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Environmental exhaust emissions reduction and performance improvement analysis of biodiesel operated diesel engine performance using operating parameters

Silambarasan Rajendran[1,4]*, Boopathi Duraisamy[2], Elangovan Murugesan[3], Chander Prakash[4] and Awadhesh Chandramauli[5]
[1]Research Fellow, Faculty of Engineering & Technology, Shinawatra University, Thailand.
[1] Department of Mechanical Engineering, Annapoorana Engineering College, Salem, Tamil Nadu, India.
[1]Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamil Nadu, India.
[2]Department of Automobile Engineering, SRM Institute of Science and Technology, Chengalpattu, 603203, TamilNadu, India.
[3]Department of Mechanical Engineering, Sri Manakula Vinayagar Engineering College, Puducherry, 605107, India.
[4]University Centre For Research and Development, Chandigarh University, Mohali, Punjab, 140413, India.
[5] Department of Civil Engineering, Uttaranchal Institute of Technology, Uttaranchal University, Uttarakhand, 248007.
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*to whom all correspondence should be addressed: e-mail: simbu2explore@gmail.com
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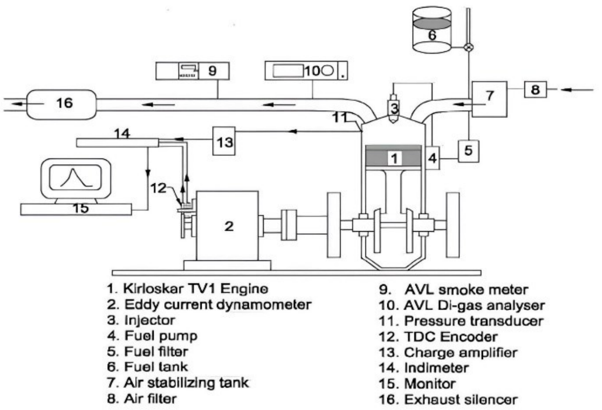
Graphical abstract



Abstract

The present investigation aims to study the performance and emission characteristics of a CI DI diesel engine using biodiesel blends derived from Jatropha seed feedstock. Four blends, namely B25, B50, B75, and B100, are employed as fuels to run the diesel engine at a rated speed of 1500 rpm, and their performance and emission characteristics are determined under different operating conditions in the first phase. The blend B25 of JME is found to be the optimum blend, and the optimum compression ratio is found to be 18.5.The optimum blend exhibits better performance in terms of brake specific fuel consumption (BSFC) and brake thermal efficiency (BTHE), along with a decline in the emissions of carbon monoxide (CO) and hydrocarbons (HC), except for the emission of nitrogen oxides (NO_X) at the optimum compression ratio of 18.5. At maximum load, with a compression ratio of 18.5, the optimum blend results in better BSFC and BTHE, which are 0.255 kg/kW-hr and 31.87%, respectively.

Keywords: Jatropha biodiesel, diesel engine, biodiesel blends, compression ratio, operational parameters

1. Introduction

Jatropha biodiesel is a renewable biofuel made from the seeds of the jatropha plant, mainly grown in tropical regions. Despite its promise as an alternative to fossil fuels, it faces several challenges. Firstly, the jatropha plant produces low oil yields compared to other biofuel crops, leading to high production costs. Secondly, the quality of jatropha biodiesel can vary, potentially affecting engine performance and emissions. Thirdly, it is currently more expensive to produce than fossil fuels or other biofuels due to the low yields and the cost of maintaining plantations. Furthermore, the cultivation of jatropha plantations for biodiesel production can cause land-use conflicts, deforestation, and displacement of food crops and indigenous people. Technical challenges also exist, such as clogging of fuel filters and increased engine wear and tear. Finally, there are concerns about the sustainability of jatropha plantations, including soil erosion, water depletion, and negative impacts on local ecosystems and biodiversity. While jatropha biodiesel has potential as a renewable fuel source, significant challenges must be addressed to make it a viable alternative to traditional fossil fuels.

