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Effect of Injection Pressure on the Performance and Emission Characteristics of Niger-Diesel-Ethanol Blends in CI Engine

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ABSTRACT

Biodiesel is promising as the best substitute/alternative fuel to most diesel engines due to its low sulfur content, lower aromatic hydrocarbon, renewable, and more oxygenated fuel. The dried Niger seeds were collected for their oil extraction and biodiesel production in the current research. This paper concerns about the influence of injection pressure on a single-cylinder VCR direct injection diesel engine using Niger oil biodiesel, diesel and ethanol blends, B5+D90+E5 (5% Biodiesel + 90% Diesel + 5% Ethanol), B10+D80+E10 (10% Biodiesel + 80% Diesel + 10% Ethanol) and B15+D70+E15 (15% Biodiesel + 70% Diesel + 15% Ethanol). The performance, combustion, and emission characteristics are observed for the above blends at the various pressures of 180 bar to 220 bar with 20 bar variations. At low injection pressures, the two blends (B5+D90+E5 and B10+D80+E10) show considerable improvement in brake thermal efficiency and mechanical efficiency compared to baseline diesel. At high injection, pressures blend B15+D70+E15 produce higher brake thermal efficiency and mechanical efficiency. Consequently, less brake-specific fuel consumption and less ignition delay period for the blends respectively. The exhaust pipe emissions such as Carbon Dioxide (CO_{2}), Carbon Monoxide (CO), Hydrocarbons (HC), Nitrogen oxides (NO_X) are measured at rated power at all injection pressures. CO_2, CO, and HC are low at high injection pressure, but NO_X increases as injection pressure increases.

Keywords: *Diesel; Niger oil methyl ester; Ethanol; Ignition delay; Missions*

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Nomenclature

B5+D90+E5	(5% Biodiesel + 90% Diesel + 5% Ethanol)
B10+D80+E10	(10% Biodiesel + 80% Diesel + 10% Ethanol)
B15+D70+E15	(15% Biodiesel + 70% Diesel + 15% Ethanol)
BTE	Brake Thermal Efficiency
BSFC	Brake Specific Fuel Consumption
CO_2	Carbon Dioxide
CO	Carbon Monoxide
COME	Cotton Seed Oil Methyl Ester
FFA	Free Fatty Acid
FIP	Fuel Injection Pressure
HC	Hydro Carbons
IP	Injection Pressure
NO_X	Nitrogen Oxides
NOME	Niger Oil Methyl Ester
O_2	Oxygen
VCR	Variable Compression Ratio

Introduction

Global utilization of automotive, industrialization, power generation units, and other sectors diminish the energy resources in a few decades. Depletion of fossil fuels and environmentally stringent pollutants encourages searching for alternative fuels. Biodiesel is derived from mono-alkyl esters of free fatty acids derived from animal fats or vegetable oils with small chain alcohols in combination with catalysts. Biodiesel is likely to be anticipated due to its many advantages such as being renewable, environment friendly, stands up in its performance against diesel, and reduced tailpipe emissions over fossil fuels [1]-[3]. Bio ethanol, vegetable oils, and animal fats for producing biodiesel are considered as the best substitute for the diesel fuel. Ethanol is easily accessible in every country from the feedstocks such as sugar cane, rice straw, corn, maize, red seaweed, starch, lignocellulosic and algal biomass through a fermentation process. Since the 19th century, bio ethanol has been widely used in conventional diesel engines due to its many advantages like ease of production, availability, low price, and more oxygenated content. It helps in improving low-temperature properties. It also aids to improve the performance of diesel engines and reduce emission characteristics [4]-[5].

Diesel engine performance mainly depends on the combustion process. As biodiesel possesses high viscosity, combustion is even more complicated. In such cases, additives such as ethanol or H_2O_2 when mixed with diesel-biodiesel blend in different proportions at various injection pressures (IPs) can improve the combustion quality of biodiesel in conventional diesel engines [6]-[7].

Fuel is usually injected into the cylinder at the end of the compression stroke. As it is disintegrated into the combustion chamber at high pressures, it atomizes into very fine droplets. By atomization, its surface area of tiny fuel droplets increases thus resulting in better mixing with air. During this period vaporization takes place due to heat transfer from the surrounding bulk air. This continues heat from the air to the fuel droplets raises auto-ignition temperature of the fuel and combustion starts spontaneously.

