Research Article

Experimental investigations on the performance and emissions characteristics of dual biodiesel blends on a varying compression ratio diesel engine

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Abstract
The present work discusses the performance and emissions characterization of dual biodiesel sample blends on a varying compression ratio diesel engine. The dual biodiesel blends were obtained by blending two biodiesels (Mahua and Jatropha) in equal proportions volume (1:1, v/v) with mineral diesel. The sample blends were obtained on a 'percentage by volume' basis and named B10, B20, B30, and B40 (B10 was a blend of 5% each biodiesel with 90% mineral diesel and similarly for all other sample blends). All the experiments were performed at a constant engine speed of 1500 rpm, 50% loading conditions (2.6 kW), and varying compression ratios of 13.5:1, 14.5:1, 15.5:1, and 16.5:1. The results revealed that the sample blends had slightly higher brake power and mechanical efficiency with sample blends B10 to B40 had (0.15–1.58%) higher brake power and (1.07–12.42%) higher mechanical efficiency as compared to mineral diesel at a compression ratio of 16.5:1. The In-cylinder peak pressure and exhaust gas temperature were observed to be lower than mineral diesel for the sample blends B10 to B40 by 0.15–0.36 bar and 11.1–69.8 ℃, respectively. Also, the emissions of carbon monoxide and hydrocarbons were lower by 33–62%, respectively, for the sample with the highest blend percentage. However, the carbon dioxide emissions were found to be higher by 42.85% than mineral diesel. From the overall performance and characterization, it is concluded that B20 had optimum properties and blend percentage to be a better substitute fuel for mineral diesel among all the tested samples.

Keywords Mahua and Jatropha biodiesel · Dual biodiesel · Engine performance · Combustion characteristics · Exhaust emission properties · Variable compression ratio

Abbreviations

FFA	Free fatty acids
VCR	Varying compression ratio
BP	Brake power
CR	Compression ratio
BTDC	Before top dead center
ME	Mechanical efficiency
BSFC	Brake-specific fuel consumption
In-CPP	In-cylinder peak pressure
EGT	Exhaust gases temperature
HC	Hydrocarbons
CO	Carbon monoxide
CO_2	Carbon dioxide
NO_x	Nitrogen oxides
PPM	Parts per million
BTE	Brake thermal efficiency
SPM	Specific particulate matter

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1 Introduction

Indigenously available energy resources play a significant role in the economic growth of a country. These resources are also important for the sustainability of a developing country. According to a report given by the Department of Energy, USA, the demand for crude oil will reach its peak by the end of this century and the fossil fuel reserves might reduce to a fractional value of their current estimates. Lately, the extensive use of petroleum products due to the rise in industry and the human population has led to the exhaustion of crude oil reserves (US Department, https://www.eia.gov/). The higher demand leads to a rise in the higher price of fossil fuels [10]. Globally, people consume more than 11 billion tons of oil from fossil fuels each year. The reserves for crude oil are declining at a very high rate of 4 billion tons per year approximately, and at this rate, the stocks of oil reserves may get depleted in just another four to five decades. Highly populated countries like China and India are consuming the maximum amount of aviation fuel [50]. Further, the emissions of harmful gases like carbon monoxide, hydrocarbons, carbon dioxide, and particulate matter are the direct result of the worldwide combustion of petroleum products. The use of fossil fuels contributes about 25% to the total greenhouse gas emissions [25]. Due to the above-mentioned reasons, finding alternate energy resources has become a necessity for researchers all over the world.

Many researchers around the globe did intensive research on biodiesels that has the potential to provide a possible way out to substitute conventional diesel at lower prices [30]. Biodiesel can be obtained from edible or non-edible vegetable and animal fat oil. It is produced by various methods like pyrolysis, emulsification, blending, and trans-esterification. However, the most commonly used method for producing biodiesel is trans-esterification since it is the most economical method among all [3, 6].

Mahua and Jatropha raw seed oil have prominent free fatty acid (FFA) content, which is around 19–23% [13]. It is possible to reduce the FFA of raw oil with a suitable pre-treatment process. The production of biodiesel from raw oil depends upon various parameters like reaction temperature, category of catalyst used, the ratio of oil to alcohol used, and purity of the reactants [1, 5].

The physicochemical properties such as iodine value, acid value, fire point, and flash point, kinematic viscosity, density, etc. make it suitable to be used as biodiesel, but its cold flow properties are still a matter of concern [20]. Contrary to Mahua biodiesel, Jatropha biodiesel has good cold flow properties. Mahua and Jatropha biodiesel also have better combustion and emissions properties. To enhance the physicochemical properties of individual biodiesel, dual biodiesel can be prepared by the blending of these two. It was reported that preheating of Jatropha oil can help to reduce its kinematic viscosity and enhance its fuel atomization for biodiesel [3, 8, 21]. Preheating of raw palm oil (up to 90 ℃) improved its density and viscosity, which in turn improves its flow properties and reduces the clogging problem of fuel injectors and fuel filters [12]. It has been reported by many researchers that the blending of biodiesel in diesel fuel can help to reduce the engine emissions to a great extent in comparison with the emissions given by the combustion of currently used diesel fuel [40, 51]. Chauhan et al. have stressed the recommendation of biodiesel prepared from Jatropha oil as a fuel and reported its engine performance, variation in combustion, and emission properties [15]. Solaimuthu and Govindarajan [53] examined Mahua oil biodiesel blend with diesel and observed that 25% blend had the lowest hydrocarbons and nitrogen oxides emissions with 100% loading conditions. A review of the literature of some researchers is presented in Table 1.

From the review of the works of literature, it is evident that extensive research has been done to determine the efficiency of engine and emissions of exhaust gases for various blended biodiesels with mineral diesel at constant CR, but only a few articles are available on the diesel engine output parameters using dual biodiesel blended with mineral diesel at VCR [2, 3, 21, 27].

The studies mentioned above were carried out in engines with different specifications and using biodiesels prepared from various first-generation or second-generation vegetable oils. In these studies, the effect of varying parameters has been emphasized by all researchers on engine combustion, engine performance, and emissions characteristics [26, 43, 54, 61]. However, it is worth noting that studies on dual biodiesel prepared by mixing different biodiesels with mineral diesel were found to be limited. All previous researches on the physical and chemical characterization of dual biodiesel prepared by mixing of different biodiesel with mineral diesel in various proportions revealed that these sample blends might become a suitable candidate to replace mineral diesel [16, 18, 29, 37]. Therefore, it is highly significant to measure the different characteristics of dual biodiesel on a VCR engine to check its emission properties and engine performance parameters.

