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Experimental investigations of CI engine performance using ternary blends of n-butanol/biodiesel/diesel and n-octanol/biodiesel/diesel

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Abstract

This study explored the ternary blends of biodiesel-diesel-n-butanol and biodiesel-diesel-n-octanol on common rail direct injection (CRDI) diesel engines. The compositions of fuels, which varied from 0% to 100%, were altered by up to 5%. On the basis of their properties, these blends were chosen, with various concentrations of alcohol at 5% and 10%, 5% diesel, and the remainder being biodiesel. Two ternary fuel blends of waste cooking oil biodiesel (90–85%), diesel (5%), and butanol (5–10%), namely BD90D5B5 and BD85D5B10, and subsequently, another two ternary similar blends of waste cooking oil biodiesel (90–85%), diesel (5%), and octanol (5–10%), namely BD90D5O5 and BD85D5O10, were used to conduct the experiments. The experiments were done with varying injection pressure from 17° to 29° crank angle (CA) before top dead centre (bTDC). The optimum condition for the blends is achieved at 26°CA bTDC for 80% loading. So, the engine trials were conducted on 26°CA bTDC to attain the results. The BD90D5O10 blend achieved the lowest brake specific fuel consumption (BSFC) reading of 0.308 kg/kWh while operating at full load. The maximum brake thermal efficiency (BTE) was 31.46% for BD90D5B5. The maximum heat release rate (HRR) achieved with BD85D5O5 fuel blend was 58.54 J/°CA. The quantity of carbon monoxide that BD85D5B10 created was the lowest (25.86 g/kWh). BD85D5B10 had a minimal unburned hydrocarbon emission of 0.157 g/kWh while operating at full load. Oxides of nitrogen (NO_x) were emitted in the maximum quantity by BD85D5O10, which was equal to 6.01 g/kWh. This study establishes the viability of blends of biodiesel and alcohol as an alternative for petro-diesel in the future to meet the growing global energy demand.

Keywords: Biodiesel; Ternary blends; Performance; Combustion; Emission

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1. Introduction

The increasing need for energy is closely related to the expansion of the human population. The need for energy has been satiated by petrochemicals and other products derived from petroleum. However, the world economy's utter reliance on fossil fuels is hastening the exhaustion of these resources and wreaking havoc on the environment [1]. The goal is to switch to renewable energy sources and abandon fossil fuels to slow down global warming [2]. Biodiesel, solar, wind, and tidal energy are popular alternatives. The most financially sound and ecologically responsible option currently available is biodiesel. It is made up of lipids derived from both plants and animals [3].

Nomenclature

Abbreviations and Acronyms

aTDC – after top dead centre
ASTM – American Society for Testing and Materials
bTDC – before top dead centre
BD85D5B10 – biodiesel (85%) + diesel (5%) + butanol (10%)
BD85D5O10 – biodiesel (85%) + diesel (5%) + octanol (10%)
BD90D5B5 – biodiesel (90%) + diesel (5%) + butanol (5%)
BD90D5O5 – biodiesel (90%) + diesel (5%) + octanol (5%)
BMEP – brake mean effective pressure
BSFC – brake specific fuel consumption
.
BTE – brake thermal efficiency
CI – compression ignition
CN – cetane number
CO – carbon monoxide
CO_2 – carbon dioxide
CRDI – common rail direct injection
UHC – unburnt hydrocarbon
HRR – heat release rate
ISO – International Organization for Standardization
NO_x – oxides of nitrogen
ppm – parts per million
WCO – waste cooking oil

Biodiesel's high manufacturing cost prevents commercialization. 70%–85% of biodiesel production costs are raw ingredients. Atabani et al. [4] observed that biodiesel production from waste cooking oil (WCO) can mitigate human activities' negative environmental effects. WCO must first be processed before being released into the environment for disposal. However, the cost of such pre-treatment is significant, leading to waste dumping directly into landfills. Correspondingly, Guarieiro et al. [5] reported that the US generated 10 million tonnes of soybean-derived waste cooking oil and China 4.5 million tonnes.

However, Suhaimi et al. [6] showed that biodiesel has some mechanical issues while operating on diesel engines, due to its low calorific value, high viscosity, and pour point. Alcohols and cold flow improvers have been tested to improve biodiesel quality [7]. Ramalingam et al. [8] showed that ethanol may increase chemical qualities. However, ethanol also changes other basic physico-chemical properties. Consequently, it develops a challenge to formulate an appropriate mixture that may effectively replace traditional diesel in diesel engines.

The disadvantage of lower alcohols, as Rosa [9] demonstrated, is that they are less solubilized and less miscible with diesel, and they are also more prone to separate at low temperatures. In a similar vein, Li et al. [10] found that carbon-rich alcohols would be used as a resource owing to the attributes that they possess in terms of both their thermal and physico-chemical properties. Cardoso et al. [11] reported significant cetane numbers for higher alcohols, easily miscible to diesel. Due to the positive stimulus of exhaust emissions, butanol has been recently accepted as a fuel additive in CI engines, according to Kumar et al. [12].

The diesel-1-pentanol combination was studied by Yesilyurt et al. [13] in a CI engine utilizing a range of blending ratios ranging from 10 to 25%. The blending ratios were presented in a diesel engine. It has been found that diesel engines can run on a mixture of diesel and pentanol, that is 75% pentanol and 25% diesel. This mixture may be used as a fuel. Kumar et al. [14] studied diesel engine performance and emissions using diesel-n-butanol binary mixes. The experimental study suggests diesel-butanol mixes might power the next generation engines in the near future. According to research conducted by Izzudin et al. [15], the ternary mixes of diesel, n-butanol and biodiesel were enhanced to reach higher performance levels while simultaneously reducing emissions. Diesel at a volumetric percentage of 65.5%, n-butanol at a volumetric concentration of 23.1%, and cotton seed oil at a volumetric concentration of 11.4% were determined to be the optimal concentrations. This occurs although the brakes use more fuel overall. When the matching mixes are employed, there is a significant reduction in the emissions of nitric oxide, carbon monoxide, and unburned hydrocarbons; the percentages of each are 11.33%, 45.17%, and 81.45%, respectively.

Charoensaeng et al. [16] investigated the use of mixtures of diesel, palm oil and n-butanol as an alternative fuel for diesel engines. In ternary blends, increasing the amount of butanol decreased NO_x, CO, CO_2 and smoke emissions while increasing unburned hydrocarbon (UHC) emissions and brake thermal efficiency.

