Combustion Characteristics of Cottonseed Biodiesel and Chicken Fat Biodiesel Mixture in a Multi-Cylinder Compression Ignition Engine

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Abstract

Although waste animal fats such as chicken fat are promising alternative energy sources, biodiesels produced from these type of feedstocks hardly satisfies the EN14214 biodiesel standards. In this study, biomixtures were prepared by blending cottonseed biodiesel and chicken rendering fat biodiesel which were produced via transesterification method. Biodiesels were blended with each other at 60/40, 50/50 and 30/70 volume ratios to produce CO60CH40, CO50CH50 and CO30CH70 fuels. First, fuel properties of the neat biodiesels and novel biomixtures were measured and compared to European biodiesel standards and diesel. Then, the engine performance, combustion characteristics and exhaust emissions of these novel biomixture fuels were measured in a three-cylinder indirect injection diesel engine under various engine loads and at constant speed of 1500 rpm. The fuel characterisation showed that CO60CH40 and CO50CH50 biomixtures met the European standards. The Brake Specific Energy Consumption (BSEC) and Brake Thermal Efficiency (BTE) of all biomixtures were comparable with CO100, CH100 and diesel at the full engine load. The combustion results revealed that the maximum in-cylinder pressure and energy release values of the CO50CH50 were 4.2% and 4.4% higher than the diesel at full engine load because of optimised fuel properties of biomixture such as molecular structure, viscosity, cetane number and iodine value. CO50CH50 had 2.9% reduced CO_2 and comparable CO emission compared to diesel, which were also 5.6% and 13% lower than cottonseed biodiesel respectively. However, NO emission of CO50CH50 was found 3.8% and 5.8% higher than diesel and cottonseed biodiesel. A 6.5% reduction on NO emission was observed when CO60CH40 biomixture fuel was used instead of diesel. To conclude, this research showed that blending of cottonseed and chicken fat biodiesels is a promising approach to meet the EN14214 standards, improve in-cylinder pressure, optimise energy release and reduce exhaust emissions. Blending of different biodiesels will be tested as a future work.

Introduction

Energy demand is increasing due to population growth and high standards of living [1]. Due to limited fossil fuel resources, the refinery capacity and strict carbon emission regulations, the need for alternative energy is increasing considerably. According to the International Energy Agency, two-thirds of overall greenhouse gas emissions and more specifically 80% of the CO_2 emission is accounted for the energy sector [2]. Many sustainable solutions studied to provide renewable energy like solar, wind, geothermal, wave, etc. [3]. Like all other renewables, biofuels are also important as they can be used for different applications such as electricity production, heating and transport [4]. The European Union encourages the utilisation of biofuels as member countries have to satisfy 10% renewable requirement for transportation fuel by 2020 [5]. Researchers investigated various biofuels like neat vegetable oils, pyrolysis oils, emulsified fuels and biodiesels [6]. Among the various biofuels, biodiesel occupies the bigger portion of the renewable energy supply. According to the UK Department for Transport, biodiesel shared 47% of the renewable fuel supply in 2018 [7]. Its inherent fuel properties, biodegradability, being carbon neutral, environmentally friendly and applicability to diesel engines without any major modifications make biodiesel a viable alternative fuel [8].

Biodiesel can be produced from a large variety of organic compounds such as plant oils, waste cooking oils, waste animal fats and algae [9–11]. Waste animal fats started to gain more attention from the researchers in the last decade due to their cheap cost and high availability [12]. Moreover, as they are waste materials, their disposal is subjected to some procedures in the UK [13]. High availability of waste chicken was reported as 86 million chickens in the UK in 2015, which makes the feedstock very attractive for the biodiesel production [14]. The waste chicken feedstocks may involve chicken trims, offal, blood, feathers and skin [15]. The feedstock is exposed to the rendering process to extract the chicken fat [12]. Depending on the type and quality of the rendered fat, a pretreatment process may be needed. Alptekin and Canakci [16] reported that any feedstock having Free Fatty Acid (FFA) level above the 1% should be pretreated prior to the transesterification process. Apart from conventional transesterification techniques, Marulanda et al [17] investigated the supercritical transesterification of chicken fat at 300-400 °C temperatures and up to 41.1 MPa pressures. They addressed that this technique had potential to provide cheaper continuous production of a biodiesel as the glycerol (a by-product of the transesterification) also decomposes under the high temperature and pressure conditions and forms additional esters in the presence of methanol [17].

Viscosity is one of the most important fuel properties of a biodiesel as it directly affects the engine operation. Biodiesels having high viscosity value may have poor fuel vaporisation and atomisation which also negatively affects the combustion and exhaust emissions [18]. Therefore, The British & European standards for biodiesel, BS EN 14214 sets the upper limit of viscosity as 5.00 mm^2/s [19]. However, biodiesels derived from waste animal fats generally have high viscosities and cannot be directly used in diesel engines [12,20,21]. Many researchers reported higher viscosity values than 5.00 mm^2/s for the chicken fat biodiesels [15,21–26]. Different solutions have been proposed in the literature to solve this problem such as blending with fossil diesel, preheating of fuel and using fuel additives. However, all of the mentioned solutions had their own problems. Firstly, diesel blending of biodiesels is one of the most common applications in literature. Although this can reduce the viscosity within the range of BS EN 14214 standards, many studies state that fossil diesel depletion is inevitable, hence diesel blending may not be available in the future [27,28]. The second technique was the preheating of the fuel. Different engine modifications developed in the literature to reduce the viscosity before the injection. For example, Nanthagopal et al [29] benefited from the high-temperature exhaust system to increase the temperature of the ethanol-diesel blend by around 50 °C. In another study, Hossain and Davies [30] achieved to increase the temperatures of the neat jatropha and karanj oils up to 75 °C and reduced the viscosities from 58 cSt to 9 cSt and from 80 cSt to 11 cSt by the help of hot jacket water, respectively. Although the heat from the exhaust system or jacket water can be used efficiently, these techniques require major engine modifications which mean extra space, increased weight and additional cost. Lastly, alcohols were one of the most frequently used fuel additives to reduce the viscosity of biodiesels [31–34]. For example, Yasin et al [31] added 5% methanol into diesel-palm oil biodiesel blend (75%/20%). They reported 1.38 mm^2/s reduction on the viscosity of the blend by the addition of methanol. However although, alcohol addition successfully reduced the viscosity, it negatively affected the engine performance and exhaust emissions. They observed an 8.3% reduction in engine power at medium engine speed and around 7% increase in NO emission at medium brake mean effective pressure after the alcohol addition [31].

Rather than mentioned solutions, chicken fat biodiesel can be blended with other biodiesels to optimise fuel properties, especially the viscosity. This technique may help to utilise chicken fat biodiesel in a more efficient manner such as avoiding fossil diesel blending, preventing any side effects of fuel additives and meeting the EN14214 standards.

