSFC

Brake thermal efficiency (BTE) is defined as the brake power of an internal combustion engine as a function of the heat input obtained from fuel burning. BTE is calculated using the formula given below:

$$\eta_{BTE} = \frac{BP \times 3600 \times 100}{m \times C_v}\%$$

where, BP is brake power, m is mass flow rate and C_v is the calorific value of the tested fuel.

Measurement of the fuel efficiency of any engine that burns the fuel and generates rotational or shaft power is BSFC.

2.4.2. Smoke Opacity, HC, CO and NO_x

Smoke opacity is defined as the amount of light concealed by the particulate matter or soot particles omitted from the combustion of diesel. Smoke opacity reflects the presence of soot in the exhaust gases. Smoke meters, also known as opacity meters, measure the amount of light blocked in the smoke emitted by vehicles. The smoke in engine exhaust depends mainly on the combustion process, formation of the air–fuel mixture, amount of fuel injected before the ignition process, and oxygen content of fuel [42]. In general, incomplete fuel combustion leads to higher smoke opacity. Smoke opacity is influenced by the engine speed, engine load, fuel viscosity, cetane number, air turbulence, and spray pattern in the cylinder [43,44]. HC is produced in the diesel engine when there is an over-rich mixture or over-lean mixtures. Physicochemical properties of the fuel, fuel injection, and engine operating conditions also play a vital role in forming HC emissions. Incomplete combustion leads to CO formation. The lower oxygen content of diesel results in higher CO emissions.

On the other hand, vegetable oil-based biodiesels have a higher oxygen content in their chains, which leads to complete combustion, and hence, lower CO emissions. NO_x emissions are influenced by the fuel's spray characteristics and oxygen content, and adiabatic flame temperature. Spray fuel characteristics refer to the size and momentum of fuel droplets, degree of mixing between fuel droplets with air, penetration rate and evaporation, and radiant heat transfer rate [45–49].

