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Research Article

Comparative analysis of performance and emission from single cylinder diesel engine fuelled with mango kernel biodiesel

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ABSTRACT

Due to their efficiency and high power output, diesel engines find extensive use in the automotive, transportation, industrial, and agricultural sectors. However, these engines encounter several challenges, including the emission of pollutants such as nitrogen oxides and particulate matter, as well as their reliance on fossil fuels. As a result, the demand for alternative fuels has risen significantly. Biodiesel, derived from various sources, has emerged as a promising substitute for diesel fuel. Among these alternatives, mango kernel biodiesel is currently being investigated as a renewable fuel option for diesel engines. In this current research study, a single-cylinder diesel engine was used to investigate the effects of mango kernel biodiesel (B10) as fuel compared to conventional diesel fuel. The engine was operated under different loading conditions (25%, 50%, 75%, and 100%) and varying fuel injection pressures (400 bar, 500 bar, and 600 bar), while maintaining a compression ratio of 18. The research focused on conducting a comparative analysis of engine performance, and emissions between the two fuels viz. conventional diesel fuel and mango kernel biodiesel blend. For major test cases, the engine recorded higher brake thermal efficiency (BTE) and lower brake specific fuel consumption (BSFC) as compared to the biodiesel blend. At full load and higher injection pressure, the B10 blend increased BTE by 4.83% and decreased BSFC by 5.40% than diesel. The smoke formation, CO, HC emissions were notably higher with B10 blend.

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INTRODUCTION

The burning of fossil fuels produces harmful gas emissions, including oxides of nitrogen (NOx), carbon monoxide (CO), carbon dioxide (CO_2), oxides of sulphur (SOx), and particulate matter (PM), which have a significant negative impact on the environment, including climate change and global warming. Due to the detrimental effects of internal combustion (IC) engine emissions on human health and the environment, a global effort has been made to reduce pollutants from IC engines. The diminishing accessibility of

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non-renewable energy sources and escalating global environmental apprehensions mandate the utilization of renewable resources in forthcoming times. In contemporary times, there has been notable interest in alternative sources for IC engines, specifically fuels derived from vegetable oils. This attention is primarily due to the accessibility, lack of toxicity, and eco-friendly properties associated with these fuels. Biodiesel, a renewable fuel derived from plant oils or fats, can be blended with mineral or pure diesel in varying proportions and used in diesel engines. One significant drawback of biodiesel is its higher NOx emissions, which can be attributed to its elevated oxygen content. Biodiesel can be produced from numerous feedstocks, such as edible vegetable oils, non-edible oils, algae, used cooking oil, and animal fats etc. The reviews on biodiesel application in IC engines focuses on the challenges and considerations related to biodiesel, including its preparation methods, production through transesterification, and its application in unmodified diesel engines.

Researchers have prepared and tested performance and emissions from the engine with biodiesel produced from edible oil sources at like soybean oil [1-3], sunflower oil [4-6], coconut oil [7, 8], rapeseed oil [9-11], corn oil [12, 13], cottonseed oil [14, 15] etc. Vellaiyan [1] investigated the combustion, performance, and emission characteristics of a diesel engine fuelled with soybean biodiesel and its water blends, revealing lower peak ICP, NHR, RPR, and IDP for soybean biodiesel in comparison to diesel, and improved emissions with water emulsified blends. Dhanarasu et al. [4] examined the effect of acetone as an oxygenated fuel additive on a sunflower oil biodiesel-diesel blend, discovering that B20A15 exhibited a slight increase in BSFC and BTE, and reductions in CO, smoke opacity, HC, and NOx compared to diesel under full load. Venkatesh and Prasanthi [7] analyzed the effect of alumina nanoparticles on the transesterification, emission, and performance of coconut biodiesel, revealing decreased NOx and smoke emissions, improved BTE, and decreased BSFC with CBD100A in comparison to CBD100. Raman et al. [9] performed an experimental study on a single-cylinder diesel engine using a B25 rapeseed biodiesel blend at 200 bar injection pressure, achieving 5.95 kW power output, and discovered that it had acceptable BTE and improved exhaust emissions compared to baseline diesel. Sathyamurthy et al. [12] investigated corn oil biodiesel and its blends in a diesel engine and revealed that B10 biodiesel blend improved BTE to 33.98% (lower than neat diesel), while B20 and B30 increased BSFC by approximately 4 and %, respectively. Higher oxygen content in the fuel was also associated with increased NOx formation and CO_2 emissions, while CO and HC emissions decreased. Selvanayagam and Arul [14] investigated the use of cottonseed oil biodiesel blends (10%, 20%, 30%, 40%) with diesel in a single-cylinder diesel engine with EGR, demonstrating improved performance characteristics including BP, BSFC and BTE, with reduction in NOx emissions.

In addition to the edible oils, numerous non-edible oils like jatropha oil [16-18], karanja oil [19, 20], neem oil [21, 22], moringa oil [23, 24] etc. are used for biodiesel production and are subsequently tested for its performance and emissions. Gad and Jayaraj [16] studied Jatropha biodiesel blends with nano additives, finding a 6.5% improvement in BTE for J20Al100, a 35% reduction in CO and a 52% reduction in NOx for J20C50, and a 22% reduction in HC and a 50% reduction in smoke for J20T25, compared to other tested fuels. Verma et al. [19] conducted an experiment to determine the effect of Karanja biodiesel blends with higher alcohols (ethanol, 2-propanol, methanol, 1-butanol, and 1-pentanol) on diesel engines. In comparison to mineral diesel fuel, KOPnE20 demonstrated a 3.3% decrease in BTE and an 11.75 % increase in BSFC at full load, while CO_2 emissions increased by 32.25 % and NO_x emissions decreased by 6.72 %. Sakthivadivel et al. [21] examined diethyl ether and alumina nanomaterial blends for Neem oil biodiesel production. The biodiesel blend with 25 ppm alumina nanomaterials improved BTE by 7.2% and BSFC by 6.7% compared to pure diesel fuel. It also reduced NOx emissions by 17.5% at 100% load and HC, CO, and smoke emissions at higher loads. Ramalingam and Mahalakshmi [23] examined the effects of advanced injection strategy on a diesel engine fueled by moringa oleifera biodiesel and its blends. At higher injection pressure and advanced injection timing, B20 had maximum BTE of 33.49%, while pure biodiesel had minimum CO (0.01% vol.) and maximum CO_2 (9.1% vol.) emissions and 3 ppm UHC.

