Investigations on performance and emission parameters of direct injection diesel engine running with *Mesua ferrea* oil methyl ester blends

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Abstract

The present study deals with the experimental analysis on performance and emission characteristics of VCR diesel engine operating through *Mesua ferrea* oil methyl ester (MFOME) blends at different injection operating pressures of 180 bar, 200 bar, and 220 bar. Four test fuels were used in this analysis namely diesel, MFOME10, MFOME20, and MFOME30. The conventional diesel has shown higher BTE than the leftover MFOME blends while the BSFC was also lowered for conventional diesel. Emission parameters namely CO, UHC, and smoke opacity were reduced while the CO₂ and NO_x were greater intended for MFOME blends than conventional diesel. The similar trend was followed at all three injection pressures and better results were noticed at an injection operating pressure of 220 bar. The performance of MFOME20 is somewhat nearer to conventional diesel and better emission concerning CO, UHC, and smoke opacity were with MFOME20.

Keywords *Mesua ferrea* · Performance · Brake specific fuel consumption · Transesterification · Emissions

Abbreviations

MFOME	<i>Mesua ferrea</i> oil methyl ester	IP	Injection pressure
MFOME 10	MFOME 10% in diesel	VCR	Variable compression ratio
MFOME 20	MFOME 20% in diesel	QB	Quantity of biodiesel (% by volume)
MFOME 40	MFOME 40% in diesel	QD	Quantity of diesel (% by volume)
K ₃ PO ₄	Tripotassium phosphate	tfc	Total fuel consumption (Kg/hr)
BTE	Brake thermal efficiency (%)	CV	Calorific value (MJ/kg)
BSFC	Brake specific fuel consumption (kg/kW h)	BP	Brake power (kW)
BSEC	Brake specific energy consumption (MJ/kW h)	N	Speed (rpm)
CO	Carbon monoxide (%)	T	Torque (N m)
CO ₂	Carbon dioxide (%)	VB	Volume of burette (m ³)
UHC	Unburnt hydrocarbon (ppm)	ρ_{diesel}	Density of diesel (kg/m ³)
NO _x	Nitrogen oxides (ppm)	$\rho_{Biodiesel}$	Density of biodiesel (kg/m ³)
CI	Compression ignition	t	Time (s)
DI	Direct injection		
ASTM	American standards for testing materials		
ADC	Analog to digital converter		
CR/CRs	Compression ratio/Compression ratios		

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1 Introduction

In the current scenario, the crude oil reserves in the world are getting exhausted more rapidly. This made investigators look for alternate resources which are able to recompense the loss. Hence, one of the superlative promising ways to achieve this by the investigators is biofuels. Biodiesel is the famous favored remedy for bulk production and additionally for scientific demand. The majority of agriculture, transportation, and industrial sectors run currently with diesel engines. Also, biodiesel is the most chosen alternative source owing to its lower carbon content and ecological benefits. Biodiesel can be derived from different oils of vegetables, crops, and fats from animals [1, 2]. There is a restriction of use of vegetable oils directly in diesel in engines on account of having higher viscosity and thus the viscosity of oils must be reduced. This could be reduced by a familiar and less expensive technique namely transesterification or alcoholysis process. For the period of transesterification reaction, the methanol or ethanol or other alcohols are used however the methanol and ethanol are extensively preferred owing to their cheaper availability. Catalysts are used with the alcohols to improve the reaction rate [3, 4]. Agarwal et al. [5] used the transesterification method as an imposing method of reducing the viscosity of oil. After this, the desirable properties need to be assessed for the acquired biodiesel (methyl ester), and hence they tested and reported the physicochemical properties of diverse biodiesels and evaluated according to ASTM standards. From their conclusion, more are less all the biodiesels are within the ASTM range. The diesel engine is required to undergo for the assessment of engine performance and exhaust emissions with several blend grouping of biodiesel and conventional diesel to find the optimum combination which can be suited for the better improvement of performance and good reduction of emissions [6]. Up to 30% blending of biodiesel with conventional diesel is favorable in CI engine for suitable performance and emissions assessment, but the combustion parameters can improve at up to somewhat blending on account of superior oxygen presence in the biodiesel [7]. Hwai et al. [8] used *Calophyllum inophyllum*, *Jatropha curcas*, and *Ceiba pentandra* oil biodiesel blends (B10, B20, B30, and B50) in their investigation. The biodiesel blend B10 shown the optimum performance than leftover blends in terms of BTE, BSFC, and torque. Further, the exhaust emissions concerning the biodiesel blends were diminished than conventional diesel. Haveer et al. [9] carried out an experimental investigation on diesel engine operating with the blends of Sal methyl ester. From their results, the BTE was found to be lowered with increase in blend ratio and the BSEC was attained minimum in favor of B10 as compared to left over test fuels. But, the exhaust

emissions of CO, UHC, and smoke were noticed less than diesel. Further, the NO_x emissions found higher with the blends of sal methyl ester.

