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Experimental study on performance and emissions *Sterculia foetida* biodiesel in diesel engine

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ABSTRACT

Crude *sterculia foetida* oil (CSFO) is one of the non-edible feedstocks for biodiesel production and suitable to use in diesel engine. The *sterculia foetida* methyl ester (SFME) was produced by degumming and two step esterification-transesterificaton processes to remove gummy material and reduce viscosity. The detailed physicochemical properties of SFME were analyzed and compared with diesel. These properties were in acceptable range compared to ASTM D6751 or EN 14214 standards. Engine tests has been conducted using the biodiesel diesel blends of 5% (SFB5), 10% (SFB10), 20% (SFB20) and 30% (SFB30) biodiesel with diesel at various speed from 1300 rpm to 2400 rpm at full throttle load. The engine performance was analyzed and found that the SFB5 is the best result for engine performance when BTE was increased and reduced in Bsfc. Besides, the SFB5 can reduce CO and smoke opacity except NOx and CO_2 are slightly higher compared to diesel. The study reveals that SFB5 can be substituted and is a viable alternative fuel for diesel engine without any engine modification.

Keywords: Diesel engine, engine performance; emission characteristic; biodiesel, *sterculia feotida*

1. Introduction

Diesel engines are most efficient for wide applications and have advantage of higher efficiency, lower fuel consumption and higher reliability compared with other types of engines such as petrol engine and gas turbine (Atabani et al., 2013). However, harmful gases are emitted from the diesel engine such as carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), unburned hydrocarbons and particulate matters (Xue et al., 2011). Diesel mainly contains these pollutants and it will cause serious pollution to environment. In fact, the global environment would be concerned and protected from long term consumption of diesel. Therefore, biodiesel as alternative fuels or substitution becomes necessary to replace diesels. Moreover, the biodiesel production using esterification and transesterification process has been proven worldwide as an effective way to reduce viscosity and acid value of crude oil using refining stage as well as pretreatment process (Demirbas, 2009, Atadashi et al., 2010, Leung et al., 2010, Silitonga et al., 2011, Atabani et al., 2012).

Several researchers such as Aliyu et al. (Aliyu et al., 2011), Ilkilic et al. (Ilkılıç et al., 2011) and Celikten et al. (Çelikten et al., 2012) have investigated the use of biodiesel–diesel blends in direct injection engine without any major modification. It was indicated that blending conventional diesel with biodiesel can reduce smoke capacity, particulates, un-burnt hydrocarbons, carbon dioxide and carbon monoxide but nitrogen oxide is fairly increased. On other hand, there are no significant engine problems observed in performance and durability test of diesel engine fuelled with biodiesel blending. A review study was reported by Ilkilic et al. (Ilkılıç et al., 2011) that performance reductions were found in blending safflower biodiesel–diesel and brake specific fuel consumption was slightly increased. However, emissions reductions were recorded in PM and smoke emissions while NOx and HC emissions increased. Sahoo et al. (Sahoo et al., 2009) tested *jatropha*, karanja and polanga in a tractor engine compared with diesel. They found that engine power of *jatropha* biodiesel diesel blends were increased from 0.09% to 2.64% at full throttle performance test. The biodiesel from Chinese *pistache* and *jatropha* as an alternative fuel were investigated by Huang et al. (Huang et al., 2010). In their experiment, the performance and emission of a diesel engine works well and the power outputs are stable running with the two selected biodiesel at different loads and speeds. It is found that the emissions are reduced to some extent when using biodiesel. All emissions are reduced and lowered significantly than fuelled by diesel. Aliyu et al. (Aliyu et al., 2011) presented the results of performance and emissions test fuelled with *croton megalocarpus* (musine) methyl ester in a diesel engines. They observed that the brake thermal efficiency was lower compared with pure diesel. This test found that emissions of smoke, CO and NO_x were reduced at higher loads with biodiesel. The experiment carried out by Devan and Mahalakshmi (Devan and Mahalakshmi, 2009) showed improved in brake thermal efficiency and reduce NO_x emissions compared to the standard diesel but hydrocarbon and CO emissions were slightly increased.

