Experimental Study on the Effect of Compression Ratio Variation on Performance, Combustion, and Emission Characteristics of Diesel Engines using Jatropha Biodiesel Blends

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Abstract

Limited fossil fuel reserves led to a focus on alternative fuels for combustion engines. Several studies reported optimal (20%) of biodiesel blend for utility in compression ignition engines. Existing research offers limited insights into how varying compression ratios (VCR) affect engine performance when jatropha biodiesel blends. This study investigates the influence of three compression ratios (15:1, 16:1, and 17:1) on the performance, combustion and emission characteristics of compression ignition engines fueled with a 20% jatropha biodiesel-diesel blend (JB20) under different loading conditions with a constant speed of 1500 rpm at injection pressure of 210 bar and injection timing of 230 bTDC. Jatropha biodiesel was produced from jatropha seed oil following two step transesterification process using methanol, sulphuric acid and sodium hydroxide and thus produced biodiesel was characterized by ASTM and Fourier-transform infrared spectroscopy (FTIR) to conform the desirable properties. The experimental results confirms that the performance, combustion and emissions properties improved to increase in compression ratio (CR) for both test fuels. It is found that increase in CR increases the Brake Thermal Efficiency (BTE) by 9.6%, Mechanical efficiency (ME) by 5.5%, Net Heat Release (NHR) by 17%, Peak Cylinder Pressure (PCP) by 20%, and reduces Specific fuel Consumption (SFC) by 11%, Exhaust Gas Temperature (EGT) by 17% with increase in CR from 15 to 17 for JB20 at 3.k kW brake power (BP). Also JB20 shows reduction in emissions of hydrocarbon, carbon monoxide and smoke opacity to be 9.5%, 14% and 31% compared to diesel. Thus inferred that JB20 fuel performed well at high compression ration without any design modifications.

Keywords: *Jatropha biodiesel, Compression ratio, Diesel engine, Performance characteristics, combustion characteristics, Emission characteristics*

1. Introduction

The depletion of petroleum reserves, escalating oil prices, and the environmental threats posed by exhaust emissions and global warming have intensified global efforts to develop alternative, non-petroleum fuels for engines. The primary cause of this issue is the heavy reliance on fossil fuels which account for nearly 80% of all energy consumption worldwide (Cherwoo et al., 2023). In response to these pressing challenges of climate change and fossil fuel depletion, there is a clear imperative to transition energy dependence from fossil fuels to renewable sources for diesel engines (Xiao et al., 2019). Biodiesel emerges as a viable, eco-friendly, low-sulfur, and non-toxic renewable fuel that can be utilized in compression ignition (CI) engines without any modification [3, 4, 5]. Biodiesel is a renewable fuel derived from biological sources such as vegetable oils, animal fats, or recycled greases. It consists of long-chain fatty acid esters and is produced through a process called transesterification, where fats or oils react with an alcohol to form esters and glycerol (Demirbas, 2009). Among the more than 350 known oil-producing plants, a limited number of edible oils, including soybean, palm, sunflower, safflower, cottonseed, rapeseed, and peanut oils, have been identified as promising alternatives to fossil fuels (Abdulla et al., 2011). However, as concerns mount regarding competition for food, land, and water resources in the production of first-generation bioenergy crops, attention has shifted towards second-generation feedstocks sourced from non- edible oil plants like Jatropha, mahua, and castor. These alternatives have garnered significant interest due to their adaptability, even thriving in adverse climatic and soil conditions prevalent in arid and semi-arid regions. Moreover, they possess a remarkably high oil content ranging between 63.2 % and 66.4 %, surpassing that of soybean (18.6 %), linseed (33.3 %), and palm kernel (44.6 %) (Ruatpuia et al., 2024). Jatropha curcas offers several advantages over other sources: it emits a pleasant or neutral odor, blends easily with diesel fuel, exhibits rapid growth, has high seed productivity, and thrives in tropical and subtropical regions (Koh & Tinia, 2011; Ruatpuia et al., 2024). Notably, Jatropha curcas oil shares similar properties with diesel fuel, allowing blends of up to 40–50% with diesel to be used in engines without modifications (Kumar et al., 2015). Jatropha curcas thrives in tropical and subtropical regions, typically between latitudes 30°N and 35°S, and at altitudes ranging from 0 to 500 meters above sea level. This succulent shrub is deciduous, shedding its leaves during dry seasons, and possesses deep roots that enhance its adaptability to semi-arid conditions. It can survive with as little as 250 to 300 mm of annual rainfall. Nepal's climatic conditions, weather patterns, annual precipitation, altitudes, and soil characteristics are favorable for Jatropha cultivation (Dralami, 2018). Integrating Jatropha curcas cultivation and biodiesel production could significantly reduce Nepal's reliance on petroleum imports and lower greenhouse gas emissions. In the fiscal year 2023/24, Nepal imported petroleum products worth approximately NPR 354 billion, accounting for 18.87% of the country's total imports (*Import And Sales*, n.d.) .

Several studies have investigated the performance, combustion, and emission characteristics of Jatropha biodiesel in compression ignition engines. Most of research studies concluded that, in existing engine design parameters operating, a 20% blend of biodiesel with diesel works considerable reduction in emission like NOx and CO and nearly same brake thermal efficiency and higher specific fuel consumption for high load (Mohamed Musthafa et al., 2019; Pramanik, 2003; Rakopoulos et al., 2006). Bhatta et al. experimentally investigated the performance and emission characteristics of various Jatropha biodiesel blends and reported that blends up to 20% (JB20) reduced smoke opacity by 31.6% compared to diesel, achieved an 18% higher mechanical efficiency with JB15 at high loads, and exhibited a 19% higher brake specific fuel consumption at lower loads, confirming their potential as a viable alternative fuel for diesel engines without requiring modifications (Bhatta et al., n.d.-a). Similarly, Devkota and Adhikari studies the performance of a compression ignition engine using waste cooking oil biodiesel blends (up to 20% biodiesel) and found to be comparable to diesel fuel in terms of brake power and brake mean effective pressure, with slightly higher indicated power and specific fuel consumption, highlighting its potential as a sustainable alternative fuel(Devkota & Adhikari, 2021). Deepak et al. investigated the effects of preheating Jatropha oil to lower its viscosity and observed that unheated Jatropha oil exhibited higher brake specific fuel consumption (BSFC) and exhaust gas temperatures compared to both diesel and preheated Jatropha oil. They found that thermal efficiency was lower for unheated Jatropha oil, while emissions of CO_2, CO, hydrocarbons, and smoke opacity were higher relative to diesel. Notably, preheating Jatropha oil brought these emission levels closer to those of diesel (Agarwal & Agarwal, 2007) . Muralidharan et al. (Muralidharan et al., 2011) investigated the use of biodiesel blends in CI engines and reported that brake thermal efficiency (BTE) increases with engine load, while brake specific fuel consumption (BSFC) decreases. This can be due to the presence of oxygen in biodiesel enhances combustion efficiency and lowers exhaust emissions. Multiple studies have demonstrated that biodiesel-diesel blends reduce particulate matter (PM), smoke opacity, hydrocarbon (HC), and carbon monoxide (CO) emissions, although they contribute to increased nitrogen oxide (NOx) formation due to higher in-cylinder temperatures (Mahmood et al., 2024; Sivaramakrishnan, 2018; Xue et al., 2011). Similarly, Schumacher et al. (Schumacher et al., 1996) identified B20 as an optimal biodiesel blend in terms of emissions and noted that retarding fuel injection timing can help mitigate NOx emissions to some extent, while PM, HC, and CO levels remain largely unchanged. However, this emission reduction often comes at the expense of power, torque, and specific fuel consumption (SFC). Additionally, Ramadhas et al. (Ramadhas et al., 2005) tested B20 in urban bus fleets and found that fuel consumption was 2-5% higher compared to pure diesel.

