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Combustion and Emission Characteristics of CI Engine Fueled with Water-Extracted Fusel-Biodiesel-Diesel Blends

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Abstract

This study investigates the effects of water-reduced fusel oil blended with biodiesel and diesel on the emission and combustion characteristics of a single-cylinder compression ignition (CI) engine. Five fuel blends were tested: F10B20, F20B30, F10B30, F30B20, and F30B30, representing varying proportions of fusel oil (10–30%), biodiesel (20–30%), and diesel (40–70%). The engine operated at a constant speed of 1800 rpm under four load conditions (25%, 50%, 75%, and 100%). Results showed that reducing water content in fusel oil from 13.5% to 6.5% led to a 7.9% increase in carbon content and a 13% rise in heating value, while oxygen content decreased by 50%. Compared to pure diesel, all fusel-biodiesel blends exhibited CO and CO_2 emissions reductions across all engine loads. Brake power slightly increased with fuel-based blends, while brake-specific fuel consumption (BSFC) also increased following water extraction. Interestingly, although thermal properties improved after water reduction, NO_x emissions tended to rise, highlighting a trade-off between improved combustion and regulated emissions. The study confirms that water-extracted fusel oil can enhance combustion efficiency and partially reduce harmful emissions, offering a viable pathway for alternative fuel development in diesel engines.

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1. Introduction

In the present century, energy has become an essential topic for discussion in the future, especially for countries dependent on energy exports and crude oil, where energy is a significant problem. Problems like this should be immediately addressed, as much as possible, concerning local resources to produce electricity, specifically on how it should be done and used [1–5]. In addition, the importance of increasing energy efficiency, various alternative energy sources and sustainability should also be considered. In industrialized countries, energy resource consumption is rapid, especially in the United States (US), where finding and creating renewable alternatives to alternative energy sources for fossils depend on petroleum-based fuels [6–8].

The global increase in vehicles daily, especially in developed countries, requires alternative fuels for internal combustion engines [9,10]. In the US and European Union (EU) countries, various initiatives have been adopted as new fuel for vehicles to reduce dependence and fuel emissions [11]. Biodiesel and bio-oils from multiple products, such as animal fats, vegetable oils, and bio-alcohol, are destined primarily for combustion engines and have become alternative fuels. Biodiesel and vegetable oils are compatible with diesel engines, whereas ignition and compression engines can use bio-alcohol fuel [12–15]. However, diesel engines are still much more popular because they use less fuel and have higher efficiency. Thus, a more important focus is on using new opportunities from three alternative fuel sources: biodiesel, bio-alcohol, and bio-oil.

Over the years, the testing of vegetable oils on diesel engines has been widely practised [1–3,16–18]. Soybean oil is better known as the most used oil in the US and worldwide. In the US, soybeans are the most dominant and are used to produce seed oil; nearly 90% of seed oil is created in the US. The highest output is mainly by regionally modified oils with various methods already in use, such as transesterification and micro-emulsion, and they are alternatives for renewable fuels [19,20]. Vegetable oils are merely used and limited to internal combustion engines due to their increased density and viscosity. Biodiesel has limited use but has the nature of better fuel and maintained power [12,21,22]. However, biodiesel production is very costly compared to diesel, which has a relatively higher viscosity and poorer cooling flow than high NOx emissions, which is also the paramount parameter in limiting the dependence on biodiesel use [23–25]. Besides, vegetable oils are well known to produce biodiesel and have impacted various food pressures; thus, recommendations on non-edible oils can be used for biodiesel production materials and applied to diesel engines as an alternative to renewable fuels. In addition, biodiesel production is best suited from waste products, such as vegetable oils, because there is no effect on food security [26,27]. However, alcohol cannot be used directly on diesel engines because it has several properties suitable as additives for biodiesel fuel and diesel [28–30]; thus, losses that occur in biodiesel can be reduced.

Meanwhile vegetable oils or biodiesel can be readily mixed with additives and alcohols [31–33]. The initiatives were taken by the EU that have targeted to increase biofuel use in diesel engines by 2020 by approximately 20% [34–36]. The most crucial goal of this achievement is that it is necessary to investigate all sources of combustion engine use and when alternative fuels can be used. Based on this objective, alternative fuels produced from bio-alcohol have become the most critical part of additives in other fuels [37–39]. A clean fuel is like alcohol because it has a hydroxyl (OH) structure inside its molecule. Diesel fuel is mixed with some organic components, such as vegetable oil-biodiesel when low temperature is used with this fuel to improve its stability [33,40–42]. Low density and viscosity have also enabled the use of vegetable oils in diesel engines, and their use can improve micro-emulsions through transesterification with little cost [43]. However, the low amount of alcohol is expected to limit its consumption in diesel engines [44]. This fuel is not the best alternative, especially for ethanol (C_2H_5OH) and also methanol (CH_3OH), due to the low number of cetane [45,46]. However, with alcohol, an adequate amount of carbon can entirely influence the nature of this fuel. Increasing the amount of carbon (high alcohol), organic molecules easily mixed with alcohol, and the amount of cetane achieved can produce higher burning heat. Thus, the high potency present in the alcohol is the best for mixing with diesel fuel compared to the low potency found in alcohol [45,46].

The n-butanol (C_4H_9OH) has been widely tested for diesel engines since it has been evaluated in recent years to serve as a mixture for biodiesel fuel [45]. However, studies relating to the use of pentanol (C5H11OH) and propanol (C3H7OH) are still insufficient for diesel engines. Therefore, this experiment only focused on mixing biodiesel with diesel using different compression and fuel ratios. The mixture of n-butanol and propanol was made using 4% and 8% volumes, which were then added to the diesel. Based on the results, it was reported that the brake thermal efficiency (BTE) can increase up to 1,579% when 4% of butanol is used at a load position of 80%. The smoke density increased to 12.891% when propane with a capacity of 4% was used, but NOx emissions were reduced to 6.098%. Zhu et al. [47] studied the use of pentanol-diesel fuel and diesel-diesel pentanol to measure combustion characteristics and emissions in diesel engines. The results indicated that simultaneous emissions of soot and NOx decreased when the load was low. In contrast, NOx emissions increased during high pressures compared to diesel fuel operations.

