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Performance of a diesel engine with blends of biodiesel (from a mixture of oils) and high-speed diesel

Hifjur Raheman*, Prakash C Jena and Snehal S Jadav

Abstract

A 10.3-kW single-cylinder water-cooled direct-injection diesel engine was evaluated using blends of biodiesel (B10 and B20) obtained from a mixture of mahua and simarouba oils (50:50) with high-speed diesel (HSD) in terms of brake specific fuel consumption, brake thermal efficiency, and exhaust gas temperature and emissions such as CO, HC, and NO_x. Based on performance and emissions, blend B10 was selected for long-term use. Experiments were also conducted to assess soot deposits on engine components, such as cylinder head, piston crown, and fuel injector tip, and addition of wear metal in the lubricating oil of diesel engine when operated with the biodiesel blend (B10) for 100 h. The amount of soot deposits on the engine components was found to be, on average, 21% lesser for B10-fueled engine as compared with HSD-fueled engine due to better combustion. The addition of wear metals such as copper, zinc, iron, nickel, lead, magnesium, and aluminum, except for manganese, in the lubricating oil of B10-fueled engine after 100 h of engine operation was found to be 11% to 50% lesser than those of the HSD-fueled engine due to additional lubricity.

Keywords: Biodiesel blend, Performance, Emissions, Soot deposit, Wear metal addition

Background

Higher soot or carbon deposits on in-cylinder engine components and lubricating oil contamination are the main causes for engine wear. Wear processes due to oil contamination lead to diminished fuel efficiency, shorter useful oil service life, reduced component life, and loss of engine performance. Hence, in addition to engine performance and emissions of diesel engine, soot depositions on engine components and wear metal additions in lubricating oil of the engine are required for the selection of a fuel that would replace conventional diesel fuel. With increase in demand for using biodiesel in place of high-speed diesel (HSD), a detailed study on these aspects is very much required for the selection of a suitable blend to replace HSD for long-term use in diesel engines.

Very few studies have been conducted on soot depositions and wear metal additions in the lubricating oil of engine that are operated with biodiesel obtained from single-vegetable oil and its blends with HSD. It was reported that metal addition in the lubricating oil of engines operated with different biodiesel (soybean, palm kernel oil, linseed oil) blends was lower or similar as compared to when the engine was operated with HSD alone [1-5]. Ramaprabhu et al. [6] reported that iron wear was almost similar, whereas copper wear was higher in the lubricating oil of diesel engine operated with Jatropha and Karanja biodiesel blend as compared with when the lubricating oil of diesel engine was operated with HSD. Lesser soot deposition on engine components was reported for biodiesel blend-operated diesel engines [6,7]. With increasing demand on the use of biodiesel, more and more oils and mixtures of oils are explored for biodiesel production [8]. Mahua (*Madhuca indica*) oil (MO) with high free fatty acids (FFA) and simarouba (*Simarouba glauca*) oil (SRO) are few such potential oils suitable for biodiesel production. Higher FFA present in oil requires higher methanol; hence, an attempt was made to produce biodiesel from a mixture (50:50) of these two oils to reduce methanol requirement in biodiesel production [9]. Performance evaluation,

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emission examination along with soot deposition on in-cylinder engine components, and wear metal addition in the lubricating oil of the engine are required for biodiesel obtained from such mixture of oils. Hence, a study was undertaken at Indian Institute of Technology, Kharagpur, India.

Methods

Biodiesel production

MO and SRO with FFA levels of 13% and 1.43%, respectively, were mixed at 50:50 *v*/*v* proportions (MSO) to reduce methanol consumption in biodiesel production. This oil mixture (MSO) had an FFA content of 7.19%. Hence, pretreatment esterification with an acid catalyst to bring down the FFA level of the oil mixture to around 1% was required.

