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ENVIRONMENTAL AND ENERGY MANAGEMENT

Influence of antioxidant additives on performance and emission characteristics of beef tallow biodiesel-fuelled C.I engine

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Abstract

This work analyses the performance and emission characteristics of biofuelled compression ignition (C.I) engine with the implementation of an antioxidant. Using the transesterification process with sodium hydroxide as a catalyst, the beef tallow methyl ester (BTME) was obtained from the beef tallow oil. Poor physical properties of biodiesel (beef tallow oil (BTO)) namely high viscosity and density cause atomization problems leading to higher smoke, hydrocarbon and carbon monoxide emissions. The purpose of this work is to enhance the performance aspects, to limit smoke emissions from BTO operation and to examine the possibility of direct use of neat BTO in CI engine. This research paves a way of investing the impact of binary blends of BHA and BTO on the research engine. The experiments were conducted on a single-cylinder four-stroke C.I engine using the following fuel compositions: 20% of BTME mixed with 80% diesel (B20), 1000 ppm mono-phenolic antioxidant (butylated hydroxyanisole (BHA)) mixed with the blends of B20 (B20 + BHA), and 100% diesel. Based on the experimental results, it was found that the brake thermal efficiency (BTE) increases by 1.8% and the brake specific fuel consumption (BSFC) decreases by 2.5% for the fuel blend B20 + BHA when compared with that for B20 fuel blend. Compared with the B20 blend, the blend B20 + BHA emits 12.2% lesser nitrogen oxide due to breaking chain reactions, scavenging the initiating radicals and reducing the concentration of reactive radicals.

Keywords Enzyme catalyst · Transesterification · Biodiesel · Performance · Emission. Butylated hydroxyanisole

Nomenclature

ASTM	American Society for Testing Materials
BD100	neat biodiesel
B20	20% of biodiesel + 80% neat diesel
B20 + BHA	20% of biodiesel + 80% neat diesel + 1000 ppm of antioxidant BHA
NO_x	Oxides of nitrogen emission
BSFC	Brake specific fuel consumption
HC	Unburned Hydrocarbon
BTE	Brake thermal efficiency
CO	Carbon monoxide
DI	Direct injection
IMEP	Indicated mean effective pressure
NO_x	Oxides of nitrogen (NO_x)
EGT	Exhaust gas temperature

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Introduction

Diesel fuel among all fossil fuels has played a crucial role in all the major sectors like power, industry, marine, transportation and agriculture owing to fuel economy, reliability and rigidity. The downside is that they emit harmful chemicals like nitrogen oxide (NO_x), hydrocarbon (HC), PM and smoke which is too hazardous for the environment. Furthermore, an increase in cost and a drastic reduction in the availability of diesel fuels have paved a way of using biodiesel as a partial alternate. To lower the above-said drawbacks, biodiesel derived from renewable sources has gained attention. In fact, many countries have started employing biodiesel (BD) as a 20% replacement of diesel fuel. Venu and Madhavan (2017), Vellaiyan et al. (2019) and Subramanian et al. (2018) have suggested that blending biodiesel, bio-oil and alcohols above 20% to diesel will result in lower calorific value which affects the overall performance of the blended fuels. Biodiesel (BD) is surmised as a capable alternative to diesel owing to its renewable nature and ease in availability. BD is liquid fuel which has similar properties to diesel. BD shall be produced by many techniques namely pyrolysis, crushing and transesterification. Among which, the transesterification is widely accepted and most trusted way for producing BD (Bharathiraja et al. 2017). This technique requires raw oil (base source), alcohol (ethanol) and catalysts (acid or base). The oil and alcohol are mixed at certain acceptable molar ratio (5–7:1) along with the catalysts at 1–1.5 %wt and heated to a temperature of 50–70 °C. The mixture is then vigorously stirred for homogenous mixing for a time interval (40–60 min). Post heating, this mixture is allowed to settle. This process results in the splitting of two products (methyl/ethyl ester and glycerol). The by-product (glycerol) is removed from an ester by gravity-based separation. Many works tried BD as partial/complete replacement (10–100%) to diesel and found a drastic reduction in tailpipe emissions with lower performance (Kavitha 2019). Many studies attempted with different resources for the progress of substitute resource and some of them were palm oil (Ganesan et al. 2019), rice bran oil (Devarajan et al. 2019a; Kavitha et al. 2019), cashew shell oil (Joy et al. 2019), Punnai oil (Devarajan et al. 2019b), orange peel oil (Siva et al. 2018), corn oil (Ganesan et al. 2018), almond oil (Devarajan 2018), Mahua oil (Sudalaimuthu et al. 2018) and neem oil (Rathinam et al. 2019). From the outcome of the above review, it is quite clear that the BD was a sustainable, promising choice for diesel. Conversely, the outcome also suggested that the usage of BD100 (100% biodiesel) will result and fuel clogging; thus, it was suggested not to use BD more than 20% in a diesel engine. The inference from the above studies concludes that the BD shall be employed as a partial replacement of diesel fuel. Moreover, blending reduces the usage of fossil fuels and lower the emissions associated with the diesel engine. Secondly, the inference also states that very limited works have been tried using waste beef tallow oil (BTO). In other words, scanty researches were recognized for employing beef tallow oil (BTO) as a potential and partial alternate of diesel fuel.

India is one of the world's largest beef exporter, almost 2100 metric tonnes of beef are exports from India. Beef tallow is one of the main residues from slaughterhouses and these are primarily used in soap industries. If the soap industry is overloaded, these extra fat residues are incinerated and disposed of in the landfill. The use of animal fat residue as biodiesel in compressed ignition (C.I) engine could reduce the burden on petroleum diesel. The market price of the BTO is comparable with conventional diesel. However, the effective use of by-products from the production of animal fat biodiesel could be competitive with the use of commercial petroleum diesel. In general, the oil produced from animal fat (beef tallow or chicken) has similar properties with petroleum diesel except for the viscosity. This is due to the presence of a high amount of saturated fatty acids and this will lead to creating ignition problems. The production of biodiesel from beef tallow oil by the transesterification process was mentioned above. Very few studies were performed in the past decades for the use of animal fatty acids as biodiesel in the diesel engine. Shahir et al. (2017) reported that the use of 30% blends of animal fat biodiesel with conventional diesel lowered carbon monoxide (CO), HC and smoke emissions with inferior performance, higher NO emissions in CRDI engine. John paneer Selvam and Vadivel (2012) analysed the effect of beef tallow biodiesel blends with diesel in a diesel engine and reported that there was a slight decrease in brake thermal efficiency with a considerable reduction in the CO, HC and smoke pollutions for all blends. In addition, the BTO possessed inferior performance and higher NO emissions than neat diesel.