At low injection pressure, fuel droplets size, and vaporization time increases thus causing more ignition delay period and engine performance decreases. For improving combustion efficiency and reducing environmental impact, fuel injection characteristics such as spray tip penetration, spray angle, fuel droplet size, and velocities are very important.

The equal diffusion of fuel droplets in a spray significantly influences the combustion parameters of the CI engine. A rise in the injection pressure reduces the diameter of fuel particles ensuring better fuel-air mixing during ignition. Generally, the injection pressure of a normal diesel engine varies from 200 to 1700 atm, with respect to engine size and the kind of combustion system used [8]. A high-pressure difference across the injector nozzle is needed to atomize the liquid fuel into small droplets, allowing rapid vaporization and high jet penetration in the combustion chamber [9]-[10]. The size distribution of droplets in a spray has a major influence on CI engine combustion. Smaller fuel droplets evaporate more rapidly than larger droplets, but their dissemination is shorter, requiring optimization of the size distribution. According to researchers' point of view, tiny droplets and a high penetration depth of the fuel jet improves the fuel-air mixture efficiency, resulting in shorter ignition delays and absolute combustion [10]-[13].

In a study by Channapattana et al. [14], the effect of injection pressure was studied on variable compression ratio (VCR) engines fuelled with honne biodiesel. The experiment was conducted at a constant compression ratio of 18 and a constant injection default timing of 23° bTDC. The experimental findings denote that the thermal performance of honne biodiesel is close to diesel and also reduced emissions were observed at full load conditions and 240 bar. As blend proportions and injection pressures increase, NO_X emissions are also increased. The advanced injection pressure system results in higher efficiency in the CI engine compared to the older injector system [9]. It is imperative to examine the impact of fuel injection pressure (FIP) on CI engine characteristics fuelled with biodiesel fuel and neat diesel fuel. Parameters that have been significant impacts on the CI engine efficiency. Previously, various authors have applied the parameters to improve the engine performance and emission characteristics [10]-[11].

The study of biodiesel and bioethanol blended diesel was observed on a diesel engine. The rice bran oil biodiesel, biodiesel-diesel, and diesel-biodiesel-ethanol were used on the engine for its performance characteristics [15]. The results show that maximum brake thermal efficiency with 30% ethanol in diesel-biodiesel-ethanol blends. The carbon monoxide, smoke, tailpipe temperature, and exhaust sound intensity are minimum with the same blend. Whereas NO_X and CO_2 increased as the ethanol is increased diesel-biodiesel-ethanol blends.

The effect of fuel injection pressures on the diesel engine was conducted with cottonseed oil methyl ester (COME) blends [16]. The test was conducted on a 3.72 kW four-stroke, single-cylinder, water-cooled engine at injection pressures of 170 to 220 bar in the variation of 10 bar using standard diesel, 100% biodiesel, 10% biodiesel and 90% diesel, 20% biodiesel, and 80% diesel and 30% biodiesel and 70% diesel. At higher injection pressures the test results show improved brake thermal efficiency at 70% load with 20% biodiesel and 80% diesel at an optimized injection pressure of 200 bar. Similarly, reduced brake-specific fuel consumption was noticed. From the emission results, it was concluded that at high injection pressures the better emission characteristics were noticed compared to diesel but NO_X was found to be slightly higher due to higher combustion temperature than diesel.

An investigation was conducted on the performance and emission characteristics of diesel engines using diesel-Niger seed oil biodiesel blends at 16.5:1 compression ratio and nozzle opening pressure of 200 to 225 bar [17]. Ethanol was blended as an additive in diesel-biodiesel blends in the volume of 7.5%. A considerable brake thermal efficiency was noticed with the blends (D72.5, B20, E7.5), (D52.5, B40, E7.5), and (D32.5, B60, E7.5) of diesel-biodiesel-ethanol blends at all loads compared to diesel. Due to the addition of ethanol in diesel-biodiesel blends, exhaust temperature, CO, unused HC, and O_2 were reduced for all blends whereas NO_X emissions were increased for all loads and all blends. The optimum blend is considered as (D72.5, B20, E7.5) at all loadings.

From the above literature results, the diesel-biodiesel-ethanol blends can be significantly used as alternatives to diesel fuel in diesel engines with no modifications. Research also reveals that due to oxygen content in ethanol and biodiesel, performance is improved and emissions such as CO_2, CO, HC, and particulate matter are reduced with increased injection pressures. While NO_X emissions are increased because of higher combustion temperature than diesel fuel.