With the exception of the above literature, a number of studies have been conducted with different vegetable oils as a biodiesel source. To the extent that this study concern, the endeavor using *Mesua ferrea* oil as the resource is quite a novel move towards the biodiesel research. Also, the variation in injection operating pressure for the assessment of performance and emission is a fresh attempt with this *Mesua ferrea* oil methyl ester blends.

2 Methodology

2.1 Production of biodiesel

In the current investigation, the *Mesua ferrea* seeds were collected from Araku tribal area which is located in Visakhapatnam District, India. This seed yields oil of 65–70%. Initially, the seed was dried up at a temperature of 60 °C using an oven and crushed through seed crusher. Thereafter, took out the oil with the assist of an oil mill. Finally, the oil was filtered and bleached to remove the powder particles present in the extracted oil. The following process was carried out for the preparation of *Mesua ferrea* oil biodiesel. The oil was undergone transesterification process to bring down the viscosity of pure *Mesua ferrea* seed oil. Throughout the process, the 500 ml of oil was heated in a round glass neck flask by maintaining a uniform temperature of 55 °C. The catalyst (K₃PO₄) and methanol solvent was supplemented to the hot oil. The stirring of the blended solution was done using a magnetic stirrer and the speed was kept up at 700 rpm. A condenser was fixed at the top of the flask and was circulated with cooling water to maintain the uniform reaction temperature. The process was continued for an hour by maintaining the reaction temperature of 65 °C. After the completion of reaction, the biodiesel and glycerin were separated with the help of separating funnel. The end separated biodiesel was allowed for heating to remove the water particles contained in it. After attaining the final methyl ester, the physicochemical properties were assessed for the MFOME as per the ASTM values and the properties were contained by the range of ASTM. Properties of MFOME were presented in Table 1.

2.2 Experimental setup

Figure 1 depicts the schematic illustration of the experimental test rig. The engine used in this investigation was a single cylinder, water cooled, and four-stroke DICl engine. The technical specifications of the engine test rig were presented in Table 2. At the inlet of the engine, the diesel and

Table 1 Properties characterization of MFOME oil and their blends

Fuel property (units)	Method (ASTM)	Test range	MFOME10	MFOME20	MFOME30	MFOME100
Kinematic Viscosity at 40 °C (Cts)	D-445	2.5–6	3.2	3.5	3.8	4.4
Cetane Number	D-976	47 (min)	57	58	58	59
Calorific value (MJ/kg)	D-4809	42	40.81	39.66	39.43	38.86
Copper corrosion	D-130	1a	1a	1a	1a	1a
Density at 15 °C (kg/m ³)	D-1298	860–900	863	872	877	888
Flashpoint (°C)	D-92	130 (min)	129	140	143	156

Fig. 1 Schematic representation of experimental setup

Table 2 Technical specifications of the experimental setup

Parameter	Description
Make	Kirloskar TAF-1
Number of cylinders	1
Stroke length/Bore	110 mm/87.5 mm
Compression ratio	17.5
BP	3.5 kW
Rotational speed	1500 rpm
Injection pressures	180 bar, 200 bar, and 220 bar
Injection point variation	30° Before TDC
Emissions measurement	MARS make

biodiesel tanks were connected individually through the burette to measure the fuel consumption. In addition, the air-box through an airflow sensor was linked to the engine.

In the same way, in order to acquire the data of exhaust emissions, the MARS makes gas analyzer and the smoke meter was used in the exhaust part of the engine. The sensors were connected to the computer through ADC. The calibration details of each instrument were reported in Table 3.