A two-step 'acid-base' process, an acid pretreatment followed by the main base-transesterification reaction, using methanol as reagent and H_2SO_4 and KOH as catalysts for acid and base reactions, respectively, was followed to produce biodiesel from MSO. The various fuel properties of MO, SRO, MSO, and biodiesel (B100)

Table 1 Technical specification of engine and hydraulic dynamometer

	Particulars	Details
Engine	Model	DM14
	Maximum power (kW)	10.3
	Type	Water-cooled, four stroke
	Rated speed (rpm)	1,500
	Number of cylinders	1
	Compression ratio	15.5:1
	Bore × stroke (mm)	114.3 × 116
	Brake mean effective pressure at 1,500 rpm (kg/cm^2)	7.054
	Combustion	Direct injection (DI) and naturally aspirated
	Injection timing	24° before TDC
Hydraulic dynamometer	Model	AWM15
	Type	Hydraulic
	Water pressure at inlet (kg/cm^2)	1.5
	Power (hp)	
	Range	1 to 100
	Accuracy	±2%
	Data resolution	0.02%
	Maximum speed (rpm)	
	Range	5,650 to 8,000
	Accuracy	±2%
	Data resolution	0.03
Exhaust gas analyzer	Model	PEA205
	CO (%)	
	Range	0 to 15
	Accuracy	±0.06
	Data resolution	0.001
	HC (ppm)	
	Range	0 to 30,000
	Accuracy	±4%
	Data resolution	1
	NO_x (ppm)	
	Range	0 to 5,000
	Accuracy	±2%
	Data resolution	1

obtained from MSO and its blends with HSD (B10, B20) were determined as per the American Society for Testing and Materials (ASTM) standards.

Experimental setup

Performance and exhaust emissions were studied for a 10.3-kW single-cylinder four-stroke direct-injection water-cooled diesel engine using biodiesel blends with HSD (B10 and B20) by varying the engine load from no-load to 100% load in steps of 20%. A hydraulic dynamometer (SAJ Model AWM 15, SAJ International Pvt. Ltd, Pune, India; 100 hp at 5,650 to 8,000 rpm) equipped with a strain gauge-based load cell and digital readout for measuring engine torque and speed was used for loading the diesel engine. Details of the technical specification for the engine, dynamometer, and exhaust gas analyzer used are given in Table 1.

Methodology

Performance tests and emission measurement of diesel engine with biodiesel blends

Performance tests were conducted in a diesel engine using HSD and blends of biodiesel (B10 and B20) following the Indian standard (IS) 10000: part 8 [10]. The rated engine load measured was found to be 57.8 Nm at 1,500 ± 10 rpm, and the corresponding rated power developed by the engine was 9.1 kW. At rated power, the load going to the engine was taken as 100%. Accordingly, intermediate loads were calculated as 11.56, 23.12, 34.68, and 46.24 Nm (corresponding to 20%, 40%, 60%, and 80% of torque obtained at rated power). The tests were conducted for 3 h and 30 min for each test fuel, and load was applied at an interval of 30 min. The readings were recorded at an interval of 10 min for a particular engine load. During this test, performance parameters such as brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), and exhaust gas temperature (EGT) were determined by measuring fuel consumption, engine torque, and EGT. During this performance test, exhaust emissions such as CO, hydrocarbon (HC), and oxides of nitrogen (NO_x) were also measured using an online exhaust gas analyzer. A suitable blend for long-term use was selected by comparing the performance and emissions of the two blends with those of HSD.

Estimation of soot deposits on in-cylinder engine components

The engine was run for 100 h (16 test cycles each of 6.25-h continuous running) with each of the two fuels (HSD and selected biodiesel blend). In 100 h, the engine was subjected to different loadings, and the lubricating oil samples were collected at an interval of 25 h of engine run. The duration for each loading was decided as per IS 10000: part 9 [11]. In each test cycle, loads were applied in a random manner for predetermined durations, i.e., 100%, 50%, 100%, no load, 100%, and 50% load for 93.75 (including 11.72 min of warm up), 93.75, 23.45, 11.72, 70.31, and 82 min, respectively. After 100 h of engine operation with each of these fuels, the engine was dismantled, and the cylinder head, piston, and fuel injector were removed carefully and kept on a clean surface. Photographs of these components were taken to visually compare the soot deposits when operated with different fuels. Later, the soot deposits were gently scraped from these components using a wooden scraper. Weights of these scraped deposits for each component were taken separately for comparison.