The prominence of fine-tuning injection timing has increased due to recent advancements in alternative fuels, including biodiesel derived from renewable sources such as vegetable oils and animal fats, as well as higher alcohols like butanol and pentanol. Recent studies have demonstrated that the advancement of injection timing using biodiesel, due to its elevated cetane number, has the potential to improve thermal efficiency and mitigate the release of nitrogen oxides (NO_x) emissions. On the contrary, the adjustment of injection timing in a retarded manner may be deemed important in order to mitigate the occurrence of knock and effectively tackle premature combustion challenges. Furthermore, it has been observed in several studies, such as those conducted by Yan et al. [17] and Zhang et al. [18], that advancing the injection timing can enhance combustion efficiency and reduce particle emissions for higher alcohols.

The analysis of relevant material discussed earlier illustrates the relevance of biodiesel concerning the fulfilment of current fuel requirements. In addition to this, it discusses the advantages and disadvantages of using used cooking oil as a feedstock to create biodiesel. Research on diesel, biodiesel and higher alcohol blends in CI engines promotes alcohol use. Higher alcohols have a higher calorific value, cetane number, and diesel and biodiesel miscibility. The efficient use of biodiesel will reduce the amount of diesel needed. This study investigates the feasibility of using ternary blends of biodiesel, diesel and n-butanol or biodiesel, diesel and octanol in common rail direct-injection diesel engines with varying injection parameters that must be updated.

2. Materials and methods

Used cooking oil was the source material for the synthesis of biodiesel in this particular investigation. It was offered at various restaurants in and around Srinagar in Jammu & Kashmir, India. The transesterification process synthesized methyl ester at the Renewable Energy and Alternative Fuel Lab of the National Institute of Technology in Srinagar, in Jammu & Kashmir. For a chemical reaction, potassium hydroxide and methanol were used, first as a catalyst and then, as a solvent. The following reaction parameters were used to achieve a biodiesel yield of 95.4%: a temperature of 60℃, a reaction period of 120 minutes, a molar ratio of 6:1, a catalyst concentration of 1.5%, and a stirrer speed of 1050 revolutions per minute. The biodiesel met all of the requirements outlined in the ASTM D6751 standard, including its colour, physical features and chemical properties. The properties of diesel, WCO and biodiesel are compared and contrasted in Table 1.

Biodiesel has a high viscosity, but its calorific value is relatively low. On the other hand, its cetane number is relatively high. The quantity of energy required to pump gasoline is increased as the viscosity of the fuel is increased since this results in less fuel being atomized during the spraying process. Alcohols and biodiesel were mixed to provide a solution to these problems. The incorporation of n-butanol and n-octanol into biodiesel helped to enhance its kinematic viscosity, as well as its cloud and pour points, and its density. In order to establish a composition that was consistent throughout, many different amounts of biodiesel-diesel-n-butanol and biodiesel-diesel-n-octanol were combined in a flask with a circular bottom using a magnetic stirrer. Between 0 and 100% of the total fuel, the proportion of each fuel was adjusted in 5% increments. A stability test lasting for four weeks was carried out on each combination while the circumstances remained the same. Because the other blends exhibited constraints such as a lower flash and fire point, miscibility, and calorific value, tests were conducted further for property characterization on blends that contained more than 85% biodiesel, 5% diesel, and 10% n-butanol. These blends met the criteria for selection.

The same behaviour was seen throughout various concentrations of biodiesel, diesel and n-octanol mixtures. Because the other blends exhibited limitations, including a lower flash and fire point, miscibility and calorific value, blends that contained 85% biodiesel, 5% diesel and 10% n-octanol were chosen for further property characterization. Blends with n-octanol content of more than 20% have flash and ignition temperatures lower than 32℃. As a consequence of this, the use of n-octanol combinations that have a higher concentration is very hazardous. Nomenclature for the test fuel blends is given in Table 2.

The fuel properties of biodiesel-diesel-n-butanol and biodiesel-diesel-n-octanol blends were used to choose the blends BD90D5B5, BD85D5B10, BD90D5O5 and BD85D5O10. These blends may be found in Table 3.

Table 1. Physico-chemical properties of diesel, waste cooking oil, and biodiesel.

Property	Diesel	WCO	Biodiesel	Limits	ASTM Standards
Density [kg/m³] at 15℃	828	916.7	876	860–890	D1298
Kinematic viscosity [cSt] at 40℃	2.39	42.53	4.76	1.9–6.0	D445
Flash point [℃]	60	327	120	60–190	D93
Fire point [℃]	54	332	160	-	D93
Cloud point [℃]	0	14	5	-	D2500
Calorific value [MJ/kg]	42	38.9	39.6	-	D1826

Table 2. Nomenclature of test fuel blends used.

Fuel	% of Biodiesel	% of Diesel	% of n-Butanol	% of n-Octanol
Biodiesel	100	-	-	-
Diesel	-	100	-	-
BD90D5B5	90	5	5	-
BD85D5B10	85	5	10	-
BD90D5O5	90	5	-	5
BD85D5O10	85	5	-	10

Table 3. Biodiesel, diesel, n-butanol, n-octanol, and biodiesel blends fuel characteristics.

Fuel	Biodiesel	Diesel	n-Butanol	n-Octanol	BD90D5B5	BD85D5B10	BD90D5O5	BD85D5O10
Density [kg/m³]	876	828	815	821	862.15	859.55	862.45	860.15
Kinematic viscosity [cSt]	4.76	2.39	2.89	5.32	3.6	2.55	3.8	4.07
Flash point [℃]	120	60	49	63	65	54	75	67
Cloud point [℃]	5	0	−32	−27	−2	−4	−2	−3
Pour point [℃]	−7	−15	−38	−32	−6	−9	−5	−6
Calorific value [MJ/kg]	39.6	42	34.65	37.1	40.21	40.05	40.44	40.15

3. Experimental setup and measurements

A 5.2 kW air cooled and common rail direct injection (CRDI) engine was operated at 1500 rpm, the injection pressure was set to 220 bar, and the injection time was varied from 17° to 29°CA bTDC. The engine's specifications are provided in Table 4. The engine's configuration is shown pictorially in Fig. 1. A differential air flow sensor is used to get the readings for the air velocity. Pressure is meticulously captured using piezoelectric sensors, synchronized with a crankshaft encoder. The sensors provide data at every 0.5°CA increment of crankshaft rotation, and this process is repeated for 100 cycles. To measure the flow of fuel, a regular burette was used. An eddy current dynamometer was coupled to the test engine to load the engine. The establishment of emissions present in the air was by using the AVL Digas analyzer. AVL smoke meter was used to determine the smoke opacity.