Cottonseed oil biodiesel is a suitable agent to be blended with the chicken fat biodiesel due to its relatively lower viscosity. Alhassan et al [35] reported the viscosity of the cottonseed biodiesel as 4.38 mm^2/s at 40°C. Similarly, Venkatesan et al [36], Alptekin and Canakci [37] and Ramirez-Verduzco et al [38] addressed promising viscosity values for the cottonseed biodiesel as 3.75, 4.06 and 4.12 mm^2/s, respectively. As these values were lower than the upper limit of the BS EN 14214 standards, blends of the cottonseed biodiesel with the chicken fat biodiesel may comply with the standards. Besides, some researchers also observed lower NO_x emission than diesel with the cottonseed biodiesel. Aydin and Bayindir [39] tested 100% cottonseed biodiesel in a single cylinder direct injection air cooled diesel engine. According to the study, cottonseed biodiesel had around 18% lower NO_x emission than diesel at medium engine speeds. Similarly, Karabektas et al [40] observed a preheated cottonseed biodiesel in a single cylinder direct injection diesel engine and reported that 90 °C preheated cottonseed biodiesel had 5% lower NO_x than diesel at 1800 rpm. In another study, Yucesu and Ilkilic [41] also tested 100% cottonseed biodiesel in a single cylinder air cooled diesel engine and reported 16% reduction in NO_x emission compared to diesel at 2200 rpm.

Modern engines equipped with selective catalytic reduction (SCR) after treatment system may reduce the NOx emissions of biodiesel very effectively. However, their fuel supply systems like common rail direct injection may cause clogging problems when operated on high viscosity fuels. On the other hand, indirect injection type diesel engines are still widely used for different applications such as power generation and agricultural purposes [42]. Nonetheless, these engines do not necessarily have any modern after treatment systems, thus this study would contribute to reducing the emissions of indirect diesel engines and any engine not equipped with the SCR.

The main aim of this study is to reduce the viscosity of chicken fat biodiesel under the upper limit of the BS EN14214 standards by blending with cottonseed biodiesel. By this technique, some blends can comply with the BS EN 14214 standards and fuel properties can be optimised. In addition, chicken fat biodiesel can be utilised without any need of fossil diesel blending, engine modification, and any additive requirement. Objectives of the study were (i) to produce biodiesels via transesterification technique and blending of chicken-cottonseed biodiesels at various ratios. (ii) To characterise the fuel properties of the test fuels. (iii) To determine blend ratios comply with the BS EN 14214 standards. (iv) To test engine performance, combustion characteristics and exhaust gas emissions of novel blends and compare them to both CO100 and CH100 and diesel.

Materials and Methods

Biodiesel Production

Initially, waste chicken skin was collected from a local butcher shop. Then they were cut into smaller pieces and placed in an oven operating at 160 °C. After 40 minutes, rendered fat was collected. The chicken rendered fat was in the liquid phase even at the room temperature Figure 1.

Fig ure 1. Chicken skin rendering fat (on the left) and cottonseed oil (on the right).

Both cottonseed oil and chicken rendering fat were converted into biodiesel via transesterification process. The laboratory scale equipment was used throughout the biodiesel production. KOH was used as a catalyst and mixed with the methanol in a baker under stirring condition. The amount of KOH was determined by the previously conducted titration method. The 1 ml feedstock was mixed with the 10 ml isopropanol and phenolphthalein indicator than titrated against 0.1 N KOH solution. The amount of KOH solution consumed was used to determine the KOH needed for transesterification. The amount of methanol was equal to 20% of the feedstock to be transesterified. After KOH was completely dissolved in the methanol, the solution was added into feedstock which was at 60°C. Then mechanical stirring applied on the mixture for about 30 minutes. Lastly, the mixture was poured into a separating funnel and allowed to have phase separation for 24 hours. The glycerol was settled down and biodiesel was accumulated at the top. The biodiesel production yield was calculated by dividing the amount of biodiesel produced by used feedstock before the transesterification [43]. For large scale production, the conventional commercial techniques can be used as described in literature [12]. Then the produced biodiesels can be blended easily without any necessity of aggressive stirring or surfactants.

Biomixtures were prepared by blending cottonseed biodiesel (CO100) and rendered chicken fat biodiesel (CH100) at 80/20, 60/40, 50/50, 30/70 and 10/90 volume ratios and named as CO80CH20, CO60CH40, CO50CH50, CO30CH70 and CO10CH90 as shown in Table 1. The commercially available Esso diesel (in the UK) was used as a reference fuel which involves 5% biodiesel in its content. Figure 2 presents the test fuels. There was no phase separation or miscibility problem in the biomixtures.

Table 1. Biodiesel percentages of the biomixtures.

Fuel	Volume percentage of		Fuel	Engine
Name	Cottonseed biodiesel	Chicken biodiesel	Characterisation	Testing
CO100	100%	0%	Yes	Yes
CO80CH20	80%	20%	Yes	NO
CO60CH40	60%	40%	Yes	Yes
CO50CH50	50%	50%	Yes	Yes
CO30CH70	30%	70%	Yes	Yes
CO10CH90	10%	90%	Yes	NO
CH100	0%	100%	Yes	Yes

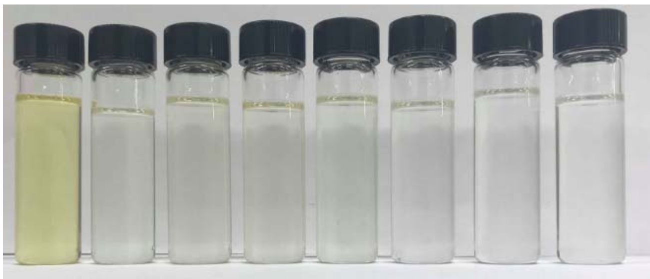


Figure 2. Appearance of the test fuels which are from left to right; Diesel, CO100, CO80CH20, CO60CH40, CO50CH50, CO30CH70, CO10CH90 and CH100.

Test Rig and Equipment

The two neat biodiesels, diesel and three biomixtures which were CO60CH40, CO50CH50 and CO30CH70 were tested in the engine to investigate the effect of cottonseed-chicken biodiesel blends on performance, combustion and emissions. Engine operating conditions like the height of the fuel tank, lubricant oil, exhaust piping, air aspiration system, brake mean effective pressure, compression ratio etc. were the same for all test fuels. It is well known that stationary engines are mainly operated at a constant engine speed especially for the agricultural purposes and power generation. Therefore, the engine speed was kept constant at the rated speed (1500 rpm) throughout the experiment, whereas engine load was changing. Six different data sets were collected at 20% (1.9 kW), 40% (3.8 kW), 60% (5.7 kW), 70% (6.65 kW), 80% (7.6 kW) and 100% (9.75 kW) engine loads to check the behaviors of the fuels at different engine loadings. An indirect injection type three-cylinder naturally aspired Lister Petter engine without EGR application was used to conduct this study. The specifications of the engine were listed in Table 2. This engine was mainly selected due to the recent trend on indirect injection engines for the advanced combustion research. Premixed Charge Compression Ignition (PCCI), Reactivity Controlled Compression Ignition (RCCI) and Homogeneous Charge Compression Ignition (HCCI) were the recent examples [44–46]. In addition, some heavy duty diesel engines also use indirect injection system [47]. Although the engine does not meet emission standards, the results of the biofuels can give good indications to the researchers as they were compared to the diesel results at the same engine.

