

Exploring the Synergistic Potential of Fuzzy Methodology Based Multi-Objective Optimisation in the Performance, Emission and Stability Trade-Off Study of an Existing Conventional CRDI Diesel Engine Powered With *Schleichera Oleosa* Biodiesel/Diesel Blends

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Abstract

The common rail direct injection diesel engine is an advanced combustion method to use alternative fuel with higher fuel economy and, reduce NO_x and soot emissions. The present paper aims to investigate the influence of *Schleichera oleosa* oil (Kusum oil) on CRDI engine performance. This paper deals with the study on the influence of the *Schleichera oleosa* oil (Kusum oil) when added to diesel blend (B25, B50, B75, B100) on the emission, combustion and performance characteristics of a four stroke, single cylinder, common rail direct injection diesel engine working at a fixed speed and varying operating scenarios. The mixture of kusum oil blend and air is ignited by diesel through fuel injector into the combustion chamber at the end of compression stroke. It is noticed from the experimental results that, with an increase of kusum oil in the blends, ignition delay (ID) increases and start of combustion (SOC) is retarded. It is noticed that B100 shows the highest ID and low in-cylinder pressure; however, B50 shows the lowest ID compared to higher fractions of biodiesel blends. An increase in biodiesel proportion reduces NO_x and smoke opacity but, HC and CO emissions increase compared to pure diesel mode engine. B25 shows the highest brake thermal efficiency (12%) compared to remaining biodiesel blends and baseline diesel engine. For finding optimum blend for lower BSFC, NO_x , UHC and higher BTE Taguchi method is considered. Then Fuzzy rule is considered for two inputs parameters (load and fuel blend) and single output variable (MPCI). By considering multi-objective optimization technique, it is found that B25 blend has optimal MPCI value (0.68) which makes it best blend for enhancing the performance and lowering the emissions.

1. Introduction

Transportation and power generation sectors in current days are majorly dependent on the compression ignition engines, due to their excellent fuel economy and low exhaust emissions (CO, UHC). But these compression ignition (CI) engines possess higher risks to the environment, being able to produce higher emission (NO_x) and particulates [Yoon et al.2011]. On the contrary, the extinguishing petroleum reserves and strict norms observed worldwide has a put a remarkable question on the practicality of diesel engines in the upcoming times. As a result, finding an alternative fuel source with increased efficiency and lesser emission factors is the main purpose of research. The current challenges mainly at low load [Selim et al.2001; Selim et al. 2004; Yuvenda et al.2020] in diesel dual fuel (DDF) engine were rising exhaust emissions and degradation of BTE. Due to the substitution relationship, it is tough to lower the levels of nitrogen oxides (NO_x) and particulate matter (PM) emissions in a diesel engine. To reduce these emissions a few advanced combustion modes have been developed [Yao et al.2009; Reitz et al.2015]. NO_x and PM emission can be reduced by dual fuel combustion mode due to its advantages of favourable mixture distribution, less utilization of diesel fuel, etc, which is considered as the most promising approaches for diesel engines [Korakianitis et al.2011; Wang et al.2016; Demirbas et al. 2002]. Hence, to ensure ignition inside the combustion chamber, the ignition has to be created by some other source. Throughout the years, few researchers have explored the CNG combustion in a CI engine with pilot diesel.

It was found by the [Hallquist et al. 2013], that diesel-fuelled buses emitted more particulates compared to the buses running on CNG. [Serrano et al. 2013] and [Karabektas et al.2014] found hydrocarbon (HC) and carbon monoxide (CO) emissions are higher in dual fuel, irrespective of the loads together with lower NO_x emissions; high loads are exceptional. It was found by [Liu et al.2013] PM and NO_x emissions were reduced by the diesel fuel mode, however, pilot fuel quantity increased with PM emissions. [Yang et al. 2015] studied over the parameters of combustion performance of diesel pilot, injection of CNG, and low load emissions on the dual fuel engine. The common rail type engine with a turbocharger was used in a diesel dual fuel (DDF) engine. To prevail optimal parameters the pressure and timing of CNG and pilot injection were varied. It was detailed that combustion process (thermal efficiency, Heat Release Rate and cylinder pressure) could be improved and emission of HC and CO gases are reduced by new timing of diesel pilot injection, enhanced pressure of diesel pilot injection, and delayed timing of CNG injection. Combustion performance and exhaust gas on DDF engine at low load affect both the parameters of diesel fuel and CNG injection. Also, to reduce the volumetric efficiency [Tarabet et al.2014] the amount of pure air entering in the cylinder is reduced by the existence of CNG fuel; the standard engine using single fuel [kalsi et al.2016] holds more amount of oxygen [Tarabet et al.2014] as compared to CNG using cylinders [Chaichan et al.2014; Abdelal et al.2012] and the reaction between the air and diesel is also interfered.

According to [Yoshimoto et al.2012], the effect of cetane number is very crucial in the study of dual-fuel operation (pilot fuel) and reported that the BTE and IMEP were impacted negatively in case of fuels having cetane number more than 45. [Selim et al.2003] and [Tomita et al.2002], have studied individually and concluded that to increase thermal efficiency and to reduce NO_x emission under CNG-diesel combination of fuel, moderate exhaust gas circulation should be used. Ethanol was used as the additive in the pilot fuel by [Paul at al.2014]. But combustion and emissions improvement were limited by the poor miscibility of ethanol in diesel. n-butanol can be mixed with diesel in any proportion due to its high cetane value as compared to ethanol making it highly suitable as a pilot fuel additive. Rubber seed methyl ester (RSME) with hydrogen was used in dual fuel mode by [Geo et al.2008] for observation and reported that smoke emission and brake thermal efficiency (BTE) are significantly improved. Honge biodiesel was used by [Banapurmath et al.2009] in pilot operation to observe a hike in CO and HC emission and a decrease in NO_x emission and BTE. CNG and hydrogen dual-fuel operation using rapeseed methyl ester as pilot fuel was experimented by [Korakiantis et al. 2011] and studies suggested that with the usage of hydrogen the NO_x increases, and with the usage of CNG, HC emission increases. [Yoon et al.2011] studied on dual-fuel combustion of biogas and biodiesel's exhaust emission and combustion characteristics. They concluded that with the mentioned fuel combinations, along with the reduction of soot emission and with the superior performance the NO_x emissions are reduced. [Ghadikolaei et al.2019] studied the formation of particulate matter and chemical properties of ternary fuel blend of ethanol-biodiesel-diesel and reported that this type of blend has a better impact on DPFE (diesel particulate filter efficiency) and the obtained value of metal elements was 0.7% and ions 1.9% and diesel particulate matter was 85.8%. [Aydin and Yesilyurt.2020] studied the performance characteristics while using the DEE (diethyl ether) and cottonseed oil blend in the diesel engine at various load conditions and was observed that thermal

efficiency was decreased by 17.39% and brake specific fuel consumption shown an increase of 29.15%. [Dogan et al.2020] studied about the diesel engine characteristics which incorporates alcohol as an oxygenated fuel by considering various parameters like sustainability, enviro-economic, exergoeconomic, exergy and energy were analysed and reported that 20% 10% and 5% 1- heptanol was added (on the basis of volume) to the pure diesel and test results show that SFC is more for 20% 1- heptanol blend of 0.221kg.kWh. [Rajasekar et al.2019] studied the impact of low viscous fuels blended with jatropha methyl ester (JOME) and reported that, minimal emission characteristics are obtained.

SOME, popularly known as Kusum oil (Schleicher Aleksa oil methyl ester) is biodiesel, that is produced by the transesterification process of the schleichera oleosa seed. It serves as an alternative to diesel which is bio-based and non-conventional. SOME chemical composition has higher oxygen levels and enables better oxidation of the fuel. It is also influential in reducing emissions and ignition delays due to its higher cetane number [Panda et al.2017; Ramachander et al.2021; Gugulothu et al.2020]. Acetylation of glycerol's three hydroxyl groups produces triglyceride Triacetin [C₉H₁₄O₆]. It is being used for the topical treatment of minor dermatophyte infections due to its fungistatic properties (based on the release of acetic acid).it has a role of antifungal drug, a food additive carrier, a food humectant, a food emulsifier, a plant metabolite, a fuel additive and a solvent as acetic acid is derived from it.

In order to improve the performance and emission in the biodiesel blended dual fuel combustion mode, SOME was blended with diesel in different compositions on common rail direct injection diesel engine. In the current study, the influence of different kusum oil blends (B25, B50, B75, B100 by volume) on CRDI engine combustion, and emissions were examined at mixed mass flow rate of biodiesel blend at constant speed and different load conditions. Optimum biodiesel blend was found for the cumulative performance of CRDI engine. The objectives of the existing work are: To investigate the effect of increase in kusum oil proportion on CRDI diesel engine combustion and emission characteristics performance at different load conditions. To reduce the cost and time for finding out the optimal operating conditions the Fuzzy based Taguchi optimisation technique which measures the certainty or uncertainty of membership of element of set is implemented.

2.materials And Methods

2.1 *Schleicher oleosa* (Kusum) Oil an Overview

Kusum oil is a native tree that is primarily found in South Asia. It is commonly referred through its scientific name as *Schleicher Oleosa*. Moreover, based on extensive study, it has identified that the seed of the tree is rich in oil, and the properties lie par with diesel fuel. The oil of the *Schleicher oleosa* seeds are dominantly extracted from its seeds using mechanical crushers. The oil has a full application in terms of medical application, hairdressing, and even as pain reliever oil in massage centres.

The oil has dominantly consisted of linoleic acid (50%), and the remaining are shared with oleic acid, stearic acid, and palmitic acid. The fatty acid composition of the oil is listed in figure 1, and the raw oil properties incomparable with the high-performance biofuels are listed in table 1. Based on the table, it

can be inferred that the *Schleichera oleosa* properties are in par with the high-performance biofuels in India. Moreover, the oil content and the calorific value are closer to more preferred biofuel (*Jatropha curcas*).

Table 1. Properties of raw *Schleichera oleosa* oil comparison with existing high-performance biofuels

Properties	Units	<i>Millettia pinnata</i>	<i>Madhuca longifolia</i>	<i>Jatropha curcas</i>	<i>Schleichera oleosa</i>
Viscosity @ 40 deg C	mm ² /s	45	35	42	40.36
Density @ 40 deg C	kg/m ³	950	925	925	860
Cetane Number	NA	55	43.5	49	47
Calorific Value	MJ/kg	37	36.2	41	38.5
Flash Point	Deg C	254	248	252	225
Oil Content Seed	wt. %	45	42	51	61

2.2 *Schleichera oleosa* oil Methyl ester Synthesis

Biodiesel is defined as mono-alkyl ester of long-chain fatty acid derived from vegetable oil (edible and non-edible) or animal fats. Biodiesel is generally produced by transesterification of triglycerides: In the presence of a strong acid or base, triglycerides react with alcohol, forming a combination of alkyl ester and glycerol fatty acids. A sequences of three consecutive and reversible reactions in which di and monoglycerides are formed as intermediates constitutes the overall process. 1 mol of a triglyceride and 3 mol of alcohol are required for the stoichiometric reaction. An excess of alcohol, however, is used to improve the yields of the alkyl esters and to allow their phase separation from the formed glycerol. The overall process for the conversion of *Schleichera oleosa* oil into *Schleichera oleosa* oil Methyl ester is graphically represented in figure 2. Reactions could be summarized as follows [Ehsan et al.2009].

- The required quantity (1 Liter) of *Schleichera oleosa* oil is taken and filtered in a reaction container.
- A stable temperature water bath is used for heating the raw oil to attain a temperature of 60 °C based on the alcohol preferred (Methanol).
- The required amount of NaOH (1-5%) and 10% of methanol (per liter of *Schleichera oleosa* oil) is mixed slowly.
- The oil and mixed solution is allowed to get reacted in a magnetic stirrer for some time (30 minutes).
- Later, the vessel is separated from the heat and is permitted to settle down all night.
- If the biodiesel obtained is slightly cloudy, then it is heated to 50°C and kept for some minutes (15 to 20 minutes) to clear the cloudiness. Finally, to get methyl ester, the biodiesel obtained is cooled and filtered with a 10-μ filter paper.

2.3 Optimization of *Schleichera oleosa* oil Methyl ester yield and the preparation of blends

Different molar proportions (Fig.3) of oil and methanol were taken, keeping the catalyst concentration 1%, reaction temperature 60 deg, and reaction time 30 minutes to be constant. It was found that maximum yield was obtained for 1:6 molar proportion of oil to methanol with a 98% yield. It has been observed from the figure that the yield percentage varies as the oil to methanol ratio increases till 1:6 and steps down slowly for 1.7 and above. It can be stated that, owing to excess alcohol, there might be a step down in the profile.

Similarly, for optimization of the situation for catalyst concentration, all the other parameters such as oil to methanol molar ratio 1:6, reaction time 30 mins, and reaction temperature 60 deg were kept constant. As presented in figure 4, it can be inferred from the picture that yield percentage varies concerning the catalyst concentration. The optimal yield percentage of 99% was obtained for 0.9% of catalyst added to the reaction. And finally, was concluded that to obtain a maximum yield, the catalyst concentration 0.9%, reaction temperature 60 deg, and reaction time 30 minutes and molar ratio of 1:6 has to be maintained.