Sterculia foetida plant belongs to Sterculiaceae family which has 2000 type of species and classified as non-drying oils. It is a wild plant native to Australia, Southeast Asia and Africa (Sudrajat R., 1987, Sudrajat R., 2005). However, *Sterculia foetida* is mainly distributed in Indonesia, Bangladesh, India, Philippines, Uganda and Somalia (Vipunngeun N and Palanuvej C., 2009, Kale et al., 2011). The plant has an average life span of more than 100 years (Sudrajat R., 1987, Sudrajat R., 2005, Munarso, 2010). The kernel of the seeds is consistent around 50–60% of bland, light-yellow fatty oil (Devan and Mahalakshmi, 2009). Devan and Mahalakshmi (Devan and Mahalakshmi, 2009) investigated the oil yield about 350 kg/oil/ha compared to *pongamia pinnata* 225 kg/oil/ha and rubber seed 120 kg/oil/ha (Atabani et al., 2012). In this study, the investigation have been undertaken to optimize the biodiesel production process analyzed and biodiesel properties. Besides, it also assessed the comparative performance and emission characteristic in a direct injection diesel single cylinder engine by using *sterculia foetida* biodiesel–diesel blends (5%, 10%, 20% and 30%). It is important to note that these properties can affect the engine performance and emission characteristic.

2. Biodiesel

2.1 Biodiesel–diesel blending

The preparation of *sterculia foetida* biodiesel–diesel blends was done at 26^{o}C by a beaker glass precisely on a volume basis and agitation of the contents is about 2000 rpm for 30 minutes to ensure homogeneity. The fuel mixtures used were 5%, 10%, 20% and 30% of *sterculia foetida* for biodiesel which were known as SFB5, SFB10, SFB20, and SFB30, respectively.

2.2 Fuel properties

The physicochemical properties were studied and analyzed for all the biodiesel. In this study, the physicochemical properties analyzed include the crude oil, produced biodiesel and their blends were determined following ASTM and EN standard specifications.

2.3 Engine test

The engine performance and emission of *sterculia foetida* biodiesel was investigated in a diesel engine. Four blends were obtained by blending diesel and biodiesel in the proportions by volume: 95% diesel + 5% biodiesel, 90% diesel + 10% biodiesel, 80% diesel + 20% biodiesel and 70% diesel + 30 % biodiesel. Those blends were compared with diesel as a baseline study. Performance parameters such as specific fuel consumption, brake thermal efficiency were measured and calculated. Moreover, exhaust emissions such as CO_2, CO, NO_x and smoke opacity are detected with gas exhaust analyzer. The engine was conducted on a single cylinder four stroke, naturally aspirated, water-cooled, direct injection diesel engine. The specification and engine testing bed are shown in **Table 1 and Fig. 1**. The engine was coupled with an eddy current dynamometer and electronic data acquisition systems. The test was firstly warmed up and started with diesel followed by biodiesel blends (SFB5, SFB10, SFB20 and SFB30) conducted on diesel engine. All parameter such as engine torque, engine power, specific fuel consumption and exhaust temperature were measured. The speed was tested at 1300 rpm to 2400 rpm with 100 rpm interval. After the engine reached the stabilized working condition, emissions and smoke opacity were measured using BOSCH 150 analyzer. The exhaust emissions were measured by a sensor filter at the end of the connector exhaust pipe. The specification gas analyzer was shown in **Table 2**. Each test was repeated three times and the mean was calculated and taken.

Table 1: Technical specification of the test engine

Type	TF 120 M Yanmar
Injection system	direct injection
Cylinder number	1
Cylinder bore x stroke volume	92 mm x 96 mm
Displacement	0.638 L
Compression ratio	17.7:1
Maximum power	7.7 kW
Maximum engine speed	2400 rpm
Cooling system	water cooling
Injection timing	17.0 bTDC
Injection pressure	200 kg/cm2

Fig. 1 The completed test bed engine single cylinder in the laboratory

Table 2: Technical data and specification of the gas analyzer device

	Technical data	
Exhaust component	Measurement range	Resolution
CO	0.000 – 10.00 % vol.	0.001 % vol.
CO_2	0.00 – 18.00 % vol.	0.01 % vol.
NO	0 – 5000 ppm vol.	< = 1 ppm vol.
Smoke opacity meter module		
Measured quantity	Measurement range	Resolution
Degree of opacity	0 – 100 %	0.1%
Oil temperature		
Measured quantity	Measurement range	Resolution
Temperature	-20 – +150 °C	0.16 C

3 Result and discussion

The physical and chemical properties biodiesel, biodiesel–diesel blends and diesel are measured and shown in **Table 3**. The properties were measured at Laboratory Energy Efficiency, University of Malaya, Kuala Lumpur, Malaysia.