The Botanical name of Niger seed in *guizotia abyssinica* and mainly cultivated in Ethiopia and India (particularly in the states of Orissa, West Bengal, Andhra Pradesh, Assam, etc.) with cereals and pulses. The *guizotia abyssinica* has highest productivity in India among its six species such as *g. abyssinica* (ga), *g. scara*, *g. reptans*, *g. villosa*, *g. arbosrescens* and *g. zavattarii* [17]-[28]. This crop is found to be easily grown in low fertility areas such as acidic soils and on rock soils etc [17]-[27]. In India, the average productivity of this crop is 253 kg/ha. Recent studies have shown that the content of free fatty acids in raw materials varies the physio-chemical properties of biodiesel to a greater extent. The free fatty acid percentage of Niger seed oil is about 75-80% linolenic, 7-8% palmatic and stearic acids, and 5-8% oleic acid. While Indian seeds contain the fatty acid composition of 30% oil with 25% oleic and 55% linoleic acids [18]-[20].

Materials and Methodology

Oil extraction

Niger seeds are available in Andhra Pradesh forests in India. The seeds were left in sunlight for one week for drying and crushed for their oil extraction. The collected oil was taken into a soxhlet apparatus. The soxhlet apparatus was fitted on a round-bottomed flask that contains hexane (250 ml). Hexane was heated at 65-70 °C and extraction was observed by thin-layer chromatography. After a few hours, hexane was distilled off and light-yellowish viscous Niger seed oils were collected for further studies.

Pre-esterification

The extracted Niger oil contains approximately 3 wt.% free fatty acids and 0.15% moisture content. The oil was heated up to 110 °C and refined to reduce moisture and free fatty acid content (FFA). Niger oil (1000 g), sodium hydroxide (4.36 g), and distilled water (30 ml distilled water) were collected in a round neck bottle with a stirrer at a temperature of 35-40 °C. After 15 minutes, the temperature was raised to 65 °C and ran for the next 30 minutes. The mixture was kept in observation for 24 hours to bring in a steady state to the flocculent particles. The refined oil (920 g) was dried in a rotary evaporator at 65 °C at reduced pressure. The refined oil has 0.05% free fatty acid and 0.06% moisture content. As FFA content is less than 1%, Alkali (Base) Trans-esterification was adopted. This process is generally conducted for breaking long-chain fatty acids in Niger oil and also to bring the viscosity of the yield closer to diesel.

Biodiesel synthesis

From the recent studies, biodiesel synthesis was carried out at optimized conditions. Initially, the catalyst (0.6 wt.% of sodium methoxide) was mixed in methanol and then directly added to the Niger oil (Molar ratio 8:1). These products were stirred using an electromagnetic stirrer till the product was found to be thick brownish. This process was held at 65 °C and 500 rpm for 3 hours. After this process, the solution was decanted to a separating funnel and left for 8 hours. After 8 hours, the solution was found to be in two layers. The upper layer was (non-polar compound) biodiesel and the bottom layer was found to be glycerol (polar compound) and other sediments. Once methyl ester was separated, it was washed with warm water till it was purified from glycerin. Finally, it was dried at a temperature of 120 °C to remove moisture content in biodiesel. The physiochemical properties of diesel, ethanol, Niger oil methyl ester (NOME), and its blends were determined and compared in Table 1.

Characterization and evaluation of fuels

After pure biodiesel was prepared by a trans-esterification process, on a volume basis biodiesel-diesel-ethanol blends were prepared. The main objective of this fuel preparation is to have complete combustion in the cylinder during its operation and to reduce emissions as biodiesel and ethanol contain more oxygen. Different blends were prepared and ensured that all fuel properties are in line with standards. The blend preparation is as follows. First ethanol was mixed into diesel properly on a volume basis then biodiesel was added on a volume basis to form the various blends. They are B5+D90+E5 (5% Biodiesel + 90% Diesel + 5% Ethanol), B10+D80+E10 (10% Biodiesel + 80% Diesel + 10% Ethanol) and B15+D70+E15 (15% Biodiesel + 70% Diesel + 15% Ethanol). The following fuel properties were measured experimentally. They were calorific value, density, viscosity, flash point, cloud point and pour point. A bomb calorimeter was used to find calorific value. Specific gravity was measured by using a hydrometer to determine the density of various fuels. By using a dynamic viscometer, viscosity was measured, and this method consists of the measurement of time to drop the known volume of fuel from the viscometer. Cleveland Flash Point Apparatus with digital temperature indicator and digital controller was used to find the flashpoint of fuels. Pour and cloud point was determined by keeping in a low-temperature cooling fridge. The fuel sample was taken in a standard glass tube with a thermometer. The circumstantial properties of various fuel blends are compared with diesel and listed in Table 1.

