



## PAPER

## OPEN ACCESS

RECEIVED  
14 July 2022REVISED  
30 September 2022ACCEPTED FOR PUBLICATION  
20 October 2022PUBLISHED  
16 November 2022

Original content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.



# Sustainable biodiesel from flex-mix feedstock and its combustion in a VCR-CRDI engine with variable exhaust gas recirculation and injection pressure

Vikas Sharma<sup>1,\*</sup> , Abul K Hossain<sup>1</sup>, Ganesh Duraisamy<sup>2</sup> and Justin Jacob Thomas<sup>2</sup><sup>1</sup> Mechanical, Biomedical and Design Engineering, College of Engineering and Physical Sciences, Aston University, Birmingham B4 7ET, United Kingdom<sup>2</sup> Department of Mechanical Engineering, College of Engineering Guindy, Anna University, Chennai 25, Tamilnadu, India

\* Author to whom any correspondence should be addressed.

E-mail: [v.sharma10@aston.ac.uk](mailto:v.sharma10@aston.ac.uk)**Keywords:** biodiesel, flex-mix, combustion, emission, variable compression, waste to energy

## Abstract

Biodiesel produced from single feedstocks has many challenges due to variations in the oil properties. The flex-mix approach is a long-term solution for turning mixed feedstock into high-quality biodiesels. In this investigation, a pre-mixed used cooking oil and animal fat (pig fat) mixture (from 20% to 80%) was transesterified to produce flex-mix methyl ester (FMME). The FMME fuel characteristics were tested and compared to biodiesel standards. Generally, biodiesel emits higher oxides of nitrogen ( $\text{NO}_x$ ) gas due to the presence of highly unsaturated compounds and oxygen. The present study aims to address this issue by adopting the flex-mix approach in combination with fuel injection strategies (400, 500 and 600 bar), exhaust gas recirculation (EGR 10%, 20% and 30%) and variable compression ratio (CR 17.5:1, 20:1 and 22:1). At a CR of 22 and an injection pressure ( $P_{inj}$ ) of 600 bar, the FMME fuel without EGR shows a minimum reduction in brake thermal efficiency of 0.15% when compared to diesel. Nitric oxide gas emissions decreased by nearly 50% for all  $P_{inj}$  and EGR values, but they rose when the compression ratio was increased to 20 and 22. Smoke and hydrocarbon emissions also increased with the exhaust gas proportion. The engine performance with FMME fuel was found to be equivalent to that with fossil diesel fuel. According to the findings, the flex-mix approach could be a long-term alternative to producing renewable fuel for off-road diesel engine application.

## Nomenclature

°C	Degree celsius
%	Percentage
ASTM	American Society for Testing and Materials
FMME	Flex-mix methyl ester
BSFC	Brake-specific fuel consumption
BTE	Brake thermal efficiency
bTDC	Before top-dead-center
BIS	Bureau of Indian Standards
CR	Compression ratio
CV	Calorific values
CO	Carbon monoxide
CO <sub>2</sub>	Carbon dioxide
CRDI	Common rail direct injection
CN	Cetane number
CD	Combustion duration
EGR	Exhaust gas recirculation
EoC	End of combustion
FAs	Fatty acids
FAME	Fatty acid methyl ester
GHG	Greenhouse gas
GC-MS	Gas chromatography and mass spectrometer
HC	Hydrocarbon
$HRR_{max}$	Maximum heat release rate
IV	Iodine value
ID	Ignition delay
KOH	Potassium hydroxide
MUSFA	Mono-unsaturated fatty acids
NO	Nitric oxide
$P_{inj}$	Injection pressure
$P_{max}$	Maximum in-cylinder pressure
PF	Pig fat
PFB	Pig fat biodiesel
PUSFA	Poly-unsaturated fatty acids
RFMO	Raw flex-mix oil
RFMO-1	WCO 80% +PF 20%
RFMO-2	WCO 60% +PF 40%
RFMO-3	WCO 50% +PF 50%
RFMO-4	WCO 40% +PF 60%
RFMO-5	WCO 20% +PF 80%
SFA	Saturated fatty acid
SoC	Start of combustion
TAG	Triacylglycerol
VCR	Variable compression ratio
VCR-CRDI	Variable compression ratio common rail direct injection
WCO	Waste cooking oil
WCOB	Waste cooking oil biodiesel

## 1. Introduction

The global energy demand is rising rapidly due to population growth and lifestyle change, impacting fossil fuel consumption [1]. There is a growing interest in a variety of biofuels, which are less expensive than fossil fuels [2]. Emissions from on-road and off-road engines are the principal source of greenhouse gas (GHG) [3]. To control GHG emissions, governments are being pushed to enact different programmes, such as the Paris Agreement 2015, the United Kingdom (UK) climate policy, and the Conference of Parties (COP26); this highlights the outlawing of diesel and gasoline-powered vehicles [3]. Biofuels have been widely investigated utilising life cycle assessment methodologies to estimate their net contribution to reducing GHG emissions associated with fossil fuels and can play a vital role in reducing the carbon footprint of the transportation industry [4]. Waste-derived fuels have gained a lot of interest since they can avoid the land-use consequences of crop-based biofuels while also helping to achieve waste treatment goals in the context of a more circular economy [5, 6]. Waste-to-energy systems, on the other hand, are complicated due to their multifunctional nature; they handle waste and can create a variety of material and energy coproducts in addition to the principal liquid fuel output [5, 7]. Biodiesel is a sustainable alternative to fossil fuels used

in diesel engine applications. Virgin plant oils, waste animal fats and used cooking oils may all be used to make them. Animal fats have a lower viscosity and a higher cetane number (CN) than plant oils [5, 7]. Therefore, the qualities of biodiesel fuel are determined by the feedstock compositions and chemical structures, such as saturated fatty acid (SFA) and unsaturated fatty acid (USFA) molecules. Fatty acids are the most important factors to alter for enhancing the fuel's physical and chemical attributes [8].

Compared to mineral diesel oil, biodiesel has a lower viscosity, higher flash point and higher CN, as well as generating lower GHG [9]. To avoid food vs fuel disputes, economies worldwide promote the use of either non-edible or waste resources to produce biodiesel. In addition to being renewable, using waste resources such as waste cooking oil (WCO) or pig fat (PF) also helps with environmental issues pertaining to improper disposal.

PF is also known as lard, and can be obtained from both the meat and the skin of the animal. The pig fat is widely available commonly consumed red meat worldwide. However, consumption of this fat is harmful for humans as it can lead to roundworm infestation, bovine spongiform, trichinosis, etc [10]. Nicolici *et al* [11] investigated a blend of PF and diesel in a compression ignition engine and observed that although the CN and calorific value of PF are closer to that of diesel, the higher viscosity and poor vaporisation characteristics are a hindrance to direct use in engines, and require pre-heating. NO<sub>x</sub> and smoke emissions decreased by 20% and 60% with a 10% blend of PF with diesel, whereas hydrocarbon (HC) emissions increased by 54%. Cican *et al* [12] studied PF-based biodiesel in aviation fuel at fractions of 10%, 30%, 50% and 100% with JetA kerosene. It was observed that the addition of PF biodiesel increases the freezing point of the blend and thus necessitates heating at higher altitudes. Although the combustion temperature increased with the increase in the proportion of biodiesel, the combustion efficiency did not show any major variations. It was also observed that the noise and vibration level with the biodiesel blend are within the limits of functionality. Although studies are available on different routes of production of PF biodiesel, only limited research is available on the effects of PF biodiesel in engine application [12].

On the other hand, WCO has been extensively studied as a fuel in diesel engines as neat fuel and as a blend with diesel fuel. WCO is generated from edible oils after frying or cooking operations. Since about 70%–80% of the cost associated with biodiesel is for the feedstock, the overall cost of production of biodiesel could be reduced through the utilisation of WCO as feedstock for biodiesel production [13]. WCO as a feedstock further mitigates the issues of water contamination and drainage system blockage caused due to improper disposal of the same [13].

Balasaheb and Padalkar [14] conducted experiments on a single-cylinder engine using neat WCO biodiesel for 0.5–4.0 kW at 1500 rpm and observed a maximum drop in efficiency by 4% compared to diesel. Smoke emissions were reduced by 47%, whereas NO<sub>x</sub> emissions increased by 10% for the same operating conditions when compared to diesel fuel. Zhu *et al* [15] studied the effects of B100 WCO biodiesel on an 88 kW, four-cylinder water-cooled direct injection engine operating at a constant speed of 1800 rpm by varying the load with 28, 84, 140, 196 and 224 Nm. They observed that there is a drop in efficiency by 2%, a 3 g kWh<sup>-1</sup> increase in CO emissions at lower load, and a 1 g kWh<sup>-1</sup> increase in NO<sub>x</sub> emissions compared to diesel fuel. Necati and Canakci [16] operated a 38.8 kW, four-cylinder, four-stroke water-cooled direct injection diesel engine at varying engine speeds of 1000–3000 rpm and constant load with neat WCO biodiesel and observed that there is an increase in brake specific fuel consumption (BSFC) of 60 g kWh<sup>-1</sup> at medium speed and a 35% increase in smoke emissions at 2000–3000 rpm. HC, CO and CO<sub>2</sub> reduced marginally, whereas there was an increase of 1% in NO<sub>x</sub> emissions compared to that of diesel [16].

One of the shortcomings of waste oils or animal fat is the availability constraint in bulk quantity. As such, the mixing of oil at a suitable proportion before transesterification (flex-mix) provides a solution to the insufficiency and poor quality of the feedstock. Mujtaba *et al* [17] produced palm-sesame biodiesel using an ultrasound-assisted transesterification reaction and optimised the process parameters using response surface methodology. They observed that the physiochemical parameters of the methyl ester were as per biodiesel standards. Hong *et al* [18] used a two-step process including esterification in the presence of sulphuric acid to convert canola-lard oil biodiesel on account of the number of double bonds and molecular weight. They stated that the higher heating value (HHV) increases with the increasing molecular weight but decreases with the increasing double bonds in the fatty acid alkyl ester (FAAE). The oxidation stability, on the other hand, decreased with the molecular weight and increased with the number of double bonds in the FAAE. Milano *et al* [19] converted waste edible oil into biodiesel by blending WCO with calophyllum inophyllum oil at a ratio of 70:30. To remove fatty acid content and impurities, they incorporated a three-step process involving degumming and esterification followed by transesterification. It was observed that the properties of the fuel resemble the ASTM D6751 and EN 14214 standards. Although there are studies available on the production of flex-mix biodiesel, only limited studies are available for performance in an engine. Most of the studies are from the author [8, 20–22] and consist of basic feasibility investigations.

Sharma *et al* [22] investigated bio-mix fuel produced through a pre-mixing approach. They mixed raw WCO and PF at different ratios, e.g. WCO80PF20 (waste cooking oil 80% and pig fat 20%); similarly, they prepared a total of five samples of raw oil mixture by varying the quantity of PF. They reported that by increasing the PF percentage in WCO, the total USFA can be reduced by 10%–15%, which enhanced the overall fuel properties of the prepared biomix biodiesel. They also investigated this biomix fuel in a stationary diesel engine to examine the performance, combustion and emissions. They observed an 8%–12% reduction in NO emissions and a 5%–10% reduction in CO<sub>2</sub> emissions when compared to single-feedstock biodiesel. To ensure the correlation between biodiesel compositions, fuel properties, engine combustion and emission studies were carried out. Sharma *et al* [21] performed a comparative study of six different biodiesels comprising coconut, castor, jatropha, palm, karanja and WCO, of which three are edible oils (coconut, palm and WCO) and three are non-edible (castor, jatropha and karanja) feedstocks. They reported that biodiesel with the optimum level of saturated and USFAs produced 10%–15% lower NO emission when compared to highly USFAs.

From the literature, it is evident that both neat PF and WCO biodiesel are compatible for operation in a diesel engine; the performance and emissions vary based on the fuel composition variability and operating conditions. Although there are few studies available on the pre-mixing concept using edible and non-edible oils, these are restrained to the production of biodiesel. The utilisation of this biodiesel on an engine and the effect it has on the engine performance and emissions have not been extensively investigated (other than in previous works of the author [8, 20–22]). The utilisation of waste resources to investigate the engine performance not only provides economic benefits (lower production cost) but also environmental benefits (solves disposal issues, lower engine-out emissions). However, higher free fatty acid (FFA) of the feedstock could lead to reduced yield due to soap formation. A higher acid value also results in the corrosion of engine components. To balance or reduce the presence of unsaturation in the biodiesel, in this study, pre-mixing of two different feedstocks (of differing saturation and unsaturation) from waste resources is proposed to produce flex-mix methyl ester (FMME) biodiesel. This technique can help in achieving some of the sustainable development goals set by the United Nations, such as (a) affordable and clean energy, (b) climate action, and (c) responsible consumption and production. WCO and PF oil are used to prepare FMME and tested in a modified variable compression ratio common rail direct injection (VCR-CRDI) diesel engine. The compression ratio, exhaust gas recirculation (EGR) flow rate and fuel injection pressure ( $P_{inj}$ ) were varied to achieve the optimum engine, combustion, emissions and performance characteristics.

The goal of this project is to create a high-quality new flex-mix biodiesel fuel from waste materials, which might help to minimise GHG emissions that would otherwise be emitted from landfills. The objectives of this study are (a) selection of waste resources for high-quality flex-mix fuel production, (b) production of biodiesel from flex-mix feedstock, (c) characterisation of flex-mix fuels to comply with biodiesel standards, and (d) experimental parametric investigation using variable compression ratios, EGR flow rates and  $P_{inj}$ .