The mixture of vegetable oils with bio-alcohol and biodiesel increases the fuel consumption of vegetable oil so that diesel fuel consumption can be reduced in diesel engines. However, there are some drawbacks to the use of pure biodiesel fuel as well as vegetable oil, so this deficiency must be overcome. A mixture of vegetable oils and biodiesel will be evaluated when a two-cylinder diesel engine is used to investigate the performance and emission characteristics of the engine [48]. The fuel mixture used in his research consisted of 5% alcohol, 20% biodiesel, 5% vegetable oil, and 70% diesel. Increases in CO, HC and NOx emissions can be reduced by using a fuel-oil-diesel-diesel-biodiesel fuel mixture instead of diesel, and an increase in lubrication by using vegetable oil. Recently, Greece made a mixture of oil fuel from cotton with methyl esters because cotton oil has a high volume [49,50]. Their study investigated the performance characteristics and emissions from diesel engines that use four cylinders and were fuelled by diesel-cotton fuel, diesel-alcohol, and a mixture of biodiesel-diesel.

Calam et al. [51] studied the effects of unleaded gasoline fuel mixtures with fusel oil for specific fuel consumption, engine torque and exhaust emissions in a single cylinder. The fuel control systems, owned by spark ignition engines on port types with varying speeds and different engine loads, were also investigated. Their results showed that increasing fusel oil mixtures can improve engine torque with all rotations and various machine loads compared to unleaded gasoline. Increases also occurred in the specific consumption of brake fuel, CO, and HC emissions, while there was a decrease in NOx emissions. A systematic investigation was made using alcohol fuels and ethers, such as methanol, ethanol, butanol, MTBE, DME, and fusel oil for spark-ignition (SI) engine fuel. Various studies have been done on the effect of SI engine performance using fuel alcohol and ether, such as brake power, brake torque, BSFC, EGT, CO, CO_2, HC, and NOx emissions [52].

Meanwhile, different studies have conducted experiments on using alcohol fuels derived from crude fusel oil, which was processed by fractional distillation and diesel mixtures with volumes of 15% and 85% alcohol-diesel [53]. Low heating, such as flash point, pour point, and density of the fuel mixture, is also essential. However, high viscosity was achieved by a combination of diesel fuel. The results showed that overall nitrogen oxide emissions have increased, while an increase in particle emissions for all loads also occurred. Investigations were also conducted for performance, emissions, and combustion characteristics with fusel oil applied in spark ignition engines at 2,500 rpm and four different engine loads [54]. Experimental results showed that engine performance decreased while CO and HC emissions increased by 21% and 25%, respectively. However, NOx emissions were reduced by about 31% due to poor combustion of fusel oil usage.

Many previous studies were limited to vegetable oils, bio-alcohols, and biodiesel. The results showed that producing vegetable oils can have high potential. Still, it depends on the source of local conditions used as alternative fuels to diesel, such as soybean oil, which is made to increase biodiesel as fuel in diesel engines. The experiment in this study will be compared to the investigation on the emission and combustion characteristics of diesel engines by using different fuel mixes of fusel oil and biodiesel, which are potential fuel sources for future generations. Based on the stated objectives, fusel-biodiesel fusel usage will be prepared in advance with different volumes of F10B20 (10% fusel, 20% biodiesel and 70% diesel), F20B30 (20% fusel, 30% biodiesel and 50% diesel), F10B30 (10% fusel, 30% biodiesel, and 60% diesel), F30B20 (30% fusel, 20% biodiesel, and 50% diesel), and F30B30 (30% fusel, 30% biodiesel and 40% diesel). The emissions and performance results of using this fuel will then be compared with the result of the mixture of diesel oil.

2. Methodology

This experiment will use a single-cylinder with a four-stroke engine. A schematic diagram of the engine is shown in **Figure 1**. Meanwhile, information on the specifications of the engines used in this experiment is found in **Table 1**. The emission measurement in the engine will be done using the EMS

5002 (exhaust gas analyser). The specifications of the exhaust gas analyser are described as follows: CO_2 0-20 vol% has a resolution of 0.1 vol%, O_2 has a range of 0-25 vol% and a resolution of 0.01 vol%, while the distance at NO 0-5000 ppm with a resolution of 1 ppm, for the range in CO 0-10 vol% has a resolution area of 0.01 vol% and the distance measurement for HC between 0-2000 ppm which has a resolution of 1 ppm. By calibrating the exhaust gas analyser (EMS 5002), less bar Gas was used during the procedure. Meanwhile, the repetition of the calibration procedure was set during the test. Fuel measurements were carried out before the test, and then every 20 minutes, the experiment will be re-measured to ensure load for each engine tank. Data from the test results and the determination of fuel consumption will be continuously monitored. Type K thermocouples were used to measure the flue gas temperature. Meanwhile, the gas emissions and combustion were tested on four different electrical loads (0 kW, 3 kW, 6 kW, and 9 kW). The experiment in this study will be compared with the emissions and combustion characteristic investigation on the diesel engine by using different fuel mixes, fusel oil, and biodiesel, which are potential fuel sources for future generations. Based on the stated objectives, fuel usage such as fusel-biodiesel fusel will be prepared in advance with different volumes of F10B20 (10% fusel, 20% biodiesel and 70% diesel), F20B30 (20% fusel, 30% biodiesel and 50% diesel), F10B30 (10% fusel, 30% biodiesel, and 60% diesel), F30B20 (30% fusel, 20% biodiesel, and 50% diesel), and F30B30 (30% fusel, 30% biodiesel and 40% diesel). Then, the emissions and performance of using this fuel will be compared with the results of the mixture of diesel oil.

