Green fuel design for diesel engine, combustion, performance and emission analysis

T. Pushparaja*, S. Ramabalan

Abstract

Vegetable oils are a potential alternative to the partial or total substitution of diesel fuels. An experimental investigation is conducted to evaluate the effects of using ethanol and diethyl ether as additives to biodiesel/diesel blends on the emission and performance of direct injection unmodified diesel engine. Biodiesel was made by pyrolysis process. Cashew nut shell liquid (CNSL) was selected for biodiesel production. The fuel containing 20% biodiesel and 80% Number 2 diesel fuel, is called here as B20, 90% B20 blend and 10% ethanol by volume is called B20+E10 and 90% B20 blend and 10% diethyl ether by volume is called B20+D10. The effect of test fuels on engine torque, power, brake specific fuel consumption, brake thermal efficiency, exhaust gas temperature, were ascertained by performance tests. The influence of blends on CO, CO2, HC, NO and smoke opacity were investigated by emission tests. The experimental results showed that the exhaust emissions for 10% diethyl ether with B20 were fairly reduced, especially the NO is reduced remarkably by 51% while comparing diesel. B20+D10 blend reflect better engine performance and lower emissions than B20+E10 and B20 blends.

Keywords: Biodiesel; Cashew Nut Shell Liquid (CNSL); Emissions; Ethanol; Diethyl ether; Pyrolysis;

1. Introduction

Biodiesel is relatively clean burning alternative fuel, produced from domestic and renewable resources. Biodiesel contains no petroleum components, but it can be blended at any level with petroleum diesel to create a biodiesel blend. It can be used in compression-ignition (diesel) engines with little or no modifications. Biodiesel is simple to use, biodegradable, nontoxic, and essentially free from sulphur and aromatics [1]. Biodiesel is produced through a chemical process called transesterification whereby the glycerine is separated from fat or vegetable oil. Transesterification is processes in which a triglyceride is made to react with alcohol in the presence of a catalyst. The process leaves behind two products namely methyl esters (the chemical name for biodiesel) and glycerine [2]. According to literature, the use of vegetable oils as fuel in diesel engines causes several problems, namely poor fuel atomization and low volatility originated from their high viscosity, high molecular weight and density [3]. After the use of vegetable oils as a fuel in CI engine for a long period of time, may cause important engine failures like injector and valve damages [4]. Biodiesel is better for the environment because it is made from renewable resources and has
lower emission compared to petroleum diesel. The transesterification is achieved with monohydric alcohols like methanol and ethanol in the presence of an alkali catalyst. Biodiesel and its blend with petroleum-based diesel fuel can be used in diesel engines without any significant modifications to the engine [5]. The advantages of biodiesel are to protects the world from global warming gas emissions, tail pipe particulate matter, hydrocarbons, carbon monoxide, and other air toxics which are common threats that one should come across in case of using petroleum product as fuel [6]. Biodiesel improves lubricity and reduces premature wearing of fuel pumps [7].

The world production figures of cashew crop, published by FAO (Food and Agriculture Organization), was around 2.7 million tons per annum. The major raw cashew producing countries with their production figures in 2005 (as per the UN's FAO) are Vietnam (960,800 tons), Nigeria (594,000), India (460,000 tons), Brazil (147,629 tons) and Indonesia (122,000 tons). India ranks first in area utilized for cashew production, though its yields are relatively low. Collectively, Vietnam, India and Brazil account for more than 90% of all cashew kernel exports. India is the largest producer and exporter of cashews, Anacardiumoccidentale Linn, in the world. In India, Cashew cultivation now covers a total area of 0.70 million hectares of land, producing over 0.40 million metric tons of raw cashew nuts. The cashew nut shell is about 3mm thick, having a soft feathery outer skin and a thin hard inner skin. Between these skins is the honeycomb structure containing the phenolic material known as Cashew Nut Shell Liquid (CNSL). Inside the shell is the kernel wrapped in a thin skin known as the testa. The researchers found the constituents of cashew nut are, kernel 20-25%, kernel liquid 20-25%, testa 2%, rest being the shell [8]. The raw material for the manufacture of CNSL is the Cashew nut shells.

Today, pyrolysis is generally used to describe processes in which preferred products are liquid oil. Pyrolysis is one of the thermo chemical conversions in absence or limited supply of air or oxygen [9]. In the cashew nut shell, cashew nut shell liquid occurs mainly as anacardic acid (~90%) and cardol around slightly lower than 10%. Risfaheri et al. narrates the pyrolysis procedure of CNSL, the pyrolysis is done in a reactor at a vacuum pressure of 5kPa and at various maximum temperature, the range of 400-600°C, with the increase of 50°C for each experiment [10]. The volatiles removed on pyrolysis are gradually condensed in a pre-weighed condensing train, from atmospheric condensation to condensation in an ice bath 5-7°C [11]. The decarboxylated cardanol is termed as CNSL biodiesel. The biodiesel obtained from CNSL is not required for further processing like transesterification and comparatively it has moderate viscosity, easily combustible, and high miscibility with diesel.