Several researchers concluded that engine design parameters viz. Compression ratio (CR), injection timing and injection pressure (IP) significantly influences the combustion, performance, and emission characteristics of compression ignition (CI) engines fueled with biodiesel blends. The extensive research has been done on biodiesel utilization at fixed CR (Bhatta et al., n.d.-b) (*View of Experimental Investigation on the Performance of a CI Engine Fueled with Waste Cooking Oil Biodiesel Blends*, n.d.). But few scattered studies explored the utilization of biodiesel by varying engine CR. For instance, an experimental investigation revealed that at a CR of 18:1, the brake thermal efficiency (BTE) of a CI engine fueled with a 20% palm biodiesel blend (B20) reached 33.8%, compared to 28.9% at a CR of 16:1. Additionally, emissions of hydrocarbons (HC), carbon monoxide (CO), and smoke opacity decreased by 47.8%, 41.0%, and 35.7%, respectively, with the increase in CR from 16:1 to 18:1, although nitrogen oxides (NOx) emissions increased by 41.1% (Rosha et al., 2019). Similarly, another study by B. De and R. S. Panua focusing on Jatropha oil-diesel blends in a direct injection variable compression ratio engine found that increasing the CR improved engine performance. Specifically, at a CR of 18:1, blends containing up to 30% Jatropha oil exhibited thermal efficiency and emission parameters such as NOx, HC, and CO comparable to those of pure diesel fuel. This suggests that blends with up to 30% Jatropha oil can be effectively used as alternative fuels without necessitating engine modifications, (De & Panua, 2016; Mohamed Musthafa et al., 2019). Koirala et al. carried out engine test under different loading conditions with a constant speed of 1500 RPM and two different compression ratios ie. 17.5:1 and 15:1. Among all the test fuels at both compression ratios, engine performance, and combustion properties improved with an increase in the zinc oxide concentration. Particularly, test fuel with 75 ppm of zinc oxide additive at a 17.5 compression ratio resulted in an overall improvement at full load like brake thermal efficiency increased by 2.45%, brake specific fuel consumption reduced by 5.45%, cylinder peak pressure increased by 3.27% and net heat release increased by 10.32% in comparison with commercial diesel (Koirala et al., 2023). MEL Kassaby et al. (El-Kassaby & Nemit-Allah, 2013) investigated the impact of compression ratio (CR) and biodiesel blend ratio on engine performance using diesel and biodiesel blends. The study evaluated B10, B20, B30, and B50 at CRs of 14, 16, and 18. The test results showed that brake specific fuel consumption (BSFC) decreased as CR increased, though higher biodiesel concentrations led to relatively higher BSFC values. Increasing the CR from 14 to 18 resulted in brake thermal efficiency (BTE) improvements of 18.39%, 27.48%, 18.5%, and 19.82% for B10, B20, B30, and B50, respectively. Additionally, carbon monoxide (CO) and hydrocarbon (HC) emissions decreased, while nitrogen oxide (NOx) emissions increased with higher CR across all biodiesel blends. Similarly, B. N. Kale et al. (Kale et al., 2022) examined engine performance and emissions at compression ratios ranging from 15.5 to 17.5, using various blends of microalgae biodiesel with diesel. For comparison, the results were benchmarked against conventional diesel fuel. The experimental findings indicated that brake thermal efficiency (BTE) increased with higher compression ratios for all biodiesel blends, while brake specific fuel consumption (BSFC) decreased as compression ratio increased. Furthermore, as CR was raised from 15.5 to 17.5, hydrocarbon (HC) and carbon monoxide (CO) emissions were significantly reduced, whereas nitrogen oxide (NOx) emissions showed a notable increase.

The literature survey indicates that the biodiesel-diesel blend ratio and compression ratio (CR) significantly influence engine performance and emissions. While extensive research has been conducted on biodiesel blends in CI engines at a fixed CR, studies on variable compression ratio (VCR) engines using biodiesel blends remain limited. Furthermore, the impact of CR on combustion, performance, and emissions for non-edible biodiesel blends, such as Jatropha biodiesel (JB20), has not been thoroughly explored. Increasing the CR can enhance fuel efficiency and reduce harmful emissions, making it a crucial parameter in biodiesel utilization. Given the sustainability and feasibility of Jatropha biodiesel as an alternative fuel, this study investigates the effect of compression ratio variation on the performance, combustion, and emission characteristics of a CI engine fueled with JB20 and pure diesel. The findings aim to bridge the research gap and provide insights into the optimal CR for improved efficiency and reduced emissions, particularly in applications such as power generation in remote and rural areas. This study will be particularly useful for countries like Nepal, which relies entirely on imported petroleum for its transportation sector. By optimizing compression ratio for Jatropha biodiesel (JB20) blends, this research could contribute to reducing fuel dependency, enhancing energy security, and promoting sustainable biodiesel adoption as an alternative fuel source.