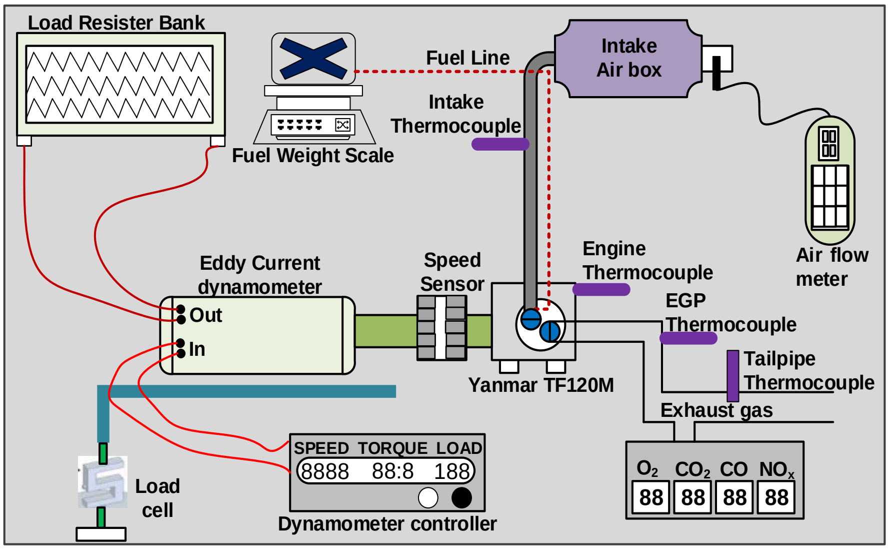


Figure 1: Schematic diagram of engine setup.

Fuels test on the engine.

Used crude oil from biodiesel (ASTM D6751) was extracted from Texas for experiments with fuel sources sourced as a global fuel alternative. The composition of fatty acids with waste biodiesel oil was measured using the Agilent Technologies Network GC 6890 system, which adapted the EN 15779 test method [55–57]. This tool has a DB-225 column and the following specifications (0.25 mm diameter, with a film of 0.2 µm thickness, and a length of 30 m). Measurement of the composition of FAME (%) fusel, diesel and biodiesel is shown in **Table 2.** The mixed quarters will be stored in a closed space for up to 15 days and will not be separated. During the test, the fuel mixture will be stabilised. The basic fuel properties used for testing in this study are shown in **Table 3**.

Table 1. Specifications of Engine.

Model	**Yanmar Model TF120M**
Type	Horizontal single-cylinder 4-stroke diesel engine
Compression ratio	17.7:1
Maximum rating output	12.0 HP @ 2400 rpm

Model	**Yanmar Model TF120M**
Continuous rating output	10.5 HP @ 2400 rpm
Fuel tank capacity	11 L
Stroke (mm)	96
Displace volume (cm^3)	638
Fuel injection type	Direct Injection
Cooling system	Water-radiation
Bore (mm)	92
Max torque	161 Nm @ 4500 rpm
Max power	7.7 kW @ 2400 rpm

Table 2. Components of fusel oil.

Constituent	**Chemical formula**	**Density (g/cm^3)**	**Molecular weight (g/mol)**	**Freezing point (˚C)**	**Boiling point (˚C)**	**Molar (%)**	**Volumetrically (%)**
Ethanol	C_2H_6O	0.789	46.07	−114.3	78.4	8.98	9.58
Water	H_2O	1	18	0	100	12.23	10.3
n-butyl alcohol	$C_4H_{10}O$	0.8098	74.122	−89.5	117.73	0.708	0.736
n-propyl alkyl	C_3H_8O	0.8034	60.09	−126.5	97.1	0.704	0.738
i-amyl alcohol	$C_5H_{12}O$	0.8104	88.148	−117.2	131.1	61.52	63.93
i-butyl alcohol	$C_4H_{10}O$	0.802	74.122	−108	108	15.87	16.66

Table 3. The basic properties of test fuels

Fuel properties	**Fusel oil**	**Biodiesel**	**Diesel**
Cetane Number	-	40	40-60
Boling point [°C]	98		-
Density at ambient (kg/m^3)	847	133	824
Moisture content %	13.5		-
Lower heat value (MJ/kg)	29.53	42.5	42.5

Table 1. Engine spec

Engine Parameter	Specification
Engine	Diesel inline 4 cylinder turbocharger
Engine model	Model YD25DDTi
Engine capacity	2.5 Liter
Bore	89 mm
Stroke	100 mm
Compression ratio	15:1

3. Result & Discussion

Engine emission

The emissions contained in spark ignition machines are related to the engine operating conditions, such as carbon monoxide (CO), carbon dioxide (CO_2) and nitrogen oxide (NOx), fuel properties and homogeneity of fuel mixtures. Mixtures of compounds, such as nitric oxide (NO), dinitrogen trioxide (N_2O_3), nitrogen dioxide (NO_2), nitrous oxide (N_2O), dinitrogen tetroxide (N_2O_4), and dinitrogen pentoxide (N_2O_5), are emissions that form nitrogen oxides (NOx) [58]. The trace of nitrogen oxides better known than others are NO and NO_2 [59–61]. The high temperatures of the nitrogen oxidation molecules in the cylinders are the primary cause of NOx by-product formation. The NOx emissions shown in some literature illustrated that the higher fuel used in a combustion engine can lower NOx emission [58,62,63].

CO Emission

The poisonous gas that is produced through engine fuel combustion is carbon monoxide (CO). Unsaturated combustion of non-homogeneous mixtures and dry machined air is the primary cause of higher CO emissions [58,64,65]. The variation of CO emissions using fusel-biodiesel fuel and pure diesel for different engine loads at 1800 rpm engine speed is shown in **Figure 2**. The increased machine load will significantly increase CO emissions. Furthermore, the fusel-biodiesel fuel mixture may increase compared to pure diesel for the overall test machine capacity. Higher potential water evaporation and latent heat can be responsible for the oxidation reaction speed for carbon monoxide, resulting in the production of CO emissions in machinery [58,66]. However, combustion temperatures and low burning speeds can result from higher latent heat, resulting in higher CO emissions. Besides, the mixture of fusel-biodiesel fuels after water extraction increased compared to before. This is as described by [58,67], where the extracted fusel oil increased by about 5% compared to before extraction.