Table 4. Specification of Engine test rig.

Make & Model	**KIRLOSKAR AV1**
No. of strokes	Four stroke
Bore x stroke	80 mm x 110 mm
Injection pressure	220 bar
Volume	661 cc
Compression ratio	16.5:1
Rated power	5.2 kW
Rated speed	1500 rpm
Dynamometer	
Description	**Specifications**
Working principle	Eddy current
Arm length	185 mm
Speed	1200–2200
Power capacity	10 kW

During the tests, a string of one hundred cycles was continuously recorded. Then those data were fed into software to calculate the combustion parameter. The experiment used the ISO 8178 test cycles and mode number D2 as its guidelines. In order to guarantee the accuracy of the results, the measurements were carried out three times, and the analysis was carried out using an average of the results from all three attempts.

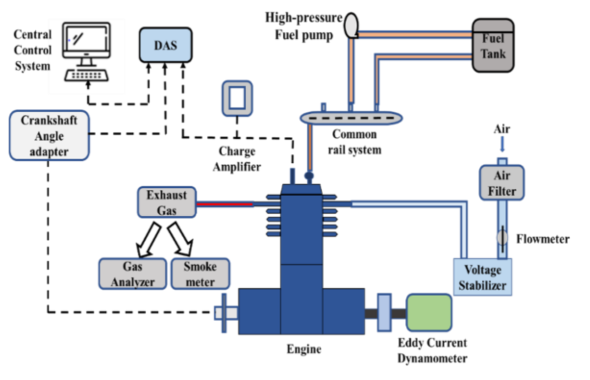


Fig. 1. Engine setup schematic diagram.

4. Results and discussion

Experiments were performed at the varying injection parameters from 17° to 29°CA bTDC for obtained test fuel blends and optimized parameters were found at 26°CA bTDC. Results are shown for the varying injection parameters with test fuel blends at 80% load, i.e. 5.2 bar and with varying load at 26°CA bTDC in the following sub-sections concerned with the engine performance, combustion and emissions.

4.1. Performance characteristics

4.1.1. Brake specific fuel consumption (BSFC)

Figure 2 illustrates the correlation between BSFC with injection timing and brake mean effective pressure (BMEP). BSFC indicates how efficiently engines convert fuel energy into useful work. As illustrated in Fig. 2(a), for biodiesel alcohol blends, the best BSFC is attained at retarded injection timing (26°CA bTDC) at 80% load whereas diesel gives the best results at 23°CA bTDC. Figure 2(b) illustrates the variation of BSFC for 26°CA bTDC. BSFC drops as the load on the engine increases from 0 to 100. The BSFC is higher at light loads but drops as the strain on the engine rises. The lowest specific fuel consumption for ternary blends is 0.292 kg/kWh for

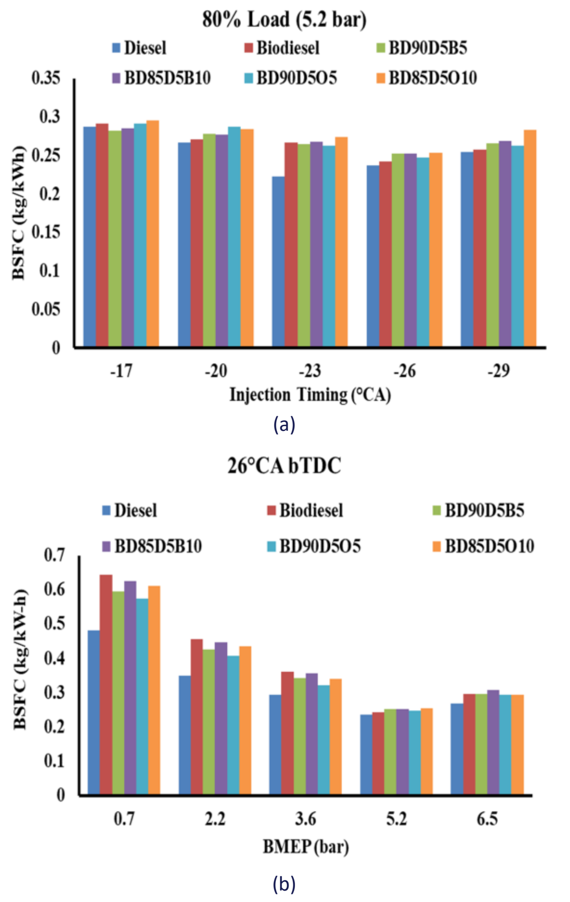


Fig. 2. Variation of BSFC with injection timing and BMEP.

BD90D5O10, which is 8.5% higher than diesel consumption but 5.1% lower than that of the BD85D5B10 mix. The BD85D5B10 blend uses the largest amount of fuel among all the ternary blends, at 0.308 kg/kWh. This is primarily because of the lower calorific value and higher viscosity of the blends. Because it has a lower calorific value than other fuels, biodiesel has the highest BSFC at 0.36 kg/kWh [19].

4.1.2. Brake thermal efficiency (BTE)

The relation between BTE with injection timing and brake mean effective pressure (BMEP) for a variety of combinations is seen in Fig. 3. In a diesel engine that uses compression ignition, BTE is established by the ratio of fuel to air, the compression ratio, the fuel's characteristics, and the fuel's combustion [20,21]. Figure 3(a) gives the variation of BTE with injection timing. It is found that diesel has the highest value of 32.2% at 23°CA bTDC for 80% load, while biodiesel blends have a peak BTE of 31.46% for BD90D5B5 at 26°CA bTDC. This is because blends of biodiesel, diesel and alcohol have a higher calorific value and low cetane number which allows for delayed combustion as compared to that of biodiesel alone [22]. Figure 3(b) depicts the variation of BTE at 26°CA bTDC for all fuel blends at varying load. BD90D5B5 had the highest BTE at 31.46%, which is 1.08% greater than that of biodiesel and 0.9% lower than that of diesel. Because of its higher viscosity and lowered calorific value, BTE for biodiesel is shown to have a lower value. At full load, the biodiesel-diesel-alcohol mix BD85D5B10 had the lowest thermal efficiency at the brakes at 28.15%. This is because biodiesel, diesel and n-octanol blends have a lower heating value but a more significant latent heat content than pure diesel or biodiesel alone [23].

