UTILIZATION OF TERNARY FUEL BLENDS IN A COMPRESSION IGNITION ENGINE– PERFORMANCE, EMISSION AND COMBUSTION STUDIES

A Thesis submitted to the Delhi Technological University, Delhi in fulfillment of the requirements for the award of the degree of

DOCTOR OF PHILOSOPHY

in

Mechanical Engineering

by

SIDHARTH

(2K16/Ph.D/ME/24)

Under the supervision of

Dr. NAVEEN KUMAR

(Professor)

Mechanical Engineering Department

Delhi Technological University

Shahbad Daulatpur, Main Bawana Road,

Delhi-110042, India

September, 2019

DECLARATION

I hereby declare that the thesis entitled "**UTILIZATION OF TERNARY FUEL BLENDS IN A COMPRESSION IGNITION ENGINE – PERFORMANCE, EMISSION AND COMBUSTION STUDIES**" is an original work carried out by me under the supervision of Dr. Naveen Kumar, Professor, Department of Mechanical Engineering, Delhi Technological University, Delhi. This thesis has been prepared in conformity with the rules and regulations of the Delhi Technological University, Delhi. The research work reported and results presented in the thesis has not been submitted either in part or full to any other university or institute for the award of any other degree or diploma.

(Sidharth)
2K16/PhD/ME/24
Research Scholar
Mechanical Engineering Department
Delhi Technological University
Delhi-110042

Date: 21 September 2019
Place: Delhi

CERTIFICATE

This is to certify that the work embodied in the thesis entitled "**UTILIZATION OF TERNARY FUEL BLENDS IN A COMPRESSION IGNITION ENGINE – PERFORMANCE, EMISSION AND COMBUSTION STUDIES**" by **Mr. Sidharth**, **(Roll No.-2K16/PhD/ME/24)** in partial fulfillment of requirements for the award of Degree of **DOCTOR OF PHILOSOPHY in Mechanical Engineering**, is an authentic record of student's own work carried by him under my supervision. This is also certified that this work has not been submitted to any other Institute or University for the award of any other diploma or degree.

(Dr. Naveen Kumar)
Professor
Mechanical Engineering Department
Delhi Technological University
Delhi- 110042

ACKNOWLEDGEMENT

It is a distinct pleasure to express my deep sense of gratitude and indebtedness to my learned guide Prof. Naveen Kumar for his invaluable guidance, encouragement and patient review. In spite of his busy schedule, he could find time to provide me precious guidance. His continuous inspiration has made me complete this thesis.

I also take this opportunity to thank Prof. R.S. Mishra, DRC Chairman, Prof. Vipin, Head, Mechanical Engineering Department, Prof. Reeta Wattal, Prof. Vikas Rastogi, Prof. R.C. Singh, Mr. Rool lal and other faculty members of Mechanical Engineering Department, DTU, Delhi for their encouragement and guidance.

I have to thank the esteemed co-associates of Centre for Advanced Studies Research in Automotive Engineering (CASRAE), Delhi Technological University; particularly ex researchers, Dr. Harveer Singh Pali, Assistant Professor, NIT Srinagar and Dr. Parvesh Kumar, Assistant Professor, Vaagdevi College of Engineering, Warangal and current research scholars, Mr. Sunil Kumar Sinha, Mr. Ankit Sonthalia, Mr. Mukul Tomar, Mr. Dushyant Mishra for their excellent tips and valuable support. I am also thankful to Mr. Kamal Nain for providing help and all the assistance in the laboratory, Mr. Surendra Singh and Mrs. Neetu Mishra, supporting staff of CASRAE, DTU, Delhi.

I am thankful to my colleagues at MAIT namely Prof. V.K. Jain, Prof. V.N. Mathur, Dr. Vipin Kumar Sharma and Mr. Ramakant Rana for their continuous motivation, support and for being my well-wishers by heart. I am also very thankful to the Founder Chairman and Chief advisor, MATES, Dr. Nand Kishore Garg who is a senior social worker and a very kind hearted man. He has full faith in me and provided me with an opportunity to work and study at the same time. I am also very thankful to the Management of MAIT for extending their kind support.

I want to express my sincere gratitude in words for the affection, encouragement and moral support by my wife Priyanka during the entire research work. I am also ever gratified to my daughter Deetya for not giving her enough attention and time during the present work.

I don’t want to leave the almighty God and my parents Mr. Virender Bansal and Mrs. Urmil Bansal who brought me to this world and has given me the strength to work on the present work with full focus.

Finally, I am also thankful to my numerous friends and family members whose names I haven’t added here but have helped me in my research and I will always be obliged for their guidance and support.

(Sidharth)

ABSTRACT

Large fluctuations in the price of a barrel of crude oil and awareness of the finite nature of fossil fuels have strongly built the general interest for biofuels. The replacement of some traditional fuels with products from biomass meets a triple challenge: economic (self-generation of energy), environmental (emissions effect) and legislative (Government mandates/standards).

Compared to the spark ignition engine, the diesel engine has the advantage of having a high efficiency owing to its higher compression ratio. In recent years, not so notable improvements in the diesel engine have been made and it is very difficult to meet pollutant emission standards.

The current research objective is to find a fuel that can help in successfully replacing a part of fossil derived diesel. In this effort diesel, biodiesel and octanol are blended in different proportions to give comparable and if possible better performance, emission and combustion characteristics.

To do so, biodiesel production from waste cooking oil was carried out. Optimization of biodiesel production using the best input parameters viz. catalytic concentration, the molar ratio (methanol to oil), the temperature of reaction, time of reaction and agitation speed was carried out. These parameters were varied on the basis of the design of experiments using Taguchi approach. Also, confirmation of experiments was carried out for the biodiesel production. The predicted yield obtained was 97.13% on using optimum parameters which were in very close agreement to confirmation experimental yield of 96.9%. From Taguchi technique results, catalytic concentration and molar ratio were found to be the most prominent parameters that affect biodiesel production.

Several properties like density, kinematic viscosity, calorific value, cetane index, cloud point, pour point, cold filter plugging point, flash point, oxidation stability, etc. were

found for the test fuels. The ternary fuel blends properties were very close to diesel and within ASTM standard limits. Apart from these, GCMS was carried out for determining the components of methyl ester. Also, FTIR results were obtained for binary and ternary fuel blends, showing the presence of biodiesel and alcohol in the blends. Phase stability of test fuel blends was analyzed using ternary phase diagram at different temperatures. The fuels were found to work at very low operating temperatures also.

The blends were used to study the brake thermal efficiency (BTE), brake specific energy consumption (BSEC) and exhaust gas temperature (EGT) of a 3.5 KW Kirloskar make water cooled diesel engine. The engine was coupled to eddy current dynamometer for loading. BTE was found higher for 10O10WB80D (10% octanol + 10% waste cooking oil biodiesel + 80% diesel by volume) blend and lower for the other ternary fuel blends when compared to diesel. Similarly, 10O10WB80D blend displayed lower BSEC compared to diesel whereas the other two ternary fuel blends displayed higher BSEC. EGT of test fuels gets reduced on increasing octanol content in the fuel whereas it increased on increasing biodiesel content.

All the blends exhibited comparable emissions. Lower smoke and CO emissions were observed for all test fuels due to more oxygen content whereas higher HC emissions were observed for ternary fuel blends. NO_X emissions were similar and related to the engine EGT. Higher the biodiesel in the blends more was the NO_X emissions whereas, higher octanol content in blends reduces NO_X because of quenching of engine cylinder walls.

Combustion characteristics like heat release rate, in-cylinder pressure and mass fraction burnt were determined and were found very similar to diesel. All the test fuels confirm the combustion and performance characteristics relationship. It is concluded that ternary fuel blend of diesel, biodiesel and octanol produces nearly the same or better engine performance and combustion characteristics with a drastic reduction in engine exhaust emissions except for unburnt HC emissions**.**

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

NOMENCLATURE

θ_s	Crank angle at the beginning of the combustion
100D	100% diesel
100WB	100% biodiesel
10O10WB80D	10% octanol, 10% biodiesel and 80% diesel
10O20WB70D	10% octanol, 20% biodiesel and 70% diesel
10O90D	10% octanol and 90% diesel
10WB90D	10% biodiesel and 90% diesel
20O10WB70D	20% octanol, 10% biodiesel and 70% diesel
A	Area of the bore of cylinder
ANOVA	Analysis of variance
ASTM	American Society for Testing and Materials
B25	25% biodiesel blend
BDC	Bottom dead center
BMEP	Brake mean effective pressure
BP	Brake power
BSEC	Brake specific energy consumption
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
CI	Compression ignition
CCI	Calculated cetane index
CFPP	Cold filter plugging point
CO	Carbon monoxide
CO_2	Carbon dioxide
CR	Compression ratio
cSt	Centistokes
C_V	Calorific value
D	Density of fuel
DEE	Di ethyl ether
DOE	Design of experiments
EGR	Exhaust gas recovery
EGT	Exhaust gas temperature
EN	European standards

FFA	Free fatty acids
FTIR	Fourier-transform infrared spectroscopy
GC-MS	Gas chromatography–mass spectrometry
HC	Hydrocarbon
HRR	Heat release rate
HVO	Hydrotreated vegetable oil
k	Constant which depends upon the capillary
L	Piston stroke length
L/ha	Litre per Hectare
M	Molar concentration of titrant
m	Total mass of gas
mbpd	Million barrels per day
m_f	Mass of fuel consumed
MMT	Million metric tons
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_X	Oxides of nitrogen
PM	Particulate matter
PPM	Parts per million
Q	Summation of HRR and heat transfer rate
Q_{rel}	Pressure rise
R	Specific gas constant
rpm	Revolutions per minute
SMD	Sauter mean diameter
SNR	Signal to noise ratio
SO_2	Sulphur dioxide
T	Torque
T_{10X}	Recovery temperature for getting 10% distillate
T_{50X}	Recovery temperature for getting 50% distillate
T_{90X}	Recovery temperature for getting 90% distillate
TDC	Top dead center
V	Volume of the cylinder.
v/v	Volume per volume

Vc	Volume of fuel consumed
W	Rate of work done
WCO	Waste cooking oil
W_{oil}	Weight of oil,
Y	Responses for the given factor level combination
γ	Ratio of specific heats
η_{th}	Brake thermal efficiency
θ	Crank angle
ν	Kinematic viscosity
ρ	Fuel density

CHAPTER 1

INTRODUCTION

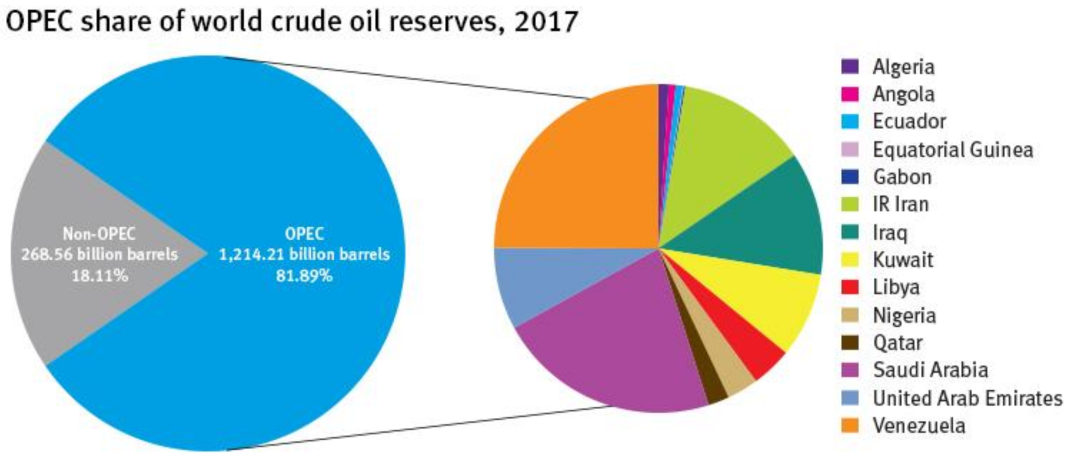
1.1 Motivation for the present work

Increase in industrialization and globalization has increased our dependence on fossil fuels tremendously. A developing country like India is importing nearly 85% of crude oil from foreign nations causing a lot of pressure on Indian economy. Apart from this, environmental pollution degradation has mandated the researchers to think about new alternative fuels. Diesel engines being robust, efficient and powerful make them very popular and has applications in agriculture, power generation and transport sectors. However, due to severe emissions (smoke, carbon monoxide, unburnt hydrocarbons and nitrogen oxide) liberated from diesel engines, a search for exploring cleaner fuel is a necessity. The objective of the current research is to find cleaner alternative fuels that can successfully run in the current engine setups.

1.2 Energy Scenario

Due to the concern of future availability of oil reserves and environmental problems, growing interest is being shown in biofuels for internal combustion engines. Diesel and petrol engines play an important role in the world's transport, power and agricultural sector. Indian economy is highly dependent upon the agriculture sector. Diesel engines are preferred because of their higher efficiencies and low-cost operations. However, with diesel fuel, compression ignition (CI) engines produce higher amounts of pollutants like smoke and oxides of nitrogen (NO_X) (Sindhu et al., 2018). Depleting fuel reserves and higher prices is also raising many questions about the usage of fossil fuels (Nanthagopal et al., 2019; Zou et al., 2016).

From Figure 1.1, it is seen that the share of OPEC equals to nearly 82% of the world's total crude oil reserves. (Annual Statistical Bulletin, OPEC, 2018). It is equal to 1214 billion barrels in the year 2017.



OPEC proven crude oil reserves , at end 2017 *(billion barrels, OPEC share)*

Venezuela	302,81	24,9%	Kuwait	101,50	8,4%	Qatar	25,24	2,1%	Gabon	2,00	0,2%
Saudi Arabia	266,26	21,9%	UAE	97,80	8,1%	Algeria	12,20	1,0%	Equat. Guinea	1,10	0,1%
IR Iran	155,60	12,8%	Libya	48,36	4,0%	Angola	8,38	0,7%			
Iraq	147,22	12,1%	Nigeria	37,45	3,1%	Ecuador	8,27	0,7%			

Source: OPEC Annual Statistical Bulletin 2018.

Figure 1.1. World's proven oil reserves (Annual Statistical Bulletin, OPEC, 2018)

From Figure 1.2, it is observed that the World's crude oil production is nearly 74.69 million barrels/day (mbpd). OPEC countries share equals to nearly 43% of total crude oil production.

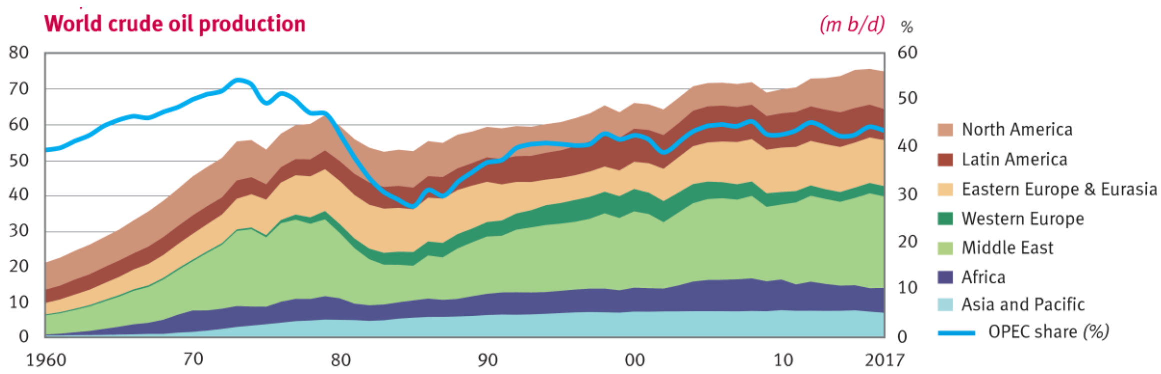


Figure 1.2. World's crude oil production (Annual Statistical Bulletin, OPEC, 2018)

Table 1.1 shows the consumption of different primary energy sources in the world. Among all fuel sources, oil, gas and coal are the most preferable fuel sources. Table 1.1 compares different fuel types from 1970-2040.

Table 1.1. Global consumption of primary energy in Mtoe (BP Energy Outlook, 2019)

Fuel type/ Years	1970	1980	1990	2000	2010	2020	2030	2040
Oil	2292	3053	3237	3691	4145	4675	4829	4860
Gas	827	1224	1676	2065	2731	3382	4041	4617
Coal	1467	1793	2222	2356	3606	3779	3647	3625
Nuclear	18	161	453	584	626	673	739	770
Hydro	266	384	489	601	778	993	1165	1245
Renewables	6	11	35	59	234	802	1674	2748

The oil demand in India in the year 2040 shall increase to 10.3 mbpd from 4.4 mbpd in 2016 (World Oil Outlook 2040, Organization of the Petroleum Exporting Countries, 2017). Worldwide passenger cars number is expected to rise to nearly double in 2040 compared to 2016, from nearly 1 billion to greater than 2 billion (World Oil Outlook 2040, Organization of the Petroleum Exporting Countries, 2017). It is concluded from Figure 1.3 that the production of crude oil in India in the years 2017-18 and 2016-17 are 35.68 million metric tons (MMT) and 36.01 MMT respectively (Indian PNG Statistics, 2018).

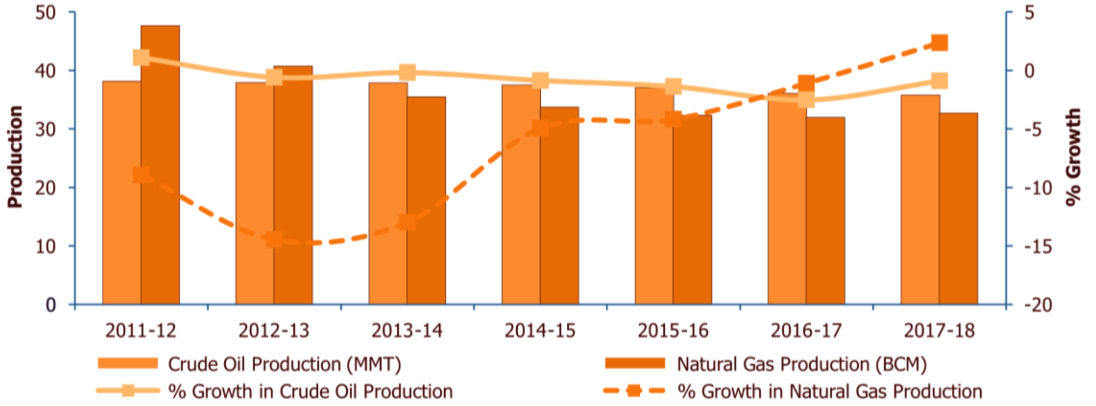


Figure 1.3. crude oil and natural gas production in India (Indian PNG Statistics, 2018)

In India, the number of passenger cars is projected to increase by 10 times i.e. from 24 million in 2017 to 152 million in 2040 (World Oil Outlook 2040, Organization of the Petroleum Exporting Countries, 2017). Figure 1.4 shows the amount spent on purchasing crude oil from the international market.

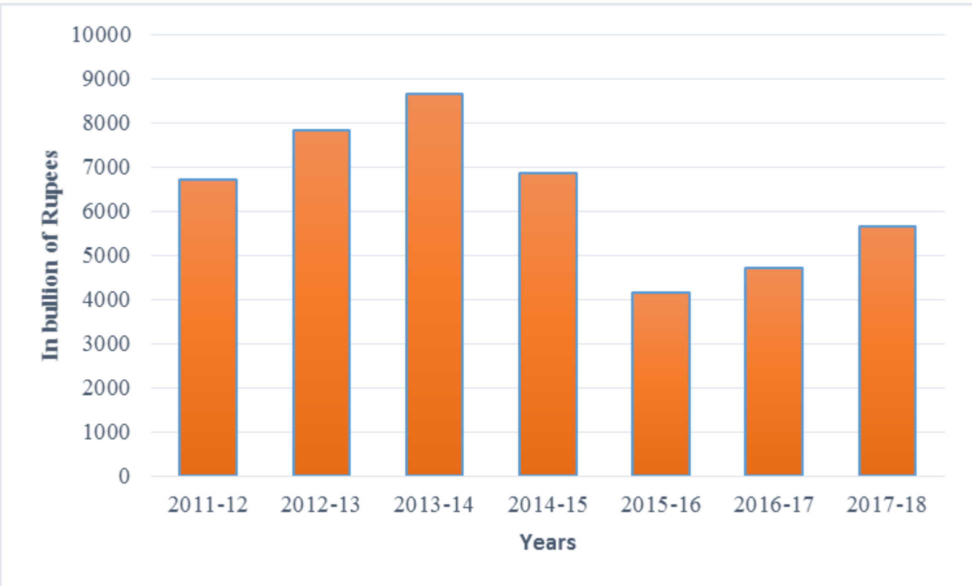


Figure 1.4. Expenditure incured in importing Crude oil (Indian PNG Statistics, 2018)

It is observed that due to lowering of crude oil prices worldwide the expenditure has decreased. However, it is again showing an increasing trend (IEA, 2019). It is observed from Figure 1.4 that nearly 6000 billion rupees have been spent in the 2017-18 for purchase of crude oil.

1.3 Diesel engine and Indian economy

Since independence, the consumption of diesel has increased multifold due to modernisation and mechanisation of many on the farm and off farm equipment. India's economy is based on agriculture. Therefore the energy produced and consumed in the agriculture sector is on high priority to the government. Diesel engines are also extensively used in transport buses, trucks, electric generators, locomotives, underground mine equipment and farm equipment.

Diesel engines are the pillar of the Indian economy. When compared to petrol, diesel fuel consumption is 4-5 times in India. This clearly indicates that India is very much dependent on diesel fuel. For transportation, energy can be obtained from petroleum products, biomass, hydrogen and fuel cells. Many practical applications namely industrial, power and transportation sectors (Chauhan et al., 2010a; Tippayawong and Sittisun, 2012) prefer diesel engines owing to higher brake thermal efficiency (BTE) (Reitz and Duraisamy, 2015) and lower cost of diesel fuel (Dabelstein et al., 2016). Therefore, diesel consumption in India is much higher than petrol (Panigrahi et al., 2014). Moreover, most of the Indian population lives in a rural area, where the source of income primarily comes from agriculture which uses diesel engines for many purposes (Kadiyala et al., 2014). However, the diesel engine is associated with higher harmful emissions like smoke, NO_X, hydrocarbon (HC), carbon dioxide (CO_2), carbon monoxide (CO), particulate matter (PM) etc. (Bhandarkar, 2013; Reşitoğlu et al., 2015;

Song et al., 2009) and therefore, cause air pollution (Shahir et al., 2015). NO_X and PM emissions are more significant as in-cylinder temperature and compression ratio are higher in the CI engine compared to spark ignition engines (EL_Kassaby and Nemit_allah, 2013).

To overcome the problem of toxic emissions from diesel engine various techniques were proposed in the past. Exhaust gas recovery (EGR), late intake valve closing, varying compression ratio, water injection, advance fuel injection, catalytic convertors, diesel particulate filter are among the few (Czerwinski et al., 2015; Kumar et al., 2018; Ma et al., 2014; Saravanan et al., 2015; Vallinayagam et al., 2013; Zhang et al., 2016). However, all these techniques alter the working of a diesel engine which may in turn cause some reduction in performance of the engine. Various techniques are there in which the petroleum diesel is replaced with biofuels that reduces the harmful emissions generated. It is very much essential to consider renewable fuel as an appropriate substitute for current fossil fuels.