Although biodiesel has a strong potential to replace conventional diesel, it has many underlying problems associated with it such as high viscosity, choking of nozzles in fuel injectors, carbon deposition inside the engine cylinder, free fatty acid content, etc. [21]. To overcome

Table 1 Literature survey from different authors

S. No	Feedstocks	Research findings/ Outcomes	References
1	Spirulina microalgae, ethanol, methanol, and diesel (base fuel)	It was observed that EBT of hybrid fuel (ethanol) emulsions were high and EGT was low compared with diesel Engine emission results show that spirulina microalgae emulsions fuel reduces the SPM, smoke emissions, and soot except for NOx & CO_2 compared with diesel fuel	[58]
2	Not mentioned	The author did a detailed review on trending modeling methods such as Analytical methods Regression methods The review recommends combining advanced statistical methods and emerging popular machine learning algorithms to engine research for deriving comprehensive pragmatic models as an empirical compromise	[44]
3	Tamanu Methyl Ester (TME)	The optimum IAT was found to be 90℃, so further experiments were carried out using the IAT 90℃ at various EGR ratios The EGR-associated HCCI engine produces ultra-lean NOx emissions, slightly lower BTE, cylinder pressure, and heat release rate than the engine operating without EGR. The results also showed that a rise in IAT above 100℃ leads to short HCCI combustion, inclining to knock, thus leading to unstable operation	[38]
4	Citronella oil and biodiesel	The biodiesel was prepared with diesel on a volume basis, namely B20, B40, and B60, and examined on a 1-cylinder CI diesel engine The BTE of citronella oil and its blend were found lower than diesel, and compared to all blend samples, the B20 blend had better efficiency. The B20 (20% Citronella oil + 80% Diesel) appealed 1.47% lower in engine BTE and 2.7% higher fuel consumption than diesel fuel The smoke emissions of biodiesel lowered by 31% than diesel fuel, with a negligible rise in NOx and CO_2 emission by 12.5% and 7.1%, respectively. Besides that, CO and HC were 16.34% and 22.2% lower than diesel fuel when the engine was running at higher load conditions	[41]
5	Karanja and Roselle biodiesel	The engine performance at different engine loads at constant speed was tested for prepared biodiesel. It was observed that In-CPP, BTE, EGT, ignition delay, and indicated thermal efficiency were reduced by 4.93, 4.3, 1.2, 2.47, and 0.71% for LA20 (20% Roselle + 80% Diesel) sample blend when compared with mineral diesel BTE, EGT, NO_X, and smoke emissions were reduced by 1.84%, 1.62%, 3.84%, and 13.53%, respectively, while BSFC was escalated up to 8.6% for KB20 (20% Karanja + 80% Diesel)	[50]
6	Karanja oil and Roselle oil biodiesel blends (KB10 and RB10)	The dual biodiesel was prepared by blending with diesel fuel The engine performance showed that the BTE was reduced and BSFC was increased for both RB10 and KB10 compared to diesel	[49]
7	Roselle biodiesel	The author analyzed B20, B40, and B100 sample blends of Roselle biodiesel on a diesel engine by changing the injection pressure during fuel injection and engine loading and compared it with mineral diesel It was found that smoke emission, thermal efficiency, ignition delay period, and indicated efficiency were reduced while mean effective pressure, In-cylinder peak pressure, CO_2, and NO_X emissions increased at high fuel injection pressure	[48]
8	Palm biodiesel and diesel	The indicated mean effective pressure, brake power, mechanical efficiency, and emissions of exhaust gas by varying compression ratios on palm biodiesel blended with diesel were investigated The study revealed that for higher compression ratios, 20% blend sample produces around 6% higher brake power and 14.6% higher mechanical efficiency compared with diesel. EGT was found to be lower for all blends. At 100% loading conditions, HC and CO content in exhaust gas was reduced by increasing the compression ratio and blend percentage. However, CO_2 content in exhaust gas was found to be more than diesel	[36]

Table 1 (continued)

S. No	Feedstocks	Research findings/ Outcomes	References
9	Waste cooking oil and mineral diesel	The fuel combustion characteristics of blends of diesel in various proportions with biodiesel prepared from the second-generation waste cooking oil through a two-step trans-esterification process	[24]
		A 4-stroke VCR; a 1-cylinder engine was used for the experimentation research work. The results revealed that increased CR (from 14 to 18) gave higher BTE (up to 27.48%), reduced HC and CO (52% and 37.5%) in the exhaust. However, the percentage of CO_2 and NOx emissions came out 36.84% and 14.28% higher, as compared to mineral diesel	
10	Cottonseed oil	Authors worked on cottonseed oil biodiesel prepared by preheating and trans-esterification at various temperature ranges (like 50, 70, and 90℃). It was reported that all the major physicochemical properties were better than earlier	[28]
		The outcomes revealed that the preheating of raw oil up to 90℃ enhances the engine efficiency and fuel consumption of fuel by the engine at higher loads in comparison with mineral diesel	

these problems, researchers have done thorough work on the blending of biodiesel obtained from various vegetable or animal fat oil with mineral diesel [52]. However, only few researches are available on the production of dual biodiesel by mixing two different biodiesels with mineral diesel. This field has good scope for research to work on [2, 13]. Dual biodiesel can decrease the emissions of harmful gases and improve engine performance [39, 60], which have been the focus of major research work worldwide. Only a few researchers have worked on the biodiesels prepared from Jatropha and Mahua blend with mineral diesel [2, 42], even though the properties of both Jatropha and Mahua oil biodiesel could be used to prepare dual biodiesel with improved physicochemical properties. There are many articles available on the investigations of emissions properties and engine performance parameters of individual Jatropha and Mahua oil biodiesel blends with mineral diesel, but the exploration of the possibilities of a dual blend of Mahua and Jatropha biodiesels with diesel fuel is still wide open.

It is evident from the literature survey that researchers have been trying to obtain a substitute fuel to the presently used mineral diesel by preparing blended dual biodiesel with enhanced engine combustion and emission properties [1, 31, 45, 56]. Further, a few researchers have also tried in the recent past to varying the engine combustion parameters with different variations of blended dual biodiesel to improve engine output and exhaust emissions [7, 22, 42, 55]. Their studies have revealed that the blending of two different biodiesels has a significant impact on the combustion and emissions properties of fuel [46]. Also, some researchers have lately successfully improved the oxidation stability of biodiesel by preparing dual biofuel with the blending of two different biodiesels [2]. The direct impact of two different biodiesels blending on the engine output parameters and emission characteristics of the dual biofuel is still limited as very few works of literature are available on the same.

Therefore, in the present work, we aim to evaluate the parameters of engine output (such as In-cylinder peak pressure, mechanical efficiency, brake power, brake-specific fuel consumption, and exhaust gas temperature) and emissions gases (carbon dioxide, carbon monoxide, and hydrocarbons) using VCR engine of Mahua and Jatropha Biodiesel and mineral diesel blend. The various compression ratios (CR) used in current research work were 13.5:1, 14.5:1, 15.5:1, and 16.5:1 at 50% loading condition.

2 Materials and methods

2.1 Preparation of various sample blends for dual biodiesel

The individual biodiesel of Jatropha and Mahua oil was prepared using a two-step trans-esterification process. The trans-esterification reaction was carried out at a temperature of 65℃ (± 1) using a water bath, and the reaction time was 30 min. During the reaction, the temperature of the water bath was constantly maintained at 65 ℃ (± 1). After every 5 min, the solution was stirred using a glass rod. In the end, the obtained solution was drained into a separating funnel and it was kept aside for the next 24 h. Finally, the biodiesel was separated, and the average yield of biodiesel was observed to be 93% for Jatropha and 89% for Mahua oil, respectively. Figure 1 illustrates the prepared sample of biodiesel using the trans-esterification process. Table 2 shows the comparison of physicochemical properties of biodiesels used in the present work.