Detection of wear metals by atomic absorption spectroscopy analysis

The lubricating oil samples collected after each 25 h of engine run were subjected to atomic absorption spectroscopy (AAS) analysis to determine the addition of metals (such as copper, zinc, iron, manganese, nickel, lead, magnesium, and aluminum) in lubricating oil of engine. Dry ashing technique was used to prepare the sample of lubricating oil for metal analysis by AAS. Each lubricating oil sample was taken in a 250-ml conical flask and thoroughly mixed in a water bath at 50°C for 1 h at constant speed. Approximately 10 g of mixed lubricating oil sample was taken in a previously washed and dried silica crucible. The crucible was then kept on a hot plate at a temperature of 120°C until the lubricating oil gets completely dried up. Thereafter, the crucible was kept in a muffle furnace for 4 h at a temperature of 450°C and then for 2 h at 650°C. The ash that remained in crucibles was dissolved in 1.5 ml of HCl solution. The solution was then diluted with 100 ml of deionized water and stored in plastic bottles in a refrigerator at a temperature of 10°C to 15°C. This method was followed to prepare all samples for metal analysis by flame AAS. Variation of these elements was found for different engine operating hours.

Results and discussion

Fuel properties

Various fuel properties of MO, SRO, MSO, biodiesel obtained from this mixture of oils, and its blends with HSD (B10 and B20) were determined as per the ASTM standards and are summarized in Table 2. It can be seen from this table that the fuel properties of biodiesel are comparable to those of HSD and are well within the latest American (D 6751–02) and European (EN 14214) standards for biodiesel. The MO, SRO, and MSO, however, were found to have much higher values of fuel properties way above any of these standard limits, thus restricting its direct use as a fuel for diesel engines.

Table 2 Fuel properties of biodiesel obtained from MO, SRO, mixture of MSO and their biodiesels

Fuel type	Acid value (mg KOH/g)	Density (kg/m^3)	Kinematic viscosity (cSt)	Calorific value (MJ/kg)	Flash point (°C)	Pour point (°C)	Carbon residue (%)	Ash content (%)	Water content (ppm)
HSD	-	812	2.85	42.5	52	−20.0	0.15	0.01	90
MO	26	913	40.92	36.5	233	14.0	1.6	1.13	1,200
MB100	0.46	861	5.38	37.05	168	3.0	0.22	0.01	450
SRO	2.86	912	44.95	36.6	245	15.0	1.50	1.17	1,400
SRB100	0.39	862	5.58	37.0	146	4.0	0.21	0.01	445
MSO[a]	14.38	912	42.94	36.55	238	14.0	1.60	1.14	1,300
B10	0.27	817	3.02	42.0	63	−18.0	0.15	0.01	126
B20	0.27	821	3.19	41.4	74	−15.0	0.16	0.01	159
B100	0.33	857	4.56	37.02	164	3.5	0.21	0.013	450
ASTM D6751	<0.80	-	1.9 to 6.0	-	>130	-	-	<0.02	<500
EN14214	<0.50	860 to 900	3.5 to 5.0	-	>120	-	<0.30	<0.02	<500
BIS15607	<0.50	860 to 900	2.5 to 6.0	-	>120	-	-	-	<500

MB100, mahua biodiesel; SRB100, simarouba biodiesel; B100, biodiesel obtained from MSO; B10, 10% MSO with HSD by volume basis; B20, 20% MSO with HSD by volume basis. [a]MSO, mixture of MO and SRO at 50:50 *v/v*.

Engine performance

The performance parameters such as BSFC, BTE, and EGT obtained with B10, B20, and HSD are found to be affected by fuel blend and engine loading and are discussed in the following sections.

Brake specific fuel consumption

The variations of BSFC with engine load for B10, B20, and HSD are shown in Figure 1. BSFC, in general, was found to increase with an increase in proportion of biodiesel in the fuel blends with HSD. Mean BSFC values with B10 and B20 were found to be 287.29 and 298.67 g/kW h, respectively, and were 2.44% and 5.63% higher than those with HSD. Among the fuel blends tested, 10% blending gave the minimum BSFC, and it increased with the increase in biodiesel percentage in the blends.