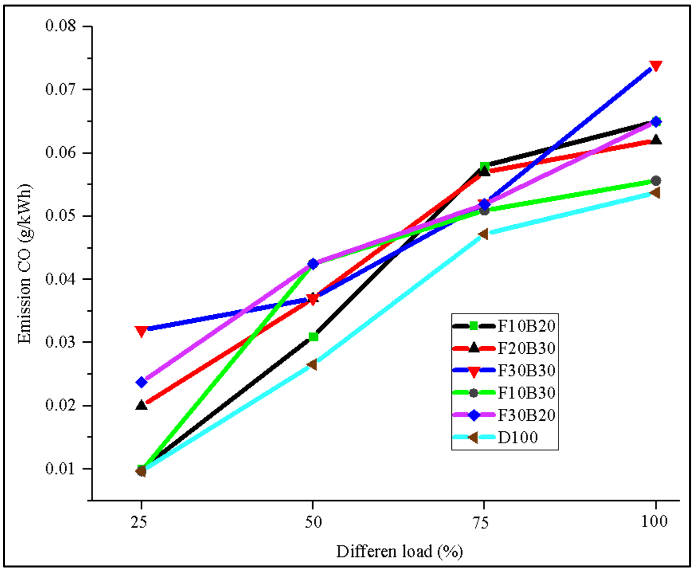


Figure 2: Comparison of CO for fuel blends and different engine loads.

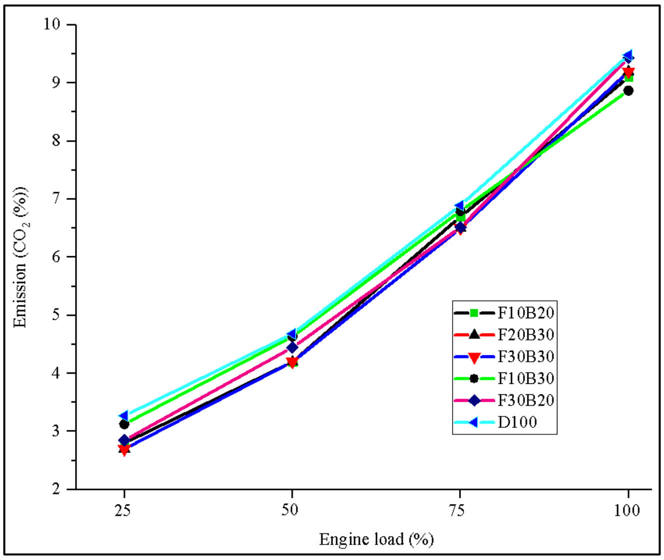


Figure 3: Comparison of CO_2 for fuel blends and different engines.

CO_2 Emission

The non-toxic gas that is not classified as a pollutant in machinery areas is carbon dioxide (CO_2). Global temperatures that affect greenhouse gases are increasing because of one of the substances of CO [68–

70]. CO_2 emission variations from test results using pure fusel-biodiesel and diesel fuels for different engine loads at speeds of 1800 rpm are shown in **Figure 3**. Increased CO_2 emissions can be seen when the engine load increases and CO_2 emissions will also be improved. Furthermore, the fraction of increased fusel oil for all test machine loads significantly increased CO_2 emissions. The water-extracted fusel-biodiesel oil mixture for all fuel volumes slightly increased compared to the before water-extracted blend. Also, the primary role of oxygen content that provides increased emissions in the combustion engine is that it apparently has increased CO_2 in the oxygen and alcohol fuel usage.

NOx Emission

Figure 4 shows the variation of NOx emissions from trials using fusel-biodiesel fuel and pure diesel. Overall, NOx emissions increase as engine loads are raised. However, at a 75% load, the F10B20 and F10B30 fuels were lower. While the F30B20 was found to be higher than diesel, this increase occurred because fusel oil has a higher water content than biodiesel. All fuel mixtures between fusel-biodiesel and diesel decreased after water extraction compared to prior extraction, as described by [58,71,72]. Furthermore, the fusel-biodiesel fuel mixture can reduce NOx emissions compared to pure diesel fuel for all tested engine loads, except for the F30B20 blend at 75% engine load. The higher fusel oil can explain this increase in higher water content by the engine combustion temperature.

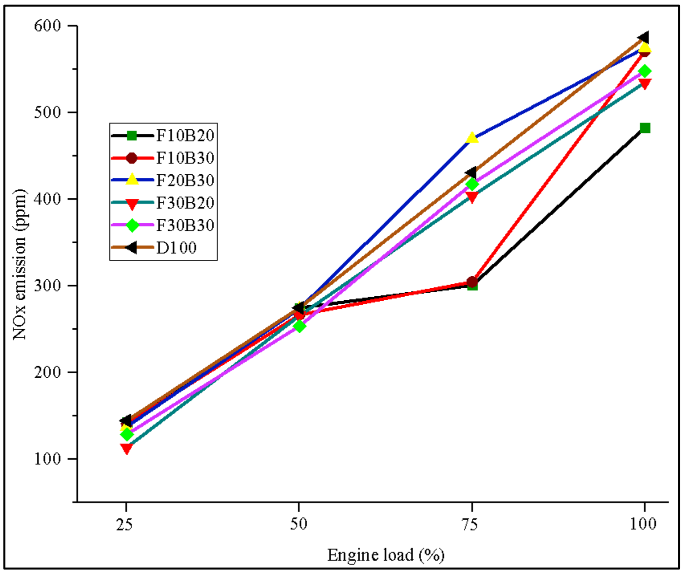


Figure 4: Comparison NOx for fuel blends and different engines.