Table 2. Physiochemical properties of test fuels [Paul et al.2014]

Property	Diesel	Raw Oil SOME	B ₁₀₀	B ₇₅	B ₅₀	B ₂₅	ASTM Standards
Density in kg/m ³	820	946	920`	773	783	796	ASTM D 4052
Kinematic Viscosity in cSt	2.9	40.36	4.7	3.24	2.41	2.39	ASTM D445
Calorific Value in MJ/kg	44.12	38.2	39.8	43.1	44.05	41.93	ASTM D5865
Cetane Number	51.3	46.4	47.1	47.1	47.4	47.4	ASTM D 613

Based on the obtained optimized biodiesel, the blends for the engine assessment was prepared as follows. Table 2 represents the physicochemical properties of the test fuel samples. The biodiesel obtained was blended with diesel fuel on a volume basis as B25% (*Schleichera oleosa* oil Methyl ester 25% and Diesel 75%), B50% (*Schleichera oleosa* oil Methyl ester 50% and Diesel 50%), B75% (*Schleichera oleosa* oil Methyl ester 75% and Diesel 25%) and B100% (*Schleichera oleosa* oil Methyl ester 100%).

2.4. Experimental Setup

The experimental setup used for this present investigation is a water-cooled four-stroke, single-cylinder DI engine operating on diesel, as shown in figure 5. The experiments were performed on a stationary, constant speed, 1-cylinder, 4-stroke, watercooled, carburetted attached CI engine (Kirloskar AV1 model). The engine has 87.5 mm bore diameter with 110 mm stroke length and 3.7 kW maximum output power for 1500 constant rpm with 17.5 CR. The total displacement of the engine was 661 cc. The experiments for different biodiesel blends were carried out at constant speed (1500 rpm), under 2.8 kW and 3.7 kW rated power of the engine. To vary the load conditions, eddy current dynamometer (0-50 kg capacity) was used. For the preparation of homogeneous charge full throttle, 500 cc Royal Enfield Micarb VM-28 carburetor was attached to the inlet manifold of the CI engine. To ignite the homogeneous charge, diesel was injected at 230 bTDC with 210 bar injection pressure. By the help of two different pressure sensors

in-cylinder pressure and fuel line pressure were measured. The inlet and outlet water temperatures, and exhaust gas temperature were measured by PT 100 type thermocouples. In this study, cooling water temperature was kept between 55-60 °C by adjusting the mass flow rate of water. The complete engine setup was computer interfaced with digital panels to record the temperatures, engine load display, orifice meter to measure air-fuel ratio, etc. "ICEnginesoft" software was used to record all pressure transducers and temperature sensor data, converted in in-cylinder pressure, fuel line pressure, mass fraction burn (MFB), PRR, HRR etc. with crank angle. 50 consecutive cycles were considered for combustion analysis. Exhaust gases like CO, CO₂, HC, NO_x and O₂ emissions were measured by INDUS five gas analyzer and smoke opacity was recorded by NETEL smoke meter. The overall engine and dynamometer specifications are listed in Table 3. Accuracies and uncertainty of measured reading are shown in Table 4. The in-cylinder pressure was measured with the help of piezo electric transducer mounted on engine cylinder head whereas HRR (heat release rate) generated during power stroke was calculated.

Table 3. Details of experimental test rig

Make and type	Kirloskar 3.7 kW vertical CRDI engine
Engine type	Automotive (Multispeed)
Stroke length	110 millimeter
Swept volume	625 cubic centimeters
Compression ratio	18.0:1
Torque/Power	30 Nm@1500 RPM, 9 bhp@2000 RPM
Injectors	Solenoid
Fuel Injection	Common rail direct injection system
Dynamometer	
Make	Power Mag
Type	Eddy current
Load measurement method	Strain Gauge
Maximum load	12-kilogram
Cooling	Water

Table 4. Accuracies and uncertainty of measured parameters

Type of Emission	Accuracy	Uncertainty (%)
NO _x Emission	±5 ppm vol	±5.41
CO emission	±0.02% vol	±0.04
HC emission	±4 ppm vol	±1.333
Smoke opacity	±1 HSU	±0.205

The test matrix for the present investigation is tabulated in table 5.

Table 5. Experimental test matrix for the fuels [Gugulothu et al.2021]

Fuel No.	Test Fuel								Short form of fuel
	Diesel, vol%				SOME, vol%				
	100%	75%	50%	25%	25%	50%	75%	100%	
1	√								D100
2		√			√				B25
3			√			√			B50
4				√			√		B75
5								√	B100

2.5. Total Uncertainty Analysis

Precise calibration with optimal atmospheric conditions is equally important while using precision measurement devices for reliability. uncertainty analysis gives a broad view of experimental repeatability by counting necessary errors during measurement. In given atmospheric conditions, the process of quantifying performance and emission parameter measurement errors due to the methodology of the experiment, observation accuracy, calibration and instrumentation employed is called the experimental uncertainty analysis. Two major components are identified with uncertainty analysis one of which is repeated measurement random variation and second is accuracy bias. The values of uncertainty are shown in table 4 for gas analyser used and performance parameters. The equation (1) shows the total uncertainty as below.

$$\Delta U = \sqrt{\left\{ \left(\frac{\partial U}{\partial x_1} \Delta X_1 \right)^2 + \left(\frac{\partial U}{\partial x_2} \Delta X_2 \right)^2 + \dots + \left(\frac{\partial U}{\partial x_n} \Delta X_n \right)^2 \right\}} \quad (1)$$

Overall uncertainty of the experiment =

$$\sqrt{(1)^2 + (0.2)^2 + (1.0)^2 + (0.2)^2 + (0.2)^2 + (0.2)^2 + (0.2)^2 + (1.0)^2 + (0.15)^2} = \pm 2.15\%$$

The evaluation of uncertainty values of each equipment was conducted, which established the experimental uncertainty (current) to be $\pm 2\%$. This value is obviously within the acceptable uncertainty range i.e., less than $\pm 5\%$.

2.6. Economic analysis comparison of biodiesel and diesel

Economic factors that affect biodiesel production can be the cost of raw material, capital, and chemicals used and also the capacity of plant and technology used. Out of these, 80% is the raw material cost, and the rest includes the cost of chemicals (catalyst and methanol) and labor [Liu et al.2013]. Estimated costs for preparing biodiesel using *Schleichera oleosa* oil and feedstock are 0.54/ltr and 0.16/ ltr US\$. These costs can be lessened if there are some ways to reuse the by-product glycerol. Also, if the feedstock is selected appropriately, the overall cost may reduce. Nowadays, since the non-food crops are popular, this can be seen as an opportunity to increase biodiesel production. Other socio-economic

factors like regional development, sustainability, agriculture with social structure, supply security can be an advantage of biodiesel over diesel and other petroleum products. The power generated by these biofuels will improve the local economy.

2.6. Fuzzy Based Taguchi Multi-Objective Optimization Technique

Optimization in general sense means maximization of desired features and minimization of undesirable factors in the process of finding the most efficient and best performing alternative under some given constraints as shown in the . Maximizing here, means maximizing the outcome or finding the best result based on some parameters. When optimization is done, there is usually a problem i.e. lack of information and time to find out the availability of information. The process of simultaneous optimization of two or more conflicting objectives based on particular constraints is known as multi-objective optimization.

Genichi Taguchi, an engineer from Japan laid down the theoretical foundations of Taguchi methods who initially worked for a telecom company called Electrical Communications Lab (ECL), a part of NT&T in 1950s. He and his team had successfully designed telephone system components better than other rivals like Bell Labs of the US after World War II. Taguchi method targets to reduce the deviation in processes by means of robust DOEs; the objective being the production of best quality product at minimal cost to the producer.

Fuzziness manifests itself commonly in real world problems like human speech recognition and handwriting character recognition. Fuzzy logic was first introduced by L. A. Zadeh in 1965. The truth values in crisp logic used by predicates or propositions always have two values, i.e. true or false which numerically corresponds to 0 or 1. But, in case of fuzzy logic, there are multivalued truth values which numerically ranging from 0 to 1 which correspond to values like partial truth, absolute truth, absolute false, very true etc [Tarabet et al.2014]. There are two major tasks to accomplish for understanding a complex problem and solving it under a fuzzy environment which are, fuzzy optimization and fuzzy modelling [Geo et al.2008]. The difference between fuzzy optimization and fuzzy modelling is that fuzzy optimization focusses on solving of the fuzzy model optimally through optimization tools and techniques based on formulation of fuzzy information in terms of possibility distribution function, their membership functions etc. while fuzzy modelling focusses on building of a suitable model based on the problem's understanding and the study of fuzzy information's. In general sense, both of these signify dissimilar processes, even if there are no specific boundaries between them. There are several factors which influence the selection of a particular approach for the fuzzy optimization problem together with decision makers preference, nature of the problem, status of the objective and its assessment.

3. Results And Discussion

3.1 Engine Behavior study

(a) Heat release rate (HRR)

The amount of heat released during the combustion cycle plays an important role in combustion analysis. Release of thermal energy during combustion (inside the cylinder) in the engine is termed as Heat Release Rate. The amount of heat released during the transition period from chemical state to thermal state can be used to define HRR, regardless of whether the combustion is premixed, rapid or controlled. In addition, ignition delay, engine knocking, flameout period can also be identified by HRR, because of high net calorific value and excellent fuel atomization. Figure 6 illustrates the variation of heat release rate with respect to crank angle for all the test fuels at different load condition. At full load condition, when compared to other blends, heat release rate of B25 is observed to be as 95 J/CA whereas in case of D100 is 70 J/CA this is due to the fact that the accumulation of diesel fuel at the primary combustion phase which is in the premixed stage. B25 blend possesses a high heat release rate of 38 J/CA (25% load), 60 J/CA (50% load), 74 J/CA (75% load) and 95 J/CA (100% load) in comparison with other diesel +SOME blends at all load conditions. The cumulative heat release rate phenomenon represents a substantial variance in ID (ignition delay period) due to excess fuel deposition in premixed combustion. It also reflects a higher heat release rate and the lowest cumulative heat release rate. Thus, here we can conclude that combustion can be improved with the use of B25 as compared to other fuels.

(b) Combustion Behaviour – Cylinder Pressure

Figure 7 brings out the cylinder pressure variation with respect to the crank angle for the base diesel fuel and diesel biodiesel blends. The pressure variation is plotted for the load ranges varying from 25% to 100% for an increment of 25%. It shows that the cylinder pressure of the biodiesel blends is always higher than diesel oil. The result obtained can be attributed owing to the presence of oxygen content in the biofuel, which enhanced the overall combustion efficiency. It has been observed that as the load increase, the cylinder pressure values increase for all the observed loads condition irrespective of the fuel samples. It can be stated owing to compensate the engine at a constant speed, and the fuel quantity is enhanced, which resulted in higher cylinder pressure. Moreover based on the detailed literature is has been reported that the reason for higher cylinder pressure for the biodiesel may vary due to the following purposes (1) viscosity variation of the biofuel that let to advanced injection timing and (2) as the variation on the result of ignition delay- typically will be higher for biodiesel blends.

Among all blends, B25 possesses the highest cylinder pressure under all reported load conditions. This could be due to optimal biodiesel- diesel blend property (high Cetane number & low auto-ignition temperature) [Hallquist et al.2013]. The presence of oxygen molecules dominated the cylinder pressure for the lower blends. In comparison, for the higher blend, the viscosity of the fuel dominates, resulting in reduced cylinder pressure as compared with the lower blends.

(c) Performance Behaviour – Brake thermal efficiency & Brake Specific Fuel Consumption

Brake thermal efficiency can be briefed up as the Input chemical energy in the form of fuel is converted to useful work output to the crankshaft. [Karaketas et al.2014]. Based on the report, it has been concluded that irrespective of the blends/fuel, as the engine load increases, the brake thermal efficiency follows an increasing profile. In contrast, the brake specific fuel consumption follows a decreasing trend. Among the

blends, B25 and B50 possesses 13% and 10% higher thermal efficiency than plain diesel in full load, respectively, as presented in figure 8. Regarding higher viscosity and the lower calorific value owing to the presence of oxygen molecule in the biodiesel blends, it is expected to have reduced thermal efficiency [Gupta et al.2020]. But it has been observed that the lower combinations have performed well in full load condition. The reason for the excellent behavior of lower biodiesel blends at higher load condition are (1) optimal viscosity and calorific value (2) dominating role of diffusion phase of combustion over the premix phase.