BSFC was also observed to decrease sharply with the increase in engine loading for all the fuels tested due to relatively less amount of heat losses at higher loads. At full load, the mean BSFCs for HSD, B10, and B20 were found to be 274.29, 281.05, and 290.00 g/kW h, respectively, as compared with 506.76, 519.52, and 550.37 g/kW h at 20% engine loading. This decrease in BSFC with the increase in engine load might be due to the fact that percentage increase in fuel required to operate the engine was less than the percentage increase in brake power as relatively less portion of the heat losses occurred at higher engine loads.

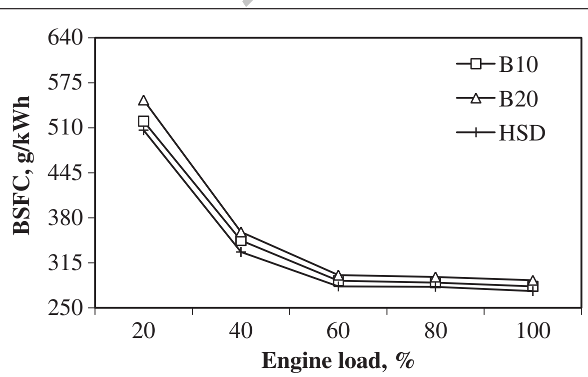

Figure 1 Variations of BSFC with engine load for B10, B20, and HSD.

Brake thermal efficiency

BTE of diesel engine when operated with HSD, B10, and B20 at different engine loads has been plotted in Figure 2. At 20% engine loading, BTE values were found to be 16.72%, 16.50%, and 15.80% with HSD, B10, and B20, respectively, which were increased to 30.89%, 30.50%, and 29.99% at full load condition. The BTE improved with the engine load for the main reason that a relatively less portion of the power was lost with the increase in engine load. The mean BTE with B10 and B20 was found to be 21.87% and 21.46%, respectively, as compared to 22.27% with HSD. There was a reduction in BTE with the increase in biodiesel percentage in the fuel blends due to the decrease in calorific value of fuel blend.

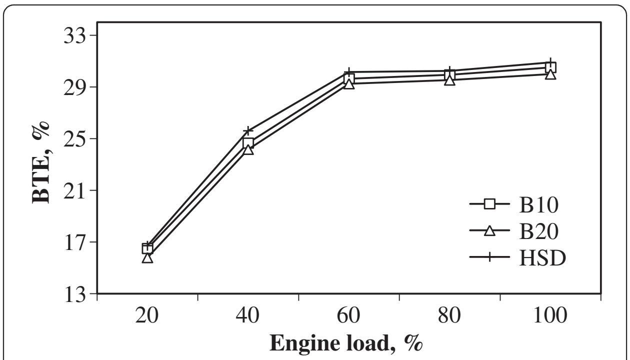

Figure 2 Variations of BTE with engine load for B10, B20, and HSD.

Exhaust gas temperature

The variations of EGT of a diesel engine when operated with HSD, B10, and B20 at different engine loads are shown in Figure 3. EGT was found to increase with the increase in both concentrations of biodiesel in the blends and engine load. The mean EGT values with B10 and B20 were found to be 308°C and 310°C, respectively, which were 4.44% and 5.12% higher than that with HSD (296°C). The maximum EGT was obtained at full load conditions with all the fuels tested and was 430°C, 438°C, and 443°C with HSD, B10, and B20, respectively, whereas it was 213°C, 224°C, and 225°C at 20% engine loading. The increase in EGT with engine load is obvious from the simple fact that a higher amount of fuel was required in the engine to generate that extra power needed to take up the additional loading.

The variations of BSFC, BTE, and EGT for blends of biodiesel (B10 and B20) obtained from the mixture of oils and HSD at different engine loadings were found to be similar to the trend as reported, while testing biodiesel blends obtained from individual oils (sunflower, linseed, Karanja, rubber seed, rapeseed, soybean, polanga, waste palm, castor, soybean, mahua, and tamanu oils) and HSD in different diesel engines [12-24].

