

Synopsis

Of the thesis entitled

Development of a Technique to Mitigate NO_x for
an Engine using Bio-diesel as a fuel

to be submitted

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Doctor of Philosophy (PhD)

by

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Table of Contents

1	Introduction.....	1
2	Literature Review.....	1
3	Objectives	4
4	Experimentation.....	4
4.1	Biodiesel.....	4
4.2	Transesterification Process.....	4
4.3	Property of Biodiesel.....	5
4.4	Experiment setup.....	5
4.5	Experimental Methodology.....	7
5	Result and Discussion.....	9
5.1	Phase-I.....	9
5.1.1	Comparison with BS VI Emission norms.....	14
5.2	Phase-II.....	15
5.2.1	Effect of water injection on NOx emission.....	15
5.2.2	Effect of Water injection on CO emission.....	16
5.2.3	Effect of Water injection on Smoke emission	18
6	Conclusion:	19
7	Tentative structure of Ph.D. Thesis.....	20
8	References:.....	20
9	Paper Publication	23

List of Tables

Table 1:Madhuca Longifoli-Diesel blend Property	5
Table 2:Test rig specifications	7
Table 3:Operating Parameters.....	8
Table 4:Operating parameters for water injection at the exhaust manifold.....	8
Table 5: Water Injection flow Rate.....	9
Table 6:Maximum NOx emission for each CR	12
Table 7: BS VI Emission standard for gen-set up to 19kW (https://dieselnet.com/).....	15

List of Figures

Figure 1: Biodiesel Preparation Setup	5
Figure 2: Biodiesel Glycerol separation	5
Figure 3: Experiment setup	6
Figure 4: Schematic Diagram of Experimental Test Setup	6
Figure 5: Emission gas Analyzer	7
Figure 6: Smoke meter	7
Figure 7: PFI Injector	8
Figure 8: Pump	9
Figure 9: NO _x Vs BP, CR-15, IP-300 bar	10
Figure 10: NO _x Vs BP, CR-16, IP-400 bar	10
Figure 11: NO _x Vs BP, CR-15, IP-500 bar	10
Figure 12: NO _x Vs BP, CR-15, IP-600 bar	10
Figure 13: NO _x Vs BP, CR-16, IP-300 bar	10
Figure 14: NO _x Vs BP, CR-16, IP-400 bar	10
Figure 15: NO _x Vs BP, CR-16, IP-500 bar	11
Figure 16: NO _x Vs BP, CR-16, IP-600 bar	11
Figure 17: NO _x Vs BP, CR-17, IP-300 bar	11
Figure 18: NO _x Vs BP, CR-17, IP-400 bar	11
Figure 19: NO _x Vs BP, CR-17, IP-500 bar	11
Figure 20: NO _x Vs BP, CR-17, IP-600 bar	11
Figure 21: NO _x Vs BP, CR-18, IP-300 bar	12
Figure 22: NO _x Vs BP, CR-18, IP-400 bar	12
Figure 23: NO _x Vs BP, CR-18, IP-500 bar	12
Figure 24: NO _x Vs BP, CR-18, IP-600 bar	12
Figure 25: NO _x Vs Injection Pressure, CR-15	13
Figure 26: NO _x Vs Injection Pressure, CR-16	13
Figure 27: NO _x Vs Injection Pressure, CR-17	13
Figure 28: NO _x Vs Injection Pressure, CR-18	13
Figure 29: NO _x Vs Fuel Blends, CR-15	14
Figure 30: NO _x Vs Fuel Blends, CR-17	14
Figure 31: NO _x Vs Fuel Blends, CR-18	14
Figure 32: NO _x Vs Water Injection, B10, CR-17,18	15
Figure 33: NO _x Vs Water Injection, B10, CR-16,15	15
Figure 34: NO _x Vs Water Injection, B20, CR-18,17	16
Figure 35: NO _x Vs Water Injection, B20, CR-16,15	16
Figure 36: NO _x Vs Water Injection, B30, CR-18,17	16
Figure 37: NO _x Vs Water Injection, B30, CR-16,15	16
Figure 38: CO % Vol Vs Water Injection, CR-18,17, B-10	17
Figure 39: CO % Vol Vs Water Injection, CR-16,15, B-10	17
Figure 40: CO % Vol Vs Water Injection, CR-18,17, B-20	17
Figure 41: CO%. Vs Water injection, CR-16,15, B-20	17
Figure 42: CO% Vol Vs Water Injection, CR-18,17, B-30	17

Figure 43:CO% Vol Vs Water Injection, CR-16,15, B-30	17
Figure 44:Smoke Vs Water Injection, CR-18,17, B-10.....	18
Figure 45:Smoke Vs Water Injection, CR-16,15, B-10.....	18
Figure 46:Smoke Vs Water Injection, CR-18,17, B-20.....	18
Figure 47:Smoke Vs Water Injection, CR-16,15, B-20.....	18
Figure 48:Smoke Vs Water Injection, CR-18,17, B-30.....	19
Figure 49:Smoke Vs Water Injection, CR-16,15, B-30.....	19

Synopsis

1 Introduction

Energy has been a need for mankind since ancient times and to fulfill energy demand is always a challenging task for human beings because the energy sources are limited and depleting every time. The environmental impact is again the important aspect and to overcome all such difficulties, invention of the new sources and improvement in existing energy sources are required to fulfill energy demand which is a continuous process. Principally there are two energy sources: 1. renewable energy sources and 2. non-renewable energy sources; renewable energy sources are like solar, energy, wind energy, and biomass, and out of these energy forms, biomass is available in an ample amount as India is an agriculture centric country. Energy extraction from biomass is possible using thermo-chemical conversion processes like incineration gasification or pyrolysis. Biodiesel is one of the renewable sources of energy that can be used as a fuel in compression ignition engines. Biodiesel can be made from the various seeds of various plants, animal fat, and waste cooking oil using a transesterification process.

The major concern is the NO_x emission during the use of biodiesel as a fuel in the case of CI engines. To mitigate the NO_x emission, various methods like changes in engine performance parameters, water injection in the exhaust manifold and in the combustion chamber, water emulsion, fuel additives, and exhaust gas recirculation (EGR) are used. The performance parameters like compression ratio, injection pressure, and blending of biodiesel are those parameters on which the present research work has been focused also attempt has been made by injecting water in the downstream (exhaust manifold) of the CI engine to analyze the effect of water injection on NO_x emission.

2 Literature Review

Nikul K Patel et al[1] focused on the thermal and emission performance of biodiesel extracted from soybean, rapeseed, jatropha, neem, and karanja. The Fluorescence spectroscopic technique is used to obtain fluorescence spectra resulting in its effect on emissions and performance of an engine. P. R. Kachhadiya et al [2] discussed *Leptadenia Reticulata* (LR) which are non-edible seeds found in Gujarat state and present research work on commercial viability and ASTM properties of biodiesel extracted from *Leptadenia Reticulata* feedstock. N. K. Patel et al [3] studied performance evaluation for a direct-injection four-in-line cylinder I C engine using *Leptadenia Reticulata* Methyl Ester (LRME) as fuel with B0, B20, B40, B60, B80, and B100 (LRME) at a compression ratio of 16:1, 17:1 and 18:1. T. K. Sahu et al [4] focused on the effect of compression on combustion characteristics of biodiesel extracted from waste cooking oil under no load to full load condition for a compression ratio of 18 and 20 and at 1500 RPM constant engine speed. Ahmed I. El-Seesy et al [5] studied the effect of nanoparticles named multiwalled carbon nanotubes by adding into waste cooking oil biodiesel on the performance and emission characteristics of biodiesel-diesel blends with no load condition and at 2000 RPM speed. In the present work, multiwall carbon nanotubes were blended with waste cooking oil biodiesel

fuel at a fraction of 25, 50, and 75 mg/L using an ultrasonicator. Selvakumar Raja et. al [6] studied the influence of compression ratio on emission characteristics of waste cooking oil (WCO) biodiesel as fuel in the engine, and in the present study 16.5, 17.5, and 18 these three compression ratios are considered. In this work emulsion and injection timings were chosen as two parameters, and their influence on the smoke and NO_x emission was studied where the engine operated with WCO. M. S. Gad et al [7] investigated the effects of blending WCO biodiesel with gasoline and kerosene on diesel engine performance, combustion characteristics, and emissions compared to fossil diesel. Murat Kadir et al [8] focused on the effect of injection pressure on performance and emission outcome of waste cooking oil biodiesel when blended with diesel and for injection pressure varying between 170-220 bars. G.R. Kannan et al [9] worked on the production of biodiesel from WCO using the response surface method and by using such biodiesel, the engine is operated at 100 % load at 1500 RPM. WCO-ME exhibited a lower heat release rate, shorter ignition delay of 10.9⁰CA, and slightly longer combustion duration of 54.4⁰ CA when compared to diesel at the same load condition. Esmail Khalife et al [10] investigated experimentally the effect of the presence of low water levels in WCO biodiesel on full load by varying engine speed in which 5% biodiesel and 2%,3%, and 4% of water are mixed with diesel which led to reduction of emission values with increment in water percentage in biodiesel. S V Channapattana et al [11] studied the effect of injection pressure in the case of variable compression ratio (VCR) for Honne biodiesel as fuel on performance and emission parameters. Injection pressures rise from 180 bar to 240 bar in steps of 30 bar and maintain a constant compression ratio at 18 and load at 12 kg. The NO_x emissions increase with the increase in IP. Z. A. Abdul Karim et al [12] used 5% palm oil methyl ester (POME) in the diesel fuel, at a constant engine speed of 2000 rpm with different engine loads and emulsion blends of B5 diesel mixed with 9%, 12% and 15% volume of water, hydrophilic-lipophilic balance (HLB) values of 6, 7, 8 and 9 %, and surfactant dosage of 5%, 10% or 15% by percentage volume of water added. Jiaqiang E et al [13] focused on the performance and emission results of the marine engine with water emulsion and with a fuel additive of a cerium oxide nanoparticle. The results showed that the water additive in the biodiesel-diesel fuel was beneficial in improving the mixing of air and fuel due to the micro-explosion. Sipeng Zhu et al [14] reviewed the effect of water injection on the performance of an internal combustion engine. Xavier Tauzia et al [15] conducted a modern high-speed common-rail automotive Diesel engine to evaluate the effects on combustion and pollutant emissions of water injected as a fine mist in the inlet manifold. Adnan Parlak et al [16] studied the effect of steam injection on performance and NO_x emission by injecting steam at the inlet manifold of a diesel engine fueled with canola oil methyl ester (COME) blends B. Tesfa et al [17] used a novel method of water injection in the combustion chamber of four-cylinder, four-stroke, direct injection (DI) as well as turbocharged diesel engine using biodiesel blended diesel. Sudarshan Gowrishankar et al [18] investigated the effect of emulsification and water injection methods to mitigate the higher NO_x emissions with biodiesel. The ignition delay time increased, and the peak pressure was reduced with biodiesel-water emulsion. Noboru Miyamoto et al [19] studied the effect of water injection into the combustion chamber; the temperature distribution in the swirl chamber was analyzed quantitatively with high-speed photography and the two-color method. Direct water injection into a swirl chamber before fuel injection reduced NO_x emission