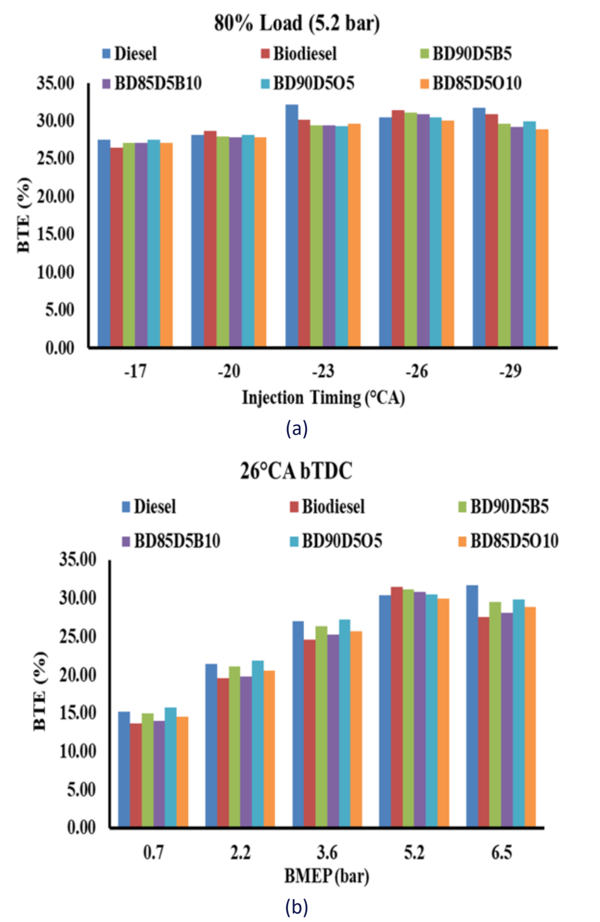


Fig. 3. Brake thermal efficiency variation with injection timing and BMEP.

4.2. Combustion characteristics

4.2.1. In-cylinder pressure

Figure 4 depicts the variation in peak pressure of the cylinder gas as a function of BMEP at 26°CA bTDC for mixtures of biodiesel, diesel and alcohol. The rise of in-cylinder gas pressure is directly proportional to the fuel used during the premixed combustion process. Because it has a higher cetane number than diesel, biodiesel has a shorter ignition delay than diesel. Because of the increased fuel evaporation rate, a high cetane number results in a shorter ignition delay time. Combustion using premixed air and fuel uses less fuel than combustion using diesel. When there is a decrease in cetane number (CN) for increased concentration of alcohols, the peak pressure of biodiesel goes down, while the peak pressure of the alcohol blend goes up [24]. In comparison to the other biodiesel-diesel-alcohol combinations, the fuel BD85D5O10 has the highest cylinder gas pressure at 2°CA aTDC when it is loaded to its maximum capacity. This pressure is the one that is most analogous to the diesel cylinder pressure. Subsequently, similar test fuels may be created; the longer the ignition delay the higher the gas pressure would be produced. Similar conclusion has been report by Gainey et al. [25].

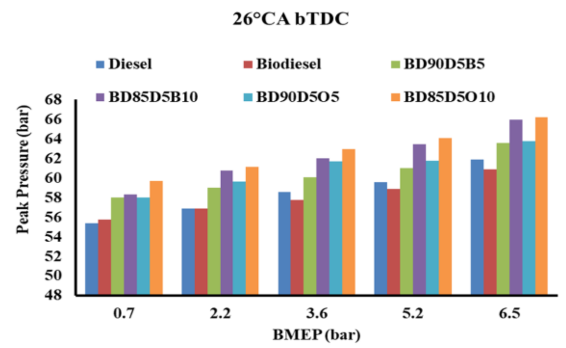


Fig. 4. Variation of in-cylinder peak pressure.

4.2.2. Heat release rate (HRR)

The heat release rate while operating under full load at 26°CA bTDC is shown in Fig. 5. The phases of combustion are called "premixed combustion", "controlled combustion" and "late combustion", respectively. During the ignition delay period, a negative slope is produced as a result of the cooling effect induced by fuel evaporation. When loaded to its maximum capacity, the BD90D5O5 blend has a heat release rate of 58.54 J/°CA. Because of its higher viscosity, lower rate of vaporization, larger molecular weight and slower burning velocity, biodiesel has a lower heat release rate than diesel. The biodiesel,

diesel and alcohol blends possess higher heat release rates comparable to diesel's heat release rate of 54.91 J/°CA. This is because a longer delay between ignition and combustion leads to a higher fuel deposit. When compared to biodiesel, blends of biodiesel and diesel with alcohol have a superior fuel-air combination, which results in a higher quantity of heat release [26].

4.2.3. Ignition delay

The ignition delay plays a role in the behaviour of the combustion process. The viscosity and density of the fuel govern the length of the physical delay. In contrast, the duration of the chemical delay is determined by the temperature and pressure of the combustion chamber, in addition to the swirl ratio and fuel properties [27]. The ignition delay of the test fuels at 26°CA bTDC is shown in Fig. 6. When increasing the load from 0% to 100%, the duration of the ignition delay drops to a lower value. All of the tested fuels had a shorter ignition delay observed when the load on the engine was low. This was because the temperature of the cylinder wall and the temperature of the residual gas were both lower, which caused the delay to last longer. The most considerable delay period for BD85D5B10 and BD85D5O10 blends was 13.7°CA and 13.95°CA, respectively, when the load was at its maximum capacity of 100%. This is comparable to the ignition delay in diesel engines. The ignition delay of biodiesel-diesel-n-butanol and biodiesel-diesel-n-octanol blends is longer than that of biodiesel alone. This is because both of these blends have a lower cetane number and a higher latent heat of vaporization [24].