2. Materials and Methods

2.1 Biodiesel Production and Blending

Jatropha seed oil was sourced from the Alternative Energy Promotion Center (AEPC) in Lalitpur and then biodiesel was then prepared through a transesterification process at the laboratory facilities of Acme Engineering College, Sitapaila. The oil's initial acid value measured 8.64 mg KOH/g, corresponding to a free fatty acid (FFA) content of 4.32%, which exceeds the optimal threshold for direct base-catalyzed transesterification. To address this, a two-step transesterification process was employed as reported in most of the literatures, (Cai et al., 2015; Mendow et al., 2011; Review on Biodiesel Production by Two-Step Catalytic Conversion - ScienceDirect, n.d.; Thoai et al., 2019; Wang et al., 2010). Fig. 1 shows the photographic images of various steps for biodiesel production and preparation. First, acid-catalyzed esterification was conducted by heating 250 g of crude Jatropha oil to 60°C. A mixture of methanol (30% w/w relative to the oil) and concentrated sulfuric acid (0.75% w/w) was preheated to 50°C and then gradually introduced into the oil under continuous stirring at 300 rpm for one hour. After allowing the mixture to settle for two hours at room temperature (27°C), impurities were removed, reducing the FFA content to below 1%. Subsequently, base-catalyzed transesterification was performed by heating the pre-treated oil to 50°C and adding a solution of potassium hydroxide (1.5% w/w) and methanol (20% w/w), also preheated to 50°C. The reaction mixture was maintained at 65°C with stirring at 400 rpm for 90 minutes. After settling overnight, the upper methyl ester layer was separated and washed multiple times with warm distilled water until clear. Finally, the biodiesel was heated to 110°C for four hours to eliminate residual moisture, yielding purified Fatty Acid Methyl Ester (FAME) biodiesel. The final product was blended with conventional diesel in a 20% biodiesel and 80% diesel ratio (JB20) for experimental evaluation.

Fig. 40. Transesterification process of biodiesel preparation

2.2 Testing of thermo-physical properties of blended biodiesel

To evaluate the thermo-physical properties of Jatropha biodiesel blend (JB20), a 500 ml sample was prepared and analyzed at the Central Laboratory of Nepal Oil Corporation, Sinamangal, Kathmandu, and the Bioenergy Lab of the National Academy of Science and Technology (NAST), Khumaltar, Lalitpur. Fourier Transform Infrared Spectroscopy (FTIR) was conducted at the Department of Plant Resources, Thapathali, Kathmandu to confirm the conversion of Jatropha oil into biodiesel by identifying characteristic functional groups such as ester (C=O) and hydroxyl (O-H) stretching vibrations within the 4000–400 cm^{-1} wavelength range. Additionally, key thermo-physical properties were examined, including density, kinematic viscosity, flash point, pour point, calorific value, cetane number, cetane index, and copper strip corrosion test were invested adopting ASTM test conventions, to assess the fuel's suitability for diesel engine applications. These parameters are critical in determining the combustion efficiency, ignition quality, and overall performance of biodiesel in comparison to conventional diesel fuel.

2.3 Experimental Test Rig

The experimental investigation was conducted using a Kirloskar-made, four-stroke, vertical, water-cooled diesel engine with variable compression ratio (VCR) capabilities as in Fig. 2(a). The setup, calibrated and installed by Apex Innovations, Sangli, Maharashtra, India, included an eddy current dynamometer for loading, a graduated burette for fuel consumption measurement (recording the time for 10 ml fuel consumption), and an orifice meter with a U-tube manometer to monitor air intake. Six thermocouples were strategically placed to measure temperatures at various inlet and outlet points with parameters such as temperature, engine speed, and load displayed on a centralized panel board. The geometry specifications of CI engine test rig are given in Table 1.

Table 9 Test engine Specifications

Parameter	Specifications
Product	Variable CR Engine test rig, 1-cylinder, 4-stroke
Engine	Make Kirloskar, Type 1 cylinder, 4 stroke Diesel, water-cooled, power 3.5 kW at 1500 rpm, stroke 110 mm, bore 87.5 mm. 661 cc, CR 17.5, Modified to VCR engine CR range 12 to 18
Dynamometer	Water-cooled, eddy current
Calorimeter	Pipe in pipe
Maximum speed	1500 rpm
Temperature Sensor	RTD type, PT 100 as well as Thermocouple, K type
Load Sensor	Load cell, type strain gauge Range 0-50 kg,
Software	"ICEngineSoft" Engine performance analysis

2.4 Mechanism of compression ratio variation

The engine's compression ratio was adjustable, allowing for testing at CRs of 15, 16, and 17. Adjustments involved loosening six vertical Allen bolts on the slanting chamber block, using a spanner to set the desired CR as indicated on the CR marker, and then retightening the bolts (Kirloskar Engine Test Rig Specifications).This mechanism facilitated the evaluation of engine performance and combustion characteristics under varying compression ratios as show in Fig. 2 (d).

2.5 Emission testing

Exhaust gas emissions were analyzed using a Horiba Automotive Emission Analyzer with technical speciation shown in Table 2, which measures concentrations of carbon monoxide (CO), carbon dioxide (CO_2), and hydrocarbons (HC). This facilitated a comparative analysis of emissions between the JB20 biodiesel blend and pure diesel. Additionally, smoke opacity measurements were conducted under full-throttle conditions using a Bosch Emission Analyzer tester (EAM) on the VAAP engine. This comprehensive approach ensured an accurate assessment of the emission characteristics of both fuel types.

Table 10 Exhaust gas analyzer specification

Parameter	Description
Model	MEXA-584L
Application	Exhaust gases in idling status from gasoline vehicle, LPG vehicle
Confirmed Standards	ISO 3930/OIML R99 (2000)
Measured parameters	Range
HC	0 ppm to 10000 ppm
CO	0.00 % vol to 20.00 % vol
CO2	0.00 % vol to 20.00 % vol
LAMBDA	0.00 to 9.99

2.6 Experimental Test Procedure

The experimental evaluation of the Kirloskar diesel engine began by operating it on pure diesel fuel at a rated steady speed of 1500 rpm, with a varying compression ratios (CRs) of 15, 16, and 17 and injection pressure of 210 bar and the injection timing was kept constant at manufacturers default value of 230 bTDC, under varying load ranged from no load to 12 kg with a step increase of 3 kg at rated speed for 15 to 20 minutes, ensuring stable operating conditions similar to that of the test setup used by Gavhane et al. (Gavhane et al., 2020) and B. N. Kale et al.(Kale et al., 2022).