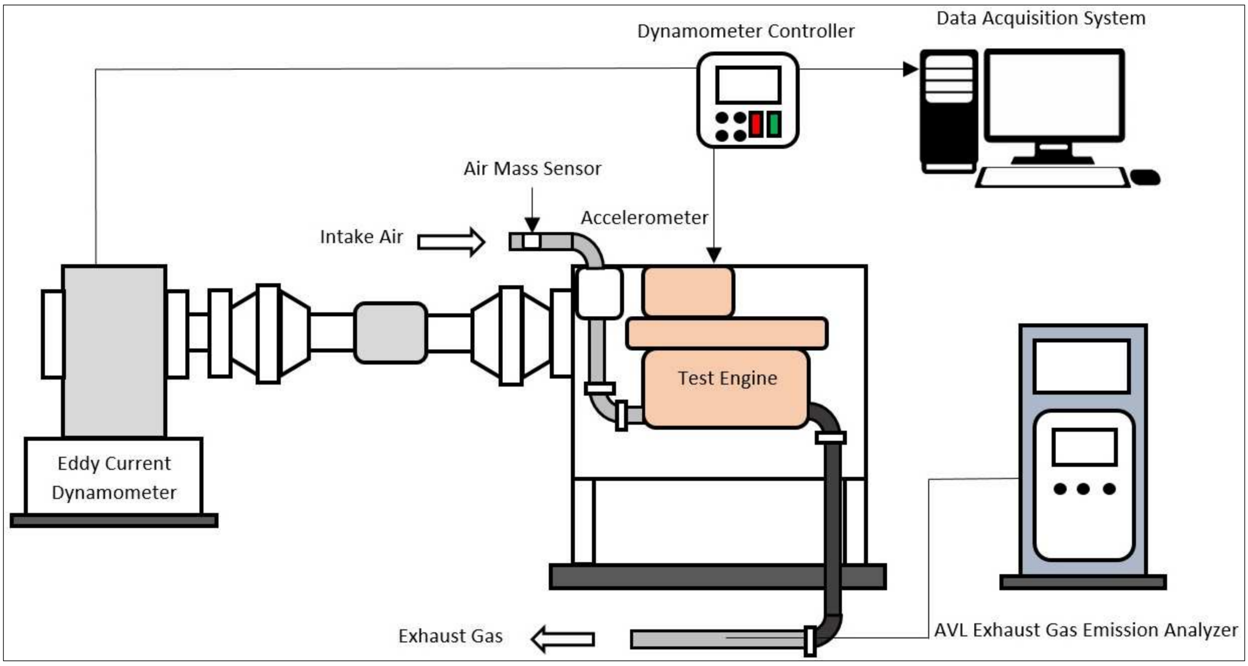

Figure 1. Schematic diagram of the diesel engine (Reprinted with permission from Elsevier, ref. [50]).

Table 4. Specifications of diesel engine [50] (Adapted with permission from the Elsevier).

No.	Description	Specifications	No.	Description	Specifications
1	Engine Model	TF 120M	5	Compression ratio	17.7:1
2	Displacement (cm^3)	638	6	Maximum power	8.8 kW/2400 rpm
3	Bore (mm)	92	7	Cooling system	Water cooling
4	Stroke (mm)	96	8	Fuel system	Pump line nozzle

Table 5. Specifications of emission analyzer.

Equipment	Measurement	Method	Measurement Range	Resolution
AVL DiGas 4000/AVL DiCom 4000	CO	Non-dispersive infrared	0–10% vol.	0.01 vol%
	HC	Non-dispersive infrared	0–20,000 ppm vol.	1 ppm
	NO_x	Electrochemical detector	0–5000 ppm vol.	1 ppm
AVL DiSmoke 4000/AVL DiCom 4000	Opacity	Photodiode receiver	0–100% vol.	0.1%

3. Results

3.1. Engine Performance Characteristics

3.1.1. Brake Power (BP)

The performance of CI diesel engines relies on the characteristics of the fuel utilized for the testing engine and fuel injection system. The fuel characteristics include kinematic viscosity, density, oxygen content, and calorific value [48,49]. Figure 2 shows the brake power (BP) of *Moringa oleifera* biodiesel blends and diesel at different engine speeds. According to the results, BP increases progressively with engine speed until 2200 rpm and then decreases. Consequently, diesel fuel has the highest BP (5.43 kW) at 2200 rpm.

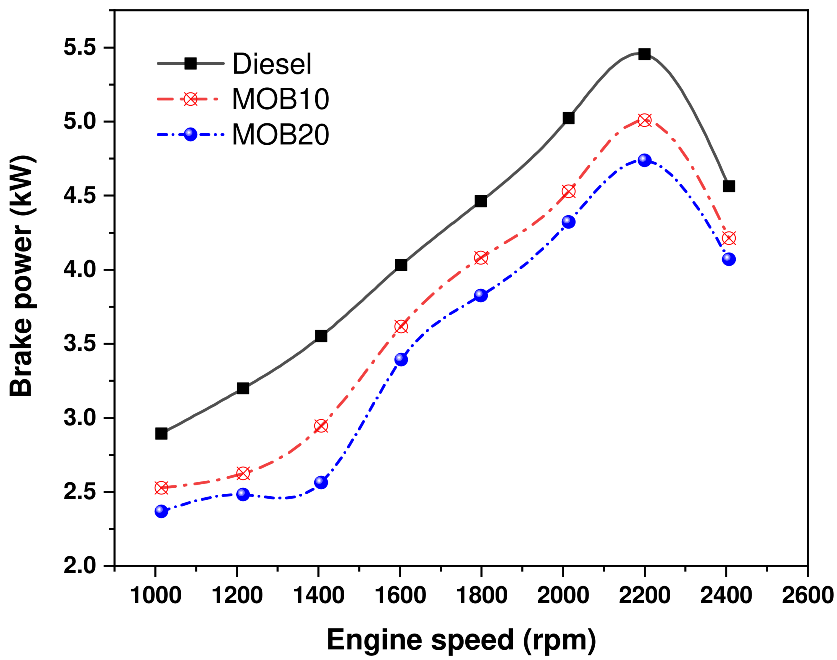

Figure 2. Variation in BP with engine speed for biodiesel blends and diesel.