India is the largest producer and consumer of the mango fruit. Mango production in India exceeds 50 million tonnes annually, making up about half of the world›s supply [25]. At present, there is more than 2.3 million acres of land devoted to mango cultivation in India [25]. Mango kernel oil is produced from mango seeds, making it a vital source for biodiesel production. Mango trees can be cultivated in wastelands across India, making it a promising and sustainable option for biodiesel production [26]. The chemical and physical properties of the mango kernel oil meets the ASTM standards for its use in IC engine as a biodiesel [25]. Numerous researchers have reported studies on biodiesel production from mango seed oil and its application in diesel engine. Reddy et al. [25] investigated how injection timing and EGR rates affected a research diesel engine fueled with 20% mango seed methyl ester (MSME 20). At full load, advanced injection timing and 5% EGR reduced NOX emissions by 43.38% compared to MSME 20. In a CI engine, Ahmad and Saini [27] examined various ternary fuel blends of diesel, mango seed biodiesel (MSB), and butanol as an oxygenated additive. MSB20B5 blend demonstrated a decrease of 25.79% in BSFC and an increase of 8.46% in BTE in comparison to MSB20B0, resulting in a reduction of exhaust pollutants and making it a recommended option for diesel engines. Okonkwo and Omenihu [28] prepared mango seed oil based biodiesel that met the standards set by ASTM-D6751 and EN14214, indicating its suitability for use in IC engines. The biodiesel exhibited comparable properties to traditional diesel, including a satisfactory BSFC that enables efficient operation of diesel engines at a reasonable cost. Reddy et al. [29] extracted mango seed biodiesel by transesterification and found that adding 5% decanol to MSME20 increased BTE by 3.19% and reduced HC, CO, and smoke emissions. Shaik et al. [26] investigated the effect of varying compression ratio and EGR rates on a diesel engine fuelled with MSME 20. The results showed that a compression ratio of 22:1 with 5% EGR reduced NO_X emissions by 40.5% without sacrificing performance. Yogesh et al. [30] examined the effects of two fuel injection pressures (200 and 300 bar) in a CI engine with B10 and B20 mango seed biodiesel blends. The blends had higher BTE and lower CO, smoke, and HC emissions but higher NOx emissions. Reddy et al. [31] worked on extracting mango seed biodiesel (MSME20) and improving engine performance by adding 5% diethyl ether, resulting in enhanced brake thermal efficiency and decreased emissions. Reddy and Sarangi [32] utilized hybrid nanoparticles and hydrogen gas in emulsified MSME fuel to optimize engine characteristics, achieving 32% BTE at a nanoparticle concentration of 75 ppm (B20W10NP75). Venkatesh et al. [33] experimentally evaluated Mango seed biodiesel blends in a single-cylinder DI diesel engine, showing enhanced cylinder pressure and HRR for B10 and B20/B100, reduced HC and CO emissions, increased NOx emissions, and decreased smoke emissions for the majority of blends.

This research study presents comparison of engine performance and emission characteristics for diesel and mango seed biodiesel B10 blend. The comparative study is conducted over a wide range of engine load (25% to full load) and injection pressure from 400 bar to 600 bar. The comparison of engine performance at different levels of injection pressures (400 bar, 500 bar and 600 bar) is the novelty of this work.

RESEARCH METHODOLOGY

Mango Kernel Oil Extraction

The mango seeds used to extract the oil were sourced from Western Maharashtra area in India. The seeds were cleaned under tap water to remove any dirt and impurities before being prepared for extraction. After cleaning, the seeds were sun-dried for 24 hours to remove moisture before being further dried at 70ºC for 4 hours in an oven. A hydraulic hammer was used for mechanical breaking to separate the mango kernel from the seeds. To ensure complete moisture removal, the mango kernels were again dried at 70ºC for 3 hours in an oven. Then, using a mechanical oil extraction mill, the oil was extracted from the dried kernels. From 1 kg of mango kernels, the oil extraction process produced about 170 gm of oil, representing a 17% oil extraction rate. The entire process of producing mango kernel oil, from the raw mango seeds, is shown in Figure 1. The properties of pure diesel and B10 blend are tabulated in the Table 1.

The technique of preparing biodiesel from waste mango kernel is an organic alternative to the conventional diesel fuel. It makes better use of the waste mango seeds from mango processing industries like pulp processing industry. The commercial preparation of the mango kernel biodiesel will also generate significant amount of employment in the rural part of India.

Table 1. Properties of diesel and B10 blend

Property	Diesel	B10	Test Method	Instrument Used
Density, kg/m³ (@ 25°C)	816	833	ASTM -D287	Hydrometer
LCV, kJ/kg	42827	41514	ASTM -D4809	Bomb calorimeter
HCV, kJ/kg	45279	44576	ASTM -D4809	Bomb calorimeter
Kinematic Viscosity (@ 40°C), kg/m-s	$1.73*10^{-3}$	$1.96*10^{-3}$	ASTM-D445	Calibrated glass capillary viscometer

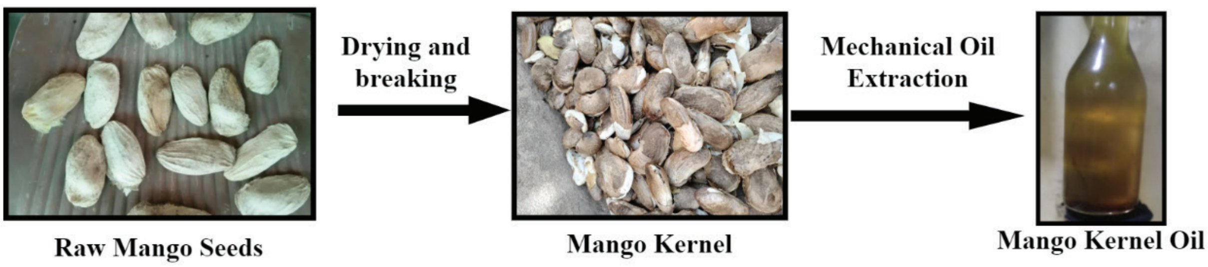


Figure 1. Mango kernel oil production process.

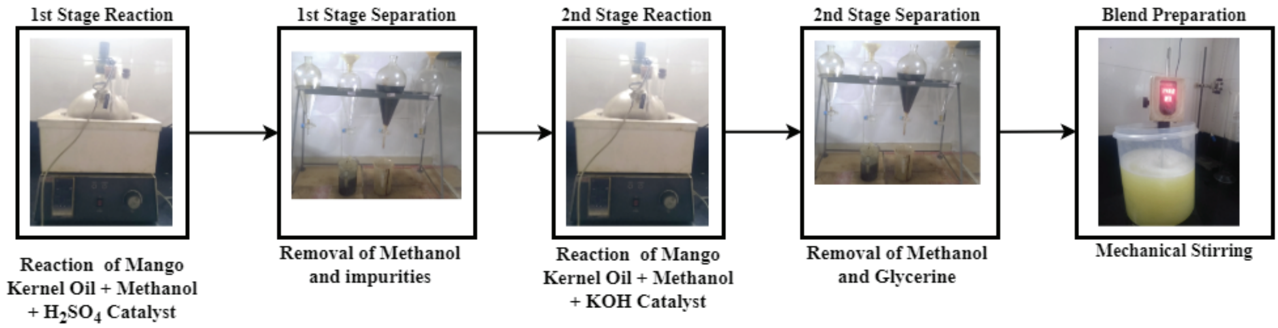


Figure 2. Biodiesel blend production process.