Brake Specific Fuel Consumption (BSFC)

The heating value and density in the fuel had significantly affected the brake-specific fuel consumption (BSFC). The ratio of fuel mass consumption and brake power was obtained from BSFC and is used only for certain fuels. Eq. (1) illustrates the BSFC. Where *mf* and *Pi* are actual fuel consumption measurements (g / h) and (kW) denotes each power.

$$\text{BSFC} = \frac{m_f}{P_i} \quad (1)$$

The BSFC difference from the mixing of fuel-biodiesel-diesel fuels for speeds of 1800 rpm and different engine loads is shown in **Figure 5**. The reduction of BSFC was found when the engine load increased for all fuels, however, when the engine load had increased braking power enhancement; therefore, a decrease in BSFC may occur. Besides, after water extraction, the fuel-biodiesel-diesel fuel mixture can lower the BSFC compared to when it was extracted for all tested fuel mixtures. This may explain the increase in the calorific value found in fusel oil. Furthermore, the fusel-biodiesel fuel mixture can lower the BSFC than pure diesel because diesel has a lower calorific value.

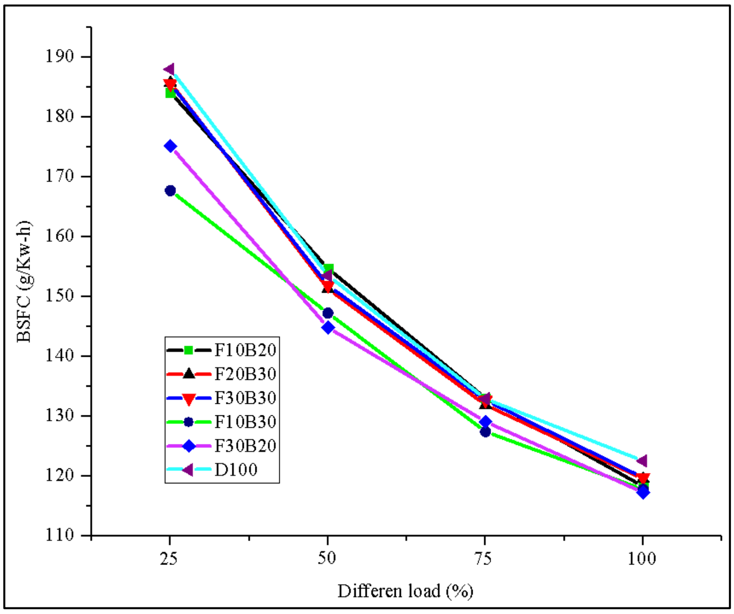
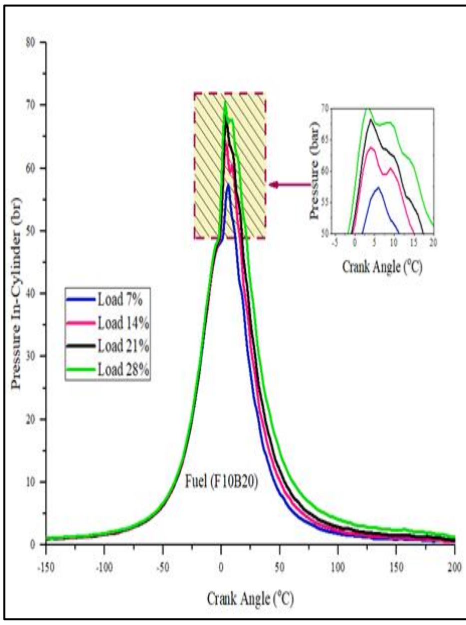


Figure 5: Comparison of BSFC for fuel blends and different engines.

Engine combustion

The fusel-biodiesel fuel mixture can compare engine combustion characteristics by using pure diesel fuel based on in-cylinder pressure, average torque adequate value pressure, heat recovery rate (HRR), combustion duration, thermal brake efficiency, brake power, and BMEP investigated explicitly in this study. Furthermore, a fuel with a physicochemical property is one of the main parameters that can provide the combustion efficiency of the machine used for internal combustion engines, as investigated by [73–75]. Pressure variations inside the cylinder by using a fusel-biodiesel mixture and pure diesel for the engine at a speed of 1800 rpm at different engine loads are shown in **Figure 6 - 10**. From experimental results conducted on a diesel engine by using a fusel-biodiesel mixture of pressure inside the cylinder. It can be seen that an increase occurred for all fuels tested at the time the engine load was raised. Furthermore, fuel testing can provide perfect results for low engine loads.



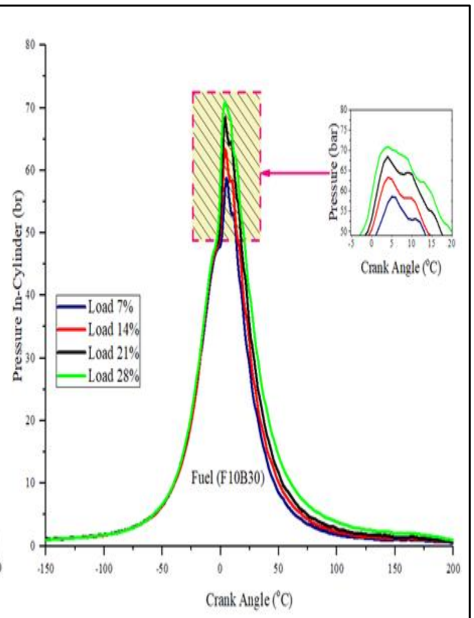
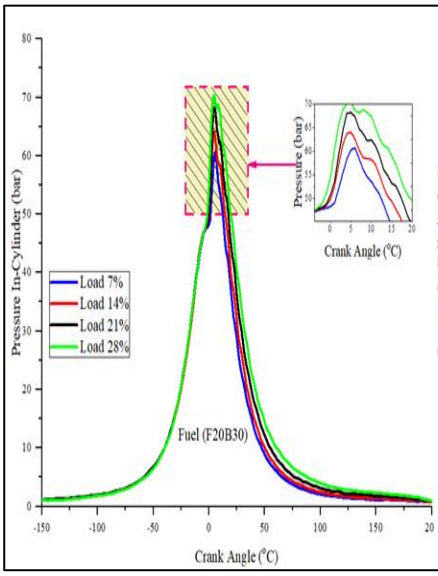


Figure 6: Pressure In-cylinder for F10B20 at the different loads

Figure 7: Pressure In-cylinder for F10B30 at the different loads

Meanwhile, when the engine load increased, the pressure inside the cylinder showed less apparent results. The maximum in-cylinder pressure will be fixed and focused. This is done to recognise areas that can be enlarged at the peak of the in-cylinder press from using a fusel-biodiesel fuel mixture higher than that of pure diesel for almost all tested engine loads. Also, after extraction, the fuel-diesel mixture's enlarged in-cylinder press peak area has more moisture than before the fusel-biodiesel mixture was extracted. It can be explained that in addition to having a high calorific value, the oxygen content contained in the fusel-biodiesel blend was also high after the water extraction, so it has imparted combustion restrictions on the engine.



