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RESEARCH ARTICLE

Experimental investigations on a diesel engine operated with fuel blends derived from a mixture of Pakistani waste tyre oil and waste soybean oil biodiesel

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Abstract The waste tyre and waste cooking oils have a great potential to be used as alternative fuels for diesel engines. The aim of this study was to convert light fractions of pyrolysis oil derived from Pakistani waste vehicle tyres and waste soybean oil methyl esters into valuable fuel and to reduce waste disposal-associated environmental problems. In this study, the waste tyre pyrolysis liquid (light fraction) was collected from commercial tyre pyrolysis plant and biodiesel was prepared from waste soybean oil. The fuel blends (FMWO10, FMWO20, FMWO30, FMWO40 and FMWO50) were prepared from a 30:70 mixture of waste tyre pyrolysis liquid and waste soybean oil methyl esters with different proportions of mineral diesel. The mixture was named as the fuel mixture of waste oils (FMWO). FT-IR analysis of the fuel mixture was carried out using ALPHA FT-IR spectrometer. Experimental investigations on a diesel engine were carried out with various FMWO blends. It was observed that the engine fuel consumption was marginally increased and brake thermal efficiency was marginally decreased with FMWO fuel blends. FMWO10 has shown lowest NOx emissions among all the fuel blends tested. In addition, HC, CO and smoke emissions were noticeably decreased by 3.1–15.6%, 16.5–33.2%, and 1.8–4.5%, respectively, in comparison to diesel fuel, thereby qualifying the blends to be used as alternative fuel for diesel engines.

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Keywords Waste tyre pyrolysis oil · Waste soybean oil · Biodiesel blends · FT-IR analysis · Diesel engine · Alternative fuel

Abbreviations

WTPO	Waste tyre pyrolysis oil
WSOME	Waste soybean oil methyl esters
FMWO	Fuel mixture of waste oils (30% WTPO plus 70% WSOME)
FMWO10	10% FMWO and 90 petroleum diesel
FMWO20	20% FMWO and 80% petroleum diesel
FMWO30	30% FMWO and 70% petroleum diesel
FMWO40	40% FMWO and 60% petroleum diesel
FMWO50	50% FMWO and 50% petroleum diesel
BTE	Brake thermal efficiency
BSFC	Brake specific fuel consumption
EGT	Exhaust gas temperature
CO	Carbon monoxide
NOx	Oxides of nitrogen
HC	Hydrocarbons
SD	Smoke density

Introduction

Since last two decades, the world is facing shortage of crude oil supply because its price has been increased to many folds. Fast population growth, prompt industrialization, global warming threats due to pollutant emissions, high costs and rapid depletion of fossil fuels have compelled the researchers to explore cheap and feasible alternative fuel from various resources (Yoon et al. 2010; Qasim et al. 2017; Li et al. 2015; Danesan 2007).

Globally, about 1.5 billion tyres are being produced every year which would consequently become waste tyres (USEPA 2014). To manage these wastes in order to get healthy and clean environment is a hot issue nowadays (Islam et al. 2008). The stockpiles of waste tyres are very difficult to ignite but once ignited, tyres burn too hot to extinguish the fire resulting in sufficient release of air pollutant emissions which bitterly harm the public health by contaminating surrounding atmosphere (Alsaleh and Sattler 2014).

Decomposition products of the tyre pyrolysis feedstock are pyrolysis oil, char and gas (Martínez et al. 2013). The produced pyrolysis oil may be upgraded to a higher quality oil and may be used as fuel. The produced gases comprise hydrogen and carbons (C1–C4) having high heating value and the gases might be recycled as a fuel in the pyrolysis process. The solid char is generally black carbon used as filler (Williams 2013).

In developing countries, from environmental perspectives, there is a disposal problem of solid tyre waste because of its nondegradability and complex structure containing steel cord, carbon black, and other complicated chemical compounds. Commonly, waste tyres are disposed in land filling but this is not an environmentally allowable option (Rodriguez et al. 2001). The waste disposal is a worldwide unsolved issue. By adopting appropriate methods, a major part of the wastes can be converted into useful energy. Since last three decades, efforts have been made by many researchers by developing various methods of pyrolysis such as flash pyrolysis (Edwin Raj et al. 2013), vacuum pyrolysis (Lopez et al. 2010; Zhang et al. 2008; Benallal et al. 1995; pakdel et al. 2001), steam pyrolysis (Kaminsky and Mennerich 2001), fluidised bed pyrolysis (Kaminsky et al. 2009; Kalitko, 2010) and catalytic pyrolysis (Dung et al. 2009a, 2009b, 2009c and 2010; Witpathomwong et al. 2011). Literature reports various operating parameters like pyrolysis temperature (Williams et al. 1990; Mastral et al. 2000; Laresgoiti et al. 2004; Murillo et al. 2006), heating rate (Rombaldo et al. 2008; Unapumnuk et al. 2006 and 2008) and characterisation of pyrolysis oil (Islam et al. 2003). Various scientists have studied diesel engine behavior for the sake of alternative, renewable and sustainable energy (Murugan et al. 2008**;** Dogan et al. 2012; Hariharan et al. 2013; Bhatt and Patel 2012a, b; Wongkhorsub and Chindaprasert 2013; Naima and Liazid 2013**).**