Experimental Setup

A Kirloskar made four-stroke single-cylinder naturally aspired water-cooled direct injection computerized variable compression ratio (12 to 18) diesel engine of 3.75 kW with 1500 rpm is directly coupled to eddy current dynamometer. Fuel, air, water flow rates, loads, and temperatures are directly obtained from a computer. The engine setup and engine specifications are seen in Figure 1 and Table 2.

Table 1: Properties of Diesel, Ethanol, and NOME and its Blends

Properties	Diesel	Bio-Ethanol	Niger oil Methyl Ester (NOME)	B5+D90+E5	B10+D80+E10	B15+D70+E15
Calorific value (kJ/kg)	43626	27500	39100	43548	42194	41342
Density (kg/m^3)	825	789	832.5	835.8	836.6	838.6
Viscosity at 40 °C (cSt)	3.1	1.35	4.30	2.56	2.73	2.97
Flash Point (°C)	65	13	157	45	48	52
Cloud Point (°C)	-2	37.9	4	-2	-1	2
Pour Point (°C)	-6	-27	-4	-15	-12	-9

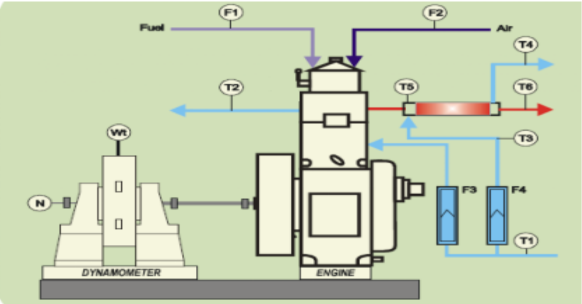


Figure 1: Flowline diagram of variable compression ratio engine setup.

Where: T1 = Inlet temperature of the engine water jacket,
T2 = Outlet temperature of the engine water jacket,
T3 = Inlet temperature of water at calorimeter,
T4 = Outlet temperature of water from calorimeter,
T5 = Inlet temperature of exhaust gases into calorimeter,
T6 = Outlet temperature of exhaust gases from calorimeter,
N = speed sensor (Non-contact type),
Wt = Load sensor (Eddy current dynamometer),
F1 = Fuel supply to engine cylinder,
F2 = Air flow to engine,
F3 = Water flow into the jacket,
F4 = Water flow into the calorimeter.

Table 2: Engine specifications

Make Type	Kirloskar
Engine Type	4-Stroke Single Cylinder, water-cooled engine
Compression ratio	Ranging from 12 to18
Rated power	3.75 kW at 1500 R.P.M
Stroke and Bore	110 mm and 87.5 mm
Loading device	Eddy current type dynamometer
Load indicator	Digital, range 0-50 kg, supply 230 V AC
Load sensor	Load cell, strain gauge type, range 0-50 kg
Speed indicator	Digital with non-contact type speed sensor
Temperature sensor	Thermocouple, K Type
Calorimeter	25-250 LPH
Rotameter	Engine cooling 40-400 LPH

Emissions such as (carbon monoxide (CO), carbon dioxide (CO_2), unburnt hydrocarbons (HC), nitrogen oxide (NO_X), and unused oxygen (O_2)) are determined by using INDUS 5 Gas Analyzer. The measuring principle is based on light absorption in the infrared region, called “non-dispersive infrared absorption”.