Inference from a few kinds of literature using beef tallow and other biodiesel suggested that the NO emissions are on the higher side with a slight reduction in performance aspects while using different BD. Improvement in brake thermal efficiency (BTE) with a significant reduction in NO_x emissions shall be achieved by fuel alteration techniques which involve no physical modification in engines. To reduce the NO_x emission from diesel-/biodiesel-fuelled engine, numerous attempts have been made by many researchers. Devarajan (2018) tried to modify the fuel properties of almond biodiesel using dimethyl carbonate (DMC) as an antioxidant and reported a noteworthy reduction in NO_x emissions. In another study, Ganesan et al. (2018) attempted to mix the DTBP (di-tetra-butyl-peroxide antioxidant) with mustard biodiesel and found a considerable fall in NO_x emissions. Joy et al. (2019) formulated the DME (dimethyl-ether) emulsified cashew shell biodiesel and propelled diesel engine. The results show that an increase in DME concentration with biodiesel directly reduces the NO_x emissions due to improved properties of DME (antioxidant) during the combustion process. Xiao et al. (2017) attempted the addition of dimethyl carbonate with diesel. The experimental results of diesel show a positive effect in terms of smoke opacity and NO_x. Hazar (2017) used the tripropylene glycol as an additive (oxygenated) for diesel-biodiesel blends fuel and recorded a significant improvement in NO_x emission characteristics. Teixeira et al. (2010) studied the characteristics of beef tallow biodiesel and reported that the use of mixtures of tallow biodiesel with soybean biodiesel and conventional diesel produces the optimum performance with the minimum emissions. Mei et al. (2017) used the dimethyl carbonate as an additive (oxygenated) for neat diesel and recorded a significant improvement in NO_x emission characteristics with a sharp reduction in brake specific fuel consumption (BSFC). Wei et al. (2017) attempted the addition of antioxidants (2,5-dimethylfuran) with biodiesel-diesel blends. Furthermore, the experimental results of formulated biodiesel show a positive effect in terms of NO_x and smoke opacity for all the test fuels with improved BTE. A promising solution for improving the oxidation stability and reducing the NO_x emission is the treatment of biodiesel with antioxidant additive. The reduction of NO_x emission is a result of the hydrogen-free radicals' reduction, which is responsible for prompt NO_x formation during the combustion process (Rashed et al. 2016a, b, c, d, Vellaiyan 2019).

Key findings from the above studies proved that the antioxidants are a promising means to lower the limitations of biodiesel and enhance its usage as fuel in CI engine. Improved properties such as higher cetane number, improved miscibility, higher calorific value, lower pressures (vapour) and flash point are the other positive properties merits of antioxidants. In addition, inference from the literature review also concludes that scanty researches were recognized with beef tallow biodiesel and butylated hydroxyl anisole (BHA) in compression ignition engine. The use of biodiesel in engine reduces emission and provides good lubrication compared with mineral diesel. In general, the biodiesel derived from the animal fat has poor oxidation stability and leads to the formation of hydroperoxides which in turn produce the insoluble gums and sediments that affect the fuel supply systems. The end product may increase the viscosity of the fuel and leads to poor fuel atomization. The addition of antioxidants in biodiesel delays and controls the autoxidation process and decrease the formation of secondary products.

This work aimed to study the performance and emission characteristics of a single-cylinder diesel engine fuelled with beef tallow biodiesel blends integrated with antioxidant butylated hydroxyanisole (BHA). The concentration of the antioxidant additive was limited to 1000 ppm, which resulted in a better induction period compared with other concentrations. The small quantity of beef tallow biodiesel (20%) was mixed with the conventional diesel (80%) and 1000 ppm of antioxidant BHA. The biodiesel prepared by this technique is referred to as B20 + BHA. The comparative performance analyses of the compressed ignition engine fuelled with B20, B20 + BHA, B100 and diesel were studied. In this study, the diesel engine initially experimented with diesel as baseline observation and the obtained results were evaluated with alternative fuel samples. The characteristics of non-edible, widely available and abundant BTO in India and exciting oil content are the major reasons for selecting beef tallow oil. However, no studies have detailed the effect of butylated hydroxyanisole (BHA) to improve the emissions characteristics of BTO. The butylated hydroxyanisole (BHA) antioxidant in biodiesel interrupts the reaction of the formation of secondary products and releases hydrogen atom to a free radical. The BHA is highly soluble in oil and insoluble in water. BHA is a combination of 3-tertiary-butyl-4-hydroxyanisole (90%) and 2-tertiary-butyl-4-hydroxyanisole (10%). BHA helps to protect the hydroxyl (OH) group and improve the thermal stability of animal fats. The properties of BHA are listed in Table 1.

Materials and methods

Biodiesel production

The beef tallow oil (BTO) was bought from the local market in Chennai, Tamil Nadu, India. For the transesterification process, methanol and a base catalyst NaOH pellets were used. Five litres of BTO was procured from Agro Biotech, Chennai, India. The cost of the BTO was 54 INR/l. Five litres of BTO yielded 4340 ml of biodiesel (86.8%) by conventional transesterification procedure. To produce biodiesel from the BTO, a molar ratio of 5:1 (methanol to BTO) and catalysts of 0.3% (wt/wt) to BTO were used in transesterification process adapting standard procedure. A batch reactor with a capacity of 5 l was equipped with a condenser, a magnetic stirrer with a tachometer, a thermometer pocket along with a thermocouple and a stopper to remove samples were used. By means of a constant temperature heating mantle, the reaction temperature was maintained within ± 0.1°. A sufficient amount of BTO was heated in the batch reactor. Methanol and the catalyst NaOH were mixed together in a conical flask and this solution is transferred into the batch reactor containing the preheated BTO. The reaction is allowed to take place for 90 min. After this, the solution is allowed to settle for 12 h in a separating funnel and the lower glycerol layers were removed. The residual methanol was removed using a rotary evaporator. Figure 1 shows the photographic view of the transesterification process. To bring the pH value to normal, the obtained biodiesel

Table 1 Properties of BHA

Property	BHA
Colour	White or slightly yellow waxy solid
Boiling point (°C)	268
Melting point (°C)	51
Flash point (°C)	113
Molecular weight (g mol^{-1})	182
Chemical formula	$C_{11}H_{16}O_2$
Solubility	Insoluble in water and freely soluble in alcohol, propylene glycol, petroleum ether fats, oils

Fig. 1 Transesterification process

crude was then washed multiple times with warm deionized water. Based on previous studies, the small quantity of beef tallow biodiesel (20%) was mixed with the conventional diesel (80%) and 1000 ppm of antioxidant BHA. The biodiesel prepared by this technique is referred to as B20 + BHA. The same methodology has been followed for the preparation B20 blend (80% biodiesel and 20% conventional diesel) without the addition of BHA. The use of 100% biodiesel in the engine is referred to as B100. Figure 2 shows the photographic view of the fuel specimen employed. Physical and chemical properties such as density, viscosity, calorific value, cetane number and flash point are measured for all the base and modified fuels using American Society for Testing Materials (ASTM) test procedures and are compared with diesel.

Table 2 shows the properties of derived biodiesel blends and conventional diesel. ASTM standards are referred and the same testing procedure is performed to find out the desired properties of fuel (Vellaiyan 2020; Raju et al. 2020; Vellaiyan et al. 2020). A DMA 4500 density meter with a range of 0 to 3 g/cm^3 and an accuracy of 5 × 10–5 g/cc is used to measure the density of testing fuels. A Brookfield Viscometer Model DV-I+ with UL adapter is employed to measure the viscosity of testing fuels. It consists of a set of seven spindles (RV Spindle Set) with accuracy ± 1%. The flashpoint of biodiesel is measured by a flash point tester which consists of an 80-ml closed copper cup, a heater and a source that gives continuous sparks. A cetane tester SHATOX SX-200 with a range of 20–100 (CN units) and an accuracy of 0.1 °C is used to measure the cetane number. A cloud and pour point analyser (ISL CPP 5Gs) having a range of − 95 to 51 ° C and an accuracy of 0.1 °C is used to measure cloud and pour point of the samples. A stainless-steel bomb jacket water calorimeter equipped with mortised heavy-duty firing unit with immunization requiring 220/203 V and AC supply single-phase ± 10‰ Hz is used to measure the calorific value of test fuels.