## 2. Materials and methods

### 2.1. Materials

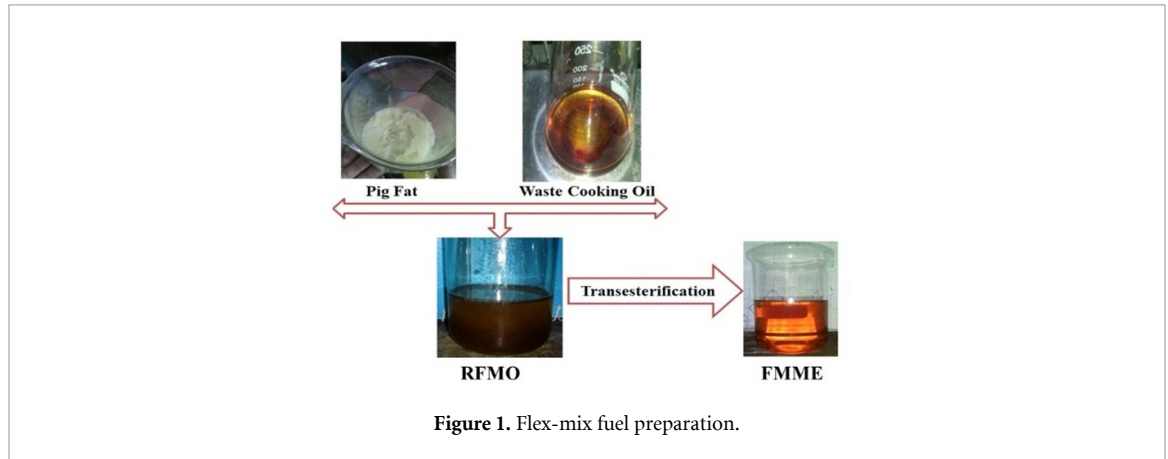
For this experimental study, two alternative oil feedstocks were chosen based on their availability in the Indian market. The used cooking oil and PF were bought from a neighbourhood market in India. Sigma-Aldrich (India) was used to acquire the ingredients needed to produce biodiesel, such as sulphuric acid (H<sub>2</sub>SO<sub>4</sub>), potassium hydroxide (KOH) and methanol (CH<sub>3</sub>OH, 98% purity).

### 2.2. FMME production

The WCO and waste animal fat (PF) were collected from the local market and subjected to pre-processing. The large pig skin was broken into smaller pieces and placed in an oven at 100 °C for 1 h. Later, the PF oil was separated and stored in a jar. After this rendering process, PF is no longer solid at room temperature. The WCO was filtered through a sock filter to remove sediment before mixing. Both feedstocks were blended at different proportions to prepare raw flex-mix oil (RFMO) samples as shown in table 1 and figure 1. The blending proportion was selected based on the chemical composition, such as the FFA content and other physical properties (viscosity). The blending was done in such a way that high SFA content oil was mixed with high USFA content oil to obtain an optimum mixture of fatty acid content, which helped to produce high-quality biodiesel meeting international standards (ASTM Standard). The RFMO was converted into FMME through the transesterification process as shown in figure 1. KOH was used as the base catalyst with a methanol-to-oil molar ratio of 4:1 [8]. The KOH–methanol mixture was added to the preheated flex-mix oil at 60 °C and stirred for 1 hour using a mechanical stirrer. After completing the process, the liquid was shifted to a separating funnel for 10 h to separate the glycerol and fuel. Hot distilled water (80 °C) was used to remove the soap that formed during the chemical reaction, a process known as biodiesel washing [8]. After

**Table 1.** Raw oils, RFMO composition and biodiesels.

Feedstock samples	Composition ratio	Biodiesel notations
WCO	100% waste cooking oil	WCOB
PF	100% pig fat	PFB
RFMO-1	WCO 80% + PF 20%	FMME-1
RFMO-2	WCO 60% + PF 40%	FMME-2
RFMO-3	WCO 50% + PF 50%	FMME-3
RFMO-4	WCO 40% + PF 60%	FMME-4
RFMO-5	WCO 20% + PF 80%	FMME-5



the water wash, the FMME fuel sample was left overnight for the water molecules to settle down. To remove the moisture content from the final flex-mix, the sample was heated and maintained at 100 °C for an hour.

### 2.3. Experimental methodology

The current research work is an extended study of the previously published article *Production, combustion and emission impact of bio-mix methyl ester fuel on a stationary light duty diesel engine* [22]. In this article, the author tested five different biomix methyl ester (BMME) samples produced from different percentages of mixture as given in table 1. These five different mixtures were tested on an unmodified water-cooled, single-cylinder, four-stroke diesel engine. The test results show that the BMME-2 sample gave the best results overall. Later, this BMME-2 sample was tested in the same modified engine under different operating conditions. To conduct the parametric experimental investigation, the test engine was run at 1500 rpm with 50% engine load at various values of CR (17.5:1, 20:1 and 22:1),  $P_{inj}$  (400, 500 and 600 bar), and EGR (10%, 20% and 30%). The EGR percentage was calculated using equation (1) [20]. The CR of 17.5:1 is almost equivalent to 18:1, hence an interval of 1 was maintained during the test. Since stationary diesel engines are mostly operated at part load, 50% of the engine full load was chosen for the experimentation. The engine performance, combustion and emission parameters were studied by sweeping the design and operating parameters. Combustion analysis was carried out by measuring the engine combustion pressure and crank angle (CA) position by captured pressure and CA encoder signals. From the captured combustion pressure signals and CA data, parameters such as the in-cylinder pressure, heat release rate (HRR), start of combustion (SoC), end of combustion (EoC), ignition delay (ID) and combustion duration (CD) were derived to determine the advantages of FMME over other fuels.

$$EGR \% = \frac{(CO_{2\_EGR(inlet)} - CO_{2\_atm})}{(CO_{2\_EGR(exhaust)} - CO_{2\_atm})} \times 100. \quad (1)$$

### 2.4. Engine modifications and instruments

The test engine is a stationary variable compression ratio direct injection diesel engine that was modified to CRDI operation mode for this study (figure 2). The specifications of the test engine are given in table 2. The mechanical fuel injection system was replaced with an electronic fuel injection system by integrating the mechanical fuel pump with a fuel rail, pressure control valve, rail pressure sensor and solenoid high-pressure diesel injector. An electronic engine control unit (ECU) was used to control the injector actuation with the help of a crank and cam position sensor. An open ECU facilitates variations in injection timing, the number of injections, injection mass and  $P_{inj}$  variations to meet the objective of the proposed parametric

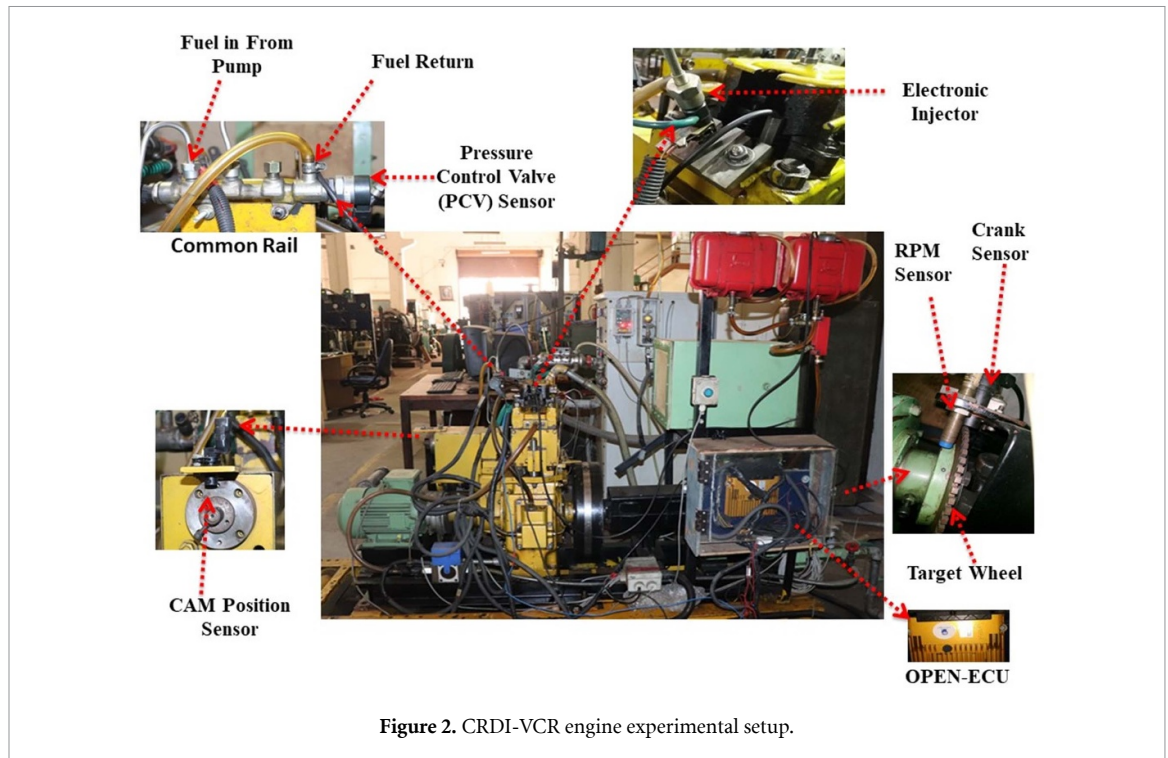


Figure 2. CRDI-VCR engine experimental setup.

Table 2. Technical specification of engine.

Model	VCR engine
Manufacturer	Accurate engineers, India
Rated power	3.6 kW at 1500 rpm
Type of cooling	Water-cooled
Number of cylinders	1
Bore (mm)	87.5
Stroke length (mm)	110
Compression ratio (variable)	17.5: 1 (12:1–22:1)
Displacement volume (cc)	661.4
SOI ( $^{\circ}$ CA bTDC) (fixed for all operating conditions)	18

experimental study. In addition, the test engine cylinder head and crankshaft were modified to mount the combustion pressure and crank angle encoder respectively to obtain the combustion pressure signal along with the crank angle of the engine for combustion parameter derivation and analysis. To capture the engine combustion data, the National Instruments data acquisition system (NI-DAQ) was used. A proprietary LABview-based software called *Engine Combustion Pressure* was used to monitor various engine parameters along with the combustion data, such as the engine coolant flow rate, temperature, air flow rate and temperature, engine rpm, engine exhaust gas temperature and engine dynamometer data. A Delphi seven-hole nozzle high-pressure solenoid injector was mounted vertically in the cylinder head through suitable modification to avoid fuel spray hitting the wall. The operating parameters for this study were selected as the compression ratio (CR17.5, 20 and 22:1) and fuel  $P_{inj}$  (400, 500 and 600 bar), with a fixed injection angle ( $18^{\circ}$  bTDC) throughout the experiment. The engine exhaust gas was cooled using an automotive EGR cooler, and its concentration varied from 10% to 20% to control the NO emissions. The modified engine was controlled by a NIRA open ECU. An eddy current dynamometer was connected to load and unload the engine. A manifold air pressure sensor was used to measure the inlet air charge flow. Multiple K-type thermocouples were employed to measure various flow temperatures, such as the inlet air, water inlet, exhaust gas and water outlet. For easy cranking, a crank motor was attached to the engine flywheel. A HORIBA (MEXA 584I) gas analyser and AVL 437 c smoke meter were used to measure the engine-out emissions, specifications of which are given in table 3.

**Table 3.** List of measurement instrumentation.

Name of instrument	Measured parameters	Range	Uncertainty
Horiba gas analyser MEXA 584 I	CO (vol.%)	0%–10%	±0.01%
	CO <sub>2</sub> (vol.%)	0%–20%	±0.17
	HC (ppm)	0–20 000	±3.3 ppm
	NO (ppm)	0–5000	±0.5 ppm
	O <sub>2</sub> (vol.%)	0%–25%	±0.5%
Smoke meter (AVL 437)	Smoke (opacity)	0–100	±1%
Pressure sensor Kistler-6613CQ09	Cylinder pressure (bar)	0–100	±1%
Autonics encoder rotary type	Crank angle	360° revolution	5VDC-12VDC±0.5%
K-type thermocouple	Temperature (°C)	0–400	2.2 °C, or ±2%

**Table 4.** Fatty acid analysis of flex-mix and biodiesel sample [15].

FAME	WCOB	FMME-1	FMME-2	FMME-3	FMME-4	FMME-5	PFB
C10:0	0	0	0	0	0	0	0.04
C12:0	0.26	0	0	0	0	0	0.35
C14:0	0.25	0.6	0.8	1.5	2	3	4
C16:0	10	12.5	13.7	16.3	18	22.2	24
C16:1	0.71	0.02	0.2	2	2.5	2	1.22
C18:0	4.5	7.9	12.9	14.5	25	26.5	28.31
C18:1	40.21	40	35.21	30.32	26.02	28.012	30.25
C18:2	22.36	22.3	20	15.5	19.2	22.2	10
C18:3	3.76	3.2	2.5	1.9	0.85	0.4	0.36
C20:0	0.22	0.35	0.25	0.3	0.39	0.4	0.4
C20:1	0.46	0.49	0.49	1.2	0.78	0.12	0.18
C22:0	0.21	0.29	0.23	0.4	0.62	0.22	0.35
C22:1	0.2	0.21	0.12	0.15	0.35	0.05	0.05
C24:0	0	0	0.25	0.28	0.12	0.02	0
C26:0	0	0	0.02	0.029	0.015	0.01	0
SFA	15.44	21.64	28.15	33.309	46.145	52.35	57.45
USFA	67.7	66.22	58.52	51.07	49.7	52.782	42.06
MUSFA	41.58	40.72	36.02	33.67	29.65	30.182	31.7
PUSFA	26.12	25.5	22.5	17.4	20.05	22.6	10.36
DU	93.82	91.72	81.02	68.47	69.75	75.382	52.42

### 3. Results and discussions

#### 3.1. Fuel characterisation

By processing 7 kg of discarded pig skin, about 3.5 kg of PF was recovered. Gas chromatography and mass spectrometry (GC-MS) were used to analyse the fatty acid composition of fuels. The SFA, MUSFA and PUSFA percentages of the WCOB, PFB, FMME-1, FMME-2 and FMME-3 were calculated and are presented in table 4 and figure 3. The fatty acid methyl esters (FAME) clearly show that WCOB has less SFA than PFB. Meanwhile, the FMME samples' SFA content is increased with the increase in high SFA PF oil (figure 3); it is a maximum of 52.35% for the FMME-3 sample, which is 3.4 times higher than the neat WCOB. The flex-mix approach clearly shows that the SFA content is increased and the USFA content is decreased, thereby resulting in good-quality biodiesel (FMME).