Biodiesel Production Process

The mango kernel oil was converted into biodiesel using a two-stage transesterification procedure. The first step involved reacting the mango kernel oil with methanol (CH_3OH) in an electric chamber at 60°C for 1h while using sulphuric acid (H_2SO_4) as a catalyst. The oil was then separated from the methanol oil impurities using a separation funnel. In the initial reaction, 17% CH_3OH (by volume) and 5% H_2SO_4 (by volume) were used. In order to prepare the oil for the second stage reaction, the first stage separation was followed by heating it to 60ºC. For the second stage reaction, mango kernel oil, methanol, and a potassium hydroxide (KOH) catalyst were allowed to react for 1h at 60ºC. After the reaction, the mixture was poured into a separation funnel to separate the glycerine and methanol. For second reaction, 17% by volume of methanol and 12% by volume of potassium hydroxide were used in this reaction.

The molecules of the mango kernel oil were chemically broken down into pure biodiesel during the transesterification process, specifically into mango kernel oil methyl esters. Mango kernel methyl esters free from impurities was further used to prepare biodiesel blends. To prepare the B10 blend, 10% (by volume) of biodiesel and 90% (by volume) of diesel were mechanically stirred for 10 minutes at 1460 rpm. The procedure of biodiesel blend production from raw kernel oil is depicted in Figure 2.

Experimental Setup

The research engine used in the experiment is a Kirloskar made single-cylinder, water cooled, four-stroke (4S) diesel engine with a provision to vary the compression ratio. The engine can run in both petrol and diesel modes and has rated capacity 3.5 kW at 1500 rpm. The eddy current dynamometer is connected to it for load testing. The system has a number of sensors that can measure engine load, temperatures, pressure, fuel flow, and other variables. Data is gathered using a 16-bit multifunctional input-output device interfaced with a high-speed data acquisition system. Rotameters are used to gauge the flow of both calorimeter water and engine cooling water. A dual fuel tank, an air box, a manometer, transmitters for measuring air and fuel, and a piezo powering unit are all housed in a panel box. Various performance parameters, including brake power (BP), brake thermal efficiency (BTE), brake mean effective pressure (BMEP), indicated power (IP), indicated thermal efficiency (ITE), and indicated mean effective pressure (IMEP), as well as heat balance parameters and combustion parameters, can be measured using the setup while the engine is running. AVL made five gas analyser and smoke meter are employed to measure engine emissions. The pictorial view of experimental setup is shown in the Figure 3. The specifications of the engine test setup are tabulated in the Table 2.

Figure 3. Experimental test setup.

Table 2. Technical specifications of engine

Parameter	Description
Bore	87.5 mm
Stroke	110 mm
Rated Capacity (Diesel mode)	3.5 kW at 1500 rpm
Injection Timing	23^0 bTDC
Compression Ratio	Provision to change from 12 - 18

Experimental Procedure

The engine was subjected to a series of tests to evaluate the impact of varying engine load and injection pressure. At injection pressures of 400 bar, 500 bar, and 600 bar, the experimental tests were conducted. At each injection pressure level, tests were conducted with engine loads of 3 kg (25% load), 6 kg (50% load), 9 kg (75% load), and 12 kg (full load). Both test fuels, diesel and a B10 blend, were subjected to the same set of tests. During each test, various output variables including BP, BTE, and BSFC were recorded using a high-speed data acquisition system. In addition, emission parameters were recorded using a gas analyser. Total 24 experimental tests were conducted including both diesel. The network diagram for experiments representing different levels of test parameters are shown in Figure 4.

Uncertainty Analysis

Even when necessary precautions are taken during the experimental tests, uncertainties and errors can still occur because of a variety of factors, including the choice, condition, and calibration of test equipment, environmental factors, recording techniques, and the test design. Recognizing that experimental errors are unavoidable makes conducting an uncertainty analysis essential for determining the validity and dependability of the experiments. The ultimate outcome of an experiment is derived from the initial measurements. The error in the final result is determined by the parameter with the largest error among those used to calculate the result. In this study, experimental measurements of performance parameters like BTE, BSFC, combustion parameters like cylinder pressure and heat release rate and emission parameters like CO, CO_2, HC, NO_x and smoke opacity were measured to evaluate the performance of the engine. Through repeated tests, uncertainty of different parameters is computed. Table 3 outlines the precision and percentage of uncertainty in the measurements of output parameters. This uncertainty analysis facilitates the comprehension of possible variations in the results and ensures a thorough evaluation of the experimental findings. The percentage uncertainty and accuracy in the measurement of each measurement parameter is presented in the Table 3. In the present study, three set of tests were conducted under identical conditions and operating parameters to measure variation in the output data i.e. repeatability test was conducted.

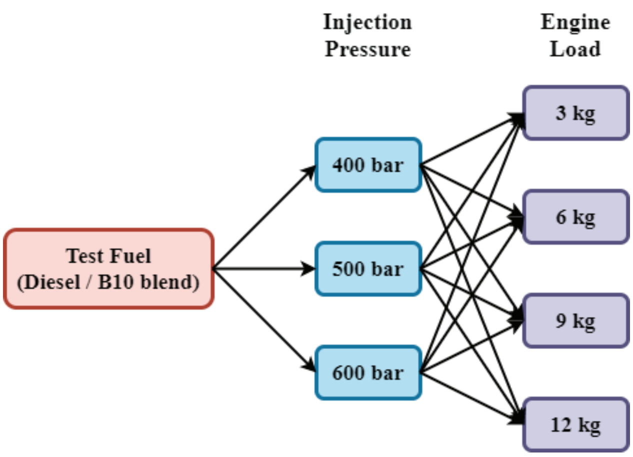


Figure 4. Network diagram for experimental tests.

Table 3. Percentage uncertainty of measurement parameter

Parameter	Accuracy	Uncertainty (%)
Engine speed, rpm	±0.05%	±0.1
Temperature, ºC	±0.5%	±0.15
Pressure, bar	±1%	±0.1
CO (% vol.)	0.01%	±0.2
CO_2 (% vol.)	±5%	±0.15%
HC (ppm vol.)	±10 ppm	±0.5
NO_x (ppm vol.)	±50 ppm	±1
Smoke opacity	±1%	±1

The total uncertainty in the experiment is calculated by using Holman's square root approach as given in the equation (1),

$$Total\ uncertainty\ (\%) = [(BTE)^2+(BSFC)^2+(CO)^2+(CO_2)^2 + (HC)^2+(NO_x)^2+(SO)^2]^{1/2} \quad (1)$$

The total uncertainty for the present experiment amounts to ±1.62% which is well within the permissible range (5%) of uncertainty.