Table 3: Properties of petrol diesel, biodiesel and biodiesel–diesel blends

Properties	Unit	Standard method	Diesel	SFME	SFB5	SFB10	SFB20	SFB30
Viscosity kinematic at 40°C	mm^2/s	ASTM D445	2.91	5.92	3.24	3.60	4.05	4.60
Density at 15˚C	kg/m^3	ASTM D1298	839.0	876.9	822.6	841.5	848.5	857.8
Acid value	mg KOH/g	ASTM D664	0.17	0.38	0.17	0.17	0.18	0.18
Calorific value	MJ/kg	EN 14214	45.825	40.493	45.317	45.250	44.149	43.859
Water content	%v	EN ISO 12937	0.0038	0.0450	0.0034	0.0031	0.0032	0.0028
Cetane number	-	ASTM D6890	49.7	56.5	50.3	51.4	52.7	54.3
Carbon	% wt	ASTM D3176	88.5	78	–	–	–	–
Hydrogen	% wt	ASTM D3176	13.5	12.5	–	–	–	–
Oxygen	% wt	ASTM D3176	0.0	11.68	–	–	–	–
Flash point	^oC	ASTM D93	71.5	156.5	80.5	82.5	85.5	87.5
Pour point	^oC	ASTM D97	1.0	2.8	1	2	3	3
Cloud point	^oC	ASTM D2500	2.0	3.0	8.0	10	10	10.7
Cold filter plugging point	^oC	ASTM D6371	–8.0	1.0	–12.0	–11.0	–10.0	–9.0
Cooper corrosion strip at 50^oC 3 hours	-	ASTM D130	1a	1a	1a	1a	1a	1a
Iodine value	g I_2/100g	EN 14111	–	103.0	–	–	–	–
Sulphated ash	% m/m	ASTM D5453	–	0.005	–	–	–	–
Sulphur content (S 15 grade)	ppm	ASTM D5453	–	13.97	–	–	–	–
Sulphur content (S 500 grade)	ppm		449.65	–	386.42	356.50	306.42	279.78
Phosphorous content	mg/ kg	EN 14107	–	4	–	–	–	–
Canradsons carbon residue (100% sample)	m/m	ASTM D4530	0.187	0.029	0.060	0.056	0.044	0.029
Oxidation stability hours, 110 ^oC	% m/m	EN 14112	23.70	4.42	16.45	15.34	11.39	10.2

The overall fuel properties of SFME were acceptable. However, they were slightly higher in viscosity (5.92 mm^2/s) and lower in calorific value (40.493 MJ/kg) compared to diesel (2.91 mm^2/s and 45.825 MJ/kg). Moreover, oxidation stability of SFME was 4.42 hours which is below the EN 14214 of 6 hours. The presence of cylopropene ester in malvalic and sterculic acids of SFME will lead lower oxidation stability. The cyclopropene ring was considered as a weaker carbon chain than other typical carbon bond such as palmitic, oleic, linoleic and linolenic. Thus, this will cause the SFME to undergo oxidation more rapidly (Bindhu, 2011). However, the SFME achieved oxidative stability above the ASTM specified value of 3.0 hours.

The cetane number and flash point are comparatively higher than diesel. However, viscosity kinematic and density were increased while percentage biodiesel blends was increased. It is shown that biodiesel is safer for storage and to be used in transportation sector. The calorific value of SFME was measured to be 40.167 MJ/kg which is around 12% less than diesel (45.825 MJ/kg).

The experimental test was carried out on the diesel engine using diesel and *sterculia foetida* biodiesel–diesel blends (SFB5, SFB10, SFB20 and SFB30). The engine performance parameter such as brake specific fuel consumptions and brake thermal efficiency were recorded and calculated. On top of that, the emission exhaust of NO_x, CO, CO_2 and smoke opacity were analyzed using the exhaust gas analyzers. The performance and emission characteristic of SFB5, SFB10, SFB20, SFB30 and diesel are analyzed and discussed below.