In contrast, the MOB20 blend has the lowest BP (4.68 kW). The average BP is higher for diesel than MOB10 and MOB20 by 12.18% and 17.32%, respectively. The average BP is lower for MOB20 than MOB10 and diesel by 6.85% and 7.17%, respectively. This may be attributed to the larger HHV of biodiesel blends [50]. The MOB10 blend has the highest HHV in comparison with other biodiesel blends examined in this study. Besides, the fuel's physicochemical properties affect the spray formation during fuel injection, which in turn, affects combustion [51]. Lower viscosity and density of the MOB10 blend may result in loss of engine power due to more significant fuel pump leakage than other fuel blends [52]. Generally, fuels with higher viscosities can reduce fuel pump leakages [53].

3.1.2. Brake Specific Fuel Consumption (BSFC)

Figure 3 shows the BSFC of Moringa oleifera biodiesel blends and diesel at various engine speeds. Diesel fuel shows lower BSFC as compared to biodiesel blends. The MOB20 blend has the highest average BSFC, with a value of 0.6115 kg/kWh. The MOB10 and MOB20 blends have a higher average BSFC than diesel by 7.03% and 12.75%, respectively. In general, biodiesels have a larger HHV due to the fuel-borne oxygen. Hence, a higher amount of fuel mass needs to be injected from the fuel injection pump into the engine due to biodiesel's higher density than diesel. More biodiesel needs to be injected into the combustion chamber for the same power output as diesel according to volumetric efficiency. The higher kinematic viscosity of Moringa oleifera biodiesel blends is the leading cause of poor air–fuel mixing resulting from slower fuel atomization. Higher density and lower calorific values than diesel are factors that lead to the higher BSFC for biodiesel blends, especially those containing higher concentrations of biodiesels [54].

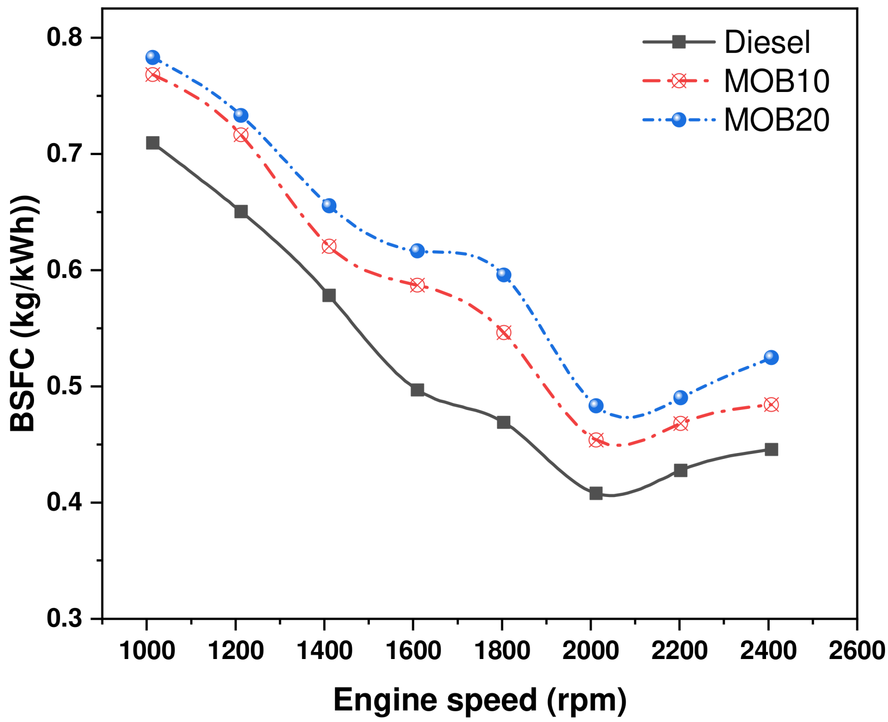

Figure 3. Variation in BSFC with varying engine speed for biodiesel blends and diesel.