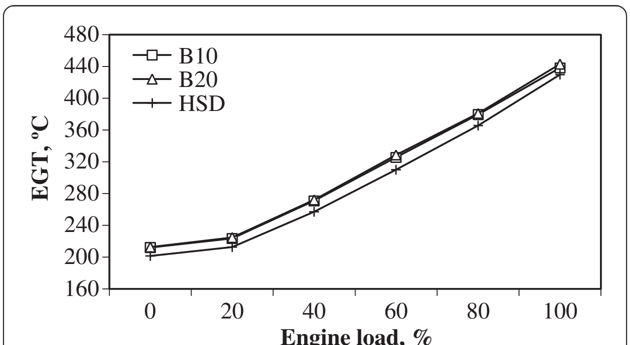

Figure 3 Variations of EGT with engine load for B10, B20, and HSD.

Engine emissions

The average exhaust emissions such as CO, HC, and NO_x from diesel engine with different fuels tested were found to be affected by biodiesel blend and engine load and are discussed in the following sections.

Carbon monoxide

The variations of CO with engine load when operated with B10, B20, and HSD are presented in Figure 4. CO emission was found to decrease with the increase in proportion of biodiesel in the fuel blends with HSD. The mean values of CO emissions with B10 and B20 were found to be 10.97% to 21.16% lower than those with HSD. Among the two fuel blends tested, B10 blending gave the maximum CO emission, and it decreased with the increase in biodiesel percentage in the blends.

The mean values of CO emissions for B10 decreased from 0.031% at no-load conditions down to 0.014% at 60% engine load and then increased up to 0.071% at 100% engine load. A similar trend was also observed for B20 and HSD. Initially, at no-load condition, cylinder temperature might be too low, and then, it increased with loading due to more fuel injected inside the cylinder. At an elevated temperature, performance of the engine improved with relatively better burning of the fuel, resulting in decreased CO. However, on further loading, the excess fuel required led to the formation of more smoke, which might have prevented the oxidation of CO into CO_2, consequently increasing the CO emissions sharply.

Hydrocarbons

The HC emissions from the diesel engine when operated with B10, B20, and HSD at different engine loadings are plotted in Figure 5. The mean values of HC emissions

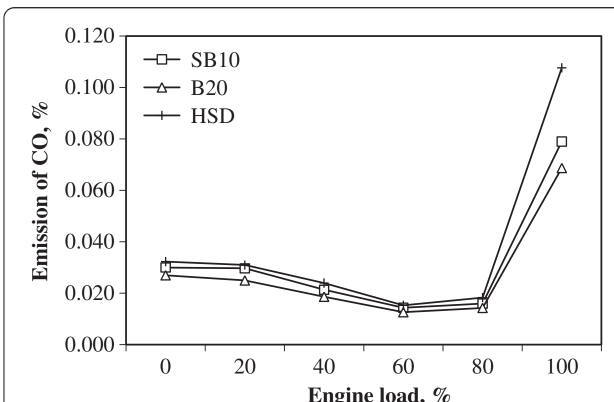

Figure 4 Variations of CO emissions with engine load for B10, B20, and HSD.

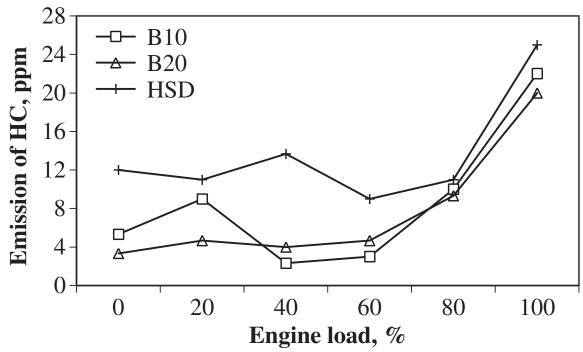

Figure 5 **Variations of HC emissions with engine load for B10, B20, and HSD.**

with all the fuels tested initially decreased from no load to 60% engine load, and then it increased with further increase in engine load up to 100%. It followed the same trend as that of CO emissions. The mean HC emissions with B10 and B20 were found to be 38.76% and 47.60% lesser than those with HSD. Among the two fuel blends tested, B10 gave the minimum reduction in HC emission as compared with HSD.