The trend of brake thermal efficiency for SFB5 blends is slightly higher than diesel as shown in **Fig. 2**. Brake thermal efficiency for SFB10, SFB20 and SFB30 were lower than SFB5 and diesel due to better combustion and lower viscosity of SFB 5 than other blends. It is revealed that SFB5 more suitable than other blends with higher brake thermal efficiency. The maximum brake thermal efficiency obtained for SFB5, SFB10, SFB20 and SFB30 were 25.96%, 21.28%, 20.25% and 19.28%, respectively at 1900 rpm. This show that higher viscosity of the SFB resulted in poorly formed fuel sprays will affect the combustion in the engine (Misra and Murthy, 2011). Moreover, it is noticed that when reaching certain limit of blending ratio, the thermal efficiency trend is reverted and starts decreasing as a function of the concentration of blends which agrees with the study by Ramadhas et al. (Ramadhas et al., 2005).

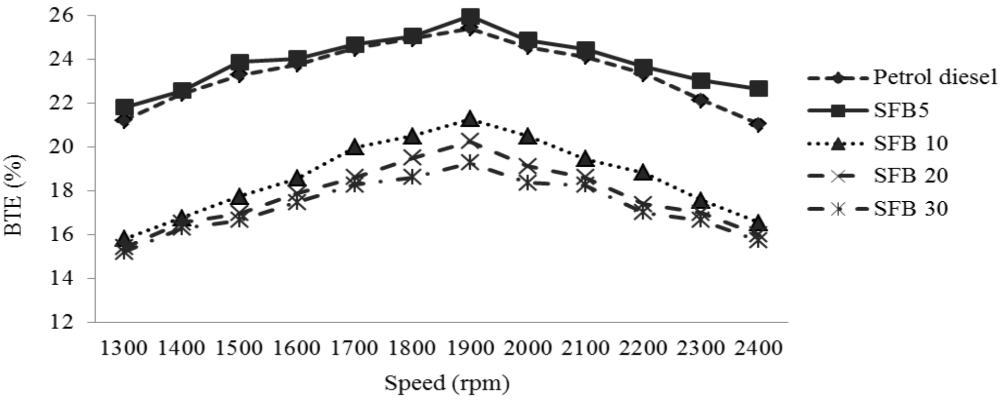

Fig. 2 BTE (%) with various engine speed at full throttle for the test fuels

The trend of Bsfc with the SFME and diesel operation at various engine speed are shown in **Fig. 3**. The optimum Bsfc values for diesel, SFB5, SFB10, SFB20 and SFB30 at 1900 rpm were found to be 495 g/kWh, 466 g/kWh, 628 kg/kWh, 648 g/kWh and 678 g/kWh respectively. The higher fuel consumption of the SFB10–SFB30 showed that those blends have lower calorific value, higher fuel density and viscosity. Qi et al.(Qi et al., 2010), Buyukkaya (Buyukkaya, 2010) and Hebbal et al.(Hebbal et al., 2006) explained that higher percentage of biodiesel and its blends are needed to produce the same amount of energy due to lower heating value. The similar study was observed by Qi et al. (Qi et al., 2009) that engine needed a larger amount of biodiesel showed that Bsfc biodiesel was higher than diesel at full throttle and load.