3.1.3. Brake Thermal Efficiency (BTE)

At full load conditions, the BTE increases, but it declines with an increasing compression ratio; it acts similar to the indicated thermal efficiency. Figure 4 illustrates the engine brake thermal efficiencies for MOB10, MOB20, and diesel fuels. According to our observations, the average brake thermal efficiency for MOB10 was 2% higher than pure diesel. However, the average brake thermal efficiency for MOB20 was 3.45% lower as compared to pure diesel. The curves were plotted by averaging three readings. Various researchers have found similar results whereby the brake thermal efficiency of the biodiesel blends was comparable with pure diesel's thermal efficiency [55,56]. In addition, they have found that preheating biodiesel fuel before injection increases the brake thermal efficiency.

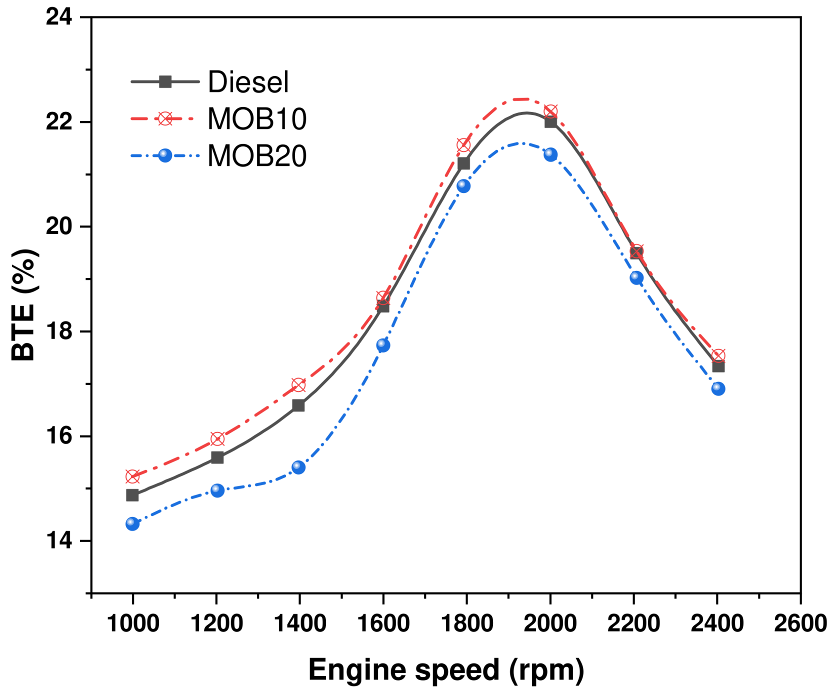

Figure 4. Variation in BTE with varying engine speed for biodiesel blends and diesel.

3.2. Emission Characteristics

3.2.1. Unburned Hydrocarbon Emissions (HC)

Figure 5 shows HC emissions for *MOB* and its blends with diesel at different engine speeds. Average HC emission is higher for diesel than that for MOB10 and MOB20 by 6.71% and 8.79%, respectively. Furthermore, the fuel blends containing 20% of biodiesel have higher HC emissions at low speeds compared to those containing 10% of biodiesel.