Waste cooking oil (WCO) is a vegetable oil obtained after frying or cooking food items. The edible vegetable oil becomes unsuitable for consumption after repeated frying for preparation of food (Nantha et al. 2014). WCO has also many disposal problems like water and soil pollution, human health concern and disturbance to the aquatic ecosystem. The WCO may be effectively used for biodiesel production instead of its harmful environmental disposal options (Wanodya and Arief 2013; Anildo et al. 2013). The collected WCO might be used to prepare soap and additives for engine oils (Maurizio et al. 2014). Successful conversion of WCO into biodiesel has been documented by many researchers throughout the world (Nabanita et al. 2014). Conversion of WCO into biodiesel contributes to lower greenhouse-gas emissions in comparison to conventional diesel (Chang et al. 1996). Many scientists have recommended the suitability of veggie oil and its derivatives to be utilized as fuel or as effective fuel additive (Lapuerta et al. 2005 and 2003; Ramadhas et al. 2004 and 2005).

The aim of this study was to carry out experimental investigations on the fuel blends obtained from waste tyre oil and waste soybean oil biodiesel-diesel mixtures in a diesel engine to assess the suitability of the fuel blends to be utilized as conventional diesel fuel substitute for diesel engines. Various physicochemical characteristics were measured and compared with diesel and biodiesel fuel standard specifications. FT-IR analysis was carried out using ALPHA FT-IR spectrometer. Different performance and emission parameters of the engine were studied.

Experimental

Pyrolysis process of waste tyres

Thermal degradation of a substance into smaller and less complex molecules in the absence of oxygen is known as pyrolysis process. In pyrolysis process, three major products are produced such as gas, char and pyrolytic oil. In this study, light fraction of waste tyre pyrolysis oil was collected from a commercial pyrolysis plant located at Muzaffargarh industrial area, near Multan, Pakistan. The schematic flow diagram of the plant setup is given in Fig. 1.

After removal of steel wires and beads, the waste tyre chips are fed into the reactor unit to decompose hydrocarbon compounds at high temperature (460–660 °C) under oxygen-free atmosphere. The process makes the restructuring of rubber and converts it into vapours and gases which pass through the separator where heavy oil is separated out from gases and the vapours of the light oil fractions are condensed into liquid after passing through the condenser yielding 42–46% tyre pyrolysis oil with 9–10% noncondensable gases which are recycled again and used for heating the reactor.

FT-IR analysis

The FT-IR analysis was carried out for fuel mixture of waste oils (FMWO) and diesel samples using ALPHA FT-IR spectrometer, Bruker Optics, Germany, having a resolution of 1.0 $cm^{-1}$and scan range of 450–4000 cm^{-1}. FTIR analysis confirms that the functional groups present in FMWO sample are almost alkanes (hydrocarbons) and halides. Comparable infrared absorption spectrums were observed for FMWO and diesel as shown in Figs. 2 and 3. The frequencies of the

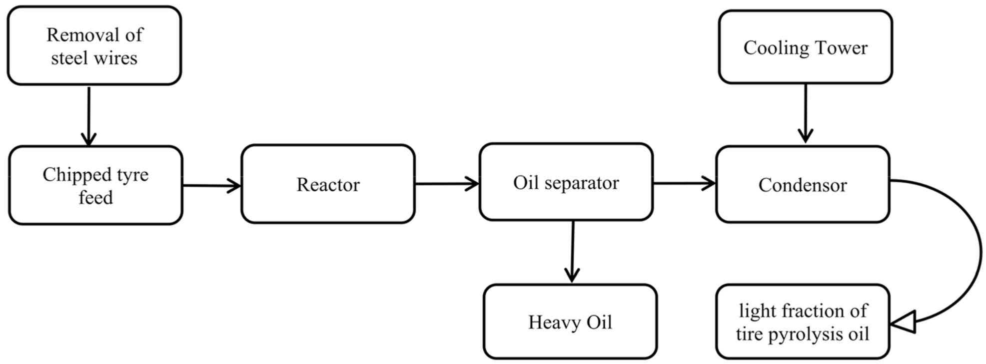

Fig. 1 Waste tyre oil pyrolysis process flow sheet

absorption spectrums are given in Table 1. Similar type of work has been reported by Kapura et al. (2014) and Bhatt and Patel (2012a, b).

Engine setup

The experiments were conducted in a stationary 5.5-kW, water-cooled, single-cylinder, four-stroke, naturally aspirated (NA) compression-ignition engine. The schematic diagram of the engine is given in Fig. 4. The engine had a stroke and bore of 110 and 87.5 mm, respectively. The compression ratio of the engine was 17.5:1.The fuel injection timing set by the manufacturer was 23° bTDC. An electronic weighing scale was used to measure the fuel flow rates. The outer temperature of the exhaust gas was measured directly from the thermocouples. AVL DiGas 444 exhaust gas analyzer was used to measure exhaust gas emissions like nitric oxide (NO), carbon monoxide (CO) and hydrocarbon (HC). An AVL 437 smoke meter was used to measure smoke opacity.