The quantity of fuel needed for producing one unit of energy by the engine is called Brake Specific Fuel Consumption (BSFC). When compared to conventional diesel fuel SOME blend has less calorific value and higher viscosity leading to lesser fuel droplets atomization and vaporization rate so in order to maintain the same output power, more fuel is being consumed during the operation of biodiesel blend.. So, when compared with conventional diesel fuel SOME blend uses more fuel for the operation. The BSFC becomes 0.34, 0.33 and 0.31 kg/kW-hr for B25, B50 and B75 respectively for maximum load which lead to lower consumption of fuel while producing same output power as presented in figure 9. The output parameters of the combination rely on the association between the fuel injection system and properties of fuel (high viscosity of the biodiesel, low calorific value, and oxygenation). At low load conditions, the fuel consumption is high owing to variation in the injection timing, the time for combustion occurrence, and the impact of the lubricating property of biodiesel. Whereas at high load condition, in the constant speed engine to compensate the engine load and to maintain the speed in the idle state of 1500 RPM the quantity of fuel is varied.

(d) Emission Behaviour – NO_x (Oxides of nitrogen) & Unburnt Hydrocarbon Emission

Figure 10 represents the variation of load with the oxides of nitrogen emission formation. At 100% load, due to high combustion temperature and the oxygen availability - nitrogen molecules present in fuel ionize to form. NO, which is considered to be the fundamental cause for the formation of NO_x. It is observed from the figure that as the engine load increases irrespective of the blends/fuel, the oxides of nitrogen tends to increase. The reason for the obtained pattern can be stated as the result of enhanced in-cylinder temperature owing to run the engine at an idle speed with varying load conditions. The results obtained can be stated owing to the following reasons (1) since biodiesel present in blend possesses a low heating value that decreases the cylinder temperature. (2) Owing to the lower percentage of unsaturation level in the biodiesel blend (3) because of pump line nozzle injection system, biodiesel properties such as high density, viscosity and lower compressibility results in variation of Start of Injection (SOI).

The increase in HC emission can be blamed for incomplete combustion of fuel, which is directly related to the presence of oxygen in the fuel sample. The result of the HC emission for the present investigation is represented in figure 11. Based on the study, It has been observed that, If there is less amount of oxygen in the fuel mixture, the hydrocarbons don't react completely, which results in more unburned HC.

Irrespective of the biodiesel blends, all the fuel samples follow a similar pattern of reduced HC emission as in comparison with the diesel fuel.

The reason for such an occurrence can be justified owing to the presence of oxygen molecules in the biodiesel blends. Moreover, as the load increases, it has been observed that the HC emission step down slowly, and it can be attributed as a result of high temperature inside the combustion on a prolonged operation of the engine by increasing the load condition. Based on the graph, it can be inferred that B25 and B50 had lowermost HC emission of 34%, 27% than pure diesel fuel. The optimal viscosity and the calorific value along with the presence of oxygen molecule supported the lower blends to achieve a reduced HC emission instead for higher blends even though the oxygen molecules are present in plenty, its viscosity and caloric value influenced a lot by increasing the HC emission formation.

3.2 Trade-off (BSFC- BTE- NOx)

Figure 12 represents the detrimental effects of soot and NOx are well known to everyone. They cause a plethora of respiratory illness and degrade the environment by causing global warming through smog formation. Furthermore, a fuel which is consumed in lesser quantity by the engine is one of the factors to choose a fuel; another reason being the depleting fuel reserves. Thus, to get a clearer picture, a trade-off study is required for comparing emission and performance of engines using various fuels with respect to SFC, brake thermal efficiency and NOx emission. It also gives scope for further explanation of intrinsic issues regarding the above. Figure 12 shows the 25% to 100% load trade-off for different combinations of fuel (B25, B50, B75 and B100) in comparison with D100. It can be noticed clearly that the trade-off shifts to the extreme left corner (minimum fuel consumption) from extreme right corner (maximum fuel consumption). From the graph, the B50 is seen to push the trade-off to a high-NOx emission zone and BTE with a reduction of BSFC. Biodiesel fuel operation reduces the equivalent BSFC along with NOx emission [49]. Of the other blends, biodiesel produces lesser NOx and more BTE. When the load is increased to 40%, the B50 blends the smoke opacity and equivalent-BSFC reduction is seen which is indicated through the shifting of trade-off zone near to origin [paul et al.2014].

3.3 Selection of parameters for multi objective optimization

Experimentations conducted for forty permutations in an orthogonal array arrangement of load (A) and different blends (B) used in a diesel engine are shown in Table 7, L25 [Gugulothu et al.2020]. S/N ratio considers as a parameter to solve the problem in Taguchi's method. It is the best method to define the optimum experimental arrangements to be conducted. S/N ratio can be found numerically by both the 'smaller-the-better' and 'larger-the-better' methods [Retiz et al.2015; Ashok et al.2019; Thiruvengkatachari et al.2020]. Equation (1) represents the 'larger-the-better' (value characteristic) for BTE [Imran et al.2014].

$$\text{Smaller-the-better} = S/N = -10 \text{Log} \frac{\sum_{i=1}^n \frac{1}{y_i^2}}{n} \quad (1) \text{ [Gugulothu et al.2020]}$$

Equation 2 calculates the s/n ratio of "smaller the better" (quality characteristic) for parameters like the BSFC, UHC, and NOx [Gugulothu et al.2020].

$$S/N = -10 \text{Log} \frac{\sum_{i=1}^n \frac{1}{y_i^2}}{n} \quad (2)$$

Here 'n' is the number, y measures with characteristic

Table 7. Taguchi's orthogonal array (L25)

Sl. No	A	B	BSFC (Kg/kwh)	BTE (%)	NOx (PPM)	HC (PPM)
1	0	D100	0.82	0.62	36	79
2	0	B25	0.73	0.89	18	30
3	0	B50	0.75	0.81	30	61
4	0	B75	0.76	0.72	37	65
5	0	B100	0.78	0.69	40	72
6	25	D100	0.62	14.33	48	75
7	25	B25	0.53	16.89	29	36
8	25	B50	0.55	16.63	41	58
9	25	B75	0.56	16.58	45	60
10	25	B100	0.58	15.34	50	69
11	50	D100	0.52	22.12	82	70
12	50	B25	0.42	25.87	50	40
13	50	B50	0.45	25.53	62	55
14	50	B75	0.46	24.26	78	59
15	50	B100	0.49	23.65	89	70
16	75	D100	0.43	27.23	100	71
17	75	B25	0.35	30.09	64	42
18	75	B50	0.37	29.99	86	50
19	75	B75	0.38	29	93	60
20	75	B100	0.4	28.72	110	71
21	100	D100	0.35	31.7	115	71
22	100	B25	0.29	34.04	82	48
23	100	B50	0.3	33.22	102	50
24	100	B75	0.31	33	111	60
25	100	B100	0.33	32.97	120	69

3.4 Statistical analysis

Emission and average performance response S/N ratios are calculated for different loads, and blends using the Taguchi method, following this normalization was accomplished [Gugulothu et al.2020; Panda et al.2018].

Figure 13 shows the plot between signal-to-noise response and BSFC, BTE, UHC and NOx varied with different process parameters like load and blends. The range of signal-to-noise ratio depends on engine output parameters. (0-1) represents the ideal range for smaller S/N ratios with all parameters normalized. The normalized equation is represented by equation (3).

$$X_{\text{Normalized}} = \frac{(X_i - X_{\text{Min}})}{(X_{\text{Max}} - X_{\text{Min}})} \quad (3)$$

Where, X_i indicates the signal-to-noise ratio for $i = 0, 1, 2, 3, \dots$

X_{min} and X_{max} indicates the least and extreme value of S/N ratio.

An optimum value of MPCl can be found using fuzzy study. Optimum performance and emission factor can be determined from table 8.

Table 8. Normalized value (Performance, emission, and MPCl)

Sl. No	Load (A)	Blends (B)	SN ratio (BSFC)	Normalize (BSFC)	SN ratio (BTE)	Normalize (BTE)	SN ratio (NOx)	Normalize (NOx)	SN ratio (UHC)	Normalize (UHC)	MPCl
1	0	D100	1.723	0	-4.15	0	36	-37.98	-37.95	0	0.25
2	0	B25	2.733	0.111	-1.01	0.09	18	-39.63	-29.54	1	0.53
3	0	B50	2.498	0.085	-1.83	0.066	30	-41.88	-35.70	0.267	0.31
4	0	B75	2.383	0.073	-2.85	0.037	37	-40.44	-36.25	0.201	0.30
5	0	B100	2.158	0.048	-3.22	0.026	40	-40.19	-37.14	0.095	0.26
6	25	D100	4.152	0.269	23.12	0.783	48	-44.95	-37.50	0.053	0.44
7	25	B25	5.514	0.419	24.55	0.825	29	-45.43	-31.12	0.811	0.62
8	25	B50	5.192	0.384	24.41	0.821	41	-47.6	-35.26	0.319	0.52
9	25	B75	5.036	0.366	24.39	0.820	45	-45.61	-35.56	0.284	0.53
10	25	B100	4.731	0.333	23.71	0.800	50	-45.44	-36.77	0.139	0.48
11	50	D100	5.679	0.438	26.89	0.892	82	-50.87	-36.90	0.124	0.47
12	50	B25	7.535	0.643	28.25	0.931	50	-52.68	-32.04	0.702	0.63
13	50	B50	6.935	0.577	28.14	0.928	62	-53.63	-34.80	0.373	0.54
14	50	B75	6.744	0.556	27.69	0.915	78	-53.59	-35.41	0.301	0.52
15	50	B100	6.196	0.495	27.47	0.909	89	-53.20	-36.90	0.124	0.46
16	75	D100	7.33	0.620	28.7	0.944	100	-55.43	-37.02	0.110	0.47
17	75	B25	9.118	0.819	29.56	0.969	64	-58.15	-32.46	0.652	0.63
18	75	B50	8.635	0.765	29.53	0.968	86	-58.92	-33.97	0.472	0.57
19	75	B75	8.404	0.739	29.24	0.959	93	-58.69	-35.56	0.284	0.51
20	75	B100	7.958	0.690	29.16	0.957	110	-58.34	-37.02	0.110	0.46
21	100	D100	9.118	0.819	30.02	0.982	115	-58.37	-37.02	0.110	0.50
22	100	B25	10.752	1	30.63	1	82	-60.01	-33.62	0.514	0.68
23	100	B50	10.457	0.967	30.42	0.993	102	-60.62	-33.97	0.472	0.60
24	100	B75	10.172	0.935	30.37	0.992	111	-60.53	-35.56	0.284	0.55
25	100	B100	9.629	0.875	30.36	0.992	120	-60.29	-36.77	0.139	0.50

Table 9. Fuzzy matrix (rule)

Sl.NO	BSFC	BTHE	UHC	NO _x	MPCI
1	LW	LW	LW	LW	EX LW
2	LW	LW	LW	MD	VE VE LW
3	LW	LW	MD	LW	VE VE LW
4	LW	LW	LW	HG	VE LW
5	LW	LW	HG	LW	VE LW
6	LW	LW	MD	MD	VE LW
7	LW	LW	MD	HG	LW
8	LW	LW	HG	MD	LW
9	LW	LW	HG	HG	MD
10	LW	MD	LW	LW	VE VE LW
11	LW	MD	MD	LW	VE LW
12	LW	MD	LW	MD	VE LW
13	LW	MD	MD	MD	LW
14	LW	MD	HG	LW	LW
15	LW	MD	LW	HG	LW
16	LW	MD	HG	MD	MD
17	LW	MD	MD	HG	MD
18	LW	MD	HG	HG	HG
19	LW	HG	LW	LW	VE LW
20	LW	HG	LW	MD	LW
21	LW	HG	MD	LW	LW
22	LW	HG	HG	LW	MD
23	LW	HG	LW	HG	MD
24	LW	HG	MD	MD	MD
25	LW	HG	MD	HG	HG
26	LW	HG	HG	MD	HG
27	LW	HG	HG	HG	VE HG
28	MD	LW	LW	LW	VE VE LW
29	MD	LW	LW	MD	VE LW
30	MD	LW	MD	LW	VE LW
31	MD	LW	LW	HG	LW
32	MD	LW	HG	LW	LW
33	MD	LW	MD	MD	LW
34	MD	LW	MD	HG	MD
35	MD	LW	HG	MD	MD
36	MD	LW	HG	HG	HG
37	MD	MD	LW	LW	VL
38	MD	MD	LW	MD	LW
39	MD	MD	MD	LW	LW
40	MD	MD	LW	HG	MD
41	MD	MD	HG	LW	MD

42	MD	MD	MD	MD	MD
43	MD	MD	MD	HG	HG
44	MD	MD	HG	MD	HG
45	MD	MD	HG	HG	VE HG
46	MD	HG	LW	LW	LW
47	MD	HG	LW	MD	MD
48	MD	HG	MD	LW	MD
49	MD	HG	LW	HG	HG
50	MD	HG	HG	LW	HG
51	MD	HG	MD	MD	HG
52	MD	HG	MD	HG	VE HG
53	MD	HG	HG	MD	VE HG
54	MD	HG	HG	HG	VE VE HG
55	HG	LW	LW	LW	VE LW
56	HG	LW	LW	MD	LW
57	HG	LW	MD	LW	LW
58	HG	LW	LW	HG	MD
59	HG	LW	HG	LW	MD
60	HG	LW	MD	MD	MD
61	HG	LW	MD	HG	HG
62	HG	LW	HG	MD	HG
63	HG	LW	HG	HG	VH
64	HG	MD	LW	LW	LW
65	HG	MD	LW	MD	MD
66	HG	MD	MD	LW	MD
67	HG	MD	LW	HG	HG
68	HG	MD	HG	LW	HG
69	HG	MD	MD	MD	HG
70	HG	MD	MD	HG	VE HG
71	HG	MD	HG	MD	VE HG
72	HG	MD	HG	HG	VE VE HG
73	HG	HG	LW	LW	MD
74	HG	HG	LW	MD	HG
75	HG	HG	MD	LW	HG
76	HG	HG	LW	HG	VE HG
77	HG	HG	HG	LW	VE HG
78	HG	HG	MD	MD	VE HG
79	HG	HG	MD	HG	VE VE HG
80	HG	HG	HG	MD	VE VE HG
81	HG	HG	HG	HG	EX HG

Figure 12 represents the fuzzy optimization performed for input and output variable using triangular membership function to obtain optimum MPCl. Input parameters for fuzzy optimization are taken from Unburned Hydrocarbon (UHC), NO_x (nitrogen oxides), BTE (Brake thermal efficiency) and BSFC (Brake Specific Fuel Consumption)[Gugulothu et al.2020]. The input variable is divided into low (LW), medium (MD) and high (HG) segments. MPCl is an output variable defined by nine steps viz., Extremely low (EX LW), very very low(VE VE LW), very low (VE LW), low (LW), medium (MD) and high (HG), very high(VE HG), very very high(VE VE HG), extremely high (EX HG).