Oxides of nitrogen

The NO_x concentration in exhaust gas from a diesel engine when operated with HSD, B10, and B20 at different engine loadings is shown in Figure 6. It increased with the increase in both engine load and biodiesel concentration in the blends. The maximum NO_x values were obtained at full load conditions and were 1,173, 1,211, and 1,230 ppm, respectively, with HSD, B10, and B20, whereas it was 265, 296, and 344 ppm at 20% engine loading. The mean NO_x values with B10 and B20 were found to be 667.5 and 693.17 ppm, respectively, and were 5.57% and 11.45% higher than those with HSD. This higher NO_x production with biodiesel blends could be attributed to the higher EGT and the fact that biodiesel had some oxygen content in it, which facilitated NO_x formation. As the engine load increased, the overall fuel-to-air ratio supplied to the engine increased, resulting in an increase in average gas temperature in the combustion chamber; hence, NO_x formation, which is sensitive to temperature, increased.

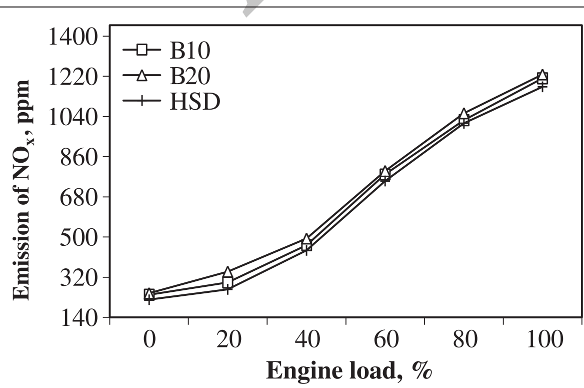

Figure 6 **Variations of NO_x emissions with engine load for B10, B20, and HSD.**

Similar findings on exhaust gas emissions were observed while operating the diesel engines with different biodiesel obtained from individual oils [23].

Selection of suitable biodiesel blend

Based on the minimum BSFC, maximum BTE, and minimum EGT, the biodiesel blend, B10, was found suitable for the running diesel engine without compromising engine performance when operated with HSD. However, from the emission point of view, this blend (B10) was found to produce higher CO and HC and lower NO_x emissions as compared with B20. However, both fuel blends tested exhibited lower CO and HC and higher NO_x emissions as compared with HSD. Considering both performance and emissions, B10 was considered as the suitable blend for replacing HSD in diesel engine and also in the long-term test of the engine that was conducted.

Soot deposits on in-cylinder engine components

The amount of soot deposits on the in-cylinder engine components when operated with different fuels were measured as per the procedure outlined in the 'Estimation of soot deposits on in-cylinder engine components' section and are summarized in Table 3.

The photographs of soot deposits formed on the cylinder head, piston crown, and fuel injector of diesel engine when operated with HSD and B10 along with a clean cylinder head, piston crown, and fuel injector are shown in Figure 7a,b,c, respectively. From these figures, it can be clearly seen that the soot deposits on the cylinder head, piston crown, and fuel injector of the engine were substantially lower when operated with B10 as compared with HSD. The amount of soot deposits on the cylinder head, piston crown, and fuel injector in the case of the B10-fueled engine was found to be 39.5%, 7.7%, and 25.0% lesser, respectively, as compared with those of the HSD-fueled engine.

A lesser amount of soot deposits on the different engine components when operated with B10 was because of the complete combustion of fuel due to the availability of extra oxygen in biodiesel molecules. The above results are in line with the findings reported by Agarwal et al. [25] when they conducted the 512-h endurance test with 20% blend of linseed oil methyl ester with HSD. They found about a 40% reduction in carbon deposits on the engine components when operated with B20 as compared with HSD.