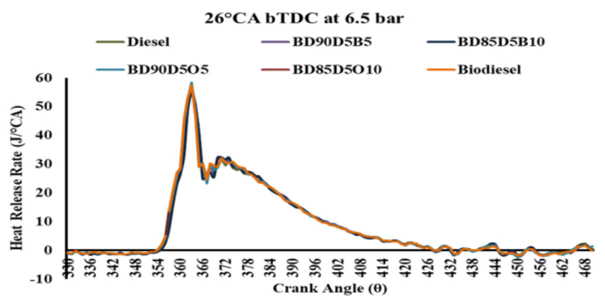


Fig. 5. Variation of heat release rate with crank angle at IT 26°CA bTDC.

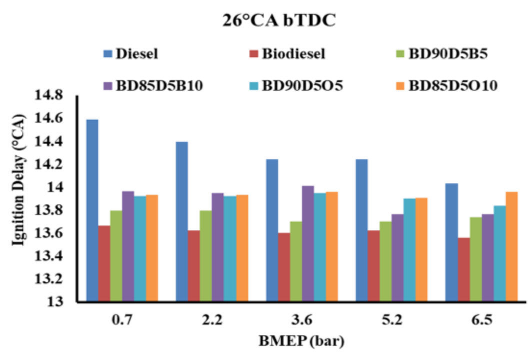


Fig. 6. Variation in ignition delay with BMEP.

4.3. Emission characteristics

4.3.1. Carbon monoxide (CO)

The variation in carbon monoxide (CO) emissions caused by combinations of biodiesel, diesel and alcohol is seen in Fig. 7. A rich fuel-air ratio and low oxygen content of blends increases the amount of carbon monoxide emissions. To reduce CO emissions, air must be heated [28]. Figure 7(a) shows that CO emissions of test fuel blends have been found lesser at 26°CA bTDC while diesel has lesser emissions at 23°CA bTDC. Biodiesel has more time to mix with air, leading to a more complete and controlled combustion process, which can further reduce CO emissions. Diesel has more CO emissions than biodiesel and ternary blends of biodiesel-diesel-alcohol at retarded injection timing. Figure 7(b) shows that the BD85D5B10 blend has the lowest CO emission rate of 25.86 g/kWh at full load condition at retarded injection timing of 26°CA bTDC, this rate is 36% lower than that of diesel. Because both biodiesel and alcohol fuels include oxygen as part of their chemical structure, they need less oxygen to complete the burning process. When more alcohol is added to mixtures of biodiesel, diesel and alcohol, CO emissions are reduced [29]. Because n-butanol fuel has a more considerable oxygen content than n-octanol fuel, biodiesel-diesel-n-butanol blends release less CO than biodiesel-diesel-n-octanol blends.

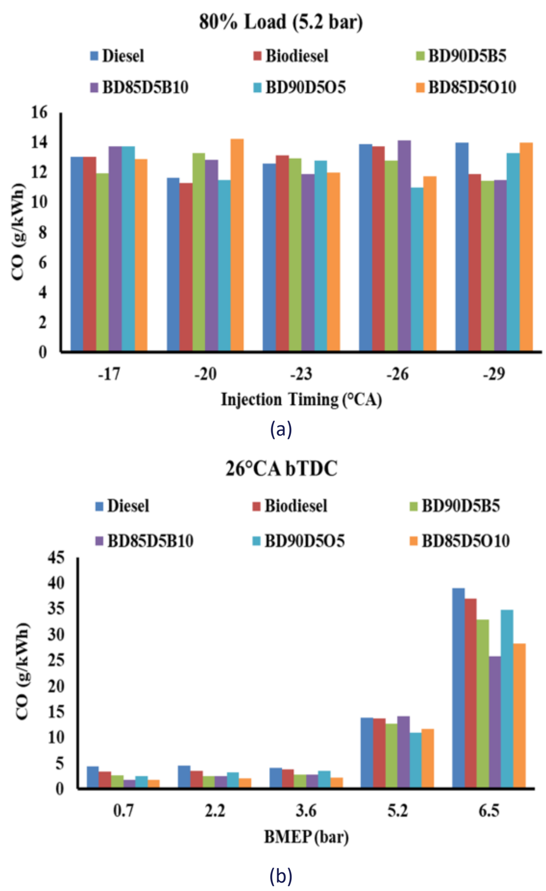


Fig. 7. Variation of carbon monoxide with injection timing and BMEP.

4.3.2. Unburnt hydrocarbons (HC)

When determining the overall quality of the combustion, hydrocarbon emissions are a crucial factor. The variation in the amount of unburned hydrocarbon emissions is seen in Fig. 8. When compared to diesel and biodiesel, biodiesel-diesel-alcohol combinations release less HC. Figure 8(a) has given best results for HC emissions at 26°CA bTDC, while diesel is characterized by lower HC emission at 23°CA bTDC. By delaying injection, biodiesel blends have more time to mix with air, leading to a more controlled and complete combustion process, which can further reduce HC emissions. Retarding injection further results in higher release of HC emissions. When operating at full capacity at 26°CA bTDC, Figure 8(b) shows that the BD85D5B10 engine has the lowest emissions. The unburned hydrocarbon content of BD85D5B10 is 0.157 g/kWh, which is 23.4% lower than that of diesel and 20.3% lower than that of biodiesel. The proportion of oxygen in biodiesel, diesel and alcohol blends directly correlates to the amount of emitted unburned hydrocarbons [30].

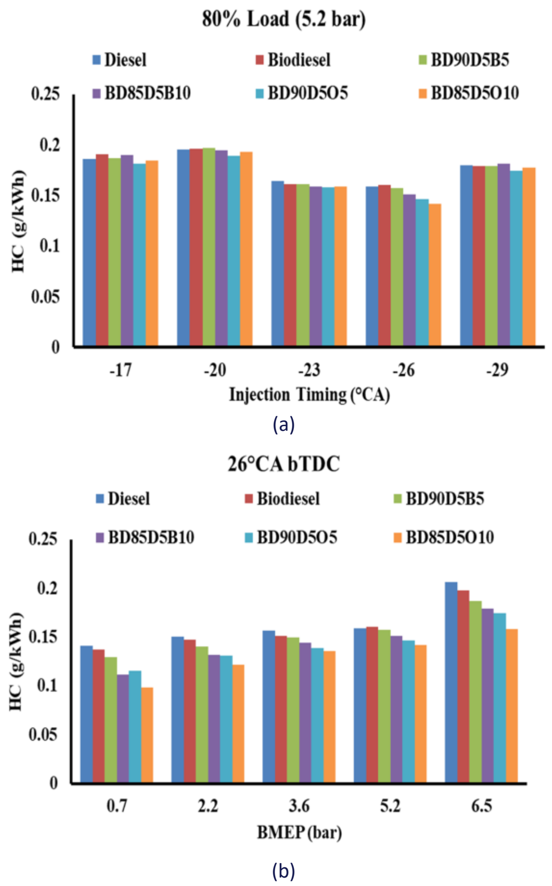


Fig. 8. Unburnt hydrocarbon variation with injection timing and BMEP.