The ability of a country to withstand disruptions in energy supply depends on how secure that supply is. Most of the world's energy comes from fossil fuels, controlled by only a few countries and sold at prices that fluctuate widely, contributing to climate change. Many countries are turning to renewable energy sources to reduce environmental damage and decrease dependence on these fuels. In 2015, global primary energy consumption exceeded 150 billion gigawatt hours (Gwh), expected to increase by almost 57% in the next 40 years. Non-edible feedstocks, also known as second-generation feedstocks, are considered a viable alternative to edible feedstocks for biodiesel production. Waste seeds from plants like cotton, rubber, stone fruit, and Jatropha have become more important in this context. Jatropha seeds, which are typically discarded since humans or animals do not consume them, have a relatively high oil content of 30% by weight, which is significantly higher than soybean or sunflower seeds. Although there have been relatively few studies on biodiesel production from non-edible feedstocks, Jatropha seed oil has been found to have a high cetane number, making it a promising replacement for conventional fuel. The fatty acid composition of Jatropha seed oil includes lauric acid, myristic acid, palmitic acid, stearic acid, arachidic acid, behenic acid, hexadecenoic acid, oleic acid, and linoleic acid.It is widely recognized that fossil fuels mainly produced from microorganisms and ancient buried animals are non-renewable because they take millions of years to form (Islam *et al*. 2016). As a result, the available stocks of fossil fuels are eventually limited due to the lack of new petroleum formation (Liu *et al*. 2019). The best solution is to switch to renewable energy, which can help to reduce emissions (Lubis *et al*. 2018). Biodiesel production from edible oils is not economically feasible, so many nations have started to produce biofuels using other sources (Niaz *et al*. 2018).

There are many advantages to using renewable energy sources, including their minimal ecological impact, limitless availability, potential for domestic production, reduced reliance on international entities, and no threat to demand security (Ogunkunle *et al*. 2019). Biodiesel also has several advantages, including portability, scalability, renewability, and lower greenhouse gas emissions compared to diesel. Biodiesel has a high cetane value, which can enhance engine performance (Vardar *et al*. 2014). Many countries use different seed oils as feedstocks for biodiesel production, depending on what is readily available (Wong *et al*. 2014). Recent studies have shown that blending crude seed oil (CSO) with diesel fuel can improve fuel characteristics, combustion, and NOX emissions (Shanmugam *et al*. 2021).

2. Feedstock employed and oil extraction

In this study, Jatropha seeds are used as a source of oil, which is extracted through cleaning and shade drying. The mechanical method of extraction yields less oil than the chemical method, but the purity of the yield is higher. Figure 1 shows the seeds used as feedstock, which contain 33% oil with high density and viscosity. However, using high-viscosity oil as fuel in a diesel engine can cause injector needle sticking, so a suitable chemical process is applied to improve its properties. While there are various techniques to reduce viscosity, such as blending, pyrolysis, and emulsification, transesterification is the most efficient method and enhances biodiesel quality.

Figure 1. Test seeds employed as feedstock

Jatropha biodiesel is a renewable fuel made from the jatropha plant, with benefits that include being renewable, low in carbon emissions, locally produced, and providing potential for rural development. It is also biodegradable, versatile, and can increase energy security. Despite challenges, jatropha biodiesel has potential to become a key player in the transition to a more sustainable energy future.

3. Methanolysis

Methanolysis is a chemical process used to convert triglycerides into biodiesel and glycerol. It involves the reaction of triglycerides with an excess of methanol and a catalyst, typically sodium or potassium hydroxide. The process is relatively simple and cost-effective, as it can be performed at room temperature and atmospheric pressure. However, the need for an excess of methanol and the potential for the catalyst to react with water can increase production costs and reduce efficiency.

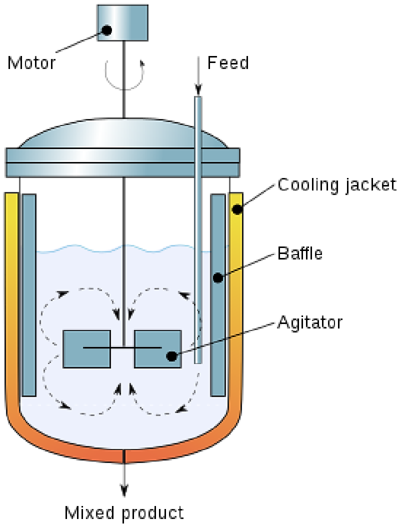


Figure 2. Schematic view of Batch reactor

Methanolysis generates glycerol as a byproduct, which must be separated and purified. In this process, methanol and powdered sodium hydroxide are used as the alcohol and catalyst, and the molar ratio of oil to methanol is maintained at 6:1. The reaction is conducted at a constant temperature of 60°C with continuous stirring at 200 rpm. The final products obtained are methyl ester of Jatropha oil (Jatropha biodiesel) and glycerol. Sodium hydroxide is preferred over potassium hydroxide due to its homogeneity and lower cost. Table 1 provides information on the physicochemical properties of Jatropha biodiesel. The biodiesel thus obtained is subjected to washing to remove the traces of unreacted methanol and then heated to 100^{0}C to remove the presence of water particles.