Table 5 shows the properties of biodiesel fuels against the biodiesel fuel standards. The fuel properties were measured in the Biofuel Laboratory of Anna University, Chennai, India. It is known that the higher viscosity of the fuels affects the fuel spray and combustion characteristics [19]. It is observed that the viscosity of WCOB does not meet the EN 14241 and BIS IS15607-05 standards, whereas for PFB, FMME-1, FMME-2 and FMME-3 the viscosity is observed to be within the standards (table 5). It is observed that the viscosity increases by increasing the PF blend percentage. It is because of the decrease in the PUSFA percentage [22]. Similarly, the density also affects the engine performance [23]. The density of the FMME sample is observed between PFB and WCOB, which is shown clearly in table 5.

The CN was calculated from the FAME composition using equation (2) [22, 23]. The CN describes the ignition quality of the fuel and it increases with an increase in the SFA percentage [22, 23]. It was observed that the CN of FMME fuel increased with an increase in the PF blend in WCO.

$$CN_{\text{Biodiesel}} = \sum (CN_{\text{FAME}}) (\text{Mass percentage of FAME}). \quad (2)$$

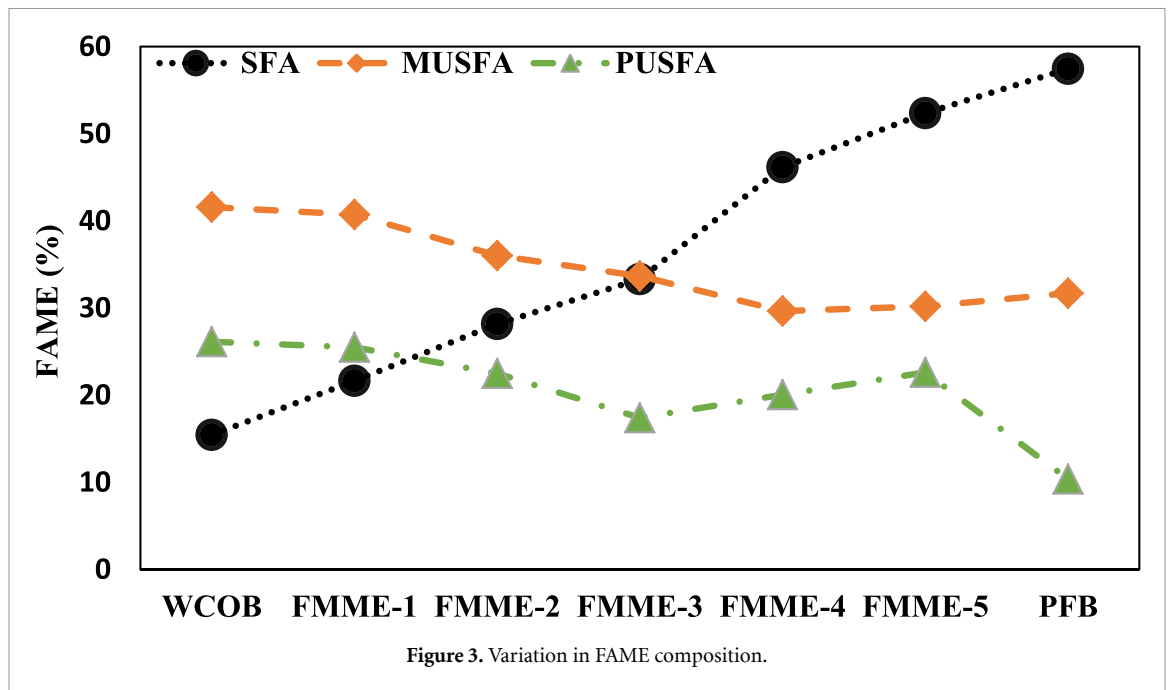


Table 5. Properties of raw oils and biodiesel fuels.

Fuel properties	Viscosity 40 °C (mm <sup>2</sup> s <sup>-1</sup> )	Density (kg m <sup>-3</sup> )	CN	CV (MJ kg <sup>-1</sup> )	FP (°C)	IV (gI <sup>2</sup> /100 g)	AV (mgKOH/g)
Raw flex-mix oil and neat oils							
WCO	37.22	904	42	37.75	222	192	5.4
Pig fat	30.2	911	54	34.62	190	134	3.4
RFMO-1	37.22	905	41	37.73	221	186	5.3
RFMO-2	36.21	906	45	37.48	207	165	4.5
RFMO-3	35.35	908	50	36.57	188	147	4.1
RFMO-4	34.21	909	50	35.98	197	140	3.7
RFMO-5	31.31	910	54	34.89	192	136	3.3
Flex-mix fuel and neat biodiesel							
Diesel	2.2	830	56	42.50	50	—	—
WCOB	5	888	51	39.6	164	174	0.44
PFB	3.5	878	62	40.5	168	61	0.31
FMME-1	4.75	886	55	39.6	165	155	0.43
FMME-2	4.6	878	57	39.4	168	139	0.4
FMME-3	4.4	877	60	39.1	168	121	0.35
FMME-4	4.45	872	60	39.1	172	102	0.37
FMME-5	4.22	870	61	39	170	80	0.35
Biodiesel standards [8]							
ASTM D6751-08	1.9–6.0	820–860	47 mini	—	93 mini	—	0.5 max
EN 14214	3.5–5.0	860–900	51 mini	—	120 mini	120	0.5 max
BIS IS15607-05	2.5–6.0	860–900	51 mini	—	120 mini	—	0.5 max

All the calculated and measured fuel properties of FMME samples are aligned between WCOB and PFB (table 5) and show a strong correlation with the SFA level. Overall, the fuel characterisation study reveals that the FMME fuel properties are better and that the derived fuel samples have good quality.

### 3.2. Engine experiment

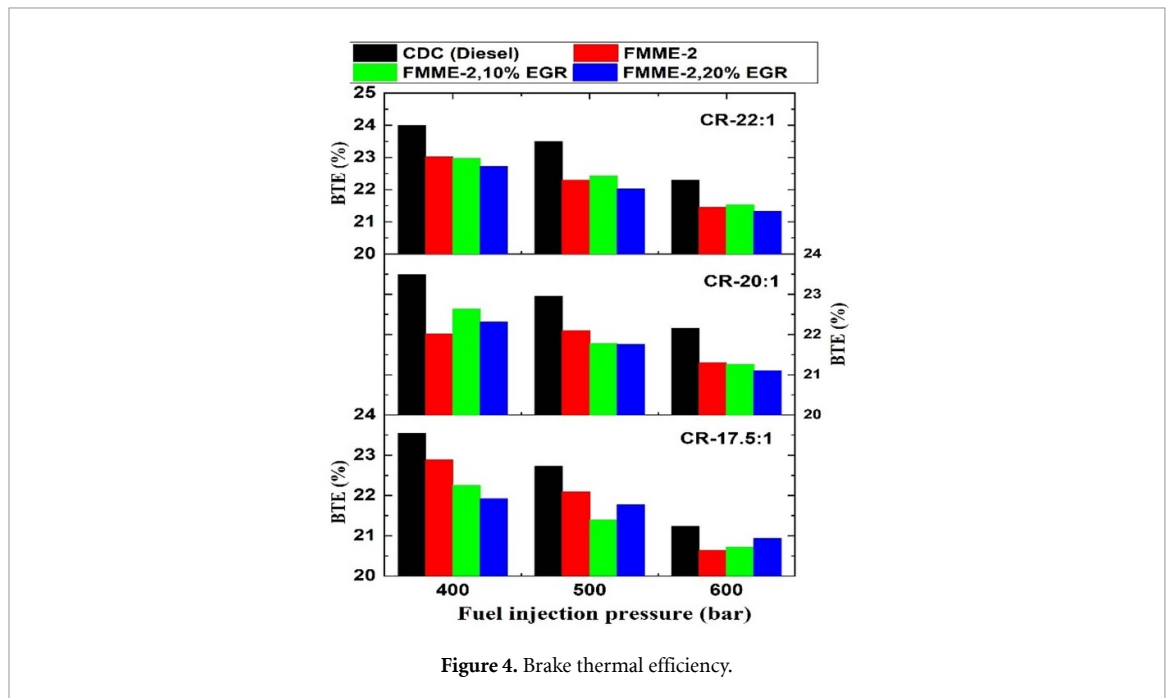
#### 3.2.1. Performance characteristics

Engine performance is analysed in terms of brake thermal efficiency (BTE) and BSFC (table 6). It was observed that at each CR, the BTE decreased by increasing the  $P_{inj}$  [23, 24]. This could be attributed to the increased fuel impingement at higher  $P_{inj}$  as it is a small-capacity engine. Figure 4 shows the variation in BTE with the increase in the CR. The higher in-cylinder temperature at high CR resulted in this characteristic. The higher  $P_{inj}$  improved the fuel spray atomisation characteristics, such as the smaller fuel droplet size and fast fuel/air mixing rate, and higher CRs increased the in-cylinder temperatures [22, 25]. The combined



**Table 6.** FMME-2 fuel performance: BTE comparison with diesel fuel.

CR	Operating conditions	BTE (%)		
	$P_{inj}$ (bar)	400	500	600
17.5	No EGR	0.7↓	0.6↓	1.3↓
	10% EGR	1.4↓	1.3↓	1.2↓
	20% EGR	1.7↓	0.9↓	1↓
20	No EGR	1.5↓	0.8↓	0.85↓
	10% EGR	0.8↓	1.2↓	0.89↓
	20% EGR	1.2↓	1.2↓	1↓
22	No EGR	0.9↓	1.2↓	0.85↓
	10% EGR	1↓	1↓	0.77↓
	20% EGR	1.20↓	1.4↓	0.97↓

**Figure 4.** Brake thermal efficiency.

effects led to an improved rate of vaporisation of the fuel, which ultimately resulted in a higher BTE of the engine at a CR of 22. FMME fuel shows a lower BTE as compared to fossil diesel fuel due to its lower HHV. Therefore, more fuel is required to produce the same torque/power [25]. The high viscosity of flex-mix fuel also influences the BTE, as the viscosity affects the fuel spray characteristics [22, 25]. A comparison of BTE for FMME-2 fuel with respect to diesel under the selected operating conditions is shown in table 6.

The BTE of FMME fuel is reduced with the increase in the EGR percentage, which acts as a charge diluent, and therefore reduced the oxygen concentration in the intake air charge [26]. Due to the presence of gases with higher specific heat ( $\text{CO}_2$  and  $\text{H}_2\text{O}$ ), the exhaust gas heat capacity is higher than the intake charge [27]. Higher heat capacity results in a lower cylinder temperature, which results in poor vaporisation [22, 27]. Therefore, the BTE of FMME fuel decreased with the increase in the EGR percentage. The FMME-2 fuel without EGR resulted in a minimum reduction in BTE (0.4% at CR 17.5 with  $P_{inj}$  500 bar, 0.2% at CR 20 with  $P_{inj}$  500 bar, and 0.15% with  $P_{inj}$  600 bar). Furthermore, the BSFC of FMME-2 fuel increased with an increase in the  $P_{inj}$  and EGR flow rate because of the wall impingement and lower cylinder temperature as shown in figure 5. Due to its lower energy content and greater viscosity, the BSFC of the FMME-2 sample is shown to be higher for all CRs and  $P_{inj}$  when compared to diesel [28]. Figure 5 shows that BSFC was reduced with the increase in the EGR percentage at  $P_{inj}$  600 bar for both the test fuels.