The emissions and engine performance of diesel engines fuelled by biodiesels have been examined by many investigators [2]. The biodiesels used in the experiments are subjected to trial for assessing its performance, are produced from different vegetable oils such as sunflower, rapeseed, soybean, karanja, and rubber seed, etc. Altiparmak et al. reported that emissions of CO, smoke, HC, and PM exhibit a decreasing trend with biodiesel and blend of biodiesel–diesel fuels compared to pure diesel fuel in expense of higher NOx emissions [13]. However, there are some investigation reports which clearly declar that the power output increases and NOx emissions decrease with the use of biodiesel. The differences in power and NOx emissions can be attributed to the engine modifications, the fuelling method, exhaust gas treatment, test procedures, and test conditions. The researchers found CNSL was used as CI engine fuel and the performance did not improve, but it was used as low cost alternate fuel for CI engine [14-15]. Pushparaj and Ramabalan did the research with CNSL and diesel blends, using ethanol as additive. This was found to improve the performance and reduces the emissions [16]. The experimental results were not uniform in the given literature. In the present work, extensive and comprehensive study was carried out to analysis the CNSL diesel fuel blends.

The engine performance with the biodiesel and the vegetable oil blends of various origins was similar to that of the neat diesel fuel with nearly the same brake thermal efficiency, showing higher specific fuel consumption and less smoke emissions [17-18]. The experimental results especially on emissions of various studies were not uniform and provided different results as can be seen in the given literature. In the present work, we intend to produce CNSL biodiesel from the waste cashew nut shell and improve the fuel's properties by ethanol and diethyl ether as additives. Diesel fuel and a blend of CNSL biodiesel 20% by volume, doped 10% of analytical ethanol, and 10% of analytical diethyl ether. All the blends were tested in a direct injection diesel engine at full load conditions. An anhydrous, analytical ethanol was imported from ChangshuYangynan Chemicals, China, and analytical diethyl ether was purchased from Merck Specialities Private Limited, Mumbai, India.

2. Experimental Procedure and Equipment

There are published works analyzing the combustion and performance of direct injection diesel engine with CNSL biodiesel as a fuel. They conclude that using a 20% blend will not give a negative impact, and therefore a 20% blend was taken for analysis [19]. Due to lower caloric value and higher viscosity, the blend percentage is limited to 20. In this study ethanol and diethyl ether were taken as additives and observe the changes in performance and emissions in C.I engine. Higher percentage of ethanol and diethyl ether addition would give cooling effect in the combustion chamber so it was limited to 10 percentages [20-21]. Some authors narrate addition of additives will improve the drawback of biodiesel [22]. CNSL is the by-product of cashew

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industries; it is generally used for medical and rubber industries. The calorific value of CNSL is high, so we try to use it as engine fuel and adding additives to get the results very near to conventional diesel fuel. The main objective of this study is to improve the fuel characteristics of biodiesel by adding additives and to utilize higher percentage of biodiesel in the diesel in an unmodified diesel engine.

The CNSL biodiesel is utilized to prepare the blends, the volume ratio of CNSL biodiesel and diesel, 20/80 are called B20, the volume ratio of B20 blend and 10% of ethanol is called B20E10, and the volume ratio of B20 blend and 10% diethyl ether is called B20D10. The properties of fuel and additives are given in Table 1.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Diesel</th>
<th>Ethanol</th>
<th>Diethyl ether</th>
</tr>
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<tbody>
<tr>
<td>Kinematic Viscosity (40 °C) cSt</td>
<td>2.82</td>
<td>1.32</td>
<td>-</td>
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<tr>
<td>Density</td>
<td>840</td>
<td>792</td>
<td>710</td>
</tr>
<tr>
<td>Calorific Value</td>
<td>43.3</td>
<td>26.8</td>
<td>36.8</td>
</tr>
<tr>
<td>Flash Point</td>
<td>74</td>
<td>16</td>
<td>-42</td>
</tr>
<tr>
<td>Cetane Number</td>
<td>46</td>
<td>7</td>
<td>-</td>
</tr>
</tbody>
</table>

The engine used is Kirloskar make single cylinder, naturally aspirated, four stroke, water cooled, 16.5:1 compression ratio, direct injection diesel engine, and the maximum engine power is 3.7 kW at 1500 rpm. All experiments were conducted at standard temperature and pressure. The engine speed was measured directly from the RPM sensor attached near its flywheel. A Kirloskar A.C Generator with resistance bank loading arrangement is also incorporated. The main components of experimental set up are combustion pressure and volume measurement (piezo electric sensor and shaft encoder) fuel flow sensor unit, electrical loading arrangement, voltmeter, ammeter, rpm meter, cooling water sensor unit and air flow sensor unit .The outlet temperatures of cooling water and exhaust gas were measured directly from the thermocouples (Cr-Al) attached to the corresponding passages. All the data are interfaced with computer using software.