Calibration of each analyzer was performed before each test. In order to obtain the reference data, the engine was run initially with diesel for no load, 20%, 40%, 60%, 80%, and full load. Similarly, the engine was again run with diesel after conducting all tests with blends so as to clean the traces of different blends. The technical specifications of the engine are listed in Table 2.

Samples description

Two liters of waste cooking oil were collected from M/S Lasani Food Restaurant, Multan, Pakistan. The waste cooking oil description was enquired from the restaurant managers and was known to be waste soybean oil. The waste soybean oil was converted into biodiesel as explained in the "Production of soybean oil methyl esters (biodiesel)" section. The light fraction of waste tyre pyrolysis oil (WTPO) was collected from a commercial pyrolysis plant located at Muzzaffar Garh near Multan, Pakistan, and was mixed with biodiesel (waste soybean oil methyl ester) in a ratio of 30:70 to form a fuel blend named as fuel mixture of waste oils (FMWO). The FMWO was further mixed with petroleum diesel in different proportions as shown in Table 3.

Production of soybean oil methyl esters (biodiesel)

The waste cooking oil was subjected to base-catalysed transesterification reaction using potassium hydroxide (KOH) as catalyst. The waste cooking oil was pretreated and

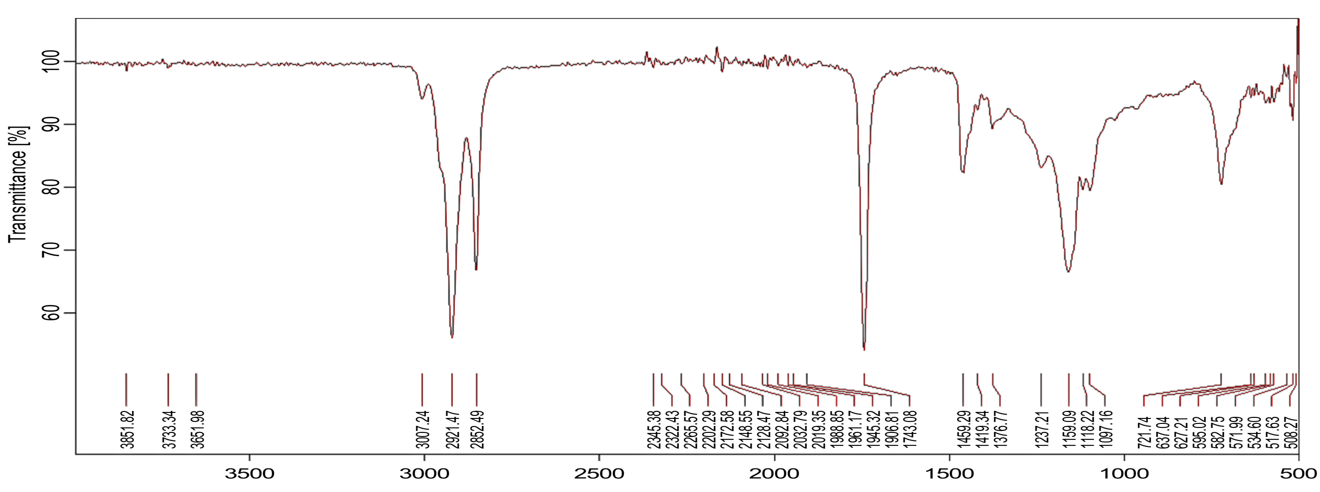

Fig. 2 FTIR spectrum of diesel

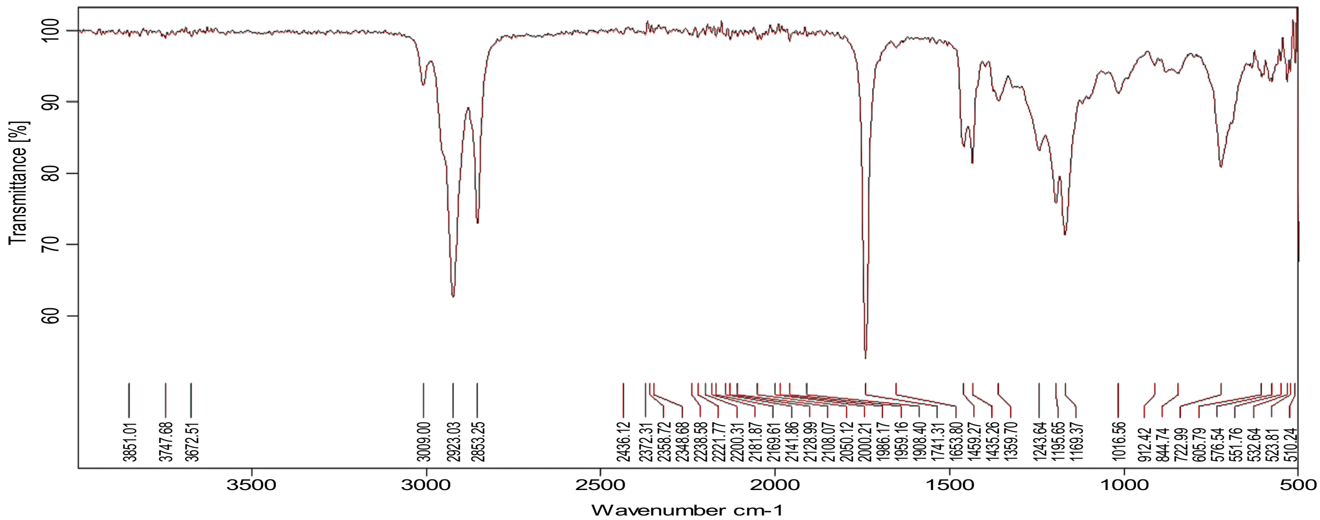

Fig. 3 FTIR spectrum of FMWO

filtered so as to remove coagulation, moisture contents and suspended particles. This pretreated waste cooking oil was stored for further reaction. Sodium methoxide was prepared by dissolving 1% sodium hydroxide (NaOH) in methyl alcohol (CH_3OH). The sodium methoxide solution was added to the pretreated waste cooking oil and the solution mixture was stirred for 1 h at 60 °C and then cooled and left overnight to settle under gravity. Two layers were formed; the upper biodiesel layer was separated out from lower glycerol layer and washed with water for purification. The biodiesel so produced was heated at 110 °C to remove moisture contents. After cooling, the biodiesel was blended with WTPO and petroleum diesel for further characterization.