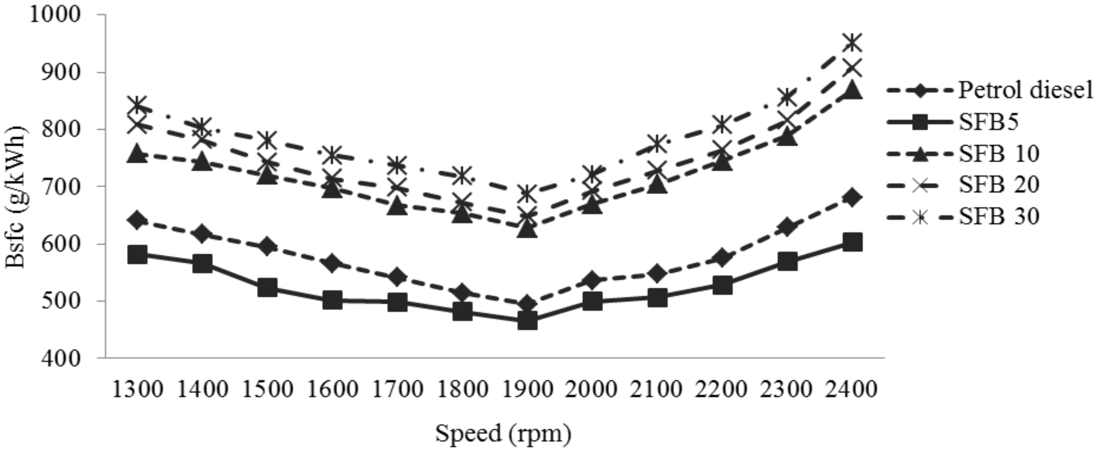

Fig. 3 Bsfc (g/kWh) with various engine speed at full throttle for the test fuels

Fig. 4 shows the variation of NO_x (ppm) emissions with engine speed for SFB compared to diesel. There was general increase of NO_x emissions which is 315.0 ppm, 339.6 ppm 342.3 ppm and 368.6 ppm for SFB5, SFB10, SFB20 and SFB30 at 2400 rpm. The higher combustion temperature and the influence of high cetane number of biodiesel in the engine cylinder caused increasing engine speeds (Vipunngeun N and Palanuvej C., 2009, Misra and Murthy, 2011, Çelikten et al., 2012). The results are consistent with the increase in cylinder temperature and exhaust temperature. That result was similar with Karabektas et al. (Karabektas et al., 2008), Nabi et al. (Nabi et al., 2009) and Wang et al. (Wang et al., 2006). The presence of oxygen with blends caused higher NO_x formation and it is indicated that exhaust gas temperature was increased. (Lin et al., 2009, Çelikten et al., 2012). However, Keskin et al. (Keskin et al., 2008) reported that NOx emissions are slightly increased due to increasing biodiesel concentration in the fuel.

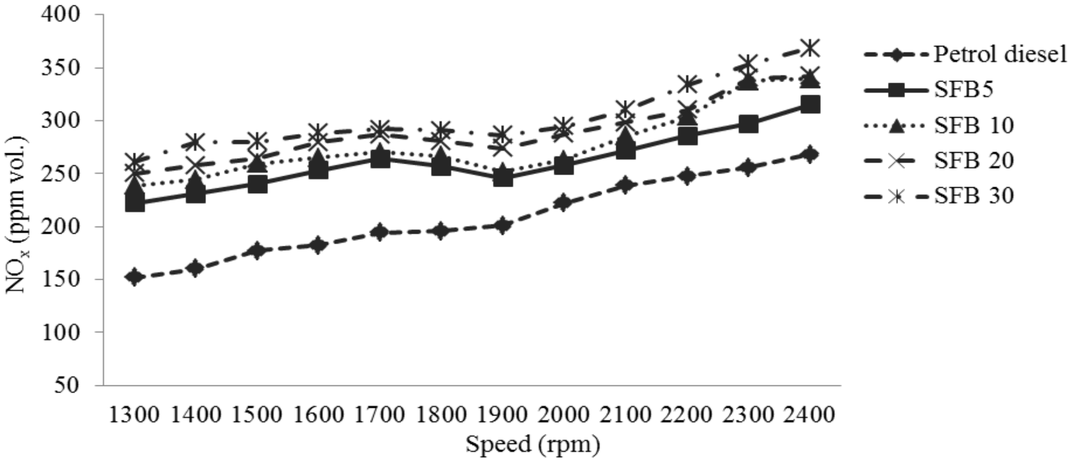

Fig. 4 Variation of NO_x (ppm) emissions with engine speed for SFB compared to petrol diesel

Carbon monoxide emission for SFB5, SFB10, SFB20 and SFB 30 were less than diesel as shown in **Fig. 5**. This is due to the turbulence occurs in the combustion chamber at higher speeds and it caused CO emissions decrease. This agreed with Ilkilic et al. (İlkılıç and Aydın, 2011) and Nabi et al. (Nabi et al.,2009) stated that CO emission increasing with rising temperature in the combustion chamber and oxygen content in the fuel. SFB5 is more complete combustion than other blends. This is because fuel viscosity on fuel spray quality would be expected to produce some CO increase with vegetable oil fuels. On other hand, it can be attributed to the higher cetane number of biodiesel fuel which improved combustion and reduced CO emissions. It is proved that engine speed and cetane number increase caused the CO emission for SFB 30 to be lower than other blends.