significantly over a wide output range without sacrificing BSFC. K.A. Subramanian [20] conducted experiments to compare the effects of water–diesel emulsion and water injection into the intake manifold on the performance, combustion, and emission characteristics of a DI diesel engine under similar operating conditions. S. Kent Hoekman et al [21] reviewed the effect of injection timing, ignition delay, adiabatic flame temperature, radiative heat loss, and other combustion phenomena on NO_x emission. S.M. Palash et al [22] discussed various NO_x mitigation technologies and their effect on the performance and emission characteristics of biodiesel-fueled compression ignition engines. K.Velmurugan et al [23] carried out detailed observations regarding NO_x formation in the biodiesel-operated engine, the influence of formation, and biodiesel properties on NO_x emissions. An enormous number of studies have shown that high isentropic bulk modulus of biodiesel causes an artificial advance injection timing relative to petro-diesel, and higher NO_x emissions. S. Arunprasad et al [24] obtained results for mixed biodiesel (*Thevetia peruviana*, *Jatropha*, *Pongamia*, and *Azadirachta indica*) operated engine by varying injection pressure and injection timing. The injection pressure is varied from 200 to 230 bar and the injection timing is varied from 23° to 29° bTDC at an increment of 10 bar and 2° BTDC, respectively. Pali Rosh et al [25] studied the effect of compression ratio on performance, combustion, and emission characteristics of palm biodiesel blended (B20) with diesel-operated engines for compression ratios 16:1, 17:1, and 18:1. The formation of NO_x emissions in CI engines largely depends upon the adiabatic flame temperature, which is closely related to the peak cylinder temperature. Meshack Hawi et al [26] concentrated on the effect of compression ratio on combustion, performance, and emission for biodiesel extracted from jojoba operated engine in which increasing CR from 18 to 23 and so cylinder pressure increased.

The major outcome of the present work is that NO_x emission is the biggest threat to biodiesel to establish as fuel, also NO_x emission is highly influenced by compression ratio, injection pressure, and blending of biodiesel. The NO_x reduction techniques like EGR, water emulsion, and water injection at the inlet manifold and inside the cylinder are good options but at the cost of thermal performance. The water injection in the downstream line (exhaust manifold) is the option on which the present research work is focused.

A detailed literature survey was carried out on various NO_x emission reduction techniques and the effect of compression ratio and injection pressure on the performance, combustion, and emission parameters of CI engines. A summary of the literature review is listed below.

- A measurable amount of reduction in NO_x emission was observed by the EGR technique, but trends for a few biodiesels show an increase in CO and HC along with a decrease in brake thermal efficiency also observed.
- Water emulsion is an efficient technique for mitigation of the NO_x however after a certain amount of water percentage increases, brake thermal efficiency decreases and HC and CO also increase.
- Fuel additives can reduce NO_x emission, on the other hand, HC, and CO increase.
- The change in compression ratio and injection pressure has a considerable effect on the emission, parameters of the IC engine

- Researchers have carried out the experimental investigation by injecting the water at the inlet manifold and inside the cylinder. These techniques have given good results for NO_x emission reduction however on the other hand the BTE decreases, and BSFC, HC, CO, and smoke increase remarkably.
- Water injection in exhaust manifolds is an area yet to be explored experimentally. So we are proposing the experimental investigation of the NO_x emission by injecting the water at the exhaust manifold of a CI engine fueled with diesel biodiesel blends.

3 Objectives

The objectives defined for the present study were as follows:

1. To prepare the biodiesel using the transesterification process.
2. To quantify the NO_x for various combinations of compression ratio, injection pressure and biodiesel-diesel blends at various loading conditions on single-cylinder diesel engines fueled with diesel biodiesel blends.
3. To carry out an experiment by injecting the water at the exhaust manifold of a CI engine fueled with diesel biodiesel blends.
4. To investigate the effect of water injection on NO_x emission.

4 Experimentation

4.1 Biodiesel

The mahua seed shows a very good commercial potential as oil. The yield of mahua seeds varies from 5-200 kilograms per tree. The yield of mahua seeds mainly depends on the age and size of the tree. The estimated mahua seed oil production is 1.8 million metric tons per year in India.[27] Biodiesel producers are focusing on substitute feed-stocks which are non-agricultural and non-food crops. This Mahua can replace the requirement of low-cost feedstock with the potential for high oil seed production and the added benefit of an ability to grow on marginal land. [28][29]

4.2 Transesterification Process

1. **Material:** 1-liter oil sample, methanol, KOH solution, methanol, three-neck glass flask, heating mantle, separating funnel with bottom side valve.
2. **Pre-treatment:** Madhuca Longifolia oil of 1 liter quantity is filtered and heated for 2-5 minutes at 60°C. Poured into a three-neck glass flask as shown in Fig 1. This 3-neck glass vessel is placed on heating mantle and has a magnetic stirring facility. Also, the thermocouple is placed to measure temperature. Oil is heated to 60°C to 65°C for 10 min for dehydration and impurities filtration. Further, it is allowed to cool to room temperature.
3. **Transesterification:** A base catalyst is used for transesterification. Potassium hydroxide (KOH) is taken 15 gm, 300 ml methanol (CH₃OH). The methanol and KOH solution is prepared and poured into oil at 60°C for 60 min.
4. **Separation:** After one hour of Transesterification reaction glycerine and fatty acid methyl ester get separated as shown in Fig 2. This is allowed to settle and separating

process for 8-10 Hrs. The bottom layer of glycerine is separated and biodiesel as FAME is taken. A condenser was used to condense ethanol. For water washing, distilled water 100 ml at 50° C is taken and mixed with 100 ml of oil. In water washing methanol and any impurity is washed away. However, water may be added to oil and almost 85% to 90% of the yield.



Figure 1: Biodiesel Preparation Setup

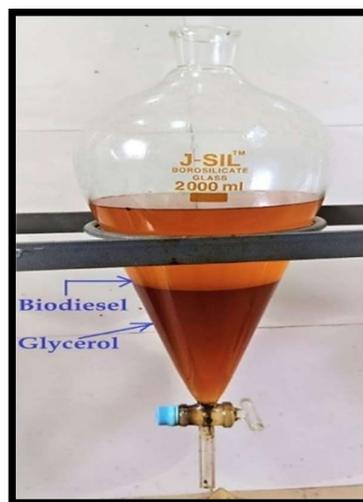


Figure 2: Biodiesel Glycerol separation

4.3 Property of Biodiesel

The properties of Madhuca Longifolia biodiesel have been investigated in the laboratory according to ASTM standards as mentioned in Table 1.

Table 1: Madhuca Longifolia-Diesel blend Property

Sample/ Properties	Calorific value	Density	Acid Value	Flash Point	Fire Point	Kinematic Viscosity	Dynamic Viscosity
Unit	kJ/kg	kg/M ³	mg of KOH gm of oil	°C	°C	cSt	cP
St. Diesel	45236	816	0.6	53	56	2.09	1.73
B10	44074	826	0.73	61	67	2.79	2.30
B20	42941	828	0.79	68	74	2.93	2.43
B30	42256	832	0.89	71	77	3.08	2.56
B100	42034	871	1.31	101	110	4.98	4.34
Raw Oil	39932	910	2.20	256	270	39.6	36.0

4.4 Experiment setup

A single-cylinder, four-stroke, and CRDI VCR diesel engine test rig as shown in Fig 3 has been used. A schematic diagram of a test rig is shown in Fig 4. A common rail direct injection (CRDI) type fuel injection system was used to maintain constant pressure in the rail. Table 2 shows the engine specifications. An eddy current dynamometer attached to the

engine is controlled by a computer interface. The cooling water for the engine jacket, eddy current dynamometer, and exhaust gas calorimeter is delivered by a water pump. RTD (resistance temperature detectors) type sensors are used to measure the temperatures at the intake and outflow of the engine jacket cooling water as well as the exhaust gas calorimeter cooling water. The engine exhaust gas temperature as well as the gas temperatures at the calorimeter's input and exit are measured using K-type thermocouples. A piezoelectric pressure sensor (Kistler Instruments, Switzerland; Model: 6613CQ09) is used to detect in-cylinder pressure.

All the instantaneous temperatures and pressure data are sent to the computer through a data acquisition system (National Instruments, USA; Model: M Series DAQ) and monitored from the computer using a software program. The Data acquisition device NI USB 6210, 16-bit Engine soft software has been used in the system developed by Apex Innovations Pvt. Ltd, for engine testing: including monitoring, data entry, reporting, and data logging.