Table 1. Physicochemical properties of JME

Sl. No.	Property	JME
1	Density (kg. mm^{-3})	8589
2	Kinematic viscosity (40^{0}C) (mm^2 S^{-1})	3.526
3	Flash Point (^{0}C)	105
4	Fire Point (^{0}C)	117
5	Calorific Value (kJ/kg)	37119
6	Specific Gravity	0.895
7	Cetane Number	53

4. Description of the test engine

In the current investigation, the objective was to determine the impact of biodiesel blends on the performance and emissions of a single-cylinder diesel engine with direct injection, water cooling, and compression ignition. To carry out this study, a specific engine was selected and utilized as a test platform for evaluating the aforementioned factors. The test engine was kept at a constant rotational speed of 1500 revolutions per minute (rpm) throughout the experiment. The load applied to the engine was systematically increased from zero to the maximum in increments of 20%.

Figure 3. Photographic view of the test engine

The engine was equipped with essential tools and equiJMEnt, including a dynamometer, an exhaust gas analyzer, a smoke meter, and a data acquisition system. These tools and equiJMEnt helped measure and record the engine's vital parameters, such as power output, fuel consumption, exhaust gas temperature, emissions, and other relevant data. The exhaust gas analyzer was used to determine the concentrations of gases like carbon monoxide (CO), nitrogen oxides (NOx), and hydrocarbons (HC) emitted from the engine during the test.

The engine's performance and emissions were also monitored and recorded using the data acquisition system. This system helped collect and analyze data related to the engine's operational parameters, such as speed, fuel flow rate, temperature, and other relevant factors. A photograph of the test engine used in the experiment was captured and is shown in Figure 3.

The test engine hasa dynamometer, exhaust gas analyzer, smoke meter, and data acquisition system. The engine load varies from zero to maximum in 20% increments.

5. Experimental methodology

This experiment initially tested both the standard fuel and biodiesel blend at a fixed compression ratio (CR) of 17.5 to determine which fuel performed better based on its performance and emission characteristics. Once the optimal fuel was identified, further tests were conducted to evaluate its performance and emission attributes at three different compression ratios (16.5, 17.5, and 18.5). However, the injection pressure (IP) and injection timing (IT) were kept constant at 210 bar and 270 CA bTDC, respectively. After conducting tests at the different compression ratios, it was found that the optimal fuel performed best at a compression ratio of 18.5, it was designated as the optimal operating parameter or optimal CR. Finally, the readings obtained at the optimal operating parameter were compared to the base-line fuel operated under the standard operating condition of CR 17.5, IP 210 bar, and IT 270CAbTDC.

6. Result and discussion

The previous section presented the comparison between the conventional fuel operating at standard compression ratio (CR 17.5) and the optimal blend B25 JME operated at the optimal operating parameter (compression ratio 18.5). This comparison involved evaluating both fuels' performance and emission attributes at maximum load.

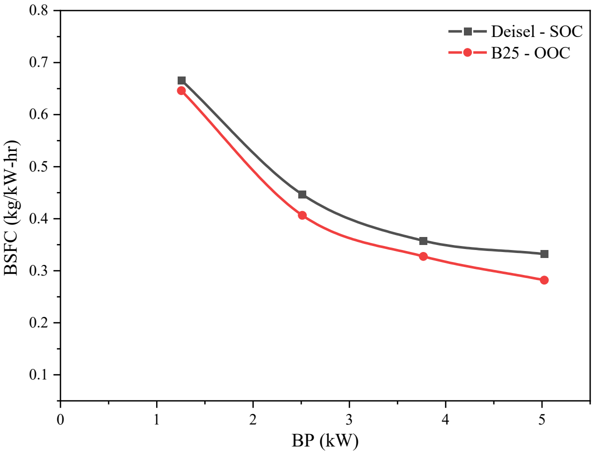


Figure 4. Variation of BSFC with BP

6.1. *Brake specific fuel consumption (BSFC)*

BSFC, or brake-specific fuel consumption, is the fuel an engine consumes to produce a unit of power. The graph shows that as the BP, or brake power, increases, the BSFC also increases. This is because biodiesel blends have a higher density than conventional fuel, resulting in a higher fuel consumption rate to produce the same amount of power. Figure 4 provides a visual representation of the correlation between BP and BSFC.