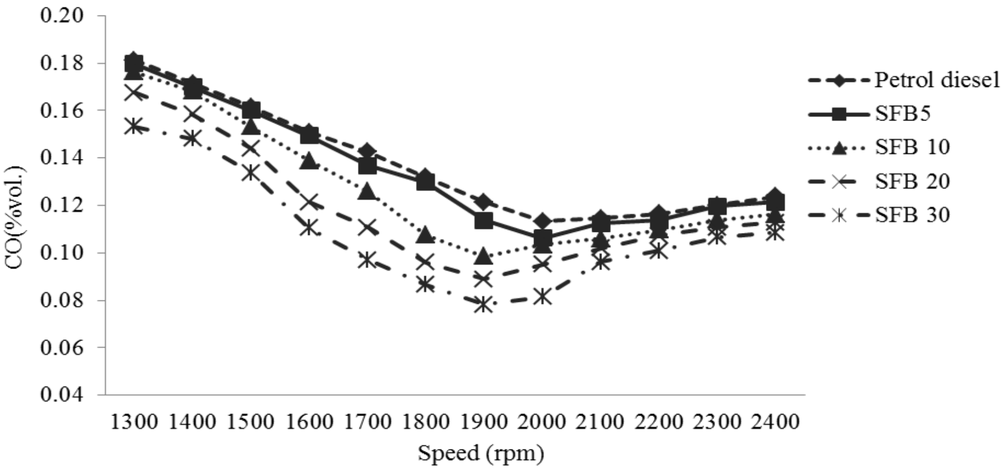

Fig. 5 Variation of CO (%) emissions with engine speed for SFB compared to petrol diesel

Carbon dioxide (CO_2) is the major emission contributing to greenhouse gas effect. **Fig. 6** shows the variation of CO_2 emissions with speed for SFB blends compared to diesel. It was observed that SFB5 has the higher CO_2 emission due to complete combustion and lower viscosity compared to SFB10, SFB20 and SFB30. The average amount of CO_2 emission for SFB5 is 3.009% followed by SFB10, SFB20 and SFB30 which are 2.903%, 2.781% and 2.664%, respectively. Biodiesel has lower CO_2 emission than diesel (2.952%). Aliyu et al. (Aliyu et al., 2011) reported that CO_2 emissions of biofuel can be considered as zero carbon emissions as they are sourced by the plant from air bourn carbon.