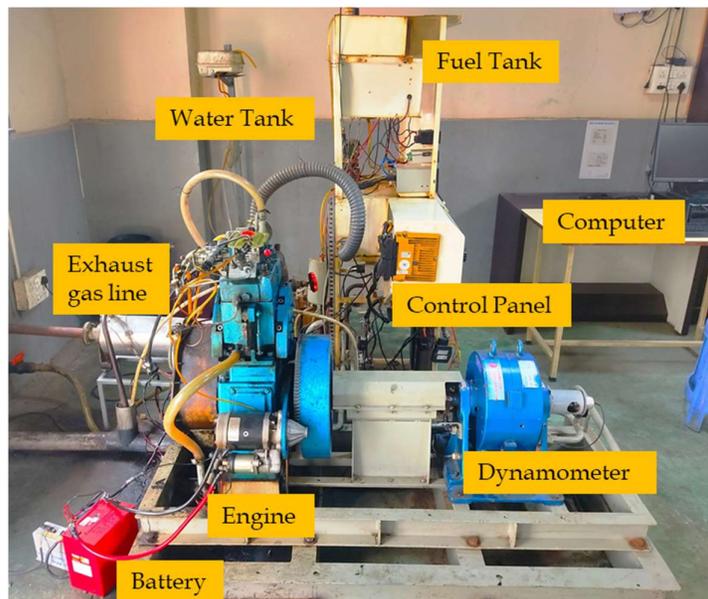


Figure 3: Experiment setup

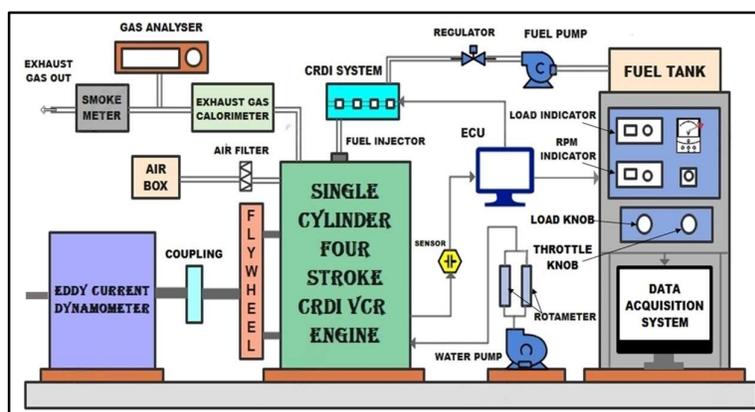


Figure 4: Schematic Diagram of Experimental Test Setup

The engine tests are conducted at a constant speed of 1500 rpm and four different loads 3 kg, 6 kg, 9 kg, and 12 kg (25%, 50%, 75%, and 100%) with diesel as fuel at different compression ratios (15:1, 16:1, 17:1 and 18:1) and different Injection pressure (300 bar, 400 bar, 500 bar, and 600 bar). In the same manner, the test was conducted with the biodiesel blends of B10 %, B20%, and B30%. All experiments are done at every load under steady-state conditions. An AVL Di-Gas 444 exhaust gas analyzer is used for the measurement of the quality of exhaust gas emissions and an AVL 437 smoke meter is used to measure the smoke.

Table 2: Test rig specifications

Engine	Diesel Engine test setup 1-cylinder, 4-stroke, water-cooled
Rated power	3.5Kw at 1500 rpm
Speed	1500 rpm(constant)
Number of cylinders	Single cylinder
Compression ratio	12:1 to 18:1(variable)
Bore	87.5 mm
Stroke	110 mm
Ignition	Compression ignition

AVL 444 gas analyser as shown in Fig 5 and AVL 437 smoke meter as shown in Fig 6 has been used to measure the emission like NOx, CO, and Smoke.

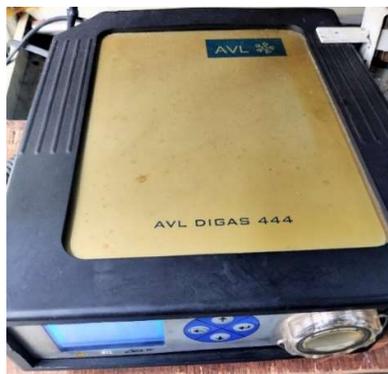


Figure 5: Emission gas Analyzer



Figure 6: Smoke meter

4.5 Experimental Methodology

The experiment is divided into two phases. In phase I, the quantification of NOx is carried out for different combinations of operating parameters as shown in Table 3.

Table 3: Operating Parameters

Sr. No	Fuel	Compression Ratio	Injection Pressure (Bar)
1	Diesel	15, 16, 17, 18	300, 400, 500, 600
2	B10	15, 16, 17, 18	300, 400, 500, 600
3	B20	15, 16, 17, 18	300, 400, 500, 600
4	B30	15, 16, 17, 18	300, 400, 500, 600

In phase II, water was injected at the downstream (exhaust manifold) of the CI engine for the operating parameters as shown in Table 4.

Table 4: Operating parameters for water injection at the exhaust manifold

Parameters	Range			
Fuel	B10	B20	B30	
CR	15	16	17	18
IP (bar)	600			
Load	75%	100%		

Water reacts with NOx emissions and generates the HNO₃ and HNO₂

NO₂ and water reaction



When any of these oxides dissolve in water and decompose, they form nitric acid (HNO₃) or nitrous acid (HNO₂) as shown in equation 1. Nitric acid forms nitrate salts when it is neutralized. Thus, NOx and its derivatives exist and react either as gases in the air, as acids in droplets of water or as a salt.[30]

The experimental setup consists of a PFI injector as shown in Fig 7 and a pump as shown in Fig 8 which are used to inject water inside the exhaust manifold which is computerized operated and supplies water at intervals of 5 ms (Millisecond).



Figure 7: PFI Injector



Figure 8: Pump

Numerous scientists have taken the stream pace of water through injectors same as the fuel stream rate to start the trial. In the main period of trial and error, the normal fuel stream rate was 16 cc/min. The injector is controlled by an electronic control unit (ECU) and software that lets you change the cycle time for the injector opening to adjust the water flow rate. The process duration can be changed in the interval of 5 ms (Millisecond) so it began with 5 ms and the first NOx reduction was recorded for 10 ms (38.7 CC/min). Then after 20 ms, 30 ms, and 35 ms process duration, the test runs were completed. The stream rate for each process duration is as below.

Table 5: Water Injection flow Rate

Cycle time of Injector (Millisecond)	Water injector flow rate (CC/min)
0	0
10	38.7
20	82.7
30	130.4
35	166.7

5 Result and Discussion

5.1 Phase-I

The first phase of experimentation was carried out by varying four compression ratios (15, 16, 17, and 18), four injection pressures (300,400,500 and 600 bar), and for fuel blends (Diesel, B10, B20, and B30) at a constant speed of 1500 RPM for 25, 50, 75 and 100% engine loading condition. For all the combinations, NOx emission values are recorded and quantified.

It is observed from Fig 9 to Fig 24, that NOx emissions increase as the fuel consumption also increases with load. It is also observed that with an increase in fuel blend percentage, NOx emission also increases as biodiesel contains more oxygen than diesel. Table 6 shows the highest NOx emission value observed for each compression ratio.