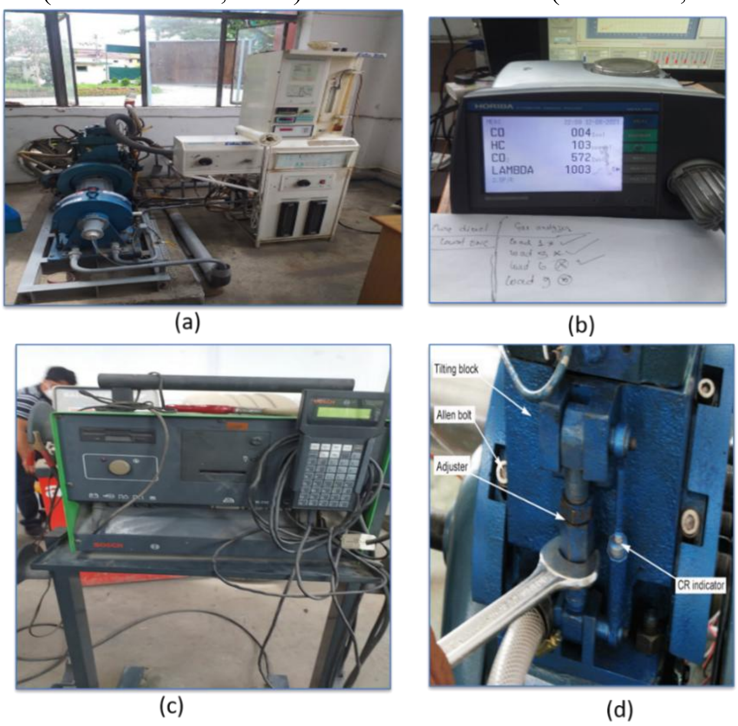

Fig. 41. Various photographic images of the experimental setup. (a) Experimental test rig; (b) Horiba Automotive emission analyzer; (c) Bosch emission analyzer; (d)Mechanism of compression ratio variation

During this period, the engine's coolant was maintained at approximately 1 atm pressure, as indicated by the integrated pressure gauge. After stabilization, the engine was fueled with a 20% Jatropha biodiesel blend (JB20) and tested across compression ratios (CRs) of 15, 16, and 17. For each CR setting, the engine was subjected to incremental loads of 1 kg, 3 kg, 6 kg, 9 kg, and 12 kg using an eddy current dynamometer, while maintaining the constant speed of 1500 rpm. Performance and combustion parameters including brake thermal efficiency, specific fuel consumption, heat balance, cylinder pressure, and net heat release were recorded using the engine's data acquisition system. Fuel consumption was precisely measured by recording the volume of fuel consumed over a 60-second interval using a burette and stopwatch setup. Simultaneously, with similar condition at same time exhaust emissions at tailpipe were analyzed using a Horiba Automotive Emission Analyzer to measure concentrations of carbon monoxide (CO), carbon dioxide (CO_2), and hydrocarbons (HC). Additionally, exhaust gas opacity was assessed using a Bosch Emissions Analyzer on the VAAP engine under full-throttle conditions for both diesel and JB20 fuels.

3. Result and discussion

3.1 FTIR and fuel Property

Fig. 3. represents the FTIR spectrum of diesel and JB20, with key absorption peaks that confirm the presence of biodiesel-specific functional groups. Peaks at 2924.09 cm^{-1} and 2854.65 cm^{-1} correspond to methylene ($-CH_2-$) stretching, while 1759.08 cm^{-1} indicates the carbonyl (C=O) stretch of esters, confirming successful transesterification. Additional peaks at 1527.62 cm^{-1}, 1442.75 cm^{-1}, 1381.03 cm^{-1}, and 1172.72 cm^{-1} represent nitro group stretching, aromatic C-C bonds, alkane vibrations, and ester C-O bonds, respectively. These results validate the conversion of Jatropha oil into biodiesel and align with findings from similar studies (Bukkarapu & Krishnasamy, 2021),(O'donnell et al., 2013) and the ASTM test are also summarized in Table 3 which shows that JB20 has slightly higher density and lower calorific value compared to diesel, consistent with biodiesel characteristics. However, all measured properties remain within acceptable limits, indicating that JB20 is a viable alternative fuel for diesel engines.

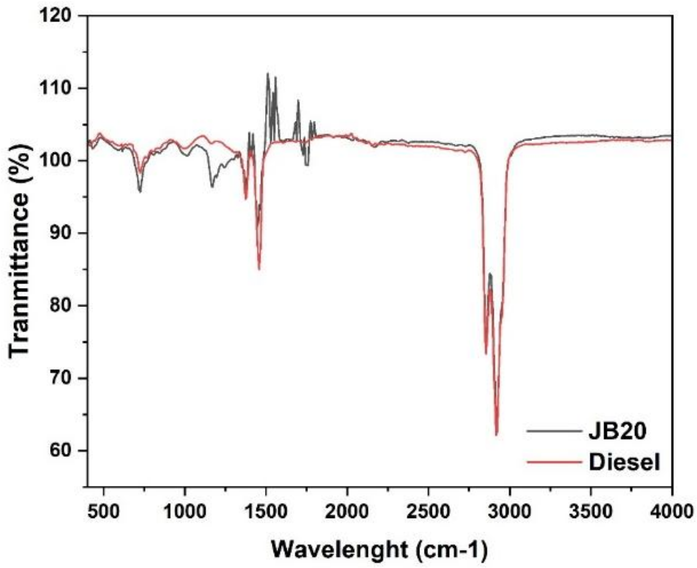

Fig. 42. FTIR analysis of JB20 with Diesel

Table 11 Physicochemical properties of JB20 and diesel

Fuel Property	JB20	Diesel	ASTM Standards
Density at 15°C, kg/m^3	840.6	810	D1298
Cetane Number	55	45	D613

Calorific value, KJ/kg	39750	43200	D2382
Kinematic viscosity at 40 ºC, Cst	2.32	2.2	D445
Flash Point (Minimum), º C	55.5^{0}C	52	D3828
Pour Point, ^{0}C	-6	-11	D97
Total Acid Number, mgKOH/g	0.42	0.2	D664
Total Water Content, ppm	566.8	200	D6304
Distillation Recovery at 360ºC	97% by vol.	95% by vol, min.	D86
Copper Strip Corrosion	1A	Not worse than 1	D130

3.2 Performance Analysis

3.2.1 Brake thermal efficiency

The variation of Brake Thermal Efficiency (BTE) with Brake Power (BP) for diesel and JB20 biodiesel blends at different compression ratios (CR) is illustrated in Fig. 4. For diesel fuel, the highest BTE of 30.58% was achieved at CR17 under the maximum Brake Power of 3.50 kW, followed by CR16 (30.04%) and CR15 (29.84%). At full load 2.5% increase in BTE with increase in CR form 15 to 17 because as higher CR enhances combustion pressure and temperature, optimizing energy conversion (Ramalingam et al., 2014). Similarly, for JB20, BTE also rises with BP, but the maximum efficiency is observed at CR 17 (28.81%), which is lower than diesel. The oxygen content in biodiesel improves combustion, but its higher viscosity and lower calorific value which cause a slight efficiency drop compared to diesel.