The test fuels were prepared by blending the MFOME with conventional diesel at different proportions of 10% (MFOME10), 20% (MFOME20), and 30% (MFOME30) by volume. The tests were carried out by varying the injection operating pressures namely 180 bar, 200 bar, and 220 bar respectively at a uniform rotational speed of 1500 rpm. The compression ratio (CR17.5) of the engine was also unchanged. Also, the test was undergone at maximum engine load (100% load condition). The experiment was conducted three times and the average values were represented as graphs. The performance parameters

Table 3 Measurement and accuracy of the devices

Measurement constraint	Accuracy	Limit
Load sensor	± 0.2 kg	0–50 kg
Speed sensor	± 25 rpm	1200–1800 rpm
Temperature sensor	± 1%	0–100 °C
Crank angle sensor	± 0.1%	Resolution of 1°
CO	± 0.001%	0–99.9%
UHC	± 2 ppm	0–15,000 ppm
NO _x	± 1 ppm	0–5000 ppm
Smoke	± 0.1%	0–99.9%

namely BTE and BSFC were calculated using the following relations.

$$BTHE = \frac{BP}{(tfc \times CV)} \quad (1)$$

$$BSFC = \frac{tfc}{BP} \quad (2)$$

where

$$tfc = \frac{VB \times (QB \times \rho_{biodiesel} + QD \times \rho_{diesel})}{t},$$

$$BP = \frac{2\pi NT}{60000}, \text{ (kW)}$$

3 Results and discussions

3.1 Performance parameters

The performance parameters namely BTE and BSFC were presented in terms of graphical representation by varying the injection pressures (IPs) and different engine load settings.

3.1.1 BTE

BTE of MFOME blends and conventional diesel at three IPs were depicted in Fig. 2. The MFOME blends have shown lower BTE than the conventional diesel. The cause behind this was that the MFOME unfortunate atomization of fuel and small ignition delay. Further increase in blend ratio leads to lower ignition delay and thus it results in the premature begin of combustion in favor of biodiesel as compared to conventional diesel [10, 11]. It can be observed that the BTE was increased at higher fuel IPs. In view of the fact that at higher IPs the fine fuel droplets atomized and vaporizes rapidly than at lower injection

Fig. 2 Variation in BTE with injection pressure (IP)

pressures (bigger fuel droplets are formed) on account of an improved air–fuel mixture [12, 13]. At utmost load, the BTE of conventional diesel, MFOME10, MFOME20, and MFOME30 were observed as 32.24%, 29.27%, 31.08% and 28.34% at 180 bar, 33.14%, 30.77%, 32.25%, and 29.54% at 200 bar, 32.21%, 31.11%, 33.17%, and 30.72% at 220 bar respectively. For all the test fuel investigated in this work, the BTE was observed greater at an IP of 220 bar.

3.1.2 BSFC

The disparity of BSFC with injection pressure is shown in Fig. 3 and it was apparent that the lower BSFC observed with conventional diesel than leftover blends of MFOME. Since the MFOME has lower viscosity, lower calorific value, and higher mass than conventional diesel. Hence, the BSFC decreased irrespective of blend ratios of MFOME. It also

Fig. 3 Variation in BSFC with different injection pressures

was found that at higher injection pressures, the BSFC for all the blends were decreased together with conventional diesel. The cause behind this was that the better integration of fuel and air caused by finer fuel droplets and hence it was noticed elevated combustion [12–14]. At maximum load state, BSFC of conventional diesel, MFOME10, MFOME20, and MFOME30 were perceived like 0.27 kg/kW h, 0.32 kg/kW h, 0.28 kg/kW h, and 0.31 kg/kW h at the injection pressure of 180 bar, 0.25 kg/kW h, 0.3 kg/kW h, 0.26 kg/kW h, and 0.28 kg/kW h at 200 bar, and 0.23 kg/kW h, 0.28 kg/kW h, 0.25 kg/kW h, and 0.26 kg/kW h at 220 bar respectively. The minimum BSFC was observed at an injection pressure of 220 bar.

3.2 Emission parameters

The emission parameters of MFOME blends and conventional diesel were assessed and represented graphically at three diverse IPs. The graphs were depicted at maximum load condition (100% load condition).

3.2.1 CO

Figure 4 portrays the distinction of CO emissions at various injection pressures. It can be observed that the MFOME blended test fuels have lesser CO emissions than conventional diesel owing to better-quality complete combustion. This was mainly owing to having greater cetane number [11] and occurrence of oxygen superiority [15]. At higher injection pressures, the CO emissions of the entire investigation fuels were inferior irrespective of fuel blends. This was because of the enhanced combustion of finer fuel droplets [12]. The CO emissions of diesel, MFOME10, MFOME20, and MFOME30 were noticed as

Fig. 4 CO emissions at different injection pressures

Fig. 5 CO₂ emissions at different injection pressures

0.099%, 0.054%, 0.046%, and 0.073% at an injection pressure of 180 bar, 0.087%, 0.042%, 0.034%, and 0.055% at 200 bar, and 0.0798%, 0.036%, 0.029%, and 0.041% respectively at 220 bar. The inferior CO emissions were perceived at 220 bar with MFOME20.