The various physicochemical properties (density, acid value, kinematic viscosity, iodine value, flash point, fire point, cloud point, and pour point) of these synthesized

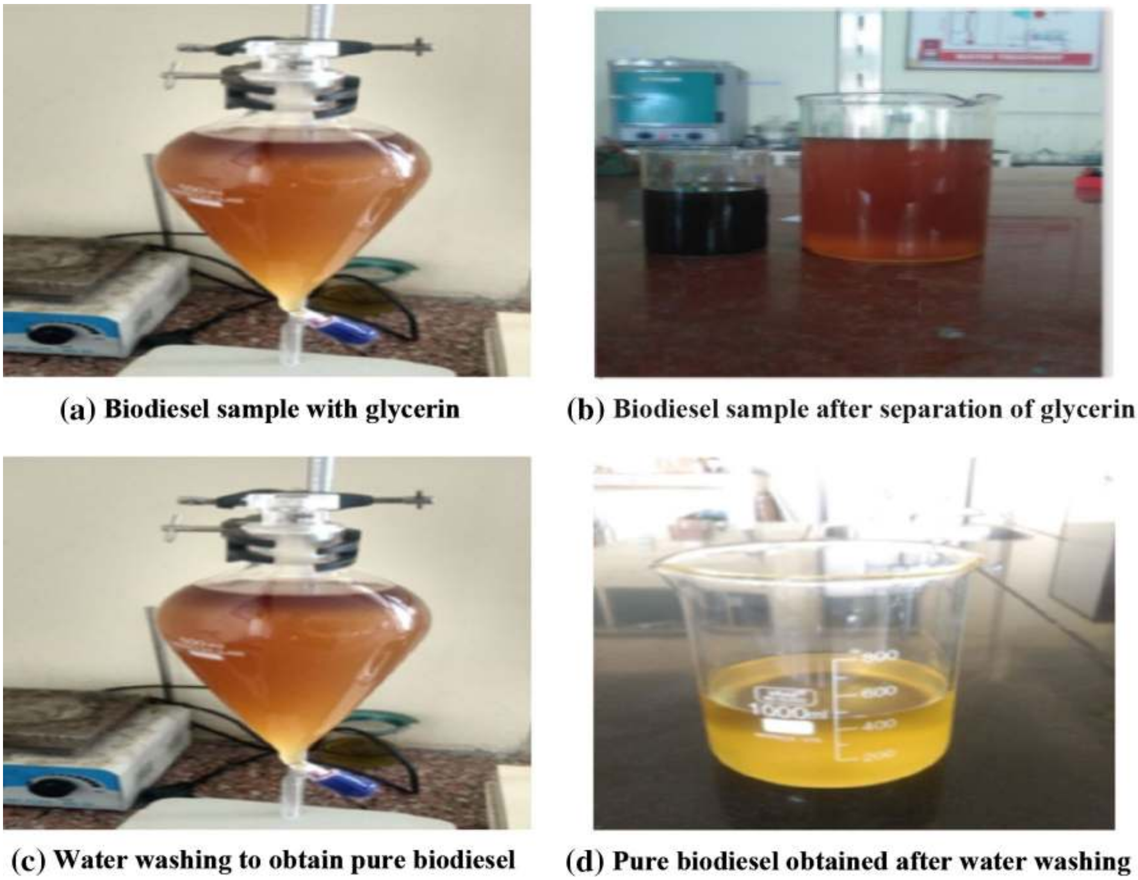

Fig. 1 **a** Biodiesel sample with glycerin. **b** Biodiesel sample after separation of glycerin. **c** Water washing to obtain pure biodiesel. **d** Pure biodiesel obtained after water washing

Table 2 Comparison of physicochemical properties of biodiesels [47]

Properties	Units	Mahua oil	Jatropha oil	Mahua oil biodiesel	Jatropha oil bio-diesel	Mineral diesel
Acid value	mg KOH/g	35.00	28.00	0.45	0.40	0.21
Iodine value	g of I_2/100 g	70.00	108.67	60.33	98.67	–
Density	kg/m^3@ 20℃	918.33	950.33	864.33	875.10	830.00
Kinematic viscosity	cSt @ 40℃	24.66	38.33	4.07	4.39	2.60
Flash point	℃	234.67	224.67	174.67	140.33	65.00
Fire point	℃	245.67	234.67	185.33	152.33	78.00
Cloud point	℃	12	6.33	5.33	− 0.67	− 3.00
Pour point	℃	8	2.67	2.00	− 6.33	− 8.00

biodiesels had been evaluated previously. The physicochemical properties were found to be within the limits of different standards of biodiesels (National and International). Further, from these biodiesels, various dual biodiesel sample blends were prepared by mixing them in various proportions with mineral diesel. The compositions of various dual biodiesel sample blends are summarized below:

B10: JBD 05%, & MBD 05% with mineral diesel 90%, by vol.

B20: JBD 10%, & MBD 10% with mineral diesel 80%, by vol.

B30: JBD 15%, & MBD 15% with mineral diesel 70%, by vol.

B40: JBD 20%, & MBD 20% with mineral diesel 60%, by vol.

Table 3 represents the comparison of physicochemical properties of biodiesel blends with mineral diesel used in the present work.

The physical and chemical properties of these sample blends (dual biodiesel) were examined as per the standards of biodiesels given by various agencies (National and International) and were found to be within limits.

The above-mentioned dual biodiesel sample blends were tested for their emission characteristics and engine performance parameters using the VCR engine at varying CR during the current research work.

2.2 Engine description

The research work was conducted on a VCR four-stroke single-cylinder diesel engine connected with an eddy current dynamometer. The setup was used to determine the results of varying CR in the engine cylinder to the operational and exhaust emissions. The performance parameters were evaluated for the engine (such as mechanical efficiency, brake power, brake-specific fuel consumption, In-cylinder peak pressure, and exhaust gas temperature).

The computerized data acquisition system coupled with the VCR engine is used to perform the experiments and to collect and store data. The experimentation setup used for the study is presented in Figs. 2 and 3. Further, Table 4 presents the various specifications of the VCR engine used for the research work.

2.3 Gas analyzer description

Five gas analyzer AVG-500 (AIRVISOR) model was connected to a VCR engine to analyze the emissions. It was provided with an exhaust gas inlet which was put in

Table 3 The comparison of properties (physical and chemical) of various dual biodiesel blend samples with the mineral diesel [47]

Physical and chemical properties	Units	Dual biodiesel sample blend B10	Dual biodiesel sample blend B20	Dual biodiesel sample blend B30	Dual biodiesel sample blend B40	Mineral diesel
Acid value(max)	mg KOH/g	0.21	0.24	0.33	0.40	0.20
Iodine value	g of I_2/100 g	89.00	90.33	91.67	94.00	–
Density	kg/m^3@ 20 ℃	839.00	850.67	865.00	870.67	830.00
Kinematic viscosity	cSt @ 40 ℃	2.68	3.13	3.67	4.09	2.60
Flash point	℃	75.00	88.00	100	114.33	65.00
Fire point	℃	86.00	98.33	112.00	124.67	78.00
Cloud point	℃	− 2.00	− 1.00	3	5.33	− 3
Pour point	℃	− 5.00	− 3.00	− 1.67	0.33	− 8.00