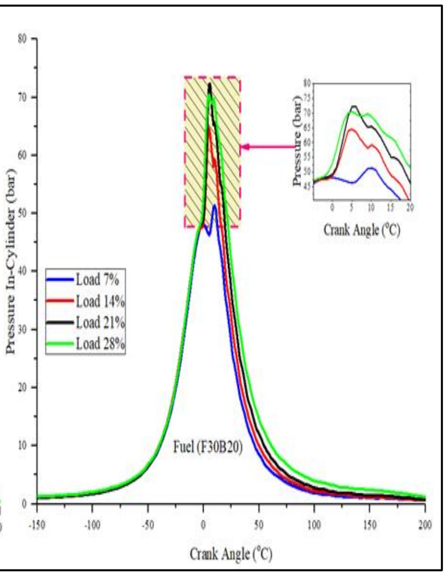


Figure 8: Pressure In-cylinder fo F20B30 at the different loads

Figure 9: Pressure In-cylinder for F30B20 at the different loads

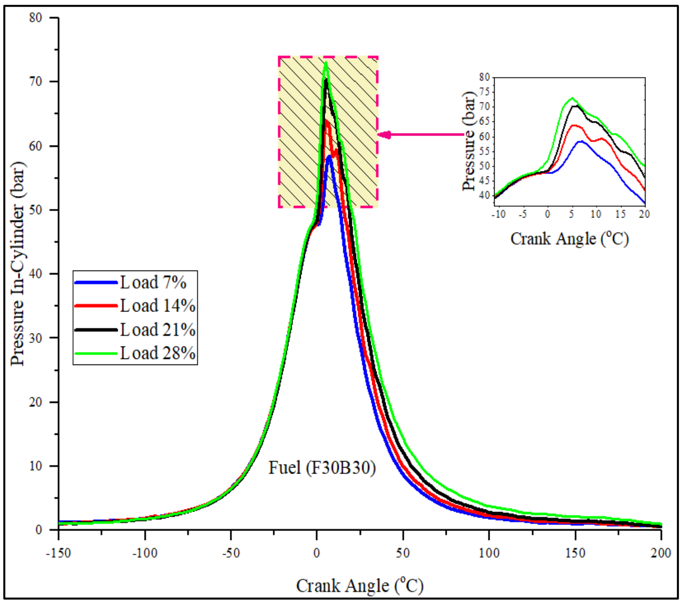


Figure 10: Pressure In-cylinder for F30B30 at the different loads

Brake Torque

The increasing fuel mix between the fusel-biodiesel can decrease the braking power, as shown in **Fig. 11**. The most likely reason for the increased amount of higher brake power for diesel versus F10B30, F30B20 and F30B30 for low overall machine loads were due to the low-calorie value contained in biodiesel fuel [76–78]. Higher viscosity and density of fusel-biodiesel blends resulted in various problems with fuel flow and reduced engine combustion efficiency to deteriorate the fuel injection atomisation state compared to diesel fuel and have a specific effect on brake density [79–81]. The percentage effect of the trial by using fusel-biodiesel and pure diesel for different engine loads on the brake torque at the engine, with a speed of 1800 rpm, is as shown in Fig. 11, where a maximum of 34.5 Nm for F10B20 mix fuel and pure diesel for all machine loads are tested. Meanwhile, the minimum break load of 28.5 Nm for 100% load was found in the fuel mixture F10B30. The proportion of fusel-biodiesel fuel mixtures into increased diesel will be more likely to decrease the brake torque value. So, the engine brake torque decrease can be understood because the fusel-biodiesel mixture has a higher heat content than the pure diesel fuel [77,82,83].

On the other hand, increased brake torque by using fusel-biodiesel fuel mixtures was due to oxygen and lubrication content in higher fuel mixed in pure diesel. **Figure 11** shows pure diesel has a higher torque value than the other, except F10B20 for all tested engine loads. The friction loss on the engine was reduced due to the properties produced by mixed fuel and resulted in complete combustion; thus, the adequate brake torque was significantly increased for higher engine loads due to the calorific value loss in the fusel-biodiesel mixture [80,84]. Improved brake torque during engine load increased due to increased combustion temperature to give perfection of engine combustion at higher engine load times, as shown in **Figure 3**.

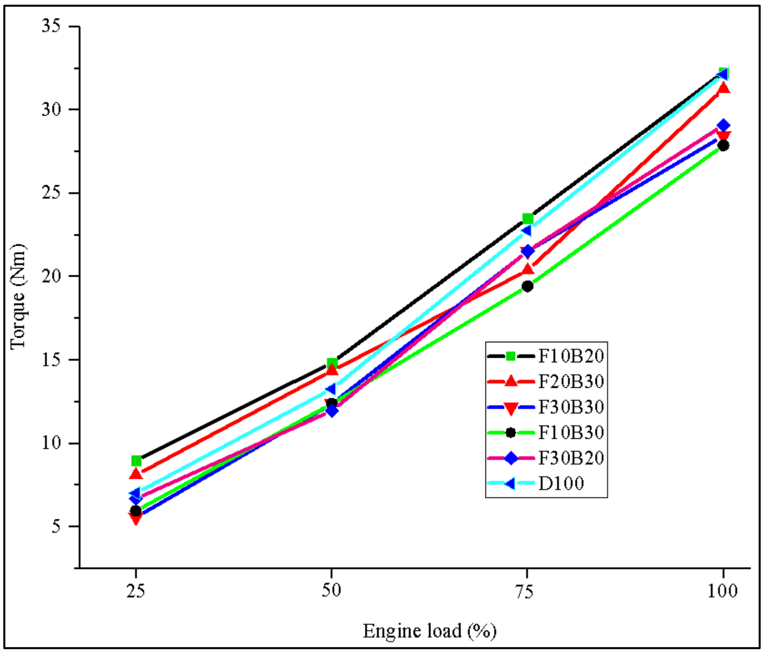


Figure 11: Effect of fuel blends on brake torque at various engine loads.