From the previous sections, it is clearly inferred that globally the twin difficulties of destruction to the environment and depletion of fossil fuels are causing a lot of problems. Due to the volatility of fossil fuel prices, a much cleaner and economical fuel than present day fossil fuels need to be explored. Usage of bio origin based fuels shall help in solving these problems. Bio origin fuels are mainly non-petroleum fuels and results in environmental benefits and energy security.

To decrease the dependance on fossil fuels, researches are carried out to find alternative fuels. Several alternative fuels namely alcohols, hydrogen, biogas, producer gas and several varieties of non edible and edible oils have already been studied by the researchers for their usage in an engine. However, for India's situation, fuels like alcohols and biodiesel can give better outcomes.

A renewable fuel known as biodiesel, in blended or in neat form can be used in a CI engine. Biodiesel is normally prepared by esterification and transesterification process. If the free fatty acids (FFA) of the oil sample is 2 or less, then direct transesterification can be followed to make biodiesel. Biodiesel is preferable owing to higher cetane number, oxygen content and comparatively lower emissions (Al-Hamamre and Al-Salaymeh, 2014; Anand et al., 2011; Devarajan et al., 2018; Killol et al., 2019). However, owing to its higher viscosity it also produces harmful effects on the engine. Moreover, most of the studies have demonstrated higher NO_X emissions from the diesel engine.

Despite having these drawbacks biodiesel is easy to produce and is a very affordable choice for the replacing petroleum diesel. The production of biodiesel in a country reduces dependency on imports and makes the country self-reliance. This saves a lot of foreign exchange. Apart from this, biodiesel production also generates opportunity for jobs which helps in fighting poverty and building the economy.

1.4 Use of binary fuel blends

A binary fuel blend (Muthaiyan and Gomathinayagam, 2016) is a combination of two fuels which mainly comprises of mineral diesel or vegetable oil or biodiesel or alcohol. In some of the literature, di-methyl ether is also used with diesel/vegetable oil/biodiesel. A binary fuel blend has some advantages over petroleum diesel in terms of reduction in emissions. However, their usage is still in the research and needs further studies. Various biofuels namely alcohols, vegetable oils and biodiesel have been utilized in a CI engine as a substitute for diesel (Le Anh et al., 2011).

1.5 Use of ternary fuels blends

A ternary fuel blend is a mixture of three different fuels preferably alcohol, biodiesel and petroleum diesel. In some literature, a combination of two different biodiesels with diesel is also said to as a ternary blend. It is stated to be the best combination as compared to neat vegetable oil, neat biodiesel or even neat mineral diesel for most of the engine parameters. A significant amount of work has been carried out in the past with binary fuel blends. Very few literature have evaluated the blends of diesel-biodiesel with higher alcohols. Moreover, very less work has been carried out with all the three fuels in previous researches.

A ternary mixture shall help in giving better emission, performance and combustion characteristics as compared to a single or a binary fuel blend. Therefore ternary fuel blends are an important basis for this study.

1.6 Organization of Thesis

The thesis includes five chapters. A brief description of these chapters are as follows:

CHAPTER 1: (INTRODUCTION) – This chapter provides an impression of the current research area. This chapter first gives an insight into the importance of energy, climate change, fluctuating prices and anticipated depletion of fossil fuels, combustion techniques, and the significance of biofuels. Then a brief background is discussed that shows the importance of blends of biodiesel, diesel and higher alcohols as a solution to the current world energy crisis.

CHAPTER 2: (LITERATURE REVIEW) – In this biodiesel is presented as one of the potential energy resources, its advantages and limitations, available feedstocks and properties and general description of physico-chemical properties, performance and emissions. This is followed by a discussion on combustion techniques for improving the performance of engines, introduction to ternary fuel blends, their benefits and limitations.

CHAPTER 3: (SYSTEM DEVELOPMENT AND METHODOLOGY) – In this an explaination for biodiesel production, optimization, blending of the diesel, biodiesel and octanol, discussion on the use of equipment and method used for determining the physico-chemical properties of the test fuel blends. Development of spraytec setup for determining Sauter mean diameter, discussion on diesel engine test rig and the equipment used for measuring engine parameters is also presented.

CHAPTER 4: (RESULTS AND DISCUSSION) – In this chapter, the discussion of results and investigations obtained by using different equipments and setups are discussed. This chapter also presents the results of the examination succeeded by a thorough discussion. The results are then analyzed and compared with the previous works.

CHAPTER 5: (CONCLUSION AND FUTURE WORK) – This chapter summarizes the major findings of the research carried out and also gives future recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Internal combustion engines are the most popular and most useful machines. A CI engine is preferred over spark ignition engine owing to higher reliability and better fuel economy. Global environmental changes have forced many countries to set progressive stringent emission norms. However, many diesel engine manufacturers are facing a lot of problems to achieve these norms due to technological challenges and fuels available in the market.

One of the major problem being faced by a developing country like India is to find an alternative fuel resource that could replace the mineral diesel to run successfully in the conventional diesel engines. With the implementation of Bharat stage VI in India, many technological advancements are desired in a diesel engine for lowering emissions, noise, vibrations and fuel consumption.

This has made it necessary to take an immediate step for finding a suitable alternative fuel that is clean, environment friendly and available in abundance for running the available diesel engines.

2.2 Introduction to diesel engines

Since the first successful practical implementation of the four-stroke process by Nikolaus August Otto in 1876 and the invention of the CI engine by Rudolf Diesel in 1890s, the internal combustion engines are constantly evolving and improving. Figure 2.1 shows the working cycle of a four-stroke engine. The basic processes i.e. suction, compression, combustion and exhaust in diesel and petrol engines do not differ, however, the types of fuel and combustion are different.

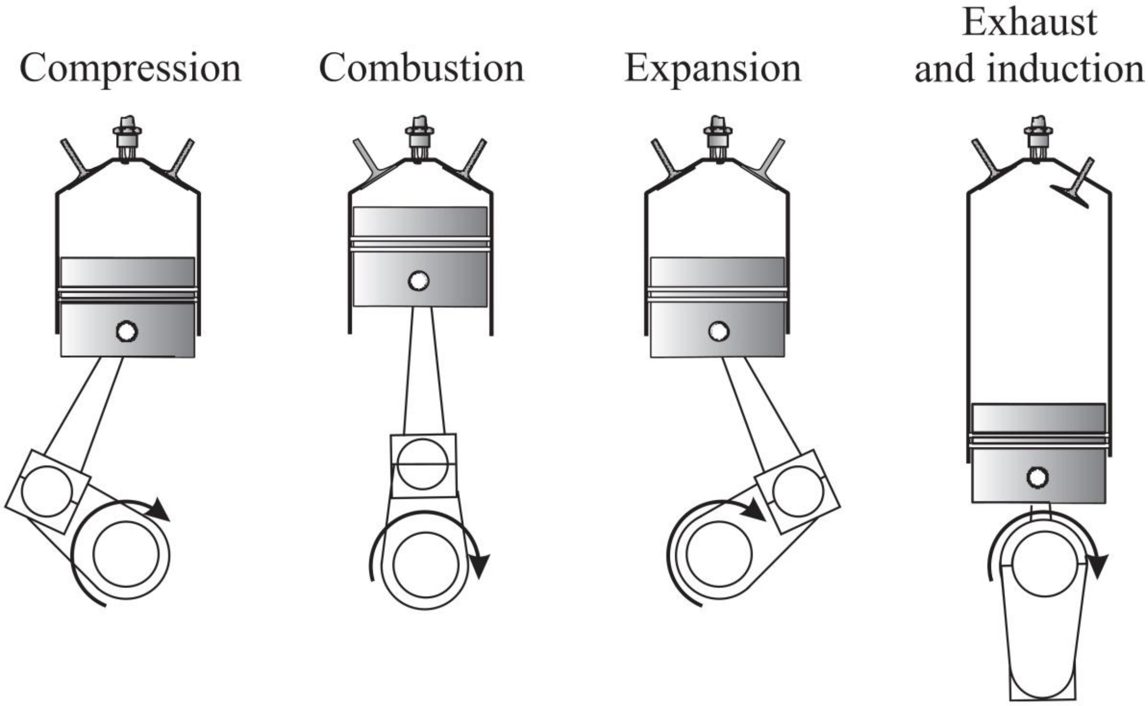


Figure 2.1. Demonstration of working of a diesel engine (Desmond E. Winterbone and Ali Turan, 2015)

2.2.1 Suction stroke

In the suction stroke, air from the atmosphere is fed towards the intake valve providing oxygen for combustion of fuel and also helps in scavenging of the burnt gases. Then in this stroke, the piston shifts from the top dead center (TDC) to bottom dead center (BDC).

2.2.2 Compression stroke

After the suction of air, the intake valve gets closed and the air inside the cylinder gets highly compressed due to the movement of the piston towards TDS. Due to this compression of air, excessive temperature upsurge is present and immediately the fuel for combustion is injected just before the piston reaches the TDC at a very high velocity and pressure.

2.2.3 Combustion stroke

It is also known as fire/power or expansion stroke. After the injection of fuel due to high in-cylinder temperature, rapid firing/burning of the atomized fuel takes place (as the fuel attains its auto-ignition temperature).

The combustion of fuel expands the burnt gases which moves the piston downward with high force, thus rotating the crank shaft. Movement of the piston is from TDC to BDC in this stroke.

2.2.4 Exhaust stroke

The exhaust valve opens after the piston has reached the BDC in this stroke. The gases burnt in the combustion chamber are liberated to the atmosphere through the exhaust manifold. This operation cleans the burnt gases and clears the space for the next operation. This completes the full cycle of operation of the diesel engine.

2.3 Role of diesel as a fuel in the Indian context

India is a diesel dependent economy. Diesel is mainly used in power sector, road transportation and agriculture sectors. Agriculture sector uses diesel engines to a large extent. Government subsidies are more for diesel fuel than for gasoline or motor spirit.

Table 2.1 compares the crude oil production and import. It is observed from Table 2.1, the domestic crude oil production is very low compared to the imports of oil from the foreign market. This causes a lot of burden on the country's foreign reserves. Moreover, higher prices of crude oil from the foreign market have also increased domestic sale price of petroleum products.

Table 2.1. Crude oil production vs imports in India (in MMT) (Indian PNG Statistics, 2018)

Year	Production	Imports
2011-12	38.09	171.73
2012-13	37.86	184.80
2013-14	37.79	189.24
2014-15	37.46	189.43
2015-16	36.94	202.85
2016-17	36.01	213.93
2017-18	35.68	220.43

From Table 2.2 it is observed that the consumption of diesel is much higher compared to petrol or motor spirit in India.

It is seen that in the year 2011-12, the consumption of diesel is 64.75 million tonnes whereas, the consumption of motor spirit is 14.99 million tonnes.

This consumption has risen to 81.07 million tonnes in 2017-18 for diesel whereas it has risen to 23.34 million tonnes for motor spirit.

There is a sharp rise in the consumption of petrol, however, diesel consumption is still very high compared to motor spirit.

Table 2.2. Consumption of High speed diesel and Motor spirit in India (in million tonnes') (Indian PNG Statistics, 2018)

Year	High speed diesel	Motor spirit
2011-12	64.75	14.992
2012-13	69.08	15.601
2013-14	68.364	16.294
2014-15	69.416	18.000
2015-16	74.647	19.623
2016-17	76.027	21.608
2017-18	81.073	23.343

Therefore, conserving diesel engine technology and finding a suitable substitute to diesel is our utmost priority.

2.4 Emissions from diesel engine

Diesel being a favorable choice in many heavy applications is also one of the major contributors to environmental emissions. The gases emitted from the exhaust on the burning of fuel cause serious harmful effects on the health of living beings. The main emissions from a diesel engine are CO, NO_X, unburnt HC and smoke.

2.4.1 Carbon monoxide

CO is odorless, colorless and tasteless gas, making it a great threat to living beings. Incomplete combustion of fuels is the main reason for CO gas formation (Reumuth et al., 2019). Its affinity to react with blood hemoglobin is almost 240 times higher than oxygen, which in turn replaces oxygen from our body and hence causes fatal effects. Therefore, it is very much necessary to remove its traces from the engine exhaust. Since the diesel engine is a major producer of CO, therefore changing the diesel engine technology and finding a suitable fuel that produces less CO emissions is desired.

2.4.2 Oxides of Nitrogen

NO_X is mainly composed of nitric oxide (NO) and a small proportion of nitrogen dioxide (NO_2). Some other components are also included in the oxides of nitrogen in negligible amounts. NO_X produces respiratory problems and also is a cause of acid rain. NO_X emissions from diesel engines are mainly formed because atmospheric air contains nearly 78% nitrogen. This air when enters the cylinder mixes with fuel at a high temperature of nearly 1500°C producing NO_X. It is therefore also known as thermal NO_X. Zeldovich in the year 1946 proposed Zeldovich mechanism and later changed to an extended or modified-Zeldovich mechanism which is the most popular mechanism that explains about thermal NO_X. The chemical reactions involved in the formation of NO (H. Chen et al., 2018) are shown in equations 2.1 to 2.3.

$$N + O_2 \leftrightarrow O + NO \tag{2.1}$$

$$N_2 + O \leftrightarrow N + NO \tag{2.2}$$

$$N + OH \leftrightarrow H + NO \tag{2.3}$$

NO_X emissions from the diesel engine is an issue and there are several techniques to reduce them. These are EGR, selective non-catalytic reduction and selective catalytic reduction (Hernández et al., 2019; Thiyagarajan et al., 2017).

Some other techniques are also there which can reduce NO_X emissions, but they are still in the research stage. These techniques have their separate merits and demerits.

2.4.3 Unburnt Hydrocarbon

These are also known as hydrocarbons which are formed because of incomplete combustion and evaporation of fuel. They are the hydrocarbons which are emitted after the fuel is burnt in the engine.

Unburned HC emissions are liberated because of unburnt fuel emitted from the engine. Unburnt HC irritates the mucous membrane of living beings and is therefore not acceptable from the engine exhaust (Woodyard, 2004).

Better atomization will help in reducing the lean or rich zones in the engine and hence reduces the HC emissions.

2.4.4 Smoke or soot

Smoke comprises of complex minute particles of gases and water vapours. Absence of oxygen and unburnt fuel are other reasons for smoke formation. Smoke causes itchy eyes, coughing, a runny nose and a sore throat.

Most of the symptoms fade away from healthy humans but for persons with respiratory diseases, small children, pregnant women and senior citizens it is very dangerous. To reduce smoke, complete and better burning is desired. Clean fuel is also another requirement for reducing smoke emissions.

2.5 Characterization of fuels used in diesel engine

2.5.1 Single fuel

For over a century diesel is the most preferred choice for the engine. It has been used successfully in various types of diesel engines. However, compression ignition engine running on diesel is a major concern today. Several researches in the past proposed different fuels utilized in a CI engine. The most preferable single fuel types used are diesel, vegetable oil and biodiesel. Some other fuels are di ethyl ether, di methyl ether, higher alcohol like octanol, decanol, etc. which are normally used in a blended form.

Table 2.3 compares the different vegetable oils used in a CI engine. Several properties of straight vegetable oils were compared for giving insight for their derivatives usage in a CI engine.

Table 2.3. Properties of different vegetable oils

Oil	Density at 15°C (kg/m^3)	Cloud point (°C)	Viscosity at 40°C (cSt)	Cetane number	Pour point (°C)	Calorific value (KJ/kg)	Flash point (°C)	Iodine number
Jatropha curcas (Chauhan et al., 2010b; Ganapathy et al., 2011; Kumar Tiwari et al., 2007)	916	—	37.28	46-70	—	38960	211.7	97.9
Mustard (Fadhil and Abdulahad, 2014; Sanjid et al., 2014)	934	-3	31.42	50.3	-19	39020	270	107
Soybean (Atabani et al., 2013; Ganapathy et al., 2011; Mihaela et al., 2013; Moser and Vaughn, 2010)	916	-5.5	31.83	40-53	-10.5	39600	254.8	109.17
Cotton Seed (Demirbas, 2008)	915	1.7	34.79	36.5	-15	39500	222	105.7

Groundnut (Bello and Fatimehin Daniel, 2015)	970	7.5	37.8	—	4	39500	178	82.36
Coconut (Atabani et al., 2013; Chinnamma et al., 2015)	914	10.15	27	52	-6	37806	265.3	10
Palm (Ganapathy et al., 2011; Moser and Vaughn, 2010; Verma et al., 2016)	897	19.8	40.65	50-65	14.53	39867	257.8	54
Hazelnut (Demirbas, 2008; Öztürk, 2015; Xu and Hanna, 2009)	945	1	24	52.9	-3	39900	325	94.32
Jojoba (Canoira et al., 2006; Saleh, 2009)	868	—	24.89	—	—	46470	285	50.17
Olive (Che et al., 2012; Lama-Muñoz et al., 2014; López et al., 2014)	908	—	46.27	—	—	40490	—	99.8
Camelina (Moser and Vaughn, 2010; Özçelik et al., 2015; J. Yang et al., 2016)	912	-10	24.16	35.6	-17	40210	227.5	151.25
Mahua (Godiganur et al., 2009; No, 2011; Pinzi et al., 2009)	942	—	32.01	45	15	36850	231	—
Sesame (Betiku and Adepoju, 2013; Demirbas, 2008; Sarve et al., 2015)	906	0.27	33.6	42.5	7	39139	264.3	95.01
Peanut (Kaya et al., 2009)	895	6.4	39.8	36.2	-0.35	39800	234.8	116.22
Castor (Armendáriz et al., 2015; Panwar et al., 2010; Sánchez et al., 2015)	950	-5.5	25.94	42.3	-25.1	36742	288.5	80.5

Canola (Moser and Vaughn, 2010)	904	-9	36.72	—	-21	39751	290.5	111.6
Kusum (Sarve et al., 2016; Sharma and Singh, 2010)	900	—	40.75	40	2	36250	240	—
Rapeseed (Demirbas, 2008; Ramadhas et al., 2005; Raman et al., 2019)	912	-3.9	38.15	37.6	-31.7	39700	263	115
Rubber seed (Aravind et al., 2015; Onoji et al., 2016; Ramadhas et al., 2005)	917	—	42.54	49.73	-14	38640	257	133.32
Sunflower (Demirbas, 2008; Efe et al., 2018; Ramadhas et al., 2005)	918	12.75	34.01	38.1	-10.85	39560	256	129.5
Tobacco (Usta et al., 2011; Veljkovic et al., 2006)	918	-7.8	27.7	38.7	-14	39400	220	135
Karanja (Karmee and Chadha, 2005; Raheman and Phadatare, 2004; Sahoo et al., 2009)	933	—	39.9	32	4	35992	222	90.7
Rice bran (Bora and Saha, 2016; Kong et al., 2015; MohamedMusthafa et al., 2011)	918	4	40.86	—	-6.5	38945	304	107
Linseed (Dixit et al., 2012; R. Kumar et al., 2013)	924	-0.6	26.24	34.6	-10.4	39300	241	156.74
Waste cooking oil (Dhanasekaran et al., 2019; Kumar et al., 2016; Ming et al., 2018)	900	16	52	53	14.8	37680	271	—

Crambe abyssinica (Rosa et al., 2014; Wazilewski et al., 2013)	905	10	46.09	44.6	-12.2	40500	274	93
Neem (Agarwal et al., 2015; Ali et al., 2013; Betiku et al., 2014)	929	19	38.87	41	10	26650	214	75.295

Below is the summary of the findings of different fuels when used as a single fuel. (Ashok et al., 2018) used 100% diesel and 100% biodiesel derived from Calophyllum inophyllum in a CI engine. When compared to diesel, authors observed for biodiesel marginally higher brake specific energy consumption (BSEC), brake specific fuel consumption (BSFC) and lower BTE. From the experiments, authors observed that biodiesel exhibited higher smoke and NO_X emissions. However, lower CO and HC emissions were observed for biodiesel. The authors also found comparable heat release rate (HRR), lower ignition delay and cylinder pressure for straight biodiesel as compared to diesel.(Rakopoulos, 2013) used three different single fuels namely diesel, cottonseed oil and cottonseed biodiesel. The author found higher BSFC and BTE of vegetable oil and biodiesel. Smoke and CO emissions of vegetable oil were found by the investigator to be higher than diesel whereas biodiesel exhibited lower CO, NO_X, smoke and total unburnt HC.

(Zhu et al., 2016) used biodiesel of waste cooking oil and diesel in neat form and compared the performance and emissions. Authors found higher BSFC and BTE of biodiesel. Authors also observed lower HC and PM emissions for biodiesel, whereas higher CO and NO_X emissions were found by the authors. Mass fraction burnt was also found to be lower for biodiesel. (Sathish Kumar et al., 2018) evaluated the effect of neat diesel and methyl ester of Manilkara Zapota in a CI engine. The authors found little lower net HRR and lower cylinder pressure for the biodiesel. BTE of diesel was higher than biodiesel whereas BSFC exhibits the opposite trend. Also, the authors found higher exhaust gas temperature (EGT) of biodiesel over diesel. Authors also observed lower CO_2 and CO emissions whereas marginally higher unburnt HC and NO_X emissions. (Atmanli, 2016) analyzed the usage of waste oil biodiesel and diesel. The author carried the performance and emission tests and found higher BTE and exhaust gas temperature whereas lower BSFC for biodiesel. Comparable NO_X and slightly higher HC and CO emissions were observed by the authors. (Ileri et al., 2016) examined diesel and rapeseed biodiesel in CI engine. The authors found higher kinematic viscosity, density, lower heating value and cetane number of biodiesel over diesel. EGT, brake torque and power were lower for biodiesel, however, higher BSFC was found. Compared to diesel, biodiesel showed lower CO_2, CO as well as HC emissions whereas slightly higher NO_X emissions.

(Chauhan et al., 2013) used biodiesel obtained from Karanja and diesel in a CI engine. The authors observed 100% biodiesel has lower CO, HC and smoke emissions whereas biodiesel produces higher CO_2 and NO_X emissions. Also, 100% diesel showed the highest thermal efficiency. (Ashok et al., 2019a) analyzed usage of 100% diesel and 100% biodiesel. Biodiesel exhibited lower BTE and higher BSFC. Authors also observed from the results that biodiesel displayed very low CO, smoke and HC emissions. However, CO_2 emissions and NO_X emissions were slightly higher than diesel. Moreover, peak in-cylinder pressure, cumulative HRR and maximum HRR were higher for diesel. Also, it was observed by the authors that the ignition delay of diesel was higher than biodiesel. (Ceviz et al., 2011) compared neat hazelnut oil biodiesel and diesel. The authors used Super Star make direct injection twin cylinder CI engine. The authors found similar brake torque and brake power for biodiesel and diesel. Moreover, effective efficiency is also nearly equal. However, Hazelnut biodiesel had slightly higher BSFC. HC and CO_2 emissions were observed to be lower for biodiesel with some penalty on CO and NO_X emissions. (Babu and Anand, 2017) used sunflower based waste frying oil biodiesel and diesel separately. Biodiesel used by the authors exhibited lower BTE, higher BSFC and higher BSEC. The peak pressure and ignition delay of biodiesel were slightly less than diesel. Biodiesel produces lower emissions namely HC, CO, NO and smoke number whereas higher CO_2 emissions.