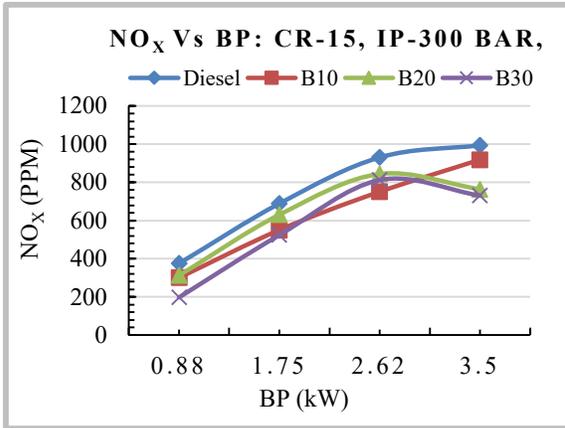


Figure 9: NO_x Vs BP, CR-15, IP-300 bar

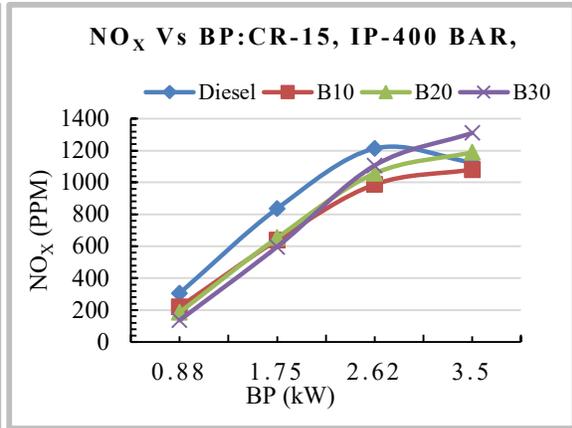


Figure 10: NO_x Vs BP, CR-16, IP-400 bar

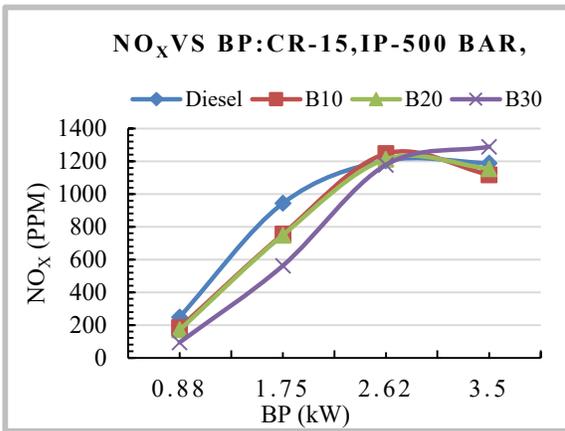


Figure 11: NO_x Vs BP, CR-15, IP-500 bar

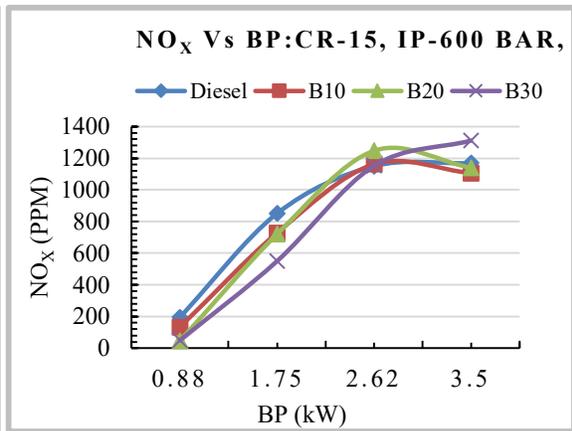


Figure 12: NO_x Vs BP, CR-15, IP-600 bar

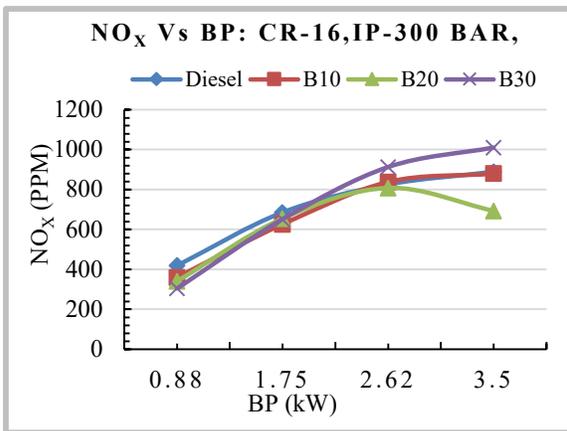


Figure 13: NO_x Vs BP, CR-16, IP-300 bar

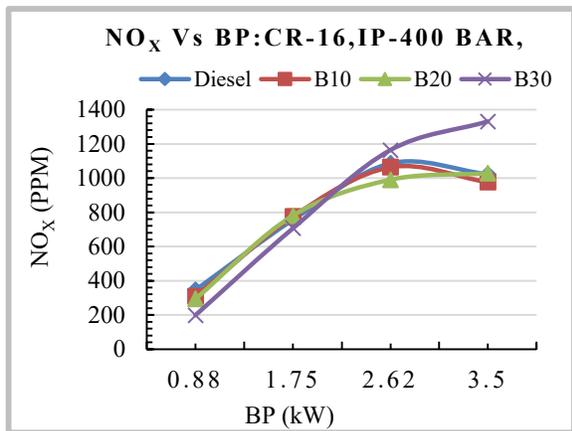


Figure 14: NO_x Vs BP, CR-16, IP-400 bar

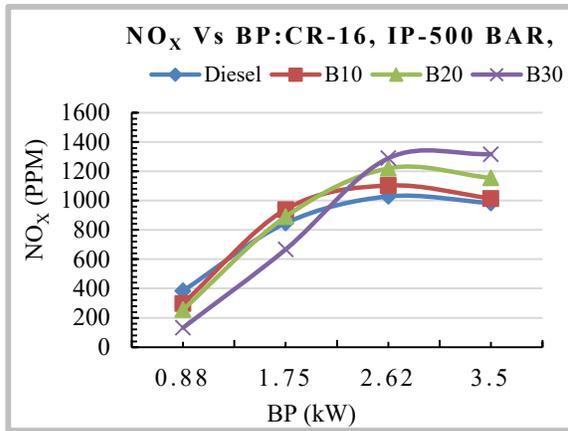


Figure 15: NO_x Vs BP, CR-16, IP-500 bar

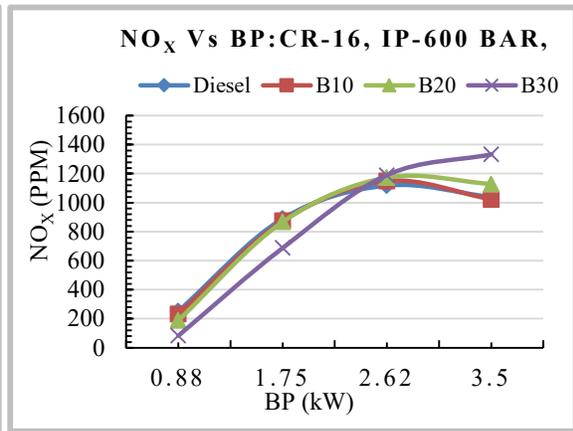


Figure 16: NO_x Vs BP, CR-16, IP-600 bar

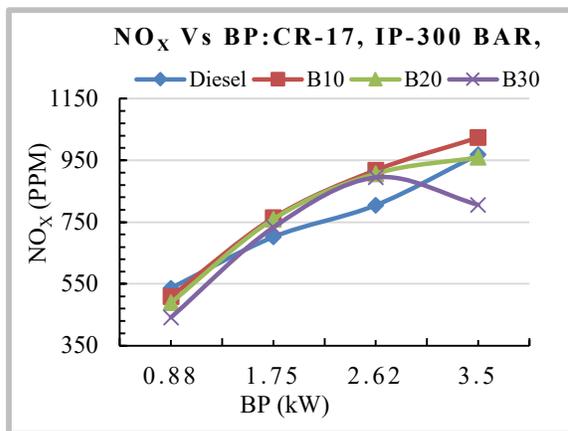


Figure 17: NO_x Vs BP, CR-17, IP-300 bar

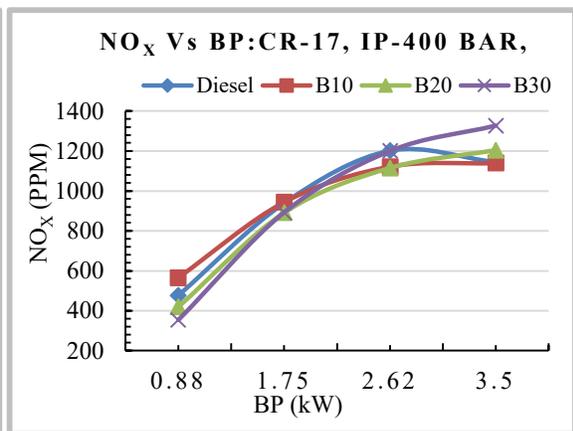


Figure 18: NO_x Vs BP, CR-17, IP-400 bar

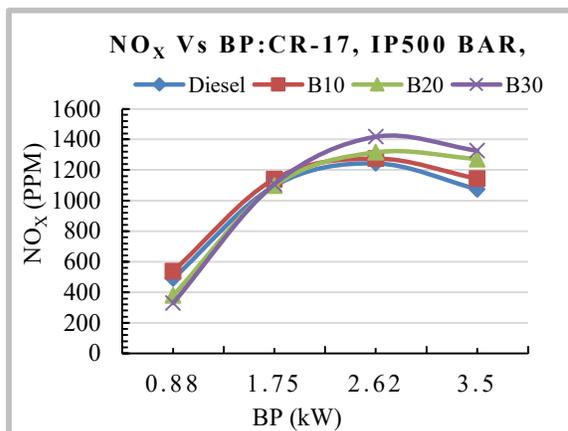


Figure 19: NO_x Vs BP, CR-17, IP-500 bar

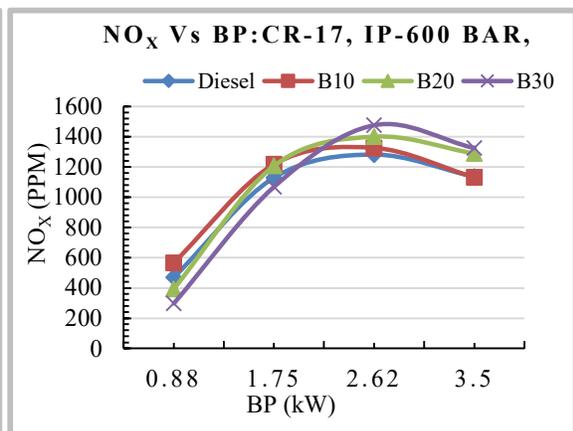


Figure 20: NO_x Vs BP, CR-17, IP-600 bar

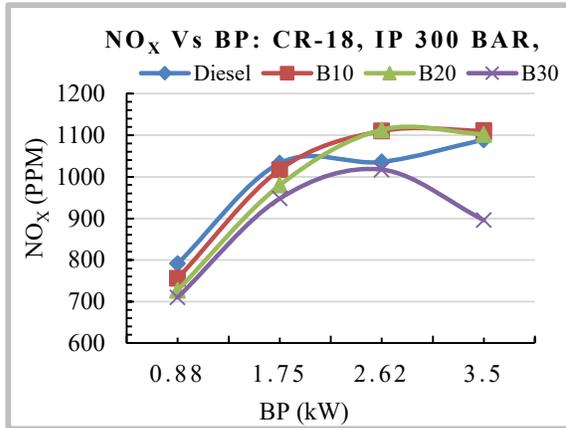


Figure 21: NOx Vs BP, CR-18, IP-300 bar

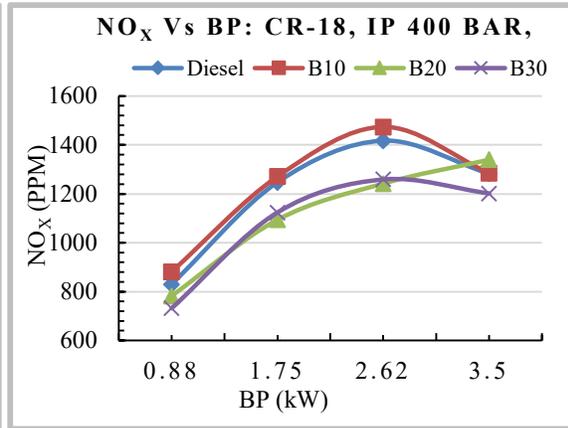


Figure 22: NOx Vs BP, CR-18, IP-400 bar

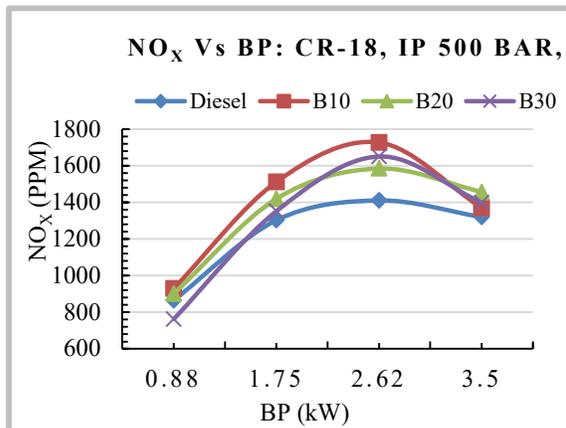


Figure 23: NOx Vs BP, CR-18, IP-500 bar

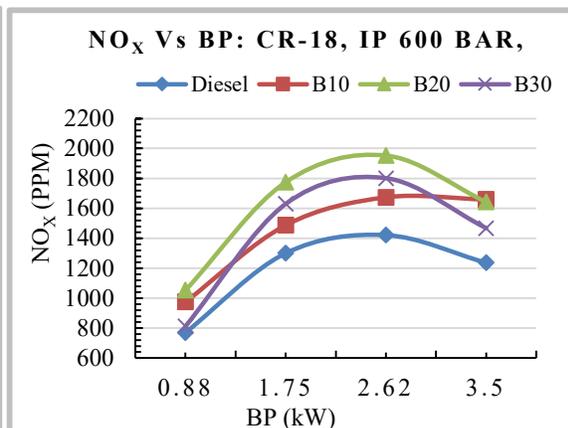


Figure 24: NOx Vs BP, CR-18, IP-600 bar

Table 6: Maximum NOx emission for each CR

Compression Ratio (CR)	Injection Pressure (IP) bar	Fuel Blend	Load (%)	NOx (ppm)	% Variation Compare to Diesel
15	600	B30	100	1311	12
16	600	B30	100	1334	28
17	600	B30	75	1476	15
18	600	B20	75	1953	37

The highest NOx emission value was observed for 600 bar injection pressure in the case of all the compression ratios and all the fuel blends, this may be due to proper atomization of the fuel which results in complete combustion. This phenomenon results in a high heat release rate which leads to higher cylinder temperature which is responsible for the thermal NOx formation.