At low BP (0.3 kW), JB20 exhibits significantly lower BTE than diesel due to poor atomization and incomplete combustion. However, as BP increases, JB20's performance improves, showing a smaller efficiency gap with diesel. At full load, increasing the compression ratio from 15 to 17 results in a more substantial improvement of about 9.61% for JB20.

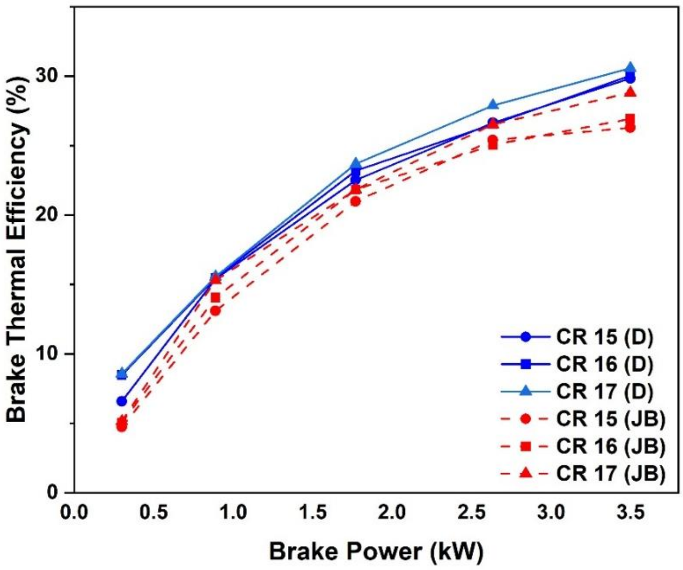

Fig. 43 BTE variation with BP at CR 15, 16 and 17

3.2.2 Specific fuel Consumption

Fig. 5 reveals the SFC decreased sharply with increase in BP from 0.3 kW to 3.5 kW. This is because as brake power increases, the resulting rise in cylinder pressure and temperature shortens the ignition delay period, leading to more efficient combustion and a corresponding decrease in specific fuel consumption. For diesel, SFC decreases consistent with increasing BP, reaching a minimum of 0.288 kg/kWh at 3.50 kW for CR 16 and CR 17 because with increase in compression ratio leads to reduction in dilution charge by residual gases and results in better BTE and lower SFC. Similarly, JB20 biodiesel exhibits higher SFC at low BP (e.g., 1.54 kg/kWh at CR 15 for 0.30 kW), attributed to its higher viscosity and lower calorific value, which impair atomization and combustion completeness. However, at high BP (3.50 kW), biodiesel at CR 17 achieves near-diesel efficiency (0.292 kg/kWh), demonstrating its viability in high-load applications with proper CR tuning.

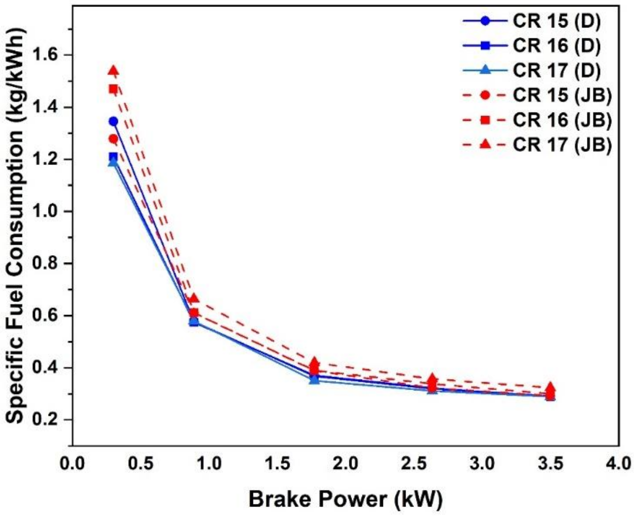

Fig. 44 SFC variation with BP for CR 15, 16 and 17

3.2.3 Mechanical Efficiency

Fig. 6 shows mechanical efficiency (ME) of diesel and JB20 biodiesel across varying compression ratios (CR). The increased in ME with rising brake power (BP) is due to reduced relative mechanical losses at higher loads. For diesel, ME at BP 3.5 kW increases from 75.74% at CR 15 to 78.95% at CR 16 (a 4.2% increase), but then slightly decreases to 79.31% at CR 17 (a 0.5% increase from CR 16, 4.7% increase from CR 15). At lower loads, such as BP 0.3 kW, ME increases from 17.02% at CR 15 to 22.78% at CR 17 (a 33.8 % increase), showing a more consistent upward trend.

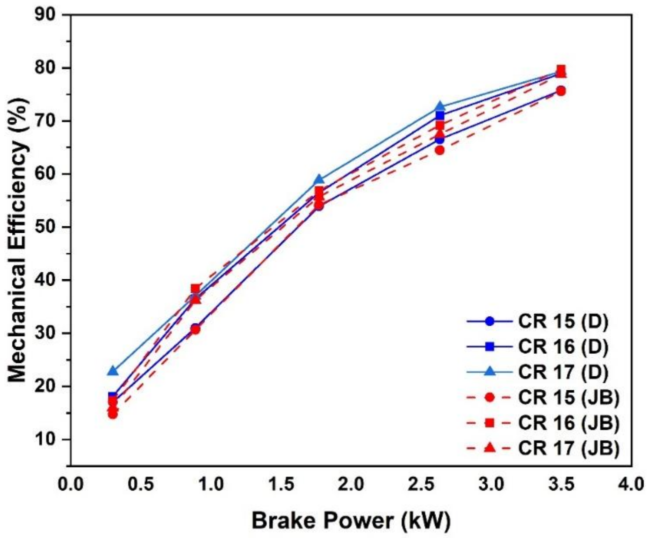

Fig. 45 ME variation with BP for CR 15, 16 and 17

Similarly, for JB20, ME at BP 3.5 kW increases from 75.56% at CR 15 to 79.72% at CR 16 ie. a 5.5% increase, but then slightly decreases to 78.73% at CR 17 which is a 1.2% decrease from CR 16, though still a 4.2% increase from CR 15. At lower loads, such as BP 0.3 kW, ME increases from 14.74%

at CR 15 to 17.36% at CR 16 with a 17.8% increase, but then decreases to 15.99% at CR 17 of 7.9% decrease from CR 16, though still an 8.5% increase from CR 15. The decrease at CR 17 suggests potential limitations at higher CRs, possibly due to poor atomization and increased resistance within engine components (Senta & Patel, 2019)(Vasudeva et al., 2016). Also, at high loads, JB20's ME decrease at CR 17 (1.2%) is larger than diesel's (0.5% increase), likely due to JB20's higher viscosity increasing FP and its lower energy content limiting IP gains.