4.3.3. Oxides of nitrogen (NO_x)

The oxygen content, in-cylinder temperature and residence duration are the three factors contributing to NO_x generation [31]. The impact that combinations of biodiesel, diesel and alcohol have on the emissions of NO_x is seen in Fig. 9. Figure 9(a) depicts variation of NO_x with varying injection timing. NO_x emissions increase for retarded injection timing due to the fact that retarded injection period can result in better combustion for biodiesel alcohol blends, leading to the formation of higher temperature combustion resulting in higher NO_x emissions at 29°CA bTDC. Figure 9(b) shows that NO_x emissions are lower for biodiesel-diesel-alcohol blends and for biodiesel than for diesel fuel at lower loads while higher at full load. The BD85D5O10 blend has a maximum NO_x emission of 6.01 g/kWh while operating under full load, which is 6.8% higher when compared to diesel at 26°CA bTDC. Because of their higher latent heat of vaporization and lower calorific value, n-butanol and n-octanol blends have a higher combustion temperature and generate more nitrogen oxide [24]. At full load, biodiesel's NO_x output is 5.45 g/kWh.

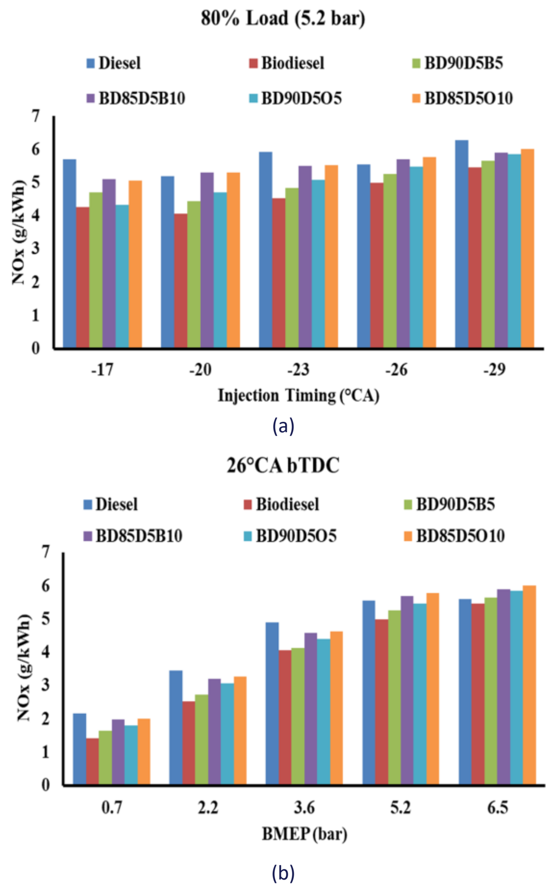
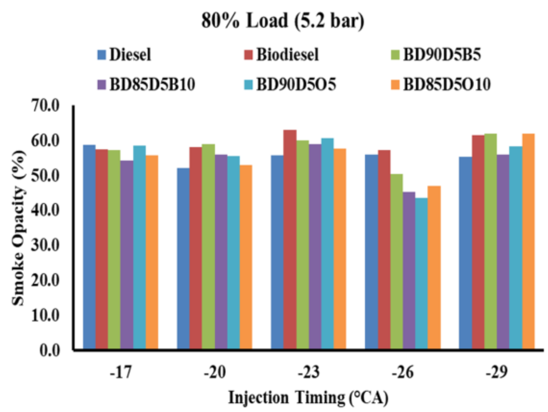


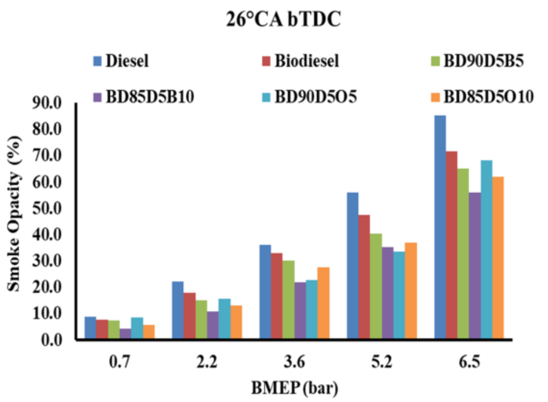
Fig. 9. Variation of oxides of nitrogen with injection timing and BMEP.

4.3.4. Smoke opacity

The range of smoke opacities produced by fuel blends is seen in Fig. 10. Figure 10(a) exhibits variation of smoke opacity percentage with various injection timing at 80% load. It shows that biodiesel-diesel-alcohol combinations yield lower smoke opacity than diesel at 26°CA bTDC. Because ester groups are present, biodiesel has oxygen molecules as part of its chemical makeup. This oxygen speeds up and promotes more thorough combustion of biodiesel, which would lessen the production of smoke at retarded injection timing. Figure 10(b) shows the fluctuation of smoke opacity with load at 26°CA bTDC. The BD90D5B10 combination generates 34.55% less smoke than diesel at full load, yielding 21.71% less smoke than pure biodiesel. A higher amount of fuel injected into the engine's cylinders increases the amount of smoke generated at maximum load [32]. A longer ignition delay time and higher volatility can potentially improve the performance of fuel-air mixtures. To put it another way, the presence of oxygen in the fuel prevents the formation of soot [18].



(a)



(b)

Fig. 10. Variation in smoke opacity with injection timing and load.