RESULTS AND DISCUSSION

Performance Evaluation

Brake thermal efficiency (BTE)

The brake thermal efficiency of the engine at different engine load is depicted in Figure 5(a), 5(b) and 5(c) at 400 bar, 500 bar and 600 bar injection pressure. At all injection pressures, the brake thermal efficiency of the engine rises with the engine load. This is due to the fact that, at lower engine loads, a major share of the power produced by the engine is lost in overcoming the engine friction. As a result of this only a minor part of the power produced by the combustion of fuel is converted to the useful work. It is also observed that, the brake thermal efficiency of the engine with B10 blend is higher than that of with diesel in major cases. The highest brake thermal efficiency for B10 blend was recorded as 23.97% at injection pressure of 400 bar and 12 kg engine load. The enhanced combustion due to the higher oxygen present with the biodiesel produces more engine power. At higher loads, the engine requires higher amount of fuel and mixture is richer. In case of biodiesel, the extra amount of fuel has the limitations of mixing with air due to higher viscosity and results in less BTE in comparison to the diesel. This problem is addressed by increasing the injection pressure (600 bar), which helps in proper mixing of fuel and air resulting in higher BTE compared to the diesel at higher loads.

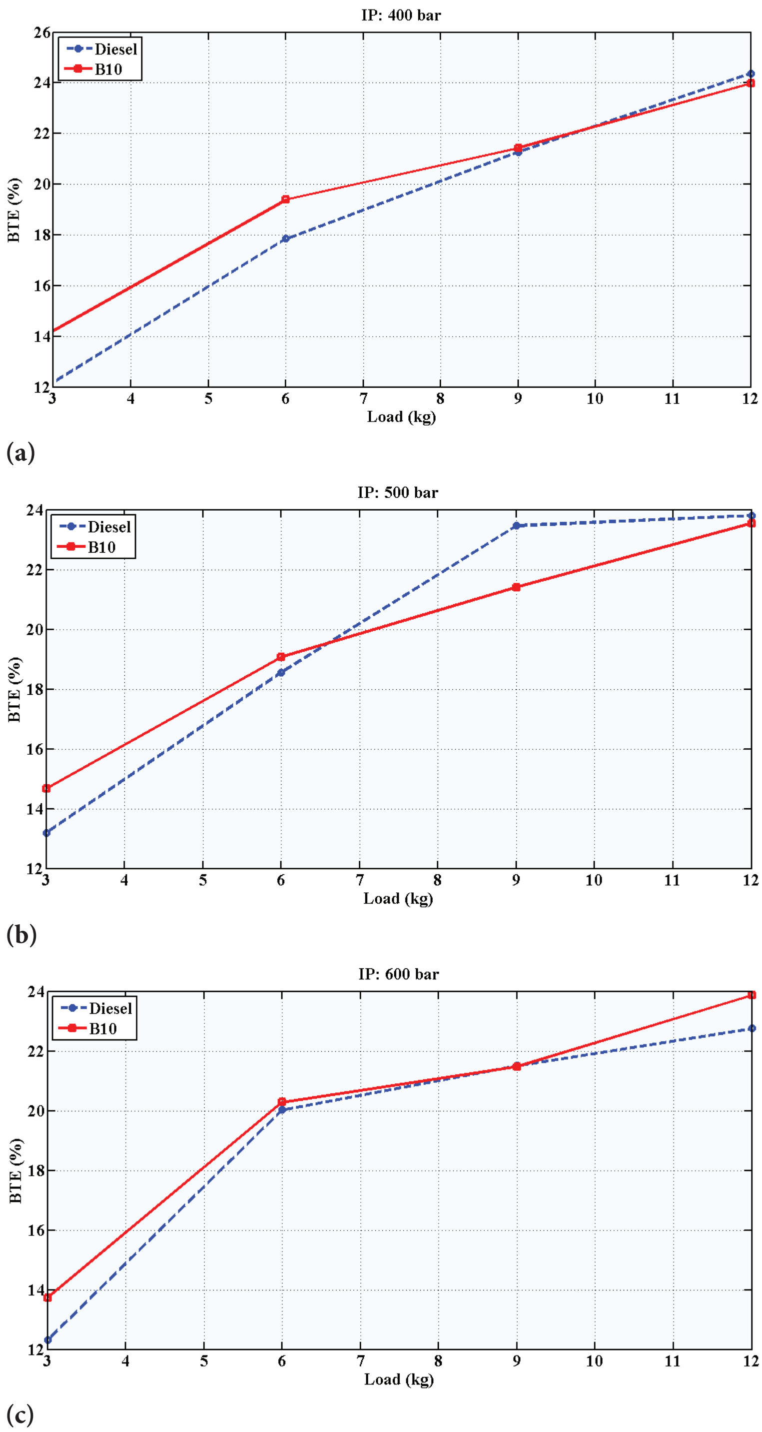
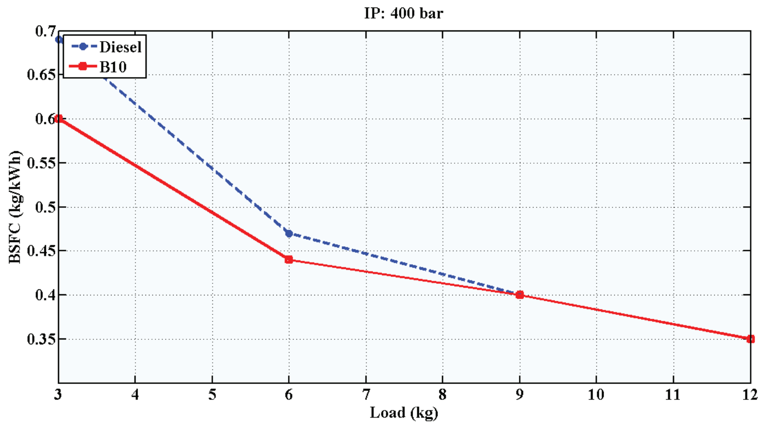


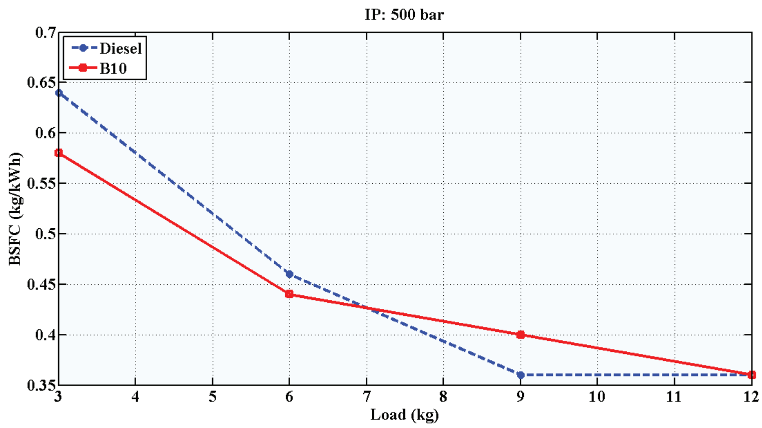
Figure 5. Variation of BTE with engine load at (a) IP: 400 bar, (b) IP: 500 bar, (c) IP: 600 bar.