Results and discussions

Physicochemical properties

The fuel blends FMWO10, FMWO20, FMWO30, FMWO40 and FMWO50 were analyzed for physicochemical properties as shown in Table 4. The obtained results of the fuel blends were compared with international fuel standards of diesel (ASTM 975) and biodiesel (ASTM 6751 and EN14214). It was observed that all the measured values of the fuel blends were found within the specified limits of above-mentioned standard fuel specifications.

Performance

Brake specific fuel consumption (BSFC) is a very important factor to compare the fuels having different densities and heating values (Agrawal 2007). Figure 5 shows the variations of the BSFC for diesel and FMWO blends. The BSFC for diesel was 343.25 g/kWh at 100% load and it was 344.63, 350.12, 362.30, 367.64 and 370.25 g/kWh for the FMWO10, FMWO20, FMWO30, FMWO40 and FMWO50, respectively, at full-load conditions. BSFC was found to decrease as the engine load was increased. FMWO10 has shown lowest BSFC among all the blends measured. FMWO10 has shown comparable BSFC value to that of diesel due to better combustion and higher heating values in comparison to other fuel blends. The FMWO40 and FMWO50 have shown higher fuel consumption values due to lower heating values.

Table 1 FTIR results for diesel and FMWO

Diesel			FMWO		
Frequency range (cm^{-1})	Bonds	Compounds	Frequency range (cm^{-1})	Bonds	Compounds
2921.47	C–H, stretch	Alkanes	2923.03	C–H, stretch	Alkanes
2852.49	C–H, stretch	Alkanes	2853.25	C–H, stretch	Alkanes
1459.29	C–H, bending	Alkanes	1459.27	C–H, bending	Alkanes
1376.77	C–X	Fluoride	1359.70	C–X	Fluoride
721.74	C–H, bending	Alkanes	722.99	C–H, bending	Alkanes

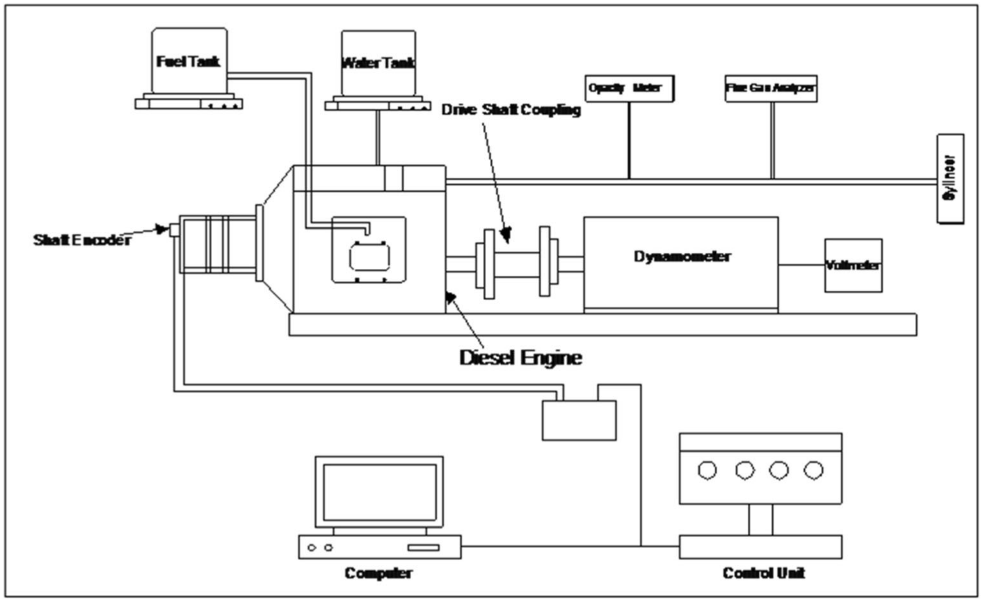

Fig. 4 Schematic diagram of experimental setup

Table 2 Technical specifications of the engine used during the research work.