3.3 Combustion analysis

3.3.1 Exhaust Gas Temperature

The Exhaust Gas Temperature (EGT) determines the temperature of the in-cylinder gases present during the exhaust stroke of the engine. Fig. 7 shows that EGT increases with BP at conditions because as load increases the amount of fuel burnt increases which liberates more heat inside the cylinder. It is also observed that EGT gradually decreases with increasing in CR. For example, for diesel EGT reduced by 6% at full load but for JB20 reduction in EGT was 17% with an increase in CR from 15 to 17. This reduction in EGT is more significant for JB20, suggesting that biodiesel combustion benefits more from increased CR in terms of reduced heat loss. Also, in case of diesel, EGT increases with BP, peaking at 338°C under high load (3.5 kW) at CR15, but decreases slightly at higher CRs (e.g., 318°C at CR17).

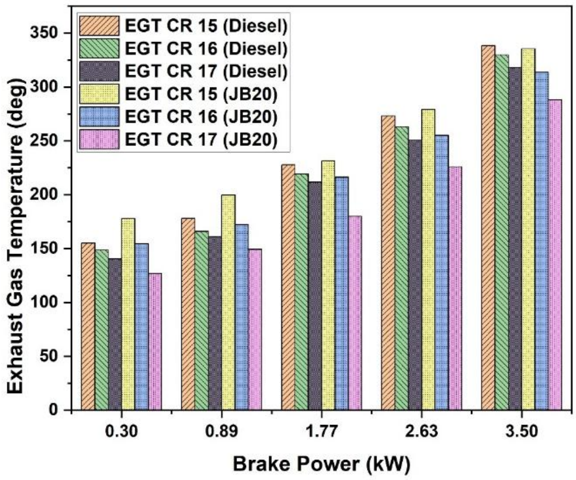

Fig. 46 EGT variation with BP for CR 15, 16 and 17

This reduction at elevated CRs is attributed to improved thermal efficiency, where higher in-cylinder pressures convert more combustion energy into useful work rather than exhaust heat (Ramalingam et al., 2014). In contrast, biodiesel blends like JB20 typically exhibit higher EGTs than diesel at lower BP. For instance, at 0.3 kW and CR15, JB20 may show an EGT of 178°C compared to diesel's 155°C. This increase is often attributed to biodiesel's oxygenated structure, which enhances combustion completeness in lean mixtures. However, at higher BP, biodiesel's EGT may lag behind that of diesel (e.g., 335 °C at CR15) due to its lower calorific value and higher viscosity, which can impair atomization and combustion efficiency. These results agree with studies which have reported that biodiesel blends tend to have higher EGTs than diesel, especially at lower compression ratios, due to increased heat loss and decreased thermal efficiency (Dhinesh et al., 2016; Renish et al., 2022).

3.3.2 Peak Cylinder Pressure

Peak cylinder pressure (PCP) is the highest pressure inside the engine during combustion. Higher PCP values typically reflect stronger combustion events, leading to improved thermal efficiency and power output. Fig. 8 shows for diesel, PCP increases consistently with both CR and brake power (BP), maximum at 67.25 bar (3.5 kW, CR17), compared to 60.39 bar at CR15 which is 11.3% increase. This rise is attributed to higher CR amplifying in-cylinder pressures and temperatures, enhancing combustion intensity and energy release (Kumar & Dixit, 2014). Biodiesel follows a similar trend, achieving its highest PCP at CR17 (63.13 bar at 3.5 kW), though lagging 6.5 % behind diesel at same condition due to its lower energy density, shorter ignition delay (ID) and lower calorific value. Notably, at low loads (0.3 kW), biodiesel at CR17 (45.91 bar) nearly matches diesel's PCP (46.09 bar), suggesting efficient combustion initiation despite biodiesel's viscosity limitations due to better atomization at high CR. Biodiesel, while less efficient, demonstrates competitive performance at CR17, benefiting from its higher cetane number and oxygenated structure that promotes complete combustion under high compression (Hosamani & Katti, 2018). Fig. 9 shows the pressure distribution with the crank angle for diesel and JB20 fuels (15 to 117 CR) at 3.5kW brake power which shows that the cylinder gas pressure of JB20 follows similar trends as diesel in all CR. The cylinder pressure increased with an increase in CR for both fuels.