Fig 25, Fig 26, Fig 27, and Fig 28 show NOx emission values corresponding to injection pressure for Diesel, B10, B20, and B30 fuel blends at compression ratios 15, 16, 17, and 18 respectively. At a compression ratio of 15 and injection pressure of 300 bar, the NOx

value was recorded at around 800 PPM while for a compression ratio of 18 and injection pressure of 600 bar NOx value was recorded at around 1700 PPM which means with increment in the value of compression ratio and injection pressure, NOx emission increases. This is maybe because at a high compression ratio, more quantity of air gets compressed and so more oxygen is available. At high compression ratios, air temperature also increases which results in better combustion; additionally, more oxygen content is there in biofuel compared to diesel. Apart from this at elevated temperatures, nitrogen can react and at a high compression ratio, more quantity of nitrogen is also available in the air. One more important observation is that at high injection pressure, more quantity of fuel is injected compared to low injection pressure. At high injection pressure, better atomization of fuel occurs so a better combustion process can be obtained so temperature inside the combustion chamber enhances which leads to higher NOx formation.

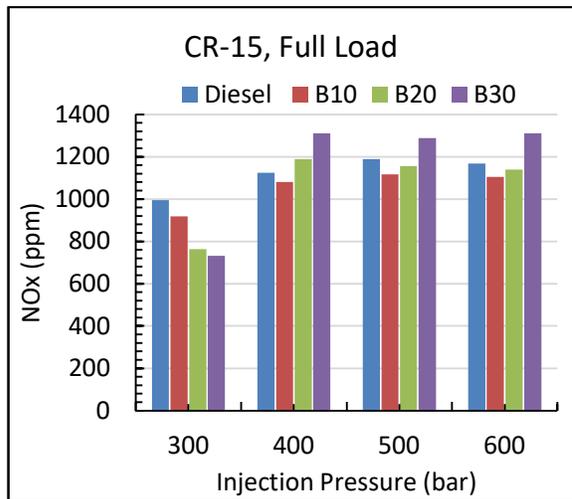


Figure 25: NOx Vs Injection Pressure, CR-15

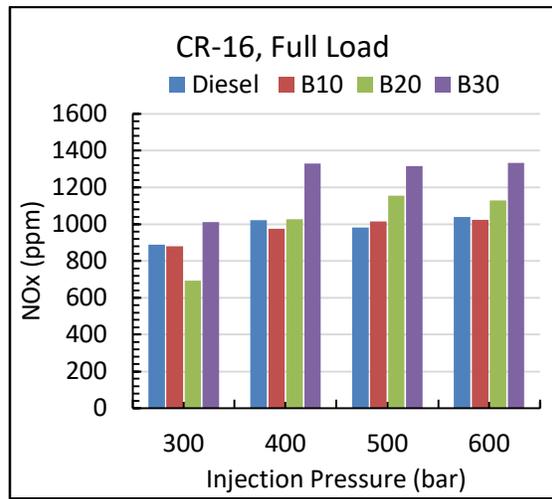


Figure 26: NOx Vs Injection Pressure, CR-16

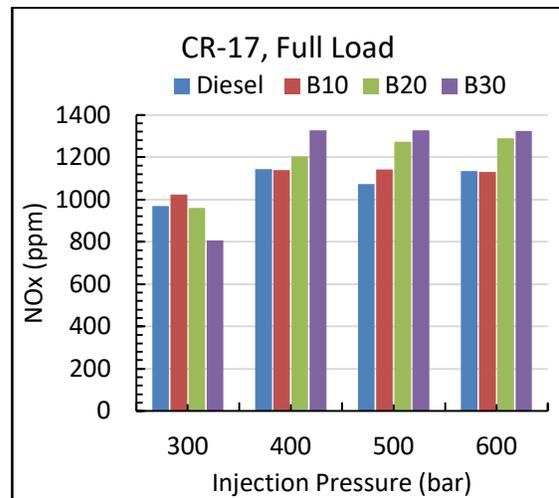


Figure 27: NOx Vs Injection Pressure, CR-17

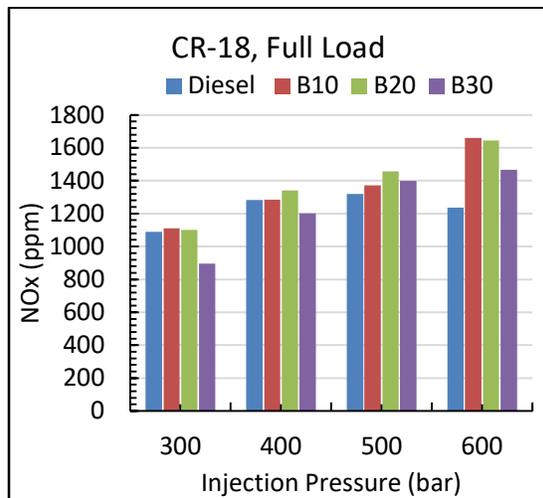


Figure 28: NOx Vs Injection Pressure, CR-18

Fig 29, Fig 30, Fig 31, and Fig 32 represent NOx emission values corresponding to fuel blends (diesel, B10, B20, and B30) for compression ratios 15,16, 17, and 18 respectively.

From the graphs it is observed that as the blend percentage rises with injection pressure and compression ratio, the NOx emission also increases, this may be due to as the compression ratio rises more quantity of air enters the cylinder. A rise in injection pressure results in a better atomization of fuel. All conditions are favourable to improve the combustion process, which leads to rises in NOx emission.

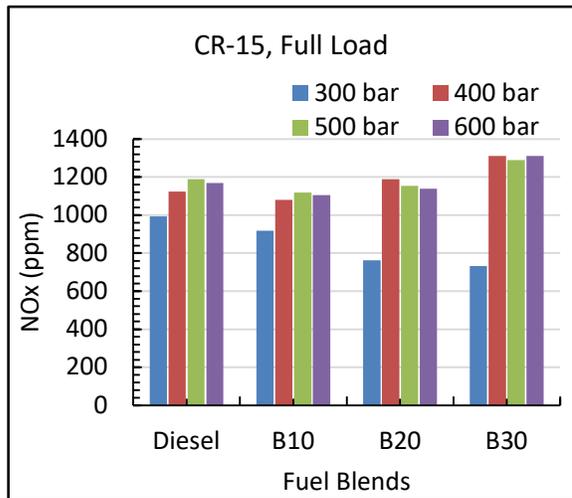


Figure 29: NOx Vs Fuel Blends, CR-15

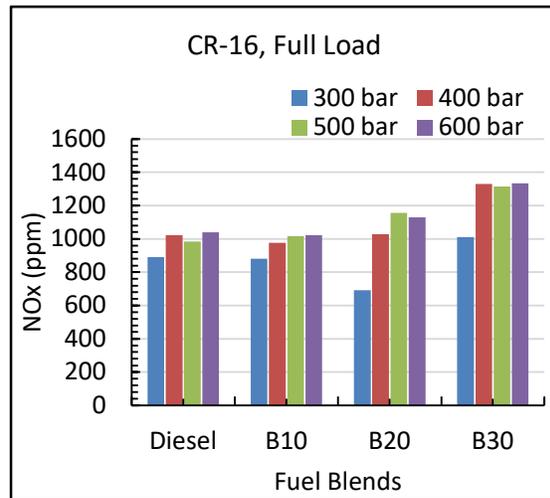


Figure 29: NOx Vs Fuel Blends, CR-15

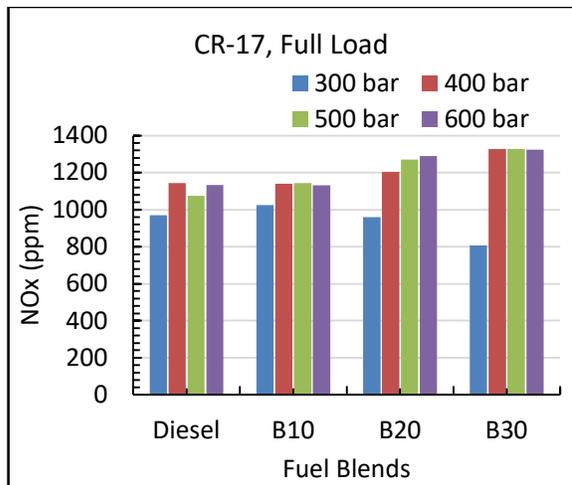


Figure 30: NOx Vs Fuel Blends, CR-17

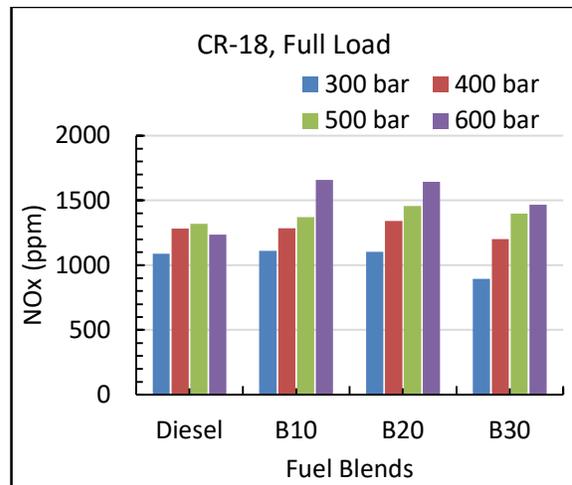


Figure 31: NOx Vs Fuel Blends, CR-18

5.1.1 Comparison with BS VI Emission norms

The engine used for the experimentation was a stationary, low-capacity engine (3.5 kW) so we have compared the emission data with emission standard gen-set application (up to 19 kW) under BS VI emission norms

Table 7 shows the allowable values for various emission elements as per the BS-VI standard for the diesel gen-set[31].