	Particulars	Details
Engine	Model	Kirolaskar TAF-1
	Maximum power (kW)	5.5
	Type	Water cooled, four stroke
	Rated speed (rpm)	1600
	Number of cylinders	1
	Bore	87.5 mm
	Stroke	110 mm
	Compression ratio	17.5:1
	Combustion	Direct injection (DI) and naturally aspirated
	Injection timing	23° before TDC
Exhaust gas analyzer	Model	AVL Di Gas 444
	HC (ppm)	
	Range	0 to 30,000
	Accuracy	± 4%
	Resolution	1
	CO (%)	
	Range	0 to 15
	Accuracy	± 0.06
	Data resolution	0.001
	NO_x (ppm)	
	Range	0 to 5000
	Accuracy	± 2%
	Resolution	1
Smoke meter		AVL 437
	Range	0–100%
	Accuracy	± 1%
	Alarming signal temperature	70 °C
	Light source	Halgen Lamp, 12 V

Table 3 FMWO and its blends composition.

Sr. no.	Fuel type	FMWO description		FMWO-diesel blends description	
		FMWO volume	WSOME volume	FMWO volume	Diesel volume
1	Diesel (FMWO0)	–	–	0 ml	1000 ml
2	FMWO10	300 ml	700 ml	100 ml	900 ml
3	FMWO20	300 ml	700 ml	200 ml	800 ml
4	FMWO30	300 ml	700 ml	300 ml	700 ml
5	FMWO40	300 ml	700 ml	400 ml	600 ml
6	FMWO50	300 ml	700 ml	500 ml	500 ml
7	FMWO100	300 ml	700 ml	1000 ml	0 ml

Brake thermal efficiency (BTE) of FMWO blends was compared with diesel fuel as shown in Fig. 6. BTE of the engine at full load was found at 29.61% for diesel and 29.24, 29.12, 28.67.16, 28.90 and 28.92% for FMWO10, FMWO20, FMWO30, FMWO40 and FMWO50 correspondingly at full load. The BTE of the fuel blends was found to be lower than diesel. This may be due to the lower calorific value of the fuel blends. The FMWO10 has shown better performance in comparison to all other fuels analyzed. The increase in BTE value for FMWO10 in comparison to other fuel blends night be attributed to its lower viscosity and better fuel atomisation.

The exhaust gas temperature (EGT) is a good indicator for amount of heat lost with exhaust gases (Ganesan 2007). Variations of EGT with respect to engine load percent are shown in Fig. 7. The EGT was found at 352, 377, 385, 376, 368 and 379 °C for diesel, and FMWO10, FMWO20, FMWO30, FMWO40 and FMWO50 correspondingly at full load. The figure shows that the EGT for all fuel blends was increased as the engine load was increased; however, the EGT of diesel was found lower than FMWO blends. This indicates that the combustion of FMWO blends might be delayed due to higher densities and viscosities.

Emissions

The hydrocarbons (HC) emissions are created as a result of incomplete combustion inside the combustion chamber, variations in the equivalence ratio and deposits on the internal combustion chamber walls (Ganesan 2007). The variations of HC emissions with engine load percent for diesel and FMWO blends are plotted in Fig. 8. It was found that the HC emissions were found to decrease with increase in engine load. The HC emissions for diesel, FMWO10, FMWO20, FMWO30, FMWO40 and FMWO50 were observed at 0.032, 0.030, 0.028, 0.029, 0.031, 0.027 g/kWh, respectively, at full load. The FMWO10, FMWO20, FMWO30, FMWO40 and FMWO50 blends have shown 6.25, 12.5, 9.37, 3.12 and 15.62% lower emissions than diesel. This indicates more complete combustions of the studied fuel blends.