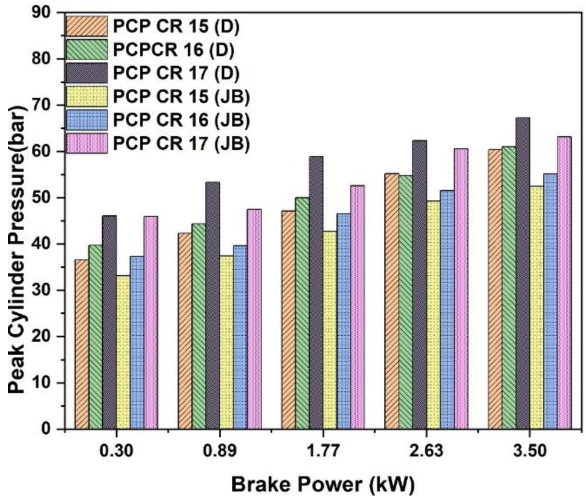

Fig. 47 PCP variation with BP for CR 15, 16 and 17

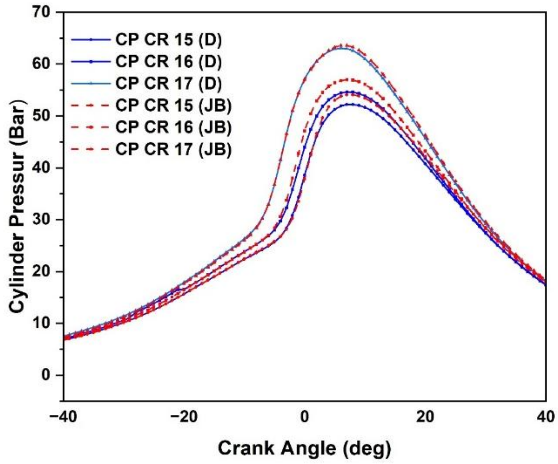

Fig. 48 CP variation with Crank angle for CR 15, 16 and 17

3.3.3. Net Heat Release Rate

The net heat release rate (NHRR) shows how quickly energy is released during combustion. The major parameters that influence the NHR are the fuel viscosity, the calorific value of fuel, the cetane number and ID period (Fattah et al., 2018). The variation in the NHR inside the cylinder with crank position at full load and the variation of NHRR with BP at various CR (15, 16 and 17) is shown in Fig. 10 and 11. At CR17, diesel achieves the highest NHRR across all loads, peaking at 64.06 J/deg (3.5 kW), compared to 59.62 J/deg at CR16 and 46.44 J/deg at CR15. This trend aligns with the principle that higher CRs elevate in-cylinder pressure and temperature, enhancing combustion efficiency and energy release (Aydın, 2020) . However, at low BP (0.3 kW), CR17 yields a lower NHRR (23.33 J/deg) than CR15 (17.04 J/deg), likely due to incomplete combustion from excessive heat dissipation at partial loads. For biodiesel (JB), CR16 optimizes performance, with NHRR rising from 18.63 J/deg (0.3 kW) to 46.71 J/deg (3.5 kW). The oxygenated structure of biodiesel improves combustion stability at CR16, partially offsetting its lower calorific value. Biodiesel's NHRR lags behind diesel at all CRs, particularly at low BP (e.g., 15.77 J/deg vs. 17.04 J/deg at 0.3 kW, CR15), attributed to its higher viscosity delaying atomization and ignition. However, at high BP (3.5 kW), biodiesel narrows the gap, achieving 46.97 J/deg at CR17 compared to diesel's 64.06 J/deg. This improvement stems from sustained combustion facilitated by biodiesel's oxygen content, which enhances late-cycle burning.

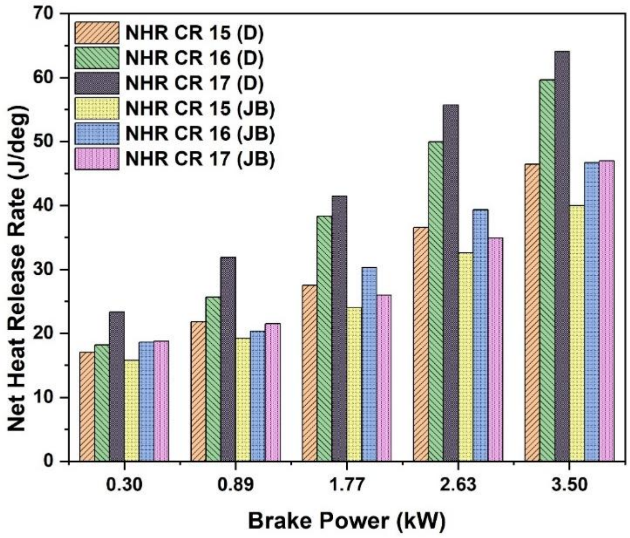

Fig. 49 NHRR variation with BP for CR 15, 16 and 17

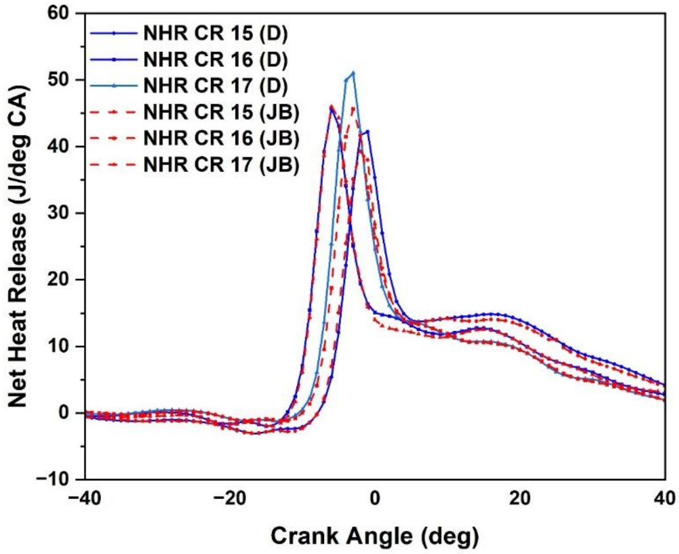

Fig. 50. NHR variation with Crank angle for CR 16, 16 and 17

3.4 Emission analysis

The exhaust emissions are measured with gas analyzer and smoke meter for diesel and JB20. The CO and unburned HC emissions for diesel and JB20 decrease with an increase in CR from 15 to 17 (Hosamani & Katti, 2018). So for emissions analysis, only CR 17 is considered in this study.

3.4.1 HC emission

Fig. 12 shows the variation of HC emission with BP for diesel and JB20 fuels at CR 17. The Hydrocarbon emission of diesel was found to be higher than Jatropha biodiesel. At low load HC of diesel and JB20 were 115 ppm and 95 ppm respectively but HC emission increases at higher load for all fuels. This is due to lack of oxygen resulting from engine operation at a higher equivalent ratio which can be shown in SFC plot also.

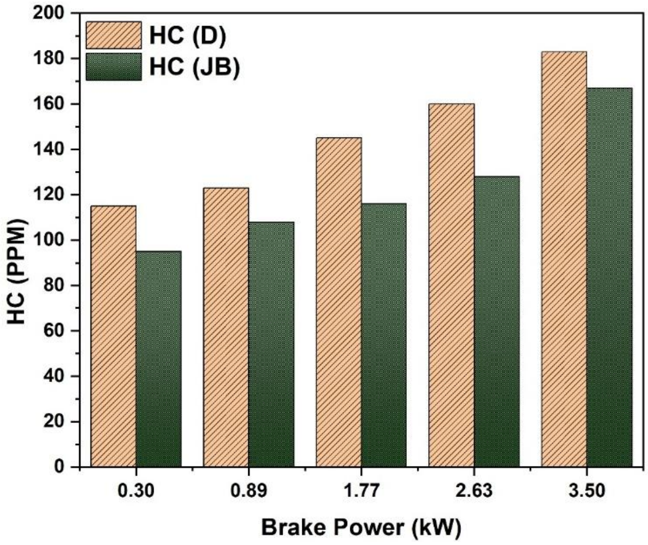

Fig. 51. HC variation with BP at 17 CR

3.4.2 CO emission

The variation of carbon monoxide (CO) emissions with load is illustrated in the Fig. 13. Initially, CO emissions decrease from low load to moderate load but then rise at higher loads. At lower loads, CO emissions from Jatropha biodiesel are comparable to those of diesel fuel. However, as the load increases, CO emissions from Jatropha biodiesel (JB20) are lower than those from diesel.