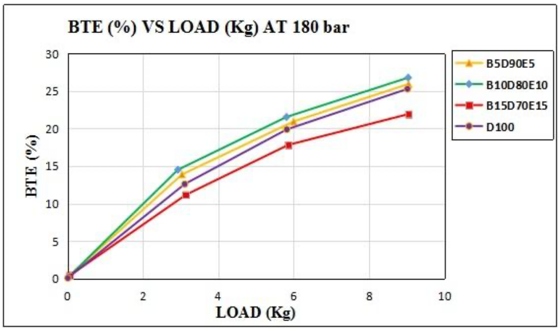
Experimental procedure

Initially, the engine was started with standard diesel at no-load conditions for a few minutes to reach a steady state at speed of 1500 rpm so that the coolant in the engine and lubricating oil reached a standard value and they were maintained throughout the experiment with all blends. The different blends were prepared with NOME, Diesel, and ethanol. From different studies, it was observed that the biodiesel and ethanol content in diesel should not exceed more than 20%. Based on this criterion and calorific values of NOME blends were selected as follows. B5+D90+E5 (5% Biodiesel + 90% Diesel + 5% Ethanol), B10+D80+E10 (10% Biodiesel + 80% Diesel + 10% Ethanol) and B15+D70+E15 (15% Biodiesel + 70% Diesel + 15% Ethanol). The required readings were taken for diesel fuel and then for NOME blends at injection pressures of 180, 200, and 220 bar at all loads respectively.

Results and Discussion

Effect of Brake Thermal Efficiency (BTE)

The effect of BTE on engine performance at various loads and at various injection pressures such as 180, 200, and 220 bar when diesel and biodiesel-diesel-ethanol blends are injected in the cylinder are shown in Figure 2. At low injection pressure (180 and 200 bar), the BTE is higher for B10+D80+E10 and B5+D90+E5 compared to diesel whereas BTE of B15+D70+E15 is decreased due to high viscosity. In such a case, it requires a large amount of heat for effective burning of fuel at low injection pressures. The other reason is due to the lack of a large heat source and leaner combustion, the ignition delay was delayed. At higher fuel injection pressures, the B15+D70+E15 blend shows better BTE than other blends. This is because of deeper penetration of fuel, nozzle cone angle, and viscosity of blend is quite enough for better atomization. In a similar study by Govinda Rao et al. [20] BTE increased with an increase of IPs for all the blends. This is because of the fact that at higher IP better atomization is observed which results in enhanced efficiency. Highest BTE is observed for the blend P90D5E5 at a pressure of 260 bar.



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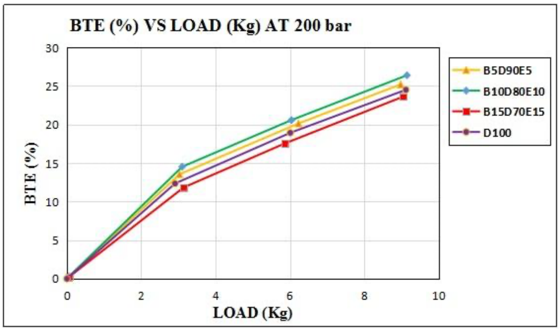

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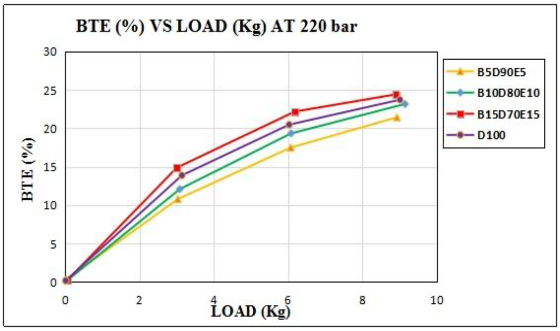

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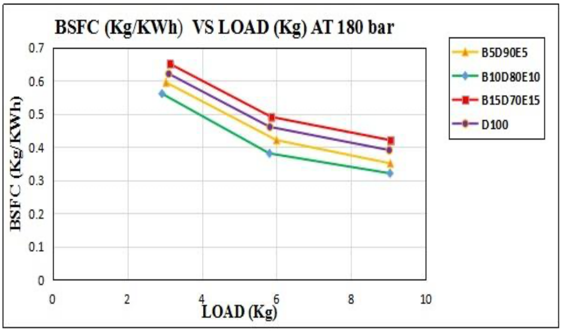
Figure 2: The effect of Brake thermal efficiency VS load at different injection pressures for various blends.