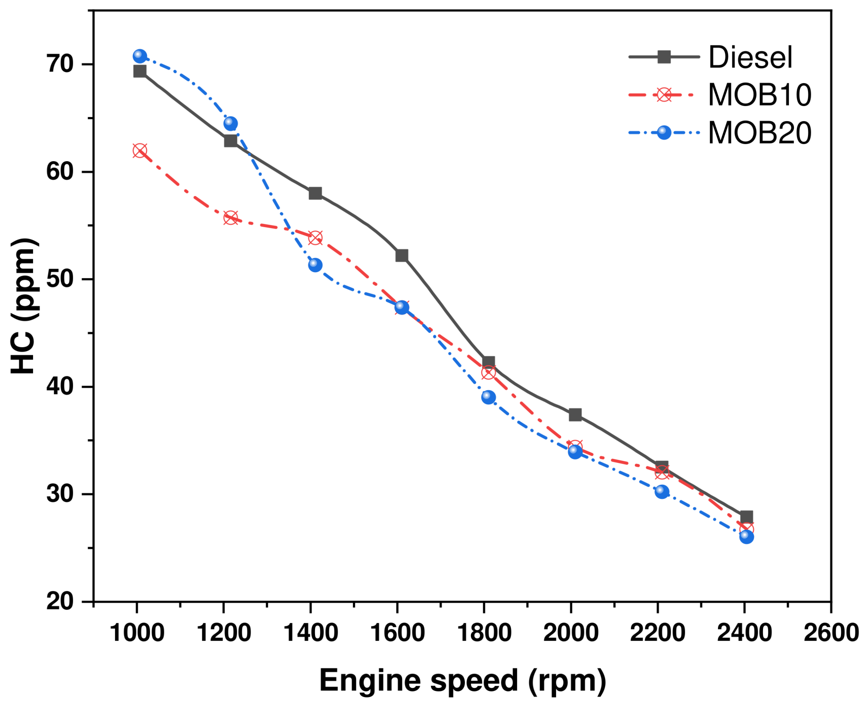

Figure 5. Unburned hydrocarbon emissions of *Moringa oleifera* biodiesel blends and diesel at varying engine speeds.

Moreover, it can be observed that each tested fuel had higher HC emissions when the engine was running at lower speeds. Conversely, the amount of HC emissions decreased when the engine's speed was higher. The lean air–fuel mixture is the primary reason for more HC emissions at lower engine speeds as well as poor fuel distribution. The lower temperature and presence of excess air are responsible for lean air-fuel mixtures [42]. Over-rich and over-lean air–fuel mixtures are typical during heterogeneous combustion in diesel engines, which leads to HC emissions. The oxygen content of biodiesels generally leads to lower HC emissions than diesel at high engine speeds due to improved fuel combustion [57].

3.2.2. Carbon Dioxide Emissions (CO_2)

Figure 6 shows the CO_2 emissions of MOB blends and diesel at various engine speeds. CO_2 emissions from the engine's exhaust reached a maximum value with MOB20 and were reduced when the biodiesel concentration in the fuel was decreased. The average CO_2 emission values for MOB10, MOB20, and diesel were 5.693%, 6.124%, and 6%; the curves were plotted by averaging three readings. MOB20 showed higher CO_2 emissions than diesel and MOB10 due to more oxygen in MOB20 relative to neat diesel and MOB10. The higher amount of oxygen in the biodiesel increased the oxidation and combustion process. Due to the higher amount of oxygen, the excess amount of CO is converted to CO_2 [52].