Brake specific fuel consumption (BSFC)

The effect of engine load on the brake specific fuel consumption of the engine at 400 bar, 500 bar and 600 bar injection pressure is depicted in the Figure 6(a), 6(b) and 6(c) respectively. For diesel as well as B10 blend, the decrease in brake specific fuel consumption was observed with increased engine load. At lower engine loads, a major part of the thermal energy produced by combustion of the fuel utilized to overcome the engine friction producing lesser amount of useful work. With increase in the engine load, more amount of thermal energy is converted to the useful brake power. In majority of the test cases, the engine has exhibited improved performance in terms of BSFC for B10 blend. The engine recorded lowest BSFC of 0.35 kg/kWh with B10 blend at full load conditions and 600 bar injection pressure which is 5.71% lower than with diesel at same conditions.



(a)



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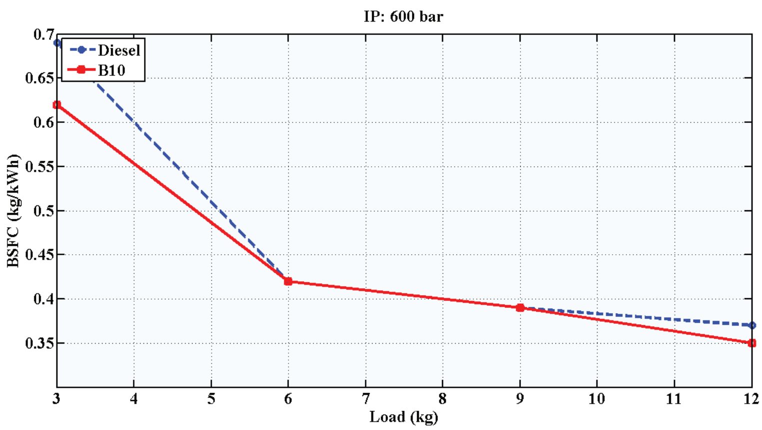


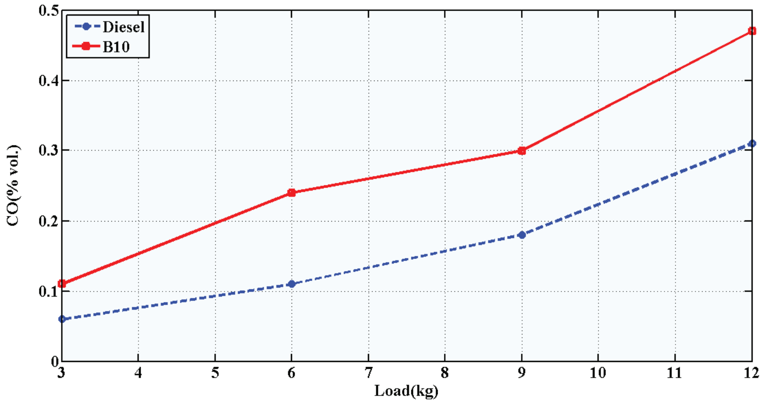
(c)

Figure 6. Variation of BSFC with engine load at (a) IP: 400 bar, (b) IP: 500 bar, (c) IP: 600 bar.

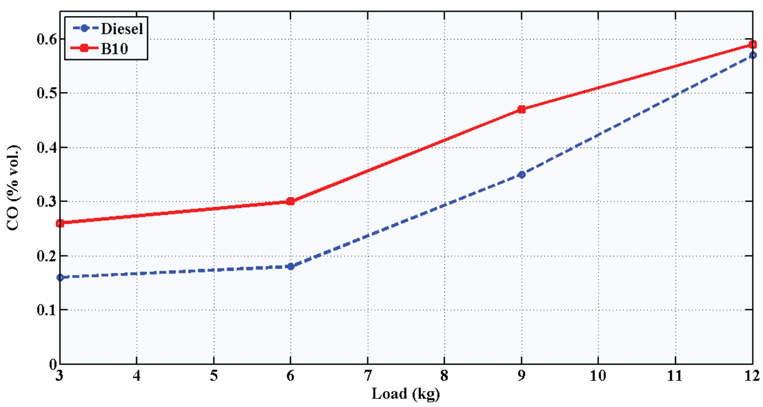
Emission Analysis

CO emissions

The CO emissions from the engine at different engine loads (3 kg, 6 kg, 9 kg and 12 kg) and at different injection pressures for diesel and B10 blend is depicted in the Figure 7(a), 7(b) and 7(c). It is evident from the Figure 3 that, increase in engine load causes increase in the CO emissions from the engine for all test fuels and at all injection pressures. To cope up with the increased loads, the engine requires richer mixture to produce more engine power. With richer mixture, the oxygen available for the oxidation of carbon the fuel becomes insufficient producing higher amount of CO emissions. At 400 bar injection pressure, for example, the air-fuel ratio reaches from 35.32 to 17.88 for 3 kg load to 12 kg load respectively for diesel fuel. Due to poor oxidation of excess carbon in the cylinder, the CO emissions increases with the engine load. Additionally, the higher amount of CO emissions were observed with B10 blend as compared to the diesel at all engine loads and injection pressures. By increasing the injection pressure



(a)



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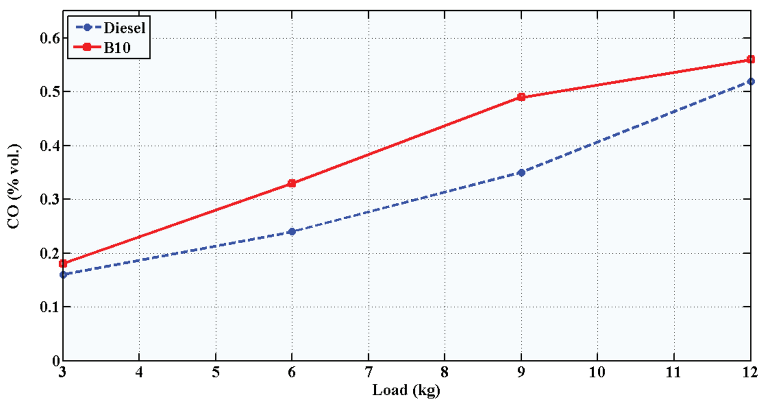


(c)

Figure 7. Variation of CO Emission with engine load at (a) IP: 400 bar, (b) IP: 500 bar, (c) IP: 600 bar.

from 400 bar to 500 bar, the engine has exhibited increased CO emissions trend for both diesel and B10 blend.