### 3.2.2. Combustion characteristics

#### 3.2.2.1. Start and end of combustion

The start of combustion (SoC) is normally calculated as the crank angle at which 10% of the cumulative heat release is observed [28]. From figure 6, it is noted that the SoC for FMME-2 fuel is more advanced than for diesel fuel at each CR (17.5, 20 and 22) and  $P_{inj}$  (400, 500 and 600 bar) due to the higher CN (see table 5). At higher  $P_{inj}$ , fuel droplet sizes were reduced, which improved the fuel/air mixing rate and vaporisation, thus

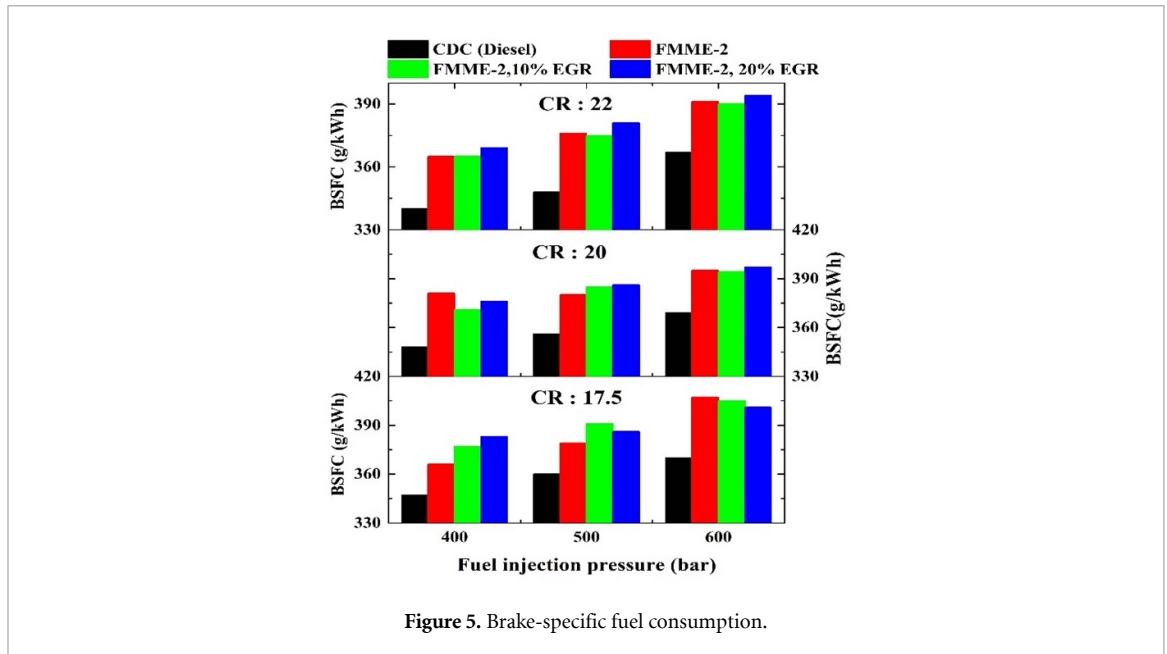


Figure 5. Brake-specific fuel consumption.

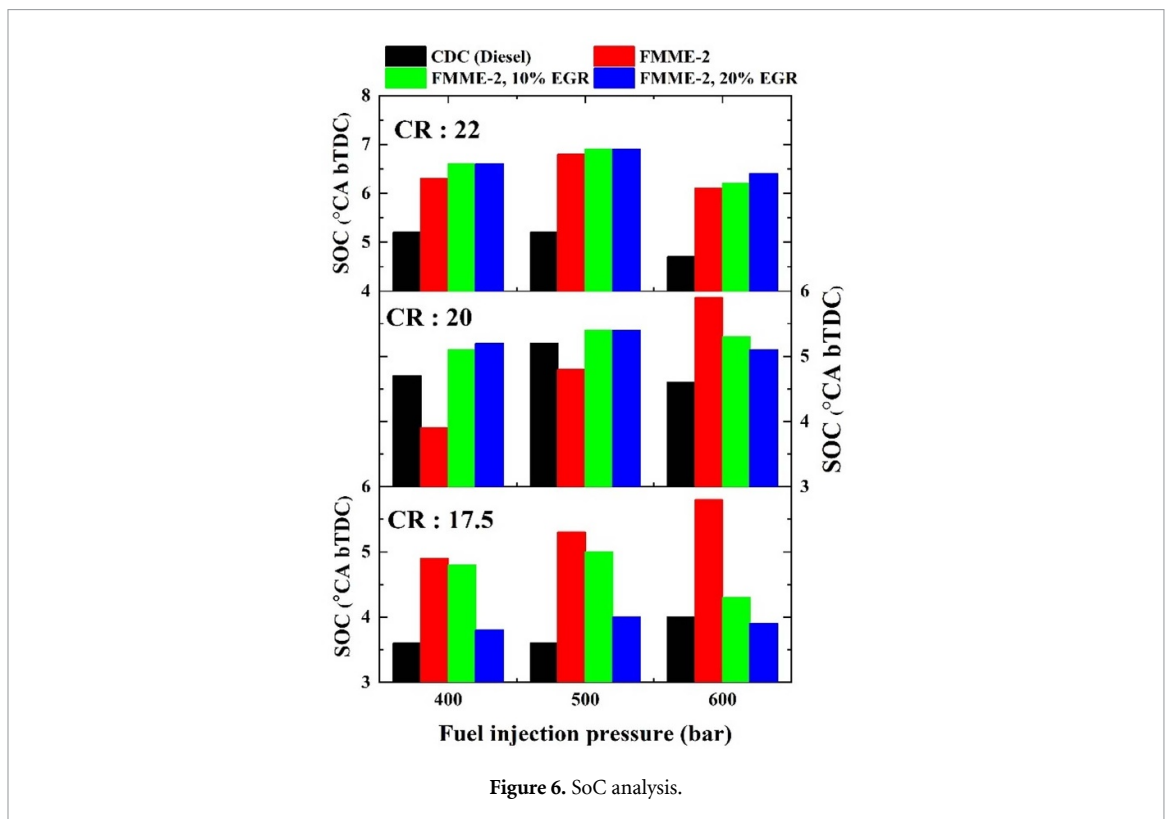


Figure 6. SoC analysis.

minimising the effect of higher viscosity and thereby advancing the SoC [22, 29]. From figure 6, it is observed that for EGR flow rates of 10% and 20%, the SoC is retarded at CRs 17.5 and 20, as well as at each  $P_{inj}$ . It is due to the EGR percentage diluting the intake charge, which reduces the combustion temperature and therefore delays the SoC [22, 29]. As the CR rises, the temperature within the cylinder rises, reducing the EGR impact on SoC [30]. Hence, the SoC is advanced with the EGR at a CR of 22.

A crank angle of 90% of cumulative heat output is used to measure the EoC [30]. From figure 7, at CR 17.5, FMME-2 fuel shows a shorter EoC as compared to diesel fuel without EGR%. Flex-mix fuel is an oxygenated fuel containing 9%–11% oxygen, which helps in completing the combustion process earlier than diesel [3]. At the same CR of 17.5, it is also observed that the EoC is extended with EGR rates of 10% and 20% compared to the case with no EGR. This is because the EGR dilution effect slows down the combustion rate by decreasing the cylinder temperature and increasing the ID period, which results in an extended EoC

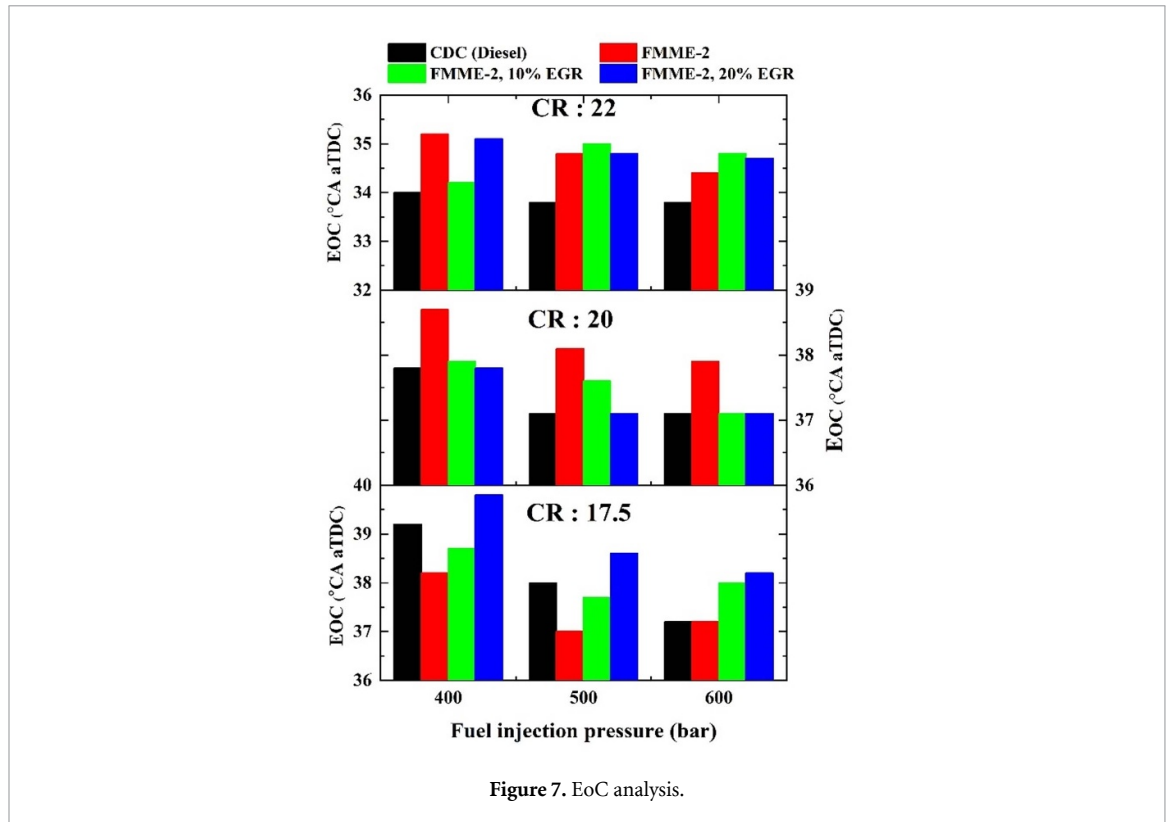


Figure 7. EoC analysis.

[31]. It is observed that the EoC increases with increasing the CR (20 and 22) at each  $P_{inj}$  as shown in figure 7. With an increase in the CR, the combustion volume is reduced, and the fuel impingement increases at a higher  $P_{inj}$  value, which results in an increased CD [31]. Therefore, it is observed from figure 7 that the duration of the EoC is affected by the increase in the CR.

### 3.2.2.2. ID and CD

The crank angle interval between the SoC and fuel injection initiation is described as the ID [31]. FMME-2 shows a shorter ID than diesel fuels at each CR and  $P_{inj}$  (figure 8). This is due to the higher CN and higher  $P_{inj}$ , which advanced the SoC and reduced the ID period [32]. Meanwhile, a higher  $P_{inj}$  improves the fuel spray characteristics and results in a shorter ID [32]. At CR 17.5 and without EGR, FMME-2 shows the shorter ID as compared to diesel fuel (figure 8). Nonetheless, it increased with the increase in the EGR flow rate; a modest rise is seen with a 10% EGR flow rate since the volume of exhaust gas flow is lower, but a higher EGR flow rate up to 20% resulted in a longer ID time at each  $P_{inj}$ . The diluting impact of the exhaust gases lowered the in-cylinder temperature, resulting in poor vaporisation and delayed SoC, leading to an increase in the ID duration with EGR [32]. The EGR dilution effect on the ID is reduced with an increase in the CR (CR 20 and 22). It is mostly due to the rise in the in-cylinder temperature as a result of the reduced combustion volume [32].

The difference between the SoC and EoC crank angle duration is used to calculate the CD [33]. FMME-2 fuel shows a longer CD than diesel fuel at all CR and  $P_{inj}$  values, as shown in figure 9. The advanced SoC and shorter ID durations are to blame for the rise in CD. A shorter ID enables less fuel to be burned in the pre-mixed combustion phase and increases the length of diffusion combustion [32, 33]. Longer carbon chain molecules present in biodiesel fuel also contribute to the increases in the CD period due to their higher boiling point. The CD also rose with the increase in the EGR percentage (figure 9), which is attributed to a drop in cylinder temperature owing to the diluting impact of the exhaust gases [32, 33]. It is also observed that with the increase in  $P_{inj}$ , the CD is reduced slightly (figure 9). A higher  $P_{inj}$  lowered the size of the fuel droplet, which enhanced the atomisation and vaporisation rate, resulting in a reduction in CD [34].