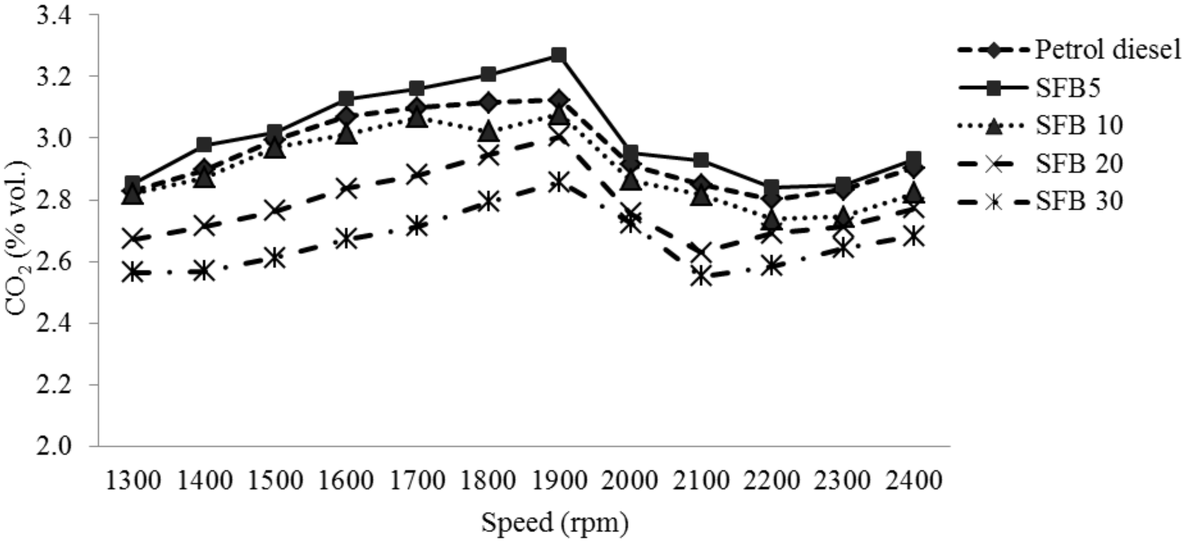

Fig. 6 Variation of CO_2 (%) emissions with engine speed for SFB compared to petrol diesel

The variation of smoke opacity with engine speed for SFB compared to diesel was shown in **Fig. 7.** The SFB5 showed better emission performance than diesel. The reason for lower smoke opacity for SFB5 are the complete combustion of fuel due to atom being present in the molecule of biodiesel itself and good properties compared to other blends. The lower thermal efficiency indicates incomplete combustion of blends fuel. Moreover, SFB10, SFB20 and SFB30 indicated high viscosity and low volatility affect the poor spray formation in combustion chamber. This outcome was similar with Banapurtmath et al. (Banapurmath et al., 2008) and Haldar et al. (Haldar et al., 2009) which reported that increasing biodiesel ratio in the blends caused slightly higher smoke opacity emission than diesel.

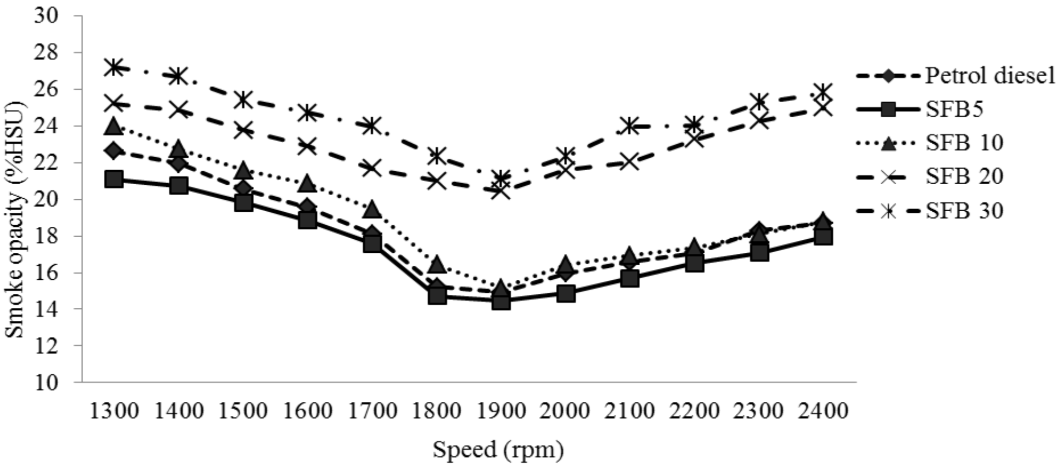

Fig. 7 Variation of smoke opacity (%) with engine speed for SFB compared to petrol diesel

4 Conclusion

This paper presents SFME as a promising non-edible feedstock to substitute diesel in CI engine. It was found that the blends of SFME with diesel could be used with acceptable performance and emissions characteristic up to certain blending ratio. The main findings of this study were can be concluded as below:

- Degumming and two step esterification-transesterification process are used for SFME and the viscosity was reduced from 63.90 mm^2/s to 5.92 mm^2/s.
- SFME blends with diesel resulted in an improvement of kinematic viscosity and oxidation stability.
- SFB5 could reduce emissions characteristic and obtained favourable engine performance which decreased the Bsfc and increased BTE. However, the use of SFB10, SFB20 and SF30 caused an increase in NOx, and smoke opacity except CO and CO2.

From the above results, it has been found that the SFB5 is the best blends compared to the diesel. The experimental result proves that SFME are potential alternative fuel for diesel engine.

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