There are two types of fatty acids in the animal oil, saturated fat and unsaturated fat. Stearic, palmitic and hydroxystearic acids are saturated fatty acids and unsaturated fatty acids are oleic, linoleic, ricinoleic, palmitoleic, linolenic and eicosenoic acids. The composition of fatty acids in the beef tallow oil esters was calculated by the gas chromatograph with a flame ionization detector (GC-FID) system (Shimadzu GD 17A) according to the norms of EN 14103. In general, saturated fatty acids have a very low oxidation rate than unsaturated fatty acids. Fuel stability research is primarily focused on the reactions of unsaturated fatty acids. Table 3 shows the fatty acid contents of the beef tallow methyl esters and it is observed that the oleic acid content in the oil is more compared

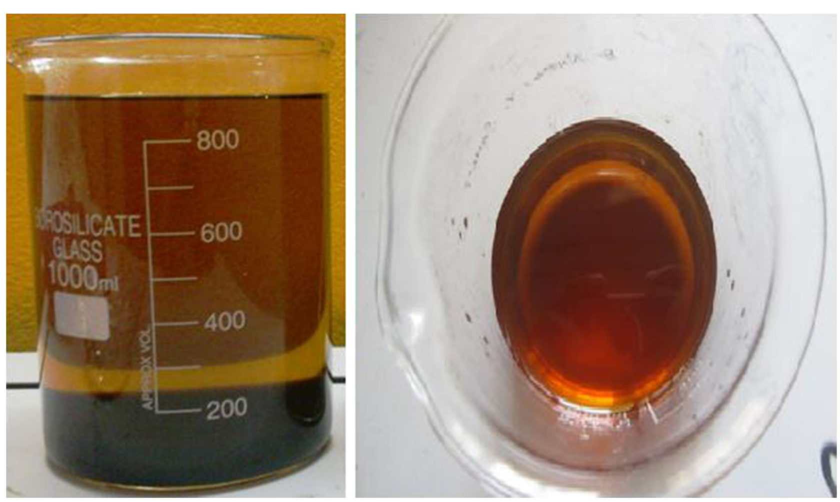

Fig. 2 Photographic view of the fuel specimen prepared

Table 2 Properties of fuels

Property	Unit	Diesel	B100	B20	B20 + BHA	Test method
Calorific value	kJ/kg	43,350	35,010	40,700	41,100	ASTM D240
Density at 15 °C	kg/m^3	828	800	795	774	ASTM D1298
Flash point	°C	68	180	88	90	ASTM D93
Cloud point	°C	8	3.2	3	3	ASTM D97
Pour point	°C	7	2.5	2.2	2.2	ASTM D97
Kinematic viscosity at 40 °C	cst	3.25	4.54	3.95	3.61	ASTM D445
Oxidative stability	h	58	9	20	40	ASTM D2274
Cetane number		48	62	52	57	ASTM D613
Molecular weight		179	312	-	-	-

with other acid contents. The oleic acid is the monosaturated fatty acid and the higher percentage composition of this acid leads to creating the cold plugging problem and thus reduces the ignition quality. The relative oxidation rate of fatty acid series stearic, oleic and linoleic acid is to be in the ratio of 1:100:1200.

The miscibility and stability of BHA antioxidant in BTO was measure by using a laser beam–assisted photonic circuit method which is shown in Fig. 3. The laser beam focused on the photoresistor connected to a multimeter in order to measure the deflection of stability. The absorption properties of BHA-BTO were investigated by the UV absorption spectrum. The photographic view of the UV absorption spectrum for BTO-BHA is shown in Fig. 4. It is seen that the absorption peak was noticed at 375 nm which confirms that the BHA was well dispersed in BTO with uniform size and shape. Also, the gravitational method is followed for evaluating the stability of the beef tallow oil (BTO) and antioxidant BHA mixed test fuel by keeping the samples for a week and the sample shows the least separation of phases (Devarajan et al. 2018). The following relation (Eq. (1)) calculates dispersion stability

$$\text{Dispersion stability} = \frac{\text{The volume of the dispersed layer}}{Totalvolumeofsample} \quad (1)$$

Table 3 Free fatty acid contents in beef tallow oil (BTO) biodiesel

Fatty acids	% composition	The molecular weight of acid	The molecular weight of the ester
Lauric, C12:0	Trace	-	-
Myristic, C14:0	24.20	228	240
Stearic, C18:0	25.80	284	298
Oleic, C18:1	37.20	282	296
Linoleic, C18:2	12.80	280	294

Based on the observations for a week, the dispersion rate and stability of BTO and 1000 ppm BHA were found to be stable.

Experimental setup

The experiments were performed on a water-cooled, single-cylinder, direct-injection diesel engine; the layout and pictorial view of the engine setup is shown in Figs. 5 and 6. Table 4 shows the test engine specifications. The test engine is coupled to an eddy current type dynamometer for load variations. The AVL Digas 444 five-gas analyser was employed for the measurement of CO, carbon dioxide (CO_2), NO_x and HC emissions at different load conditions. The diesel engine output shaft is connected with the eddy current dynamometer, which is used to measure the power and torque. The load cell is connected to the dynamometer for varying the load on the engine (0–100%). Table 5 illustrates the details of an exhaust gas analyser. First, the engine is started using diesel and is run for about 15 min to warm it up. At a constant speed of 1500 rpm, the performance parameters and emissions were measured at 4 different engine loads (25%, 50%, 75% and 100%). At the steady-state conditions, the readings were taken. Now, the engine is run on two test fuels (B20 and B20 + BHA) and the results were noted. Engine performance parameters like brake thermal efficiency, brake specific fuel consumption and exhaust gas temperature and emission parameters were analysed in terms of CO, HC and NO_x emissions.