Table 3 Soot deposits on cylinder head, piston crown and fuel injector of an engine

Engine parts	Operated with HSD (g)	Operated with B10 (g)	Variation as compared to HSD (%)
Soot deposits on cylinder head	0.38	0.23	−39.47
Soot deposits on piston crown	0.52	0.48	−7.69
Soot deposits on fuel injector	0.04	0.03	−25.00

Addition of wear metals in lubricating oil

Addition of wear metals in lubricating oil after 100 h of engine operation each with HSD and B10 was determined by following the procedure outlined in the 'Estimation of soot deposits on in-cylinder engine components' section and is summarized in Table 4. From this table, it can be seen that the concentrations of heavy metals such as Cu, Zn, Fe, Pb, Mg, and Al, except for Mn and Ni, were lower in the lubricating oil of engine when fueled with B10 as compared with when it was fueled with HSD. This could be due to the lesser friction of engine components because of additional lubricating property and presence of fatty acid compounds such as fatty acid methyl esters, FFA, monoglycerides, etc. in B10 fuel. According to some researchers, the presence of long-chain molecules, degree of unsaturation, and oxygenated moieties in the biodiesel play an important role in improving its lubricity [2,26,27]. Another reason for this could be the higher viscosity of B10 blend (5.96% higher) as compared with HSD.

Similar findings on the addition of metals on lubricating oil were also reported while conducting 100-and 512-h

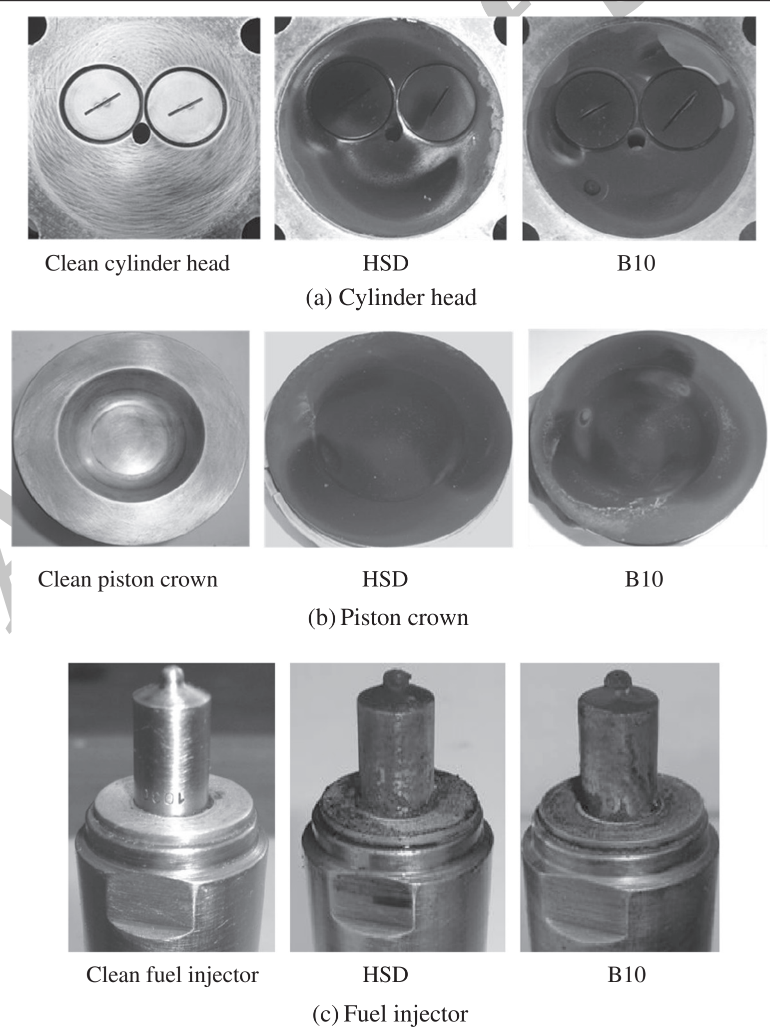

Figure 7 **Soot deposits on (a) cylinder head, (b) piston crown, and (c) fuel injector of diesel engine.**

Table 4 Wear metal addition in lubricating oil of engine when operated with HSD and biodiesel blends