Figure 9 shows carbon monoxide (CO) emissions for diesel and FMWO blends. The CO emission for diesel, FMWO10, FMWO20, FMWO30, FMWO40 and FMWO50 was found at 0.012, 0.010, 0.0080, 0.0092, 0.0086 and 0.0084, respectively, at full-load conditions. The CO emissions were found to decrease from no load to 100% load. All the FMWO blends

Table 4 Comparison of physicochemical properties of FMWO with diesel and biodiesel standards

Sr. no.	Description	Density kg/m^3	Viscosity at 40 °C cSt	Flash point °C	Water contents Mgl^{-1}	Calorific Value MJ/kg	Cetane number
1	Method (ASTM)	D-1298	D-445	D-93	D-95	D-240-17	D-976
2	FMWO10	842	3.34	78	65	42.62	46.0
3	FMWO20	847	3.46	84	72	42.41	45.0
4	FMWO30	862	3.80	87	87	41.83	44.0
5	FMWO40	869	4.12	96	110	41.62	44.0
6	FMWO50	874	4.30	102	135	41.28	43.5
7	FMWO0 (diesel)	839	3.18	72	Nil	42.85	47.5
8	Specifications						
	ASTM 6751	–	3.5–5.0	> 120	< 500	–	–
	En 14214	860–900	2.5–6.0	> 120	< 500	–	–
	ASTM D975	–	1.3–4.1	60–80	< 500	–	40–55

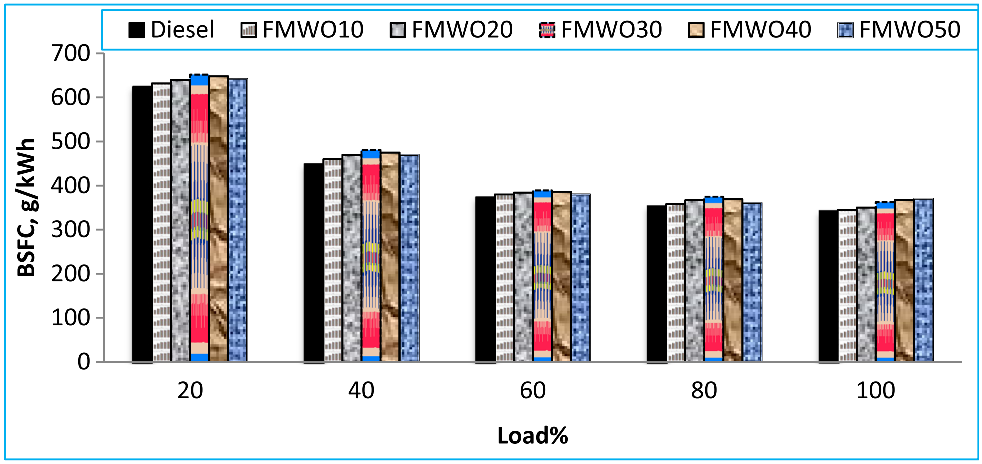

Fig. 5 Variations of BSFC with engine load%

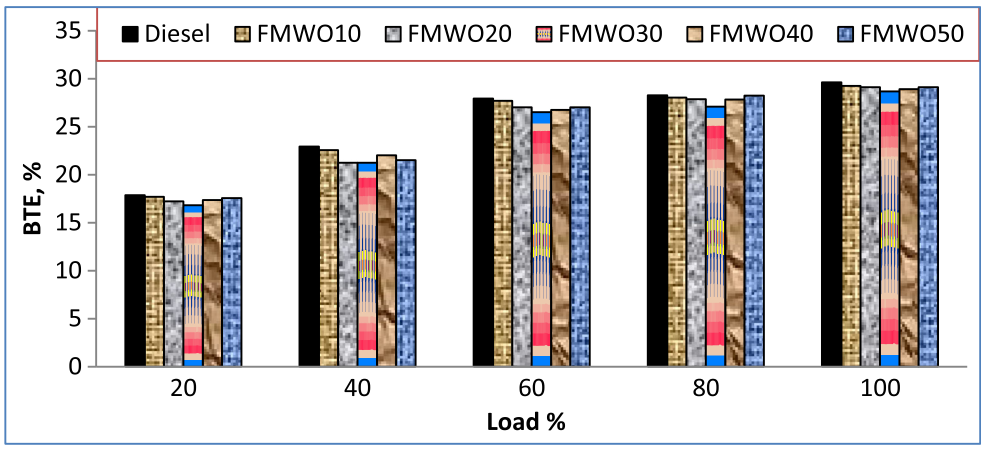

Fig. 6 Variations of BTE with engine load%

have shown 16.5–33.2% lower CO emissions in comparison to diesel. This indicates complete mixing and complete combustion of the fuel blends.

The availability of oxygen, combustion duration, temperature, pressure and higher compression ratio are the factors which affect nitric oxide emissions (Murugan et al. 2008). The variations of NOx emissions with engine load for diesel and FMWO are plotted in Fig. 10. The CO emissions for diesel, FMWO10, FMWO20, FMWO30, FMWO40 and FMWO50 were observed at 5.41, 5.62, 5.72, 5.70, 5.71 and 5.72 g/kWh, respectively, at maximum load conditions. NOx emissions were found to increase as the engine load was