Methodology

Initially, the engine is allowed to run for 10 min with diesel to obtain a steady state and at atmospheric conditions. Subsequently, the experimental results are recorded for various fuel blends (B20 and B20 + BHA) at constant engine speed at 1500 rpm and the injection timing and pressure at 17° bTDC and 200 bar respectively. For each fuel sample (B20 and B20 + BHA and diesel), the experiments are

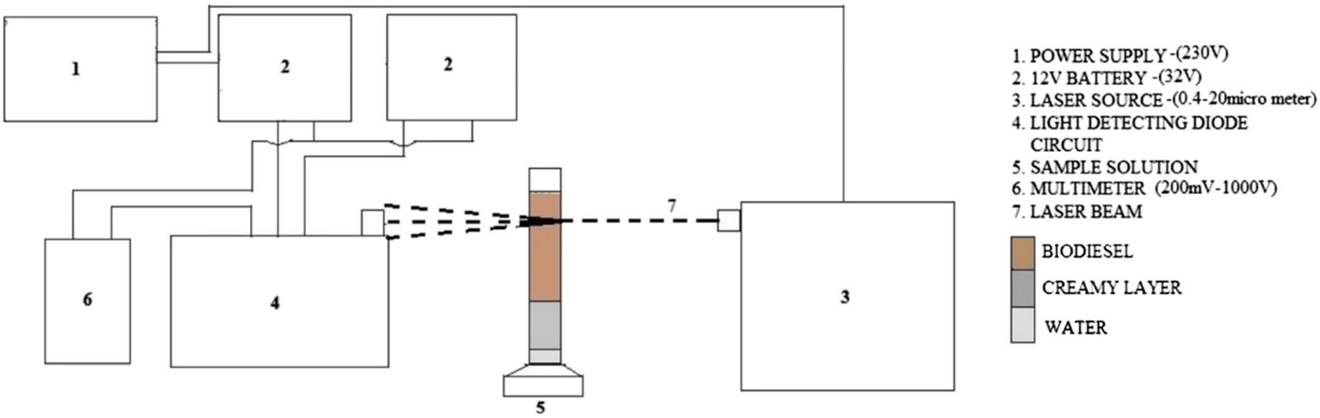

Fig. 3 Laser beam–assisted photonic circuit (Vellaiyan 2019b)

repeated 5 times at similar conditions, and the average value is considered for assessment to lessen the experimental errors.

Uncertainty analysis

Every work includes some amount of uncertainty. These uncertainties mainly result in calibration, sensors, observations, test procedure and environmental conditions. In view of uncertainties, the preferred test results can be examined for any work. If a quantity to be measured "R" has a function of many self-regulating variables like the following

$$x_1, x_2, x_3, \ldots x_n \text{ then } R = R(x_1, x_2, x_3, \ldots x_n) \quad (2)$$

let the measured quantity uncertainty be expressed as W_R and the independent variables uncertainties are expressed as W_1, W_2, W_3, $\ldots W_n$.

Subsequently, the uncertainty in the measured quantity is given by

$$W_R = \sqrt{\left[\left(\frac{\partial R}{\partial x_1}W_1\right)^2 + \left(\frac{\partial R}{\partial x_2}W_2\right)^2 + \left(\frac{\partial R}{\partial x_3}W_3\right)^2 + \ldots\ldots\ldots\left(\frac{\partial R}{\partial x_n}W_n\right)^2\right]} \quad (3)$$

where $W_R = \frac{\delta R}{R} \pm \delta R$ is the error in R. The uncertainty percentage of various measured and calculated parameters are listed in Table 5, and the overall uncertainty percentage of experimental results is calculated as 1.3% using the following equation:

$$\text{Overall uncertainity} = \sqrt{\text{uncertainity of } \left(\text{HRR}^2 + P^2 + N^2 + \text{BSFC}^2 + \text{BTE}^2 + \text{CO}^2 + \text{HC}^2 + \text{NO}_x^2 + \text{smoke}\right)} \quad (4)$$

Results and discussion

Performance characteristics

Brake specific fuel consumption

Brake specific fuel consumption (BSFC), expressed in kg/kWh, is defined as the mass of fuel consumed by the engine per unit brake power output. Figure 7 shows the variation of BSFC for B20, diesel and B20 + BHA with the load. BSFC varies from 0.58 to 0.28 kg/kWh for all fuels. BSFC of B20 varies from 0.56 kg/kWh (no load) to 0.31 kg/kWh (full load), whereas it changes from 0.54 kg/kWh (no load) to 0.29 kg/kWh for diesel and 0.58 kg/kWh (no load) to 0.34 kg/kWh for B20. With the increase in load from no to full load, BSFC rates for B20, diesel and B20 + BHA reduce by 22.3, 24.1 and 21.5% respectively. It owes to drop in the ratio between brake power and friction power for tested fuels. BSFC rates for B20 and B20 + BHA are 0.02 and 0.05 kg/kWh higher than diesel. BSFC for diesel is least owing to its approving physicochemical properties. In addition, many researchers describe that an increase in BSFC of biofuels (B20 and B20 + BHA) was due to its lower energy content and high viscosity than diesel. Equally, B20 exhibited higher BSFC than B20 + BHA and diesel because of poor physicochemical properties. However, in comparison with B20, B20 + BHA exhibits lower BSFC of about 0.05 kg/kWh at full load. The kinematic viscosity of B20 + BHA exhibits 17.2% lower viscosity than B20. Furthermore, the oxidation stability of B20 + BHA is 20% higher than B20. Fuel with higher oxidation stability and lower viscosity improves the combustion. The addition of 1000 ppm of BHA to B20 lowers the cohesion between the fuels and disintegrates into finer droplets. There, finer droplets of fuels are surrounded by air in all directions leading to

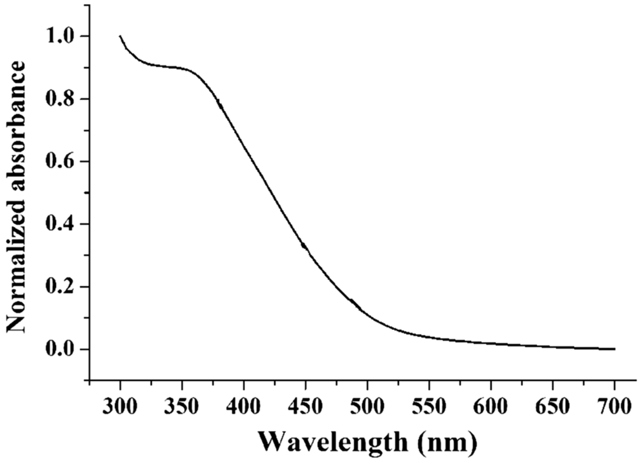

Fig. 4 UV absorption spectrum (Vellaiyan 2019b)

complete combustion and lower BSFC. Furthermore, friction reduction properties of antioxidants are the reason for the reduction in BSFC, which could result in high power output (Pullen and Saeed 2014, Varatharajan and Pushparani 2018). Similar inferences were observed in the different kinds of literature (Vellaiyan, 2020b; Mahalingam et al. 2018; Jayabal et al., 2019; Ganesan et al. 2019; Devarajan et al. 2019a, b; Ravikumar and Saravanan 2016) mentioning that the small viscosity reduction can lower BSFC.