Effect on Brake Specific Fuel Consumption (BSFC)

The effect of BSFC at different loads and injection pressures is shown in Figure 3. BSFC decreases as load increases for all injection pressures. The BSFC of blends B10+D80+E10 and B5+D90+E5 decreases at injection pressures of 180 and 200 bar respectively at higher loads. While BSFC of blend B15+D70+E15 decreases at higher injection pressure (220 bar). This is attributed to the spraying of fuel in the combustion chamber as very fine droplets lead to a decrease in specific fuel consumption for the plastic oil ethanol blends when compared with diesel [13, 21]. The droplet's momentum is rapid and burns spontaneously in the first stage of combustion thus releasing high temperature. During the second stage of combustion, it attains maximum peak pressure. Hence greater power output. The increase in IP decreases the fuel droplet size resulting in better vaporization and mixing of the fuel [21].



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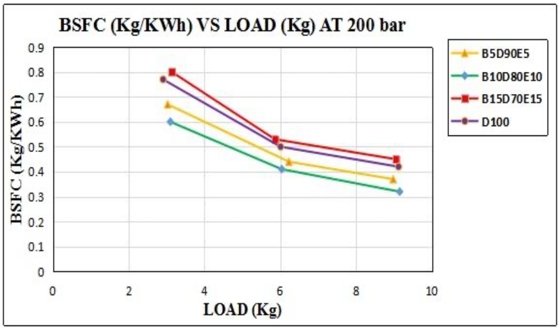

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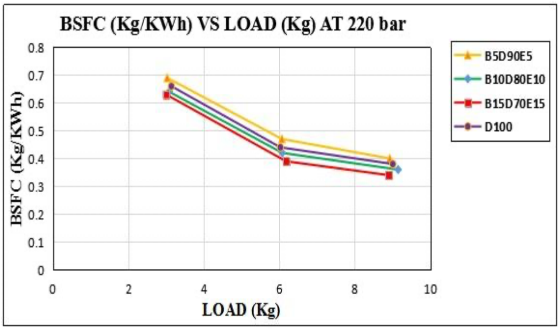


(c)

Figure 3: The variation of BSFC VS load at different injection pressures for different blends.

NO$_X$ Emissions

During biodiesel performance, NOX emissions are more common as it is more oxygenated fuel and more residence time for combustion which leads to producing a high temperature of gasses. The effect of NO$_X$ emissions at various injection pressures is represented in Figure 4. At all fuel injection pressures, the NO$_X$ emissions are noticed to be increased compared to baseline fuel. At low pressures, B10+D80+E10 and B5+D90+E5 show higher values of NO$_X$ emissions than B15+D70+E15 and diesel. However, at higher injection pressures, blends B15+D70+E15 and B10+D80+E10 are higher values. The main reason is at low injection pressures, the oxygen content of the fuel is very rich in biodiesel and as well as ethanol which releases high heat in the combustion zone hence NO$_X$ emissions are increased [13]. Whereas at high injection pressures, due to fine spray of biodiesel and ethanol content fuel particles high heat release takes place which is evidence for increasing temperature. But more ethanol in the blends cools the cylinder temperature which causes a reduction in NO_X emissions [13]-[21].

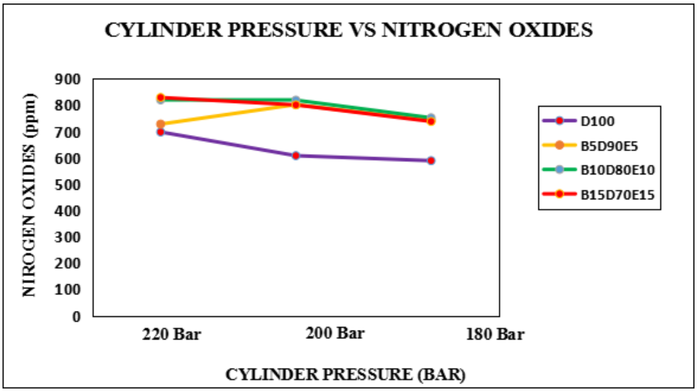
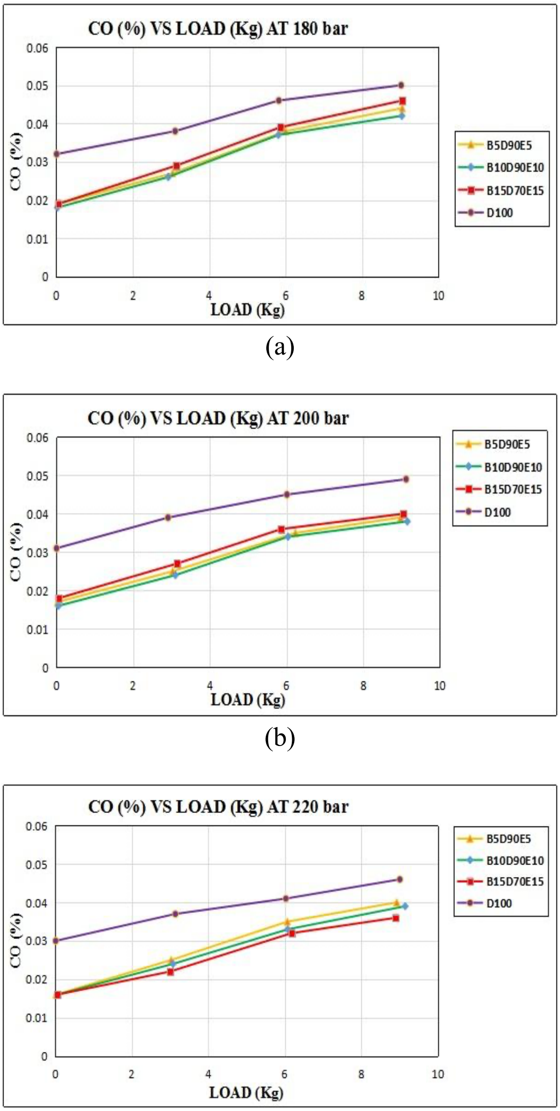