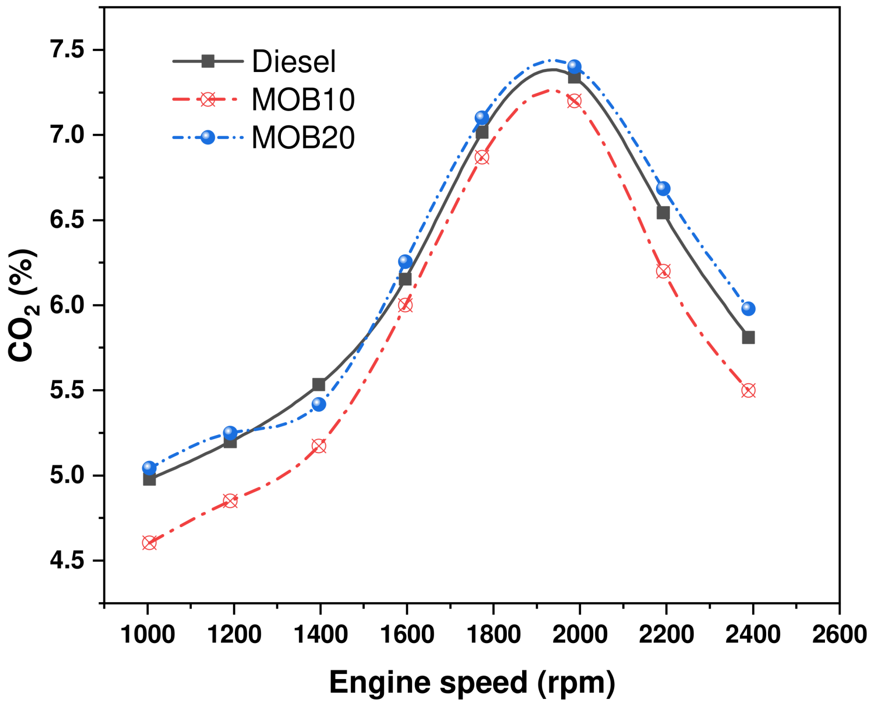

Figure 6. Carbon dioxide emissions of *Moringa oleifera* biodiesel blends and diesel at various engine speeds.

3.2.3. Carbon Monoxide Emissions (CO)

According to previous reports, oxygenated fuels reduce up to 30% of CO emissions compared to diesel—however, the magnitude of the reduction depends on the engine type and age, and ambient conditions [58,59]. Figure 7 displays CO emissions of *Moringa oleifera* biodiesel blends and diesel at various engine speeds. It can be observed that the MOB20 blend produces the highest amount of CO emissions at an engine speed of 1400 rpm.

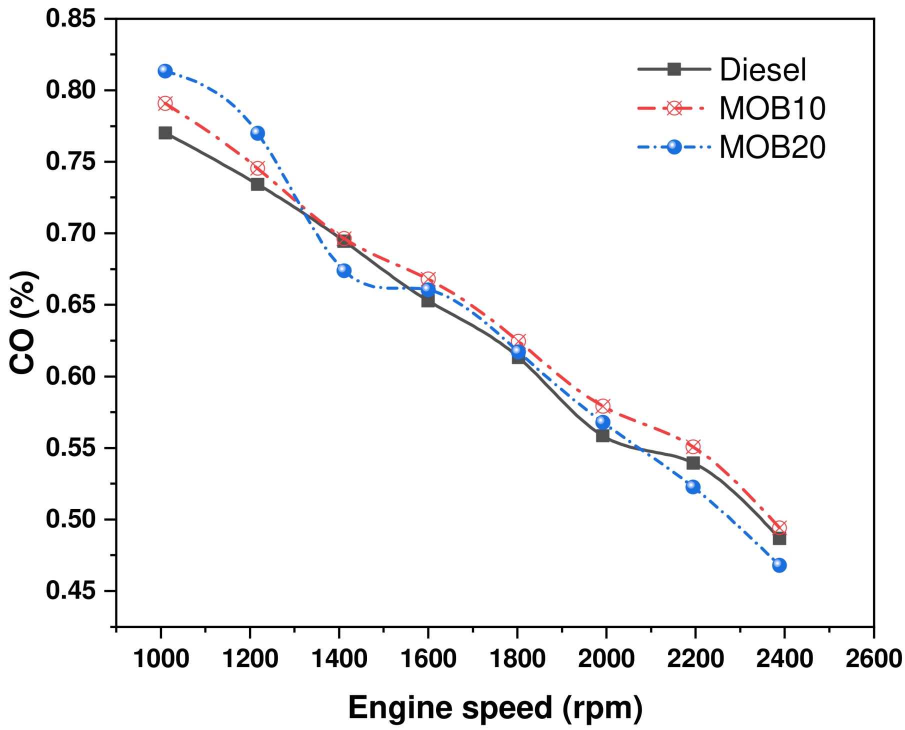

Figure 7. Carbon monoxide emissions of *Moringa oleifera* biodiesel blends and diesel at various engine speeds.