A Froude Hofmann AG80HS brand eddy current dynamometer was used for engine loading. A graduated cylinder was installed to fuel line to measure the fuel consumption. To measure the combustion characteristics Kistler products were used. A 6125C11 pressure sensor along with a 5064B11 charge amplifier was installed for the in-cylinder pressure measurement on the first cylinder. Fuel injection pressure was observed with the 4065A500A pressure sensor and the 4618A0 amplifier. Crank angle was measured via 2614A optical sensor. All data were processed and analysed through the 2893AK8 KiBox data acquisition hardware equipped with the Cockpit software. LabVIEW data acquisition system integrated with K-type thermocouple used to monitor exhaust gas temperature. Figure 3 explains the test rig setup. The exhaust gases were analysed through Bosch BEA 850 gas analyser. The exhaust gases were measured directly from the exhaust pipe without any dilution.

Table 2. Engine specifications.

Number of cylinders	3
Engine manufacturer	Lister Petter (UK)
Engine model	LPWS Bio3 water cooled
Exhaust gas recovery (EGR)	0%
Rated speed	1500 rpm
Continuous power at rated speed	9.9 kW
Fuel pump injection timing	20º bTDC
Fuel injection type	Indirect injection. Self-vent fuel system with individual fuel injection pumps
Cylinder volume	1.395 litre
Aspiration	Naturally aspired

Initially, the engine was started and run on diesel for 30 minutes to avoid the cold start effect. Then tests were started with fossil diesel. Before switching to new fuel, the fuel supply system was flushed with the new fuel prior to measurements. Moreover, the engine was run at least 4 minutes after each load change to collect data in the steady-state condition. 51 cycles of combustion data were collected via KiBox, and then the average of readings calculated for minimising the cycle errors. Engine geometry, pressure versus volume cycle, and the first law of thermodynamics were used in the evaluation of combustion characteristics. Adiabatic expansion and compression were assumed during the combustion process and heat losses to walls did not take into account. KiBox cockpit software was used to analyse the start of injection (SOI), start of combustion (SOC), ignition delay (ID), end of combustion (EOC), combustion duration (CD), in-cylinder pressure and total heat release. The crank angle when the fuel injection pressure was built up was assumed as a SOI point. Moreover, 5% and 90% of heat release were assumed as the start and end of combustion. Ignition delay corresponds to crank angle difference between the SOC and SOI. Similarly, combustion duration is the crank angle difference between the EOC and SOC.

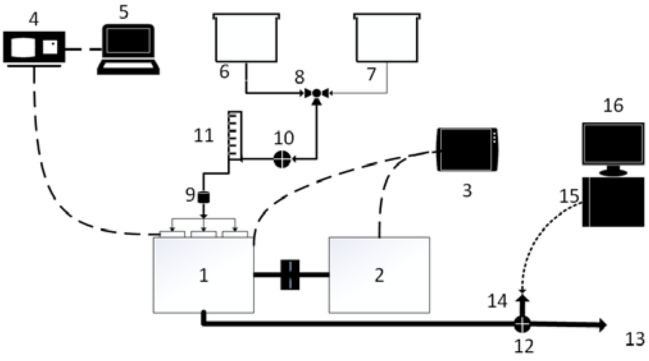


Figure 3. Schematic diagram of the experimental setup. 1 engine, 2 Dynamometer, 3 Dynamometer controller, 4 KiBox combustion analyser,5 laptop to record combustion data, 6 diesel tank, 7 biofuel tank, 8 three-way valve, 9fuel filter, 10 valve, 11 fuel meter, 12 valve, 13 Exhaust pipe exit, 14 Exhaust pipe opening to measure emissions, 15 emission analyser, 16 computer to record emission data.

Results and Discussions

Fuel Characterisation

Approximately 2.2 kg of fat rendered out of the 5kg chicken skin, thus the yield of rendering process was calculated as 43.5%. However, yields of biodiesel productions for both cottonseed oil and chicken fat were around 92%. All biofuels were tested in a gas chromatograph and mass spectrum (GC-ms) analyser to find fatty acid methyl ester (FAME) compositions. The Trace 1300 type Thermo Scientific brand gas chromatography equipped with the ISQLT brand mass spectrum analyser was used at Aston University chemical engineering laboratories. The samples were prepared by dissolving 0.1 g of biofuel in 100 ml of methanol. The 0.1μL volume of samples was tested through the Perkin Elmer brand column which was 30 m in length, 0.22 mm in diameter and 0.25 μm of film thickness. The injector was set to 280 °C and a split mode (with 1:10 ratio) was used during the injection of the samples. The oven was at 100 °C at the first 1 minute and the temperature was increased by the increments of 10°C per minute up to 275 °C. Electron impact ionisation was used at the mass spectrometer to scan within the range of 50-600 m/z. The temperatures of the ion source and mass transfer line were 200 °C and 250 °C respectively. Figure 4 illustrates the sample GC-ms results which belong to CO50CH50 biomixture. It should be noted that free glycerol, mono-, di-, tri- glycerides, oxidation stability and metals content were not measured in this study. However, according to Figure 4, there was not any significant peak which might belong to free glycerol, mono-, di-, or tri-glycerides. The EN 14214 standard limits the mole percentages of mono-glyceride maximum to 0.8, di- and tri-glycerides maximum to 0.2 and free glycerol maximum to 0.02.

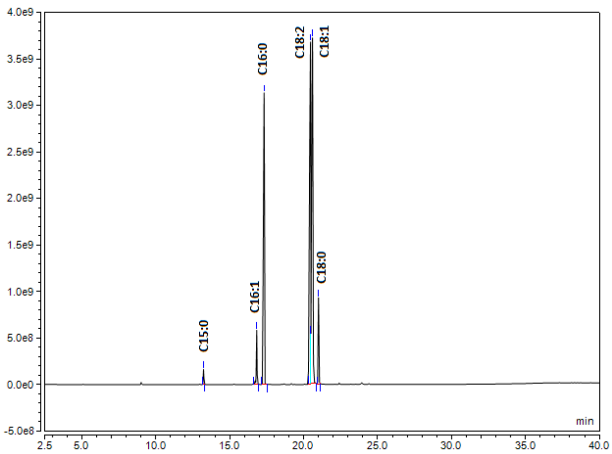


Figure 4. FAME distributions of the CO100, CH100 and biomixtures according to saturated, monounsaturated and polyunsaturated FAME percentages.

Table 3 shows the FAME mass percentage breakdowns of the biofuels. Results showed that both base fuels i.e. cottonseed biodiesel and chicken biodiesel have a similar fraction of saturated FAMEs as 26.7% and 28.8% respectively. Ultimately, their total unsaturation percentages were also close to each other as 73.3% and 71.2% respectively. However, the type of unsaturated FAME has a vital influence on the iodine value of biodiesel [48]. The results revealed that cottonseed biodiesel was mainly consisted of polyunsaturated FAME (C18:2) as 51.7%, whereas chicken biodiesel had the monounsaturated FAMEs (C16:1 and C18:1) as 48.8% in total.