Conventional fuel has a better BSFC than the optimal fuel, as it has a higher density and calorific value. At a standard CR of 17.5, the BSFC values for conventional and optimal fuel are 0.256 and 0.279 kg/kW-hr, respectively. The BSFC value for the optimal fuel at the optimal CR of 18.5 is 0.255 kg/kW-hr, which is slightly lower than the BSFC value at the standard CR. An increase in CR results in a decrease in BSFC for the optimal fuel, with a reduction of 8.6% observed between the standard CR and the optimal CR.

6.2. Brake thermal efficiency (BTHE)

The graph clearly shows that the conventional fuel outperformed the biodiesel blend B25 in terms of BTHE, likely due to its higher calorific value and lower density. Figure 5 depicts the correlation between BTHE and BP. The optimal fuel had lower BTHE than conventional fuel due to its higher density and lower calorific value.

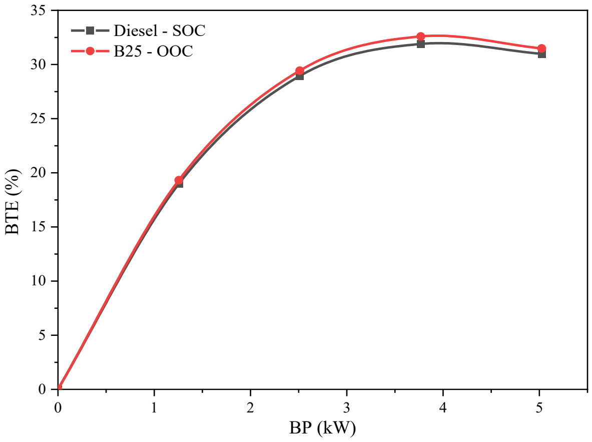


Figure 5. Variation of BTHE with BP

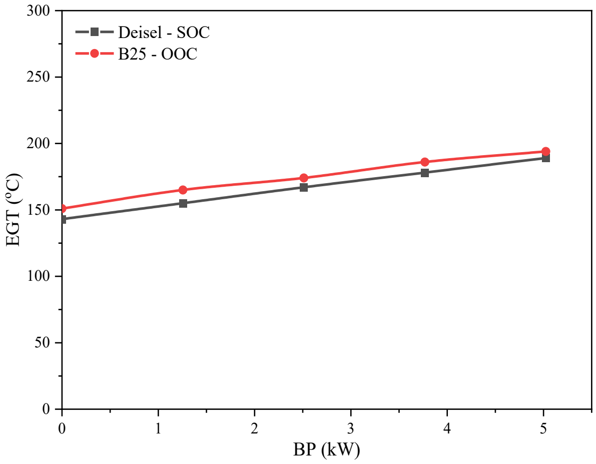


Figure 6. Variation of EGT with BP

At maximum load, the BTHE values for conventional and optimal fuel at standard CR were 31.44% and 31.46%, respectively. Increasing the CR to 18.5 improved BTHE to 31.87%, a 1.2% increase compared to the standard CR of 17.5.

6.3. Exhaust gas temperature (EGT)

In conclusion, the presence of excess oxygen in biodiesel blends has positively impacted combustion rate and reduced exhaust gas temperature (EGT) compared to conventional fuel. Figure 6 displays the correlation between EGT and BP. The slower combustion rate associated with increased wall wetting is the primary factor contributing to the higher EGT of conventional fuel. At CR 17.5 and CR 18.5, the EGT of optimal fuel is 3180C and 3110C, respectively, whereas for conventional fuel, it is 3210C at CR 17.5. An increase in CR has resulted in a 2.2% reduction in EGT for optimal fuel.