Figure 4: The effect of NO_X Emissions at different injection pressures for various blends.

CO Emissions

Figure 5 is the evidence for the effect of CO emissions with respect to fuel injection pressures. From the following figures, the CO emissions are decreased at all injection pressures in comparison to standard diesel. At 180 bar and 200 bar injection pressures, the blends B10+D80+E10 and B5+D90+E5 are found to be low which means that the complete combustion is due to more oxygen content in the biodiesel and ethanol. Complete combustion would be achieved which leads to a reduction in CO emissions [21]. In the same manner at higher injection pressures, the blend B15+D70+E15 also shows lower CO emissions. [21]-[23] CO emissions were found to reduce for all the blends with the increase of IPs due to the high temperatures inside the combustion chamber. The CO emissions are reduced by 42 and 61% for the blend P80D10E10 when compared with diesel and pure plastic oil respectively at IT 210 BTDC, IP 260 bar, and CR18.


CO (%) VS LOAD (Kg) AT 180 bar

(a)

CO (%) VS LOAD (Kg) AT 200 bar

(b)

CO (%) VS LOAD (Kg) AT 220 bar

(c)

Figure 5: Effect of CO Emissions at various injection pressures for various blends.

CO_2 Emissions

The effect of carbon dioxide at three injection pressures for various blends is shown in Figure 6. From the below results, it is found that CO_2 emissions are increased for all blends at different injection pressures than diesel. At higher injection pressures B15+D70+E15 shows higher CO_2 emissions than other blends. As biodiesel and ethanol are more oxygenated fuels, a higher amount of biodiesel and ethanol in diesel blends convert all the carbon particles to CO_2 emissions when absorb oxygen during combustion.