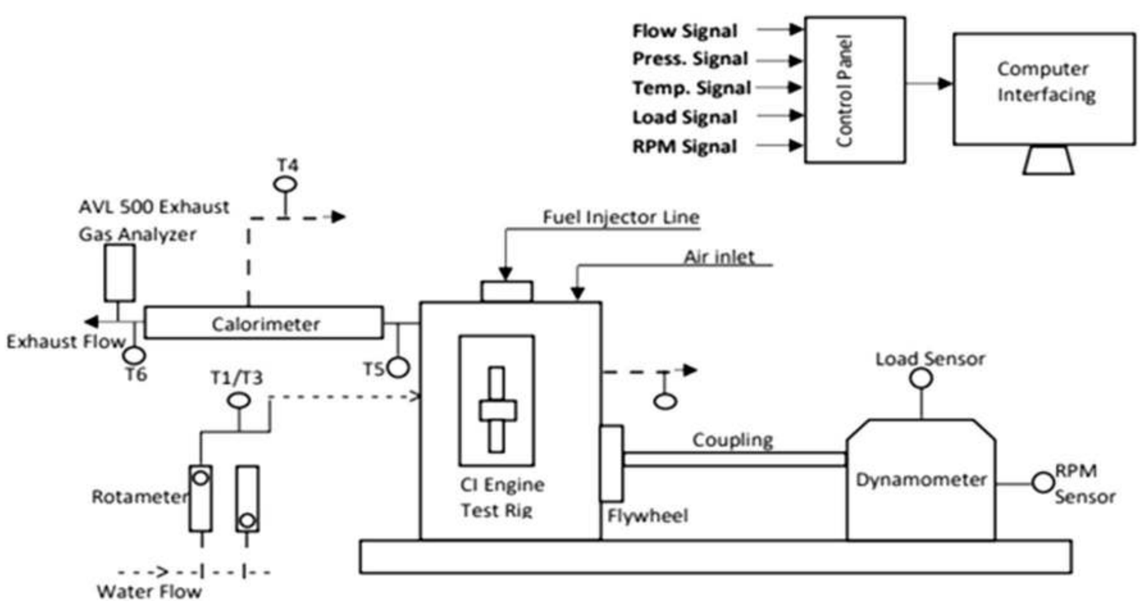

Fig. 2 The schematic diagram of the experimental setup (VCR engine) used

Fig. 3 The photographic view of the experimental setup (VCR engine) used

Table 4 Details of specifications: engine used and instruments

Parameter	Specifications
Engine make	Kirloskar
Type	Kirloskar, inline, vertical, water cooling
Cylinders	Single
Strokes	Four
Power rating	5.2 kW
Rated rpm	1500
Compression ratio	13.5:1; 14.5:1; 15.5:1 and 16.5:1
Pressure sensor	Piezo-electric sensor
Injection timing	23° BTDC
Type of ignition	Compression-ignition
Loading method	Eddy current dynamometer
Starting method	Self-start
Fuel tanks	One
Software used	National Instruments Software

Fig. 4 Photographic view of the gas analyzer AVG-500

the exhaust gas pipe. Hydrocarbons, carbon monoxide, and carbon dioxide were analyzed during this work. The photograph of the exhaust gas analyzer is given in Fig. 4.

Table 5 The summary of accuracy ranges for the measurements taken on VCR engine

Instrument-Kirloskar VCR engine	Accuracy for measurements	Uncertainty (%)
Pressure transducer	± 0.5 bar	± 0.2
Speed sensor	± 2 rpm	± 0.2
Load sensor	± 0.5 N	± 0.25
Temperature sensor	± 1℃	± 1.2
Power	± 1%	± 0.1
Specific fuel consumption	± 2%	± 0.2

Table 6 The summary of accuracy ranges for the measurements taken on AVG exhaust gas analyzer

Instrument-AVG exhaust gas analyzer	Accuracy for measurements	Uncertainty (%)
HC	± 10 ppm	± 0.2
CO	± 0.02% vol	± 0.2
CO_2	± 0.5% vol	± 0.15
NOx	± 15 ppm	± 0.1

2.4 Experimental methodology

To start and run the engine, ignition self-start switch was used, and initially, it was fueled with mineral diesel. When the operating temperature of the engine is reached, a 50% load is applied to the engine. The warming phase ends when the cooling water temperature shows a stabilized reading of 60 ℃. The engine was tested at a fixed speed of 1500 rpm. During experiments, the readings were measured and recorded digitally in the computer system. The readings for combustion and emission parameters with respect to different CR were evaluated for mineral diesel and dual biodiesel sample blends.

2.5 Error and uncertainty analysis

Error and uncertainties in the conduct of experimentation may arise due to many factors such as environmental conditions, the selection, and calibration of instruments and equipment used for research [21]. The accuracy of the experiments performed requires the analysis of uncertainties to be done. The analysis is done as explained by Dubey and Gupta [21] using the formulation given by authors the uncertainty for whole experimentation was calculated and found to be ± 0.58%. The uncertainty ranges for different parameters of VCR engine and exhaust gas analyzer are shown in Tables 5 and 6.

2.6 Statistical regression analysis

The MS Excel Software was used to perform all the statistical regression analysis and to develop a mathematical model. This model is used to develop the linear equations for fuel combustion characteristics and exhaust emission properties of different dual biodiesel sample blends with the changing parameters such as varying compression ratio and the blend percentage of biodiesel with mineral diesel. The developed linear equations along with the coefficient of regression (R^2) can be effectively used for statistical analysis and to estimate the parameters at any given compression ratio and percentage of blending for the change in properties for the sample blends used. Further, some other researchers have also tried to develop models on similar grounds either for biodiesel-diesel blends or biodiesel-biodiesel blends [9, 59]

3 Results and discussion

3.1 Characteristics of engine operation

The current research work evaluated the engine's operational parameters and characteristics of exhaust emissions using various sample blends of dual biodiesel. These sample blends of dual biodiesel were prepared earlier by the mixing of Jatropha and Mahua oil biodiesel in equal proportions of volume (1:1) with mineral diesel. The various sample blends were obtained on the percentage by volume basis B10, B20, B30, and B40 (B10 is a blend of 5% each biodiesel with 90% mineral diesel and similarly for all other sample blends). The dual biodiesel sample blends were tested for engine operational performance characteristics (mechanical efficiency, brake specific fuel consumption, brake power, and tailpipe gases temperature) and emission characteristics (carbon dioxide, carbon monoxide, and hydrocarbons) at different compression ratios (13.5:1, 14.5:1, 15.5:1, 16.5:1) by using the VCR engine. The results for various parameters are summarized in Table 8.

3.2 Brake power (BP)

BP is the power generated by the engine at the output. It defines the engine's capacity to do work with the fuel used. The brake power with the variation in CR for different tested dual biodiesel sample blends is presented in Fig. 5. The results revealed that the brake power escalated with the increase in CR. At a lower compression ratio of 13.5:1, it was found to be highest (0.994 kW) for blend B40 and at a higher CR of 16.5:1, it also came out to be highest (1.283 kW) for the same blend sample. The performance of B40 was better than other fuel blends and it was found

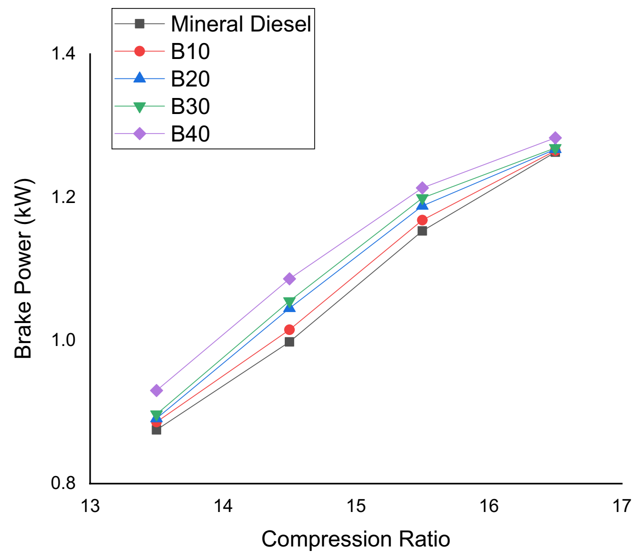

Fig. 5 Variation of BP of dual biodiesel sample blends at different compression ratios

to be greater by 1.58% than mineral diesel (1.263 kW) at a compression ratio of 16.5:1. It is worthwhile to note that the brake power also surged as the CR was increased at fixed loading. The other blend samples also had better brake power as compared to mineral diesel at different CR. The increase in brake power was seen to be linear to the compression ratio. Nagaraja et al. [34] also reported an increase in brake power for percentage increase in biodiesel blend while working on palm biodiesel. The reason for the same could be an improvement in the mixing of air–fuel ratio, better atomization-spray characteristics, and proper combustion of fuel due to preheating. Also, another reason can be the density of the B40 blend, which was more in comparison with mineral diesel. As the denser fuel–air mixture goes into the engine cylinder, the engine brake power is improved [33, 35].