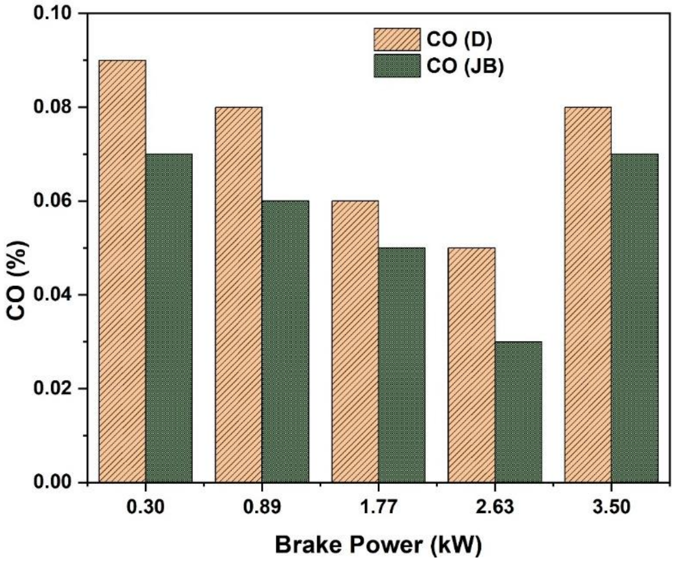

Fig. 52 CO variation with BP for CR 17

This reduction is attributed to the oxygenated nature of biodiesel, which enhances combustion efficiency by promoting more complete oxidation of the fuel. For diesel and JB20, CO emissions were recorded as 0.09 vol% and 0.07 vol%, respectively, at low load. Also at higher loads, JB20 consistently demonstrated lower CO emissions. The reduction in CO emissions with Jatropha biodiesel can be attributed to its inherent oxygen content, which facilitates better combustion and minimizes the formation of incomplete combustion byproducts (Chauhan et al., 2010).

4.3 Smoke Opacity

One of the major challenges in diesel engines is smoke opacity. The Fig. 14 illustrates the variation in smoke opacity between diesel fuel and jatropha biodiesel blend (JB20). It is observed that the smoke density decreases as the proportion of biodiesel increases compared to pure diesel. This reduction in smoke emissions indicates more complete combustion of the fuel, primarily due to the presence of additional oxygen in the biodiesel itself. At full throttle conditions, jatropha biodiesel blends exhibit a 31.68% reduction in smoke opacity compared to diesel fuel. This reduction occurs because biodiesel contains inherent oxygen molecules, which enhance the combustion process by promoting better oxidation of the fuel. In contrast, diesel fuel lacks this additional oxygen and tends to produce higher levels of soot due to incomplete combustion. Furthermore, biodiesel has a lower aromatic content, which reduces the formation of carbon-rich soot precursors. As a result, the improved combustion characteristics of biodiesel contribute to lower smoke emissions.

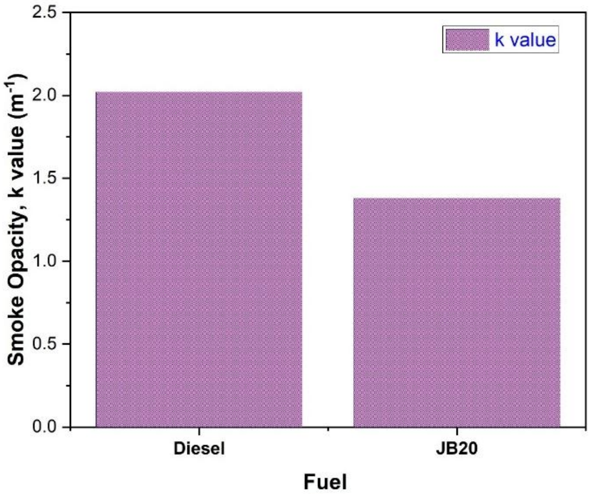

Fig. 53. Smoke Opacity

4. Conclusions

The combustion, performance and emissions characteristics of a single cylinder DI engine filled with jatropha biodiesel (JB20) blends for different compression ratio compared by commercial diesel and the study draws following conclusions:

- Due to higher Free Fatty Acid concentration on jatropha seed oil two step transesterification process was selected for maximum yield of biodiesel.
- The physio thermal properties of biodiesel were compared with ASTM standard and are found within limits. JB20 has high cetane number but lower calorific value. Also, density and viscosity were higher than that of diesel. The engine operates smoothly, did not show any starting problem and no audible knock while running on jatropha biodiesel blend.
- The performance characteristics were enhanced with increasing in CR. At full load BTE increased 9.6% and 2.5% for JB20 and Diesel with increasing CR from 15 to 17, at low load SFC decrease by 4% for Diesel and 11% for JB20 and ME increase by 5.5 % for JB20 and 4.4% for diesel with increasing in CR from 15 to 17.
- There is no unusual combustion behavior for JB20 at different CRS. The EGT, PCP and NHR were comparable with diesel fuel at all conditions. EGT decreases with increase in CR for both test fuels. For JB20, EGT decrease by 17% and for diesel by 6% at full load. The JB20 exhibit's the same trend of pressure rise with a variation of crank angle as diesel. The PCP was found higher in diesel compared to JB20 and with increase in CR from 15 to 17, the PCP increase by 11.1% for diesel and by 20% for JB20 at full load and the maximum Increase in HR for diesel was 37.97% and for JB20 was 17% at high load.
- Emissions parameters like, HC, CO and smoke opacity decrease with the use of JB20 biodiesel by 9.5%, 14% and 31% respectively.

NOx emissions play a significant role in assessing the suitability of biodiesel as an alternative fuel. However, due to the unavailability of a NOx emission analyzer in the experimental laboratory, this study was unable to include NOx measurements. This limitation restricts a comprehensive analysis of the emission characteristics of the diesel engine operating on Jatropha biodiesel blends. Future studies should consider including NOx testing to provide a more complete assessment of engine emissions under varying compression ratios.

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