### 3.2.2.3. In-cylinder pressure and HRR

Figure 10(a) shows the maximum in-cylinder pressure ( $P_{max}$ ) at different CRs and  $P_{inj}$ . FMME-2 fuel shows a lower  $P_{max}$  than the fossil diesel fuel at all CRs and  $P_{inj}$ . The duration of the pre-mixed combustion phase was reduced with the advanced SoC and shorter ID by allowing less fuel to be burnt in this period and extending the diffusion combustion phase, which resulted in lowering the  $P_{max}$  [35]. In general,  $P_{max}$  was increased

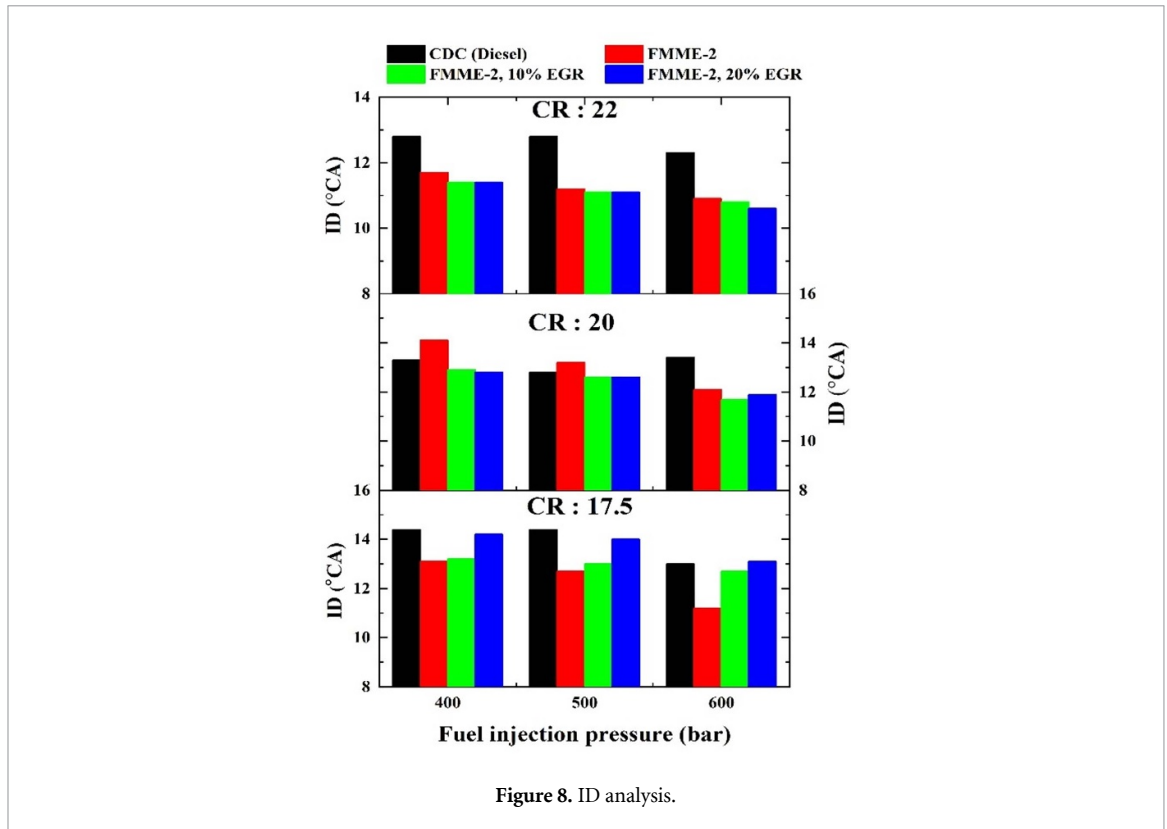


Figure 8. ID analysis.

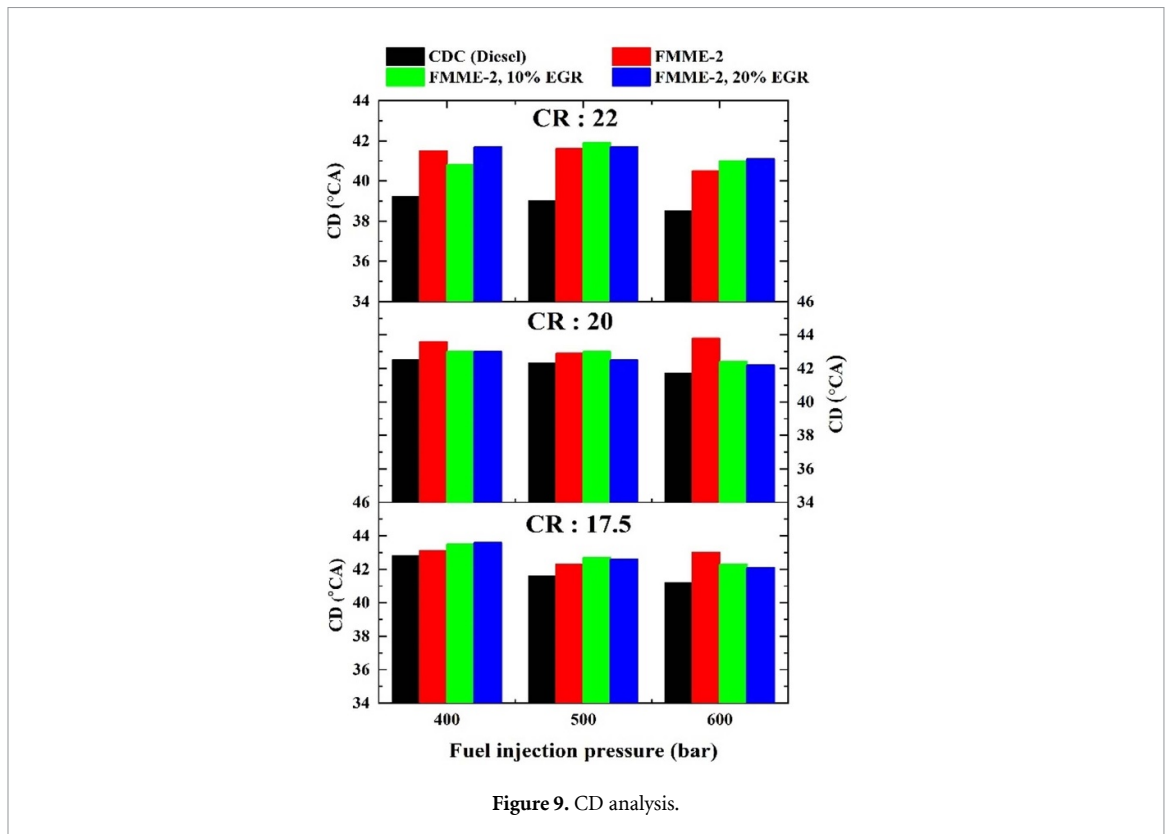
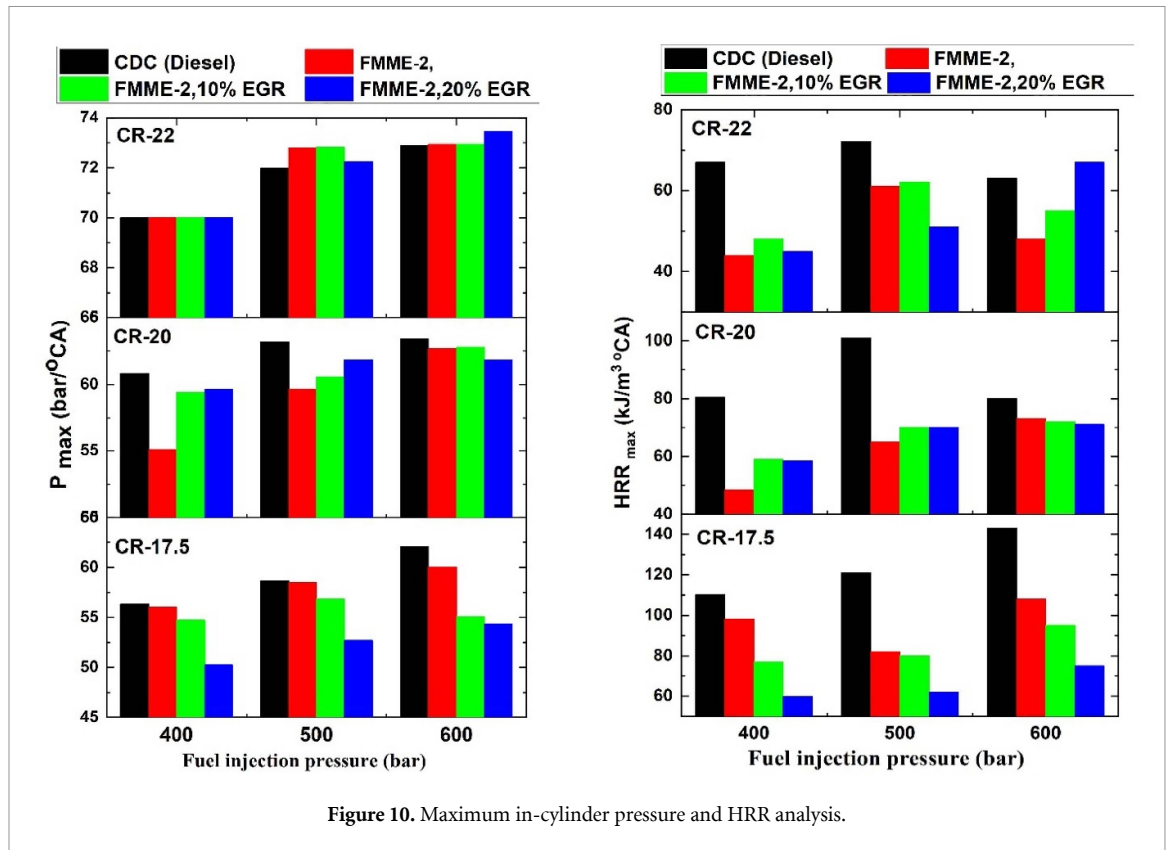


Figure 9. CD analysis.

with the increase in  $P_{inj}$  and CR. A higher  $P_{inj}$  improved the atomisation and vaporisation rate by reducing the fuel droplet size, resulting in a better combustion efficiency. A higher CR resulted in a higher in-cylinder temperature, which ultimately gave a higher  $P_{max}$  [36].

The  $P_{max}$  was observed to be lower when EGR was applied (figure 11). The EGR diluted the intake air and resulted in lower in-cylinder temperatures and  $P_{max}$  [37] (figure 11). The in-cylinder pressure of FMME-2 fuel was observed to be lower with all EGR flows and at all  $P_{inj}$  values. The findings were consistent with the



literature, showing that the combined effects of EGR and lower ID periods caused reduced in-cylinder pressure [38].

At a CR of 20 and without EGR, the FMME-2 fuel shows lower in-cylinder pressure as compared to diesel fuel at 400 bar and 500 bar  $P_{inj}$  (figures 11(d) and (e)). The in-cylinder pressure for FMME-2 fuel was higher when the fuel  $P_{inj}$  was increased to 600 bar (figure 11(d)). Better fuel atomisation and vaporisation at higher  $P_{inj}$  caused this. It was revealed that when the EGR flow rate rose, the in-cylinder pressure for FMME-2 fuel increased. As the EGR flow rate rises, the ID period lengthens, extending the pre-mixed combustion phase and raising the in-cylinder pressure at each  $P_{inj}$ , as shown in figures 11(d)–(f). Furthermore, at a higher compression ratio, no significant differences were observed in the in-cylinder pressure when the EGR rate was increased (figures 11(g)–(i)). Higher in-cylinder temperatures at higher CRs caused this behaviour.

Figure 10(b) shows the maximum heat release rate ( $HRR_{max}$ ) at different CRs and different  $P_{inj}$ . The  $HRR_{max}$  increased with an increase in the fuel  $P_{inj}$ , as higher pressure creates fine droplets and better fuel/air mixing [36, 38]. FMME-2 fuel shows a lower  $HRR_{max}$  as compared to diesel fuel at all CRs and  $P_{inj}$  due to the lower HHV and shorter ID period (i.e. shorter pre-mix combustion phase). Interestingly, it was revealed that  $HRR_{max}$  decreased with an increase in the CR. Higher fuel  $P_{inj}$  at higher CR might cause incomplete combustion and low fuel economy due to higher fuel impingement and an increased late combustion phase [39]. At CR 17.5 and without EGR,  $HRR_{max}$  decreased with the increase in the EGR flow rate for both the test fuels (figure 10(b)). The exhaust gas dilution effect reduced the cylinder temperature and slowed down the rate of fuel burnt, thus resulting in a reduced  $HRR_{max}$  [39, 40]. The effect of EGR dilution on  $HRR_{max}$  was minimal due to the rise in in-cylinder temperature at higher CRs [40, 41].

Figure 12 shows the variation in HRR at different CRs and  $P_{inj}$ . Because of the lower combustion temperature, the HRR was shown to decrease as the EGR flow rate increased at CR 17.5 [40, 41]. The literature mentions that higher specific heat of the exhaust gases ( $CO_2$  and  $H_2O$ ) reduces the combustion efficiency, resulting in a reduced HRR [42]. The HRR was raised with an increase in the  $P_{inj}$  as shown in figures 12(a)–(c). At high  $P_{inj}$ , improved fuel atomisation and better air/fuel mixing allowed more fuel to burn during the pre-mix combustion process, resulting in a higher HRR [42].