Brake thermal efficiency

The brake thermal efficiency (BTE) is commonly known as fuel conversion efficiency and it is calculated as the ratio between the brake power to energy introduced through fuel injection. Figure 8 represents the BTE variation for Diesel, B20 and B20 + BHA with the load. BTE varies from 15.78 to 30.68% for all fuels. BTE of B20 + BHA varies from 15.78% (at 25% load) to 25.23% (at full load), whereas for B20 fuel, the BTE changes from 15.98 to 27.78%. The engine performance with these fuels is always less than diesel (30.68% BTE) due to the following factors such as shorter ignition delay of biodiesel, higher viscosity, density, low calorific value, high volatility and poor spray properties compared with those of diesel fuel. Madiwale et al. (2020) describe that the biodiesel has a higher viscosity and density leads to poor atomization and fuel vaporization, resulting in uneven combustion compared with that of diesel fuel. Kivevele et al. (2011) investigated that the ratio of friction to brake power decreases due to in reduction in heat loss and an increase in power. Furthermore, the addition of an antioxidant into the B20 fuel lowers the BTE by 1.5%. This is due to

Fig. 6 A photographic view of the experimental setup

Fig. 5 Schematic of the test engine

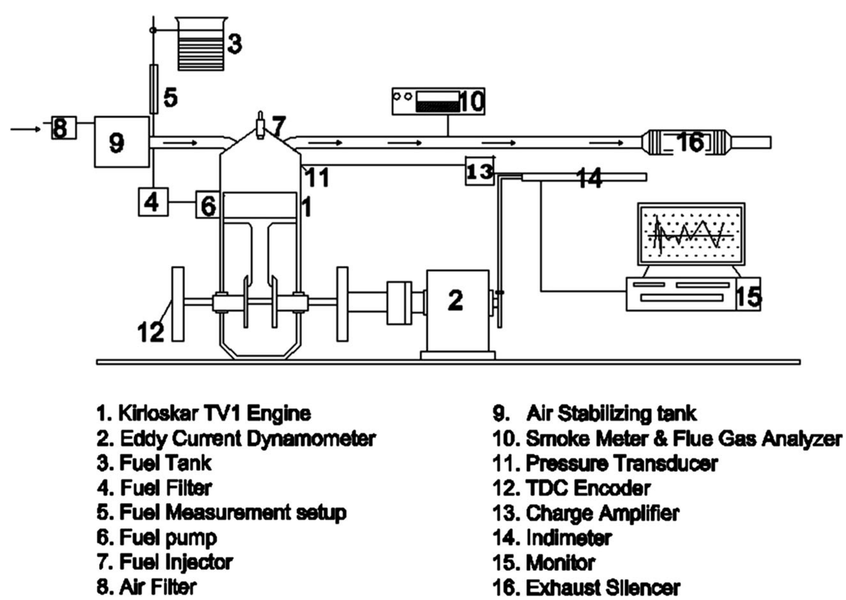

Table 4 Engine specifications

Make	Kirloskar
Stroke	4
Cylinder	Single
Rated power	4.4 kW
Rated speed	1500 rpm
Bore diameter (*D*)	87.5 mm
Stroke (*L*)	110 mm
Compression ratio	17.5;1
Injection timing	17°bTDC
Injection pressure	200 bar
Fuel pump plunger diameter	8 mm
Number of injector nozzle	4
Diameter of injector nozzle	0.32 mm
Cooling	Air-cooled
Position	Vertical
Type	Eddy current dynamometer
Make	Benz systems
Dynamometer constant	2000
Supply voltage	240 ± 10% AC,50 Hz, 1ϕ
Maximum excitation current	6 to 8 A

partial burning fuel and reduction in combustion chamber pressure by the effect of the addition of antioxidant additive in the B20 fuel. The results obtained by this work are in line with the research work carried out by Dueso et al. (2018) which inferred that the addition of antioxidant in the sunflower biodiesel results in the reduction in BTE by 0.1–0.8%. Furthermore, in another investigation, Ramalingam et al. (2019), experienced the same pattern and reported that the addition of antioxidant *p*-phenylenediamine in Annona biodiesel (A20 blend) decreases BTE.

Emission characteristics

Carbon monoxide emission

The variation in carbon monoxide (CO) emissions with load is shown in Fig. 9. The most important reason for the formation

Table 5 Range and accuracy details of exhaust gas analyser

Pollutant	Range	Accuracy	Uncertainty (%)
CO	0–15.0 vol.%	± 0.01 vol.%	± 1.1
HC	0–30,000 ppm vol.	± 1 ppm vol.	± 1
NO_x	0–5000 ppm vol.	± 1 ppm vol.	± 1.3
Smoke meter	0–100%	± 0.1%	± 1.2
BTE	-	± 0.4	± 0.04
BSFC	-	± 0.02 kg/kW/h	± 1.1

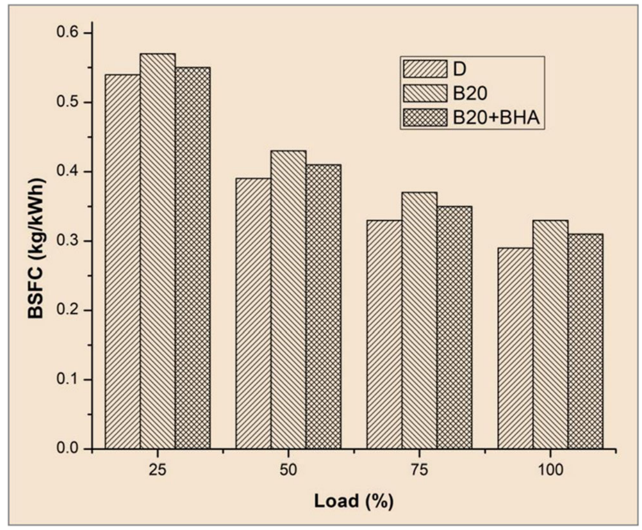

Fig. 7 BSFC vs. load for test fuels

of CO emission in the exhaust gas is due to incomplete combustion coupled with rich fuel to air ratio and low oxygen concentration. CO emission is produced when the conversion of CO to CO_2 is insufficient (Ashok et al. 2017). At full load (100%) conditions, the CO emission values for the fuel blends D (100% diesel), B20 and B20 + BHA were 0.43, 0.31 and 0.35 g/kWh respectively whereas the CO emission changes from 0.15 to 0.21 g/kWh at 25% load. The CO emission for fuel B20 is low by 27.9% compared with that for diesel fuel. This is due to the combined effect of high oxygen content in the chemical structure of biodiesel fuels and high cetane number (Rizwanul Fattah et al. 2014a, b, c; Ileri New York and Kocar 2013; Rashed et al. 2016a, b). The presence of antioxidants in the fuel blend B20 + BHA increases the CO emission by 14.2% compared with that in B20. The antioxidant reduces the conversion of CO to CO_2 and resulted in higher CO emission for antioxidant-treated biodiesel blends (Rizwanul Fattah