(Ashok et al., 2019b) found lower ignition delay and peak cylinder pressure on using Calophyllum Inophyllum biodiesel and diesel separately. Compared to diesel, biodiesel exhibited lower BTE values. Smoke opacity, CO and HC emissions decreased for the biodiesel whereas NO_X emission increased. (Patil and Patil, 2017) compared rubber seed biodiesel and diesel. Authors investigations concluded higher BTE for biodiesel with similar BSFC and brake power. Slightly lower CO, CO_2, NO and HC emissions were recorded by the authors for biodiesel.

(Jaichandar and Annamalai, 2015) investigated the effect of diesel and methyl ester of Pongamia oil. Authors found higher BSFC and lower BTE for the biodiesel. Authors also observed lower smoke, CO and HC emissions. Slightly higher NO_X was also recorded for biodiesel. Also, the authors found from the results, biodiesel exhibited lower pressure rise and maximum HRR. (Pandian et al., 2018) investigated the effects of cashew nut shell biodiesel and diesel in a 4.2 KW Kirloskar make diesel engine. Authors found biodiesel exhibited lower HC, CO and smoke emissions. Whereas, NO_X emissions were higher than diesel. Compared to diesel, biodiesel exhibited higher BSFC and lower BTE. (Mahalingam et al., 2018) used the neat mahua biodiesel and diesel in an AVL 5402 CI engine. Authors found lower HC, CO and smoke emissions for biodiesel compared to diesel.

2.5.2 Binary fuel

A binary fuel is a mixture of two different fuels which on blending together can overcome the disadvantages of a single fuel. A binary fuel can be a blend of biodiesel-diesel, alcohol-diesel, diesel-vegetable oil, biodiesel-alcohol, biodiesel-vegetable oil, biodiesel-biodiesel, etc. in varying quantities. Many researchers have investigated the benefits of binary fuel blends. The major advantages of binary fuel blends are fewer emissions and comparable performance to diesel. They also help in partial replacement of mineral diesel. The primary/secondary fuels used in the binary fuel blends are renewable in nature and hence reduce our dependency on fossil fuels. As most of the binary fuels consist of diesel with vegetable oil/biodiesel/alcohols, Table 2.3 compares the properties of different vegetable oil and Table 2.4 compares the different alcohols used in a CI engine.

Table 2.4. Properties of different alcohols compared to petroleum diesel (Akhtar et al., 2015; Fernández et al., 2012; Kremer et al., 2015; S. Kumar et al., 2013; Lapuerta et al., 2010)

Property	Diesel fuel	Methanol	Ethanol	Butanol	n-Pentanol	n-Octanol
Chemical formula	C_xH_y	CH_3-OH	C_2H_5-OH	C_4H_9-OH	C_5H_{11}-OH	C_8H_{17}-OH
Density at 15 °C (kg/m^3)	830	788	789	809	814	827

Boiling point (°C)	187-343	65	78	117-118	137	195
Cetane number	40-55	5	5	17	22	37
Calorific value (MJ/kg)	42.8	20.1	26.9	33.1	34.6	37.5
Enthalpy of vaporization (KJ/kg)	276.00	1162.64	918.42	581.40	308.05	408.00
H (%wt)	13.8	12.5	13	13.5	13.6	13.8
C (%wt)	86.2	37.5	52.2	64.8	68.1	73.7
O (%wt)	0	50	34.8	21.7	18.3	12.5
Flash point (°C)	74	12	13	35	49	81
Auto ignition temp (°C)	235-300	463	423	345	300	270
Solubility in water	Immiscible	Miscible	Miscible	Immiscible	Immiscible	Immiscible
Viscosity (cSt) at 40°C	2.72	0.58	1.13	2.22	2.89	5.9

Many studies have been done for determining the suitability of different binary blends. The summary of the investigations is shown below.

(De Poures et al., 2017) used a binary fuel blend of hexanol (10, 20 and 30) and diesel. The benefits of adding hexanol are more oxygen, low kinematic viscosity and low density. However, when compared to diesel, hexanol blends exhibited lower calorific value and cetane number. The authors investigated the emission and performance characteristics of Kirloskar model TAF 1 direct injection single cylinder 4.4 KW CI engine and observed lower smoke and CO emissions. However, slightly higher smoke and HC emissions were also observed. Authors also observed that for the hexanol-diesel fuel blends, the HRR and peak pressure rise values are higher, whereas, the ignition delay is lower. (Zubel et al., 2017) used 20% and 50% octanol blend with diesel. For the test fuel blends authors found slightly lower heating value, higher density, higher oxygen content, lower cetane number and higher viscosity. Authors evaluated binary fuel blends and observed lower smoke and NO_X emissions for the blends. Authors found somewhat higher CO and HC emissions for the diesel and octanol fuel blends.

(Atmanli and Yilmaz, 2018) investigated pentanol and butanol fuel blends in 5, 25 and 35% by volume basis with diesel and found slightly lower cetane number for the blends. The authors found higher oxygen content in butanol than in pentanol. 1-pentanol has very less solubility in water compared to butanol. Cetane number, viscosity and density of 1-pentanol was also higher than butanol. The authors used Onan DJC model, 4 cylinder 4 cycles naturally aspirated air cooled 12 KW engine for determining the performance characteristics and emission characteristics. The authors found a reduction in BTE for blends and an increase in BSFC. 5% pentanol-diesel blend had the highest BTE whereas 35% of butanol-diesel blend has the lowest BTE. The authors also found that the BSFC increases for the blends. BSFC increase may be because of lowering in cetane number and heating values of the test fuels. 5% of butanol blends show the lowest BSFC among all the blends. Diesel showed the lowest BSFC and highest BTE. For the emissions, the authors observed higher HC and CO emissions with binary fuels and lower nitrogen oxide emissions. Authors concluded that 5% of butanol/pentanol blends can safely and efficiently be used under any operating conditions.

(Zhang et al., 2015) had used diesel-butanol and diesel-octanol in different proportions in an AVL 501 diesel engine which is having one cylinder and found that by adding alcohols to diesel slightly more BSFC and less BTE were obtained. Owing to more oxygen content in the binary blends of diesel with butanol/octanol reduced CO emissions were observed. Authors also observed that on adding butanol/octanol to diesel, HC emissions were increased slightly, however, their values were still below the Euro 5 norms. Moreover, little higher NO_X emissions were found owing to more oxygen content. It was also observed that HRR of diesel-butanol and diesel-octanol binary fuel blends were slightly lower.

(Rajesh Kumar et al., 2016b) analysed the effects of adding four different higher alcohols (isobutanol, pentanol, hexanol and octanol) in 30% volume. It was found by the authors that oxygen wt% decreased on going up the alcohol chain, however, the carbon wt% increased. Also, the octanol cetane number is 37 which is comparable to diesel than hexanol having cetane number of 23. Moreover, higher alcohols have a higher flash point and latent heat of vaporization. Higher alcohols have a density slightly lower than diesel. The authors utilized these fuels in Kirloskar make TAF1 diesel engine and observed ignition delay of iso-butanol-diesel was the highest owing to the lower cetane number whereas 100% diesel exhibits lowest ignition delay. In terms of alcohol blends octanol-diesel has the lowest ignition delay which is slightly inferior to diesel. Also, iso-butanol blends exhibited highest peaks of HRR and in-cylinder pressure in comparison to all the alcohol blends. Diesel exhibited the lowest HRR and in-cylinder pressure values. Moreover, better emission characteristics were found for the test fuel blends. Blends exhibited lower emissions (HC, CO, smoke and NO_X).

(Tutak et al., 2017) conducted investigations using ethanol-biodiesel and ethanol-diesel blends. Authors observed lower in-cylinder pressure for a diesel-ethanol blend. Lower HRR peak with biodiesel-ethanol blends was also observed. It was found that ethanol addition was decreasing the peak pressure. A similar trend was seen for diesel-ethanol blends at a higher concentration of ethanol. Higher exhaust gas temperature was seen for diesel-ethanol blends than biodiesel-ethanol blends. Indicated thermal efficiency increased on adding ethanol in diesel/biodiesel. For the fuel blends, total HC and NO_X emissions reduced by 35% ethanol blends whereas CO and CO_2 emissions increased.

(Fernández et al., 2012) used fuel blends of diesel-butanol (10% to 30% 1-butanol) besides diesel-1-pentanol fuel blends (10% to 25% of 1-pentanol). The authors have carried out engine trials and found slightly better BTE than diesel and marginal power loss with alcohol fuel blends on comparison with diesel. Also, lower BSFC of butanol-diesel binary fuels was found when compared with neat diesel. The authors concluded that without any engine modification blends containing 25% pentanol with diesel and 30% butanol with diesel can be successfully utilized. (Chauhan et al., 2013) used Karanja biodiesel blended with diesel in a Kirloskar make CI engine. Similar emission and performance characteristics were observed for the blends and diesel. The results also illustrated that the emissions (smoke, CO and HC) for the blends were lower than diesel. Also, 100% of diesel showed the highest thermal efficiency. Authors observed that blends of biodiesel-diesel can suitably be utilized in a diesel engine without any modification. (Ashok et al., 2019a) investigated the biodiesel-pentanol blends in a CI engine. The volume percentage of pentanol was varied from 10-50%. The authors observed a reduction in calorific value, cetane number, kinematic viscosity and density on the addition of n-pentanol to biodiesel. The authors used a Kirloskar make one cylinder CI engine for performance and emission measurements. Authors used Calophyllum Inophyllum biodiesel in the tests. The authors concluded that the biodiesel-pentanol samples were having good miscibility. Authors observed slightly higher BTE for 90% biodiesel-10% pentanol blends, however, higher blends give lower BTE. BSFC and BSEC followed the inverse trend to BTE. Marginally lower NO_X emissions for 10% pentanol blends and longer ignition delay were observed for the blends. Binary fuel mixtures give lower HC and CO emissions. It was also found that on increasing the amount of alcohols in fuel mixtures, CO_2 emissions also decrease. Also, smoke opacity of the test fuel blends was lower than diesel and with the increase in alcohol, smoke level increased.

(Sanli, 2018) used blends of waste frying oil with diesel in different proportions. Authors found that on adding upto 25% waste frying oil, the viscosity still remained below the EN14214 standards. It was found that BSFC of blends was more. Also, the diesel-waste frying blends offered lower BTE. It was also found that waste frying oil increased the emissions (CO, CO_2 and NO_X). For the blends, total HC values were found higher. It was also found that on increasing the waste frying oil percentage in the blends, it's BTE and BSFC worsened. Similar effects were also observed for emissions. (Yerrennagoudaru et al., 2018) examined palm, mahua and coconut oil with methanol in 50%-50% basis, The authors used four stroke twin cylinder diesel engine. The authors found that the BTE of straight diesel was higher for the blends whereas BSEC of diesel was lower. The authors also observed the lowest HC emissions for palm oil and methanol blends when compared to other test fuels. For all the test fuel blends CO and NO_X emissions were lower than diesel while smoke opacity was higher.

(Ceviz et al., 2011) used blends of biodiesel processed from hazelnut oil and diesel. 20%, 40%, 60%, 80% binary fuel blends were utilized in the CI engine. The authors found comparable engine performance parameters for the blends. Authors observed a slight increase in BSFC with the blends, however, not much significant loss was observed in brake power. Biodiesel blends especially 20% and 40% exhibited lesser CO, HC and smoke emissions. (Ashok et al., 2018) used Calophyllum inophyllum biodiesel and diesel blends with 30% and 60% composition of biodiesel. The biodiesel used has slightly higher density and viscosity while lower calorific value, however, it has a cetane index of 59.5 as compared to 39 of diesel. The authors observed that the BTE of the test fuel blends decreases on increasing the biodiesel percentage. Diesel showed the highest BTE followed by 30% biodiesel blends and 60% biodiesel blend. BSFC and BSEC also displayed a similar trend as observed for BTE. Unburnt HC, CO and smoke emissions remained less than diesel whereas NO_X emissions were greater. Moreover, biodiesel-diesel blends showed lower ignition delay, similar in-cylinder pressure and HRR. (Song et al., 2010) observed the carbonyl emissions of diesel and diesel-ethanol blends. For diesel-ethanol blends, the authors found more total carbonyl emissions (acetaldehyde and formaldehyde).

(Li et al., 2015) used two binary fuel blends of biodiesel-diesel and pentanol-diesel. Authors fixed the biodiesel/pentanol percentage to 30%. The authors observed that adding pentanol/biodiesel to the blends increases their oxygen content. Viscosity and density of diesel-biodiesel blends were higher than diesel-pentanol blends or neat diesel. Biodiesel fuel blends show lower ignition delay whereas pentanol fuel blends exhibited slightly higher ignition delay. However, pentanol diesel binary fuel blends showed lower combustion duration. It was also found by the authors that the pentanol blends showed the highest maximum HRR whereas biodiesel blends showed the lowest. Higher NO_X emissions were observed for biodiesel-diesel blends. For both the binary fuel blends, soot and CO emissions were lower. CO emissions were lower mainly at higher loads. From the results discussed by the authors, pentanol blends exhibited lower indicated specific fuel consumption and higher indicated thermal efficiency compared to diesel or biodiesel-diesel blends. Biodiesel binary fuel blend with diesel exhibited the lowest efficiency and highest fuel consumption.

Three different oils namely Jatropha, soybean and waste cooking were blended in 20%, 30%, 40% and 50% by volume without any conversion by (Chaurasiya et al., 2019). The authors found that at all engine loads, the addition of straight oils to diesel reduces their BTE whereas fuel consumption increased. For the blends, a small upsurge in NO_X emissions and EGT was found. However, HC and CO emissions decreased for the diesel-oil binary fuel blends. (Rakopoulos, 2013) used different binary fuel blends of cottonseed oil/biodiesel with butanol/ di ethyl ether (DEE). Composition of butanol/DEE were set to 20%. The authors used a Ricardo Hydra engine. Authors found that there was some decrease in smoke and NO_X with the use of binary fuel blends. However, slightly higher CO and total unburnt HC was observed for vegetable oil-alcohol blends. However, blends of biodiesel-alcohol exhibited lower CO and total unburnt HC emissions. Moreover, the blends displayed higher BTE and BSFC.

(Huang et al., 2017) utilized castor oil-diesel fuel blends in an oil fired furnace. The authors varied oil concentration from 0-30%. The authors found stable combustion with blends. The authors found that by the addition of castor oil, oxygen requirement reduced while burning. The gas temperature and cylinder wall temperature also gets reduced. CO emission concentration reduced for the castor oil-diesel blends. NO and sulphur dioxide (SO_2) emissions were nearly the same for the blends. Jajoba oil-diesel was utilized by (Al Omari et al., 2019) in a furnace with a diameter of 60 cm and length 150 cm. The authors analyzed the consequence of the addition of jajoba oil in diesel and detected lower NO_X and HC emissions whereas, slightly higher CO emissions were observed.

(Huang et al., 2016) found higher BSFC, lower output for pine oil-diesel fuel blends. The authors used pine oil in 20%, 40% and 50% with diesel. Higher BSFC was observed on adding pine oil. Higher the percentage of pine oil higher was the BSFC. Similarly, power output was reduced on increasing oil composition in binary fuel blends. Soot emissions were found by the authors to reduce, whereas, CO, NO_X and total HC emissions were slightly higher for the blends.

(Zhu et al., 2016) checked the feasibility of blends of n-pentanol (10 to 30%) and waste cooking oil (WCO) biodiesel. The authors have found that pentanol addition caused a delay in the start of combustion. All the blends showed better BTE and BSFC compared to diesel. For the blends, lower PM emissions were observed whereas HC, NO_X and CO emissions were higher. (Nour et al., 2019a) had investigated the use of higher alcohols and diesel binary fuel blends. The authors used butanol, heptanol and octanol (10% and 20% by volume). The authors analyzed the emission and performance characteristics of the fuel blends. For heptanol or octanol binary fuel blends authors found lower BSFC and lower BTE. NO_X and soot emissions decreased for all the binary fuel blends, whereas HC and CO emissions increased when compared to petroleum diesel. The authors also found that the combustion duration of octanol and heptanol blends were longer then butanol-diesel binary blends and neat diesel. Authors (Sathish Kumar et al., 2018) experimentally determined the emission and performance profiles of binary fuel blends of Manilkara Zapota biodiesel and diesel. The authors used Kirloskar make water cooled, 4 stroke, 1 cylinder, 661cc diesel engine. The authors found the highest peak pressure was recorded for 50% biodiesel-50% diesel fuel blends. B25 blends displayed the second highest peak pressure. Also 50% of biodiesel blends exhibited higher net heat release. Moreover, the authors found that 50% biodiesel binary fuel and 25% biodiesel binary fuel blends displayed increased BTE and reduced BSFC when compared to neat diesel. The blends used displayed lower CO and unburnt HC emissions with some penalty on NO_X and CO_2 emissions.

(Emiroğlu and Şen, 2018) have demonstrated the use of three different binary fuel blends of diesel when blended with alcohols (10% in v/v basis). The authors used methanol, butanol and ethanol as alcohols. The authors determined the properties of the fuel blends and found lower density, cetane number and heating value. Kinematic viscosity of binary fuel blend of butanol/diesel was slightly higher. Though, ethanol/methanol fuel blends displayed lower kinematic viscosity. Authors observed lower smoke and CO emissions for the blends. However, higher NO_X emissions were observed with the blends. Moreover, BTE of diesel was highest among all fuels whereas BSFC was lowest. (Atmanli, 2016) studied the effect of binary fuel blends of diesel and waste oil biodiesel. The author carried the performance and emission tests and found higher BTE and EGT whereas lower BSFC for the 50% biodiesel-50% diesel fuel blend. Lower NO_X, CO and higher HC emissions for the blends were also found. (Ileri et al., 2016) investigated the effect of fuel blends of 20% rapeseed oil biodiesel and

80% diesel. The authors used four stroke, four cylinders, direct injection diesel engine. The authors found similar brake torque and brake power for the blends whereas increased BSFC and decreased EGT. Authors found comparable NO_X and CO emissions for the blends and marginally lower HC and CO_2 emissions. (Leevijit et al., 2017) used blends of diesel and degummed crude palm oil/esterified crude palm oil in a diesel engine. Authos found that the blends produced lower BTE, slightly more BSFC, less EGT, less CO and marginally higher NO_X emissions.

(Rajesh Kumar et al., 2016a) used binary fuel blend of diesel and n-octanol. Ultra-low sulfur diesel was blended with 10%, 20% and 30% n-octanol. Authors found very good miscibility of octanol in diesel. A longer ignition delay and higher peaks of HRR were observed for the blends. On increasing the octanol content in the blends, authors found better BTE, lower BSFC and exhaust gas temperature. CO, HC, smoke and NO_X were observed to be lower for the blends. (Senthur Prabu et al., 2018) used diesel/palm oil blends in a diesel engine. The authors preheated palm oil-diesel blends and found higher BSFC and lower BTE. CO emissions were higher for all the blends, however, NO_X, HC and smoke emissions were lower. 40% of pine oil-diesel showed the lowest smoke emissions. (Abed et al., 2019) utilized different diesel-biodiesel blends in a CI engine. Authors used biodiesels of waste cooking oil, jatropha oil, palm oil, and algae. All the binary fuel blends of diesel and biodiesel exhibited higher cetane number and density. The authors observed lower CO, CO_2, smoke and HC emissions. Compared to diesel NO_X emissions were comparatively higher.

(Yilmaz et al., 2014) used (5%, 10%, and 20%) butanol and biodiesel. Slightly lower CO emissions were seen for the blends. In the blends addition of butanol decreased the NO_X emissions and EGT. Similar HC emissions were observed by the authors for the blends and diesel. (How et al., 2018) used binary fuel blends of biodiesel obtained from Calophyllum Inophyllum and diesel. The authors observed that with the addition of biodiesel to diesel cetane number, density, flash point and kinematic viscosity increased with some drop in calorific value. The authors found lower torque, brake power and BSEC with the blends, however, for 50% diesel-50% biodiesel blends little higher BTE and BSFC was observed at higher speeds. Lower CO, PM and smoke emissions were recorded for the binary fuel blends, however, NO_X emissions increased for all the blends. It was also found that higher the amount of biodiesel, higher were the NO_X emissions. Moreover, blends exhibited lower peak cylinder pressure and peak HRR.

(Gnanamoorthi and Devaradjane, 2015) examined the effect of binary fuel blends of ethanol/diesel. Ethanol percentage used were 10%, 20%, 30% and 40%. The authors added Ethyl Acetate (1%) and diethyl carbonate (1%) to the blends for maintaining the phase. At higher compression ratio of 19.5, BTE of all the binary fuel blends were higher, however, at lower compression ratio blends with less percentage of ethanol were exhibiting higher BTE. For the blends, CO, HC and smoke emissions were less, however, more NO_X emissions were seen. (Choi et al., 2015) blended diesel with 5%, 10% and 20% butanol. The blends exhibited lower power and torque. 5% and 10% butanol blends exhibited lower BSFC whereas 20% of butanol-diesel blends show higher BSFC. Higher CO emissions and lower HC emissions were found by the authors for the blends. (Tüccar et al., 2014) used one binary fuel blend of diesel (80%) and microalgae biodiesel (20%) and compared with diesel. The blend exhibited lower torque, brake power and higher BSFC values. NO_X, smoke and CO emissions decreased for the fuel blends. (Zhu et al., 2018) studied the effects of blending n-butanol to diesel. Authors compared 30% butanol-70% diesel fuel blend. Higher CO emissions were observed for the blends, however, NO_X and smoke emission decreased. Also, the ignition delay of 30% butanol binary fuel blend was longer than diesel. (Prakash et al., 2018) used diesel and castor oil binary fuel blends in a Kirloskar make diesel engine. Compared to diesel the authors observed lower BTE and longer combustion duration for the blends. (Wei et al., 2018) used binary fuel blends of biodiesel with ethanol/butanol and determined the emissions, combustion and performance parameters. Authors observed higher CO and HC emissions for both alcohol blends. Compared to diesel, butanol binary fuel blends were having less upsurge in CO and HC emissions. Blends showed a similar reduction in PM emissions whereas, a substantial decrease in NO_X emissions was observed by the authors. Ethanol-diesel binary fuel blends exhibited a reduction in NO_X by 28% compared to 6.5 % in butanol-diesel blends. All the blends exhibited a shorter combustion duration. Similar maximum HRR values and in-cylinder pressure values were observed by the authors.

(Ramírez et al., 2014) utilized blends of diesel with phytol ($C_{20}H_{40}O$) in a CI engine. Authors observed similar emission and performance characteristics of the blends and diesel. Lower NO_X emissions and lower BTE were observed for the blends, however, authors have observed higher BSFC for the blends. (Millo et al., 2015) blended diesel with hydrotreated vegetable oil (HVO)/30% rapeseed biodiesel. Higher cetane number was observed by the authors for the blends. Biodiesel-diesel blends exhibited lower calorific value whereas HVO-diesel blends exhibited higher calorific value. Similarly, biodiesel blends exhibited an increase in viscosity whereas HVO exhibited lower viscosity. Authors found binary fuel blends shows similar BSFC and torque. It was also observed that on the addition of biodiesel/HVO, smoke emission decrease drastically. Also, reduction in CO, HC and NO_X emissions were observed. (Fang et al., 2013) used binary fuel blends of biodiesel (10%) and diesel (90%) in a four cylinder CI engine. The authors found lower ignition delay for the blends. Authors also found that the blends exhibited lower BTE, higher BSFC, lower smoke and CO emissions. Authors also found higher NO_X and HC emissions.