The HRR for FMME-2 fuel was found to be lower than fossil diesel at CR 20:1 with no EGR. A higher CN and lower HHV caused this characteristic [42]. The shorter ID time shortened the pre-mixed combustion phase and lengthened the diffusion and late combustion phases, resulting in a decreased HRR [43]. On the other hand, at CR 20, the HRR for FMME-2 fuel with EGR flow rate was found to be greater than HRR for no-EGR fuel (figures 12(d)–(f)). This was due to EGR's dilution effect, which decreased the in-cylinder

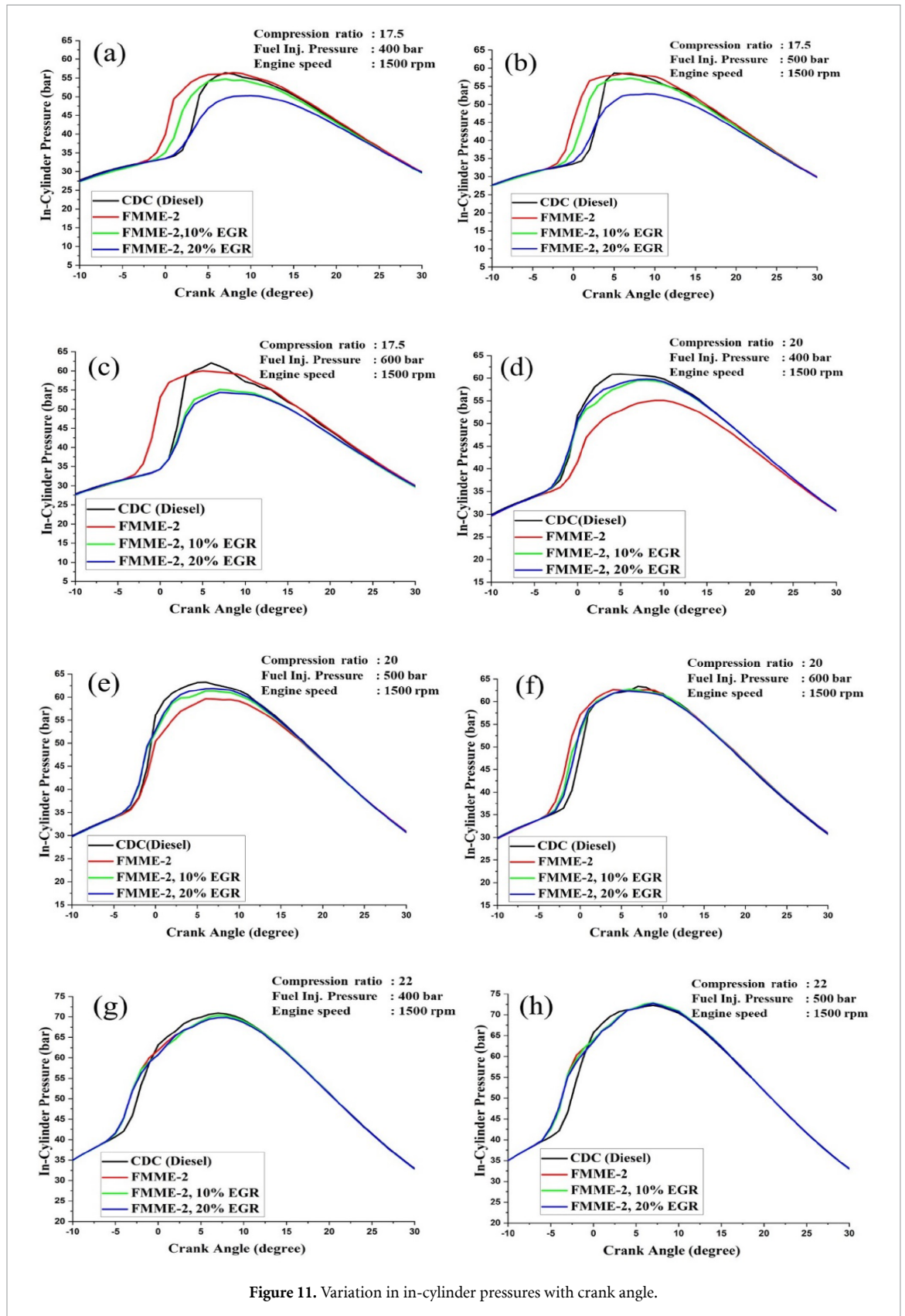


Figure 11. Variation in in-cylinder pressures with crank angle.

temperature and lengthened the ID time [39, 43]. Because of the longer ID duration, more fuel may be burned in the pre-mixed combustion phase, resulting in a higher HRR, although it is still lower than that of diesel due to the lower HHV. A similar trend was observed when the CR was increased from 20 to 22. With an increase in the EGR rate, the HRR for FMME-2 fuel rose (figures 12(g)–(i)). The effect of EGR was minor at a higher CR of 22 because of the increased in-cylinder temperature [39, 43].

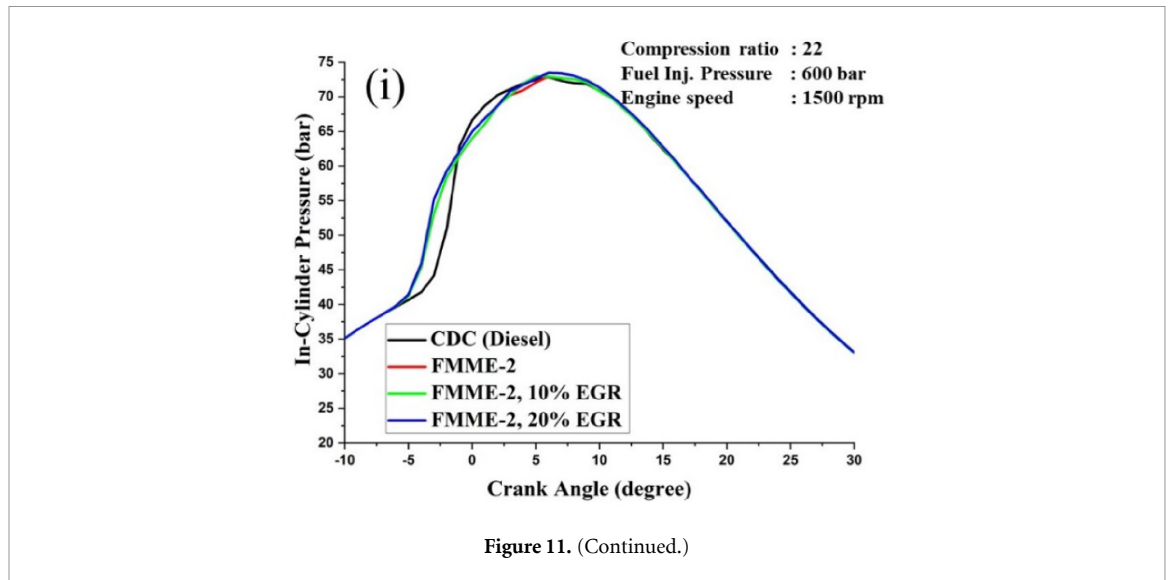


Figure 11. (Continued.)

### 3.2.3. Exhaust emission characteristics

At all CRs and  $P_{inj}$ , NO emissions from FMME-2 fuel were found to be lower than diesel (figure 13). The formation of NO generally takes place in a pre-mixed combustion phase [39, 43]. A shorter ID period reduces the duration of pre-mixed combustion, resulting in the reduced formation of NO [44]. It was discovered that when the  $P_{inj}$  increased, so did the NO emissions. The greater the  $P_{inj}$ , the better the fuel atomisation and vaporisation rate, which improved the combustion efficiency and raised the temperature in the cylinder [45]. Table 7 shows the comparison of NO gas emission reduction for FMME-2 fuel with diesel. A significant reduction in NO was observed with the EGR. The EGR decreased the oxygen concentration in the reaction zone, which reduced the adiabatic flame temperature, resulting in reduced formation of NO gas emissions [45].

A decrease in NO emissions is usually followed by a rise in smoke emissions. The incomplete combustion is the cause of the increased smoke emissions [45]. The smoke opacity for flex-mix fuel and diesel fuel are shown in figure 14. At CR17.5 and with no EGR, FMME-2 fuel shows lower smoke opacity compared to diesel fuel. An increase in the EGR flow rate led to a higher smoke opacity. The dilution effect reduced the combustion efficiency, which caused higher smoke emissions [45]. It was observed that at low CR, the smoke opacity decreased with an increase in the  $P_{inj}$ . A higher  $P_{inj}$  improved the fuel combustion efficiency, resulting in lower smoke emission [45]. Smoke emission decreased at 600 bar  $P_{inj}$  with no EGR; this was due to the fine droplets at higher  $P_{inj}$  which led to improved combustion efficiency. The smoke emissions increased with the increasing EGR flow rate [46].

At CR 17.5 and 20, and with no EGR, the HC emission for FMME-2 fuel was found to be lower than that of diesel fuel. Biodiesel is an oxygenated fuel that enhances the combustion efficiency and reduces the amount of HC released into the atmosphere [45, 46]. A higher  $P_{inj}$  also produced lower HC emissions with no EGR (figure 15). An enhanced air/fuel mixing rate at high  $P_{inj}$  gave better combustion efficiency, resulting in a lower HC emission [38, 47]. It is also noted that the HC emission increases with an increase in the EGR flow rate at each CR and  $P_{inj}$  (figure 15). As mentioned, this test was conducted on a modified stationary VCR engine. Normally, a stationary engine is operated at 250–300 bar injection pressure. Moreover, the modified VCR-CRDI engine was operated at 400, 500 and 600 bar fuel injection pressure. The may increases the causes of wall impingement at higher CR and  $P_{inj}$ . The HC emissions increased with the increase in the EGR% due to the dilution of hot gases, which slowed down the combustion process [38, 47]. The HC emission was observed to be higher at a higher CR of 22, due to the insufficient time to complete the combustion process and high fuel wall impingement due to the reduction in compression volume. When compared to a traditional mechanical injector (three holes), the location of electronic injection ( $45^\circ$  slanted) and the larger number of nozzle holes (Delphi seven-hole nozzle) were the key reasons for the enhanced HC emission in this investigation. Due to the  $45^\circ$  angled location and high injection pressure of the electronic injector, at least two fuel sprays immediately impact the cylinder head, increasing the potential for wall quenching, resulting in partly oxidised HC and greater HC emission [38, 47]. The incomplete combustion produces CO emissions. The CO gas emission is influenced by a lack of oxygen, a decreased oxidation rate, and the time it takes for CO to  $CO_2$  to oxidise [48]. From figure 16, it is observed that CO emission increased with the increasing  $P_{inj}$  and CR as compared to diesel fuel. Incomplete combustion of the fuel due to wall impingement caused this behaviour [48]. At each CR and  $P_{inj}$ , CO emissions for FMME-2 fuel were found to

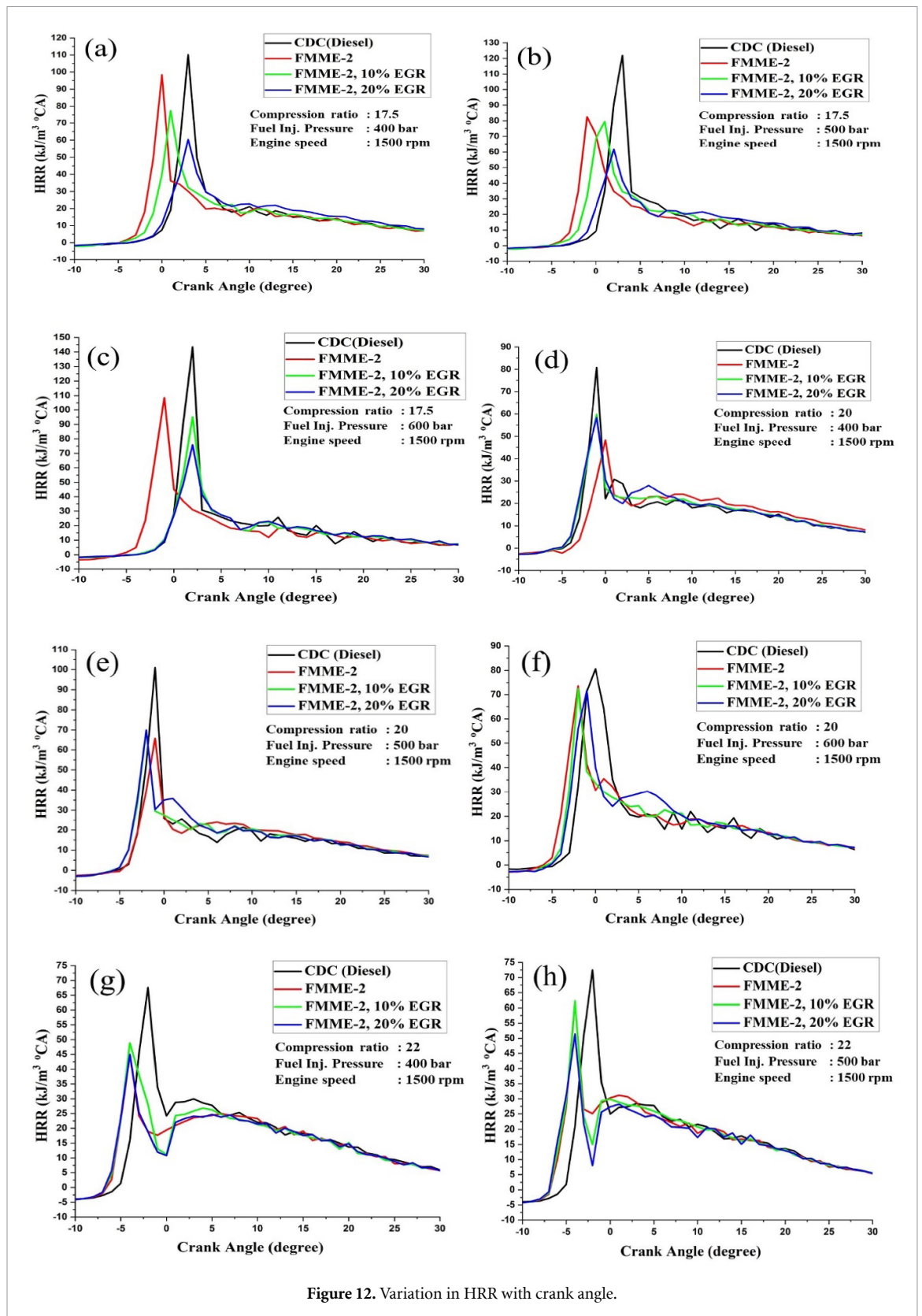


Figure 12. Variation in HRR with crank angle.

be greater than diesel fuel with and without EGR. The insufficient time for the oxidation of CO caused this characteristic at the CRs [48]. The CO was observed to be lower at CR 20 without EGR due to the higher in-cylinder temperature, which enhanced the CO oxidation rate [49]. At CR 17.5:1, FMME-2 with 10% and 20% EGR emits more CO at each  $P_{inj}$ . Exhaust gases resulted in a lower oxidation rate and hence larger CO emissions [50]. FMME-2 emits less  $\text{CO}_2$  than diesel fuel at each CR and  $P_{inj}$ , owing to a slower rate of CO oxidation to  $\text{CO}_2$  (figure 17). The in-cylinder temperature was greater at a higher CR of 22, which accelerated the oxidation rate of CO to  $\text{CO}_2$ , resulting in decreased CO emission for FMME-2 at 500 and 600 bar  $P_{inj}$ .