Various Fuzzy rules (81) are set for input and output level of which few are shown in Figure 14 and table 9. MPCl value helps in finding the optimum process, so the process of finding the same is incorporated in the present study. For this, Taguchi method which converts the response value into an equivalent S/N ratio is opted. The variation in the response to the target value is determined by the ratio of S/N, which can be done by increasing the ratio to a peak value. In the Taguchi method, parametric positions can then be calculated by small-is-better (for UHC, BSFC, NO_x) and large-is-better (BTE)[Gugulothu et al.2020]. The response of BTE is considered to be S/N ratio for L25 orthogonal array of (A) different load and (B) different load combinations signals. Fig 15 (A, B, C, D) represents combination of various parameters and their corresponding effect on S/N ratio. For (0% load, D100) fuel, S/N ratio of BSFC is estimated as 1.723 (least among all S/N ratios) and that of BTE is estimated as 30.639 (height among all S/N ratios). For (100% load, B100) fuel case, S/N ratio of NO_x is estimated as -60.624 (least among all S/N ratios) whereas for (100% load, D100) fuel case, S/N ratio of UHC is estimated as -37.952 (least among all S/N ratios). From the data of simulations, the highest value of MPCl is found as 0.68 for the fuel combination of (100% load, B25). Final study concluded that B25 blend is optimum for full load conditions.

Conclusions

The present research work is to study the feasibility and performance of a novel bio-diesel fuelled compression ignition engine. Fuel is prepared from *Schleichera oleosa* oil (Kusum oil) and the process of synthesization is made optimum with different blends of methane-oil and use of catalyst to increase the yield to 99%. On the basis of experiments with different blends, following conclusions are drawn.

- BTE increased with load, irrespective of blend ratio. Out of all the blends considered, B25 and B50 showed an improvement of 12% and 11% respectively when compared with conventional diesel under full load condition.
- Under peak load conditions B25, B50, B75 blends showed (25, 22.5, 20) % lower BSFC than the plain diesel owing their lower density and heat content.
- NO_x emissions of B25 and B50 blends are 10% and 8% lower respectively when compared with normal diesel. Moreover, UHC emissions of B25 and B50 blends are 23% and 27% lower than the normal diesel at 100% load.

The experimental study with Taguchi- Fuzzy has drawn the following observations:

- For finding optimum blend for lower BSFC, NO_x, UHC and higher BTE Taguchi method is considered. Then Fuzzy rule is considered for two inputs parameters (load and fuel blend) and single output variable (MPCI).
- It is found that the B25 blend has optimum MPCI value (0.68) by considering multi-objective optimization strategy, which allows it the right blend to boost performance and minimise emissions.

Abbreviations

B.T.E., <i>bte</i>	Brake Thermal Efficiency
BBDC	Before Bottom Dead Center
BDC	Bottom Dead Center
BP	Brake Power
<i>Bsfc</i> , BSFC	Brake Specific Fuel Consumption
CA	Crank Angle
CHR	Cumulative Heat Release
CI	Compressed Ignition
CR	Compression Ratio
D100	Pure Petroleum Diesel
D.I.	Direct Injection
Deg.	Degree
EGT	Exhaust Gas Temperature
NHRR	Net Heat Release Rate
NDIR	Non dispersive infrared
NO _x	Oxide Of Nitrogen
O ₂	Oxygen
rpm	Revaluations Per Minute
BSFC	Specific Fuel Consumption
VCR	Variable Compression Ratio

Declarations

Author contributions

S.K.Gugulothu: Conceptualisation, methodology, writing, review and editing, J. Ramchander : Formal analysis and investigation, writing original draft and preparation.

Data Availability: All data generated or analyzed during this study are included in this article.

Compliance with ethical standards

The present study work was not conducted on human or experimental animals where national or international guidelines are used for the protection of human subjects and animal welfare.

Ethical Approval: Not applicable

Consent to participate: Not applicable

Consent for publication: We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that all the authors listed in the manuscript has been approved by all of us.

Competing interests: The authors declare that they have no competing interests.

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Figures

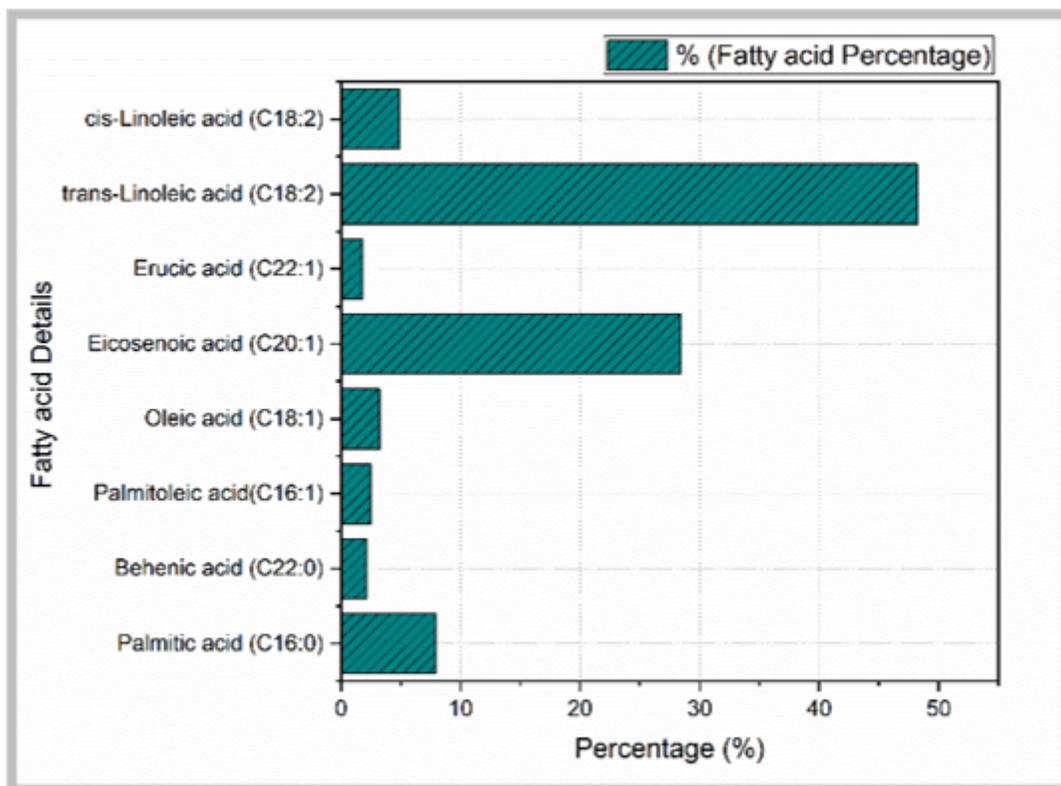


Figure 1

Fatty acid composition of the oil [45]

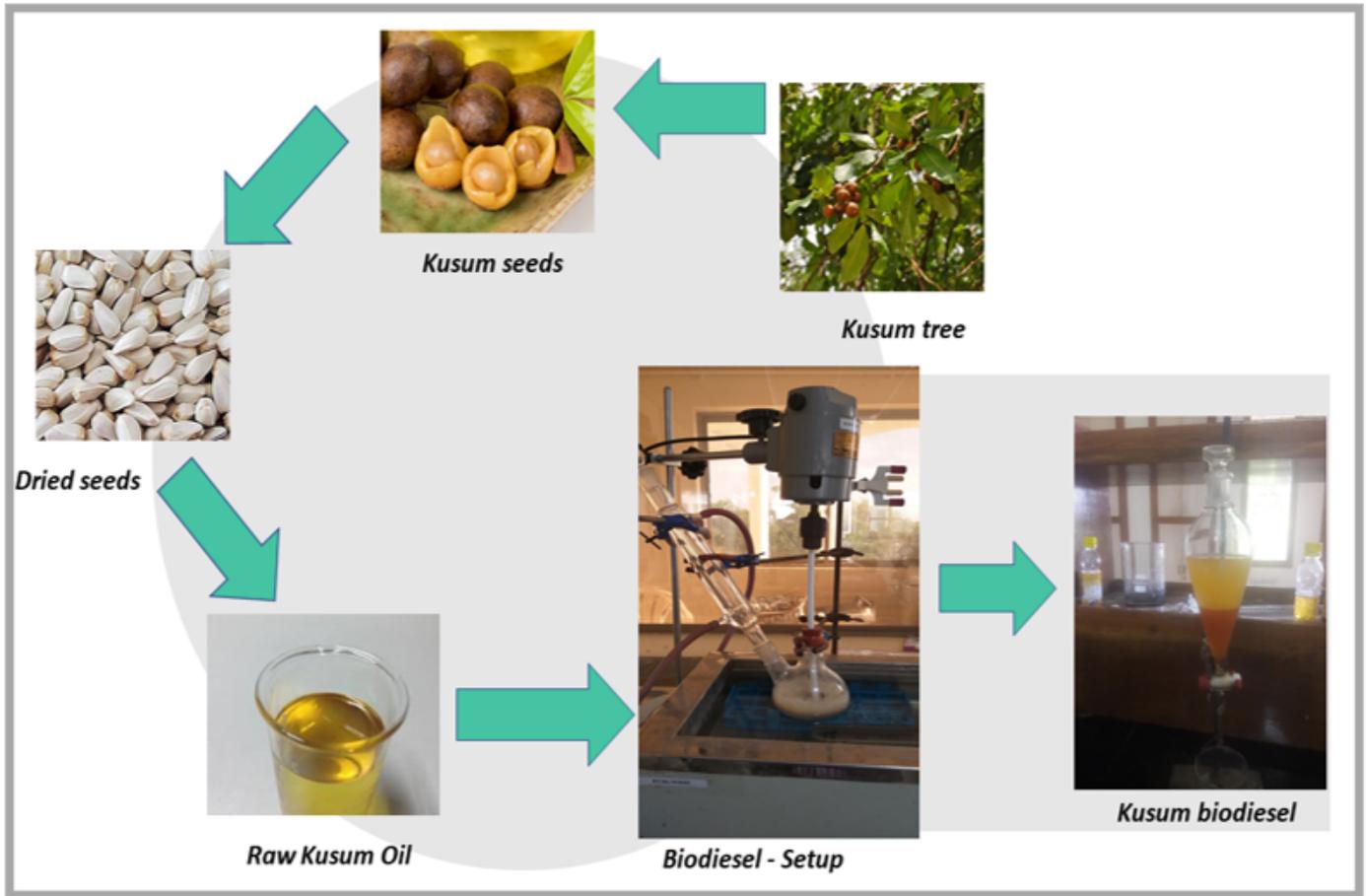


Figure 2

Schleichera oleosa oil Methyl ester Synthesis

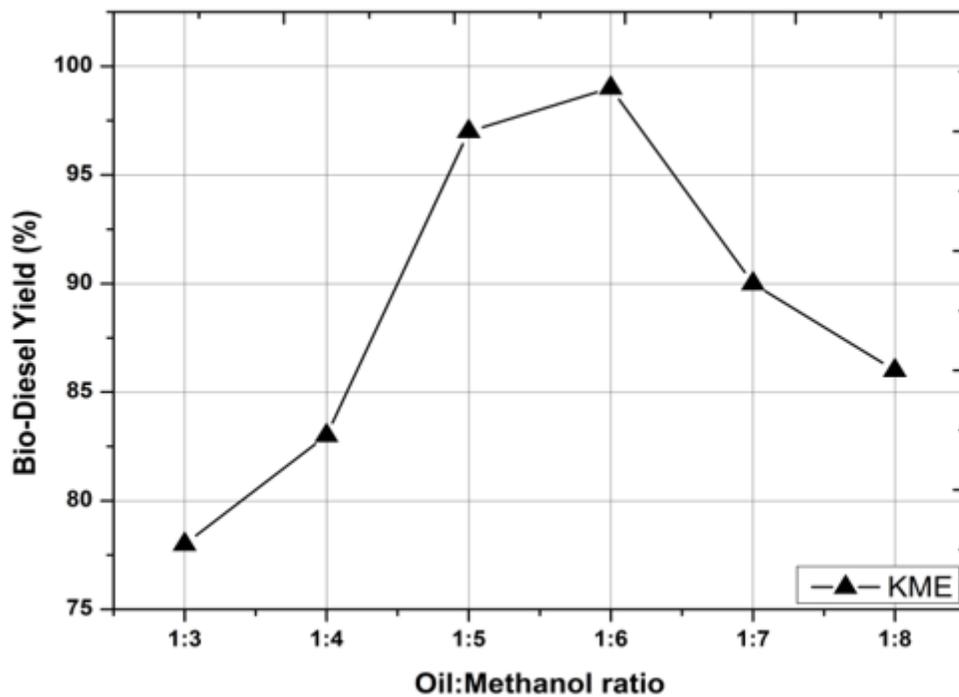


Figure 3

Schleichera oleosa oil Methyl ester Yield Optimization - Molar ratio Vs. biodiesel yield