The FAME breakdowns of each biofuel were used to determine some fuel properties such as cetane numbers, carbon, hydrogen and oxygen contents, lower heating values, iodine numbers and degrees of unsaturation. On the other hand, viscosity, density, flash point, higher heating value and acid value were measured at the Aston University laboratories according to the methods declared by the European standards i.e. EN ISO 3675 for density, EN ISO 3104 for the kinematic viscosity, and EN ISO 3679 for flash point.

Table 3. Fatty Acid Methyl Ester compositions of the biofuels.

	mass percentage (%)						
FAME	CO100	CO80CH20	CO60CH40	CO50CH50	CO30CH70	CO10CH90	CH100
C15:0	0.7	0.6	0.6	0.6	0.6	0.6	0.6
C16:0	23.2	21.8	21.7	21.5	21.6	21.5	21.7
C16:1	0.5	1.4	2.1	3.1	4.0	5.1	5.4
C18:0	2.8	3.8	5.2	5.0	5.7	6.2	6.6
C18:1	20.9	25.8	30.9	32.6	36.8	40.9	43.0
C18:2	51.7	46.5	39.4	37.3	31.3	25.4	22.4
C19:1	0.2	0.2	0.0	0.0	0.0	0.3	0.4
C20:0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Total saturated	26.7	26.2	27.6	27.1	27.9	28.3	28.8
Monounsaturated	21.6	27.3	33.0	35.7	40.8	46.3	48.8
Polyunsaturated	51.7	46.5	39.4	37.3	31.3	25.4	22.4

The physicochemical properties of CO100, CH100, biomixtures, and diesel were presented in Table 4 along with The British & European

Table 4. Fuel properties of the test fuels with the corresponding EN14214 biodiesel *[19]* and EN 590 diesel [49] standards.

Fuel	**Units**	**Biofuels**								**EN 14214**	**EN 590**
Properties		**CO100**	**CO80CH20**	**CO60CH40**	**CO50CH50**	**CO30CH70**	**CO10CH90**	**CH100**	**Diesel**	**Biodiesel Standards**	**Diesel Standards**
Viscosity at 40°C	mm^2/s	4.33	4.48	4.66	4.92	5.10	5.16	5.36	2.78	3.5 - 5.0	2.0 - 4.5
Density	g/cm^3	0.884	0.882	0.882	0.881	0.880	0.880	0.878	0.828	0.86 - 0.90	0.820 - 0.845
Flash Point	°C	176	176	173	171	168	165	165	61.5	> 101	> 55
Cetane number	-	54	55	57	57	59	60	60	45.7	> 51	> 51

Carbon	%	76.13	76.23	76.34	76.32	76.29	76.02	75.95	86.6 [50]	n/a	n/a
Hydrogen	%	11.93	11.97	12.05	12.06	12.10	12.10	12.11	13.4 [50]	n/a	n/a
Oxygen	%	10.97	10.98	11.00	11.01	11.02	10.99	10.99	0.07 [50]	n/a	n/a
HHV	MJ/kg	39.4	39.4	39.6	39.4	39.1	39.6	39.3	45.2	n/a	n/a
LHV	MJ/kg	37	37	37	37	37	37	37	42	n/a	n/a
Iodine number	g/100g	111	108	101	100	94	88	85	n/a	< 120	n/a
Acid value	mg KOH/g	0.228	0.200	0.200	0.171	0.172	0.172	0.172	0.091	< 0.5	n/a
Degree of Unsaturation	Weight %	125	120	112	110	103	97	94	n/a	n/a	n/a

biodiesel standards, BS EN 14214 [19] & EN 590 diesel standards [49]. Viscosity, cetane number and iodine value were found as mostly effected fuel properties due to the blending of cottonseed-chicken biodiesels. Figure 5 illustrates the variation of viscosity and cetane number with respect to cottonseed-chicken biodiesel ratio. Both properties were increased with the increased fraction of the chicken biodiesel in the blends. This can be attributed to the relatively low amount of polyunsaturated FAME content of the CH100 as 22.4%.

Viscosity is a crucial fuel property as it directly affects the atomisation quality of the fuel [37]. The viscosity of CH100 biodiesel was measured as 5.36 mm^2/s which was not complied with BS EN 14214 standards. The main reason of high viscosity was relatively low degree of unsaturation and iodine value of the CH100. It is well known that FAMEs with low number of double bonds (low degree of unsaturation and iodine value) have higher viscosities [50]. However, blends containing at least 50% cottonseed biodiesel like CO50CH50, CO60CH40, CO80CH20 and CO100 had viscosities less than 5.0 mm^2/s limit and met the standards. Similarly, density also influences the combustion and engine performance [43]. All biofuels met the BS EN 14214 standards in terms of density. The CO100 had the highest density of 0.884 g/cm^3. The density of the blends reduced with the increased percentage of chicken biodiesel. Flash point is an important parameter for safe storage and transport of the fuels. The flash points of all biofuels were changing between 176°C and 165°C which complied with the standards. Cetane number is a good measure of the ignition quality of any fuel [51]. CN numbers of each biofuel were calculated from their FAME compositions as shown in equation 1 [52].

$$CN_{biodiesel} = \sum (CN_{FAME})\ (mass\ percentage\ of\ FAME) \tag{1}$$

All biofuels had higher CN values than the 51 limit declared by the standards. Among the biofuels, CO100 had the minimum CN as 54 and CN of the biofuels was increasing in accordance with the increasing chicken biodiesel fraction. The CO60CH40 and CO50CH50 biomixtures had similar CN as 57, and maximum CN value was observed with CH100 as 60. The carbon, hydrogen and oxygen contents of the biofuels were found very close to each other and matched with the literature [53]. All biofuels had almost the same energy contents and lower heating values as 39.4 MJ/kg and 37 MJ/kg which were slightly lower than diesel. Iodine number and degree of unsaturation both measures the saturation level of any animal fat or vegetable oil [54]. The iodine value of any FAME increases with an increasing number of double bonds in its molecular structure and the biofuels becomes more unsaturated. All biofuels met the iodine value standard which was declared as maximum 120 g iodine/100g in BS EN14214. Iodine values of the blends decreased with respect to the increased percentage of the chicken biodiesel. The acid value is a good indication of biodiesels resistance to ageing [55]. The acid values of all biofuels were below the maximum limit of 0.5 mg KOH/g. This shows that biofuels can be safely used in an engine in terms of pump plugging and corrosion [43,55]. Consequently, Chicken biodiesel did not meet the BS EN 14214 standards in terms of viscosity. However, blending of cottonseed biodiesel with chicken biodiesel at 60/40 and 50/50 volume ratios generated high-quality biomixtures complied with the standards. In other words, no other additives, engine modification or fossil diesel blending was required for the engine application.

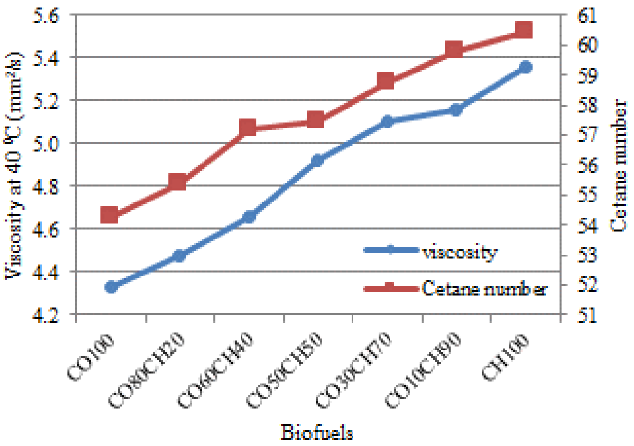


Figure 5. Variation of viscosity and cetane number with respect to cottonseed-chicken biodiesel ratio.