3.3 Mechanical efficiency (ME)

ME indicates overall engine performance with the calorific value given by the combustion of fuel. The trends of mechanical efficiency for various dual biodiesel sample blends at variable compression ratios are shown in Fig. 6. It was noted that the overall ME of the sample blends (dual biodiesel) increased as the CR was increased, that means the ME of the dual biodiesel samples varied directly with the variation of CR. ME was found 19.66, 21.28, 21.92, and 23.97% for B10, B20, B30, and B40 at CR of 13.5:1, respectively. For higher CR of 16.5:1, it came out to be 30.1, 31.64, 32.55, and 33.48% for B10, B20, B30, and B40, respectively. The mechanical efficiency was found to be 18.95% and 29.78% for mineral diesel at 13.5:1 and 16.5:1

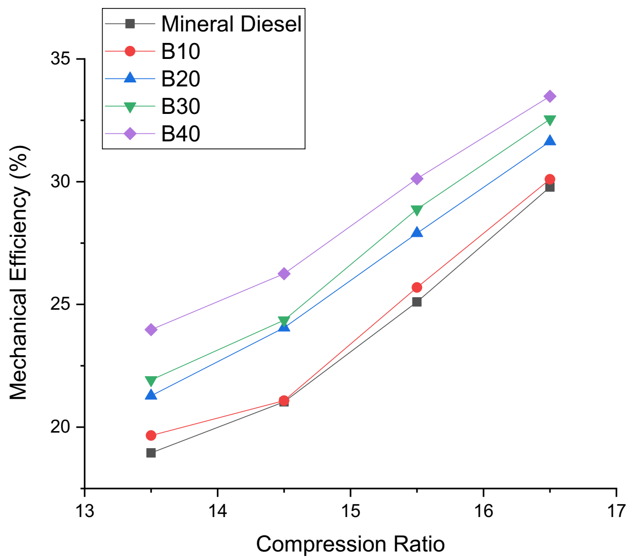

Fig. 6 Variation of ME of dual biodiesel sample blends at different compression ratios

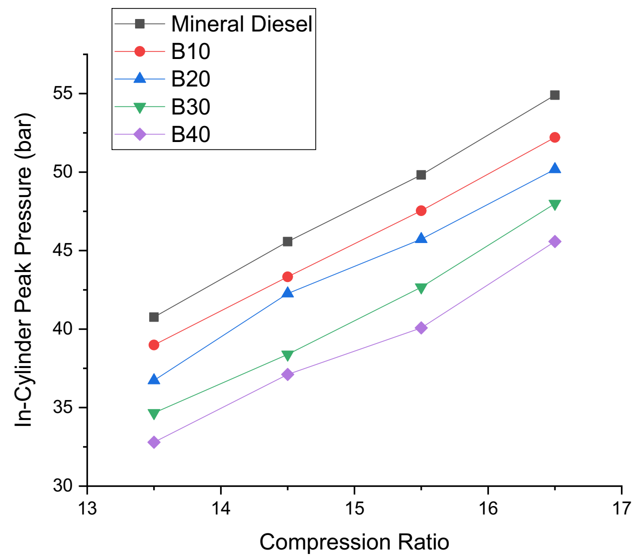

Fig. 7 Variation of In-CPP of dual biodiesel sample blends at different CR

CR, respectively. The blend sample B40 had the maximum ME for CR 16.5:1 which was 33.48%. Further, it was 12.42% greater than conventionally used diesel fuel.

Agarwal and Rajamanoharan [4] also reported an increase in engine ME with the rise in blend percentage at a higher CR in the case of Karanja biodiesel blends. This could be due to the better lubrication properties of blended dual biodiesel samples owing to the presence of methyl esters in the fuel samples used for combustion [37].

3.4 In-cylinder peak pressure (In-CPP)

The peak pressure produced in the combustion chamber inside the engine cylinder just after the TDC is known as the In-cylinder peak pressure. The trends of In-cylinder peak pressure were found to be increasing with an increase in CR. However, it was revealed to be decreasing with the higher blend percentage of biodiesels in mineral diesel. The trends for various sample blends tested at different CR are presented in Fig. 7.

At lower CR, mineral diesel (D100) had a lower value of In-CPP (1.23 bar) whereas it surged with the increase in CR and was found to be highest (2.14 bar) for mineral diesel at 16.5:1 CR. The results revealed that the dual biodiesel sample blends had a lower value of In-CPP. At CR of 13.5:1, it was found to be low and similar to that of diesel for samples B10, B20, and B30 (1.21, 1.2, and 1.2 bar, respectively), and B40 had an even lower In-CPP of 1.19 bar. However, even though In-CPP of biodiesel samples surged for higher CR, it was still found to be lower in comparison with mineral diesel. The value of In-CPP for mineral diesel (D100) came out to be 2.14 bar, for B30 it was 1.84 bar, and for B40 1.78 bar at the maximum CR (16.5:1). On average, it was evident that among all the tested samples of dual biodiesel, the B40 had the lowest value which was 16.82% lower than mineral diesel. The reason for the same could be the lower calorific values of biodiesel than mineral diesel. Muralidharan and Vasudevan reported a similar decrease in In-CPP during their research on biodiesel produced from the waste cooking oil and diesel blends. [33].

3.5 Brake-specific fuel consumption (BSFC)

BSFC indicates the fuel efficiency of an IC engine. It primarily compares the consumption of fuel to the power produced by the engine. BSFC reduced progressively with the increase in CR from 13.5 to 16.5 for all tested dual biodiesel sample blends and a similar trend was also observed for mineral diesel. At CR of 13.5:1, the BSFC was found to be 1.69 (B10), 1.71 (B20), 1.72 (B30), and 1.78 (B40) kg/kW-s. At CR of 16.5:1, it was lower at 1.35 (B10), 1.41 (B20), 1.48 (B30), and 1.59 (B40). It was evident that as the blend percentage increased, the BSFC of the fuel also got higher. The dual biodiesel blend B40 had the highest BFSC at CR of 16.5:1 which was 20.45% greater as compared to mineral diesel.

This possible reason for this could be because of the lower heat content value of B40 due to the higher methyl ester content present in the dual biodiesel sample blends when compared with the mineral diesel. Mathew and Anand reported similar results during their work on biodiesel prepared from fresh and waste cooking oil [32]. The variation of BSFC of dual biodiesel sample blends at different CRs is presented in Fig. 8.