HC emissions

The effect of varying engine load on engine HC emissions at 400 bar, 500 bar and 600 bar injection pressure for diesel and K10 blend is depicted in the Figure 8(a), 8(b) and 8(c) respectively. The HC emissions shows increased trend with increased engine load irrespective of the injection pressure. The primary cause of this is the incomplete combustion of the fuel due to reduced supply of oxygen for the combustion at higher engine loads. For example, at 600 bar injection pressure, the air to fuel ratio was recorded as 40.96 at 25% engine load. The mixture becomes richer at full load condition with air-fuel ratio of 17.83. The insufficient amount of oxygen available for the oxidation of hydrogen and carbon in the fuel leads to incomplete combustion and increases HC emissions at with increased engine load. The

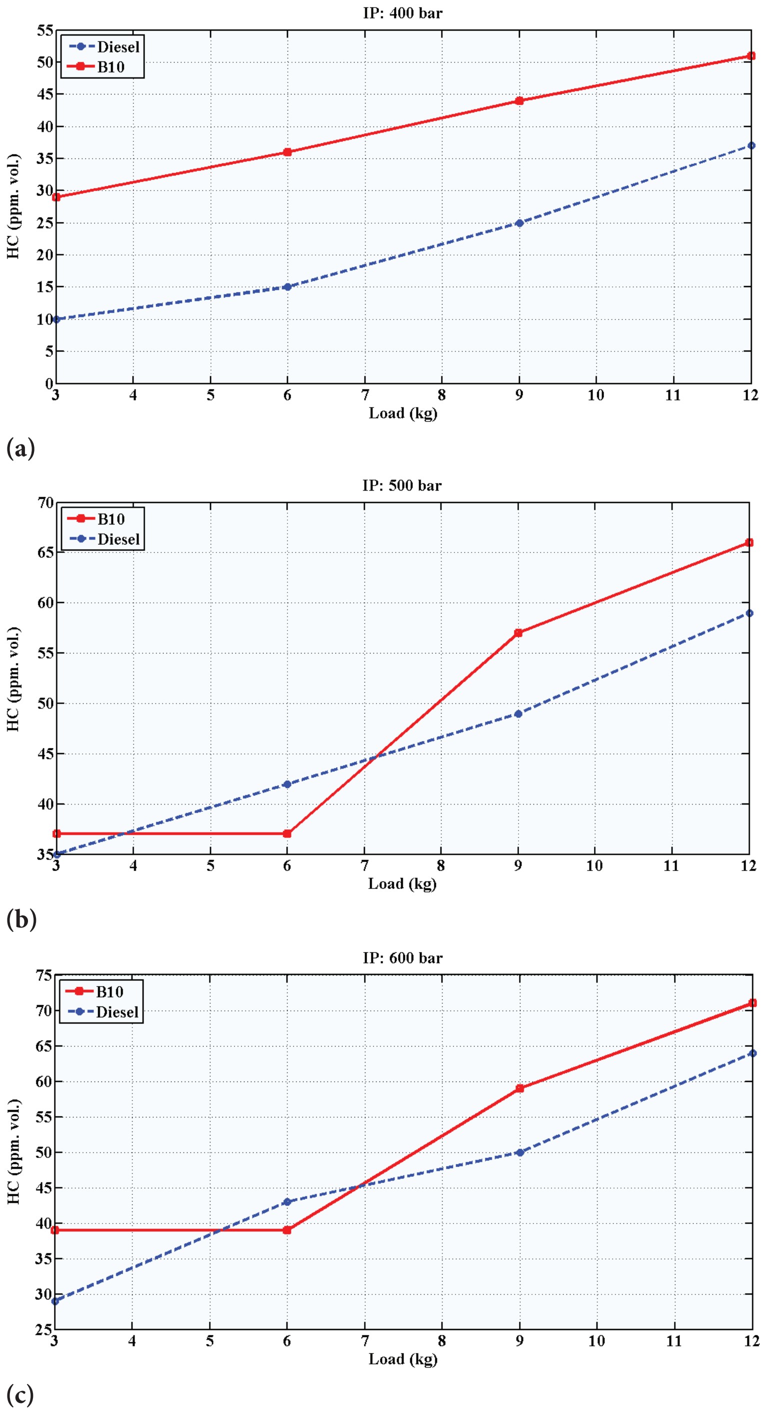
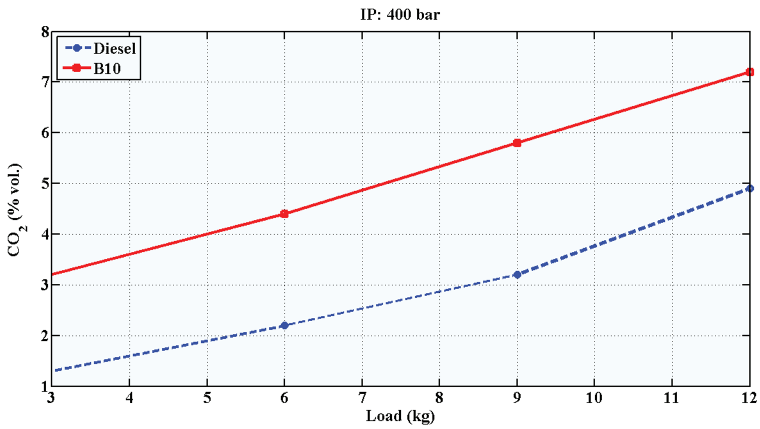


Figure 8. Variation of HC emissions with engine load at (a) IP: 400 bar, (b) IP: 500 bar, (c) IP: 600 bar.

higher density and viscosity of B10 blend leads to the poor combustion and causes increased HC formation as compared to diesel at major cases of engine loads and injection pressures. At 6 kg engine load, the B10 blend reduces HC emissions by 13.51% and 10.25% at injection pressure of 500 bar and 600 bar respectively as compared to the diesel. For injection pressure of 500 and 600 bar, engine exhibited higher HC emissions at 6 kg engine load, whereas HC emissions are lower for diesel fuel in comparison to B10 blend for remaining engine loads.

CO_2 emissions

The effect of varying engine load from 25% to full load on the CO_2 emissions for diesel and B10 blend is shown in Figure 9(a), 9(b) and 9(c) at 400 bar, 500 bar and 600 bar injection pressures respectively. It is clear from the Figure 9 that, engine emits higher amount of CO_2 at higher engine



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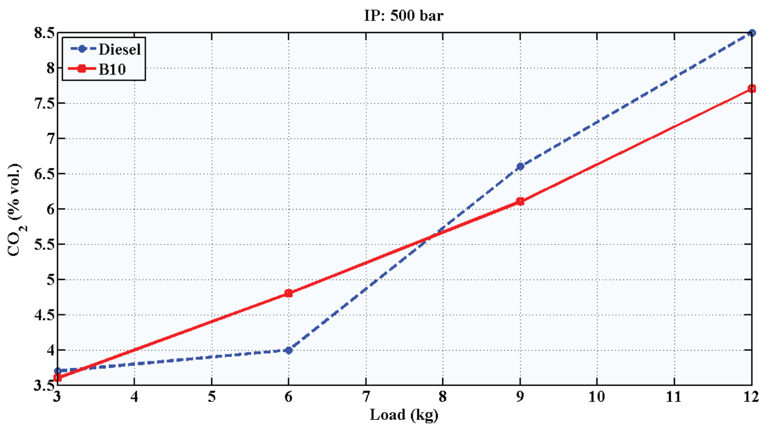