The fuel properties of the biomixtures i.e. CO50CH50 were in good agreement with the similar studies in the literature. For example, Benjumea et al [56] blended the palm and linseed biodiesels in 50/50 volume fraction. This biofuel blend had comparable density (as 0.885 g/cm^3), HHV (as 39.8 MJ/kg) and iodine value (as 112.7 g/100g) with the CO50CH50. Moreover, the mentioned biofuel blend had a 10% lower cetane number (as 51.3) than the CO50CH50 biomixture investigated in this study. In another study, Sanjid et al [57] studied the Kapok biodiesel-Moringa biodiesel-diesel blend which had volume percentages of 10/10/80 respectively. This fuel had around 30% lower viscosity value (as 3.40 mm^2/s) than the CO50CH50, because of the high percentage of diesel as 80%. However, the cetane number of the mentioned fuel was approximately 16% lower than the CO50CH50. Overall, the biomixtures investigated in this study had comparable fuel properties with the similar type of biofuel blends in literature. Moreover, the fuels presented in this study were better in terms of the cetane numbers as the chicken biodiesel had relatively high CN as 60.

Engine Performance

Figure 6 demonstrates the Brake Thermal Efficiency (BTE) of the test fuels with respect to different engine loads. Blends having relatively higher cottonseed biodiesel ratio had better performance at low and medium engine loads. CO100, CO60CH40, CO50CH50 had around 10% higher BTE than other biofuels and diesel at 40% load. This is due to the presence of oxygen in the content of biodiesel which enhances the combustion characteristics of the fuel. However, all biofuels had slightly reduced 1.6% BTE than diesel at the full load condition. This result is in agreement with the literature. Despite the presence of oxygen, diesel can provide higher BTE than biodiesel due to its higher Lower Heating Value (LHV) than biodiesel [43].

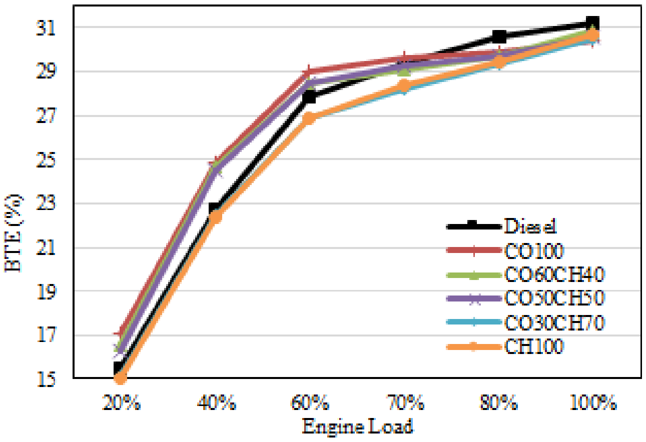


Figure 6. BTE of the test fuels.

Figure 7 shows the (a) Brake Specific Fuel Consumption (BSFC) and (b) Brake Specific Energy Consumption (BSEC) of the test fuels at different engine loads. BSFC of all biofuels found higher than the diesel at each engine load and was 15.4% higher than the diesel at full load condition. An increasing trend on BSFC was observed with the decreasing iodine number, especially at low and medium engine loads. To illustrate, CH100 and CO30CH70 biofuels with relatively high iodine numbers had 5.6% and 14.4% higher BSFCs than the other biofuels and diesel at 60% engine load, respectively. However, all biofuels had the same BFSC at the high engine loads due to the same LHV. In order to eliminate the effect of LHV, BSEC can be used to compare the energy consumption of an engine when operated on different LHV fuels [58,59]. This allows comparing the test fuels in terms of the energy consumed to produce the same power output. Figure 7 (b) indicates that CO100, CO60CH40, CO50CH50 had around 11.8% lower BSEC than the CO30CH70, CH100 and diesel at 40% engine load. Moreover, all test fuels including diesel had almost the same BSEC at the full engine load condition. To sum up, the engine consumed comparable energy on every test fuels. In other words, diesel did not have any superiority to biofuels at the full load condition.

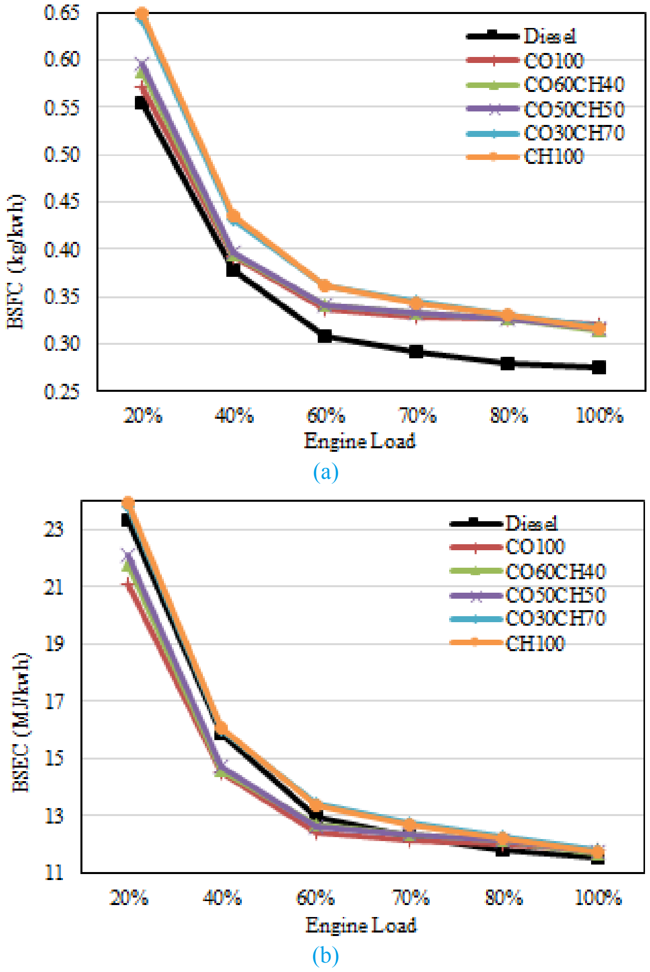


Figure 7. BSFC and BSEC of the test fuels.

Injection and Combustion Characteristics

Figure 8 represents the start, end times of the combustion as well as overall combustion duration for the all test fuels. No significant change on SOC was observed with respect to engine load, whilst EOC was linearly increasing according to increasing engine load for all fuels. This is due to increased amount of fuel at higher engine loads to overcome the higher resistance. Ultimately, the total combustion durations of all test fuels were also higher at the high engine loads.