The engine exhaust NO, CO, HC, CO₂ were measured with AVL-444 Di gas analyzer (specification shown in Table 2). The exhaust emissions were measured at 200 mm from the exhaust valve. The smoke opacity was measured by AVL-437C smoke meter after reducing the pressure and temperature in the expansion chamber. Engine start at no load and feed control was so adjusted that it can attain the rated speed and steady state condition. Fuel consumption, rpm, exhaust gas temperature, and power output were measured and displayed in the monitor. Engine was loaded gradually to keep the speed within the permissible range. The pressure and crank angle diagram of the test engine for diesel and fuel blends with full load were taken, and their performance and emission characteristics were evaluated to compare with diesel fuel. Each experimental data reading was taken three times and the mean of the three was taken.

<table>
<thead>
<tr>
<th>Measured quantity</th>
<th>Measuring Range / Resolution</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>0...10 % Volume / 0.01 % Volume</td>
<td>±0.03% Volume</td>
</tr>
<tr>
<td>CO₂</td>
<td>0...20 % Volume / 0.1 % Volume</td>
<td>±0.4% Volume</td>
</tr>
<tr>
<td>HC</td>
<td>0...20000 PPM / 1 PPM / 10 PPM</td>
<td>±10 PPM</td>
</tr>
<tr>
<td>O₂</td>
<td>0...22 % Volume / 0.01 % Volume</td>
<td>±0.1% Volume</td>
</tr>
<tr>
<td>NO</td>
<td>0...5000 PPM / 1 PPM</td>
<td>±50 PPM</td>
</tr>
</tbody>
</table>

3. Results and discussions

3.1. Combustion Pressure and Crank Angle

In Fig. 1 the variation in the cylinder pressure with crank angle for diesel, B20E10 and B20 D10 blends at maximum engine loads were shown. It was clear that the peak cylinder pressure is higher for diesel. One of the most important parameters in the combustion phenomenon is the ignition delay. The combustion starts earlier for biodiesel than for diesel. This is owing to a short ignition delay and advanced injection timing for biodiesel [23]. In spite of the slightly higher viscosity and lower volatility of biodiesel, the ignition delay seems to be lower for biodiesel than for diesel [24]. In this study, the ignition delay was calculated in terms of the crank angle between the start of fuel injection and the start of combustion. The maximum pressure was observed at
64 bar, 52.9 bar and 48.2 bar for diesel, B20E10 and B20D10 respectively, at full loads. However the peak cylinder pressure obtained nearly the same crank angle positions that were 6 to 9 degree after top death centre for all fuels. Due to the longer ignition delay, the peak cylinder pressure was reduced [25].

3.2. Engine Performances

The variation of Break Thermal Efficiency (BTE) with different load for all four fuels was shown in Fig. 2. The BTE of the engine increases with increasing load for diesel and bio diesel blend. It was observed that BTE has increase due to increases in power developed with increase in load. The variation of BTE at full load operation is 25.48, 23.6, 24.1 and 24.3 for B20D10, B20E10, diesel and B20 respectively. At full load operation B20D10 fuel BTE is 25.48% that is 5% higher than diesel, 7.38% higher than B20E10 and 4.63% higher than that of B20. From the experimental observed data a small gain percentage noticed for the blend B20D10 over the other blend ratio. The variation in Brake Specific Fuel Consumption (BSFC) was found decrease in the biodiesel blends compared with diesel, and also it is noticed that BSFC decreased sharply with increase in load for all fuels. This is may be due to higher energy required per kilowatt is higher than that of lower load. The BSFC of B20D10 was slightly lower, and that of B20E10 is almost similar to that of B20 was shown in Fig. 3.

Exhaust gas temperature is affected by the changes in ignition delay. Higher ignition delays result in a delayed combustion and higher exhaust temperature [26]. But here the ignition delay was less compared to diesel as discussed earlier. So this reduction in ignition delay may reduce the premixed combustion which in-turn increases the afterburning combustion. The exhaust gas temperature is higher, compared to diesel that was shown in Fig. 4.
Fig. 2. Comparison of BTE variation with load and fuel blends.

Fig. 3. Comparison of BSFC variation with load and fuel blends.