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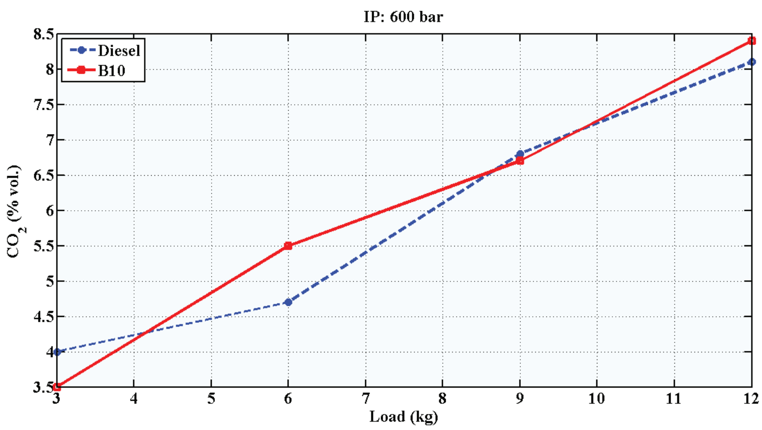


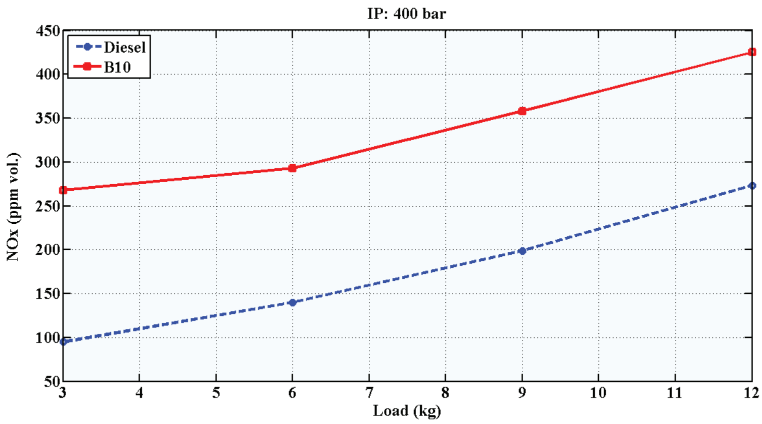
(c)

Figure 9. Variation of CO_2 emissions with engine load at (a) IP: 400 bar, (b) IP: 500 bar, (c) IP: 600 bar.

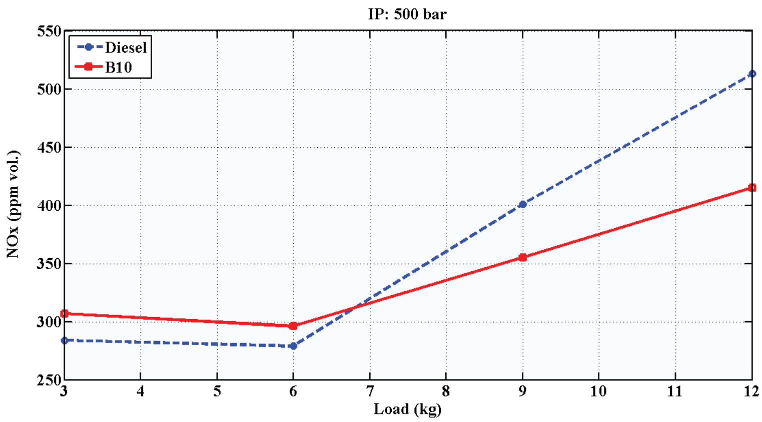
loads. In major test cases, the engine produces higher quantity of CO_2 with B10 blend due to the oxyrich properties of the mango kernel oil. For diesel fuel, the CO_2 emissions increases significantly with increase in the injection pressure. At higher injection pressures (500 and 600 bar), better atomization of biodiesel resulted in better utilization of oxygen present in the engine cylinder resulting in emissions of CO_2 very close to that of diesel. This is not the case at 400 bar pressure, where CO_2 emissions from the engine with biodiesel are significantly higher than diesel.

NOx emissions

The NOx emitted by the engine at varying engine loads and injection pressure is depicted in the Figure 10(a), 10(b) and 10(c). For all cases of injection pressures, the increase in the engine load tends to increase NOx emissions for both test fuels. As discussed earlier, higher amount of fuel



(a)



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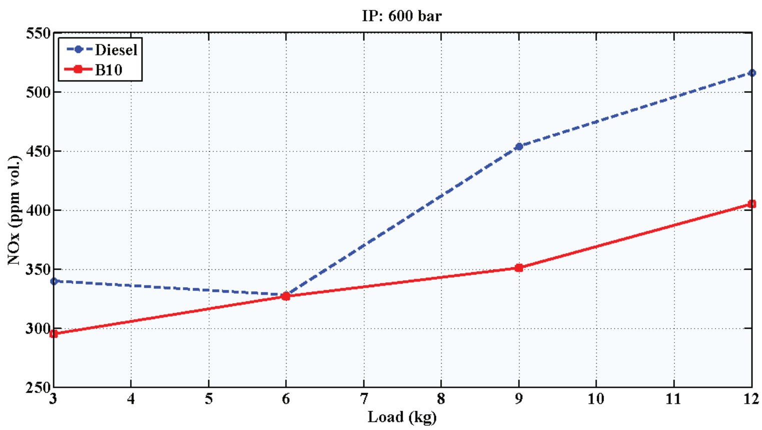


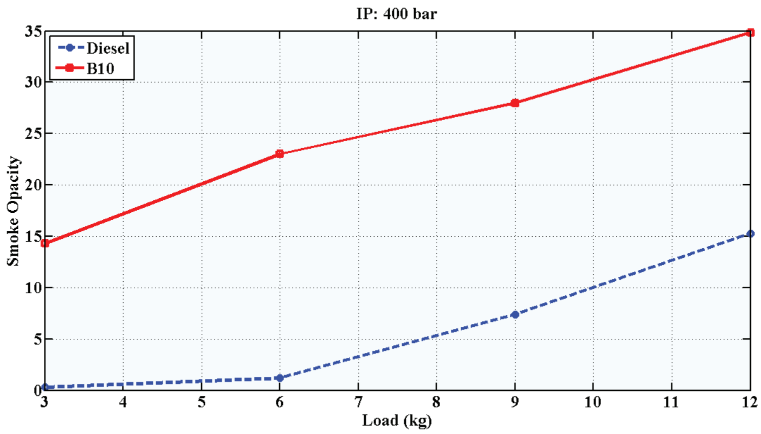
(c)

Figure 10. Variation of NOx emissions with engine load (a) IP: 400 bar, (b) IP: 500 bar, (c) IP: 600 bar.