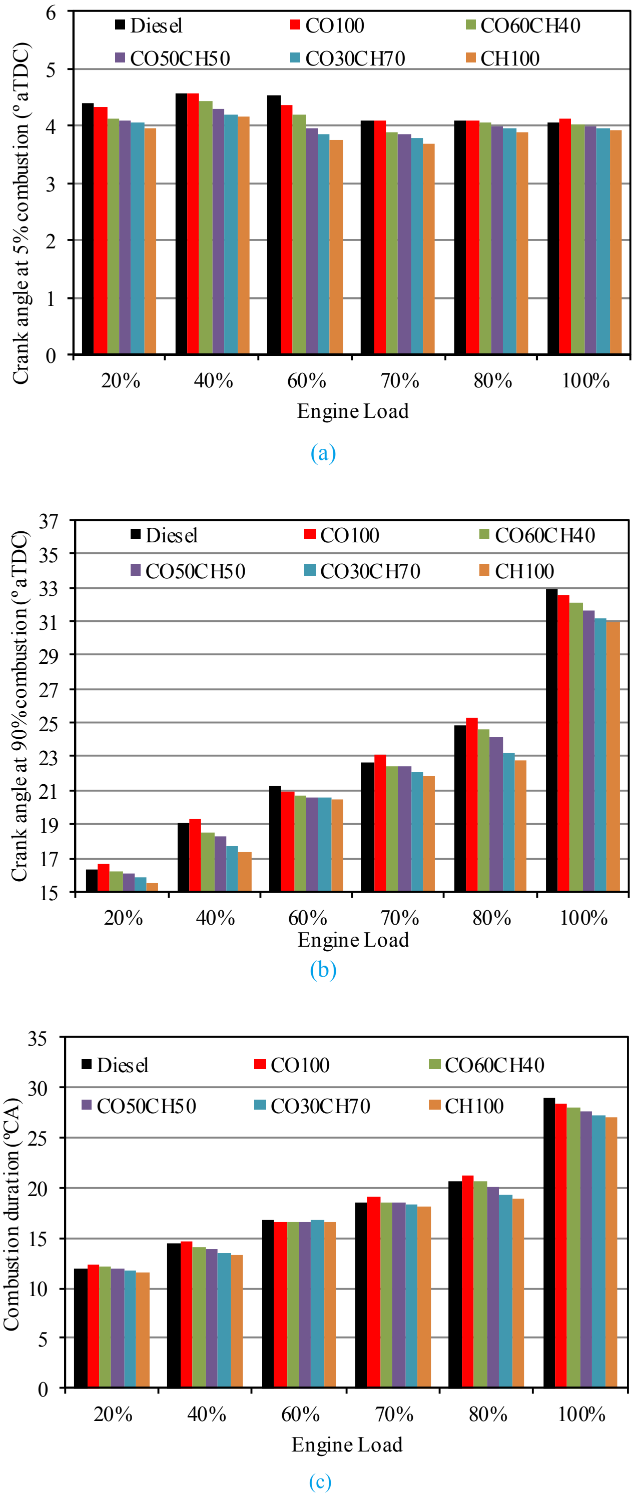


Figure 8. Combustion (a) start, (b) end times and (c) combustion duration in terms of crank angles.

Ignition delay and combustion durations were investigated in more detail in Figure 9. Chicken biodiesel had the shortest ID at all engine loads due to its high cetane number. Approximately 0.2°CA and 0.1°CA longer ID were measured for each 2 reduction on cetane number at medium and high engine loads respectively. In other words, the higher the cottonseed biodiesel ratio, the longer the ignition delay and combustion duration. This can be explained by the relatively higher iodine number, density and lower cetane number of cottonseed oil. Both CO60CH40 and CO50CH50 biomixtures had the average ID and CD values as 4.0°CA and 28°CA at the full engine load condition.

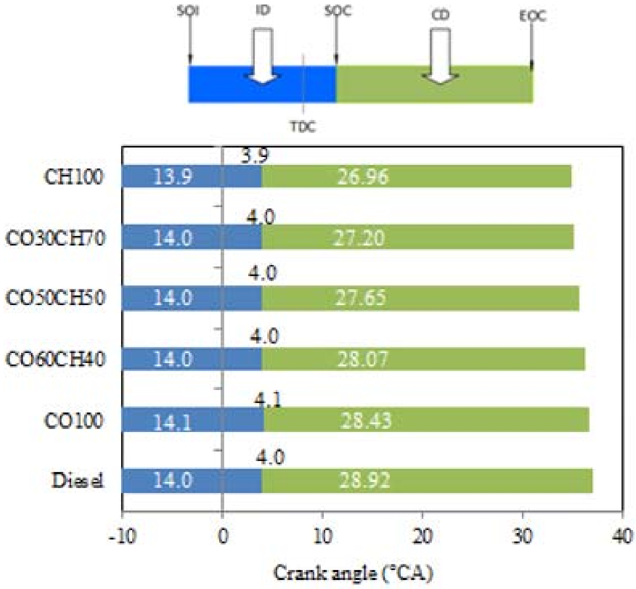


Figure 9. Ignition delay and combustion duration of the test fuels at the full engine load.

The effective heat energy of any fuel can be understood by the exhaust gas temperature (EGT) [60]. The higher the EGT, the lower the conversion of energy to useful work [43]. Moreover, NO_x emission and BSFC are likely to increase with the higher EGT [60]. EGTs of the test fuels were measured and given in Figure 10. Like in the case of CD, EGT also rose with the increasing engine load because of the escalating amount of consumed fuel. In general, all biofuels had lower EGT than the diesel. The CO50CH50 biomixture had the lowest EGT at each engine load i.e. 7.8%, 6.9% and 2.4% lower than diesel, CO100 and CH100 at full engine load respectively. Diesel had the highest EGT and it was followed by the CO100 and CO60CH40 at each engine load. Longer combustion durations may cause some of the fuel to be burned in the expansion stroke where the combustion chamber volume gets larger. This phenomena results in converting the fuel energy in to exhaust temperature rather than useful energy [61], which explained the reason of higher EGT of diesel, CO100 and CO60CH40. To illustrate, diesel had 0.5°CA longer combustion duration than CO50CH50 at 60% engine load which result in 10°C higher EGT.

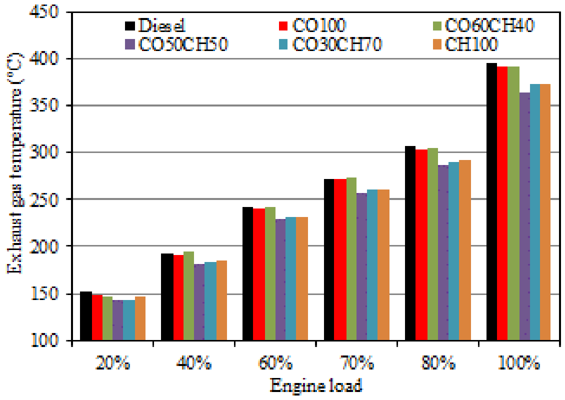


Figure 10. Exhaust gas temperature at different engine loads.