On the other hand, the MOB20 blend produces the lowest CO emissions at 2400 rpm and the lowest average CO emission in this study. The average CO emission of diesel is 0.82% higher than that for MOB20. However, the average CO emission is 1.99% lower than that for MOB10. In general, for the same blend ratio, the CO emissions decreased as the engine's speed changed from a lower to a higher value for all fuels. This is due to higher oxygen content and the higher cetane number of biodiesel fuel than diesel fuel. Higher cylinder pressure and temperature promote complete combustion at high engine speed, especially for biodiesel fuel that contains higher oxygen content. This enables the conversion of CO to CO_2, reducing the amount of CO emission [60–62].

3.2.4. Nitrogen Oxide Emissions (NO_x)

Many studies have shown that biodiesel fuels produce higher engine NO_x emissions compared to diesel [63–70]. Figure 8 displays NO_x emissions of *MOB* blends and diesel at various engine speeds. Several factors influence the production of $NO_{x,}$ and one of them is the oxygen content. In general, vegetable oil-based biodiesels have higher oxygen content (with a difference of 12% relative to diesel) as well as low nitrogen content. This results in higher NO_x emissions when there is an increase in the combustion chamber temperature, which improves the combustion process [66]. The MOB20 blend has the highest NO_x emissions (416 ppm) at an engine speed of 2400 rpm. *Moringa oleifera* biodiesel has more oxygen content as compared to neat diesel fuel. Besides, NO_x emissions increase with an increase in the concentration of biodiesel in fuel blends. Average NO_x emissions are lower for diesel compared to MOB10 and MOB20 by 4.71% and 8.12%, respectively. Abedin et al. [71] found that fuel blends containing 10% and 20% of palm biodiesel reduce NO_x emissions by approximately 3.3%. Rahman et al. [70] discovered that a fuel blend containing 10% biodiesel produces higher NO_x emissions by 9% relative to diesel. In general, biodiesels have a higher adiabatic flame temperature because of their high unsaturated fatty acid content, leading to more NO_x emissions [69]. The higher viscosity and density of biodiesels are also responsible for higher NO_x emissions [33].

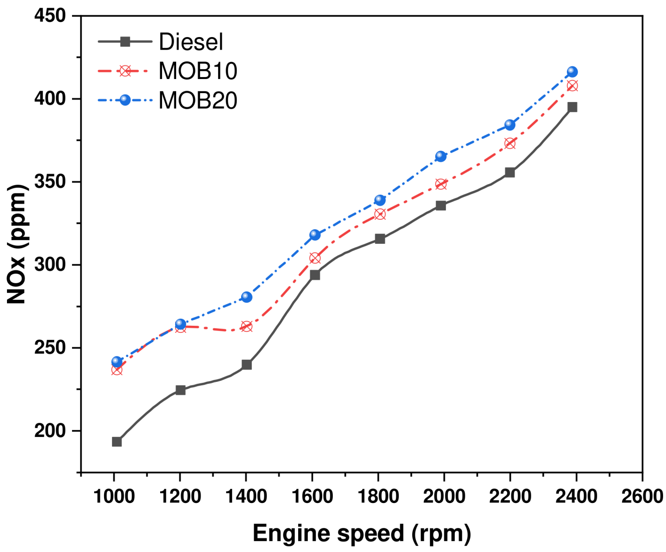

Figure 8. Nitrogen oxides emissions of *Moringa oleifera* biodiesel blends and diesel at various engine speeds.

3.2.5. Smoke Opacity

Figure 9 displays the smoke opacity for *Moringa oleifera* biodiesel and its blends with diesel tested at different engine speeds. For diesel, the average smoke opacity is higher than MOB10 and MOB20 by 33.49% and 22.73%, respectively. The MOB10 blend has the lowest average smoke opacity (32.2%) compared to MOB20 and neat diesel. At higher engine speeds, the smoke opacity of *MOB* blends increased significantly. Several studies have shown that the smoke opacity was lower due to more oxygen contents in biodiesel. A lower ratio of carbon–hydrogen and non-availability of aromatic compounds in the biodiesel reduced the smoke emissions [72]. According to Gumus and Kasifoglu [73], more oxygen in biodiesel blends can reduce smoke exposure in exhaust gasses. Zhang et al. [74] found that combustion of biodiesel blends occurs earlier than diesel. Smoke emissions are reduced due to advanced injection timing, which results from the combustion process's quick start. In contrast, diesel has higher sulfur content than biodiesel blends, which is the main reason for high smoke opacity [75].