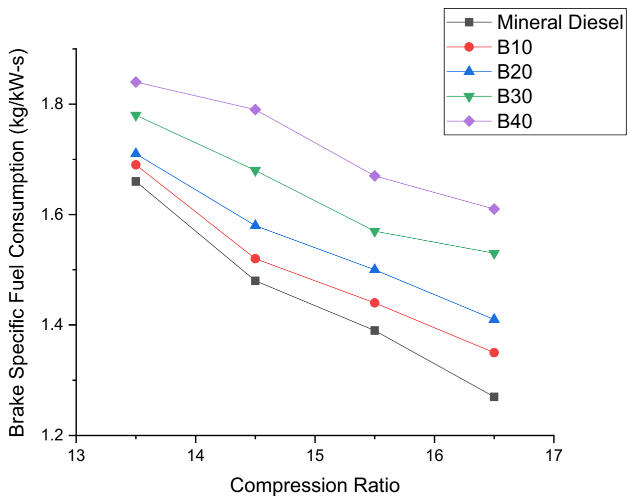

Fig. 8 Variation of BSFC of dual biodiesel sample blends at different compression ratios

3.6 Exhaust gas temperature (EGT)

The results of EGT for different dual biodiesel sample blends are shown in Fig. 9. The results clearly show that the temperature of exhaust gases was lower for all the sample blends when compared to EGT of mineral diesel when the CR was raised from 13.5:1 to 16.5:1. The B10 blend, however, had nearly the same values of EGT as that of mineral diesel (D100) which was recorded to be 185.7 ℃ at the lowest CR and 279.4℃ at the higher CR. The B40 blend had the lowest EGT among all tested sample blends. It was found to be 132.1 ℃ and 220.7 ℃ for the lowest and highest

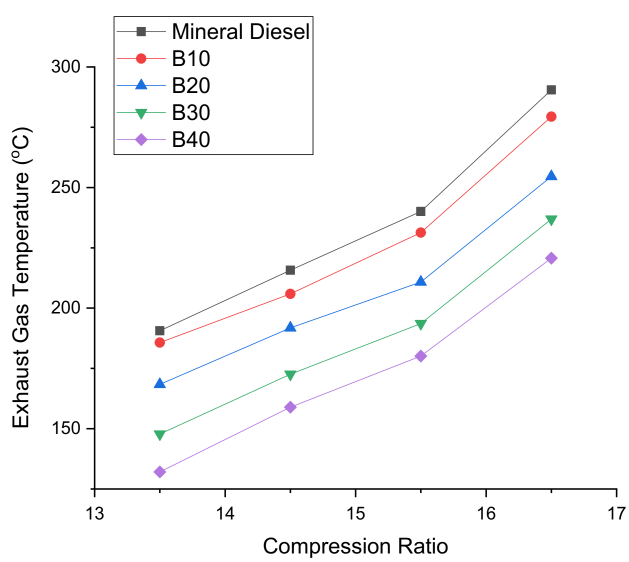

Fig. 9 Variation of EGT of dual biodiesel sample blends at different compression ratios

tested compression ratios. For the highest sample blend B40, the EGT was 11.1–69.8 ℃ lower than mineral diesel for different CR (13.5:1–16.5:1). The lower EGT recorded for dual biodiesel sample blends could be due to the lower heat value of the biodiesel in comparison with the mineral diesel. The present study as discussed above also showed similar results. The lower amount of exhaust losses could also be attributed to higher brake power and mechanical efficiency [11].

3.7 Emission analysis

The emission analysis was done with the help of a 5-gas analyzer to evaluate the exhaust emissions of carbon dioxide (CO_2), hydrocarbons (HC), and carbon monoxide (CO) for all dual biodiesel samples. The Indian National standards followed for the analysis of emission are given in Table 7.

3.8 Carbon monoxide (CO)

The CO emissions of an engine largely depend upon the quality of fuel used, amount of oxygen present in the fuel, ratio of the A/F mixture, turbulence, and temperature inside the engine cylinder. The trend of CO exhaust for dual biodiesel sample blends at various CR is presented in Fig. 10. The results revealed that the CO emissions were found to be 0.07, 0.06, and 0.06% at CR of 13.5:1 for sample blends B10, B20, and B30, respectively. Further, with the increase in CR, the CO emissions were found to be even lower. It was 0.06, 0.05, and 0.04% for sample blend B10, B20, and B30, respectively. However, the sample blend B40 had the lowest value for CO gas emission with the values of 0.05% at a lower CR of 13.5:1 and 0.04% at a higher CR of 16.5:1. This percentage was even lower than that of mineral diesel. The CO emission of other samples was also less than mineral diesel at various CR's. In comparison with mineral diesel, B40 blend emitted 33.33% lesser CO gases (Table 8).

The reason behind less emission of CO gas by all dual biodiesel samples is the preheating process that improves the fuel atomization and sprays characteristics [21]. These trends revealed the quality of the combustion of dual biodiesel due to more quantity of oxygen present in these

Table 7 The summary of Indian National standards used for the analysis of emission

Elements	Standards for measurements
HC	–
CO	IS 11293: 1992
CO_2	IS 13270: 1992 (1999 reaffirmed)

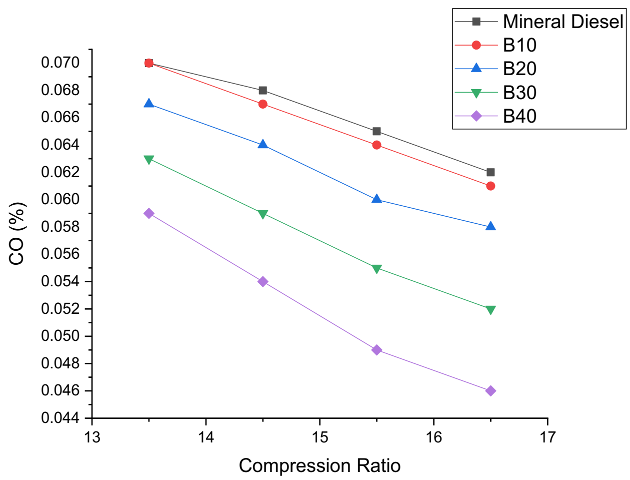

Fig. 10 Variation of carbon monoxide emissions of dual biodiesel sample blends at different compression ratios

samples. Further, results showed that as the blend percentage rises, the emission of CO decreases. The increase in the compression ratio reduced the carbon monoxide output due to the higher amount of temperature produced during the air–fuel combustion [19]. The result analysis clearly revealed that a greater blend percentage of biodiesel results in lower emissions of toxic CO. Dubey and Gupta reported lower CO emissions during the analysis of Jatropha and turpentine biodiesel at a constant speed using a diesel single-cylinder engine [21]. Chauhan et al. also reported similar results in the case of diesel and Jatropha biodiesel blends in a diesel single-cylinder engine at constant load. A similar decrease in carbon monoxide emission was also reported by other researchers with the increase in CR and blend percentage during their research work [15].

3.9 Carbon dioxide (CO_2)

The trend of CO_2 emission for dual biodiesel sample blends at different CRs is presented in Fig. 11. All sample blends emit higher CO_2 as compared to mineral diesel with increasing CR. The emissions of carbon dioxide were found to be lower for all dual biodiesel sample blends at CR of 13.5:1 (1.09, 1.43, 1.61, and 1.8% for sample blends B10, B20, B30, and B40, respectively). However, the emissions values increased with the increase in compression ratio. At a higher CR of 16.5:1, it was recorded to be 1.7, 1.8, 2.0, and 2.1% for sample blend B10, B20, B30, and B40, respectively. The CO_2 emissions were recorded lowest for mineral diesel. At a lower CR of 13.5:1, it was recorded to be 0.98%, whereas at a higher CR (16.5:1) it was observed to be 1.2%. It was observed that CO_2 emission was 42.85% lower when compared with the highest percentage blend of biodiesel.