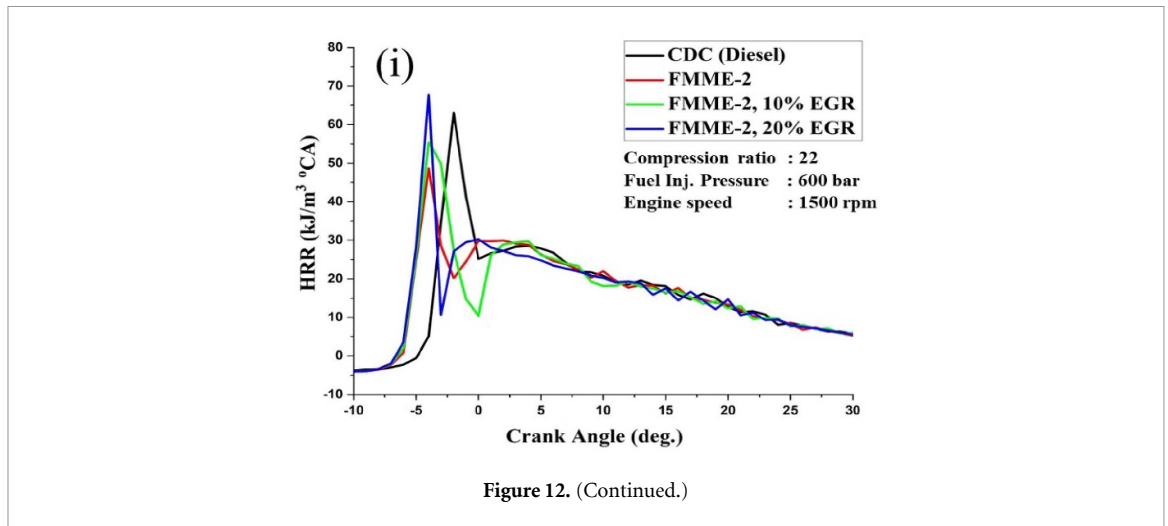


Figure 12. (Continued.)

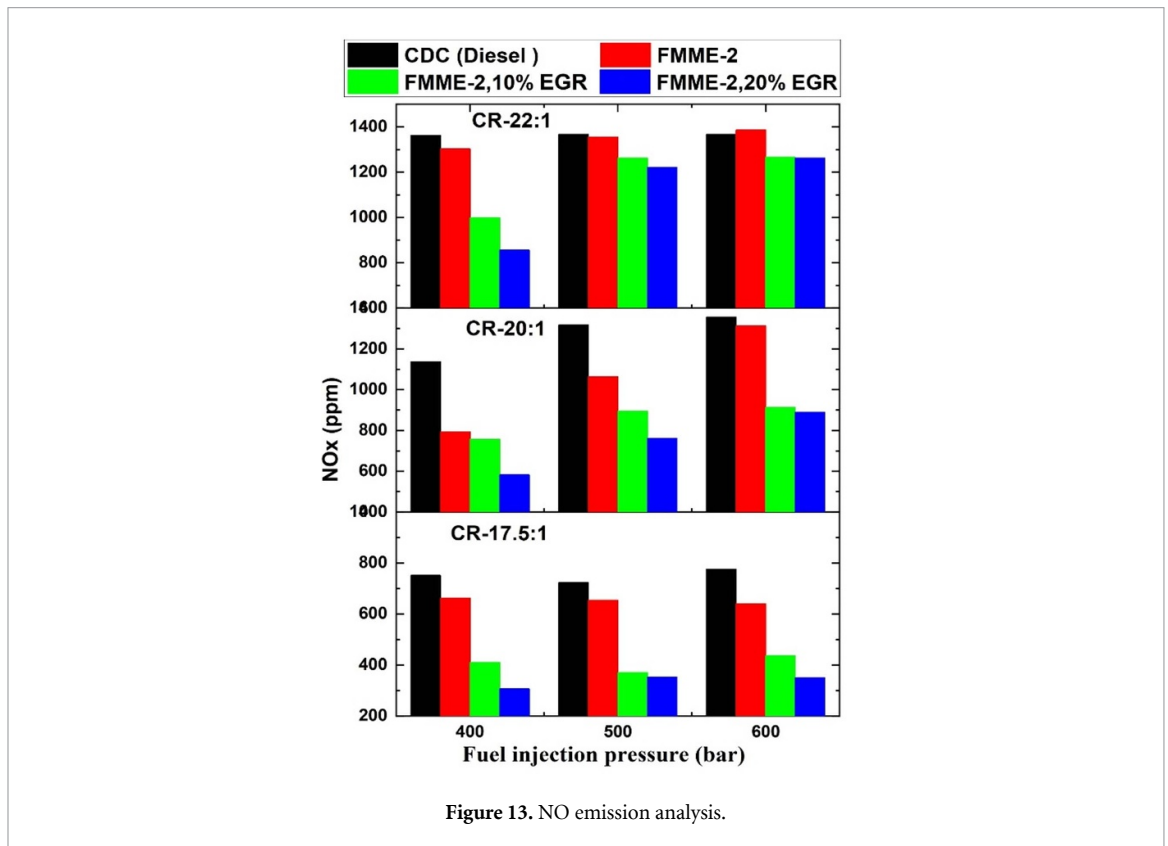


Figure 13. NO emission analysis.

Table 7. NO emission reduction—FMME-2 fuel with diesel.

CR	Operating conditions	NO emission reduction (%)		
	$P_{inj}$ (bar)	400	500	600
17.5	No EGR	11↓	9↓	17↓
	10% EGR	45↓	48↓	43↓
	20% EGR	59↓	51↓	54↓
20	No EGR	30↓	19↓	3↓
	10% EGR	33↓	32↓	32↓
	20% EGR	48↓	42↓	34↓
22	No EGR	4↓	0.8↓	1↑
	10% EGR	26↓	7↓	7.3↓
	20% EGR	37↓	8↓	7.6↓

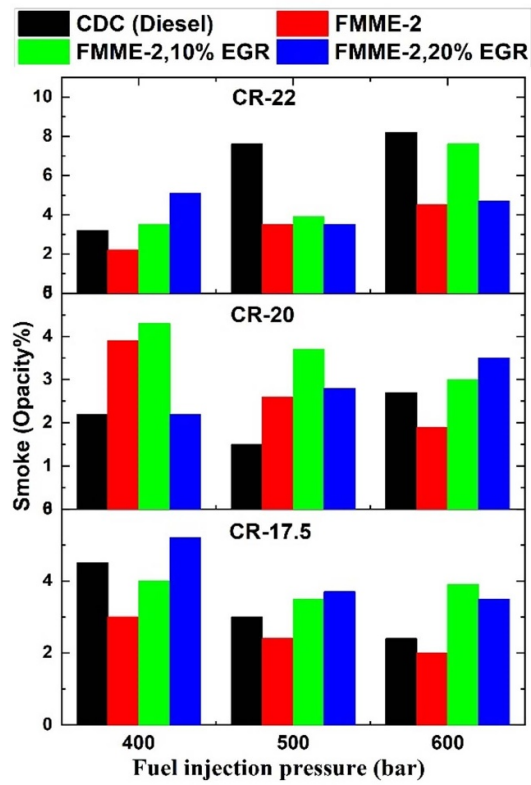


Figure 14. Smoke emission analysis.

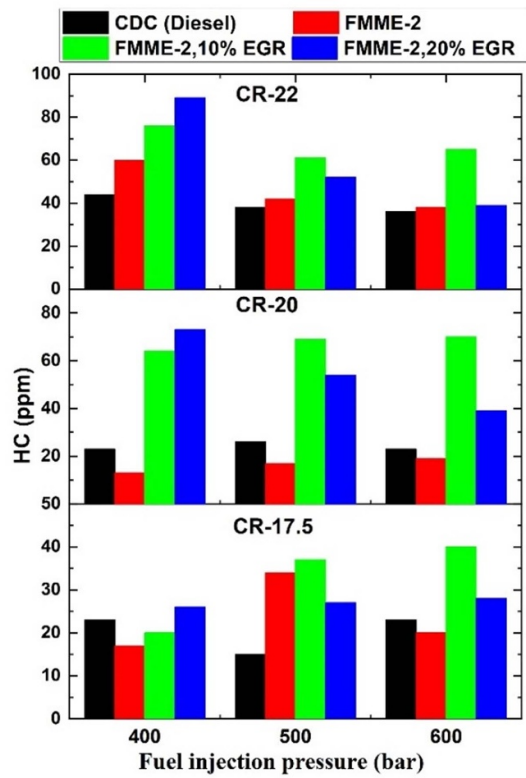


Figure 15. HC emission analysis.

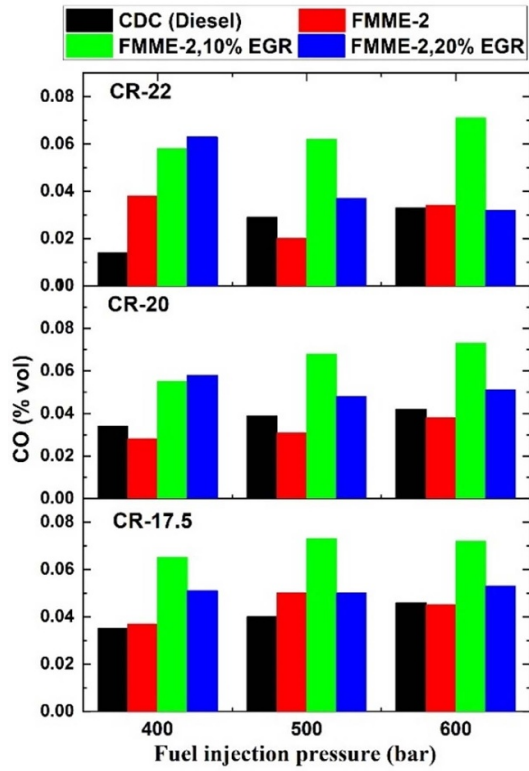


Figure 16. Carbon monoxide emission analysis.

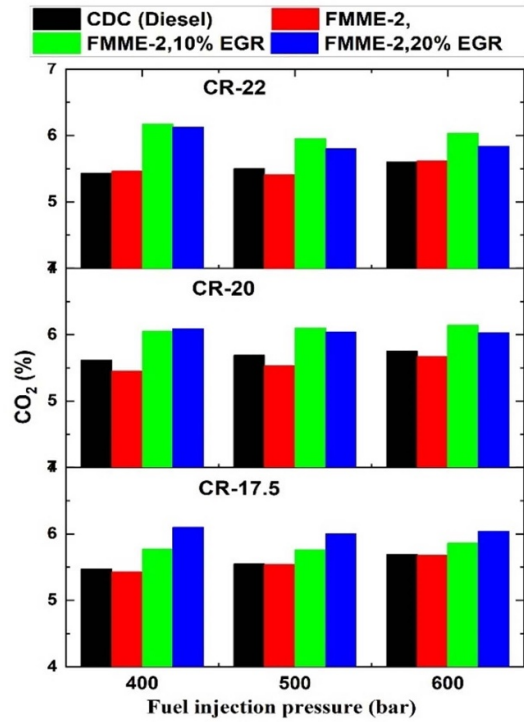


Figure 17. Carbon dioxide emission analysis.

## 4. Conclusion

Generally, biodiesel is produced from a single feedstock; hence, it is challenging to produce biodiesel that can meet international standards. The flex-mix is a novel method that involves the pre-mixing of feedstocks before converting them into biodiesel. The flex-mix approach opens a new way for researchers and the industry involved to find suitable combinations of feedstock, which can ultimately be turned into high-quality biodiesels. The flex-mix approach also helps to manage waste disposal and make waste into valuable products. Through the flex-mix approach, we can reduce the high cost of fuel production that is experienced when we rely on single feedstock. Another advantage is that we can use locally available feedstock mixture to make this flex-mix fuel. Waste pigskin rendering fat and WCO were chosen as feedstock for flex-mix fuel generation in this investigation. The prepared biodiesel fuel was of good quality and fulfilled the EN 14241 biodiesel standard. The qualities of biodiesel were discovered to be altered by different saturated and unsaturated SFAs. The kinematic viscosity, density, calorific value, flash point, iodine value and acid value of the FMME fuel were all lowered, but the SFA percentage and CN were raised. The following is a summary of the FMME-2 fuel combustion and emission characteristics:

- (a) The BTE of FMME-2 fuel was found to be roughly 0.7% lower than diesel fuel under all operating circumstances. However, BSFC was around 3.2% more expensive than fossil diesel.
- (b) The SoC for FMME-2 fuel was found to be more advanced than that of diesel fuel at each CR (17.5, 20, 22) and  $P_{inj}$  (400, 500, 600 bar). This was due to the higher CN of FMME-2 fuel. The SoC was retarded when EGR was introduced. The CD decreased with the increase in CR but increased with the EGR percentage. The  $P_{max}$  for FMME-2 fuel was decreased by 1% as compared to diesel fuel due to the advanced SoC.
- (c) When compared to diesel fuel at  $P_{inj}$  500 bar and a 10% EGR rate, the FMME-2 fuel produced approximately 20% less NO gas. At CR 17.5 with no EGR, the HC, smoke opacity, CO and CO<sub>2</sub> gas emissions of FMME-2 fuel were determined to be lower than diesel.