5. Conclusions

The fuel properties of biodiesel were enhanced by adding diesel, n-butanol and n-octanol as blending stocks. The 5% mix of diesel initiates the combustion of fuel due to a lower ignition temperature of diesel. Optimal outcomes for various fuel mixtures can be achieved by adjusting the injection time to 26°CA bTDC, which effectively balances performance, combustion efficiency and emissions. The chosen timing facilitates comprehensive mixing, resulting in a decrease in NO_x emissions, alongside producing cleaner combustion with a reduced amount of particle emissions. Consequently, this timing option is seen as advantageous for the purpose of sustainable and efficient engine running. The following outcomes are achieved from the research:

- The BD90D5O10 blend has the lowest BSFC when compared to the other blends at full load conditions when injected at 26°CA bTDC. Its performance was by 1.01% lower as compared to pure biodiesel and 8.5% superior to diesel. At injection timing of 23°CA bTDC, diesel has the lowest BSFC of 0.223 g/kWh for 80% loading.
- The BD90D5B5 blend has the highest BTE content (31.46%) of all the test fuel blends at full load with 26°CA bTDC. It was found by 1.08% higher than for biodiesel and comparable to that of diesel.
- At full load and 26°CA bTDC, the BD85D5O10 blend achieved the most significant in-cylinder pressure. Compared to diesel, it was 6.55% higher, while for biodiesel was 8.04% lower. The rate at which BD85D5O5 releases heat is the greatest. It had a lower energy content than diesel by 6.65% and higher than biodiesel by 5.65% for injection timing of 26°CA bTDC.
- The test fuel BD85D5B10 and BD85D5O10 blends at full load had a delay period of 13.7°CA and 13.95°CA, respectively, which was the most significant delay period.
- The CO emissions of test fuel blends were found to be lower at the injection timing of 26°CA bTDC, whereas diesel emissions were found to be lower at the injection timing of 23°CA bTDC. The BD85D5B10 blend had the lowest CO emission rate, which was 25.86 g/kWh at full load condition when the injection time is retarded to 26°CA bTDC. This amount is by 36% lower than diesel's value.
- The best results for HC emissions were achieved at 26°CA bTDC, although diesel had lower levels of HC emission at 23°CA bTDC. The unburned hydrocarbon content of BD85D5B10 was 0.157 g/kWh, which was lower by 20.3% than the unburned hydrocarbon content of biodiesel and lower by 23.4% than the unburned hydrocarbon content of diesel.
- There was an increase in NO_x formation at 29°CA bTDC when the injection time was retarded because of the fact that a retarded injection periods contribute to improved combustion for biodiesel alcohol blends. When operating at full load, the BD85D5O10 blend produced maximum NO_x emissions of 6.01 g/kWh, which were by 6.8% greater than the NO_x emission produced by diesel at 26°CA bTDC.
- At 26°CA bTDC, biodiesel-diesel-alcohol blends exhibited lower smoke opacity than diesel. At full load, the BD90D5B10 combination emitted 34.55% less smoke than diesel and 21.71% less smoke than pure biodiesel.

Performance and combustion were improved when diesel was blended with biodiesel, and the amounts of pollutants produced were reduced significantly. Consequently, biodiesel-diesel-n-butanol and biodiesel-diesel-n-octanol blends proved as feasible fuels for internal combustion engines.

References

[1] Singh, A.K., Sharma, A., & Kumar, N. (2014). *Performance and Emission Analysis of a CI Engine in Dual Mode with CNG and Karanja Oil Methyl Ester*. SAE Tech. Pap. doi: 10.4271/2014-01-2327

[2] Deep, A., Kumar, N., Kumar, M., Singh, A., Gupta, D., & Patel, J.S. (2015). *Performance and emission studies of diesel engine fuelled with orange peel oil and n-butanol alcohol blends*. SAE Tech. Pap. doi: 10.4271/2015-26-0049

[3] Kumar, N., & Pali, H.S. (2016). Effects of n-Butanol Blending with Jatropha Methyl Esters on Compression Ignition Engine. *Arabian Journal for Science and Engineering*. 41, 4327–36. doi: 10.1007/s13369-016-2127-1

[4] Atabani, A.E., & Al Kulthoom, S. (2020). Spectral, thermoanalytical characterizations, properties, engine and emission performance of complementary biodiesel-diesel-pentanol/octanol blends. *Fuel*, 282, 118849. doi: 10.1016/j.fuel.2020.118849

[5] Guarieiro, L.L.N., de Souza, A.F., Torres. E.A., & de Andrade, J.B. (2009). Emission profile of 18 carbonyl compounds, CO, CO2, and NOx emitted by a diesel engine fuelled with diesel and ternary blends containing diesel, ethanol and biodiesel or vegetable oils. *Atmospheric Environment*, 43, 2754–61. doi: 10.1016/J.ATMOSENV.2009.02.036

[6] Suhaimi, H., Adam, A., Mrwan, A.G., Abdullah, Z., Othman, M.F., Kamaruzzaman, M.K., et al. (2018). Analysis of combustion characteristics, engine performances and emissions of long-chain alcohol-diesel fuel blends. *Fuel*, 220, 682–91. doi: 10.1016/j.fuel.2018.02.019

[7] Pali, H.S., Sharma, A., Kumar, M., Annakodi, V.A., Nguyen, V.N., Singh, N.K., et al. (2022). Enhancement of combustion characteristics of waste cooking oil biodiesel using TiO2 nanofluid blends through RSM. *Fuel*, 331, 125681. doi: 10.1016/j.fuel. 2022.125681

[8] Ramalingam, S., & Mahalakshmi, N.V. (2020). Influence of Moringa oleifera biodiesel-diesel-hexanol and biodiesel-diesel-ethanol blends on compression ignition engine performance, combustion and emission characteristics. *RSC Advances*, 10, 4274–85. doi: 10.1039/c9ra09582a

[9] Rosa, J.S., Altafini, C.R., Wander, P.R., Telli, G.D., & Rocha L.A.O. (2019). Wet ethanol fumigation on a compression ignition engine: effects of air intake throttled. *Journal of the Brazilian Society of Mechanical Sciences*, 41, 1–16. doi: 10.1007/s40430-019-2023-1

[10] Li, Y., Tang, W., Abubakar, S., & Wu, G. (2020). Construction of a compact skeletal mechanism for acetone–n–butanol–ethanol (ABE)/diesel blends combustion in engines using a decoupling methodology. *Fuel Processing Technology*, 209, 106526. doi: 10.1016/j.fuproc.2020.106526

[11] Cardoso, C.C., Celante, V.G., De Castro, E.V.R., & Pasa, V.M.D. (2014). Comparison of the properties of special biofuels from palm oil and its fractions synthesized with various alcohols. *Fuel*, 135, 406–412. doi: 10.1016/j.fuel.2014.07.019