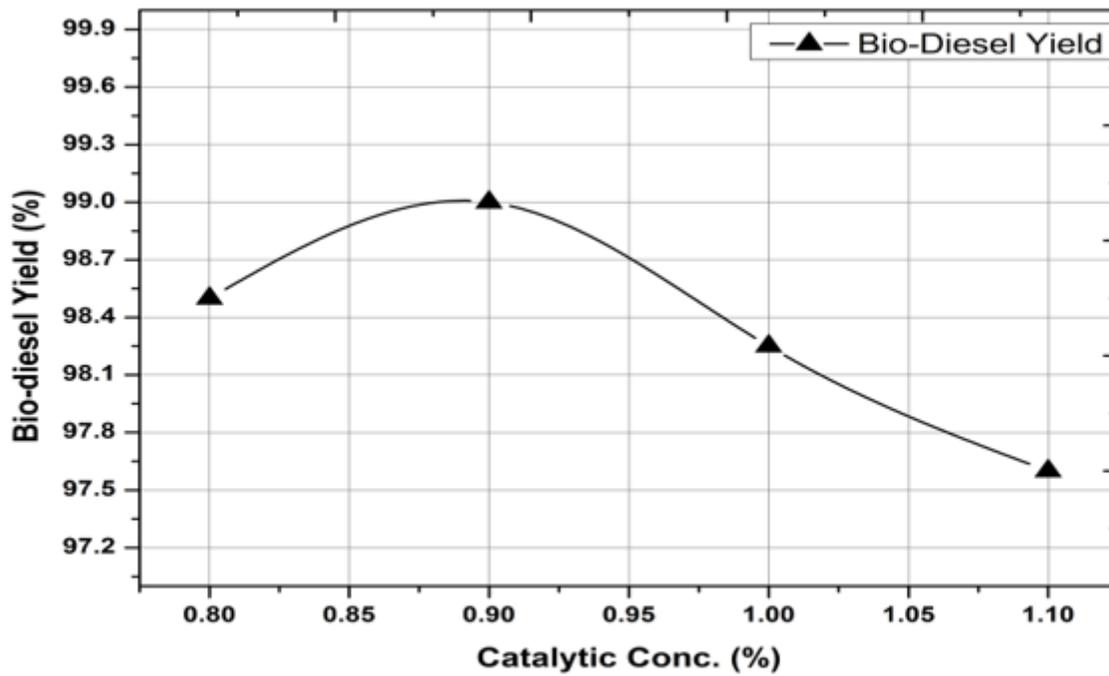


Figure 4

Schleichera oleosa oil Methyl ester Yield Optimization - Catalyst concentrations Vs. Yield

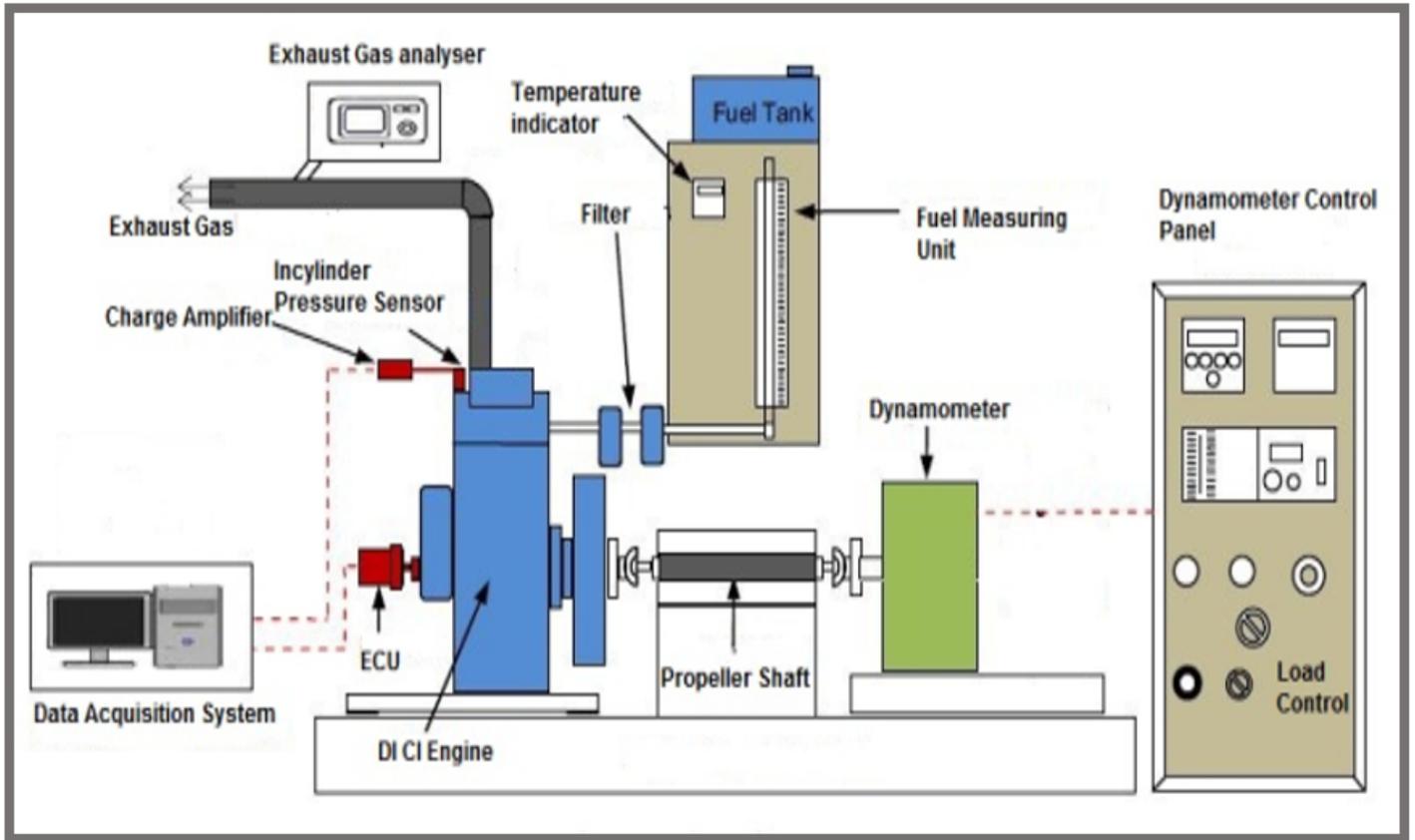


Figure 5

Experimental setup

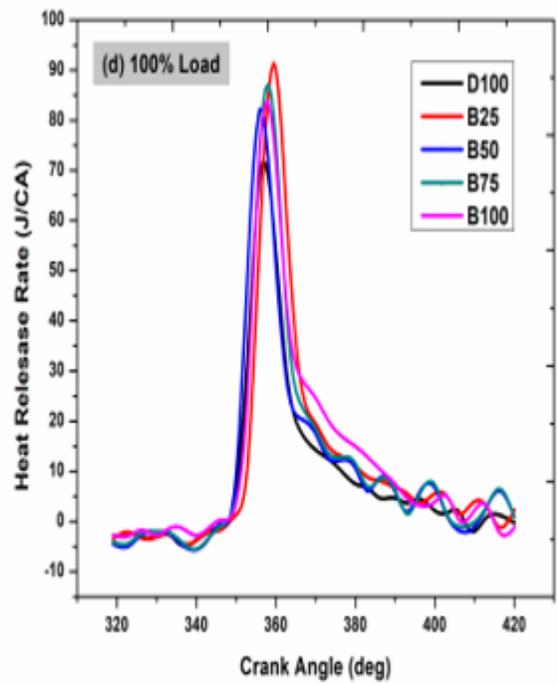
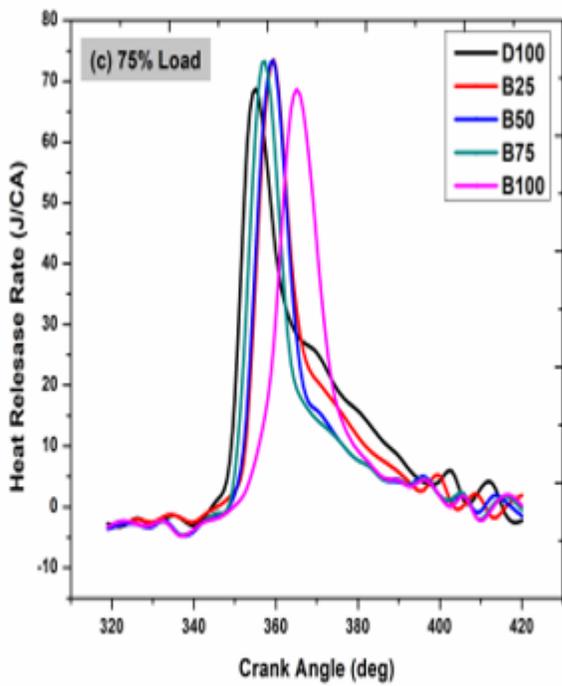
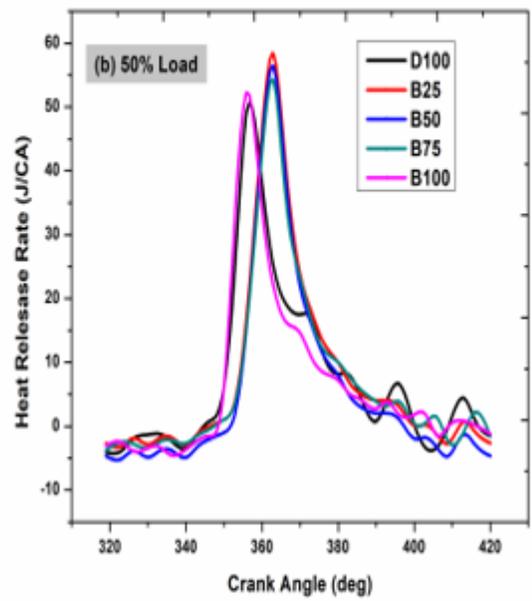
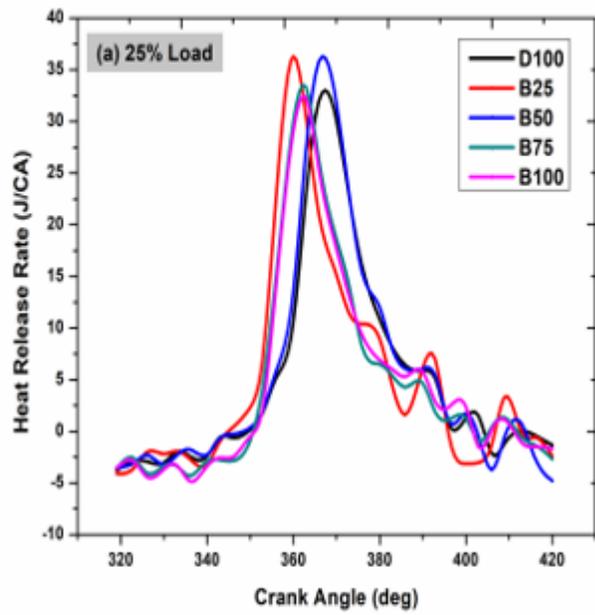