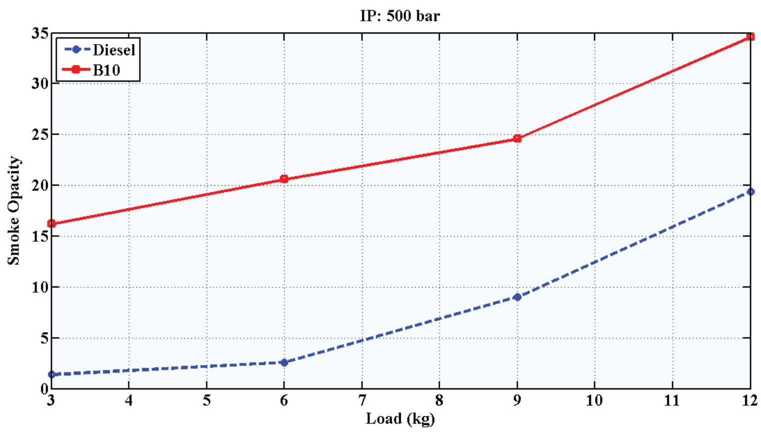
is present for combustion at higher loads due to richer mixture at higher loads. All this fuel burns instantaneously and elevates the cylinder temperature. This allows nitrogen and oxygen in the air to react at higher temperature leading to increased amount of NOx formation. At lower injection pressure (400 bar) the NOx formation with B10 blend is significantly higher than that of diesel. However, at increased injection pressures (500 bar and 600 bar), engine produces lower NOx emissions with B10 blend than diesel. The higher injection pressure enhances mixing of B10 blend leading to the smooth combustion. At full engine load, the engine produces 19.10% and 21.51% lower amount of NOx with B10 in comparison to the diesel at 500 bar and 600 bar injection pressure respectively.

Smoke Opacity

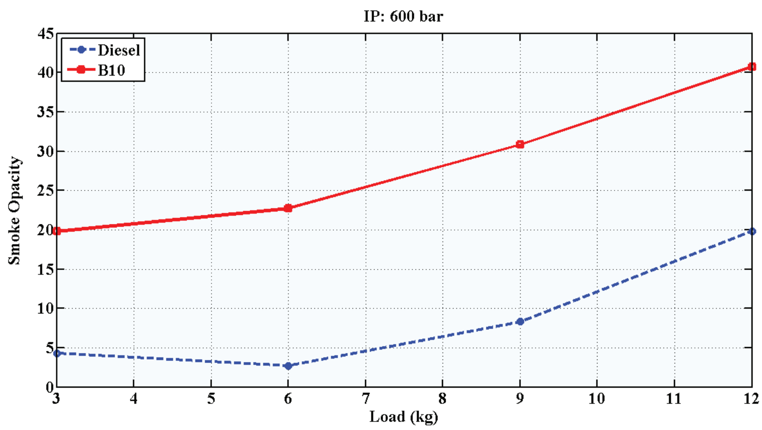
The smoke produced by the engine with B10 blend and pure diesel at varying engine load and different



(a)



(b)



(c)

Figure 11. Variation of smoke opacity with engine load at (a) IP: 400 bar, (b) IP: 500 bar, (c) IP: 600 bar.

Table 4. Comparison of results with literature

Parameter	Present work	Literature [33]
BTE	Increasing with engine load	Increasing with engine load
BSFC	Decreasing with engine load	Decreasing with engine load
CO_2	Increasing with engine load (Increased from 3.2 – 7.2% for 25% - full engine load)	Increasing with engine load (Increased from 2 – 9% for 25% - full engine load)
NO_x	Increasing with engine load (Increased from 270- 420 ppm. vol. for 25% - full engine load)	Initially increasing and then decreasing (bell curve) (For engine load of 25%, 50%, 75% and full load recorded NOx emissions of 18, 20, 23 and 21 g/kWh)
Smoke opacity	Increasing with engine load (Increased from 15 -35% for 25% - full engine load)	Increasing with engine load (Increased from 2.5 - 27% for 25% - full engine load)
HC	Increasing with engine load (Increased from 29 ppm. vol. to 52 ppm. vol. for 25% load to full load)	Decreasing with engine load (Decreased from 2.8 g/kWh to 0.5 g/kwh for 25% load to full load)

injection pressures is shown in Figure 11(a), 11(b) and 11(c). Incomplete combustion of fuel can lead to smoke formation due to factors such as inadequate air for combustion, low oxygen content in the fuel, the formation of highly rich mixtures, and low cylinder temperatures [34]. The high density and viscosity of the biodiesel affects the mixing and leads to the incomplete combustion resulting in the higher smoke formation. As a result of this, the smoke formation for B10 blend is higher than diesel at all operating conditions. The presence of highly rich mixture at higher loads increases smoke formation with increased engine load for both test fuels. The engine produces smoke with 19.5%, 15.2% and 20.9% higher opacity with B10 blend than diesel at full load conditions and injection pressure of 400 bar, 500 bar and 600 bar respectively.

Venkatesh et. al. [33] have conducted performance and emission analysis of single cylinder diesel engine with mango kernel biodiesel. Similar to this work, the present work shows increasing trends for BTE, CO_2 and smoke opacity and decreasing trend for BSFC with engine load. The details are tabulated in the Table 4.

CONCLUSION

The research work focusses on the comparison of engine performance and emissions with pure diesel and mango kernel oil biodiesel (B10 blend) at varying operating conditions. For this purpose, engine performance and emissions characteristics were evaluated at four levels of engine load (25%, 50%, 75% and full load) and three levels of injection pressure (400 bar, 500 bar and 600 bar). The effect of varying engine load and injection pressure on performance as well as emissions was studied. The research finding are summarized as:

The engine exhibits higher BTE with B10 biodiesel in comparison to the diesel in majority of the test cases. At 500 bar injection pressure and 75% engine load, the BTE of the engine is 4.86% higher with B10 biodiesel blend than that of diesel.

Further, BSFC of the engine is lower with B10 blend for most of the test cases. At low load conditions, engine recorded 18.04%, 9.38% and 10.14% lower BSFC with biodiesel blend at 400 bar, 500 bar, 600 bar fuel injection pressure than that of diesel.

The increases in engine load tends to rise emission of all gases (CO, CO_2, HC, NOx and SO) irrespective of the test fuel and fuel injection pressure due to the presence of richer mixture at higher engine loads.

The engine emits higher quantity of CO and HC with B10 biodiesel at major cases of engine loads and injection pressures. In comparison with diesel, CO_2 and NOx emissions are higher for B10 blend at low injection pressure. At higher injection pressures, engine produces higher amount of CO_2 and NOx than that of diesel. At 25% load and higher injection pressure, engine produces 12.5% and 13.23% lower amounts of CO_2 and NOx emissions respectively.

The mango kernel oil biodiesel (B10 blend) exhibits better performance than diesel in terms of BTE and BSFC. However, the emission profile of the blend is poor in comparison the diesel especially at lower injection pressure. There is a scope to improve emission performance of biodiesel with use of certain additives to reduce emissions.

ABBREVIATIONS

NO_x	oxides of nitrogen
CO_2	carbon dioxide
HC	hydrocarbon
IC	internal combustion
BSFC	brake specific fuel consumption, kg/kWh
B10	blend of biodiesel containing 10% biodiesel and 90% diesel
CI	compression ignition
VCR	variable compression ratio
IP	injection pressure, bar
IMEP	indicated mean effective pressure, bar
ASTM	American society for testing and materials
bTDC	before top dead center

CO	carbon monoxide
SOx	oxides of sulphur
PM	particulate matter
BTE	brake thermal efficiency, %
BP	brake power, kW
4S	four stroke
BMEP	brake mean effective pressure, bar
ITE	indicated thermal efficiency, %
CR	compression ratio
InP	indicated power, kw

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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