(Rajesh Kumar and Saravanan, 2016) investigated n-pentanol/diesel and iso-butanol/diesel in a CI engine. Authors used 40% n-pentanol - 60% diesel fuel blend and 40% n-butanol - 60% diesel fuel blends. The authors observed higher peak pressure for both pentanol and butanol binary fuel blends compared to diesel. Authors found longer ignition delay with butanol blends compared to diesel and pentanol binary fuel blends. Authors found that EGR reduces the peak pressure values for the blends. When compared to diesel HRR of the blends were found to be higher. Authors found CO emissions with alcohol blends were lower. Authors observed that butanol blends gave better performance compared to pentanol due to the lower viscosity, lower density and higher calorific value. Butanol blends exhibited improved performance with EGR. Compared to pentanol authors found, BSFC of butanol blends were lower. (Ashok et al., 2019b) evaluated the influence of the addition of n-octanol and Calophyllum Inophyllum biodiesel. Five blends of n-octanol and biodiesel were formed varying octanol percentage from 10% to 50%. Authors found butanol addition increased the BTE, ignition delay and in-cylinder pressure. HC, smoke opacity and CO emissions decreased for the mixtures whereas NO_X emission increased.

(Patil and Patil, 2017) used four binary fuel blends of rubber seed biodiesel and butanol. Authors compared the results of performance and emissions for the blends and neat diesel. Authors recorded reduction in BTE and increase in BSFC for the blends. Total heat release was higher for diesel compared to the blends. CO emissions were higher whereas significant reduction was observed by the authors for NO emissions. At low loads, HC and CO emissions were lower whereas they increase at higher loads compared to diesel. (Jaichandar and Annamalai, 2015) examined the utilization of binary fuel blends of diesel and biodiesel of pongamia oil. Authors found higher BSFC and lower BTE for the blends. Authors also observed lower CO, smoke and HC emissions with some penalty on nitrogen oxide emission on increasing biodiesel percentage in the blends. Also, authors found from the results, lower pressure rise and maximum HRR for the blends.

(Pandian et al., 2018) investigated in a four stroke 4.2 KW Kirloskar make diesel engine different blends of cashew nut shell biodiesel (90%/80%) and hexanol(10%/20%). Authors found that the biodiesel and hexanol were completely miscible. Blends exhibited 9.3%, 1.8% and 1.4% lower HC, CO and smoke emissions respectively compared to biodiesel. BTE increased whereas BSFC decreased on the addition of hexanol to biodiesel. However, their values were inferior to diesel. (Yang et al., 2016) used a binary fuel blend of butanol and diesel for comparing their performance and emission characteristics in a Suburu make air-cooled, single cylinder, 230 cc, 3.3 KW diesel engine. Authors found higher BSFC for binary fuel blend. However, NO_X and PM decreased with some increase in CO emissions compared to diesel. PM10 of diesel fuel was 555 µg $kWhr^{-1}$ whereas PM10 emission of the blend was 490 µg $kWhr^{-1}$.

(Mahalingam et al., 2018) used the blends of mahua biodiesel and octanol (10%/20%) in a CI engine. Authors found lower CO, smoke and HC emissions with the blends. Authors observed that on increasing the octanol percentage, exhaust emissions get reduced. (Devarajan et al., 2019) used blends of heptanol and mustard oil biodiesel. Authors found no phase separation in the blends. Authors found lower CO and HC emissions compared to biodiesel. Authors found that by increasing heptanol composition in blends, NO_X and smoke emissions decreased. Higher BTE and lower BSFC were observed for the blends. (Joy et al., 2018) used biodiesel/octanol blends in a diesel engine. Authors observed a reduction in CO and HC emissions and little higher NO_X emissions with blends. Compared to diesel, authors also observed lower smoke emissions.

2.5.3 Ternary fuel

A ternary fuel is a mixture of three different fuels blended together. These fuel blends can help in finding a replacement for diesel. It can be best suited to provide superior performance and emission characteristics. The fuel burnt gets better atomized and also higher cetane number fuels can be used. Moreover, oxygenated fuels can also be used in blends to reduce emissions.

(Yesilyurt et al., 2018) has used a ternary fuel blend of diesel/biodiesel/n-pentanol and diesel/ biodiesel/1-butanol. The authors used alcohols 5% and 10% by volume and varied the biodiesel composition to 2% and 20%. The authors found that the low temperature properties, kinematic viscosity and density of the blends improved on adding the alcohol in the blends whereas, heating value, cetane number and flash point got worsened on adding alcohols. The authors concluded that the addition of pentanol is more favorable for the properties of the blends than butanol. Also, it was concluded that pentanol fuel blends displayed better performance and emissions than butanol blends. The authors observed that the brake power and torque decrease on increasing alcohol content. It was found that the BTE of 5% butanol/pentanol with 2% biodiesel blend increased whereas it decreased by 10 % alcohol blends compared to diesel. The BSFC of n-pentanol is 7.27% higher than diesel whereas BSFC of 1-butanol is 8.07%

higher than diesel. Moreover, maximum HRR values of alcohols were higher than diesel. Also, ignition delay increased on the addition of alcohols. The authors also found a slight reduction in exhaust gas temperature for pentanol-diesel-biodiesel blends. Authors have also concluded from the results that the addition of alcohols shows a drastic reduction of nearly 32.4% in CO and 44.43% in smoke emissions. Moreover, it was also seen from the results that higher alcohols mainly n-pentanol helped in reducing the NO_X emissions which is the major problem with the usage of biodiesel. (Saravanan et al., 2019) has used different proportions of diesel-heptanol and algae biodiesel ternary fuel blends. The results were very favorable for the ternary fuel blends as almost all the blends give slightly superior performance parameters and much better emission characteristics. A substantial decrease in CO, HC and NO_X emissions were observed. Moreover, blends give better BTE and reduced BSFC than straight diesel. Little higher smoke emission was observed on increasing the content of heptanol in blends, but, as per the conclusion drawn a tradeoff can be attained between NO_X and smoke. (Paul et al., 2017) performed experimental analysis to determine the suitability of diesel-ethanol and Pongamia piñata biodiesel. TV1 Kirloskar 4 stroke water cooled 3.6 KW diesel engine was utilized. Biodiesel percentage was set to 50% and ethanol percentage was varied from 5-35%. 35% ethanol-15% diesel-50% biodiesel shows the highest BTE. All other blends show comparable BTE to diesel. Similarly, BSEC decreases by 4.61% at full load. Lower HC and CO emissions while higher NO_X emissions were observed for the blends. It was also observed by the authors that the HRR and maximum peak pressure of ternary blends was higher.

(Li et al., 2015) utilized diesel, biodiesel and pentanol ternary fuel blend and compared the results with diesel. Authors observed that the ternary fuel blend shows similar physico-chemical properties to diesel. The authors used four stroke single cylinder CI engine. The authors have concluded from the results that indicated thermal efficiency was better and indicated specific fuel consumption was lower for the blends. Also, comparable maximum HRR and in-cylinder pressure were observed for blends. The combustion duration was less for the ternary fuels compared to diesel. All the emissions namely NO_X, soot, CO and total HC were lower for the ternary fuel blends. The authors concluded that the ternary fuel blends with pentanol shall be a possible substitute for diesel. (EL-Seesy and Hassan, 2019) used ternary fuel blend with 40% diesel, 50% biodiesel and 10% butanol. The ternary fuel blends displayed marginally lower BTE and higher BSFC. However, NO_X and HC emissions were observed to reduce with some penalty on CO emissions at low load. While running at higher loads carbon monoxide emissions get reduced for the blends.

(Atmanli, 2016) compared and analyzed the effect of ternary fuel blend of biodiesel-diesel-alcohol. The author used propanol, butanol and pentanol as alcohol and waste oil for making biodiesel. The author performed the engine trials and found marginally higher BTE, BSFC and EGT for the fuel blends. At low loads, authors found lesser HC emissions for the blends. Compared to diesel authors observed lower NO_X and CO emissions for the ternary fuel blends. (Ileri et al., 2016) used 70% diesel, 10% n-butanol and 20% rapeseed oil ternary fuel blends. The authors compared the results with diesel. The authors used Land rover 110 model, 82 KW turbocharged direct injection CI engine. For the blends, authors found more kinematic viscosity and density than diesel whereas cetane number and calorific value were lower. Ternary fuel blend, when compared to diesel, shows higher brake torque and power. BSFC of ternary fuel blends were very high due to shorter duration and higher friction losses. The EGT of ternary fuel blend was very less than diesel. NO_X and CO emission were higher for the blends whereas, HC emissions were lower for most of the engine speeds.

In the investigation carried out by (Yasin et al., 2015) two ternary fuel blends of diesel (70%/75%), methanol (10%/5%) and biodiesel (20%/20%) were used. The authors found lower flash point and viscosity of ternary fuel blends. The authors performed engine trials and found higher BSFC. Higher NO emissions with the addition of methanol were seen, however, the CO emissions dropped. (Leevijit et al., 2017) utilized ternary blends of biodiesel-diesel and ethanol. Composition of diesel was set to 80%, biodiesel to 5% and ethanol to 15%. The authors detected higher HRR, ignition delay, BTE and NO_X emission. Authors found on comparing with diesel, the blends exhibited lower BSFC, CO, HC, PM and CO_2 emissions. Also, the duration of combustion was lower for the blends. (Žaglinskis et al., 2016) used a ternary fuel blend of 30% rapeseed biodiesel, 10% methanol with diesel. The authors found during the engine trials that HC, CO and NO_X emissions were higher. BTE of the blends were also higher than diesel. (Senthur Prabu et al., 2018) utilized n-butanol, diesel and palm oil blends. 20% pine oil and 20% butanol was blended with diesel. Lower BTE and higher BSFC was seen by the authors for the blends. Lesser CO emissions were seen for the blends, however, NO_X and HC were higher. Smoke emissions were lower for the blend at low loads and high at higher loads. (Babu and Anand, 2017) used 5% diesel blended with 5% and 10% pentanol/hexanol and remaining was biodiesel derived from waste frying oil. For the blends, the authors observed higher BSFC, BSEC and lower BTE. The peak pressure and ignition delay for diesel were lower than blends. The blends produce lower emissions namely CO, HC, NO, smoke and higher CO_2 emissions.

(Tüccar et al., 2014) used two ternary fuel blends of microalgae biodiesel, diesel and butanol. Diesel percentage used was 60% and 70%, biodiesel is fixed to 20% and butanol as 20% and 10%. The blends exhibited lower brake power (BP) and torque values. NO_X, smoke and CO emissions decreased for the ternary fuel blends, whereas BSFC emissions increased. Higher the butanol in the blends more is the change. (Prakash et al., 2018) used diesel/castor oil/bio ethanol ternary fuel blends. The authors fixed the percentage of diesel to 30% and varied the quantity of castor oil to 60%/50%/40% and ethanol to 10%/20%/30%. For the blends, authors found lower in-cylinder pressure and comparable peak pressure. Blends exhibited higher ignition delay. As seen from the results, the authors found higher smoke, CO and HC emissions, while, NO emissions decreased. The blends also exhibited lower BTE, BSEC and exhaust gas temperatures. (Liu et al., 2016) examined the addition of higher alcohols to ethanol-diesel blends. The authors observed that due to finite miscibility of hydrous ethanol in diesel, the addition of higher alcohols namely butanol, hexanol, octanol and decanol will help in forming a stable blend. Authors added 10% higher alcohol to diesel-ethanol blends. Authors found higher carbon chain alcohols helped in getting better miscibility, however, n-decanol has lower pour point and therefore gel formation takes place. So, the authors concluded that addition of hexanol and octanol can be a beneficial step to form a stable diesel-ethanol blend.

(Fang et al., 2013) used blends of biodiesel, ethanol and diesel in a four cylinder CI engine. Authors found higher ignition delay for the blends. Blends exhibited lower BTE and higher BSFC. Authors found that the blends produce lower smoke and NO_X emissions. Authors also found higher HC and CO emissions. (Atmanlı et al., 2015) blended cotton oil, diesel and butanol. The authors found the ternary fuel blends can be used effectively without any phase separation upto -15°C. The authors found that on increasing n-butanol concentration in the blends, its density, viscosity and cold filter plugging point (CFPP) got better while its calorific value and cetane number decreased. Authors found that n-butanol addition reduces its torque, BTE, brake power and EGT whereas the opposite trend was observed by the authors on addition of cotton oil. Also higher BSFC, NO and NO_2 emissions was seen for the ternary fuel blends whereas authors found great reduction in CO and HC emissions.

(Yang et al., 2016) examined the usage of ternary fuel blends of WCO biodiesel, diesel and n-butanol. Authors recorded higher BSFC for ternary fuel blends than diesel. Highest BSFC was observed for 40% biodiesel, 10% butanol and 50% diesel whereas the lowest BSFC was observed for 10% biodiesel, 10% butanol and 80% diesel. Authors observed a decreasing trend for CO, NO_X and PM10 emissions. A significant drop was observed for particulate matter. Diesel showed the highest PM10 of 555 µg $kWhr^{-1}$ whereas 40% biodiesel, 10% butanol, 50 % diesel showed the lowest PM10 of 260 µg $kWhr^{-1}$. (Silitonga et al., 2018) used ternary fuel blend of diesel/biodiesel/bioethanol. Authors observed the lower concentration of biodiesel/ethanol in the blends displayed lower BSFC and higher BTE whereas a reverse trend was observed for higher concentrations on comparing with diesel. Blends exhibited lower smoke and CO emissions whereas somewhat higher NO_X emissions were observed by the authors when compared to diesel.

(Selvaraj and Thangavel, 2019) used ternary fuel blends of biodiesel-diesel and di-ethyl ether. Authors found that on adding DEE in the ternary fuel blends their BTE increased. Diesel exhibited highest BTE. Since BSFC is the opposite of BTE, a similar trend is observed. Diesel displayed, lowest BSFC whereas blends exhibited slightly higher

BSFC than diesel. Authors observed that the blends exhibited, lower cylinder pressure and lower HRR. Blends exhibited lower ignition delay, CO and HC emissions. Authors also observed little higher NO_X emissions for the blends.

2.6 Optimization of biodiesel production

It is very much necessary for controlling and optimizing the parameters that help in making biodiesel. Some researchers have investigated the influence of different parameters for biodiesel production using Taguchi approach. Some of the researches are summarized below:

(Kim et al., 2010) examined the effects of catalyst concentration, catalyst type, the temperature of reaction and molar ratio (alcohol to oil) for transesterification of rapeseed methyl ester using Taguchi approach. Authors developed an orthogonal array for the approach. Authors found that the effect of catalytic concentration was highest for better yield of biodiesel. (Karabas, 2014) produced biodiesel from safflower oil and optimized reaction time, reaction temperature, molar ratio and catalytic concentration using Taguchi approach. Authors found that the molar ratio played the most important role in biodiesel production. (Karabas, 2013) produced a corn kernel methyl ester using transesterification and used Taguchi approach for its optimization. Authors found reaction time as the most effective parameter in biodiesel production among all other parameters whereas alcohol: oil molar ratio attains the second most effective parameter in production of biodiesel. (Singh et al., 2018) used grape seed oil for producing biodiesel. Authors investigated the effect of parameters reaction temperature, catalyst concentration, molar ratio and the reaction time. Authors found catalytic concentration as the most vital parameter for producing biodiesel.

(Sathish Kumar et al., 2015) transesterified Manilkara Zapota oil and used Taguchi approach for optimizing biodiesel production. Authors found molar ratio as the most significant parameter while producing biodiesel. Authors found that on using the optimum conditions, biodiesel yield was 94.83%. (Saravanakumar et al., 2016) optimized Pongamia oil transesterification process by Taguchi technique. Authors found sodium hydroxide can maximize ester formation during biodiesel production.

(Kumar et al., 2017) used Taguchi approach and using L-9 array for optimizing biodiesel production from safflower oil. Authors found from the results that methanol-to-oil ratio (4:1), reaction temperature (60°C), catalyst concentration (1.5 wt%), and reaction time (90 min) gives the 93.8% yield of biodiesel with a viscosity 5.60 cSt. Authors found catalytic concentration as the main contribution factor for biodiesel production.

2.7 Outcomes of Literature

As an outcome of the exhaustive review of literature, the following major findings can be drawn;

- Diesel is the most used fuel in transportation and agriculture sector.
- Combustion of diesel creates serious environmental effects.
- Straight vegetable oil when used as fuel may cause severe engine deposits, injector coking and piston ring sticking. It also results in a reduction in BTE and higher exhaust emissions.
- Biodiesel used as a fuel for CI engines resolves this problem by some extent but results in higher NO_X emissions.

- Binary fuel blends usage in CI engines improves the emission characteristics of the engine. However, the performance characteristics of the engine get reduced.
- Binary fuel blends emitted higher HC emissions when compared to conventional diesel fuel.
- The usage of ternary fuel reduced the emissions of CI engine, while the performance was found comparable and in some cases better than diesel.
- The stable ternary mixture (which does not undergo any phase separation) can be formed with higher alcohols.
- Higher alcohol blends have a higher cetane number than lower alcohol blends.
- Physico-chemical properties of ternary fuel blends are comparable to petroleum diesel. However, the physico-chemical properties of binary blends are quite different than diesel fuel.

2.8 Research gap analysis

On the basis of exhaustive literature review, the following research gaps are identified.

- Majority of research work has been done on binary fuel bends. However, very few literature are available for ternary fuel blends.
- The use of binary blends of different alternative fuels and diesel in CI engine reduced the performance of the engine.
- The use of ternary blends as fuels in CI engines are not fully explored.

- Very few literature studied the phase diagrams (phase separation) of ternary fuel blends.
- Limited work has been done on single cylinder stationary engines using ternary fuel blends as fuel.
- Works with higher alcohols including pentanol, octanol, etc. are very limited.
- Literature does not clearly mention the long term storage stability of ternary fuel blends.
- Limited work has been done to analyze the performance of CI engines using ternary mixture at different weather conditions.

2.9 Problem Statement

After undergoing the exhaustive and comprehensive literature review, utilization of biodiesel of WCO in a ternary fuel blend is still not fully explored and is viable to work as a potential substitute to diesel.

Various research reported in the literature utilized different non-edible and edible feedstock. Usage of edible feedstock will pose a serious danger to our country which can create issues related to food security in the long-term. Vegetable oil is quite popular to be used directly in a diesel engine. However, its usage is limited in the neat form. Moreover, as discussed in the literature, biodiesel produced from vegetable oil is seen to be a good contender due to its low viscosity and density than vegetable oil. Most of the literature discussed utilize oils derived from the fruit which gets cultivated during a particular season in a year. So, waste cooking oil its biodiesel may be used as a potential feedstock in the ternary blend. It is also worth mentioning that various higher alcohols namely butanol, propanol, pentanol and octanol, etc. have been used in many binary fuel blend applications. Octanol can be used because of its easy miscibility and no phase separation with diesel engine fuels. Octanol has higher calorific value and cetane number than butanol. Therefore, octanol is supposed to be a viable option to be used in the ternary blend.

Therefore, to get the understanding of the usage of a ternary mixture of mineral diesel, waste cooking oil biodiesel blended with higher alcohols like octanol in various proportions need to be carried out in an engine. Exhaustive engine trials and the subsequent analysis are to be carried out for knowing the suitability of the fuel blends.

2.10 Research Objective

- Identification of utilized oil feedstock and alcohol for ternary fuel blend.
- Prepare the different ternary fuel blends according to blending norms.
- Study the storage stability of all test fuels.
- Analyze the phase stability of all test fuels at different weather conditions.
- To study the ternary phase diagrams of the blends.
- Determine the physico-chemical properties of all test fuels and compare the results with petroleum diesel.
- Determine the oxidation stability of all test fuels.
- Determine the performance, emission and combustion characteristics of single cylinder CI engines using prepared ternary fuels and compare the results with petroleum diesel fuel taking it as base line data.

CHAPTER 3

SYSTEM DEVELOPMENT AND METHODOLOGY

3.1 Introduction

This chapter gives a detailed description of the entire research carried out and also reveals the steps followed to carry out the present research based to attain the research objectives. The sequence of steps followed for the current research are as follows:

- Selection of fuels for blends
- Biodiesel production
- Optimization of parameters of biodiesel production
- The blending of selected fuels
- Determination of test fuel blends physico chemical properties
- Development of expermintal setup for determination of Sauter mean diameter of test fuel blends
- Diesel engine test rig system development
- Analysis of emissions, performance and combustion characteristics of the test fuel blends and comparison of these results with baseline diesel

Based on the review of literature, the best combinations of fuels for binary and ternary blends were selected. Production of biodiesel was carried out and the reaction parameters were optimized to get a higher yield of the prepared methyl ester. Several physico-chemical properties including kinematic viscosity, cetane index, calorific value, density, cold filter plugging point, cloud point, flash point, pour point, free fatty acid, etc. of test fuels were determined. Fourier-transform infrared spectroscopy (FTIR) and Gas chromatography–mass spectrometry (GC-MS) tests were carried out for the prepared biodiesel. A setup for determination of sauter mean diameter was also developed. After determining the important properties, emission, performance and combustion parameters of the engine were assessed. A diesel engine setup was used to measure the characteristics. All the parameters, equipment and methods and system development are explained in detail in this chapter.

3.2 Selection of Fuels

On the basis of the detailed literature survey, the primary challenge of the selection of fuels for the blends were being conceded upon. The selection was done on the basis of different physico-chemical properties (particle size, calorific value, density, viscosity, etc.), availability, storage, safety, etc. The best combination of fuels is biodiesel, diesel and alcohol. Diesel is the most widely available and accepted fuel for a CI engine. It is suited for both on road and off road applications. However, due to depletion, higher cost and harmful emissions from the combustion of diesel, biodiesel should be used. Biodiesel is eco-friendly and cost effective. A variety of biodiesel fuel sources were discussed in the previous chapter. Apart from these two fuels alcohols are the oxygenated fuels that can be suitably substituted in a CI engine to reduce harmful emissions.

Alcohols like butanol, pentanol, hexanol, octanol have successfully been used in a diesel engine. Octanol is the best choice in the current study owing to its better miscibility with diesel and biodiesel. Moreover, octanol also has a high cetane number and energy content than other lower carbon chain alcohols. Therefore ternary fuel blends of biodiesel, octanol and diesel are found to be the best choice.

3.2.1 Biodiesel

Vegetable oils owing to their lower heating value and very high viscosity are avoided to be directly utilized in a CI engine. Apart from these several other issues related to the use of vegetable oil for a diesel engine are also there.

These problems cause improper functioning of the diesel engine. The main problems are ignition delay, misfire and engine starting problem in cold weather. Apart from these problems, coking of injector, deposits formation in the engine, incomplete combustion, sticking of piston rings and dilution of lubricating oil were observed (Corsini et al., 2015; Ma and Hanna, 1999; Ryan and Bagby, 1993).