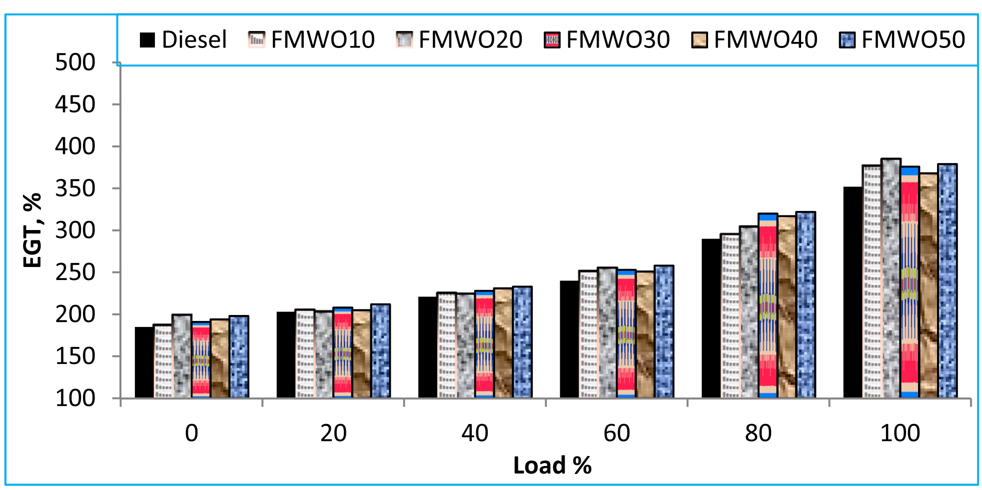

Fig. 7 Variations of EGT with engine load%

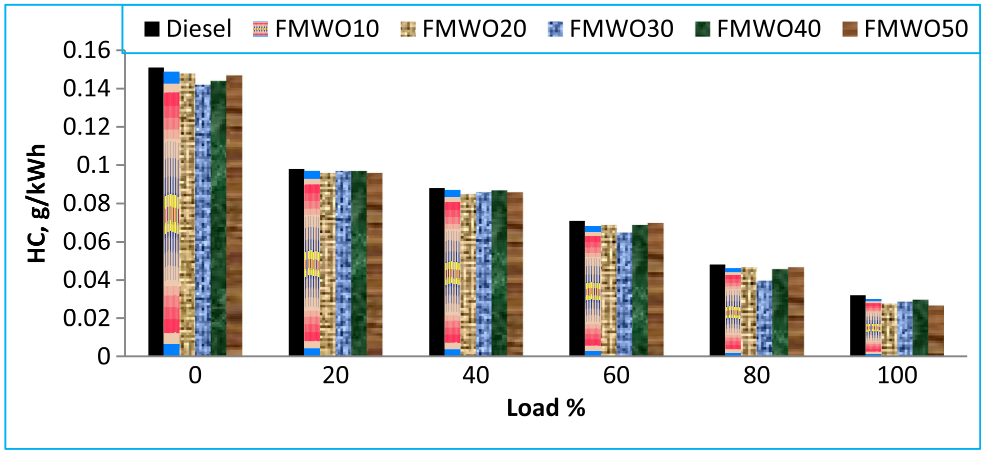

Fig. 8 Variation of HC emissions with engine load %

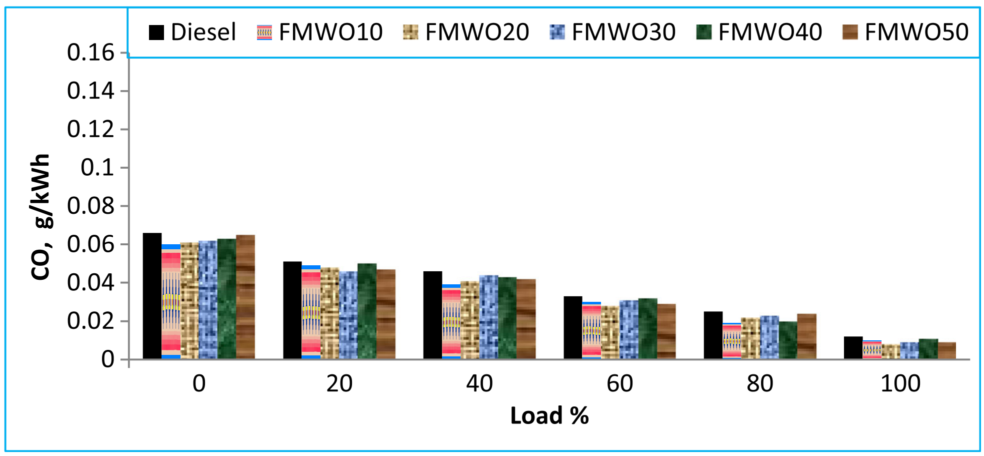

Fig. 9 Variation of CO emissions with engine load %

increased. All the FMWO fuel blends have shown marginally higher NOx emissions as compared to diesel might be due to higher oxygen contents in the biodiesel portion of the blends.

Figure 11 depicts the smoke emissions of FMWO fuel blends and diesel. Generally, smoke opacity occurs due to the incomplete combustion inside the combustion chamber of the engine (Murugan et al. 2008). The smoke emissions for diesel, FMWO10, FMWO20, FMWO30, FMWO40 and FMWO50 were found at 58.21, 55.56, 57.14%, 55.23, 56.02 and 55.33%, respectively, at full load. Smoke emissions were found to increase as the engine load was increased. Lower smoke emissions were noticed for FMWO blends as compared to diesel. This indicates the better combustion of the fuel blends in the combustion chamber of the engine.