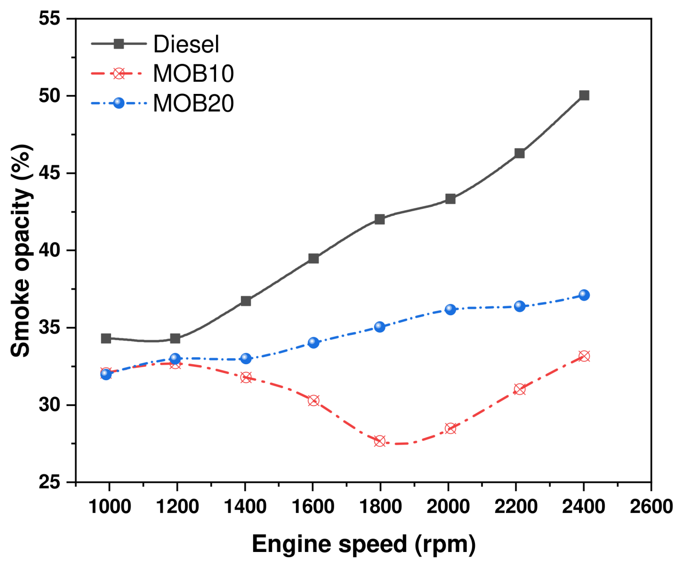

Figure 9. Smoke opacity of *Moringa oleifera* biodiesel blends and diesel at various engine speeds.

4. Conclusions

The performance and exhaust emission characteristics of Moringa oleifera biodiesel blends were analyzed in this study. The results of the experimental investigation show that the MOB10 blend is the best blend ratio based on the following criteria:

- At optimum speed, the BTE for MOB10 and MOB20 was 2.54% higher and 3.45% lower, respectively, than that of pure diesel.
- MOB10 and MOB20 blends had a higher average BSFC than diesel by 7.03% and 12.75%, respectively, due to the higher density and lower calorific values of biodiesel blends.
- MOB10 produced slightly lower BP when compared to diesel, by 0.26 kW. The MOB20 blend was the worst performer, producing less usable power than diesel by 0.36 kW.
- The average HC emission for MOB10 and MOB20 were lower than diesel, with a difference of 8 ppm.
- The average NO_x emission for blended fuels was significantly higher than the neat diesel, and the MOB20 blend produces more NO_x emissions due to increased oxygen content in fuel blends.
- MOB10 produced lower smoke opacity than those of neat diesel and MOB20 due to good combustion.
- Therefore, MOB10 is suitable to use in conventional compression-ignition diesel engines.

Future Recommendation: The NO_x emissions slightly increased in the combustion of biodiesel blends compared to conventional diesel. The researchers could pursue this work using different fuel additives such as nanoparticles or alcohols to reduce NO_x emissions.

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Nomenclature

MOB	Moringa Oleifera Biodiesel
CI	Compression Ignition
BP	Brake Power
BTE	Brake Thermal Efficiency
BSFC	Brake Specific Fuel Consumption
MOB10	Moringa Oil Biodiesel 10% + Diesel 90%
MOB20	Moringa Oil Biodiesel 20% + Diesel 80%
CO	Carbon Monoxide
CO_2	Carbon Dioxide
NO_x	Nitrogen Oxides

HC	Hydrocarbons
EGT	Exhaust Gas Temperature
FAC	Fatty Acid Composition
MOME	Moringa Oleifera Methyl Ester
COME	Canola Oil Methyl Ester
SOME	Soybean Oil Methyl Ester
SCDE	Single Cylinder Diesel Engine
CFPP	Cold Filter Plugging Point
HHV	Higher Heating Value
DW	Deionized Water

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