So to solve the problems associated with vegetable oil, certain approaches can be used. These methods are catalytic cracking and pyrolysis, transesterification, blending with diesel fuel and micro-emulsions (Agarwal, 2007; Balat and Balat, 2008; Demirbas, 2008). Transesterification is the easiest approach among all the techniques for reducing the viscosity of vegetable oils.

Biodiesel is renewable in nature. Also, the production of biodiesel is not a very complex process. It can easily be prepared from a variety of oils. For developing countries who are net importers of fossil fuels, it is very much beneficial as it increases a country's self-reliance. Apart from these benefits, usage of biodiesel helps in reducing the overall greenhouse gas emissions. Due to easy production method, biodiesel can be used for running farm equipment, pumps, tractor, engines and generators. The biodiesel can be produced even at a small scale with minimum efforts and investment. Biodiesel usage as a fuel can be carried without difficulty in a diesel engine. However, before usage of this alternative fuel, exploring the properties of biodiesel is very much necessary.

Although there are many feedstocks of biodiesel available, however, most of them have similar properties and performance.

On the basis of Table 3.1, it is seen that WCO can be used extensively in a diesel engine. Moreover, no footprint related to water use was there for WCO.

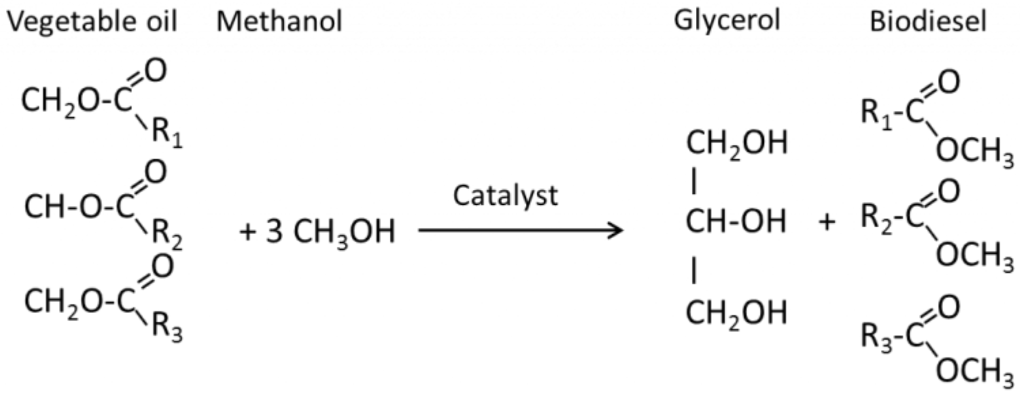
Table 3.1. Comparison of oil yield and water footprints (Abed et al., 2018; Chisti, 2007)

Feedstock	Average yield of oil (L/ha)	Average global water
Soybean	446	4190
Corn	172	2575
Linseed	478	9415
Cotton seed	325	3957
Safflower	779	16046
Rapeseed	1190	4301
Mustard	572	5600
Sesame	696	21793
Jatropha	1892	870
Sunflower	952	6792
Groundnuts	1059	7529
Microalgae	136900	0
Olives	1212	14578
Castor	1413	24740
Coconuts	2689	4490
WCO	No need for land	No footprint

Apart from this, on the basis of the literature survey carried out in the previous chapter, WCO is well suited for the production of biodiesel owing to its comparable physico-chemical properties with diesel. Several studies have used WCO in the diesel engine without a noticeable change in its emission, combustion and performance characteristics. Moreover, WCO biodiesel has also been used successfully with better emission characteristics with similar performance and combustion profiles.

3.2.1.1 Method of biodiesel production

Transesterification is the process of having a chemical reaction between alcohol and oil/fat to get esters and glycerol.



(3.1)

Equation 3.1 shows the chemical reaction involved in producing biodiesel. Here R, R_1, R_2 and R_3 represent different carbon chain lengths and –COO- is a carboxyl group of alkyl groups.

A catalyst is normally required for decreasing the reaction time and increasing the yield percentage. As it is a reversible process and to shift the equilibrium to the product side, excess alcohol is desired. Numerous studied have been conducted on the use of different use of alcohols in the transesterification process.

Methanol, ethanol, propanol, etc. are typically being used to produce biodiesel. Studies carried in the past also found that alkali-catalyzed transesterification is mostly used commercially and much faster than acid-catalyzed transesterification when compared to alkali-catalyzed transesterification (Agarwal, 2007). Figure 3.1 shows the flowchart or the step by step method used for producing biodiesel.

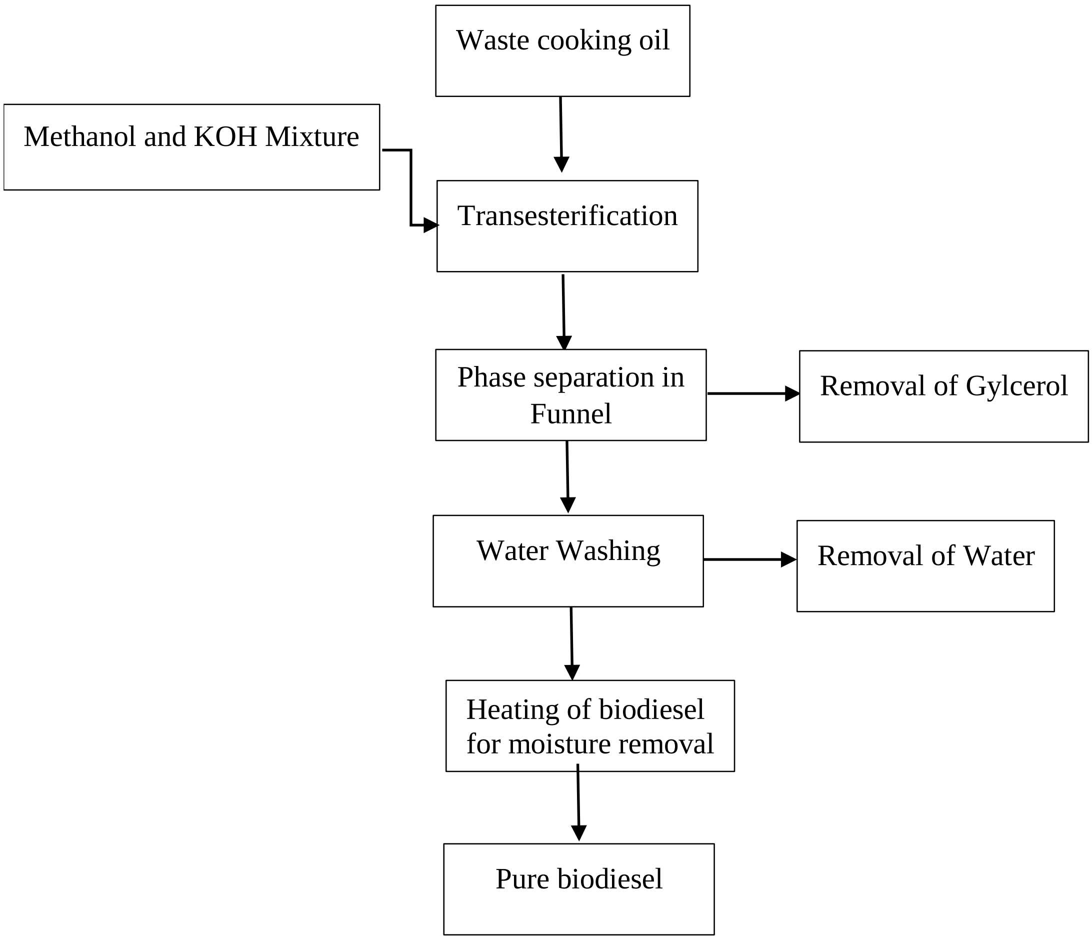


Figure 3.1. Flow chart for producing biodiesel by direct transesterification process

The flowchart shown in Figure 3.1 is used for making biodiesel from WCO. ASTM-D644 standard was used for determining the FFA content of the oil. Titration of oil with N/10 sodium hydroxide solution is carried out in this method. Phenolphthalein is used as the indicator and iso-propyl alcohols are mixed with the oil for the determination of FFA. The acid number is found using equation 3.2.

$$Acid\ \ Number = M \times V \times (\frac{56.1}{W_{oil}}) \tag{3.2}$$

W_{oil}= weight of oil, M= Molar concentration of titrant, V=Volume of titrant consumed

Free fatty acid is half of the acid number. In the present study, the FFA of WCO was found to be 1.9. Therefore one-step transesterification process is used for producing biodiesel from WCO. For conversion of WCO to biodiesel, a sieve of medium permeability was utilized to eliminate substantial filths and froths from the oil. Then filter paper was used for removing the unwanted impurities. Heating of oil (temperature greater than 100°C) was carried out for removing the moisture from the oil. Heating was done for nearly 30 minutes. Then the well-known transesterification process (Sheet, 2018) as discussed in the earlier section was used. Methanol and KOH mixed together was then added to WCO. The mixture is maintained at nearly 60°C temperature. Then the mixture was continuously stirred for approximately an hour.

Then the mixture was kept for cooling and further fed inside separating funnel to settle heavier and denser glycerine at the bottom, shown in Plate 3.1. The knob of separating funnel was opened to remove glycerol from the funnel. Water washing of methyl ester so formed was carried out in slightly warm water.

Plate 3.1. Separation of biodiesel and glycerol

The process is repeated until the undissolved and unused chemicals were flushed out, shown in Plate 3.2. Then the methyl ester was heated over 100°C for evaporating moisture.

Plate 3.2. Separating funnel showing water washing process

3.2.1.2 Optimisation of biodiesel production

Biodiesel is studied as a useful fuel for a diesel engine. However, the cost of fuel plays a very important rule for its selection or rejection. If the cost is economical and justifiable then only that fuel can be used extensively. Also, biodiesel production depends upon the amount of methanol consumed, amount of catalyst, electricity and heating cost, etc. Therefore, the cost of biodiesel production can be minimised after analysing and optimising the parameters mentioned above.

As discussed in the previous sections, biodiesel is prepared from WCO. The oil used was having a low FFA value of 1.9. Therefore, the direct transestrification process was carried out. Total twenty five number of experiments were carried for this process and their influence was evaluated for finding the optimum results.

To get the value of yield equation 3.3 was used

$$Yield\ \ percentage = \frac{methyl\ ester\ \ produced\ (by\ weight)}{quantity\ of\ \ oil\ used\ (by\ weight)} \times 100 \qquad (3.3)$$

Table 3.2 describes the parameters selected for applying the optimization process. These parameters were carefully selected on the basis of former literature works and initial experiments.

Table 3.2. Input parameters and their levels are taken for applying the Taguchi approach

Parameter	Level				
	1	**2**	**3**	**4**	**5**
Catalytic concentration (% wt.)	0.25	0.50	0.75	1.00	1.25
Molar Ratio (Methanol to oil)	2:1	4:1	6:1	8:1	10:1
Temperature of Reaction (°C)	56	58	60	62	64
Time of Reaction (in minutes)	40	50	60	70	80
Agitation speed (in rpm)	150	200	250	300	350

Orthogonal arrays were formulated for experimentation. It decreases the number of random experiments and reduces the efforts without compromising with the results.

Signal to noise ratio (SNR)- It represents the variation of expected results and quality function. There are three different types of SNRs used in Taguchi approach. They are larger-the-better used for maximizing the output. Second is smaller the better for minimizing the output and third is nominal the best which is used in normalizing problems. In the current study, output i.e. the yield needs to be maximized. Therefore larger the better approach is used.

Equation (3.4) gives the formula for Signal to Noise ratio.

$$SNR_i = -10\log\frac{1}{n}\left(\sum_{k=1}^{k=n}\frac{1}{y_k^2}\right) \tag{3.4}$$

Here, i is the experiment number

y is the responses for the given factor level combination

n is the number of trials

k is the trial number

For determining the number of experiments, equation 3.5 (Christiansen and Shuwaikh, 2019) is used

n= 1+P (L-1) (3.5)

P is the number of parameters

L is the number of levels.

In this study, P=6 and L=5

Therefore, n= 1+ 6 (5-1) =25.

On the basis of Taguchi approach minimum of 25 experiments need to be carried out. Table 3.3 shows the matrix selected for applying the Taguchi approach. This matrix is predefined for applying Taguchi and the same set of experiments need to be followed for getting the larger value of output on giving input. If the same set of experiments are not followed then the matrix is not said to be an orthogonal matrix and will not give the optimum values. Therefore it is necessary to follow the same set of experiments given by the Minitab software while designing the experiments. After conducting these set of experiments, the yield was calculated and the computer software gives the values of the optimum parameters to get the maximum yield using larger the better approach.

Table 3.3. Matrix of input parameters used for applying Taguchi approach

Run	Catalytic concentration (% wt.)	Molar Ratio (Methanol to oil)	Temperature of Reaction (°C)	Time of Reaction (in minutes)	Agitation speed (in rpm)
1	0.25	2	56	40	150
2	0.25	4	58	50	200
3	0.25	6	60	60	250
4	0.25	8	62	70	300
5	0.25	10	64	80	350
6	0.50	2	58	60	300
7	0.50	4	60	70	350
8	0.50	6	62	80	150
9	0.50	8	64	40	200
10	0.50	10	56	50	250
11	0.75	2	60	80	200
12	0.75	4	62	40	250
13	0.75	6	64	50	300
14	0.75	8	56	60	350
15	0.75	10	58	70	150
16	1.00	2	62	50	350

17	1.00	4	64	60	150
18	1.00	6	56	70	200
19	1.00	8	58	80	250
20	1.00	10	60	40	300
21	1.25	2	64	70	250
22	1.25	4	56	80	300
23	1.25	6	58	40	350
24	1.25	8	60	50	150
25	1.25	10	62	60	200

ANOVA approach was used for making a relation between the parameters and the SNR. Since analyzing through Taguchi method cannot provide the effects directly, therefore for determining the percentage contribution of each factor ANOVA is used. It gives the magnitude of the parameters that affect the output.

For determining the percentage contribution of each factor equation 3.6 is used

$$Percentage\ Contribution = \frac{SS_x}{SS_y} \times 100$$

(3.6)

Where, SS_x = sum of the square of individual factor

&, SS_y = sum of the square of total factors

This percentage contribution is very essential as it tells the users which parameters are important to study.

3.2.2 Octanol

Alcohols have been gaining an increasing amount of interest owing to the oxygen present that leads to better and complete combustion leading to lower emissions. Octanol has many advantages discussed in the previous sections. Currently, petroleum is the source of producing 1-octanol (Xia et al., 2015). However many researchers have now produced octanol from a renewable route (Akhtar et al., 2015; Julis and Leitner, 2012) making it a desirable choice. Diesel, biodiesel and octanol can easily be blended without any phase separation.

3.3 Preparation of test fuel blends

WCO biodiesel, petroleum diesel and octanol are blended in different proportions. Cost-effective splash blending method was used for the preparation of the blends. The test fuels were stirred rigorously for some time for making homogenous fuel blends. The blending percentage was selected based on an initial experimentation and literature survey.

10% and 20% octanol was blended with 10% and 20% biodiesel and 90%, 80% and 70% diesel for the formation of blends. 2 binary fuel blends and 3 ternary fuel blends were prepared to form test fuels. Terminology and composition of fuel blends are defined in Table 3.4. Also, no surfactant or cetane improver was added for the formation of blends. All the samples were checked under a light source at regular intervals for seeing the phase separation.

100D is notated that contains 100% diesel and no other fuel. 10O90D contains 10% octanol and 90% diesel. Blend 10WB90D contains 10% WCO biodiesel and 90% diesel. Similarly, three ternary fuel blends namely 10O10WB80D contains 10%

octanol, 10% WCO biodiesel and 80% diesel, 10O20WB70D contains 10% octanol, 20% WCO biodiesel and 70% diesel and 20O10WB70D contains 20% octanol, 10% WCO biodiesel and 70% diesel. The nomenclature of test fuels is presented in Table 3.4 shows the different composition of test fuels.

Table 3.4. Nomenclature of the test fuels

S.No.	Name	WCO Biodiesel	Diesel	Octanol
1	100D	0%	100%	0%
2	100WB	100%	0%	0%
3	10WB90D	10%	90%	0%
4	10O90D	0%	90%	10%
5	10O10WB80D	10%	80%	10%
6	10O20WB70D	20%	70%	10%
7	20O10WB70D	10%	70%	20%

Plate 3.3 shows different test fuels used for the current study.

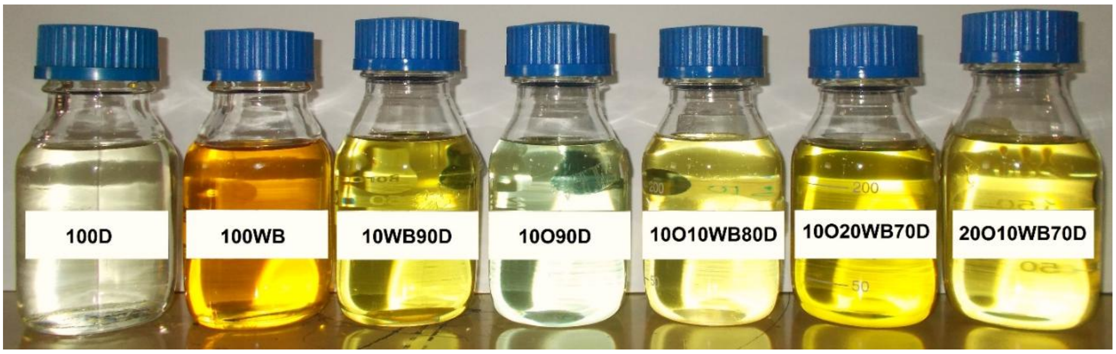


Plate 3.3. Fuel samples

3.4 Determination of physico-chemical properties

Test fuel blends properties were determined by means of different types of equipment. Table 3.5 summarized the properties of different equipment used.

Table 3.5. Equipment details used for determining physico-chemical properties

S. No.	Property to be determined	Equipment used	Manufacturer of equipment	Test standard	Principle of testing
1.	Density	DMA 4500	Anton Parr	ASTM D4052	oscillating U-tube method
2.	Kinematic viscosity	Capillary tube	Petrotest	ASTM D445	the relation between viscosity and time and taking gravity as driving force
3.	Calorific value	Parr 6100 Oxygen Bomb Calorimeter	Parr	ASTM D240	Constant volume and constant temperature
4.	Gas chromatography and mass spectroscopy (GC-MS)	QP-2010 Plus	Shimadzu Corporation	ASTM D3973	On heating, the fuel sample will separate into discrete substances
5.	Cetane Index	NA	NA	ASTM D4737	Four variable equation
6.	Flash Point	Pensky-Martens Closed Cup Tester	Dott Gianni Scavini& C.	ASTM D93	The integrated fire-extinguishing system automatically controlled

		(AD0093-600)			
7.	Cloud Point	KLA-3-TS	Koehler Instrument	ASTM D2500	A light pulse was transmitted from an optical cable positioned for every decrease of 1°C to check the appearance of crystallization
8.	Pour point	KLA-3-TS	Koehler Instrument	ASTM D97	To remove the test fuel from the cooling jacket at every 3°C decrease in temperature and tilting it to 90° angle until no flow is observed
9.	Cold filter plugging point (CFPP)	NEWLAB 200/1	Linetronic Technologies	ASTM D6371	Fuel is sucked through a filter in a definite time after cooled under desired conditions
10.	Oxidation stability	873 biodiesel rancimat	Metrohm India Private Limited	ASTM D 6751 / ASTM D7467	Air is fed inside the fuel into the glass vessel at a higher temperature for aging the sample.
11.	FTIR	Nicolet 380	Thermo Fisher Scientific	ASTM D7371	For representing the bonds present in the molecule, infra-red light is transmitted over the molecules.

3.4.1 Density and Specific Gravity

Density is a very significant characteristic parameter of a fuel. It gives the relationship between the volume and mass of the fuel. Mass divided by the volume of fuel gives its density. For determining density various methods are available. A simple Anton Paar make DMA 4500 working on U tube oscillating method is used for the determination of density. The fuel density is calculated at a temperature of 15 °C. The measuring principle for the density is the change of the oscillation frequency of a bending oscillator. Before starting the measurement, the measuring cell was rinsed with toluene. Calibration of the setup was carried out for removing errors during measurement.

The same equipment is used to measure the value of specific gravity. It is the ratio of the density of the test fuel to the density of reference fluid. Plate 3.4 shows the instrument used for measuring density and specific gravity.

Plate 3.4. The instrument used for measuring density and specific gravity

3.4.2 Viscosity

It measures the internal resistance offered to the fuel layers for the flow. For fuels, kinematic viscosity determination is preferable. It is the ratio of fuel's dynamic viscosity and density. It varies with temperature. The viscosity of the fuel affects its atomization and proper mixing of air and fuel. Therefore, low viscosity values are desirable (Suthisripok and Semsamran, 2018; Vallinayagam et al., 2015). Kinematic viscosity was determined using the viscometer. The temperature of the experiment for determining the viscosity was set as per the ASTM D445 test standard which is equal to 40°C. A definite amount of fuel quantity was permitted to free flow from the selected capillary tube. A stopwatch was used for noting the time taken for the fuel passing from the capillary tube's upper level mark and lower level mark. Plate 3.5 shows the kinematic viscometer used for the experimental purpose. Viscosity measurements were conducted for different blends under consideration using equation 3.7.

Plate 3.5. The instrument used for measuring Kinematic viscosity

$$v = k \times t \tag{3.7}$$

here, ν = Kinematic viscosity

k = constant which depends upon the capillary

t = time taken by the fuel for passing from upper to lower level marks

3.4.3 Calorific value

For the determination of calorific value, an instrument known as Bomb calorimeter was used. Calorific value is known as the heat released in the presence of oxygen on combusting unit quantity of fuel. It was measured as per ASTM D240 standard. Plate 3.6 shows the bomb calorimeter used.

Plate 3.6. Bomb calorimeter

The model of the bomb calorimeter used was Parr 6100. For the measurement, the fuel sample was burned by the electrical current from the electrodes inside the bomb. Calorific value is measured which is the amount of heat extracted during the formation of steam in the process of combination of hydrogen and oxygen. Hydrogen atoms of fuels react with oxygen and form steam during combustion. This heat from the steam is measured and gives the value of fuel's calorific value.

3.4.4 Cold Filter Plugging Point (CFPP)

CFPP of the fuel is the minimum temperature that allows the passage of fuel through the filter in a definite time. At low operating temperature fuel gets thick and loses its flowing property that hampers working of a fuel pump, pipes and injectors. CFPP of fuels reveals about its usage in cold weather conditions. Apparatus used for CFPP measurement is shown in Plate 3.7.