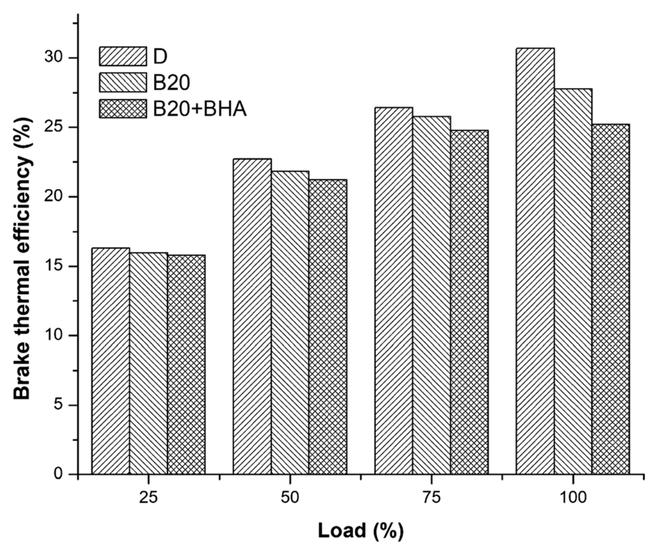

Fig. 8 BTE vs. load for test fuels

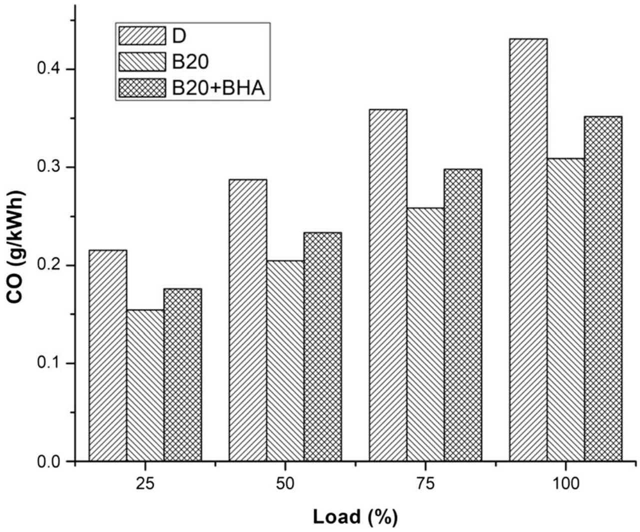

Fig. 9 CO vs. load for test fuels

et al. 2014a, b, c). During combustion, peroxyl (HO_2) and hydrogen peroxide (H_2O_2) radicals formed during oxidation are further converted into hydroxyl radicals (OH) by absorbing heat from the combustion chamber. The conversion of CO to CO_2 is mostly affected by these OH radicals (Palash et al. 2014; Rashed et al. 2016a, b).

Hydrocarbon emission

The variation in hydrocarbon (HC) emissions with brake power for all fuel blends is shown in Fig. 10. The HC emission values for B20, B20 + BHA and diesel (D) at 25% load (1.25 kW BP) were 0.0468, 0.0527 and 0.06 g/kWh respectively whereas at full load, the HC emission for all fuels changed from 0.0622 to 0.0689 g/kWh. It is seen that the HC emission for all biodiesel blends is low compared with conventional petroleum diesel. HC emission for B20 and B20 + BHA fuel is 20% and 12.17% lower than diesel respectively. The concentration of 20% in the biodiesel in the conventional fuel exhibits more oxygen and enhances the combustion rate. Also, due to the rich oxygen content in the blends of biodiesel fuel, the ignition delay was reduced to a shorter time period and result in the early start of fuel injection and prolonging of the combustion process. The antioxidant in fuel B20 + BHA increases in HC emission by 10.6% compared with that in B20 blend. The presence of antioxidants in the biodiesel reduces peroxyl and hydrogen peroxide radicals, which are responsible for converting CO into CO_2 and HC into H_2O and CO_2, and induces a significant increase in the volume of HC in the exhaust gases. Also, the obtained results are in good agreement with the research work carried by Balaji and Cheralathan (2015), Varatharajan et al. (2011), Radhakrishnan (2017) and Debbarma and Misra (2018).

Nitrogen oxide emission

Higher combustion temperature, longer combustion duration and high oxygen concentration of the fuel are the main reasons for nitrogen oxide (NO_x) formation. The variations in NO_x emission for B20, B20 + BHA and diesel with respect to different loading conditions are represented in Fig. 11. At low load (25%) condition, NO_x emission varies from 1.062 to 1.531 g/kWh for all fuels whereas, at full load (BP 3.55 kW) condition, NO_x emissions of fuel diesel, B20 and B20 + BHA are 3.836, 4.685 and 4.128 g/kWh respectively. It is seen that the NO_x emission is high for both biodiesel blends compared with diesel. The use of B20 fuel in an engine results in high NO_x concentration. This could be correlated to higher exhaust gas temperature for biofuels which is 12% higher than conventional diesel fuel. The mixture of 20% biodiesel and 80% conventional diesel possess rich oxygen content and results in a reduction of ignition delay period and early start of

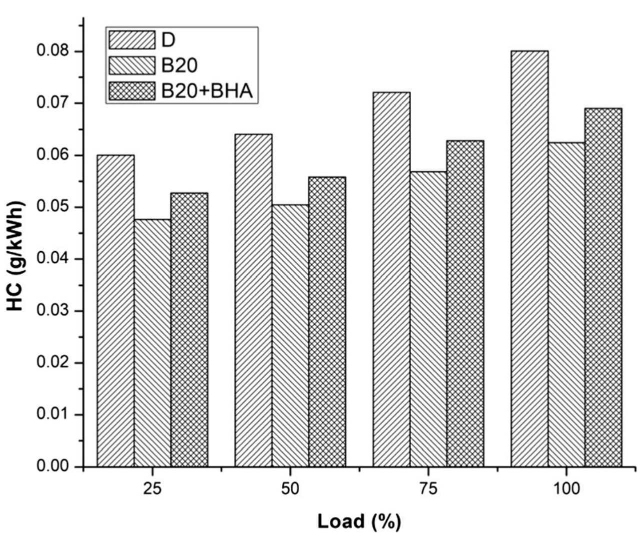

Fig. 10 HC vs. load for test fuels

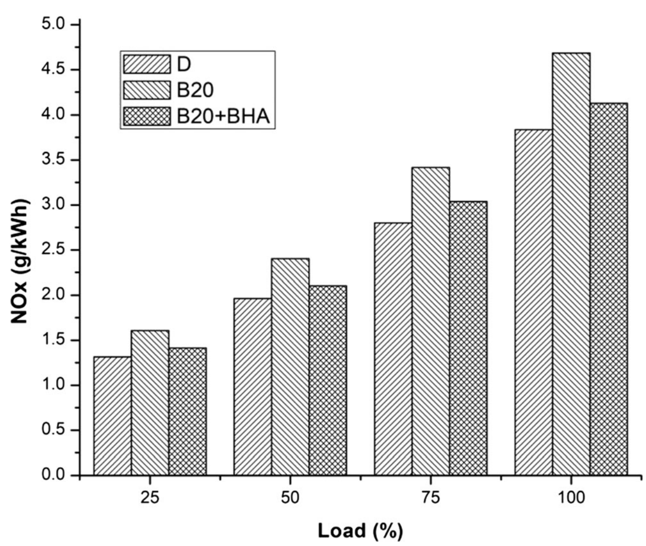

Fig. 11 NO_x vs. load

combustion (Velmurugan and Sathiyagnanam 2016, Ramalingam et al. 2016). Due to the early start of injection, modified fuels produce high combustion temperatures and increased formation of NO_x (Mueller et al. 2009). The use of antioxidant BHA in biodiesel blend B20 reduces NO_x emission by 8.2% than B20 fuel. The catalytic activity of BHA improved the reaction time of combustion and lowered the combustion temperature that results in lower NO_x emissions. Different kinds of literature such as Varatharajan and Pushparani (2018), Rashed et al. (2016a, b, c, d) and Rashedul et al. (2015) stated that reactions between molecular nitrogen and hydrocarbon-free radicals (CH, C_2, C and CH_2) play a role in prompt emission of NO_x during biodiesel combustion. Antioxidants can prevent radical reactions and, consequently, reduce the formation of NO_x.