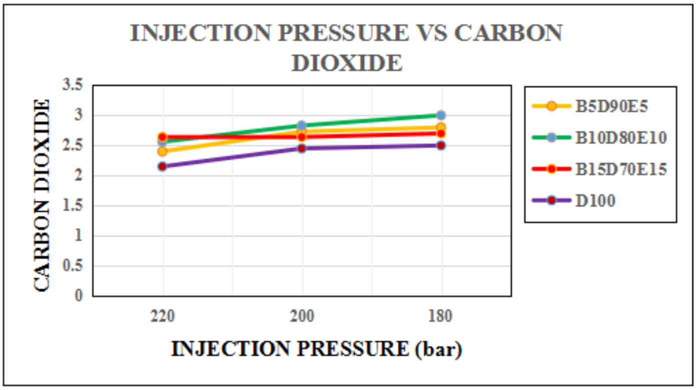
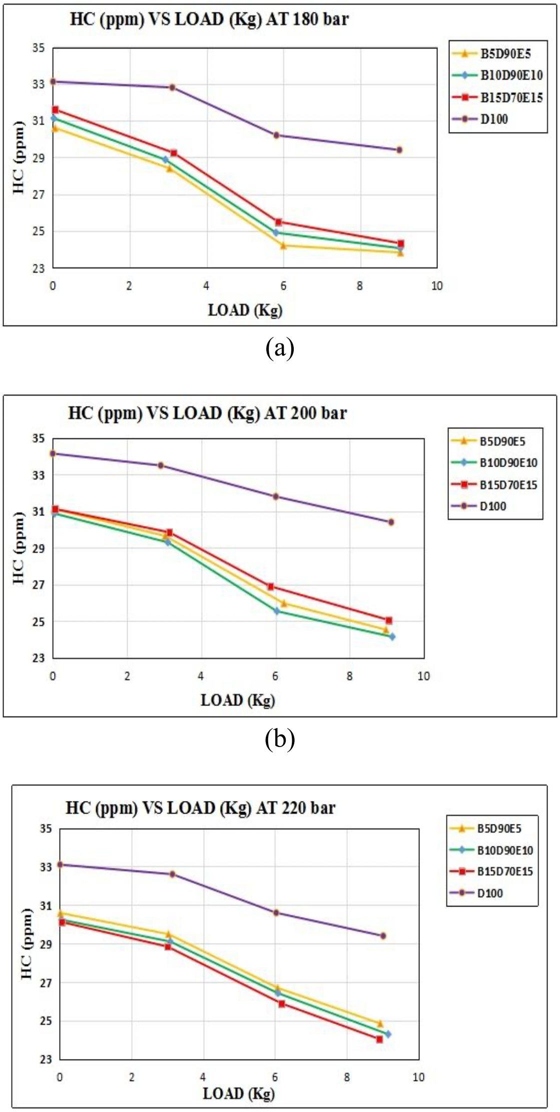


Figure 6: The effect of CO_2 Emissions at different injection pressures for various blends.

HC Emissions

The effect of HC Emissions for Niger biodiesel-ethanol blends with diesel at different fuel injection pressures are given in Figure 7. It is observed from the following figures that the HC Emissions are reduced significantly with an increase in injection pressure and also found that all HC Emissions are lower than diesel fuel. The Blends B15+D70+E15 and B10+D80+E10 show lower HC emissions at various injection pressures than other blended fuels. HC mass emissions decreased with increasing IP due to superior fuel-air mixing in the combustion chamber [11, 21]. The decrease in HC emissions is due to the oxygen content in biodiesel and ethanol which aids to complete combustion. It is evident that as the percentage of ethanol content in the blend increases, the quantity of HC emissions is reduced. This is because of the increase of oxygen content with the ethanol blend. HC emissions decrease with the increase of IPs for all the blends because of the better atomization in the combustion chamber [5, 21, 24-26].


HC (ppm) VS LOAD (Kg) AT 180 bar

(a)

HC (ppm) VS LOAD (Kg) AT 200 bar

(b)

HC (ppm) VS LOAD (Kg) AT 220 bar

(c)

Figure 7: The effect of HC Emissions at different injection pressures for various blends.

Conclusion

The effect on performance and emission characteristics of direct injection diesel engines with Niger biodiesel, diesel, and ethanol blends were investigated at different injection pressure in this work. The following were noticed during engine testing:

i. The engine could successfully run at three injection pressures of 180, 200, and 220 bars with diesel and Niger biodiesel-diesel-ethanol blends at a constant engine speed of 1500 rpm.
ii. At higher injection pressures the blend B15+D70+E15 shown high BTE compared to diesel. While the blends B10+D80+E10 and B5+D90+E5 proved better BTE than diesel at low injection pressures.
iii. BSFC of the blends B15+D70+E15, B10+D80+E10 and B10+D80+E10 are lower (0.34, 0.32 and 0.32 kg/kWh) than diesel at high and low injection pressures (220 bar, 200 bar and 180 bar) respectively.
iv. NO_X emissions of Niger biodiesel-diesel-ethanol blends are increased than diesel at three fuel injection pressures due to the high temperature of exhaust gasses and high heat release rate.
v. At three fuel injection pressures, CO emissions of all blends are found to be lower than diesel.
vi. Due to the effective heat release rate of all blends CO_2 emissions are increased than diesel at three different injection pressures.
vii. HC emissions of Niger biodiesel- diesel- ethanol blends are lower than diesel.

From the above experimentation and analysis, it is concluded that Niger oil biodiesel-diesel-ethanol blends are well suitable in diesel engines. These blends can also sustain at higher fuel injection pressures and produce better efficiency, reliable performance, and less harmful emissions.

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