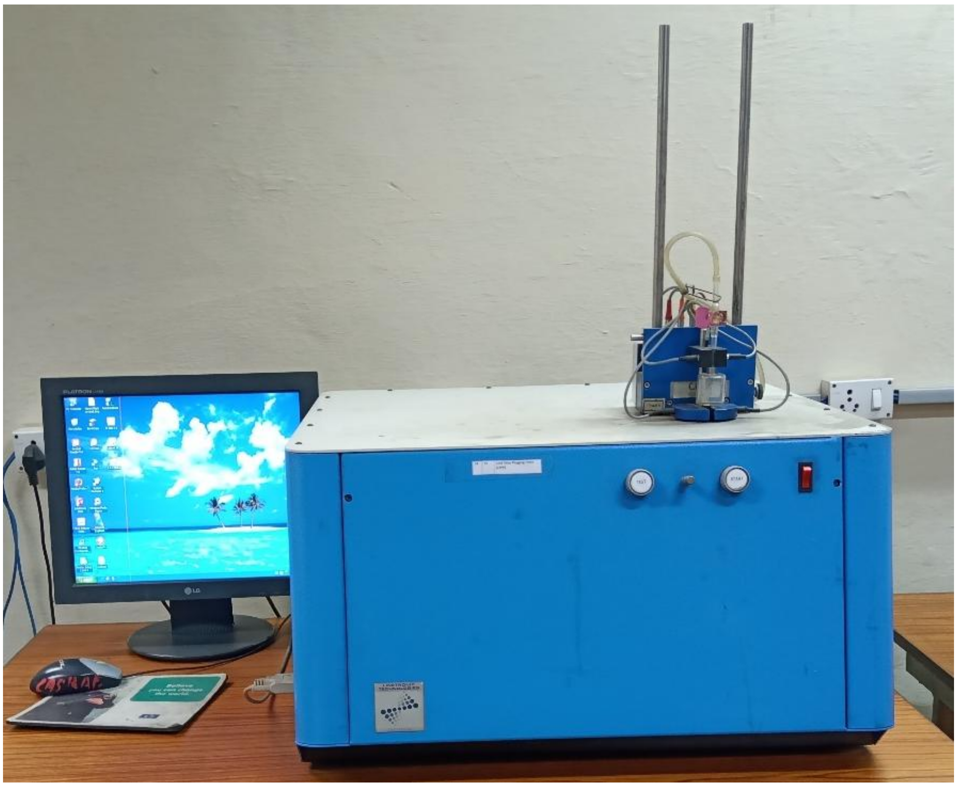


Plate 3.7. The instrument used for measuring CFPP

3.4.5 Cetane index

This term is very important for diesel or diesel like fuel as it represents the quality of fuel. Cetane index gives the approximation of cetane number of the fuel based on its density and volatility. If the fuel has a low cetane number then a problem of knocking or late combustion will be present. It causes devastating effects on engine operation in the long run. Therefore measurement of cetane number/index is very much important while studying the fuels used in a diesel engine.

The standard test method as described by ASTM D4737 was used for measurement of cetane index. Equation 3.8 describes the formula utilized for measurement of calculated cetane index (CCI).

Distillation recovery temperature was measured from the instrument is shown in Plate 3.8. In this process, fuel sample is distilled in a specified distillation flask. The temperature was observed from the instant of the first drop of condensate falling from the lower end of the condensate tube and to the last drop till the desired quantity of the fuel is condensed. The maximum temperature observed for the last drop was recorded for determining the distillation temperatures.

$$CCI = 45.2 + 0.0892(T_{10X}) + [0.131 + (0.901)H](T_{50X}) + [0.0523 - (0.420G](T_{90X}) + (0.00049)[(T_{10X})^2 - (T_{90X})^2] + 107G + 60G^2 \quad (3.8)$$

Where, $G = (e^{-3.5H}) - 1$

H=D-0.85

D= Fuel Density

T_{10X} = Recovery temperature for getting 10% distillate

T_{50X} = Recovery temperature for getting 50% distillate

T_{90X} = Recovery temperature for getting 90% distillate

This four variable equation was used to calculate the cetane index of test fuel samples.

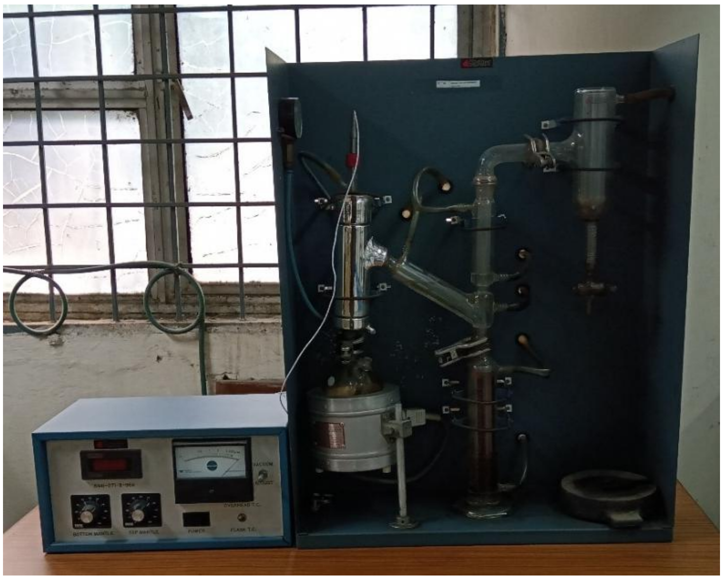


Plate 3.8. Distillation temperatures measurement

3.4.6 Flash point

Flash point is known as the minimum temperature at which fuel gets ignited or its vapours become ignitable. Lower the value of flash point, easily the fuel gets burned. However, for safety and storage consideration, very low flash point is not desirable. Plate 3.9 shows the flash point apparatus. For the measurement of flash point, a Scavini make Pensky-Martens apparatus was used.

Plate 3.9. Pensky Martens apparatus used for determining flash point

It works as per ASTM D93 standard. In this experiment, a test cup containing the fuel sample was heated. Then pilot flame direction was moved towards the cup by the automatic feeder at regular intervals from the opening provided at the top of the instrument.

3.4.7 Copper strip corrosion

The corrosive property of fuel can be determined by this test. To check the corrosiveness a copper strip is submerged in the fuel for the specified time of 3 hours at 50°C. Then the copper strip is removed and its colour is compared with a standard colour chart. This colour tone gives the copper strip corrosion code. It varies from 1 to 4. ASTM D130 standard method was adopted for the measurement of copper strip test.

Plate 3.10 shows the copper strip corrosion apparatus to determine the corrosiveness of the fuel

Plate 3.10. Copper strip corrosion apparatus

3.4.8 Saponification Number

The average molecular weight of triglyceride present in the sample is its saponification number. In this process, neutral fats were broken down into fatty acids and glycerol by treatment with an alkali catalyst given in equation 3.9.

Triglyceride + 3 KOH →3 Fatty acid salts of potassium + Glycerol (3.9)

The amount of KOH that saponify one gram of fat or oil gives the value of the saponification number. In an ethanol solution containing known excess of KOH, the lipid is dissolved. For the completion of the reaction, this solution is then heated. For determination of un-reacted KOH, the sample is titrated with hydrochloric acid.

The indicator (phenolphthalein) was also added to the solution. From the weight of the sample and the amount of KOH reacted the value of saponification number was evaluated. Lesser the saponification number of the oil greater are the triglycerides that exist in it.

3.4.9 Elemental analysis

The elemental analyzer was used to find the amount of carbon and hydrogen in the test fuel samples. Plate 3.11 shows the setup used to determine carbon and hydrogen percentage present in the fuel. The percentage content of carbon and hydrogen was detected against the total weight of these elements. In this technique, the fuel was combusted in the presence of oxygen inside a furnace at high temperatures. The products of the combustion are normally oxides in the form of gases of the concerned elements. The detector then detects these gases separately using the inert gases like helium or argon.

Plate 3.11. Elemental analyzer

3.4.10 Cloud point and pour point

Cloud point is the temperature below which wax or biowax was formed in diesel/biodiesel. This affects the fuel filters working by clogging it. Another low temperature measurement is normally carried for pour point. It is the lowest temperature at which fuel will flow. Pour point helps in understanding the applications of fuels in cold weather. ASTM D2500 and D97 test methods were used to determine cloud point and pour point. For determination of cloud point, a light pulse obtained from an optic cable at an interval of 1°C was used to check the appearance of crystallization. The instant at which first cloud or hazy formation in the fuel sample was observed, that temperature gives the cloud point. For determination of pour point, the fuel sample was removed at 3°C intervals from the cooling jacket and leaning it to 90° angle until no flow is observed. The temperature at which fluid loses its flow characteristic gives the pour point value.

Plate 3.12. shows the equipment utilized to determine cloud and pour point.

Plate 3.12. Cloud point and pour point measuring equipment

3.4.11 Carbon residue

It is defined as the quantity of decomposed matter left on evaporation/pyrolysis of fuel to form coke like substance. This test method helps in getting a likely indication of deposit formation in the combustion chamber of an engine. ASTM D524 test method was used for the determination of carbon residue. In this method, 90% of the sample was first recovered after distillation. The residue was measured and weighed. It is then heated in a special glass bulb to 550°C inside a furnace. The sample in the bulb gets evaporated or decomposed. The remaining sample is then cooled and again measured for loss of weight. This gives the amount of carbon residue left.

Plate 3.13 shows the equipment used to measure the carbon residue of fuels.

Plate 3.13. Equipment used to determine carbon residue

3.4.12 Oxidation stability

Oxidation stability is the chemical reaction between oxygen and fuel. This oxidation stability is affected by temperature, catalysts, etc. Therefore to determine the suitability and shelf life of fuel and its blends, oxidation stability is very much necessary to be measured. Due to oxidation of fuel, fatty acids will form. These acids being corrosive can damage the fuel injection system. The oxidation stability of the test fuels was measured using Biodiesel Rancimat of Metrohm Company. The fuels were subjected to a condition of high temperature and continuous air flow for oxidation. ASTM D 6751 and EN 14112 are the standards for measurement of the test fuels.

Plate 3.14 shows the setup for measuring oxidation stability of test fuels.

Plate 3.14. The setup used to determine the Oxidation stability

3.4.13 Fourier transform infrared spectroscopy (FTIR)

FTIR is employed to find the components present in the fuel. FTIR spectrum obtained from the equipment gives the functional group in the test fuels. Vibrating molecules emit IR which gets absorbed during FTIR analysis and hence tells the functional group. The principle of FTIR spectroscopy is based on the fact that the molecules present in the fuel sample absorb infrared light at certain wavelengths due to their typical binding form. In comparison with the fresh oil reference spectrum, changes in the fuel can be determined, calculated and interpreted in the form of typical bands at certain wavelengths.

Figure 3.2 shows the schematic of the setup used for determining the components in fuel using FTIR

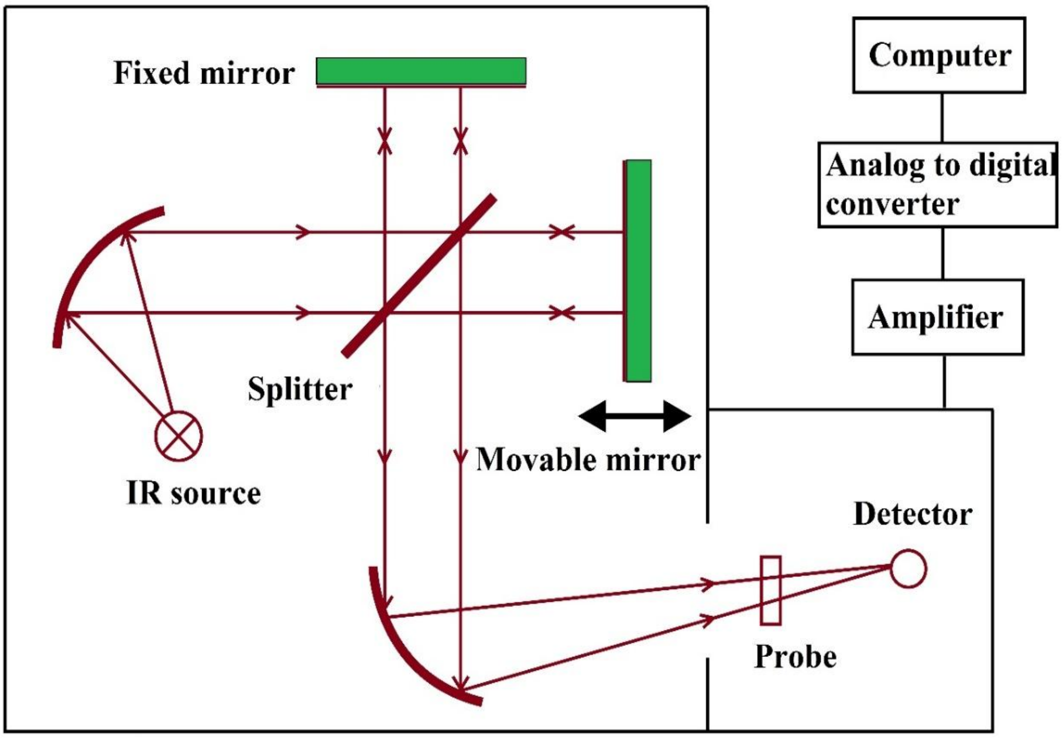


Figure 3.2. Schematic of FTIR setup

The main component of an FTIR spectrometer is an interferometer in which the parallel beam when passed through an opaque mirror gets split. Splitter interferes with both beams. Half of the split beam is passed back to the fixed mirror and half of the light moves to the movable mirror. Both mirrors have the same distance to the beam splitter. The interference behind the beam splitter is either constructive or destructive, depending on the phase. The portion of the light from the moving mirror reflects the light to the beam splitter. Beam splitter then recombines the beams depending on the phase difference (i.e. wavelength). This gives the interference pattern which can mathematically be Fourier transformed on a computer to produce an IR spectrum.

Plate 3.15 shows the actual setup of FTIR.

Plate 3.15. FTIR setup

3.4.14 Fatty acid composition

Fatty acid composition and molecular weight of the fuel was found using gas chromatography and mass spectroscopy (GS-MS). A capillary column is used in a gas chromatography apparatus. A flow-through thin tube named as the column was used. A gas chromatograph uses a column, from which different fuels samples pass in a gas medium at different rates based on their physical and chemical properties. When substances move out from the column, they get distinguished and recognized electronically. The purpose of the immobile phase present in the column was to discrete dissimilar components, affecting the exit of the product at separate retention time. Column length, carrier gas flow and temperature can also be changed for altering the retention time. In a mass spectrometer, the gas is converted into ions.

Plate 3.16 shows the typical GS-MS setup.

Plate 3.16. GC-MS setup

3.5 Sauter mean diameter (SMD)

SMD assists in learning about the atomization for a particular fuel. It is defined as a fuel spray volume to its surface area. SMD of a pressurized fuel was measured from the fuel injected by the injector of a diesel engine. Various components of the SMD setup are:

- Fuel tank
- High pressure pump
- Injector
- Fuel filter
- Hoses and pipes
- Power supply
- Computer system and software
- Malvern Spraytec laser diffraction system

Plate 3.17 shows the fuel tank and fuel pump system used for storing and filtering the fuel. This tank is having a capacity of 3 liters for storing one fuel at a time. The fuel is fed from the tank to the fuel pump. This pump is having ample power to help in atomizing the fuel through the injector. Plate 3.18 shows the pump used in the setup.

Plate 3.17. Fuel tank of SMD setup

Plate 3.18. Motorized system for a fuel pump of SMD setup

This pump pulls the fuel and passes it through the fuel filter which is then connected to the fuel injector. A return pipe is also present that returns the fuel. Plate 3.19 shows the diesel fuel injector used for measurement of SMD. The injector was set to work at 190 bar which works with the help of the pump.

Plate 3.19. Injector used for determining SMD

The injector then sprays the fuel at the set pressure. Figure 3.3 shows the complete setup to determine SMD.

This highly pressurized fuel when coming out of the injector gets dissociated into a fine spray. The transmitter module transmits a laser beam illuminating the fuel spray with the help of collimated laser light. Scattered light obtained from fuel spray was detected by the receiver module.

The computer software finally evaluates and computes the droplet or the particle size of the fuel known as SMD. Figure 3.3 shows the schematic used for measurement of SMD of test fuels with its major components.

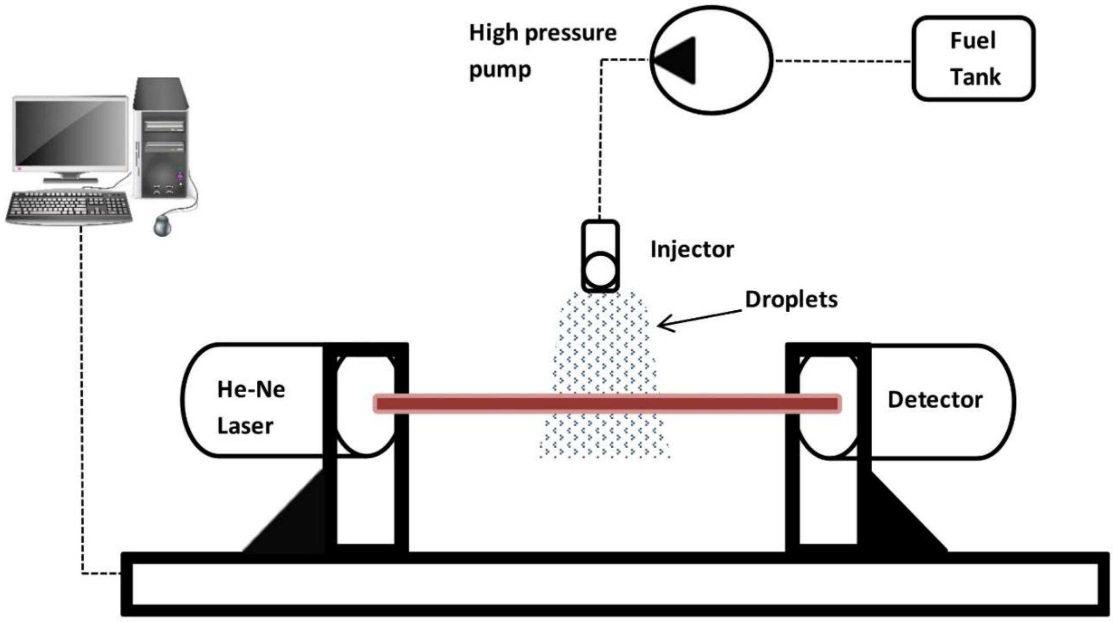


Figure 3.3. Schematic of setup used to determine SMD

3.6 Selection of Diesel engine

Single cylinder Kirloskar make diesel engine was used in the test rig. It is a four stroke engine. Compression ratio (CR) for the engine can be varied making it a variable compression ratio engine. The engine is having a specially fabricated tilting cylinder block arrangement. Changing the CR also does not alter the combustion chamber geometry. An eddy current type dynamometer was used for engine loading. Crank-angle and combustion pressure was measured with the help of crank encoder and pressure transducer. These sensors then send the signals to the computer software connected to test setup. Temperatures, fuel flow, airflow and loads can be measured. Cooling water was fed from the cooling tower for cooling calorimeter, pressure transducers, dynamometer, etc. Enginesoft software tool provided by the manufacturer gives several parameters for evaluating the test rig.

The typical specification of the test rig is summarized in Table 3.6.

Table 3.6. Specification of Diesel engine test rig

Make	**Kirloskar**
Brake Power (kW)	3.5
Cylinders	One
Rated Speed (rpm)	1500
Compression Ratio	17.5:1 (VCR engine)
Stroke X Bore (mm)	110 x 87.5
Cooling type	Water Cooled
Variable compression ratio	12 to 18
Piezo sensor	Range 5000 PSI, with low noise cable
Dynamometer type	Eddy current
Crank angle encoder sensor	5500 RPM with TDC pulse and resolution of 1 Degree
Engine Cubic Capacity	661cc
Load sensor	strain gauge type (0-50 Kg range)
Inlet valve closes at	35.5 degrees ABDC
Inlet valve opens at	4.5 degrees BTDC
The exhaust valve closes at	4.5 degrees ATDC
Exhaust valve opens at	35.5 degrees BBDC
Fuel Injection Timing	26 degrees BTDC

The exhaust manifold was mounted with the K type thermocouples to determine the exhaust gas temperature. AVL Di Gas 4000 Analyzer and AVL 437 smoke meter were used for measuring exhaust gas emissions.

3.7 Parameters Selection

Testing was done as per IS:10000 standards. The important parameters observed are listed below. These parameters are very much essential to be determined.

- Air flow rate
- In cylinder pressure
- Fuel consumption rate
- Engine load
- Speed of the engine
- Smoke opacity
- Exhaust emissions (NO_X, CO and HC)

From the parameters mentioned above, the following factors were calculated

- Brake thermal efficiency (BTE)
- Brake specific energy consumption (BSEC)
- Brake mean effective pressure (BMEP)
- Mass fraction burnt
- Heat release rate (HRR)

3.7.1 Measured parameters and calculations

In the previous section of this chapter, several parameters and the instruments utilized for the measurement of these parameters were discussed. This section elaborates the instruments used for measuring the parameters.

The engine consists of a decompression lever that is used to start the engine. Hand cranking is done by significantly decreasing the compression due to the release of decompression lever. It opens the exhaust valve and reduces the effort required for hand cranking. An injector injects fuel in the combustion chamber. The most common pressure set for the injector is normally 190 bar.

The flywheel is mounted on the crankshaft to store the rotational energy of the engine. The energy that is stored is related to its moment of inertia. It helps in smooth operation during the increase and decrease of power requirements. Plate 3.20 shows the engine selected for determining performance, emission and combustion attributes.

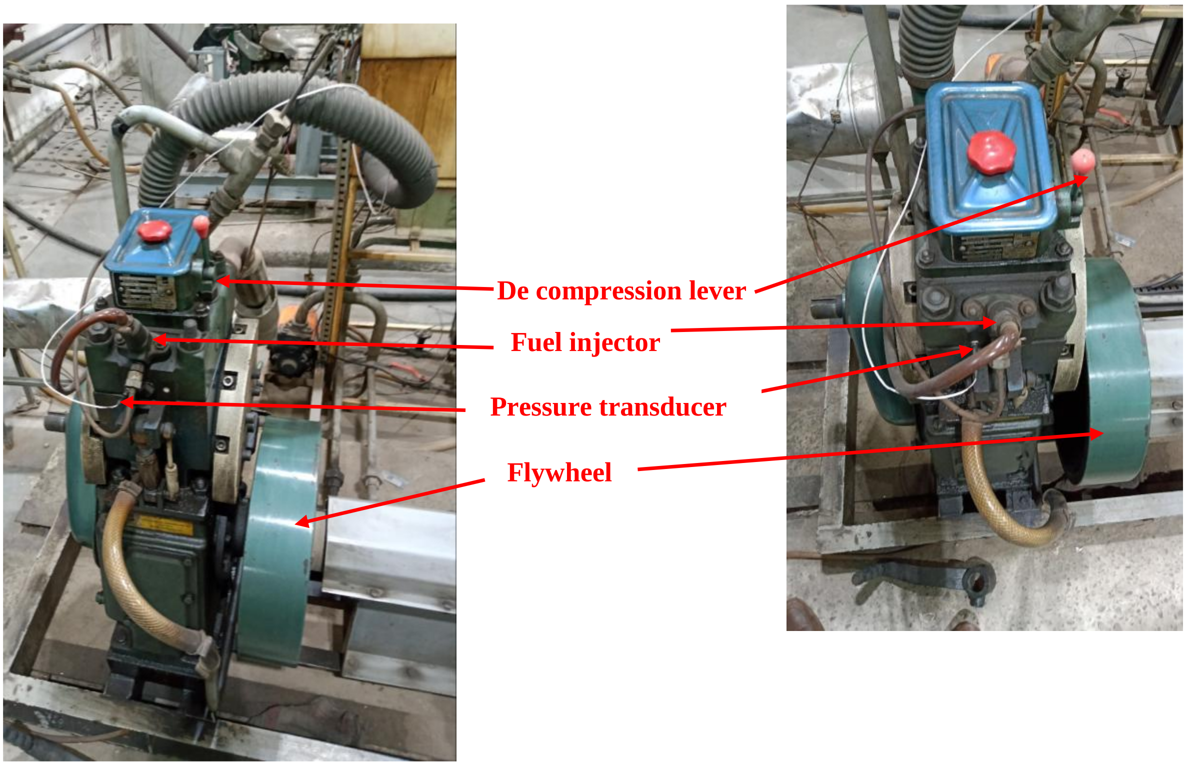


Plate 3.20. Diesel engine used for conducting the experiments

A pressure transducer (piezoelectric type) fixed into the head of the cylinder was used to determine the change in pressure readings per degree change in crank angle.