Figure 6

(a, b, c, d) Variation of heat release rate with load

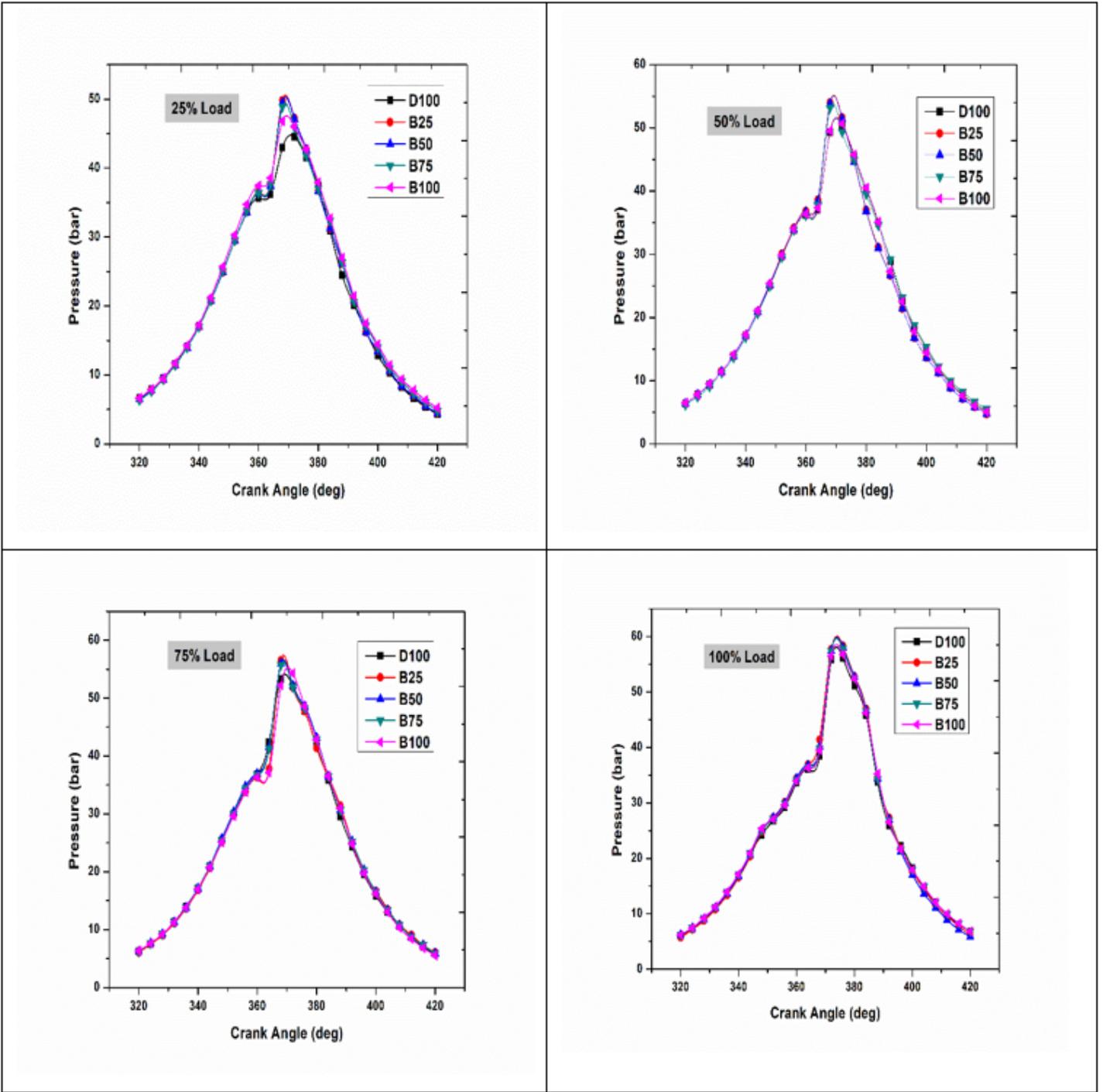


Figure 7

Variation of in-cylinder pressure with load

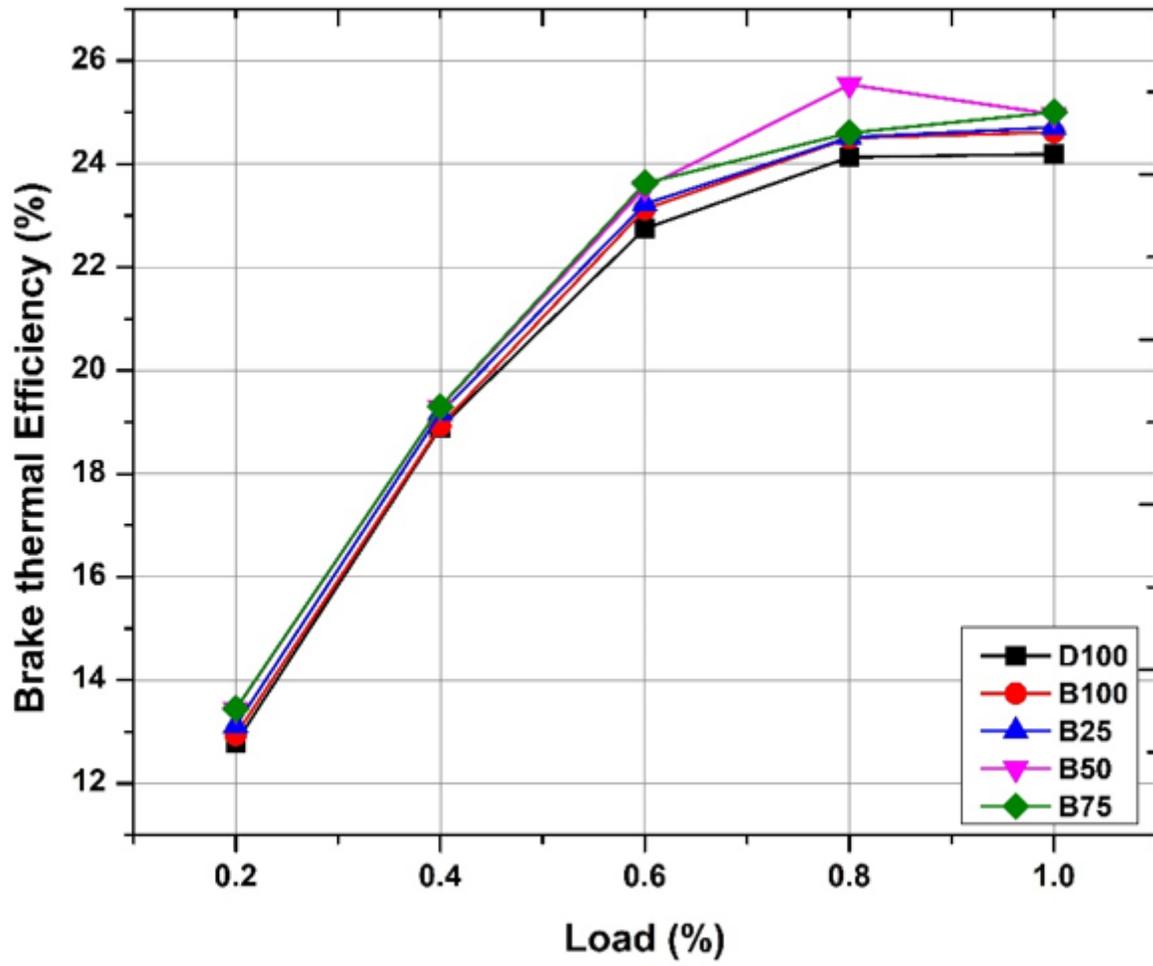


Figure 8

Brake thermal efficiency variation for different load condition

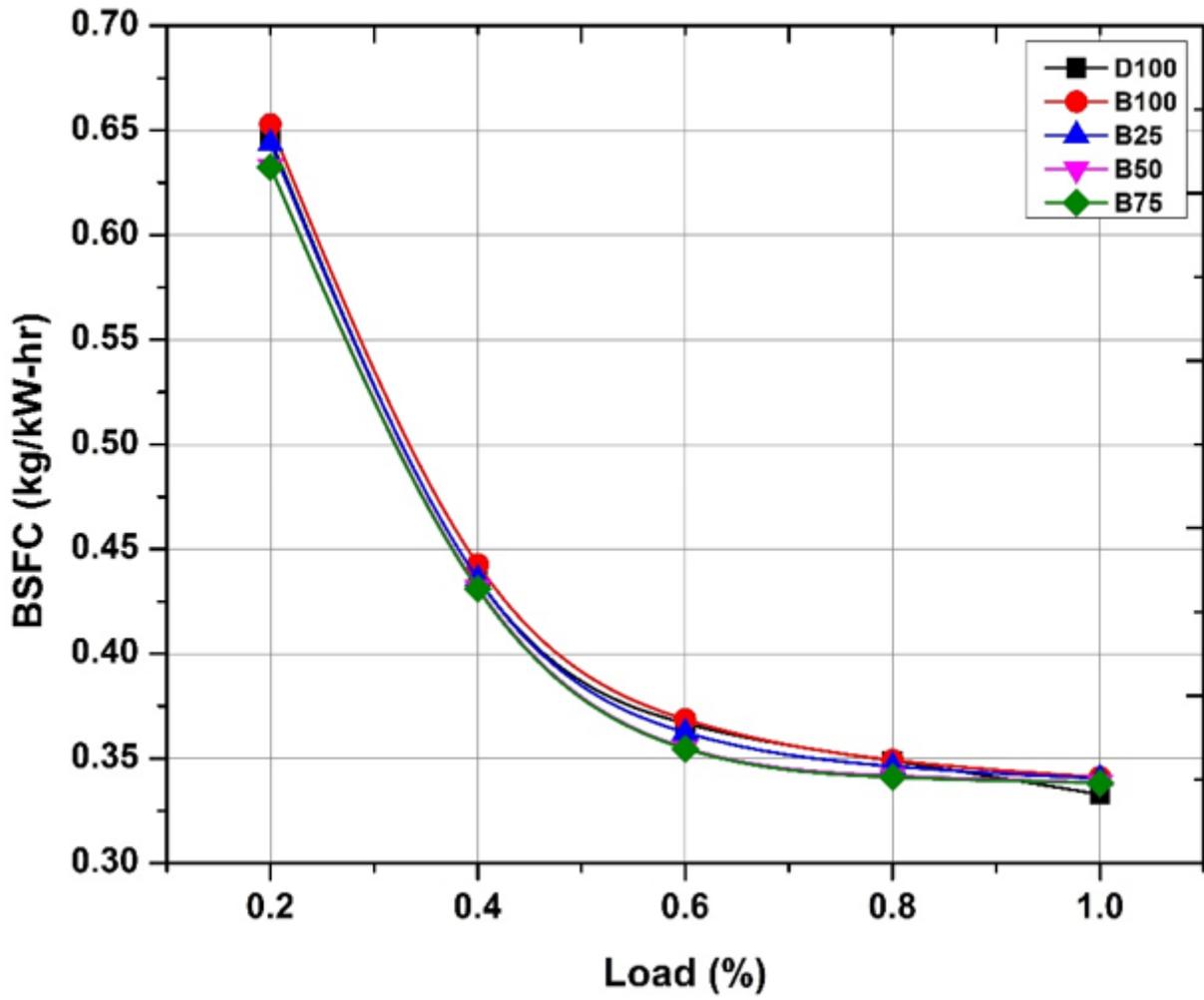


Figure 9

Brake Specific Fuel consumption variation for different load condition