3.2.2 CO₂

The variation of CO₂ with injection pressure was depicted in Fig. 5. It has become aware of lesser CO₂ of MFOME blends than conventional diesel. The principal reason behind this was that the more oxygen present in MFOME blends and thus the combustion efficacy was improved [16]. Further, the CO₂ was augmented towards elevated injection pressures. This was on account of whole combustion of fuel which was due to finer fuel droplets mix up the fuel and air suitably. At lower injection pressures the ignition delay was more due to enlarged fuel droplet diameter and hence the combustion was incomplete. Thereby, the CO₂ was lowered at lower injection pressures [17]. At 220 bar, the CO₂ was observed higher with MFOME20. CO₂ emissions of diesel, MFOME10, MFOME20, and MFOME30 were 7.21%, 8.21%, 8.4%, and 8% at an injection pressure of 180 bar, 7.5%, 8.25%, 8.45%, and 8.05% were at 200 bar, 7.9%, 8.29%, 8.5%, and 8.06% at 220 bar correspondingly.

3.2.3 UHC

Figure 6 represents the change in UHC emissions at different IPs. The UHC emissions were lowered for MFOME blends than diesel. At higher IPs, the UHC emissions were inferior on behalf of all the blends. This was primarily on account of raise up combustion temperatures and appropriate combustion owing to better fuel atomization [11, 12]. The MFOME20 has shown lower UHC emissions at

Fig. 6 UHC emissions at different injection pressures

an IP of 220 bar. UHC emissions of conventional diesel, MFOME10, MFOME20, and MFOME30 were illustrated as 158 ppm, 130 ppm, 109 ppm, and 141 ppm at 180 bar, 146 ppm, 125 ppm, 104 ppm, and 136 ppm at 200 bar, and 139 ppm, 120 ppm, 99 ppm, and 131 ppm at 220 bar correspondingly.

3.2.4 NO_x

Figure 7 shows the variation in NO_x emissions with injection pressure. NO_x increased for MFOME blends. In addition, the NO_x was high with an increase in injection pressures as a result of speedy combustion and rise of in-cylinder temperature [12]. The analogous trends were sustained for all the test fuels. NO_x emissions of diesel, MFOME10, MFOME20, and MFOME30 were pointed up as 609 ppm, 834 ppm, 848 ppm, and 704 ppm at an injection pressure of 180 bar, 625 ppm, 841 ppm, 855 ppm, and

Fig. 7 NO_x emissions at different injection pressures

Fig. 8 smoke opacity at different injection pressures

711 ppm at 200 bar, and 643 ppm, 848 ppm, 862 ppm, and 718 at 220 bar in that order. MFOME20 was found higher NO_x emissions at an injection pressure of 220 bar than leftover test fuels.

3.2.5 Smoke opacity

Smoke emissions at various injection pressures were depicted in Fig. 8. The smoke opacity basically based on the type of fuel and ratio of fuel and air [18]. Consequently, the smoke opacity was decreased somewhat with MFOME blends. Since the MFOME require lesser stoichiometric air due to better-oxygenated nature of the fuel. As the injection pressure increases, the smoke opacity was decreased and MFOME20 has given away fewer than remaining test fuels [12]. The similar observation was made with all the fuel blends. Smoke opacity of diesel, MFOME10, MFOME20, and MFOME30 were observed as 36.54%, 34.91%, 34.72% and 35.91% at an injection pressure of 180 bar, 36.34%, 35.41%, 34.67%, and 35.71% at 200 bar, and 36.14%, 35.21%, 34.62%, and 35.51% at 220 bar.

4 Conclusions

The following conclusions were made during this investigation

- The transesterification using K₃PO₄ catalyst has improved the yield of the methyl ester.
- The physicochemical properties of MFOME were corresponding to ASTM standards. The cetane number was reasonably enhanced which leads to better combustion in the diesel engine.

- Performance characteristics namely BTE and BSFC were higher for conventional diesel compared to MFOME blends. MFOME 20 has reached somewhat nearer to diesel. The maximum BTE and BSFC were observed at an injection pressure of 220 bar.
- The emission characteristics of MFOME 20 were observed lower than leftover test fuel blends. The decrease in CO, UHC, and smoke opacity were 57.91%, 28.77%, and 4.2% respectively while the increase in CO₂ and NO_x were 8.97% and 34.05% respectively compared to conventional diesel at an injection pressure of 220 bar. Further, MFOME 10 and MFOME 40 have shown better emission characteristics after MFOME 20.

From the above conclusions, MFOME can be the best trusted alternative fuel source in CI engine and the MFOME 20 can be replaced in the engine without any amendment.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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