Plate 3.21 displays a close-up view of the pressure transducer. Plate 3.22 shows the close view of the decompression lever and fuel injector mounted inside the cylinder head.

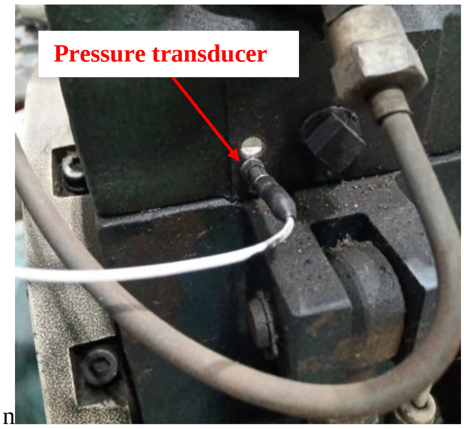


Plate 3.21. Closer view of the Pressure transducer

Plate 3.22. Close view of Fuel injector and de-compression lever

For measuring the load and power of the engine, an eddy current dynamometer was utilized. A load cell (strain gauge type) of high precision is used for measuring the load. At the end of the dynamometer, a crank encoder or sensor which was used to measure the crank angle rotation and the engine speed was fixed.

Plate 3.23 shows the eddy current dynamometer which is used in the current setup. Plate 3.24 shows the crank encoder used for measuring the crank angle. Plate 3.25 and Plate 3.26 shows the front view and side view of the load cell used for measuring the applied load.

Plate 3.23. Eddy current dynamometer

Plate 3.24. Crank encoder and RPM sensor

Plate 3.25. Front view of Load Cell

Plate 3.26. Side view of Load Cell

Plate 3.27 and Plate 3.28 shows the front and back panel of the control unit. This front panel consists of the indicators that show the value of the applied load, a voltmeter and an rpm indicator.

The front panel has a burette for manually noting down the fuel consumption rates and manometer to determine air pressure. A fuel stop valve or fuel cock is connected to the fuel supply pipe and burette. At the back of the control panel, two fuel tanks are used to supply diesel or any other fuel as desired only one at a time.

Air sensor and the fuel pump are mounted in the back panel of the control panel. Also, a data acquisition system consisting of NI USB 6210 is mounted that connects the various sensors of the test rig to the computer system. Temperature transmitters and power supply are also present in the back panel.

A cooling tower is installed that feeds 350 liters per hour of water to the engine and 120 liters per hour of water to the eddy current dynamometer. Two different rotameters are used to measure the supplied water flow rate.

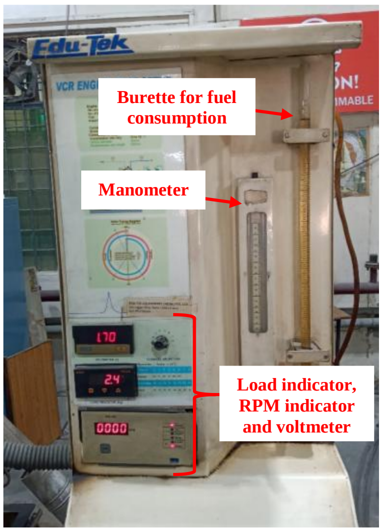


Plate 3.27. Front Panel of Control Unit

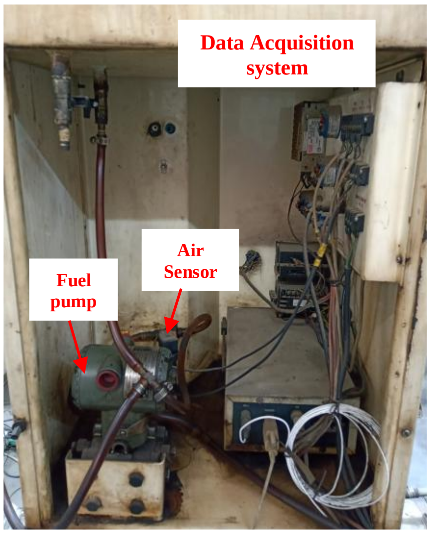


Plate 3.28. The back panel of Control Unit

Plate 3.29 shows the photograph of rotameters and the dynamometer loading unit. The load can be increased by the use of the dynamometer loading unit clamp.

Plate 3.30 shows the smoke meter and emission analyzer used for determining the smoke opacity and emissions. AVL 437 smoke analyzer and AVL 4000 Light Di-Gas Analyzer were used for measuring smoke opacity and emission respectively.

Smoke meter determines the percentage opacity through the exhaust gases. A light beam projected the exhaust gases. Part of the light gets absorbed or gets dispersed by the soot particles. The light which was remaining passes and generates a photoelectric current after reaching the photocell giving the percentage of smoke in the exhaust.

AVL 4000 Light Di-Gas Analyzer was used to measure the HC, CO and NO_X emissions from the exhaust. It is a five gas measuring device. This device detects infrared light that measures CO and HC emissions whereas electrochemical gas sensors measure NO_X emissions.

Plate 3.29. Rotameters and dynamometer loading unit

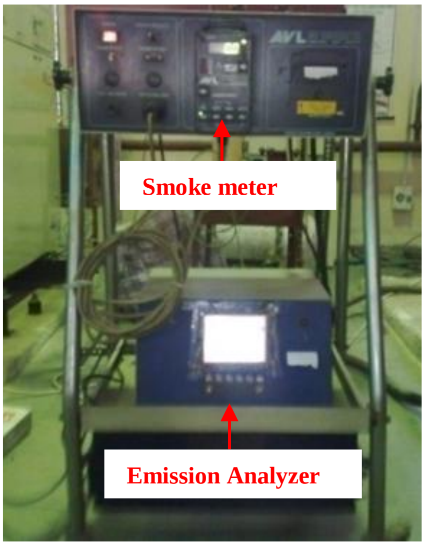


Plate 3.30. Smoke meter and Emission Analyzer

Figure 3.4 shows the schematic of the diesel engine test rig with all the components attached to it.

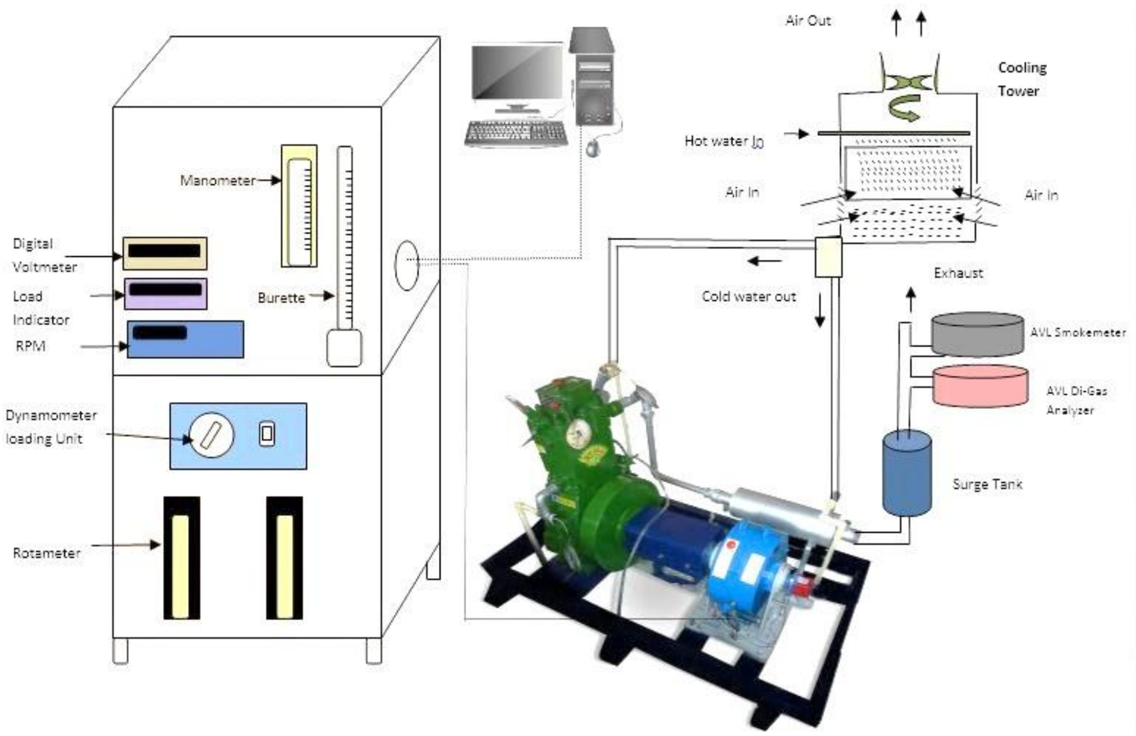


Figure 3.4. Typical Layout of diesel engine test rig

Plate 3.31 shows the actual diesel engine test rig. All the equipment and components explained earlier in this section were connected to analyze the diesel engine performance, emission and combustion parameters.

Plate 3.31. Actual diesel engine test rig

3.8 Measurement of Engine parameters

3.8.1 Performance Parameters

The power developed at the output shaft of the engine is known as brake power (BP). It is used to calculate several other parameters of the engine. Equation 3.10 to 3.16 gives formulae used for determining different performance characteristics.

$$BP = \frac{2\pi NT}{60} \quad (3.10)$$

Here N is speed

And T is torque

BMEP is the theoretical pressure when applied at the pistons would produce BP.

$$BMEP = \frac{BP \times n \times 60}{L \times A \times N} \quad (3.11)$$

A = Area of the bore of a cylinder

L = Piston stroke length

N = Revolutions per minute

n= number of revolutions per cycle, 1/2 for four stroke engine and 1 for two stroke engine

BTE depends upon fuel consumption, calorific value and BP of fuel. It gives an idea about the energy required to produce that BP.

$$m_f = \frac{Vc \times \rho}{t} \quad (3.12)$$

m_f = Mass of fuel consumed

Vc= Volume of fuel consumed

ρ= Fuel density

t= Time taken consumption of fuel volume under consideration

$$\eta_{th} = \frac{K_f}{C_v \times BSFC} \quad (3.13)$$

Here, η_{th} = Brake thermal efficiency

K_f = Unit constant (3600)

C_V = Calorific value

$$BSFC = \frac{m_f \times 1000}{BP} \quad (3.14)$$

Also, BTE can directly be determined from brake power

$$\eta_{th} = \frac{BP}{m_f \times C_V} \quad (3.15)$$

BSEC is inversely proportional to BTE. BSEC and BSFC are interrelated. Below formula was used to determine BSEC from BSFC.

BSEC= BSFC x C_V (3.16)

3.8.2 Calculations for measuring Heat release rate

Knowledge of HRR becomes necessary for understanding the burning of the fuel. Many investigations were carried out in the past by the researchers for determining the HRR. For the current study the investigation carried out by (Ma et al., 2015) was referred.

Despite the fact, the combustion in a CI engine is assumed to be heterogeneous. However, as suggested in the literature, in the present study, a homogeneous model is considered for determining the HRR. That means, the current study neglects pressure waves, fuel vaporization, non-equilibrium conditions, temperature gradients, etc. Equations 3.17 to 3.24 were used to derive the formula for HRR. The first law of thermodynamics gives

$$\Delta U = W + Q \tag{3.17}$$

Or

$$dU = dW + dQ \tag{3.18}$$

Here, W is the rate of work done.

And Q is a summation of HRR and heat transfer rate to engine cylinder walls.

Also, $$\frac{dU}{dt} = mC_v \frac{dT}{dt} \tag{3.19}$$

And, $$W = P\frac{dV}{dt} \tag{3.20}$$

$$mC_v \frac{dT}{dt} = \dot{Q} - \dot{P}\frac{dW}{dt} \tag{3.21}$$

From the ideal gas equation

PV=mRT (3.22)

On differentiating

$$\frac{dT}{dt} = \frac{1}{mR}\left[p\frac{dV}{dt} + v\frac{dP}{dt}\right] \tag{3.23}$$

On combining these equations, the heat release rate is determined from the equation 3.24

$$\dot{Q} = \frac{\gamma}{\gamma - 1} p \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dP}{d\theta} \quad (3.24)$$

Here **γ** represents the ratio of specific heats, θ represents the crank angle, P represents pressure inside the cylinder and V represents the volume of the cylinder, R represents specific gas constant, m represents the total mass of gas.

3.8.3 Measurement of mass fraction burnt

The calculation for the burned mass fraction is one of the means of understanding combustion during an engine cycle. The determination of this fraction makes several parameters, such as the transfer of heat to the walls of the cylinders, or the richness of the mixture. To determine the mass fraction burned, the first law of thermodynamics was used, assuming the thermal equilibrium at every crankshaft angle, a uniform mixture, and the behavior of the gases (Stewart and Clarke, 2010). Equations 3.25 to 3.27 derives mass fraction burnt formula.

$$\dot{Q} = \frac{\gamma}{\gamma - 1} P \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dP}{d\theta} + \frac{dQ_w}{d\theta} \quad (3.25)$$

In this study, no loss of heat to the walls was considered i.e. $\frac{dQ_w}{d\theta} = 0$. Therefore Equation 3.25 becomes:

$$\dot{Q} = \frac{\gamma}{\gamma - 1} p \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dP}{d\theta} \quad (3.26)$$

The pressure variations inside the cylinder are given by the transducer. The instantaneous volume of the cylinder is known.

Q_{rel} represents the pressure rise.

$$Mass\ fraction\ burnt = \frac{\int_{\theta_s}^{\theta} \frac{dQ_{rel}}{d\theta} d\theta}{\int_{\theta_s}^{\theta_e} \frac{dQ_{rel}}{d\theta} d\theta} \qquad (3.27)$$

θ_s corresponds to the beginning of the combustion, θ_e corresponds to end of the combustion and θ corresponds to crank angle in-cylinder pressure

3.9 Experiment procedure

Tests on an engine test bench, calibrated to the manufacturer's recommendations, were measured at a rated speed of 1500 rpm. Fuel injection timing was set before the top dead center. Parameters, such as cylinder pressure, intake air flow, fuel consumption were recorded to analyze the engine performance. All the tests were conducted as per IS:10000 standards. A diesel engine was operated in conventional mode and it was considered as a reference for comparison of the results at variable loads. The engine was started on diesel fuel and then switched to the fuel blends. The charges taken into consideration were set at 20%, 40%, 60%, 80% and 90%, 100% of the full engine load, keeping the speed of rotation constant at 1500 rpm. All the readings after this were taken at steady state. The test engine was run for approximately half an hour to attain a steady state condition. The time taken for fuel burning was set for the consumption of 20 ml of fuel in the burette several times. Manometric readings of air consumption were also taken repeatedly. The data recorded manually was compared to the data obtained from the Enginesoft software. The data obtained manually and from the software were in close agreement. Thereafter emission, performance and combustion characteristics were calculated from the observed readings. For removing the discrepancy the tests were repeated several times and the average of the results was taken. Table 3.7 shows the uncertainty and accuracy of the measurements.The system represents higher accuracies owing to repeated engine trials and an average of the results. All results repeatability were analyzed regularly and found to be nearly same for all the experiments.

Table 3.7. Uncertainty and accuracy of the measurements

S.No.	Parameter	Principle of measurement	Range	Accuracy
1	Speed	Optical	0-2000 rpm	±20 rpm
2	Engine load	Strain gauge type load cell	0-25 kg	±0.1 kg
3	Exhaust Temperature	K-type thermocouple	0-1000°C	±1°C
4	Time	Stop watch	-	±0.2%
5	Unburnt hydrocarbons	Non-dispersive infrared	0-20,000 ppm	±2 ppm
6	Carbon monoxide	Non-dispersive infrared	0-10% vol.	±0.2%
7	Smoke opacity	Photochemical	0-100%	±2%
8	Oxides of nitrogen	Electrochemical	0-4000 ppm	± 15 ppm
9	Pressure	Piezoelectric	0-200 bar	± 1 bar
10	Crank angle encoder	Optical	0-720 °CA	± 0.2°CA
Calculated results				Uncertainty
11	Fuel consumption	Level sensor	-	±2.0%
12	Engine power	-	0-8 kW	±1.0%
13	BTE	-	-	±1.0%
14	Air consumption	Turbine flow type	-	±1.0%
15	Heat release	Sorenson model	-	±5.0%
16	BSEC	-	-	±1.5%
17	In-cylinder temp.	Ideal gas equation	Up to 3000 K	±5.0%

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter explains the results of investigations carried. Optimization of biodiesel production was carried out for different parameters. Taguchi method was used in the optimization process. Discussion about the physico-chemical properties of diesel and biodiesel was also presented. Furthermore blending of test fuels was done and their important properties were determined. Also, the effect of storage on test fuel blends was evaluated. Followed by this, the effect of blending at different temperatures, their oxidation stability and FTIR tests carried were analyzed. Finally, discussion of emission and performance parameters was presented for the binary and ternary fuel blends. Also, a discussion was presented for combustion results of all test fuel blends.

4.2 Biodiesel production

A detailed explanation of biodiesel was presented in the previous chapter. A single step direct transesterification was followed in the biodiesel production as the FFA of oil is 1.9. This favors direct transesterification process.

If the FFA of oil is greater than 2 then both esterification and transesterification are required. Esterification helps in reduction of FFA to the desired level for undergoing transesterification process. Esterification uses acid based catalyst like H_2SO_4, PTSA (Cardoso et al., 2008), etc. whereas transesterification uses base catalyst like KOH, NaOH (Ali et al., 2016), etc. So biodiesel was produced from WCO using transesterification.

4.2.1 Optimisation of biodiesel production

As discussed earlier waste cooking oil was used for producing biodiesel. The production process gets affected using the parameters such as catalytic concentration, the temperature of reaction, time of reaction, molar ratio and agitation speed. Since the experiments help in learning about the best yield, it is very difficult to conduct a large number of experiments to get the best output. Therefore, adopting the Taguchi approach reduces the number of experimental trails to get the optimum yield. 25 experiments were conducted for the production of biodiesel. Larger the better approach was used for the current study.Table 4.1 shows the orthogonal array of input and output parameters. The yield percentage was found experimentally. SNR is calculated on the basis of larger the better approach in the present study. Minitab software is used for designing and analyzing the results. On analyzing the results from Table 4.1 and using Taguchi analysis, Figure 4.1 to Figure 4.5 were obtained.

Table 4.1. Orthogonal parameters with their response & SNR

Catalytic Concentration (%wt.)	Molar Ratio (Methanol to Oil)	Temperature of Reaction (°C)	Time of Reaction (minutes)	Agitation Speed (rpm)	Yield (%)	SNR
0.25	2	56	40	150	58	35.26856
0.25	4	58	50	200	67	36.5215
0.25	6	60	60	250	85	38.58838
0.25	8	62	70	300	74	37.38463
0.25	10	64	80	350	67	36.5215

0.5	2	58	60	300	67	36.5215
0.5	4	60	70	350	81	38.1697
0.5	6	62	80	150	84	38.48559
0.5	8	64	40	200	72	37.14665
0.5	10	56	50	250	80	38.0618
0.75	2	60	80	200	74	37.38463
0.75	4	62	40	250	88	38.88965
0.75	6	64	50	300	92	39.27576
0.75	8	56	60	350	86	38.68997
0.75	10	58	70	150	82	38.27628
1	2	62	50	350	72	37.14665
1	4	64	60	150	83	38.38156
1	6	56	70	200	95	39.55447
1	8	58	80	250	79	37.95254
1	10	60	40	300	82	38.27628
1.25	2	64	70	250	70	36.90196
1.25	4	56	80	300	65	36.25827
1.25	6	58	40	350	72	37.14665
1.25	8	60	50	150	59	35.41704
1.25	10	62	60	200	67	36.5215

The main effect plots give the average yield for all the input variables independently. The main effect plots of the five parameters i.e. the temperature of reaction, time of reaction. catalytic concentration, molar ratio and agitation speed show the best parameter value for getting higher production yield of WCO biodiesel.