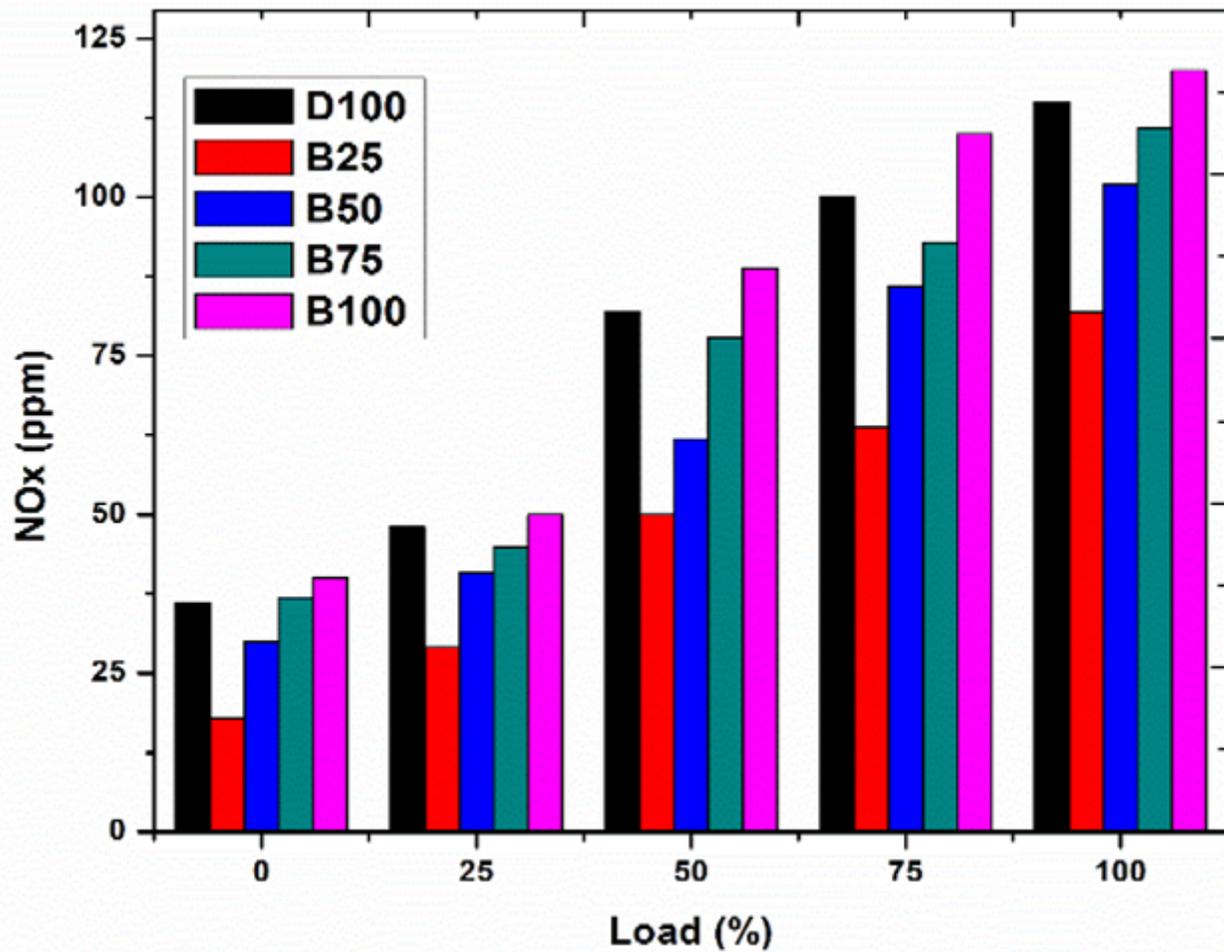


Figure 10

Oxides of Nitrogen variation for different load condition

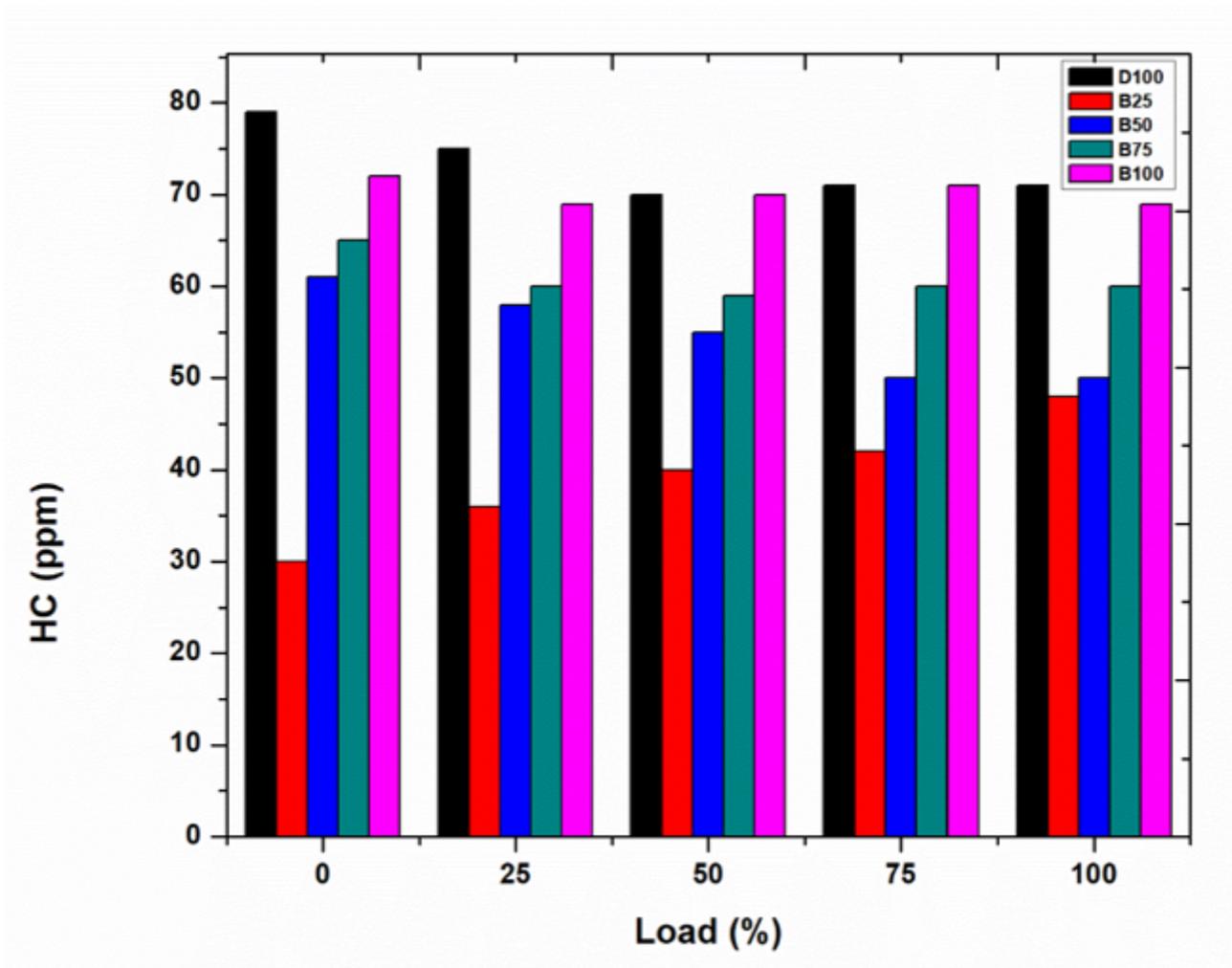


Figure 11

Unburnt Hydrocarbon emission variation for different load condition

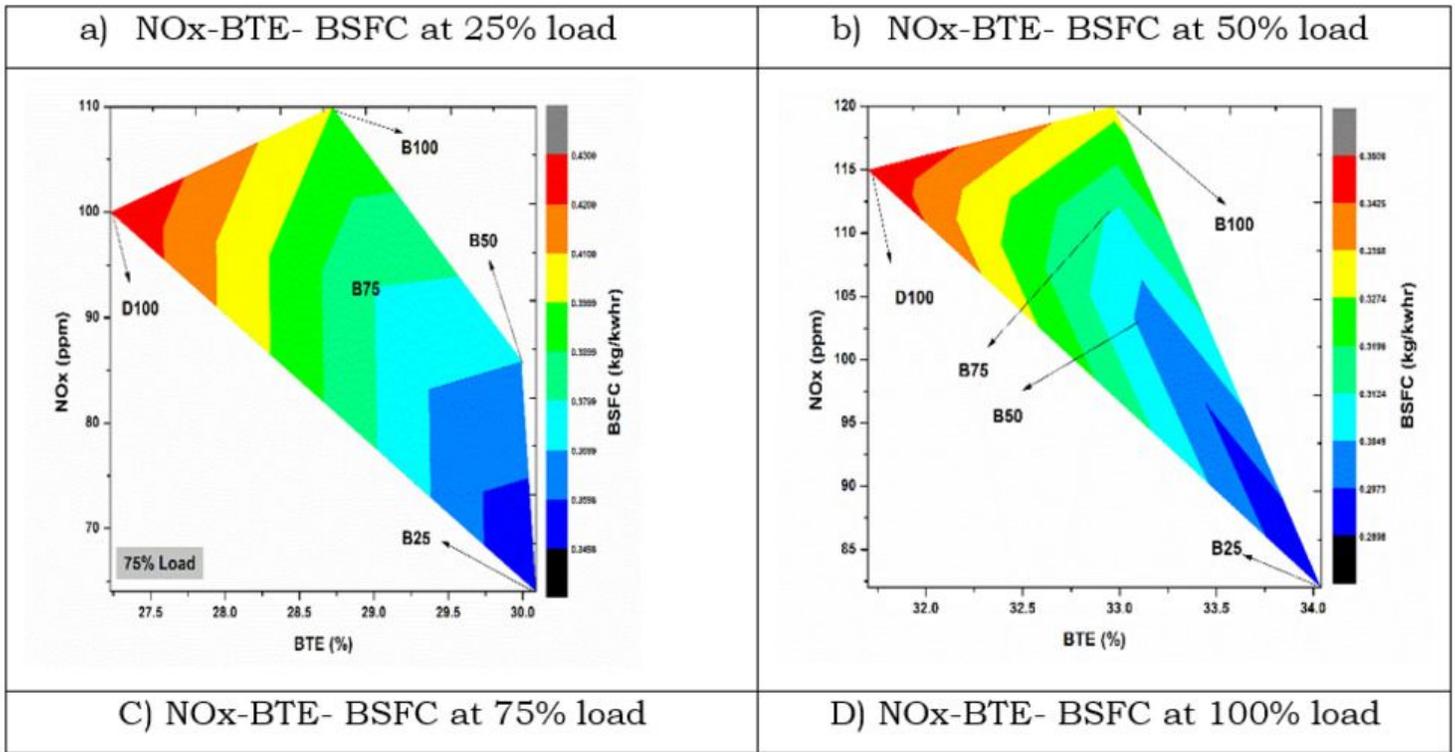
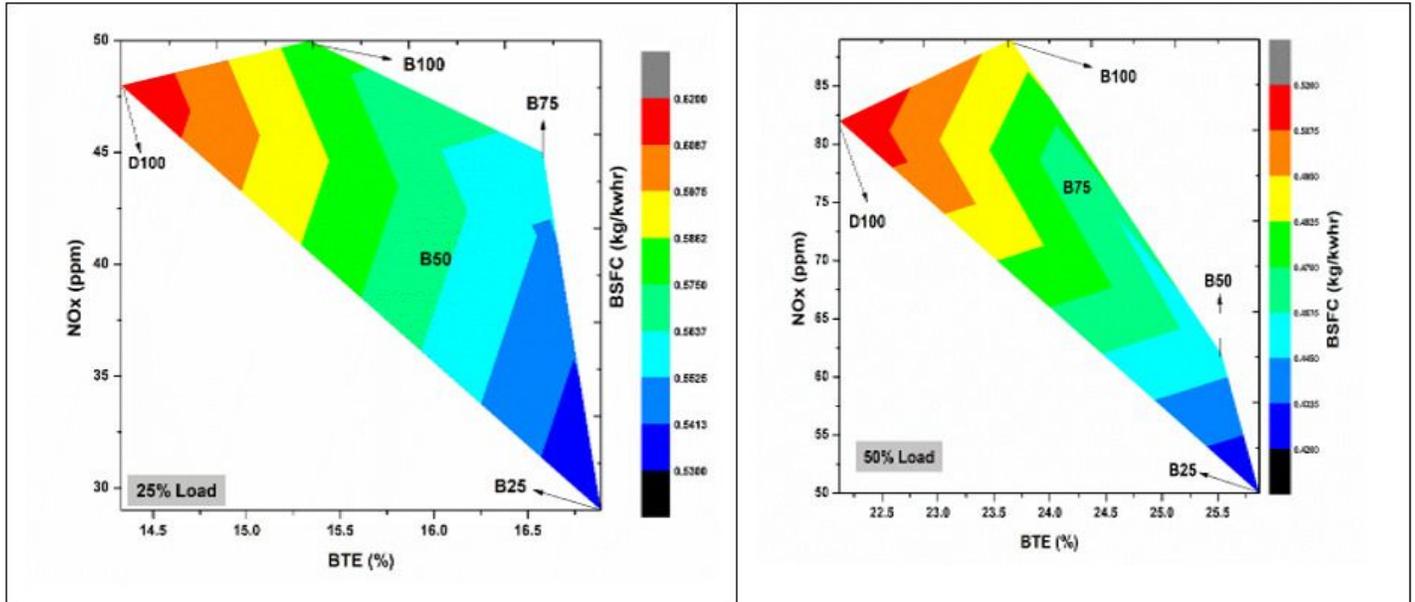


Figure 12

Trade-off study (BSFC- BTE- NO_x)