6.4. Smoke density (SD)

In summary, the biodiesel and its blends exhibited lower smoke emission compared to conventional fuel, which can be attributed to the presence of oxygen molecules that enhance the combustion rate. Figure 7 illustrates the correlation between SD and BP. The slower combustion rate of conventional fuel resulted in higher smoke emission than the optimal fuel. At standard CR 17.5, the smoke emission of conventional fuel and optimal fuel were 50.62 HSU and 49.02 HSU, respectively. Furthermore, an increase in CR for optimal fuel to 18.5 resulted in a 4% reduction in smoke emission, with a value of 47.28 HSU.

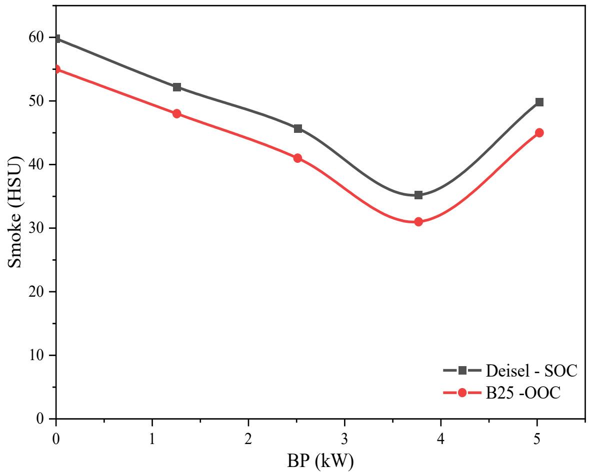


Figure 7. Variation of SD with BP

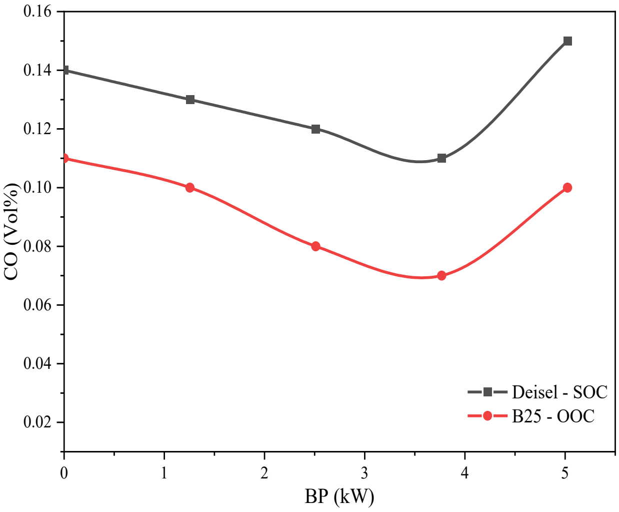


Figure 8. Variation of CO emission with BP

6.5. Emission of carbon monoxide (CO)

The presence of oxygen molecules in biodiesel blends not only enhances combustion, but also the rate of oxidation, leading to a decrease in CO emissions when compared to conventional fuel. Figure 8 shows the correlation between CO emissions and BP. Due to the increased oxidation rate, the optimal fuel produced less CO emissions at both CR 17.5 and CR 18.5 compared to conventional fuel. Increasing the CR further decreased CO emissions by 2.1%. At maximum load, the CO emissions of optimal fuel at CR 17.5 and CR 18.5 were found to be 0.095% and 0.093% (by volume), respectively, while for conventional fuel at CR 17.5, it was found to be 0.1%.

6.6. Emission of hydrocarbon (HC)

Using biodiesel blends as fuel leads to fewer unburnt particles near the crevice region and significantly reduces wall wetting. Additionally, at all load levels, the biodiesel blends produce less hydrocarbon (HC) emissions than conventional fuel. Figure 9 illustrates the correlation between HC emission and BP. Similarly to CO emission, the optimal fuel also results in lower HC emission than conventional fuel. At the standard compression ratio of 17.5, conventional fuel emits 58 ppm of HC. On the other hand, the optimal fuel at standard and optimal CR emit 55 and 49 ppm of HC, respectively. The graph shows that increased CR leads to an 11% decrease in HC emission.