Carbon dioxide emission

In general, the complete combustion of fuel leads to the high formation of carbon dioxide (CO_2) in a diesel engine, which is always higher when compared with that in gasoline engines. Figure 12 represents the variation in CO_2 emission for all test fuels under varying loads. The results show that the fuel B20 and B20 + BHA promote a high magnitude of CO_2 emission compared with diesel due to more oxygen available during the combustion process. At lower load, the CO_2 emission varies from 1.308 to 1.512 g/kWh whereas at full load condition, the CO_2 emissions of fuel diesel, B20 and B20 + BHA are observed as 1.82, 2.936 and 2.063 g/kWh respectively. It is observed that the CO_2 emission for B20 fuel is almost 30% higher compared with that for diesel. Oxygen availability in the chemical structure of biodiesel and its lower carbon content strengthens the combustion and increases CO_2 formation. The addition of BHA in the blend of biodiesel fuel reduces the formation of CO_2 emission by 26.73% compared with B20. In BHA, the oxygen-donating catalysts cause the combustion reaction and lower CO_2 emissions (Rashedul et al. 2014; Alagu et al. 2018; Anderson et al. 2008).

Exhaust gas temperature

The exhaust gas temperature (EGT) of all test fuels with respect to load is depicted in Fig. 13. In general, the drop in EGT is not proportional to the drop in fuel quantity. It could be the result of efficient combustion, lower ignition delay period and lower heating value of the fuel (Özener et al. 2014). At full load condition, the EGT of fuel blends D (diesel 100%), B20 and B20 + BHA were 305, 316 and 310 °C respectively. It is obvious that at a lower load level, the EGT is always low compared with that at a higher load and it varied as 180 °C, 184 °C and 186 °C for the use of fuel diesel, B20 + BHA and B20 respectively. From the graphical representation, it is noted that the use of conventional diesel has lower EGT for all loading conditions compared with biodiesel fuel blends B20 and B20 + BHA. The lower ignition delay period and enriched oxygen content in biodiesel result in higher EGT compared with that in diesel. Sathiyamoorthi and Sankaranarayanan (2017), Rizwanul Fattah et al. (2014) and Senthil Ramalingam et al. (2019) describe that higher viscosity of biodiesel blend causes poor atomization resulting in the presence of unburned fuel particles in the premixed combustion phase. This will burn later in the diffusion combustion phase resulting in increased exhaust gas temperature. This phenomenon reflects the loss in heat energy and, in turn, decreases the thermal efficiency. The presence of antioxidants in the fuel blend B20 + BHA reduces the EGT by 1.9% compared with that in B20 and thus, the stable combustion takes place inside the cylinder.

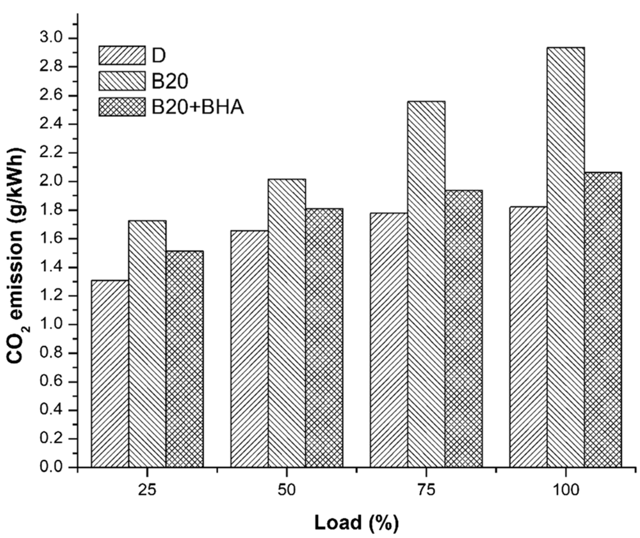

Fig. 12 CO_2 vs. load for test fuels

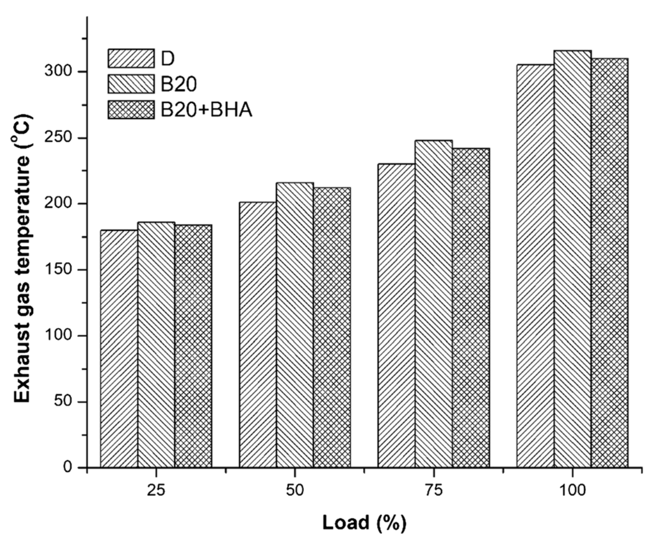

Fig. 13 EGT vs. load

Combustion characteristics

Pressure vs. crank angle

Figure 14 illustrates the variation of cylinder pressure vs. crank angle at the highest load. Emissions and performance analysis shall be correlated with in-cylinder pressure analysis. The extreme pressure values of diesel, B20 and B20 + BHA are 66.114 bar, 65.407 bar and 64.597 bar respectively. Peak cylinder pressure is registered for diesel; this may be owing to extended ignition delay period which paves the way for more mixing time of the blend, causing a rapid premixed burning phase of combustion resultant in augmented highest cylinder pressure. Reduction in pressure is observed for B20 + BHA than B20. The presence of BHA lowered the NO_x emissions for B20. The catalytic activity of BHA in B20 increased the reaction time of combustion and lowered the combustion temperature that results in lower NO emissions and peak pressure. The variations in peak pressure are due to high fractions of molecular weight (fatty acids) and other fuel properties, such as high viscosity and cetane number, and low biodiesel volatility (Imtenan et al. 2015). Li et al. (2018) reported that supplying the fuel into the cylinder takes a lengthier ignition delay period and increases the rate of premixed combustion. The antioxidant in biodiesel fuels is very effective in reducing cylinder pressure (Sajjad et al. 2015; Damodharan et al. 2018).