Fig. 4. Comparison of EGT variation with load and fuel blends.
3.3. Pollutant Emissions

3.3.1. Carbon Monoxide

The variation of Carbon monoxide (CO) emissions with engine loading for different fuel blends is compared in Fig. 5. The minimum and maximum CO produced was 0.01 and 0.31% (vol). It can be observed from the figure, that the CO initially is decreased up to 80% load, and later increased sharply up to full load. As for higher engine load there may not be enough time for complete combustion and hence more CO emissions. Lower CO emissions were observed in B20D10 blend, the amount is about 19% lower than that of B20E10 at full load condition.

3.3.2. Hydrocarbons

Hydrocarbons (HC) emission variation with engine loads for the analyzed fuels is shown in Fig. 6. In general, the magnitude of HC emission for the biodiesel fuels was enhanced, owing to the higher accumulation of fuel in the premixed combustion phase as a result of prolonged ignition delay. This effect could have led to increased HC emissions for the biodiesel fuel compared to that of diesel fuel. But B20D10 blend showed less emission when comparing all fuel blends and it is decreased about 35% while comparing B20 at full load. This decrease in HC emission may be explained as the oxygen content in the biodiesel fuel blend helps to complete combustion.

![Fig. 5. Comparison of CO variation with load and fuel blends.](image)

![Fig. 6. Comparison of HC variation with load and fuel blends.](image)
3.3.3. Nitrogen oxide

The engine’s Nitrogen oxide (NO) emission level for the analyzed fuels at different loads is presented in Fig. 7. It may be observed that the presence of oxygenated components in the studied fuels at small loads has an unimportant influence on the NO emission level, presenting especially a small reduction. At medium and high engine loads the NO emission level was greater for B20 blend, compared to diesel fuel. The increased NO emission level is explained by the increased fuel combustion temperature, concentration of oxygen and nitrogen atoms, time of oxygen and nitrogen reaction, injection timing and peak cylinder pressure and oxygen content in biodiesel, which results in the generation of NO. But the NO emission was found to be reduced on the addition of ethanol and diethyl ether to bio diesel, where an average reduction of around 57% was found to occur with B20E10 blend and 69% for B20D10 blend when comparing with B20 blend. A detailed flame analysis could possibly lead to the exact reasons behind the observed phenomenon, as the behaviour could be due to a complex interaction among factors such as the combustion temperature, reaction time, and the oxygen content.

![Fig. 7. Comparison of NO variation with load and fuel blends.](image)

3.3.4. Smoke

The CI engine’s smoke emissions were evaluated through exhaust gases opacity measurements, made obvious by the light absorbing coefficient. The measured smoke opacity of exhaust gas is in fact an indication of particulate matter. Soot formation mainly takes place in the fuel-rich zone at high temperature and high pressure, particularly within the core region of fuel spray, and is caused by high temperature decomposition. If the fuel is partially oxygenated, it could reduce locally over-rich regions and limit primary smoke formation. Fig. 8 shows the smoke opacity of tested fuels in the exhaust. From this figure, it can be seen that B20 blend produced less smoke than pure diesel, at medium load a better results was obtained for B20D10 blend.

![Fig. 8. Comparison of Smoke opacity variation with load and fuel blends.](image)
minimum and maximum smoke densities produced for B20D10 and diesel at full load was 77% and 93% respectively, and the reduction percentage was 17. This could be due to the presence of oxygen molecule in the biodiesel chain, which enhanced its complete burning as compared to diesel, also when the engine load is increased, more fuel is consumed and more fuel is burned in the diffusion mode.

4. Conclusions

The CNSL bio oil is cheaper than other kinds of vegetable oils, which is an important advantage for biodiesel production. Some fuel properties of B20 such as cetane number, calorific value, sulphur content, and flash point are better than those of diesel fuel. In addition, diethyl ether and ethanol as additives decreases the density and the viscosity of blends. The BSFC of B20D10 was slightly lower, and that of B20E10 was almost similar to that of B20. The B20E10 and B20D10 blends, having higher oxygen content than B20, so smoke emission was reduced, especially at high engine load. Diethyl ether has higher volatility than ethanol, so B20D10exhibits more reduction of smoke. The NO emission for B20D10 was reduced to 28% while comparing with B20E10 blend, but NO emission was observed high, when B20 is used. The HC emission for B20D10 was lowered in comparison with B20E10. The addition of higher oxygen content and high volatility fuels, such as diethyl ether and ethanol, can be a promising technique for using biodiesel/diesel blend efficiently in diesel engines without any modifications in the engine. Therefore Cashew nut shell liquid blends can be used in CI engines in rural area for meeting energy requirement in various agricultural operations such as irrigation, harvesting, threshing, etc; Hence CNSL can be alternately used as fuel for diesel engine. Consequently 20% CNSL biodiesel and 10% diethyl ether as additive can effectively be used in diesel engines without any modification.

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References