The in-cylinder pressures of the biofuels and diesel were demonstrated in Figure 11. The in-cylinder pressure trends of the biomixtures were smooth like diesel which prove there was no abnormalities or uneven burning of the novel biomixtures [62]. The CO50CH50 had the highest peak in-cylinder pressure as 71.8 bar at 10.7°CA; which was approximately 4.2% and 4.5% higher than the diesel and other biofuels at full load. The optimised fuel properties (by blending) might be the reason why the pressure of CO50CH50 was the highest. In other words, although CO100 had the lowest viscosity value as 4.33 mm^2/s; it had lower CN (as 54) and higher degree of unsaturation (as 125) than CH100 (which has CN as 60 and a degree of unsaturation as 94). This shows that the high viscosity detriment of CH100 and the low CN disadvantage of CO100 were both eliminated when they were blended to form CO50CH50. Figure 12 presents the heat releases of the test fuels at different crank angles. Similar to in-cylinder pressure, CO50CH50 had the highest heat release at the early phase of the combustion between 5°CA and 25°CA aTDC. To illustrate, figure 12 (b) presents that CO50CH50 released 249 J of heat at 12°CA, whereas diesel released 238 J of heat at the same crank angle which was 4.4% lower than the CO50CH50. After the 35° CA, CO60CH40 had the highest heat release which was approximately 3.8% higher than the other fuels including the diesel at 69°CA. The main reasons for the changes in heat release might be the varying iodine values (and the degrees of unsaturation) and viscosities of the test fuels. It was observed that biofuels having relatively lower iodine values tends to burn quicker because of the less number of double bonds in their chemical structures [48]. Nevertheless, their relatively high viscosities lead to poor atomisation which reduces the burning quality of the fuel [20]. Therefore, CO50CH50 and CO60CH40 had the highest heat releases due to optimised iodine values and viscosities.

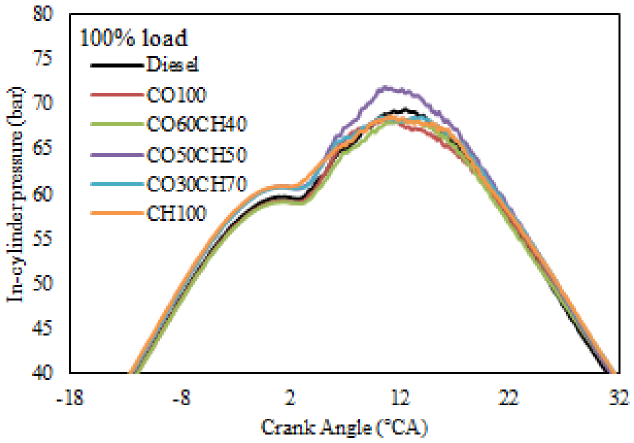
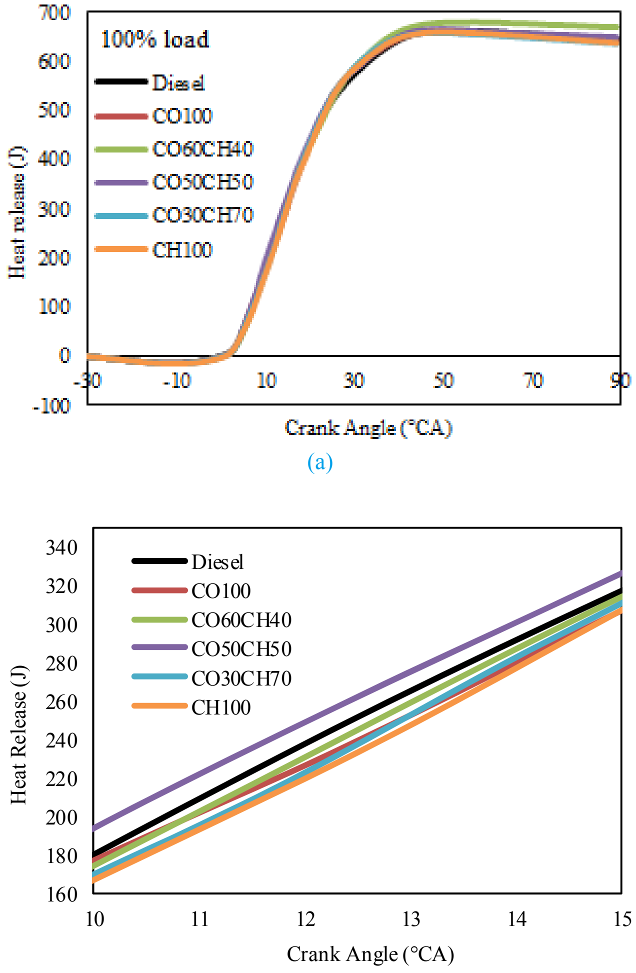


Figure 11. In-cylinder pressure versus crank angle.



(a)

(b)

Figure 12. Heat release of test fuels at versus crank angles (a) whole combustion period, (b) early combustion phase between the crank angles of 10 and 15.

Exhaust Gas Emissions

CO_2, CO and NO emissions of biomixtures were analysed as instantaneous pollutant concentrations and compared to CO100, CH100 and diesel. The readings were collected at the steady-state condition which was monitored by the stability of the instantaneous readings. As shown in Figure 13, the CO_2 emission rose with increasing load. This was due to the increased fuel consumption at high engine speeds which increased the carbon atoms in combustion reaction. Oxygen content and burning efficiency are the other important factors in CO_2 emission of any fuel [63]. Carbon and oxygen contents of the test fuels were reported very close to each other in Table 4. Ultimately, any difference on CO_2 emissions can be attributed to burning efficiency of the test fuels. The results indicated that among the two neat biodiesels, CO100 had 5.4% more CO_2 emission than CH100. Compared to diesel, CO100 had 2.8% higher CO_2 emission, whereas CH100 had 2.8% lower CO_2 emission. Although however, chicken fat biodiesel has viscosity limitations according to BS EN 14214 standards and cannot be directly used in an engine, this advantage of the chicken biodiesel was also observed on the CO50CH50 biomixture. Results in Figure 13 addressed that the CO50CH50 biomixtue also had a promising burning efficiency like CH100. The CO50CH50 had the lowest CO_2 emission which was 5.8% and 2.9% lower than CO100 and diesel at the full load respectively. Consequently, CO_2 emission at high engine loads can be reduced by cottonseed biodiesel and chicken biodiesel blending.

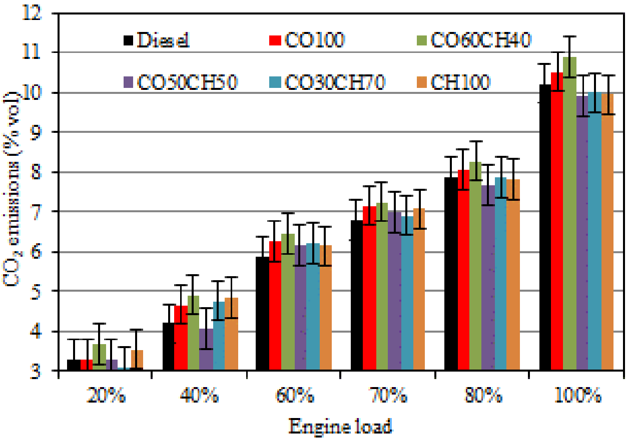


Figure 13. CO_2 emissions of the test fuels at different loads.