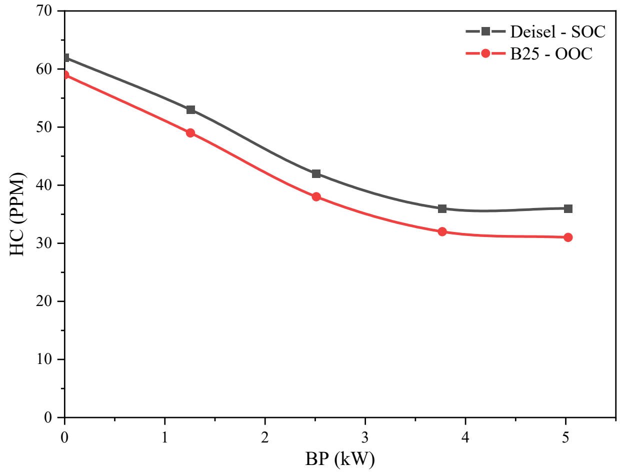


Figure 9. Variation of HC emission with BP

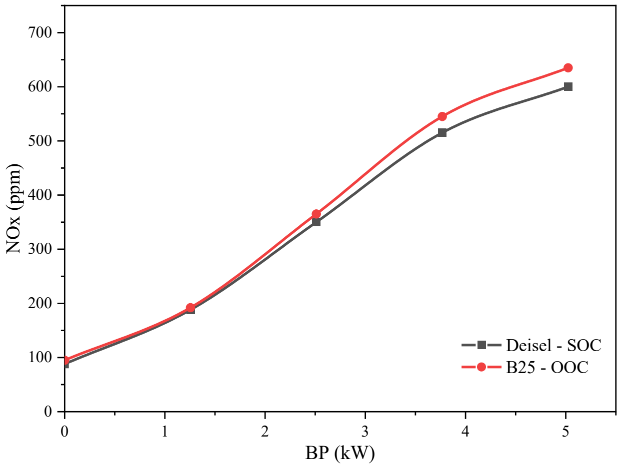


Figure 10. Variation of NO$_X$ emission with BP

6.7. Emission of nitrous oxide (NO$_X$)

The graph indicates that using biodiesel blend B25 led to higher NO$_X$ emissionsthan conventional fuel. The excess oxygen and high inline temperature facilitated the formation of NO$_X$ emissions. Figure 10 illustrates the correlation between NO$_X$ emission and BP. The increased inline temperature due to the rise in CR and the presence of oxygen molecules increased the emission of NOX compared to standard CR. The optimal fuel resulted in higher NO$_X$ emissions than the conventional fuel. At optimum CR 18.5, the NO$_X$ emission produced by optimal fuel was 1012 ppm, 2.37% higher than that at standard CR 17.5 (988 ppm).

In comparison, conventional fuel produced lower NO$_X$ emissions. At a standard CR 17.5, the conventional fuel produced 970 ppm of NO$_X$ emission, 1.82% lower than the optimal fuel at standard CR and 4.15% lower than the optimal fuel at optimum CR 18.5. B30 biodiesel fuel significantly increased NO$_X$ emissions while decreasing CO emissions.

The presence of oxygen molecules and a higher inline temperature due to an increase in compression ratio (CR) has resulted in the increased emission of NO$_X$compared to standard CR. At an optimum CR of 18.5, the NO$_X$ emission of the optimum fuel was 1012 ppm, which is 2.37% higher than that at a standard CR of 17.5 (988 ppm). The conventional fuel resulted in lower NO$_X$ emission than the optimum fuel, with the emission at standard CR 17.5 being 970 ppm, which is 1.82% less than the optimum fuel at standard CR and 4.15% less than the optimum fuel at optimum CR 18.5. B30 biodiesel fuel significantly increased NO$_X$emissions while decreasing CO emissions.

7. Conclusion

Apart from NOx emissions, the optimum fuel produced lower tail emissions. Additionally, the BSFC and BTHE of the optimum fuel were comparable to those of the conventional fuel, even at the standard CR. Increasing the CR to 18.5 enhanced the BTHE and NO$_X$ emissions by 1.2% and 4.15%, respectively, while reducing CO and HC emissions by 2.1% and 11%, respectively. Although the optimum fuel exhibited lower EGT and SD than the conventional fuel at standard CR 17.5, increasing the CR to 18.5 further reduced the EGT and SD by 2.2% and 4%, respectively, compared to those at CR 17.5.

Nomenclature

JME	Jatropha oil methyl ester,
CR	compression ratio,
IP	injection pressure,
IT	injection timing,
BP	brake power,
BSFC	brake specific fuel consumption,
BTHE	brake thermal efficiency,
CO	carbon monoxide,
HC	hydrocarbon,
NO$_X$	nitrous oxide

SOP	standard operating condition/parameter,
OOP	optimum operating condition/parameter.

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