Table 7: BS VI Emission standard for gen-set up to 19kW (<https://dieselnet.com/>)

NO _x		CO		Smoke	
(g/kWh)	ppm	(g/kWh)	% Vol	(k Coefficient of light absorption, M ⁻¹)	Opacity Value
≤ 7.5	≤ 263	≤ 3.5	≤ 0.020	≤ 0.7	≤ 26

NO_x emission: In the case of compression ratios 15 and 16, NO_x emission was recorded below the limit of BS VI for all the blends at 25% loading condition. Except for all the combinations, NO_x emissions were recorded above the BS VI limit.

CO emission: None of the test runs have given the CO emission below the BS VI standard limit.

Smoke: The smoke value of all the test runs remains below the allowable value.

5.2 Phase-II

The second phase of the experiment was conducted by injecting the water at the exhaust manifold and NO_x emission values were recorded for the four different compression ratios (15,16,17 & 18), 600 bar injection pressure, 75%, and 100% engine loading condition for B10, B20 and B30 fuel blends.

5.2.1 Effect of water injection on NO_x emission

Fig. 33 to fig. 38 shows the behaviour of NO_x emission concerning water injection. It is observed that the NO_x emission reduces as the stream rate of water injection increases almost for all the cases. The average reduction of NO_x emission is 7.89%, 12.19%, and 17.73% for the 38.7 CC/min, 82.7 CC/min, and 130.4 CC/min respectively. The trend line of NO_x emission remains almost horizontal, which means at 130.4 CC/min flow rate, the highest reaction rate between the NO_x emission and H₂O has been achieved.

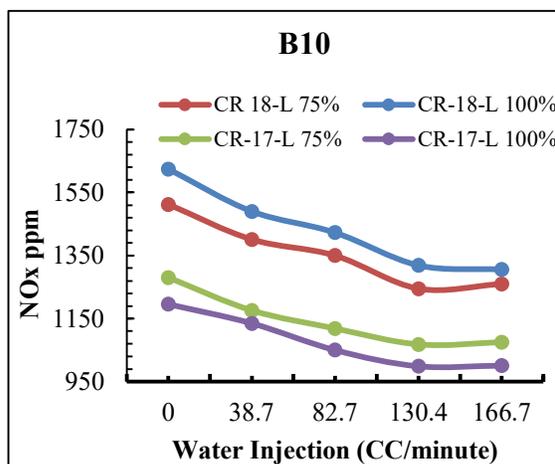


Figure 32:NO_x Vs Water Injection, B10, CR-17,18

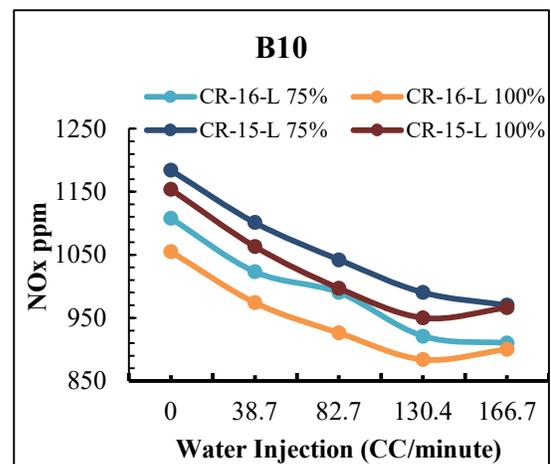


Figure 33:NO_x Vs Water Injection, B10, CR-16,15

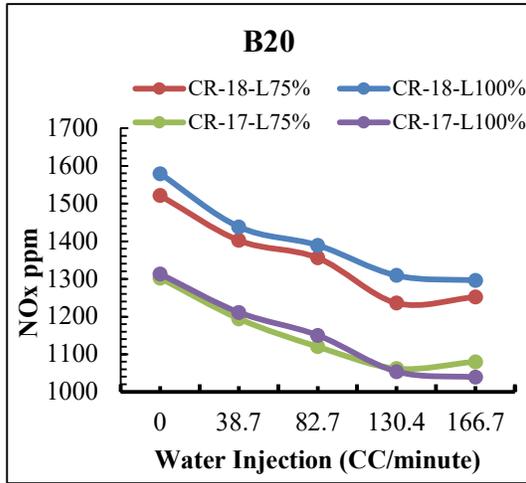


Figure 34: NOx Vs Water Injection, B20, CR-18,17

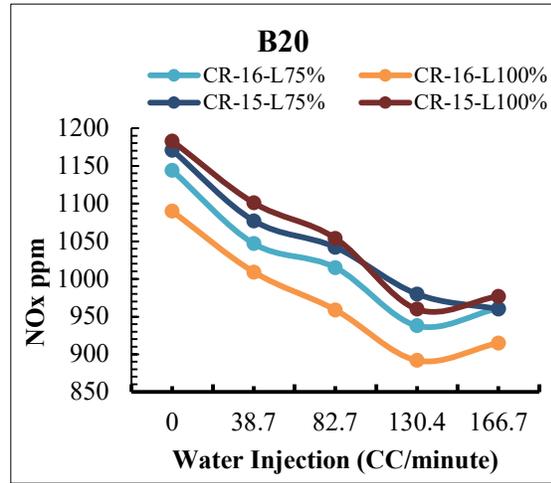


Figure 35: NOx Vs Water Injection, B20, CR-16,15

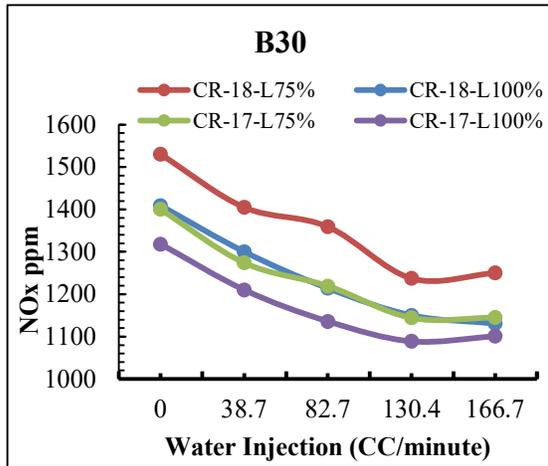


Figure 36: NOx Vs Water Injection, B30, CR-18,17

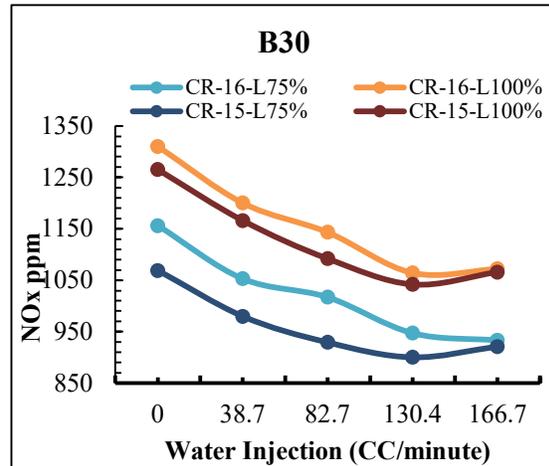


Figure 37: NOx Vs Water Injection, B30, CR-16,15

5.2.2 Effect of Water injection on CO emission

The water-gas shift reaction (WGSR) describes the reaction of carbon monoxide and vapour to form carbon dioxide and hydrogen:



The effect of water injection on CO emissions has been studied. The behaviour of the CO emission concerning water injection has been analyzed in Fig 39 to Fig 44. It has been observed that the CO emission is decreasing as the water flow rate increases. This trend is observed for all the fuel blends and compression ratios. The average reduction of CO emission is 17.14%, 32.77%, and 41.99% for the 38.7 CC/min, 82.7 CC/min, and 130.4 CC/min respectively. The trend line of CO emission remains almost horizontal, which means at 130.4 CC/min flow rate, the highest reaction rate between the CO emission and H₂O has been achieved.