The proposed flex-mix concept will also help in reducing the production time and cost involved, as this is a single-stage transesterification process. From a technological and economic standpoint, the study determined that flex-mix is a viable alternative to fossil diesel fuel. The use of flex-mix fuel instead of fossil diesel would result in significant reductions in GHG emissions. FMME fuel is suitable for off-road diesel engine applications. Testing these FMME fuels in advanced combustion modes, such as HCCI and RCCI techniques, is recommended. A long-term storage stability study of FMME fuels using novel catalysts is another topic for future work. More research on other waste-derived flex-mix fuels is also recommended as a future study.

## Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

## Acknowledgments

The study was funded by the UKIERI Project (Grant No. DST-UKIERI 18-19-04): Waste to Energy—Low Temperature Combustion of Sustainable Green Fuels.

## ORCID iD

Vikas Sharma  <https://orcid.org/0000-0002-0603-8208>

## References

- [1] Gaur A, Dwivedi G, Baredar P and Jain S 2022 Influence of blending additives in biodiesel on physiochemical properties, engine performance, and emission characteristics *Fuel* **321** 124072
- [2] Cheng S Y, Tan X, Show P L, Rambabu K, Banat F, Veeramuthu A, Lau B F, Ng E P and Ling T C 2020 Incorporating biowaste into circular bioeconomy: a critical review of current trend and scaling up feasibility *Environ. Technol. Innov.* **19** 101034
- [3] Karami R, Rasul M G, Khan M M K and Mahdi Salahi M 2021 Experimental and computational analysis of combustion characteristics of a diesel engine fueled with diesel-tomato seed oil biodiesel blends *Fuel* **285** 119243
- [4] Khoo K S, Chew K W, Yew G Y, Leong W H, Chai Y H, Show P L and Chen W H 2020 Recent advances in downstream processing of microalgae lipid recovery for biofuel production *Bioresour. Technol.* **304** 122996

- [5] Meng F and McKechnie J 2019 Challenges in quantifying greenhouse gas impacts of waste-based biofuels in EU and US biofuel policies: case study of butanol and ethanol production from municipal solid waste *Environ. Sci. Technol.* **53** 12141–9
- [6] Yogesh P, Murali B and Muniyandhu S 2022 Experimental analysis of CI engine running with mango seed biodiesel at optimum fuel injection pressure *Mater. Today Proc.* **62** 1889–93
- [7] Sharma V, Hossain A K, Griffiths G, Duraisamy G and Jacob Thomas J 2022 Investigation on yield, fuel properties, ageing and low temperature flow of fish oil esters *Energy Convers. Manage.* **14** 100217
- [8] Sharma V and Duraisamy G 2019 Production and characterization of bio-mix fuel produced from a ternary and quaternary mixture of raw oil feedstock *J. Clean. Prod.* **221** 271–85
- [9] Manigandan S, Atabani A E, Ponnusamy V K, Pugazhendhi A, Gunasekar P and Prakash S 2020 Effect of hydrogen and multiwall carbon nanotubes blends on combustion performance and emission of diesel engine using Taguchi approach *Fuel* **276** 118120
- [10] Ejikeme P M, Anyaogu I D, Egbonu C A C and Eze V C 2013 Pig-fat (Lard) derivatives as alternative diesel fuel in compression ignition engines *J. Pet. Technol. Altern. Fuels.* **4** 7–11
- [11] Nicolici A, Pana C, Negurescu N, Cernat A and Nutu C 2018 The use of animal fats in the diesel fuelled engine *IOP Conf. Ser.: Mater. Sci. Eng.* **444** 072003
- [12] Cican G, Deaconu M, Mirea R, Ceatra L, Cretu M and Dobre T 2020 Investigating the use of recycled pork fat-based biodiesel in aviation turbo engines *Processes* **8** 1196
- [13] Farooq M, Ramli A and Subbarao D 2013 Biodiesel production from waste cooking oil using bifunctional heterogeneous solid catalysts *J. Clean. Prod.* **59** 131–40
- [14] Balasaheb J and Padalkar A S 2012 Performance and emission analysis of a compression ignition engine operated on waste fried oil methyl esters *Appl. Energy* **90** 68–72
- [15] Zhu L, Xiao Y, Cheung C S, Guan C and Huang Z 2016 Combustion, gaseous and particulate emission of a diesel engine fueled with n-pentanol (C5 alcohol) blended with waste cooking oil biodiesel *Appl. Therm. Eng.* **102** 73–9
- [16] Necati A and Canakci M 2010 The emission analysis of an IDI diesel engine fueled with methyl ester of waste frying palm oil and its blends *Biomass Bioenergy* **34** 1870–8
- [17] Mujtaba M A et al 2020 Ultrasound-assisted process optimization and tribological characteristics of biodiesel from palm-sesame oil via response surface methodology and extreme learning machine—Cuckoo search *Renew. Energy* **158** 202–14
- [18] Hong I K, Lee J R and Lee S B 2015 Fuel properties of canola oil and lard biodiesel blends: higher heating value, oxidative stability, and kinematic viscosity *J. Ind. Eng. Chem.* **22** 335–40
- [19] Milano J, Chyuan H, Masjuki H H, Silitonga A S, Chen W, Kusumo F, Dharma S and Sebayang A H 2018 Optimization of biodiesel production by microwave irradiation-assisted transesterification for waste cooking oil-Calophyllum inophyllum oil via response surface methodology *Energy Convers. Manage.* **158** 400–15
- [20] Sharma V, Duraisamy G and Arumugam K 2020 Impact of bio-mix fuel on performance, emission and combustion characteristics in a single cylinder DIC VCR engine *Renew. Energy* **146** 111–24
- [21] Sharma V and Hossain A K 2021 Experimental investigation of neat biodiesels' saturation level on combustion and emission characteristics in a CI engine *Energies* **14** 5203
- [22] Sharma V, Duraisamy G, Cho H M, Arumugam K and Alosius M A 2019 Production, combustion and emission impact of bio-mix methyl ester fuel on a stationary light duty diesel engine *J. Clean. Prod.* **233** 147–59
- [23] Tamilselvan P, Sassykova L, Prabhakar M, Bhaskar K, Kannayiram G, Subramanian S and Prakash S 2020 Influence of saturated fatty acid material composition in biodiesel on its performance in internal combustion engines *Mater. Today Proc.* **33** 1181–6
- [24] Elkelawy M, El Shenawy E A, Khalaf Abd Almonem S, Nasef M H, Panchal H, Bastawissi H A-E, Sadasivuni K K, Choudhary A K, Sharma D and Khalid M 2021 Experimental study on combustion, performance, and emission behaviours of diesel/WCO biodiesel/Cyclohexane blends in DI-CI engine *Process Saf. Environ. Prot.* **149** 684–97
- [25] Karthikeyan S, Periyasamy M and Mahendran G 2021 Impact on combustion of biodiesel mixtures of heavy alcohol and microalgae in diesel engines *Mater. Today Proc.* **11** 1029
- [26] Sathyamurthy R, Balaji D, Gorjian S, Muthiya S J, Bharathwaaj R, Vasanthaseelan S and Essa F A 2021 Performance, combustion and emission characteristics of a DI-CI diesel engine fueled with corn oil methyl ester biodiesel blends *Sustain. Energy Technol. Assess.* **43** 100981
- [27] Uyumaz A, Aydoğan B, Yılmaz E, Solmaz H, Aksoy F, Mutlu İ, İpci D and Calam A 2020 Experimental investigation on the combustion, performance and exhaust emission characteristics of poppy oil biodiesel-diesel dual fuel combustion in a CI engine *Fuel* **280** 118588
- [28] Rahman M A and Aziz M A 2021 Biodiesel from water hyacinth biomass and its influence on CI engine performance, emission, combustion and heat loss characteristics with the induction of hydroxy *Energy* **224** 120151
- [29] Gad M S, Kamel B M and Anjum Badruddin I 2021 Improving the diesel engine performance, emissions and combustion characteristics using biodiesel with carbon nanomaterials *Fuel* **288** 119665
- [30] Sunil Kumar M, Rajasekar R, Ganesan S, Venkatesan S P and Praveen Kumar V 2020 Evaluation of metal oxide nano particles in lemongrass biodiesel for engine performance, emission and combustion characteristics *Mater. Today Proc.* **44** 3657–65
- [31] Liang J, Zhang Q, Chen Z and Zheng Z 2021 The effects of EGR rates and ternary blends of biodiesel/n-pentanol/diesel on the combustion and emission characteristics of a CRDI diesel engine *Fuel* **286** 119297
- [32] Jayabal R, Thangavelu L and Subramani S 2020 Combined effect of oxygenated additives, injection timing and EGR on combustion, performance and emission characteristics of a CRDi diesel engine powered by sapota biodiesel/diesel blends *Fuel* **276** 118020
- [33] Guan C, Cheung C S, Ning Z, Wong P K and Huang Z 2017 Comparison on the effect of using diesel fuel and waste cooking oil biodiesel as pilot fuels on the combustion, performance and emissions of a LPG-fumigated compression-ignition engine *Appl. Therm. Eng.* **125** 1260–71
- [34] İşik M Z 2021 Comparative experimental investigation on the effects of heavy alcohols- safflower biodiesel blends on combustion, performance and emissions in a power generator diesel engine *Appl. Therm. Eng.* **184** 116142
- [35] Baweja S, Trehan A and Kumar R 2021 Combustion, performance, and emission analysis of a CI engine fueled with mustard oil biodiesel blended in diesel fuel *Fuel* **292** 120346
- [36] Gad M S and Ismail M A 2021 Effect of waste cooking oil biodiesel blending with gasoline and kerosene on diesel engine performance, emissions and combustion characteristics *Process Saf. Environ. Prot.* **149** 1–10
- [37] Shi X, Liu B, Zhang C, Hu J and Zeng Q 2017 A study on combined effect of high EGR rate and biodiesel on combustion and emission performance of a diesel engine *Appl. Therm. Eng.* **125** 1272–9
- [38] Can Ö, Öztürk E, Solmaz H, Aksoy F, Çinar C and Yücesu H S 2016 Combined effects of soybean biodiesel fuel addition and EGR application on the combustion and exhaust emissions in a diesel engine *Appl. Therm. Eng.* **95** 115–24

- [39] Alhikami A F, Yao C E and Wang W C 2021 A study of the spray ignition characteristics of hydro-processed renewable diesel, petroleum diesel, and biodiesel using a constant volume combustion chamber *Combust. Flame* **223** 55–64
- [40] Asokan M A, Senthur Prabu S, Sai Akhil V, Sai Bhuvan P and Bhuvan Reddy Y 2021 Performance and emission behaviour of diesel and blends of watermelon seed oil biodiesel in direct injection diesel engine *Mater. Today Proc.* **45** 3274–8
- [41] Qi D, Leick M, Liu Y and Lee C F F 2011 Effect of EGR and injection timing on combustion and emission characteristics of split injection strategy DI-diesel engine fueled with biodiesel *Fuel* **90** 1884–91
- [42] Balamurugan G and Gowthaman S 2021 A review on split injection performances in DI diesel engine with different injection strategies and varying EGR using biodiesel as fuel *Mater. Today Proc.* **12** 627
- [43] Kumar V and Mahla S K 2021 Influence of EGR on a CI engine running on 20% blend of jatropha biodiesel *Mater. Today Proc.* **43** 273–80
- [44] Manieniyani V, Velumani V, Senthilkumar R and Sivaprakasam S 2021 Effect of EGR (exhaust gas recirculation) in diesel engine with multi-walled carbon nanotubes and vegetable oil refinery waste as biodiesel *Fuel* **288** 119689
- [45] Praveena V, Leenus Jesu Martin M and Edwin Geo V 2020 Effect of EGR on emissions of a modified DI compression ignition engine energized with nanoemulsive blends of grapeseed biodiesel *Fuel* **267** 117317
- [46] Rami Reddy S, Murali G, Ahamad Shaik A, Dhana Raju V and Sreekara Reddy M B S 2021 Experimental evaluation of diesel engine powered with waste mango seed biodiesel at different injection timings and EGR rates *Fuel* **285** 119047
- [47] Ayhan V, Çangal Ç, Cesur İ and Safa A 2020 Combined influence of supercharging, EGR, biodiesel and ethanol on emissions of a diesel engine: proposal of an optimization strategy *Energy* **207** 118298
- [48] Putrasari Y, Jwa K and Lim O 2019 Influence of EGR and intake boost on GCI engine fueled with gasoline-biodiesel blend using early single injection mode *Energy Proc.* **158** 565–70
- [49] Thomas J J and Nagarajan G 2021 Residual cooking oil biodiesel and hexanol as alternatives to petroleum-based fuel in low-temperature combustion: parametric study *SAE Technical Paper* 2021-01-0520
- [50] Thomas J J, Sabu V R, Nagarajan G, Kumar S and Basrin G 2020 Influence of waste vegetable oil biodiesel and hexanol on a reactivity controlled compression ignition engine combustion and emissions *Energy* **206** 118199