The higher value of CO_2 emissions could be due to enhanced air–fuel combustion inside the cylinder due to the greater oxygen content present in the dual biodiesel blends. Higher CO_2 emission as compared to CO is the indication of better fuel combustion in an engine cylinder. The higher quantity of CO_2 is although harmful to the environment, but less toxic than CO and also consumed by various plants for the photosynthesis process. Dubey and Gupta revealed greater CO_2 in the exhaust for Jatropha and turpentine dual biodiesel sample blends tested at a fixed speed in the 4-stroke, 1-cylinder CI engine [23]. Other researchers also reported similar results in case of other different biodiesel blends [21, 27].

3.10 Hydrocarbons (HC)

The trend of HC emission for different dual biodiesel sample blends at various CR is shown in Fig. 12. All the dual biodiesel sample blends had lower HC emissions than mineral diesel at all CRs for fixed loading conditions. The HC emissions were recorded to be highest (44 ppm) for mineral diesel at the lowest CR of 13.5:1. However, with the rise in CR, the HC emissions were reduced and were recorded to be 32 ppm for mineral diesel. The dual biodiesel sample blends had lower HC emissions as compared to the mineral diesel. Further, HC emission was found to be the lowest for the highest sample blend percentage B40. The emissions of HC have recorded 28 ppm at a lower CR (13.5:1), and it even lower down to 12 ppm at a higher CR (16.5:1) for dual biodiesel sample blends. Also, the other sample blends had lower HC emissions when compared with the mineral diesel at all CRs.

The increased value for CR in the engine resulted in lowering the HC percentage in the exhaust for all tested dual biodiesel sample blends. The lowering of HC emissions could be attributed to the higher amount of temperature inside the engine cylinder with the increase in CR. HC emissions for B10 blend and mineral diesel were 31% and 32%, respectively. Further, B20, B30, and B40 blends had 22%, 18%, and 12% HC emission, respectively, at CR of 16.5:1.

Chauhan et al. also analyzed Jatropha biodiesel blends on the CI engine and reported a decrease in emissions of HC for biodiesel than mineral diesel [15]. Similar results of HC emission were also reported by other researchers in the case of other different biodiesel blends [17, 57].

Saravanan et al. [46] prepared a mixture of Mahua and Rapeseed oil biodiesel in the same proportions by volume and performed an experimental analysis. They observed that the performance of the B20 blend was very close to that of mineral diesel during testing. The brake thermal efficiency for sample blend B20 was noted 2.8% lower than that of mineral diesel. Also,

Table 8 Summarizes the variation of engine performance and emission characteristics of all dual biodiesel samples at different compression ratios compared with mineral diesel

Compression ratio	Parameter	Units	B10	B20	B30	B40	B20 Blend [14]	Mineral diesel
13.5:1	BP	kW	0.886	0.891	0.897	0.994	–	0.875
	ME	%	19.66	21.28	21.92	23.97	–	18.95
	In-CPP	bar	1.21	1.2	1.2	1.19	–	1.23
	BSFC	kg/kW-s	1.69	1.71	1.72	1.78	–	1.66
	EGT	℃	185.7	144.1	148.2	132.1	–	190.6
	CO	%	0.07	0.06	0.06	0.05	0.035	0.07
	CO_2	%	1.09	1.43	1.61	1.73	–	0.98
	HC	PPM	43	41	36	28	–	44
14.5:1	BP	kW	0.998	1.12	1.185	1.189	–	1.165
	ME	%	21.08	24.05	24.36	26.25	–	21.03
	In-CPP	bar	1.54	1.55	1.52	1.52	–	1.65
	BSFC	kg/kW-s	1.51	1.54	1.58	1.57	0.31 (kg/kWh)	1.48
	EGT	℃	201.8	194.5	177.1	167.1	410	215.7
	CO	%	0.07	0.06	0.05	0.05	0.038	0.07
	CO_2	%	1.3	1.5	1.8	1.9	2.6	1.1
	HC	PPM	40	33	27	23	14	40
15.5:1	BP	kW	1.204	1.208	1.255	1.276	–	1.197
	ME	%	25.69	27.9	28.88	30.12	–	25.1
	In-CPP	bar	1.73	1.56	1.5	1.56	–	1.89
	BSFC	kg/kW-s	1.44	1.5	1.53	1.58	0.33 (kg/kWh)	1.39
	EGT	℃	225.3	201.8	193.6	180.1	395	240.1
	CO	%	0.06	0.05	0.05	0.04	0.018	0.06
	CO_2	%	1.6	1.7	1.9	2	2.5	1.1
	HC	PPM	31	22	18	12	8	32
16.5:1	BP	kW	1.265	1.267	1.269	1.283	–	1.263
	ME	%	30.1	31.64	32.55	33.48	–	29.78
	In-CPP	bar	1.99	1.86	1.84	1.78	–	2.14
	BSFC	kg/kW-s	1.35	1.41	1.48	1.59	0.31 (kg/kWh)	1.32
	EGT	℃	279.4	254.6	223.3	220.7	380	290.5
	CO	%	0.06	0.05	0.04	0.04	0.010	0.06
	CO_2	%	1.7	1.8	2	2.1	2.5	1.2
	HC	PPM	31	22	18	12	7	32

carbon monoxide, unburned hydrocarbons, and smoke outlets for emissions were found to be 20.7%, 8.6%, and 7% lower as compared to diesel, whereas NO_x emissions increased by 3.8% [46]. Srithar and Balasubramanian [55] have also prepared a fuel from the combination of two biodiesels blend with diesel and found two samples among them had properties almost similar to that of diesel fuel. The thermal efficiency of DPJ1 (DPJ1 = Diesel 90% + Pongamia Pinnata 5% + Jatropha 5%) and DPJ2 (DPJ2 = Diesel 80% + Pongamia Pinnata 10% + Jatropha 10%) were closer to that of diesel, and their specific fuel consumption was almost equal to that of diesel. From the emissions analysis, the results of DPJ1 and DPJ2 were found to be similar to diesel. The authors recommended these blend fuels as fuel for stationary diesel engines used for agricultural purposes [55].

3.11 Statistical regression analysis

The variation in engine emission and performance characteristics of all the sample blends of dual biodiesel were compared graphically with the change in CR. The MS Excel software was used for statistical regression analysis to determine the linear equations, correlation coefficient or regression coefficient (R^2), and regression equations. The regression coefficient (R^2) depicted the trends of various combustion and emission properties with the change in CR for any particular blend. The outcomes showed that all the engine performance parameters were directly proportional to the CR except CO and HC emissions which were found to be inversely proportional to the CR.