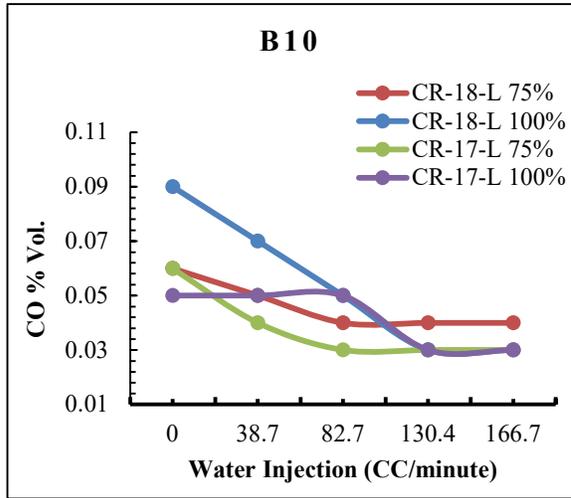


Figure 38: CO % Vol Vs Water Injection, CR-18,17, B-10

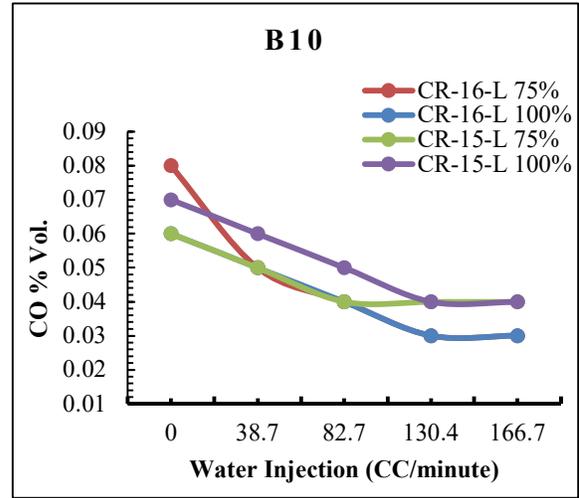


Figure 39: CO % Vol Vs Water Injection, CR-16,15, B-10

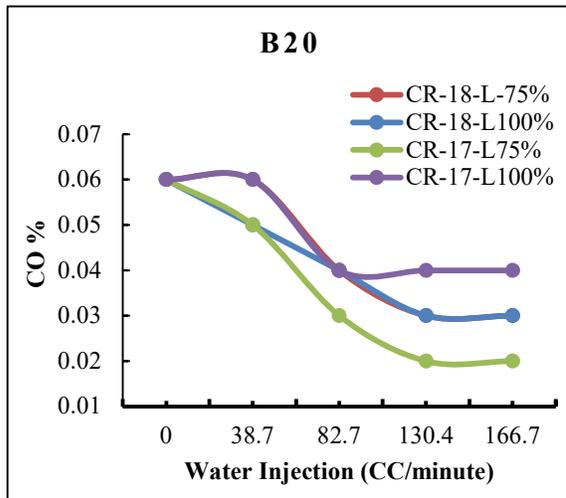


Figure 40: CO % Vol Vs Water Injection, CR-18,17, B-20

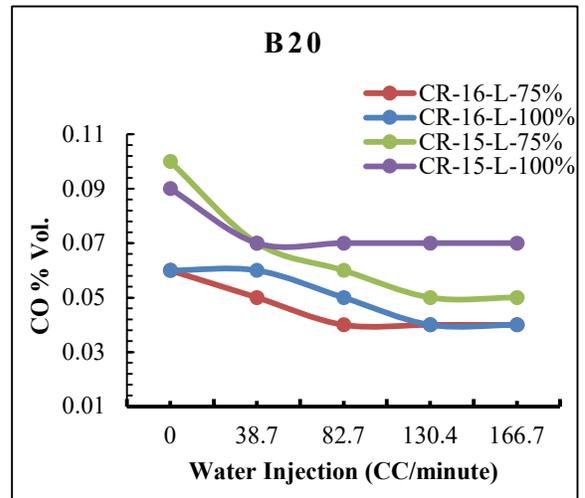


Figure 41: CO% Vs Water injection, CR-16,15, B-20

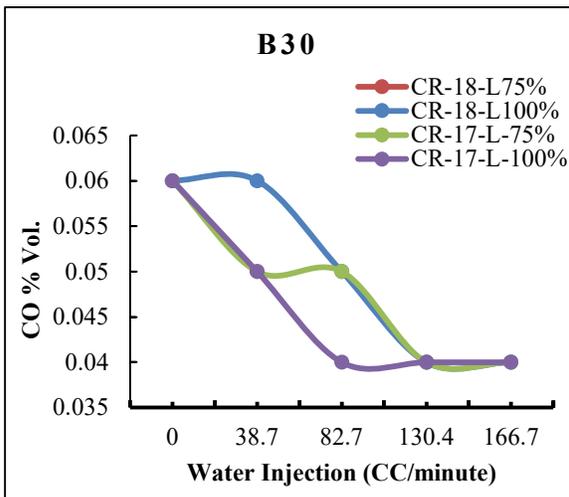


Figure 42: CO% Vol Vs Water Injection, CR-18,17, B-30

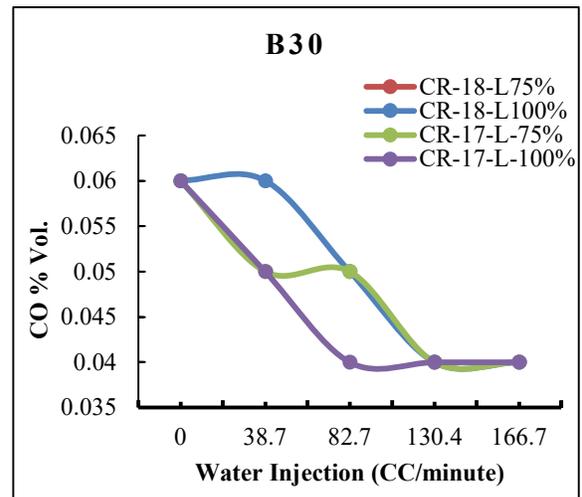


Figure 43: CO% Vol Vs Water Injection, CR-16,15, B-30

5.2.3 Effect of Water Injection on Smoke emission

The effect of water injection on smoke emission has been analysed and the behaviour of smoke emission concerning water injection is recorded as shown in Fig 45 to Fig 50. It has been observed that the smoke emission decreases as the water flow rate increases for all the fuel blends and compression ratios. The average reduction of smoke emission is 28.84%, 55.54%, and 56.26% for the 38.7 CC/min, 82.7 CC/min, and 130.4 CC/min respectively. The trend line of smoke emission remains almost horizontal, which means at 130.4 CC/min flow rate, the highest reaction rate between the CO emission and H₂O has been achieved.