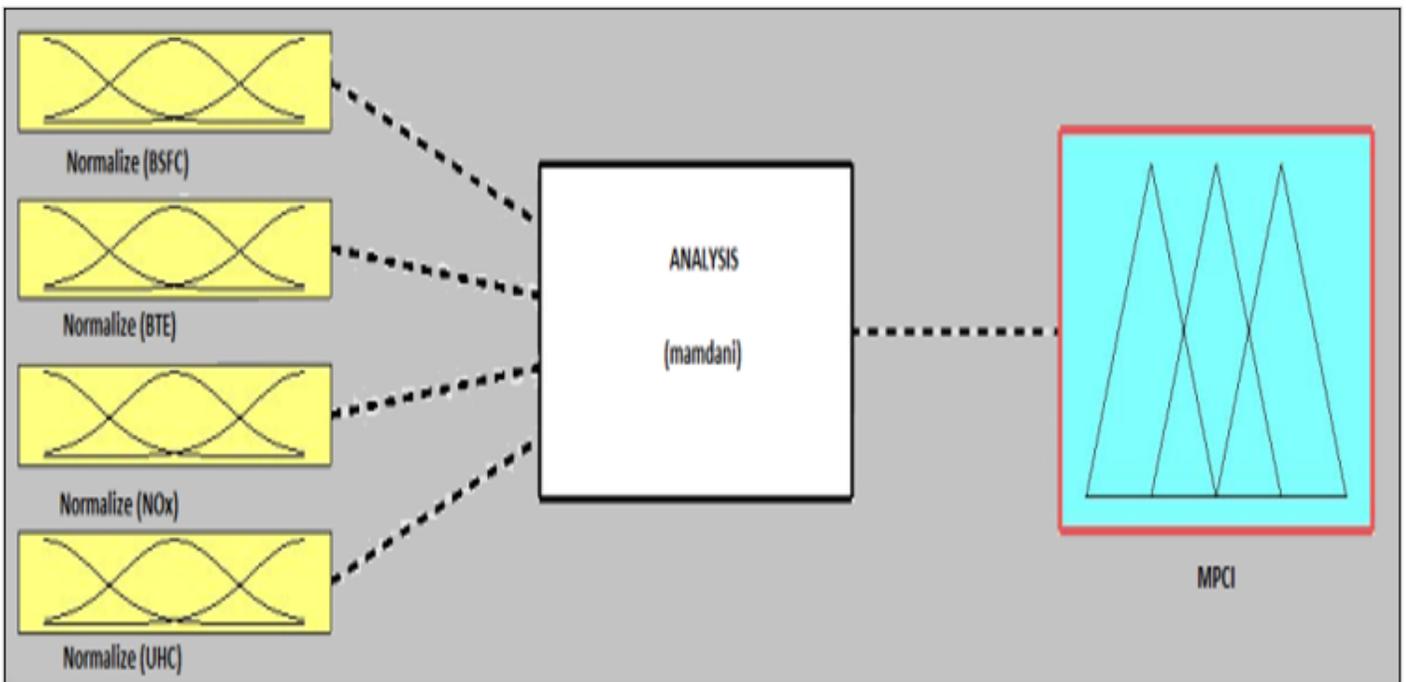
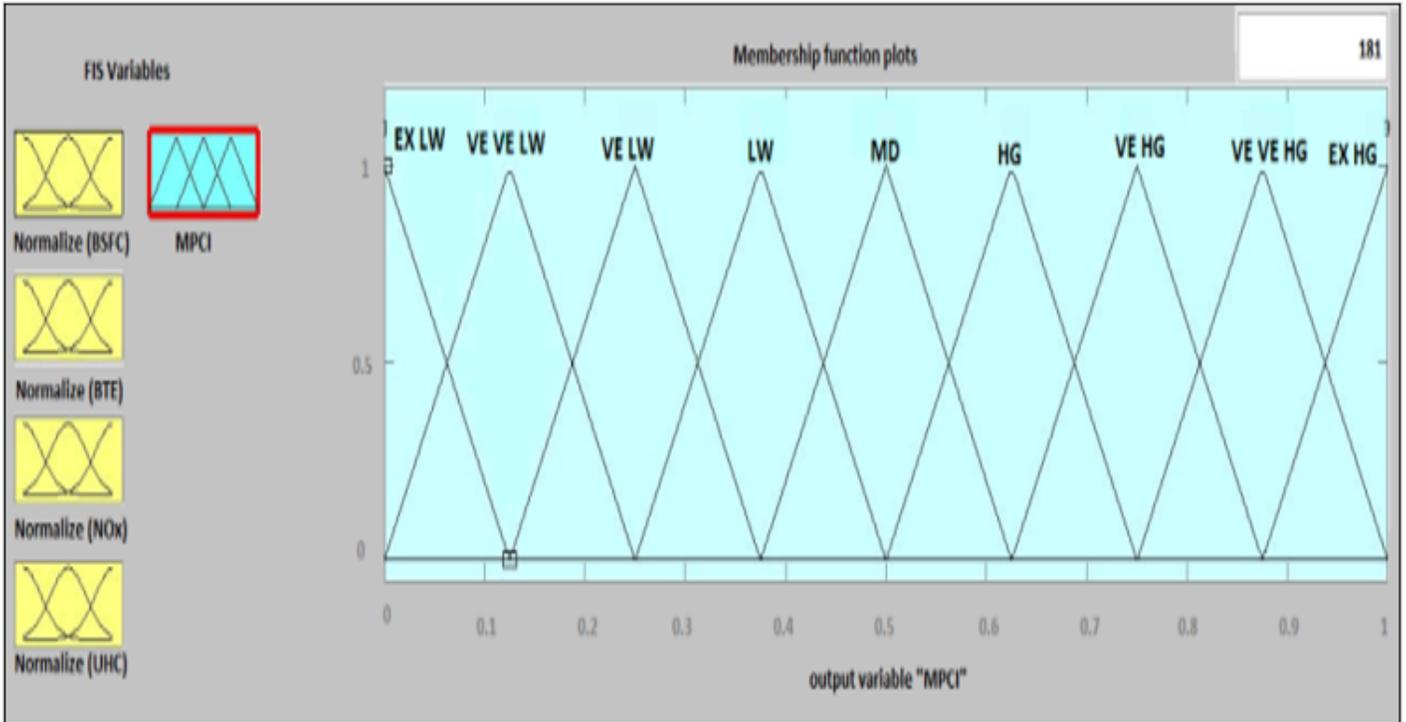


Figure 13

Membership functions (MPCI)

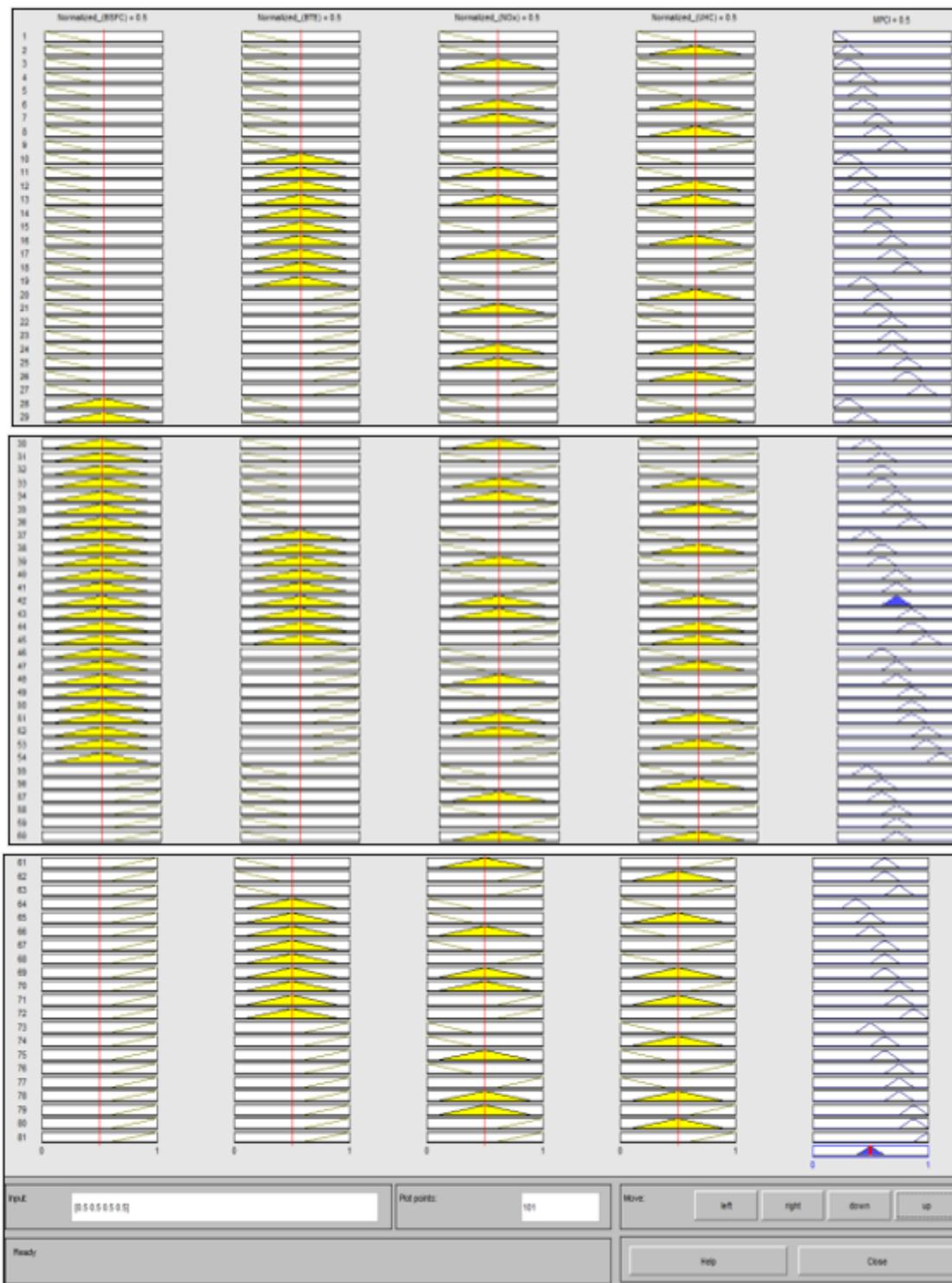


Figure 14

Fuzzy rules

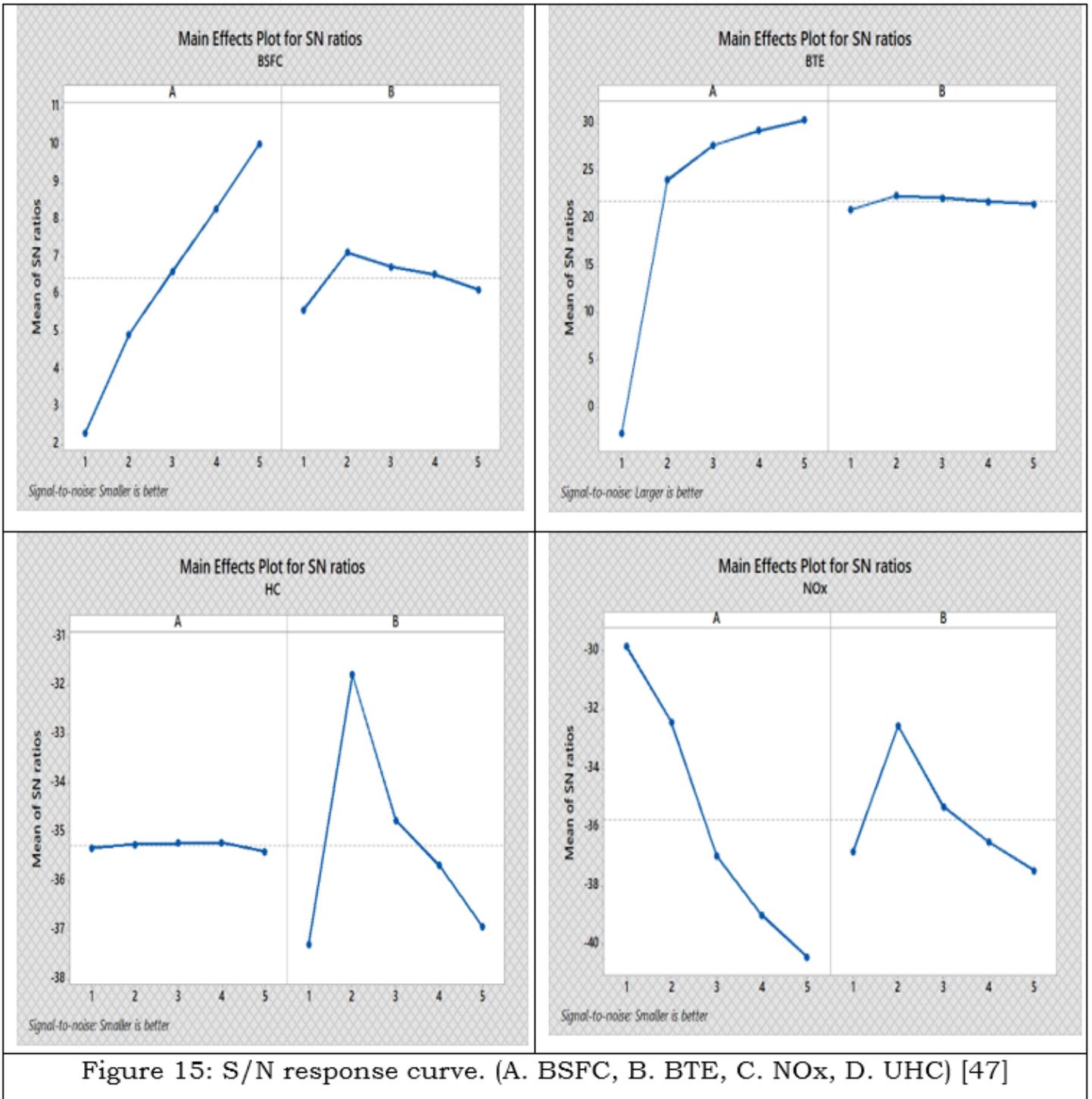


Figure 15: S/N response curve. (A. BSFC, B. BTE, C. NO_x, D. UHC) [47]

Figure 15

S/N response curve. (A. BSFC, B. BTE, C. NO_x, D. UHC) [47]

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