The mathematical models developed revealed a high coefficient of regression or regression coefficient (R^2)

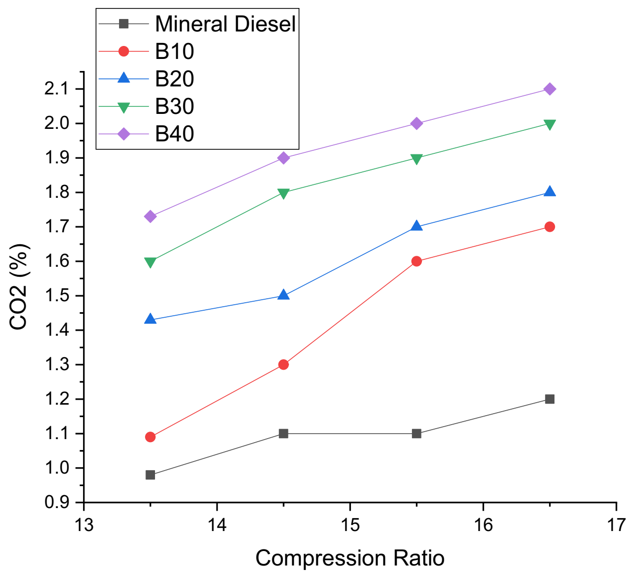

Fig. 11 Variation of carbon dioxide emissions of dual biodiesel sample blends at different compression ratios

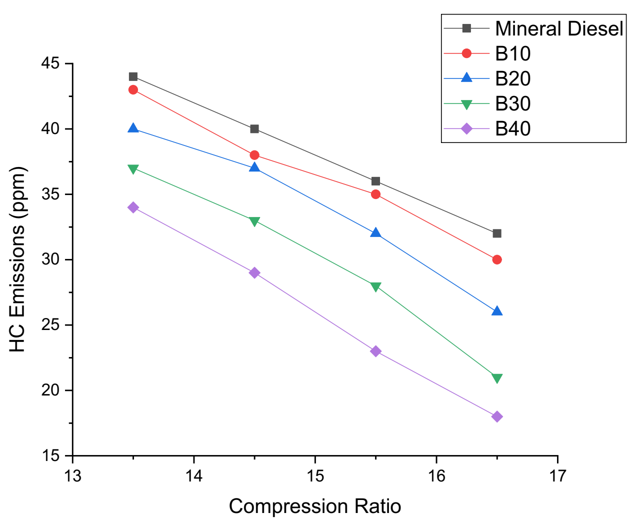

Fig. 12 Variation of hydrocarbon emissions of dual biodiesel sample blends at different compression ratios

between engine operational parameters and different compression ratios. The mathematical equation and regression coefficient for different dual biodiesel sample blends are summarized in Table 9.

4 Conclusions

In the current experimental work, dual biodiesel blends with diesel in different ratios were evaluated and compared with diesel for engine performance and emission characteristics on a VCR engine. The outcomes of the study revealed that the change in CR leads to the varied engine outputs and emissions characteristics which are comparable with those of mineral diesel in a significant way. The conclusions drawn from the present experimental study are summarized below:

- All dual biodiesel samples tested had slightly greater brake power than mineral diesel. It varied from 0.15% to 1.58% more than mineral diesel (for sample blends B10 to B40) at the maximum value of compression ratio and under fixed loading conditions.
- The mechanical efficiency increased with an increase in CR at fixed loading conditions for both dual biodiesel samples and mineral diesel. Again, sample blends B10 to B40 had a little higher mechanical efficiency of 1.07% to 12.42% more than mineral diesel.
- The In-cylinder peak pressure of mineral diesel had a comparatively higher value than dual biodiesel samples and it lowered among the blend samples; B10 to B40 by 0.15 to 0.36 bar at the highest compression ratio tested.
- The increase in biodiesel blending percentage in the dual biodiesel samples resulted in higher brake specific fuel consumption, which was observed to be the highest for sample B40 (26.77% more than mineral diesel) and least for sample B10 (2.27%) when compared with mineral diesel.
- The exhaust gas temperature of all the dual biodiesel samples was found to be lower as compared to mineral diesel. B20 recorded 35.9℃, B30, and B40 blend had 53.6℃ & 69.8℃ while B10 had EGT 11.1℃ lower than EGT of mineral diesel at 16.5:1 compression ratio.
- The emissions for carbon monoxide were recorded to be lower for all dual biodiesel samples than that of mineral diesel at maximum compression ratios. Further, the exhaust emissions of hydrocarbons were also reduced significantly for all dual biodiesel samples.
- The carbon dioxide gas emission was higher for all dual biodiesel samples in comparison with mineral diesel at all compression ratios.
- The fuel parameters tested on the engine in terms of combustion, efficiency, and emissions reported better results for dual biodiesel samples.

The current research study revealed that taking into consideration the overall engine combustion performance and emission parameters, the dual biodiesel B20 had superior fuel combustion and emission properties among all tested samples at a compression ratio of 16.5:1 and 50% loading on the engine. From current findings, it may be concluded that the blended dual biodiesel showed comparatively better combustion and emissions properties at

Table 9 The mathematical relation between different engine output parameters and compression ratio (x) for various dual biodiesel sample blends and mineral diesel

Compression ratio	Properties	Units	Mathematical relation	Regression coefficient(R^2)
Mineral diesel	BP	kW	0.119 x −0.669	0.809
	ME	%	3.656 x −31.12	0.974
	In-CPP	Bar	0.297 x −2.727	0.979
	BSFC	kg/kW-s	− 0.141 x + 3.552	0.985
	EGT	℃	32.41 x −251.9	0.964
	CO	%	− 0.004 x + 0.125	0.8
	CO_2	%	0.066x + 0.105	0.896
	HC	PPM	4x + 98	1.0
B10	BP	kW	0.134 x −0.926	0.962
	ME	%	3.593 x −29.76	0.958
	In-CPP	Bar	0.253 x −2.177	0.989
	BSFC	kg/kW-s	− 0.109 x + 3.132	0.953
	EGT	℃	30.46 x −233.8	0.922
	CO	%	− 0.004 x + 0.125	0.8
	CO_2	%	0.273 x −2.722	0.938
	HC	PPM	− 4.1 x + 98.75	0.991
B20	BP	kW	0.121 x −0.702	0.904
	ME	%	3.493 x −26.17	0.995
	In-CPP	Bar	0.199 x −1.442	0.906
	BSFC	kg/kW-s	− 0.094 x + 2.95	0.932
	EGT	℃	33.88 x −309.4	0.935
	CO	%	− 0.004 x + 0.115	0.80
	CO_2	%	0.317 x −3.302	0.841
	HC	PPM	− 6.2x + 124	0.990
B30	BP	kW	0.118 x −0.627	0.777
	ME	%	3.641 x −27.68	0.988
	In-CPP	Bar	0.19 x −1.335	0.880
	BSFC	kg/kW-s	− 0.077 x + 2.732	0.924
	EGT	℃	24.18 x −177.1	0.988
	CO	%	− 0.006x + 0.14	0.90
	CO_2	%	0.379 x −4.067	0.734
	HC	PPM	− 6x + 115.5	0.952
B40	BP	kW	0.095 x −0.245	0.836
	ME	%	3.24 x −20.14	0.990
	In-CPP	Bar	0.169 x −1.052	0.805
	BSFC	kg/kW-s	− 0.069 x + 2.632	0.426
	EGT	℃	27.88 x −243.2	0.967
	CO	%	− 0.004 x + 0.105	0.8
	CO_2	%	0.1 x + 0.45	1.0
	HC	PPM	− 5.3 x + 99.75	0.997

a higher compression ratio. Further, these could become a substitute for mineral diesel in the future.

4.1 Future work

Further experimental studies can be conducted to check the oxidation stability of the various dual biodiesel sample blends. The sample blends having better oxidation resistance can be further tested for their commercial viability.

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