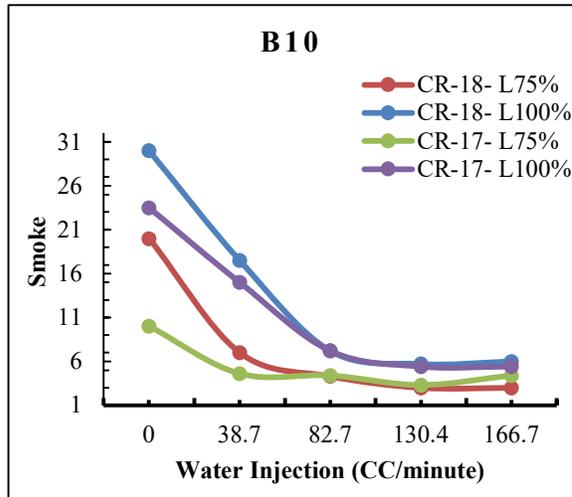


Figure 44: Smoke Vs Water Injection, CR-18,17, B-10

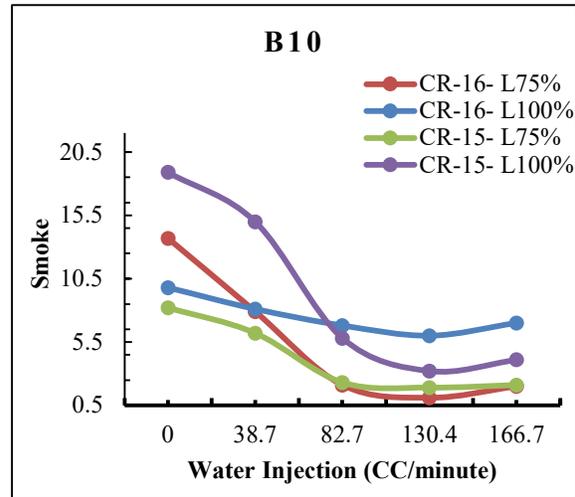


Figure 45: Smoke Vs Water Injection, CR-16,15, B-10

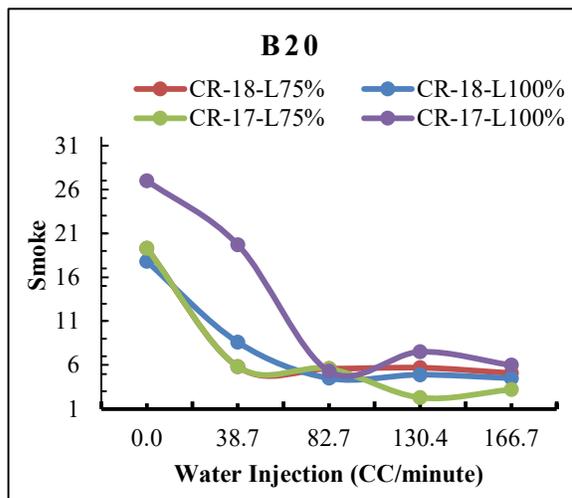


Figure 46: Smoke Vs Water Injection, CR-18,17, B-20

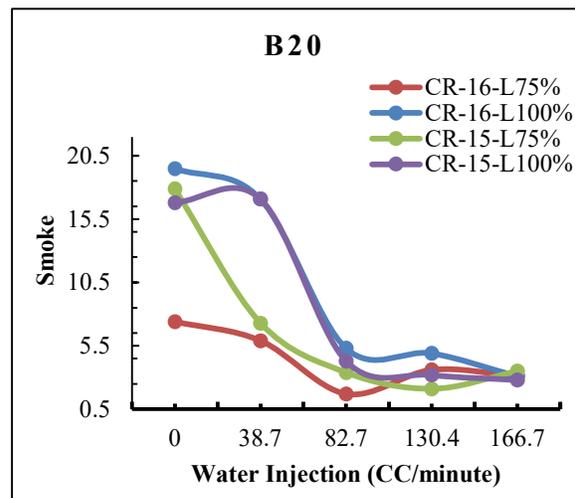


Figure 47: Smoke Vs Water Injection, CR-16,15, B-20

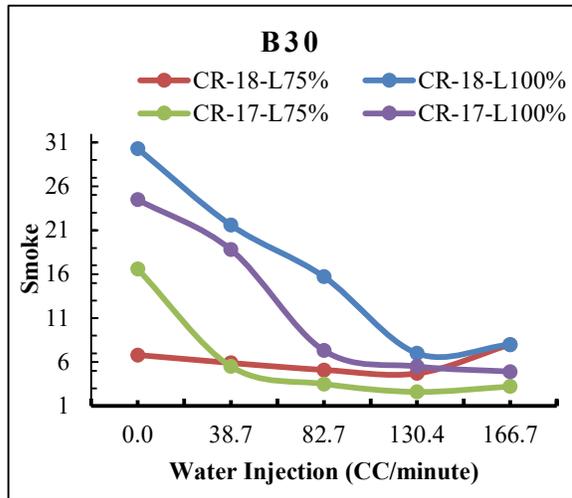


Figure 48: Smoke Vs Water Injection, CR-18,17, B-30

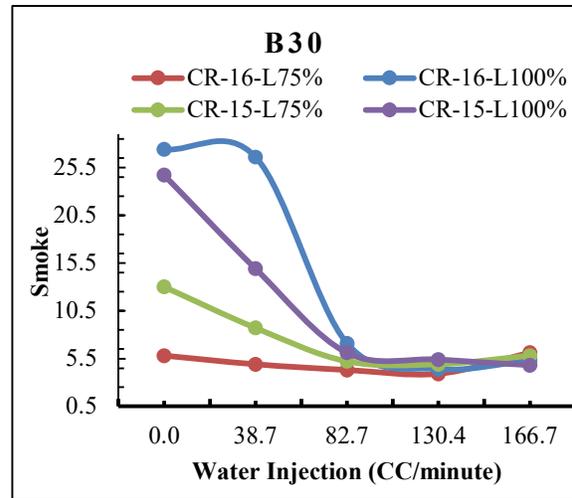


Figure 49: Smoke Vs Water Injection, CR-16,15, B-30

6 Conclusion:

- The effect of compression ratio and the injection pressure has a considerable effect on the NOx emission. As the biodiesel blend percentage increases, NOx emission increases.
- Maximum NOx recorded at the 75% and 100% engine loading condition for all the Compression ratio, injection pressure, and fuel blends.
- Maximum NOx recorded for the 600-bar injection pressure for all the Compression ratios and fuel blends.
- The average reduction of NOx emission by incorporating a water injection system in the exhaust manifold is 7.89%, 12.19%, and 17.73% for the 38.7 CC/min, 82.7 CC/min, and 130.4 CC/min respectively. The trend line of NOx emission remains almost horizontal, which means at 130.4 CC/min flow rate, the highest reaction rate between the NOx emission and H₂O has been achieved.
- The average reduction of CO emission is 17.14%, 32.77%, and 41.99% for the 38.7 CC/min, 82.7 CC/min, and 130.4 CC/min respectively. The trend line of CO emission remains almost horizontal, which means at 130.4 CC/min flow rate.
- The average reduction of smoke emission is 28.84%, 55.54%, and 56.26% for the 38.7 CC/min, 82.7 CC/min, and 130.4 CC/min respectively. The trend line of smoke emission remains almost horizontal, which means at 130.4 CC/min flow rate.

At a higher compression ratio and higher fuel injection pressure, better thermal and combustion efficiency of a CI engine can be achieved, but on the other hand, NOx emissions increase. Water injection in the exhaust manifold is the better option to mitigate the NOx, CO, and smoke emissions without disturbing performance and combustion efficiency. For the mitigation of the NOx emission, a dedicated engine should be designed and fabricated but the different biodiesels have different fuel properties so it is not practically an option.

7 Tentative structure of Ph.D. Thesis

Chapter 1: Introduction

This chapter has provided an introduction to the topic and motivation for carrying out this research. It also discusses the environmental, health, and energy scenarios.

Chapter 2: Literature Review

Describes the various techniques to mitigate the NO_x emission of the compression ignition engine. Describes the effect of compression ratio and injection pressure on performance, combustion, and emission parameters of CI engine. An exhaustive literature survey defines the research gap and identifies the research objective of the thesis.

Chapter 3: Experiments

This chapter discusses biodiesel, the production of the biodiesel by transesterification process, preparation of diesel-biodiesel blends, measurements of the diesel-biodiesel blend's properties, details of the experimental setup, measuring instruments, experimental methodology, water and NO_x emission reaction, recording and storage management of experimental data,

Chapter 4: Results & Discussion

This chapter describes the effect of various compression ratios, injection pressure, and fuel blends on NO_x emission. The chapter also describes the effect of water injection effect on NO_x emission.

Chapter 5: Conclusions and future scopes

The chapter summarises and discusses all the results obtained by the author. The limitations and assumptions are also discussed in the chapter. The future scope of the research work also has been discussed.

Chapter 6: Bibliography

This chapter includes the list of references used in each chapter and a list of publications and presentations done based on the research work.

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9 Paper Publication

Journal Papers (Scopus Indexed)

1. A. Shekh, N. Patel, and B. Pathak, “Experimental Study of Exhaust Manifold Water Injection on Emission of CI Engine Fueled with *Madhuca Longifolia* and Diesel Blends,” vol. 2, no. 2, pp. 116–136, 2023. (Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, Scopus Indexed) ISSN: 2289-7879
2. Asfakahamad Shekh,” no. X, p. 20220922. Multi-Parameter Analysis of Low-Capacity C I Engine Powered with Biodiesel from Various Feedstock using Diesel R K Software. (Journal of Heat and Mass Transfer Research) ISSN: 2383-3068
3. A. Shekh and N. Patel, “IMPACT OF COMPRESSION RATIO & INJECTION PRESSURE ON NO X EMISSION BEHAVIOUR OF VCR DIESEL ENGINE POWERED BY MADHUCA,” pp. 1106–1127, 2023. (European Chemical Bulletin, ISSN: 2063-5346, Scopus Indexed)

Conferences (International)

1. Presented a Review article “A Review on Techniques to mitigate NO_x in CI engine fueled with various biodiesel blends “at 7th International Conference on Engineering Research and Innovation (ICERI 2022) organized by Terna Engineering College (TEC), Nerul, Navi Mumbai
2. Presented paper with the title “Assessment of Critical Parameters of Low Capacity Diesel Engine Fueled by Multiple Biodiesel Blends Using Diesel RK Software”. in the 1st International Conference on Sustainable Energy Sources, Technologies, and Systems (ICSESTS-2023) at the Division of Research and development, lovely professional university, pagwara, Punjab.
3. Presented paper with the title “Influence of Varying Compression Ratio on Performance and Combustion characteristics of a VCR engine using *Madhuca Longifolia* biodiesel and diesel blends”. in the International Conference on Advances

in Renewable and Green Energy Technology (ICARGET-2023) Guru Ghasidas Vishwavidyalaya, Bilaspur (Chhattisgarh).

Journal Papers (Scopus Indexed)

1.

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 112, Issue 2 (2023) 116-136



Experimental Study of Exhaust Manifold Water Injection on Emission of CI Engine Fueled with Madhuca Longifolia and Diesel Blends

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Research Article

Multi-Parameter Analysis of Low-Capacity C I Engine Powered with Biodiesel from Various Feedstock using Diesel R K Software

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ABSTRACT

3.

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IMPACT OF COMPRESSION RATIO & INJECTION PRESSURE ON NO_x EMISSION BEHAVIOUR OF VCR DIESEL ENGINE POWERED BY MADHUCA LONGIFOLIA BIODIESEL

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1.

CERTIFICATE

— OF PRESENTATION —

7th International Conference on Engineering Research and Innovations - (ICERI-2022)

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This is to Certify that Asfakahemad Shekh.....of

THE MAHARAJA SAYAJIRAO UNIVERSITY OF BARODA.....presented his/her research paper titled A Review on Techniques to mitigate NO_x in CI Engine fueled with various biodiesel blends.....in

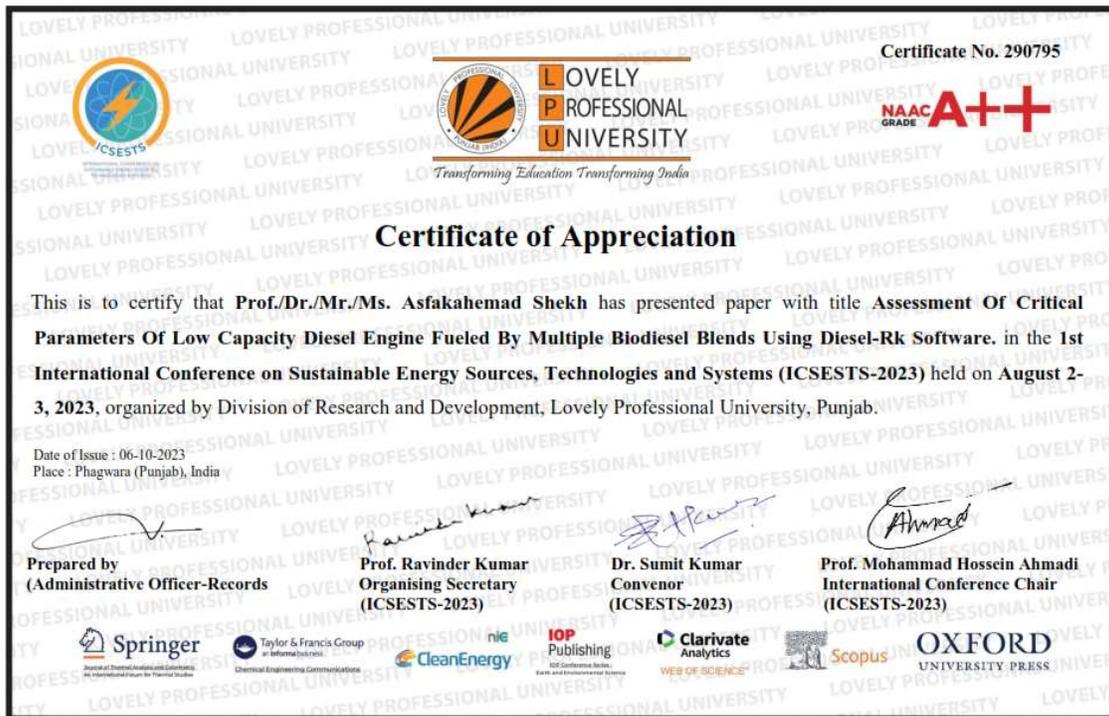
the “7th International Conference on Engineering Research and Innovations (ICERI-2022)” organized by Terna Engineering College (TEC), Nerul, Navi Mumbai, in association with Institute For Engineering Research and Publication (IFERP) held on 22nd & 23rd September 2022 (Virtual Conference).

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3.