Metals	Concentration at 0 h (ppm)	Concentration after 25 h (ppm)		Variation (%)	Concentration after 50 h (ppm)		Variation (%)	Concentration after 75 h (ppm)		Variation (%)	Concentration after 100 h (ppm)		Variation (%)
		HSD	B10		HSD	B10		HSD	B10		HSD	B10	
Cu	0.8	2.8	2.4	−14.3	4.4	3.0	−31.1	5.5	3.9	−29.1	7.02	4.7	−33.0
Zn	915.1	951.1	945.0	−0.64	1,027.8	1,012.0	−1.5	1,063.4	1,042.2	−2.0	1,260.0	1,120.8	−11.0
Fe	17.8	33.7	28.5	−15.4	43.6	37.7	−13.5	55.3	44.4	−19.7	60.9	48.6	−20.2
Mn	1.1	1.4	1.5	7.1	1.6	1.7	6.3	1.7	1.9	11.8	1.9	2.3	21.1
Ni	0.3	0.4	0.4	0	0.4	0.5	25	0.5	0.5	0	1.1	0.9	−18.2
Pb	1.3	2.2	1.4	−36.3	2.8	1.6	−42.8	3.4	1.9	−47.8	4.5	2.8	−37.8
Mg	50.6	59.8	54.2	−9.4	77.2	55.3	−28.4	89.2	57.2	−35.9	115.8	57.9	−50.0
Al	36.6	38.7	37.8	−2.5	58.5	49.3	−15.7	59.6	53.8	−9.7	66.3	57.5	−13.3

tests in diesel engines using palm kernel oil biodiesel blends (B7.5 and B15) and linseed oil methyl ester blend (B20), respectively [2,25].

Conclusions

The following conclusions have been made in this study:

1. The fuel properties of biodiesel obtained from the mixture, MSO, were found to be within the limits specified by the biodiesel standards ASTM D 6751–03, DIN EN 14214, and BIS 15607. The fuel properties of biodiesel blends approached those of HSD with a decrease in concentration of biodiesel in the blends.
2. BSFC and EGT of the 10.3-kW diesel engine when operated with biodiesel blends as compared with HSD at different engine loads were found to increase by 2.49% to 5.62% and 4.44% to 5.2%, respectively, whereas BTE was found to decrease by 1.48% to 3.22% with an increase in biodiesel concentration in the fuel blends. Among the two fuel blends tested, B10 had lower mean BSFC (287.29 g/kW h) as well as EGT (308°C) and a higher mean BTE (21.87%).
3. With an increase in engine load, the BSFC decreased, whereas both EGT and BTE increased for all the fuels tested. However, BTE for all biodiesel blends as compared with HSD was reduced on average by 2.09% at full load, and it was further reduced to 3.41% at 20% engine loading due to higher losses.
4. The CO and HC emissions of the diesel engine when operated with biodiesel blends as compared with HSD were reduced by 10.97% to 21.16% and 38.76% to 47.6%, whereas NO_x emissions increased by 5.57% to 11.45%.
5. Based on the performance (minimum increase in BSFC and EGT and with lesser reduction in BTE) and emissions (minimum reduction in CO and HC and minimum increase in NO_x), biodiesel blend B10 was selected for long-term use in diesel engine.
6. As compared with HSD-fueled engine, lesser carbon deposits on the in-cylinder parts (such as cylinder head, piston crown, and fuel injector) were observed for the B10-fueled engine due to better combustion of biodiesel blend.
7. Lower concentrations of all heavy metals (such as Cu, Zn, Fe, Pb, Mg, and Al, except for Mn and Ni) in the lubricating oil of diesel engine were found inB10-fueled engine as compared with those in HSD-fueled engine. This could be due to the lesser friction of engine components because of additional lubricity and higher viscosity of the B10 blend as compared with HSD.

Findings of this study would encourage the use of biodiesel obtained from the mixture of oils and would help in reducing the dependency on a particular oil for biodiesel production.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
All the authors - HR, PCJ, and SSJ - collectively carried out experiments, collected data, and analyzed them. HR wrote the manuscript. All authors read and approved the final manuscript.

Authors' information
HR is a professor at Indian Institute of Technology. PCJ is a scientist at Central Institute of Agricultural Engineering. SSJ is a systems engineer at John Deere India Pvt. Ltd.

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