Heat release rate

Figure 15 portraysthe disparity of heat release rate vs. crank angle at the highest load. The extreme heat release rates for diesel, B20 and B20 + BHA are 72.419 J/°, 66.741 J/° and 67.714 J/° respectively. In the beginning, a negative heat release is observed due to the vaporization of the fuel accumulated

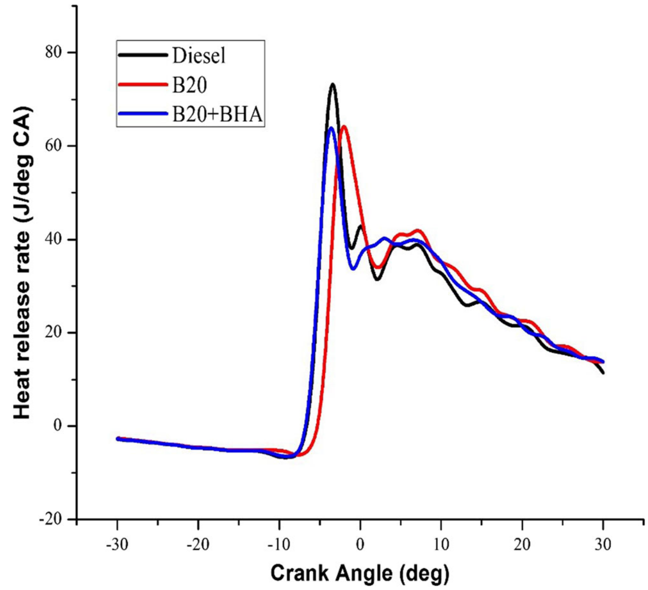

Fig. 15 Heat release rate vs. crank angle

during an ignition delay, and this heat release becomes positive after the combustion is initiated. The higher cetane number in the biodiesel fuels (B20 and B20 + BHA) leads to shorter ignition delay and early start of combustion (Qi et al. 2009; Mamat et al. 2009). In comparison with B20, the use of fuel B20 + BHA increases the heat release rate from 66.741 to 67.714 J/°. The mixing of antioxidant in the biodiesel provides stable combustion by preventing radical reactions. BHA addition to B20 improves the atomization process and in turn enhances HRR. Zhu et al. (2011) stated that the net combustion period shortened the premixed heat release proportion and highest cylinder pressure increased which results in higher HRR.

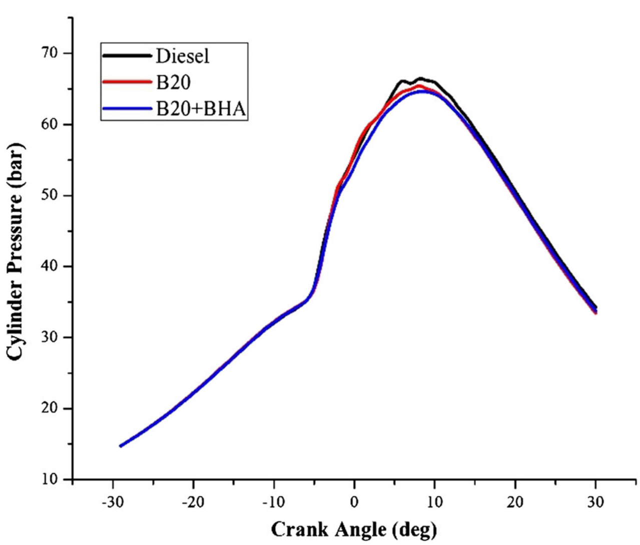

Fig. 14 Cylinder pressure vs. crank angle

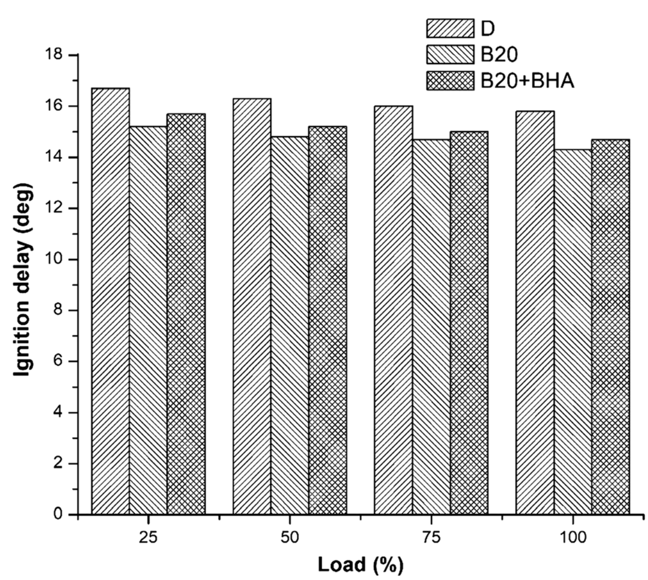

Fig. 16 Ignition delay vs. load

Ignition delay

The ignition delay is inferred as the time gap among fuel ignition and injection. Two factors govern ignition delay, one being a physical delay where the fuel atomization, fuel mixing and fuel vapourization is involved. The other is a chemical delay which is controlled by the pre-combustion reaction. Atomization, vaporization and mixing rate of fuel come under physical delay and the cetane number responsible for auto-ignition comes under a chemical delay (Devarajan et al. 2020). Ignition delay for all tested fuel blends is represented in Fig. 16 for all load conditions. At full load conditions, the ignition delay values for the fuel blends D (100% diesel), B20 and B20 + BHA were 15.8, 14.3 and 14.7 respectively. It is also observed that the ignition delay values for both biodiesels blends B20 and B20 + BHA were shorter compared with that for conventional diesel. This is because lower fatty acid methyl esters, compressibility, higher cetane and flashpoints initiate the early combustion for biofuels. The addition of BHA in the B20 fuel blend increases the ignition delay by 2.72% when compared that in the fuel B20 without BHA. This is correlated to lower viscosity, better combustion characteristics and improved fuel atomization, a superior flashpoint of fuel (Varatharajana and Pushparani et al. 2018, Devaraj et al. 2018). Owing to the above-mentioned properties, the combustion starts early for the use of biofuel in a diesel engine.

Conclusion

The combustion, performance and emission characteristics of 20% beef tallow biodiesel, 80% of conventional diesel and 1000 ppm of BHA are detailed in the present study and the results are compared with the performance of the conventional diesel-fuelled engine. The study conclusions are as follows:

- The physicochemical properties of 20% beef tallow biodiesel, 80% of conventional diesel and 1000 ppm of BHA included fuels are at par with EN 14214 standards and these fuels can be used in existing diesel engine without any modification.
- The addition of BHA in the blend of B20 (20% beef tallow biodiesel + 80% conventional diesel) results in the reduction in BSFC about 2% than B20 blend; this is due to the friction reduction properties of antioxidants.
- The use of petroleum diesel in engine always results in higher BTE and the use of 20% beef tallow oil biodiesel in the diesel results lower BTE due to higher viscosity, density, low calorific value, high volatility and poor spray properties. This loss has been recovered by the addition of BHA in the blend B20.
- The CO emission value for the use of B20 blend in the engine without antioxidant additives was low by 27.9% when compared with diesel fuel. The presence of antioxidant BHA in the blend B20 increases the CO emission by 14.2% when compared with that in B20 without BHA. The antioxidant reduces the conversion of CO to CO_2 and resulted in higher CO emission for antioxidant-treated biodiesel blends.
- NO_x emission of B20 was increased by 22% compared with conventional diesel. The use of BHA antioxidant in the blend B20 + BHA emits 12.2% lesser NO_x when compared with that in B20. This is due to breaking chain reactions, scavenging the initiating radicals and reducing the concentration of reactive radicals.
- In addition, the EGT, ignition delay, HC, CO_2 and the heat release rate for the use of fuel blend B20 + BHA were controllable to meet the diesel engine performance for all load conditions when compared with B20 blend.

Overall, it can be concluded that the addition of BHA antioxidant in the beef tallow biodiesel blend B20 has the potential to promote beef tallow biodiesel as a greener alternative fuel for existing diesel engines. To increase the percentage concentration of beef tallow biodiesel with diesel, the modified exhaust gas after-treatment systems have to be considered.

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