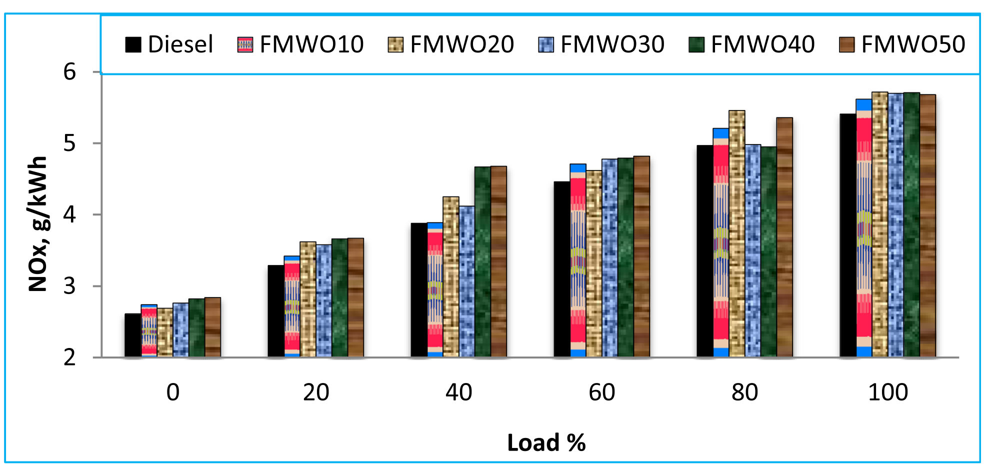

Fig. 10 Variation of NOx emissions with engine load %

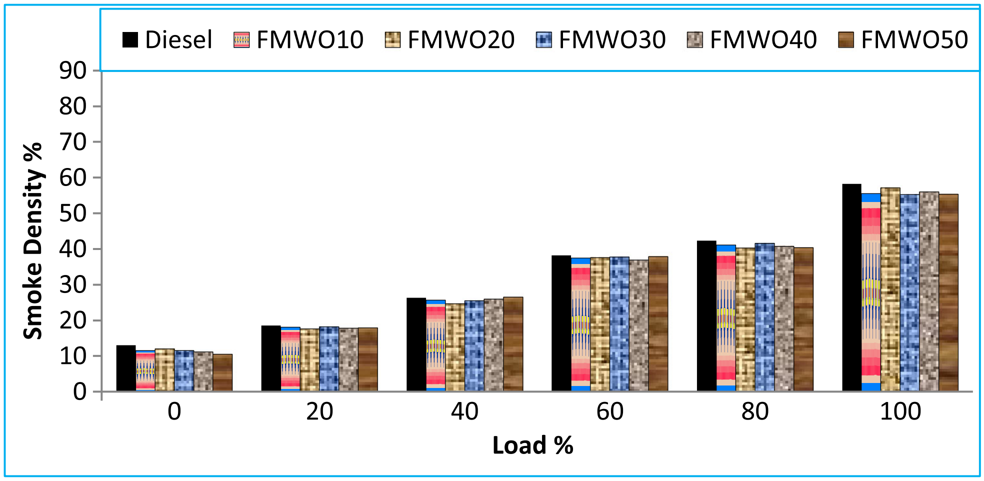

Fig. 11 Variation of smoke opacity with engine load %

Conclusion

In present study, FMWO fuel blends obtained from a mixture of waste tyre oil and waste soybean oil biodiesel with various proportions of petroleum diesel were investigated in a diesel engine for emission and performance parameters. The physicochemical properties were measured by using ASTM standards. On the basis of analysis results, the important conclusions are as follows;

- All the physicochemical properties of the FMWO fuel blends were found within the international fuel standards of diesel (ASTM 975) and biodiesel (ASTM 6751 and EN14214).
- The BSFC of FMWO fuel blends was decreased with increase in the engine load. In comparison to diesel fuel, the BSFC of all the fuel blends was marginally increased. FMWO10 has shown lowest BSFC (344.63 g/kWh) and FMWO50 has shown highest BSFC (367.64 g/kWh) among all the fuel blends analyzed.
- All the tested fuel blends exhibited lower BTE value than diesel; however, FMWO10 has shown higher BTE (29.24%) than other FMWO fuel blends.
- 3.12–15.62% and 16.5–33.2% lower CO and HC emissions were observed for overall FMWO fuel blends in comparison to diesel fuel. Decrease in smoke emissions was noticed to be 1.83–4.5% for FMWO blends in comparison to that of diesel.
- The overall NOx emissions were increased as the engine load was increased; however, FMWO10 has shown less NOx emissions among all the FMWO fuel blends.
- The engine was successfully operated with all FMWO blends without engine failure but the performance of FMWO10 was found outclass among all the fuel blends.

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Compliance with ethical standards

Conflict of interests The authors declare that they have no conflict of interests.

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