[12] Kumar, N., & Sidharth. (2018). Some Studies on use of ternary blends of diesel, biodiesel and n-octanol. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 40, 1721–1728. doi: 10.1080/15567036.2018.1486902

[13] Yesilyurt, M.K., Yilbasi, Z., & Aydin, M. (2020). The performance, emissions, and combustion characteristics of an unmodified diesel engine running on the ternary blends of pentanol/safflower oil biodiesel/diesel fuel. *Journal of Thermal Analysis and Calorimetry*, 140, 2903–294. doi: 10.1007/s10973-020-09376-6

[14] Kumar, N., Bansal, S., Vibhanshu, V., & Singh, A. (20123). *Utilization of blends of Jatropha Oil and N-butanol in a naturally aspirated compression ignition engine*. SAE Tech. Pap., doi: 10.4271/2013-01-2684

[15] Izzudin, I., Yusop, A.F., Sapee, S., Hamidi, M.A., Yusri, I.M., Mamat, R., et al. (2020). Experimental studies of single cylinder engine run on diesel-biodiesel-butanol blends. *IOP Conference Series: Materials Science and Engineering*, 863. doi: 10.1088/1757-899X/863/1/012060

[16] Charoensaeng, A., Khaodhiar, S., Sabatini, D.A., & Arpornpong, N. (2018). Exhaust emissions of a diesel engine using ethanol-in-palm oil/diesel microemulsion-based biofuels. *Environmental Engineering Research*, 23, 242–249. doi: 10.4491/eer.2017.204

[17] Yan, J., Gao, S., Zhao, W., & Lee, T.H. (2021). Study of combustion and emission characteristics of a diesel engine fueled with diesel, butanol-diesel and hexanol-diesel mixtures under low intake pressure conditions. *Energy Conversion and Management*, 243, 114273. doi: 10.1016/j.enconman.2021.114273

[18] Zhang, T., Munch, K., & Denbratt, I. (2015). An Experimental Study on the Use of Butanol or Octanol Blends in a Heavy Duty Diesel Engine. *SAE International Journal of Fuels and Lubricants*, 8, 610–621. doi: 10.4271/2015-24-2491

[19] Kumar, K., & Sharma, M.P. (2016). Performance and emission characteristics of a diesel engine fuelled with biodiesel blends. *International Journal of Renewable Energy Research*, 6, 658–62. doi: 0.5383/ijtee.13.02.007

[20] Sharbuddin Ali, S., & Swaminathan, M.R. (2020). Effective utilization of waste cooking oil in a diesel engine equipped with CRDi system using C8 oxygenates as additives for cleaner emission. *Fuel*, 275, 118003. doi: 10.1016/j.fuel.2020.118003

[21] Pradeepraj, R., & Rajan, K. (2020). Performance Analysis of Diesel Engine using Moringa Oil Methyl Ester with Fumigation Technique. *International Journal of Innovative Technology and Exploring Engineering*, 9, 1783–1786. doi: 10.35940/ijitee.b7242.019320

[22] Patil, K.R., & Thipse, S.S. (2015). Experimental investigation of CI engine combustion, performance and emissions in DEE–kerosene–diesel blends of high DEE concentration. *Energy Conversion and Management*, 89, 396–408. doi: 10.1016/j.enconman.2014.10.022

[23] Atelge, M.R. (2022). Investigation of a ternary blend of diesel/ethanol/n-butanol with binary nano additives on combustion and emission: A modeling and optimization approach with artificial neural networks. *Fuel Processing Technology*, 229, 107155. doi: 10.1016/j.fuproc.2021.107155

[24] Santhosh, K., & Kumar, G.N. (2020). Impact of 1-Hexanol/diesel blends on combustion, performance and emission characteristics of CRDI CI mini truck engine under the influence of EGR. *Energy Conversion and Management*, 217, 113003. doi: 10.1016/j.enconman.2020.113003

[25] Gainey, B., & Lawler, B. (2021). The role of alcohol biofuels in advanced combustion: An analysis. *Fuel*, 283, 118915. doi: 10.1016/j.fuel.2020.118915

[26] Pan, W., Yao, C., Han, G., Wei, H., & Wang, Q. (2015). The impact of intake air temperature on performance and exhaust emissions of a diesel methanol dual fuel engine. *Fuel*, 162, 101–110. doi: 10.1016/j.fuel.2015.08.073

[27] Thomas, J.J., Manojkumar, C.V., Sabu, V.R., & Nagarajan, G. (2020). Development and validation of a reduced chemical kinetic model for used vegetable oil biodiesel/1-Hexanol blend for engine application. *Fuel*, 273, 117780. doi: 10.1016/j.fuel.2020.117780

[28] Singh, D., Sharma, D., Soni, S.L., Inda, C.S., Sharma, S., Sharma, P.K., et al. (2021). A comprehensive review of biodiesel production from waste cooking oil and its use as fuel in compression ignition engines: 3rd generation cleaner feedstock. *Journal of Cleaner Production*, 307, 127299. doi: 10.1016/j.jclepro.2021.127299

[29] Jamrozik, A., Tutak, W., Pyrc, M., Gruca, M., & Kočiško, M. (2018). Study on co-combustion of diesel fuel with oxygenated

alcohols in a compression ignition dual-fuel engine. *Fuel*, 221, 329–345. doi: 10.1016/j.fuel.2018.02.098

[30] No, S.Y. (2020). Utilization of Pentanol as Biofuels in Compression Ignition Engines. *Frontiers in Mechanical Engineering*, 6, 1–19. doi: 10.3389/fmech.2020.00015

[31] Aldhaidhawi, M., Chiriac, R., & Badescu, V. (2017). Ignition delay, combustion and emission characteristics of Diesel engine fueled with rapeseed biodiesel – A literature review. *Renewable* and *Sustainable Energy Reviews*, 73, 178–86. doi: 10.1016/j.rser.2017.01.129

[32] Teoh, Y.H., Yu, K.H., How, H.G., & Nguyen, H.T. (2019). Experimental investigation of performance, emission and combustion characteristics of a common-rail diesel engine fuelled with bioethanol as a fuel additive in coconut oil biodiesel blends. *Energies*, 12, 1–17. doi: 10.3390/en12101954