The rate of Heat Release (ROHR)

The essential combustion parameters in the engine obtained from the application of the first thermodynamic law to the gas pressure variables within the cylinder represent the rate of heat release rate (HRR). In engine combustion, this parameter is the most important to define combustion during the initial phase of combustion, controlled combustion, the period after combustion and rapid combustion. The variations of heat dissipation rates can be studied to determine the combustion characteristics in engines plotted at crank angles test results using different fuels and machine loads, as shown in **Figure 12 - 16** of all fuel samples tested in the study. Combustion results using a fusel-biodiesel fuel mixture were higher than that of pure diesel, as this was closely related to higher calorific and latent heat values than pure diesel. The initiation of combustion engines using fusel-biodiesel mixtures showed that pure diesel is slower to burn than when a fusel-biodiesel mixture is used. This is reasonable because fusel-biodiesel fuels have a higher cetane number than diesel. However, low cetane numbers are obtained from high fusel-biodiesel blends, thus providing longer ignition delays and can cause delays when combustion begins. The low heat release from adding a higher fusel compared to pure biodiesel and diesel has also caused a reduced calorific value of the fusel-biodiesel fuel blends. Of all fusel-biodiesel blends, a higher HRR value for all different machine loads was found from the F30B30 mixture of 64,000 kW at 75% engine load, while lower HRR values were found in F10B30 blends of 1600 kW for 75%. Mixed fuels with more fuel consumption during the combustion phase can increase the speed of heat release and the pressure increase inside the engine. Adding biodiesel fuels into the higher diesel can increase the HRR because there is a higher calorific value, resulting in better combustion efficiency than pure diesel fuel.

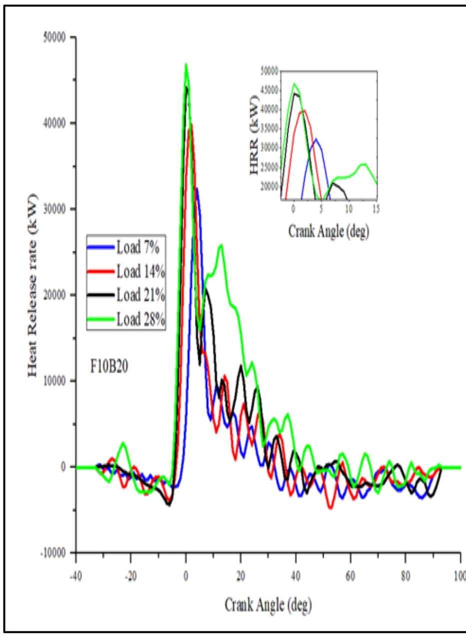


Figure 12: Variations of HHR for the test fuel F10B20 at the different engine loads.

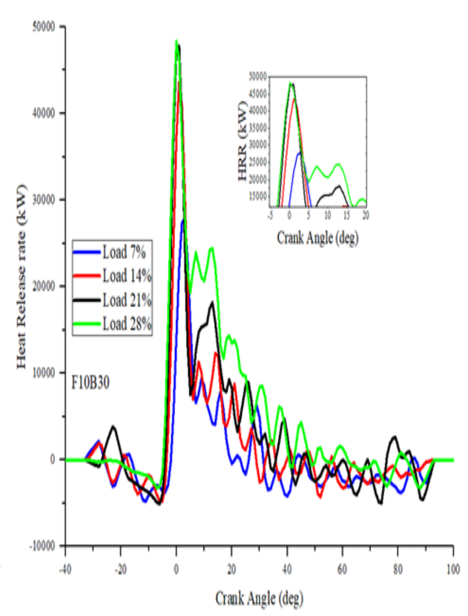


Figure 13: Variations of HRR for the test fuel F10B30 at the different engine loads.

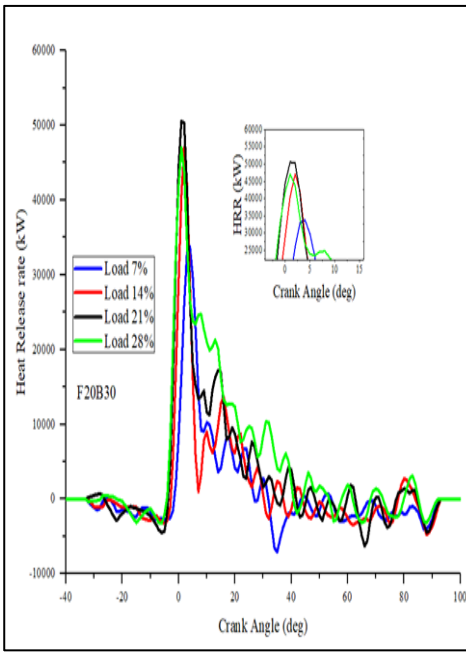


Figure 14: Variations of HRR for the test fu F20B30 at the different engine loads.