Figure 14 illustrates the CO emissions of the test fuels at different engine loads. The CO50CH50 had a comparable CO emission with diesel and approximately 15% lower than both CO100 and CH100 at the full engine load. Better burning efficiency of CO50CH50 might have caused this. Unlike CO50CH50, other biomixtures CO60CH40 and CO30CH70 had around 17% higher CO emission than both CO100 and CH100. However, in overall CO50CH50 biomixture proved that blending of cottonseed biodiesel with chicken biodiesel can also reduce CO emission.

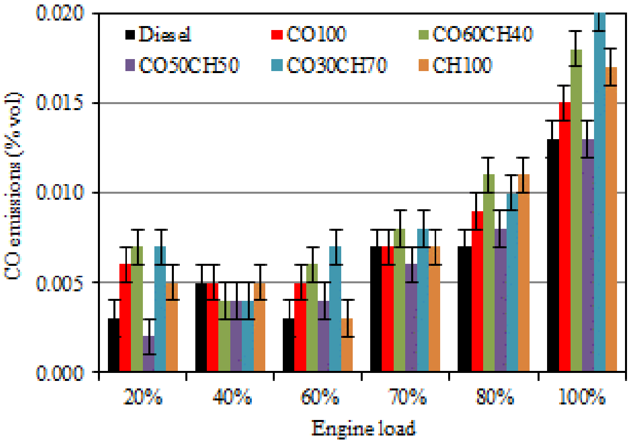


Figure 14. CO emissions of the test fuels at different loads.

NO emissions of the test fuels presented in Figure 15. Although the NO_x emission was not measured directly, the manufacturer of the equipment stated that NO_x can be estimated as approximately 1.2 times greater than the measured NO emission. An increasing trend of NO emission was observed until 80% engine load, then slightly reduced NO emissions were spotted towards the full engine load. As the engine speed was kept constant at 1500 rpm, the air aspiration was the same at every engine load. Among the tested neat biodiesels, CO100 had approximately 3%, 4% and 2% lower NO emissions than diesel at high engine loads i.e. 70%, 80% and 100% engine loads respectively. On the other hand, CH100 had almost the same NO emissions with the diesel. The reduced NO emissions of CO100 were in good agreement with the literature [39–41]. Like CO100, CO60CH40 also had 6.5% lower NO emission than the diesel at full engine load. This decrease on NO emission might be explained by the lower in-cylinder pressure and thus the lower combustion temperature because of lower LHV of CO60CH40. However, it has to be concluded that various factors affects the NO and NO_x formation which may result in contradictory readings. The ambient conditions, gas residence time of the fuels, fuel spray characteristics, EGR application, oxygen content, physical condition of the experimental equipment, and fluctuations can all affect the NO and NO_x formation of any fuel, hence it is difficult to figure out the most dominant parameter causing the difference [43,64–66].

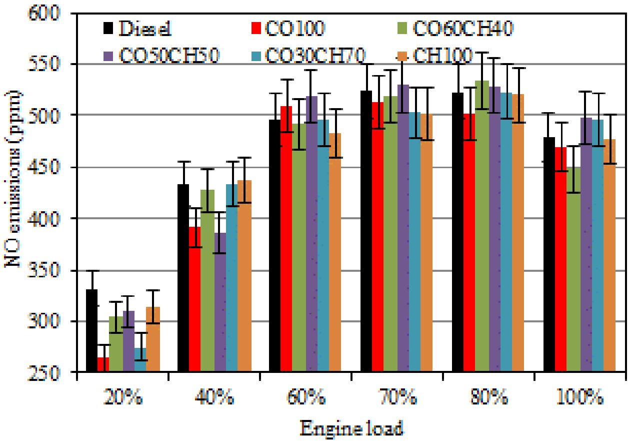


Figure 15. NO emissions of the test fuels at different loads.

Conclusion and Recommendations

In this study, waste chicken skin rendering fat was selected as a target feedstock due to its high availability and promising fuel properties like cetane number. However, due to the limitations regarding the high viscosity, it did not meet the BS EN 14214 standards. To reduce the viscosity, the chicken biodiesel was blended with cottonseed biodiesel. The blends having 50% or higher cottonseed biodiesel met the standards. Main conclusions of the biomixtures were;

- BSEC of all the biofuels were comparable with the diesel at the full load condition. However, all biomixtures, CO100, and CH100 had slightly lower (1.6%) BTE than diesel.
- The CO50CH50 biomixture had the lowest EGT which was 7.8%, 6.9% and 2.4% lower than diesel, CO100 and CH100 at full engine load, respectively.
- The CO50CH50 had 4.2% higher peak in-cylinder pressure than the diesel. Similarly, heat release of the CO50CH50 was 4.4% higher than the diesel at the early phase of the combustion i.e. between 5°CA and 25°CA aTDC.
- The CO50CH50 had the lowest CO$_2$ emission which was 5.8% and 2.9% lower than CO100 and diesel. The CO emission of CO50CH50 was also found comparable with diesel and approximately 15% lower than both CO100 and CH100 at full engine load. However, NO emission of CO50CH50 was observed around 6% higher than diesel. The reduction on NO emission was reported by the CO60CH40 by 6.5% lower than diesel at full engine load.

The biomixtures can be tested under different engine operations such as different engine speeds, transient engine operation, EGR, direct injection or in the presence of after treatment techniques. Moreover, blending of other biodiesels can also be investigated as a future work. This study recommends blending of biodiesels with other biodiesels to enhance or optimise the fuel properties rather than blending with fossil diesel or other additives. Uninvestigated fuel properties such as oxidation stability, metals content, water content etc. should be investigated as a future work to be able to declare that the biomixtures fully complies with the European standards.

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Definitions/Abbreviations

aTDC	After top dead centre
BSEC	Brake specific energy consumption
BS EN 14214	British & European biodiesel standards
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
CA	Crank angle
CD	Combustion duration
CH100	Chicken biodiesel
CN	Cetane number
CO	Carbon monoxide
CO$_2$	Carbon dioxide
CO100	Cottonseed biodiesel
CO80CH20	80% cottonseed biodiesel blended with 20% chicken

	biodiesel
CO60CH40	60% cottonseed biodiesel blended with 40% chicken biodiesel
CO50CH50	50% cottonseed biodiesel blended with 50% chicken biodiesel
CO30CH70	30% cottonseed biodiesel blended with 70% chicken biodiesel
CO10CH90	10% cottonseed biodiesel blended with 90% chicken biodiesel
EGR	Exhaust gas recirculation
EGT	Exhaust gas temperature
EOC	End of combustion
FFA	Free Fatty Acid
GC	Gas chromatography
HCCI	Homogeneous charge compression ignition
ID	Ignition delay
KOH	Potassium hydroxide
LHV	Lower heating value
ms	Mass spectrum
NO	Nitric oxide
NO_x	Nitrogen oxides
PCCI	Premixed charge compression ignition
RCCI	Reactivity controlled compression ignition
SCR	Selective catalytic reduction
SOC	Start of combustion
SOI	Start of injection
UK	United Kingdom