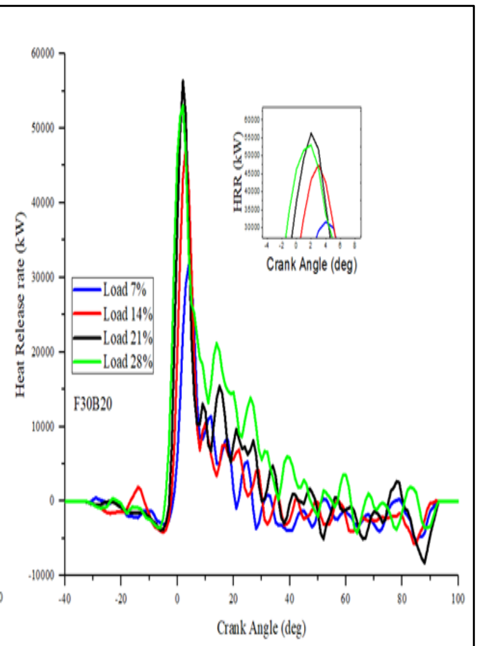


Figure 15: Variations of HRR for the test fuel F30B20 at the different engine loads.

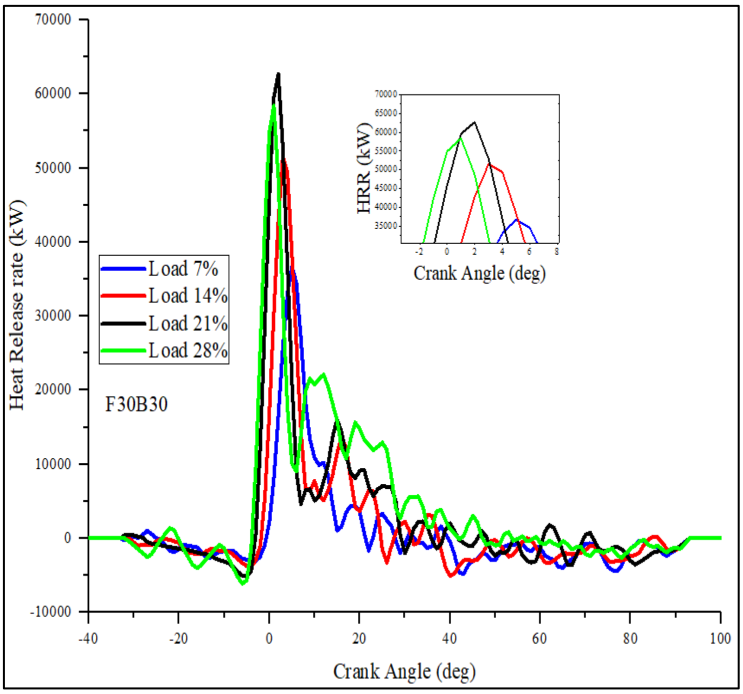


Figure 16: Variations of HRR for the test fuel F30B30 at the different engine loads.

BMEP

The speed function of mixed fusel-biodiesel and pure diesel fuels produced more optimal results, as shown by the BMEP variation in **Figure 17**. The engine rotation and torque function were the results of BMEP to produce similar trends. The fusel-biodiesel fuel mixture was higher for all engine loads, except at 100% load, where the F30B30 was lower than in diesel at the same speed for all engine conditions. Minimum BMEP values were about 1.06 and 3.08 for machine loads of 25% and 75%, while for engine loads, 50% and 100% of the minimum BMEP were found in F30B30 fuel mixtures of 3.05 and 5.08 at 1800 rpm engine speeds; thus, the decrease in BMEP for all fuel mixtures and different engine loads was strongly influenced by the calorific value and the value of heat released.

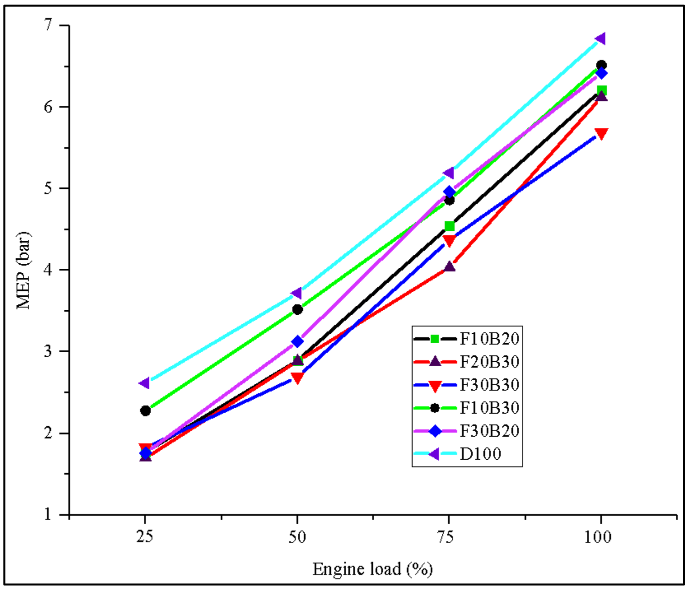


Figure 17: Comparison of BMEP for fuel blends and different engines.

4. Conclusion

A comprehensive experimental analysis was conducted on a single-cylinder diesel engine operating at 1800 rpm under four load conditions (25%, 50%, 75%, and 100%) using various fusel-biodiesel-diesel blends. The study demonstrated that water extraction from fusel oil notably improved its fuel properties, with the heating value increasing from 29.9 MJ/kg to 33.8 MJ/kg, a 13% enhancement primarily due to an increase in carbon content (from 54.2% to 58.45%) and a corresponding decrease in oxygen content (from 30.32% to 26.1%). Additionally, water extraction slightly increased the fuel's strength, resulting in higher thermal efficiency and brake-specific fuel consumption (BSFC). Emission analysis revealed that, compared to pure diesel, the fusel-biodiesel-diesel blends generally reduced CO and CO_2 emissions across all engine loads. However, NO_x emissions exhibited a more complex behaviour: they were lower in the blend overall yet increased following water extraction of the fusel oil. The rise in combustion temperature, coupled with the enhanced oxygen content and viscosity of the modified fusel oil, contributed to more complete combustion, thereby improving engine performance. These findings underscore the potential of water-extracted fusel oil as a valuable component in developing alternative fuel blends for diesel engines.

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