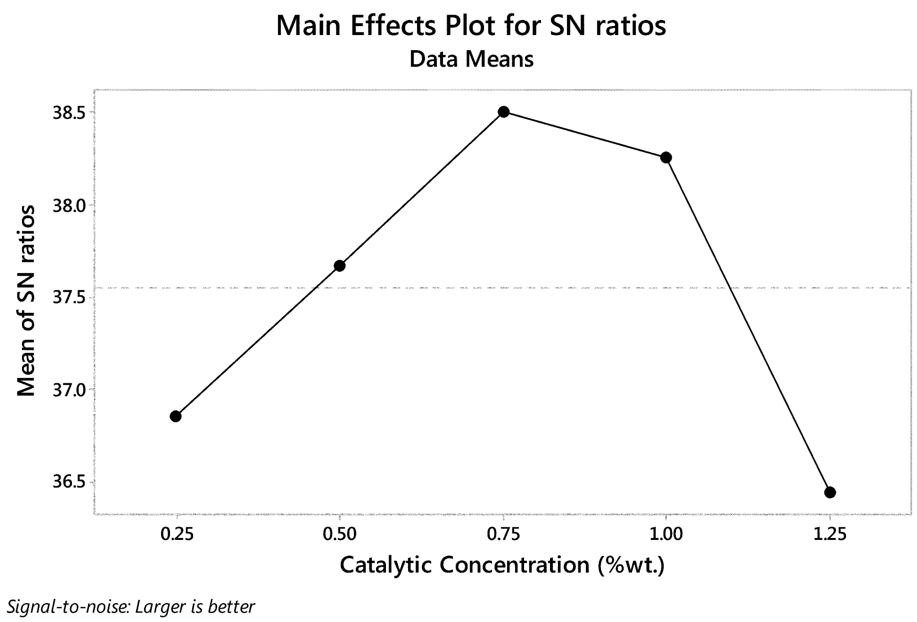


Figure 4.1. Main effect plot for SNR with catalytic concentration

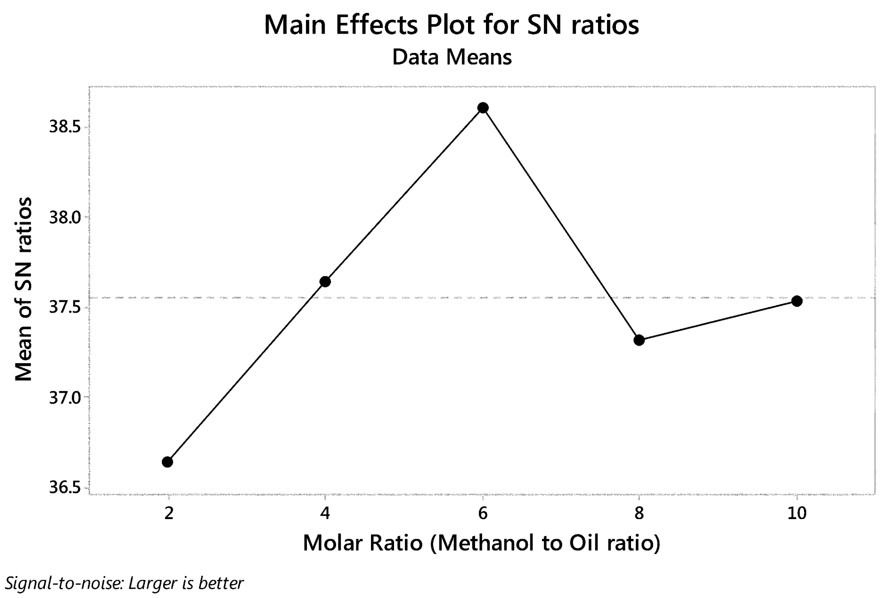


Figure 4.2. Main effect plot for SNR with Molar ratio

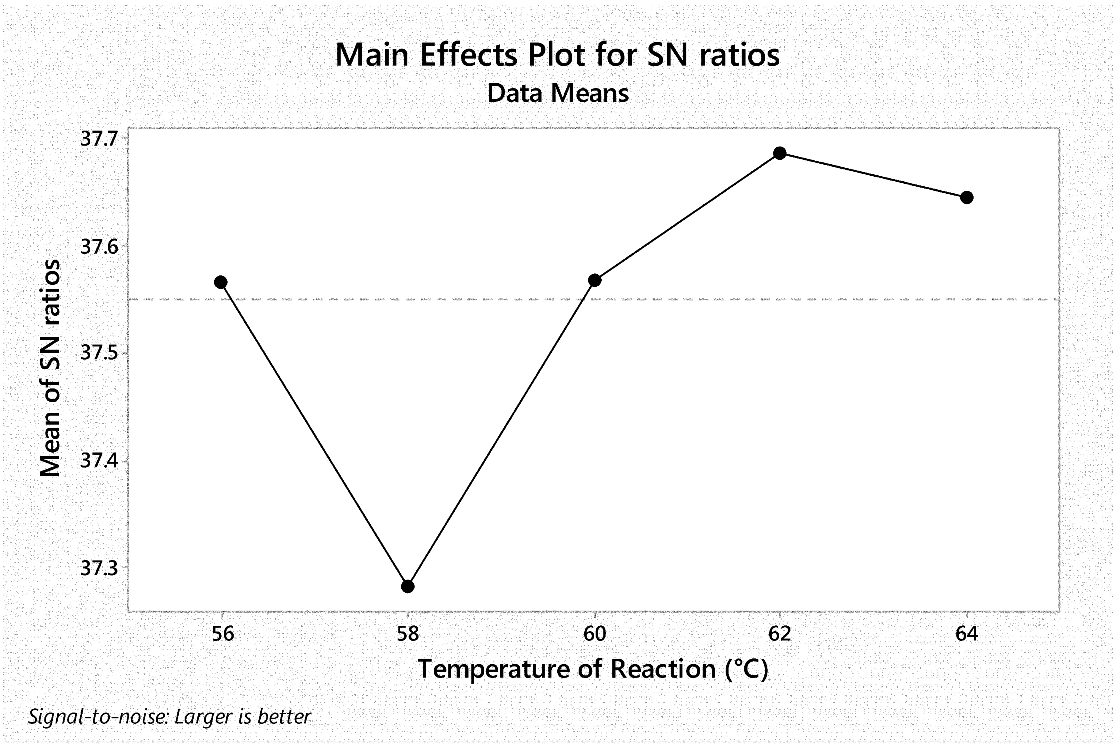


Figure 4.3. Main effect plot for SNR with Temperature of reaction

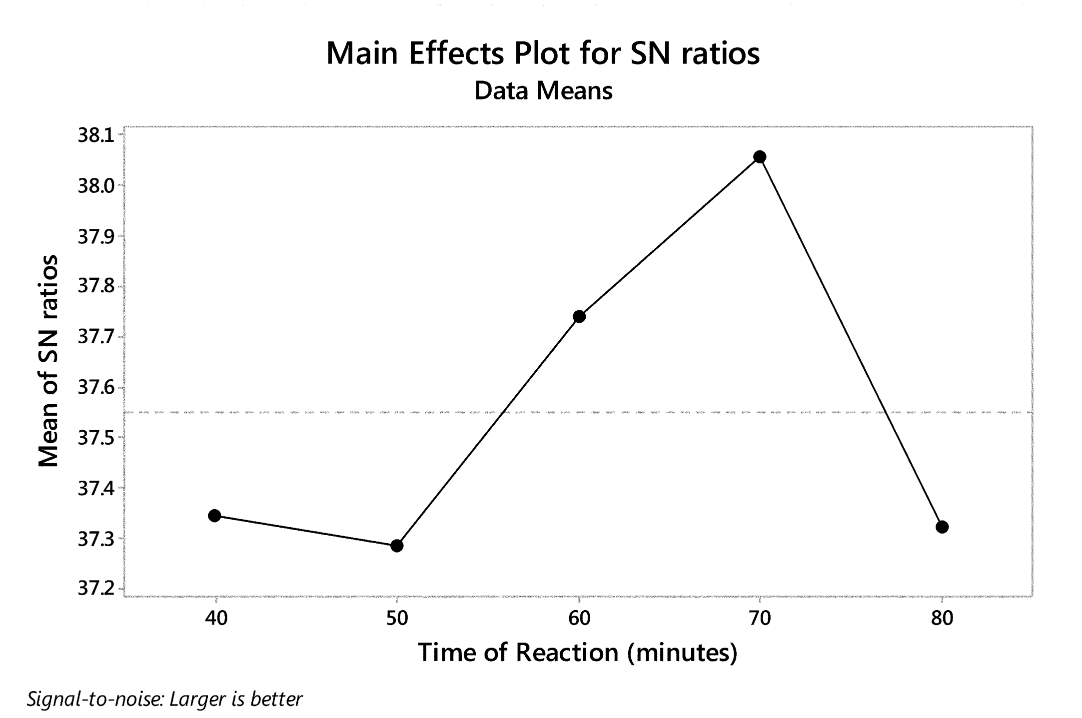


Figure 4.4. Main effect plot for SNR with Time of reaction

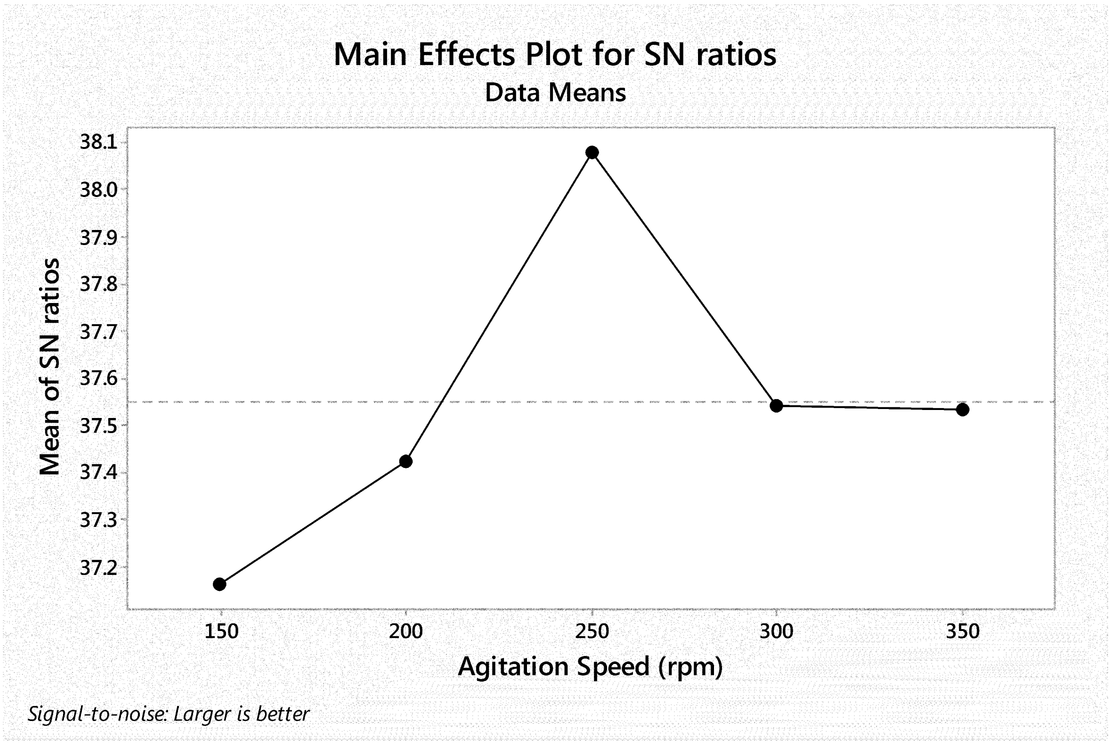


Figure 4.5. Main effect plot for SNR with Agitation speed

On the basis of Figures 4.1 to 4.5, mean effects plots for SN ratio of the optimum input parameters were determined to get the maximum yield which is shown in Table 4.2.

Table 4.2. Value of Optimum parameters for getting a higher yield

S.No.	Parameter	Optimum Value
1	Catalytic concentration (% wt.)	0.75
2	Molar Ratio	6:1
3	Temperature of Reaction (°C)	62
4	Time of Reaction (in minutes)	70
5	Agitation speed (in rpm)	250

On the basis of the obtained optimum parameters, experiments were performed and the yield values were determined theoretically and experimentally. This helps in understanding the contribution of input parameters on output yield.

Higher the delta which is the variation in the highest and lowest value of SNR more is the effect of the parameter. Delta helps in determining the rank order of the parameters.

Table 4.3 shows the SNR of the input parameters and hence helps in determining the Rank order of the input parameters.

From Table 4.3 rank of catalytic concentration is first, molar ratio is second, agitation speed is third, time of reaction is fourth and the temperature of reaction is last i.e. fifth.

Table 4.3. Rank order and Response Table for Signal to Noise Ratios

Level	Catalytic concentration (% wt.)	Molar Ratio (Methanol to oil)	Temperature of Reaction (°C)	Time of Reaction (in minutes)	Agitation speed (in rpm)
1	36.86	36.64	37.57	37.35	37.17
2	37.68	37.64	37.28	37.28	37.43
3	38.5	38.61	37.57	37.74	38.08
4	38.26	37.32	37.69	38.06	37.54
5	36.45	37.53	37.65	37.32	37.53
Delta	2.05	1.97	0.4	0.77	0.91
Rank	1	2	5	4	3

4.2.2 Confirmation of results

Results were confirmed for the biodiesel production using optimum parameters. Biodiesel was produced three times using the given parameters and the average yield obtained is over 96.9% which validates the model. Predicted values at 95% confidence are 97.13 yield percentage. Since both the predicted and experimental results are nearly equal and the yield percentage is also high.

So, these input parameters can be used for the production of WCO biodiesel from the same source to get optimum yield percentage. Table 4.4 shows the percentage contribution of each process parameter.

Table 4.4. Percentage contribution of each process factor

S.No.	Factor	Sum of squares	Percentage contribution
1	Catalytic concentration (% wt.)	1158.16	49.77
2	Molar Ratio (Methanol to oil)	788.96	33.90
3	Temperature of Reaction (°C)	45.36	1.95
4	Time of Reaction (in minutes)	166.56	7.16
5	Agitation speed (in rpm)	141.76	6.09
6	Errors	26.16	1.12

For determining the percentage contribution of each parameter, ANOVA or analysis of variance approach is used. In this approach, the sum of squares or variance of an individual parameter is determined. On the basis of that percentage contribution of each parameter can be determined. From Table 4.4 it was observed that the percentage contribution of catalytic concentration and molar ratio was the highest for biodiesel production. All other parameters were having very less effect on the yield. Surface graphs were plotted to understand the contribution of two input parameters on the yield of biodiesel.

4.2.3 Surface graphs for input and output parameters

Surface graphs were plotted between different input parameters for attaining maximum yield. At a time two input parameters were selected that affects the response i.e. yield in the current case. Surface graphs are a very good tool to show the dependence of one output parameter with two input parameter. From Figure 4.6 it was observed that maximum yield is obtained for molar ratio near to 6 and at higher catalytic concentrations. At lower catalytic concentrations, the yield was very less for lower as well as a higher molar ratio. The molar ratio of 5 to 7 and a catalytic concentration of 0.5 %wt to 1 %wt gives the maximum value of yield percentage. Therefore, higher catalytic concentrations and moderate molar ratios are desired for getting better yield.

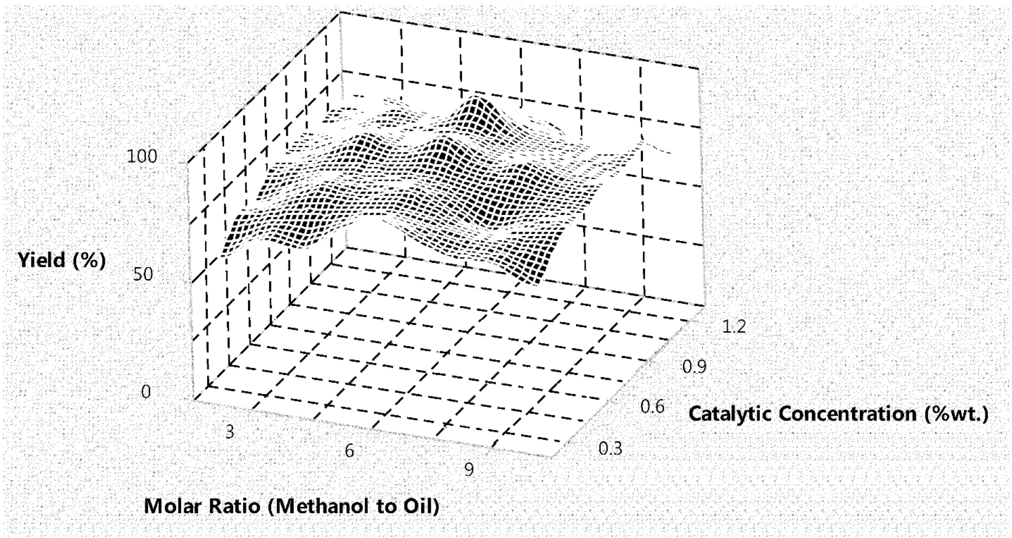


Figure 4.6. Surface Plot of Yield vs Catalytic Concentration and Molar Ratio

Figure 4.7 shows the interaction of catalytic concentration and temperature of reaction on yield. From the plot, it is observed that at very low temperatures of 56°C, the yield percentage is lowest. However, on increasing the catalytic concentration some increase in yield percentage is observed. It was also observed that in the moderate temperature regions of 58°C and 60°C, the yield percentage was highest at low as well as medium catalytic concentrations of 0.3 to 0.6 %wt.

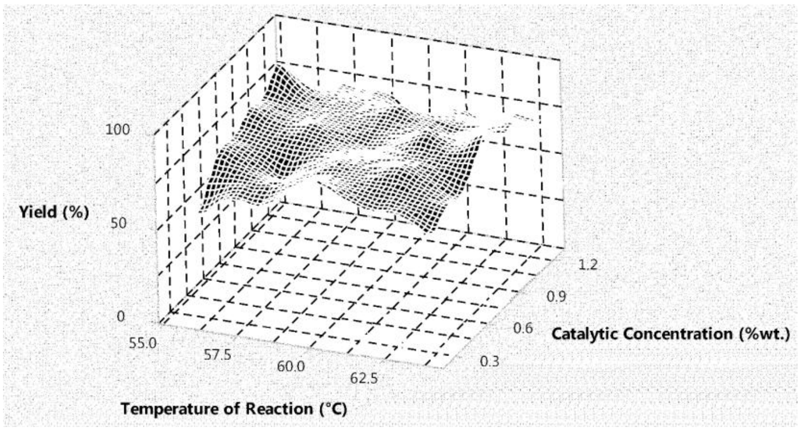


Figure 4.7. Surface Plot of Yield vs Catalytic Concentration and Temperature of Reaction

From Figure 4.8, the relation between time of reaction and catalytic concentration was observed on yield. It was observed that better yield was achieved at a reaction time of nearly 70 minutes and catalytic concentration of nearly 1 %wt.

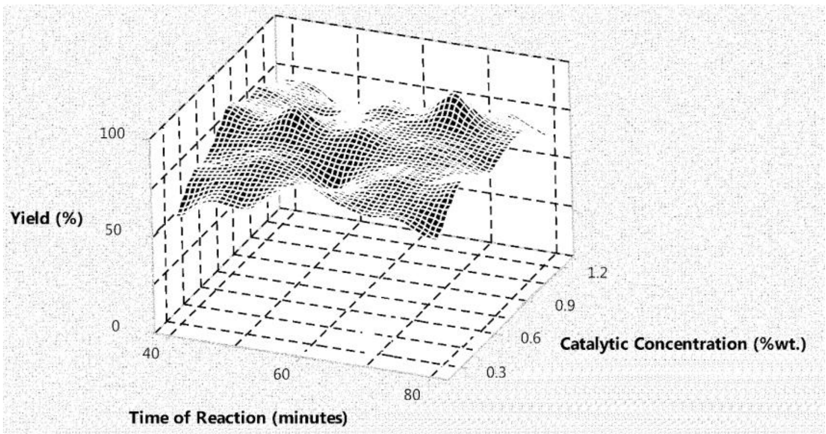


Figure 4.8. Surface Plot of Yield vs Catalytic Concentration and Time of Reaction

Figure 4.9 shows the relationship between agitation speed and catalytic concentration with yield. It was observed that at higher catalytic concentration and lower speeds, the better yield is obtained. Similarly, at an agitation speed of nearly 250 rpm and 0.75 %wt. catalytic concentration, the good yield is obtained. Also, lower yield was obtained at very low agitation speed and lower quantity of catalyst.

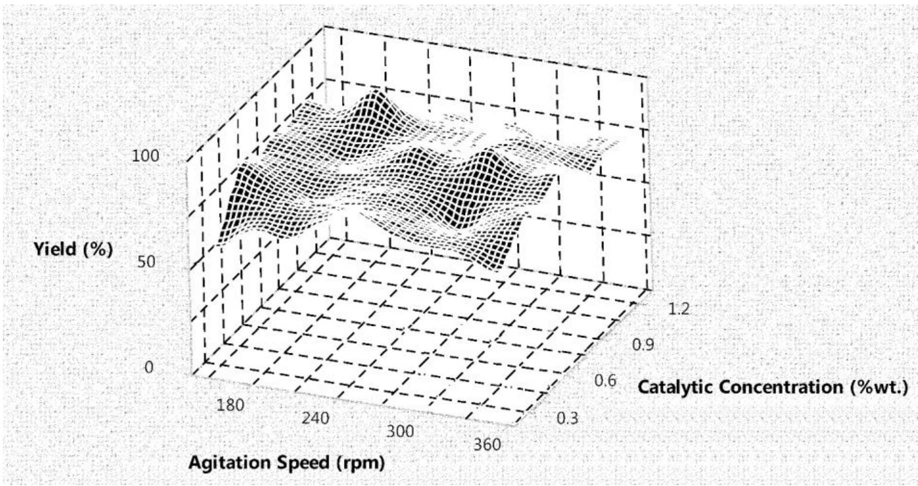


Figure 4.9. Surface Plot of Yield vs Catalytic Concentration and Agitation Speed

Figure 4.10 shows the effect of temperature of reaction and molar ratio on the biodiesel yield. It was observed that at a temperature range of 55°C and molar ratio of 6, higher yields are obtained. Also, all extreme ends of the surface plots exhibit a lower yield. Therefore all the parameters values should be in the middle.

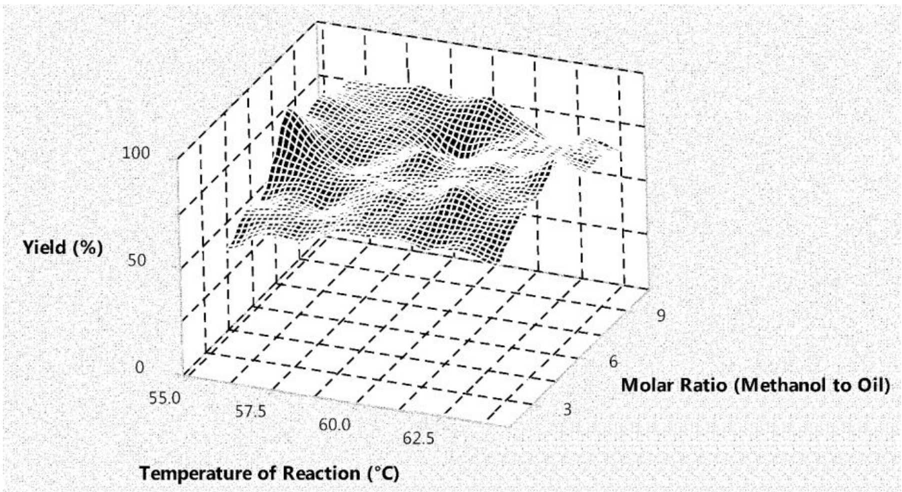


Figure 4.10. Surface Plot of Yield vs Molar ratio and Temperature of Reaction

From Figure 4.11 it was seen that the maximum yields were obtained at molar ratio near to 6 and time of reaction within 50-70 minutes. So, these input parameters can be used to get higher yield values.

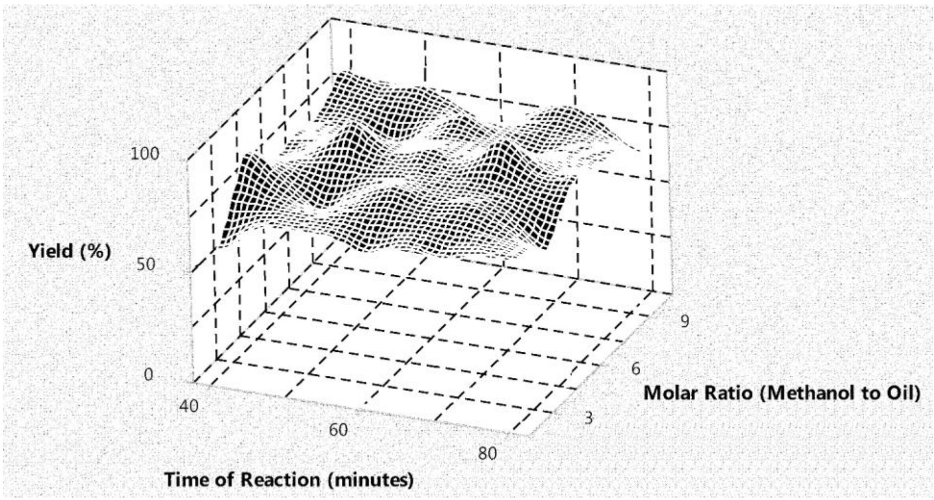


Figure 4.11. Surface Plot of Yield vs Molar ratio and Time of Reaction

From Figure 4.12, it was found that at an agitation speed of 350 rpm and higher molar ratios, the yield was minimum. Therefore, lower agitation speed and molar ratio are preferred to get maximum yield

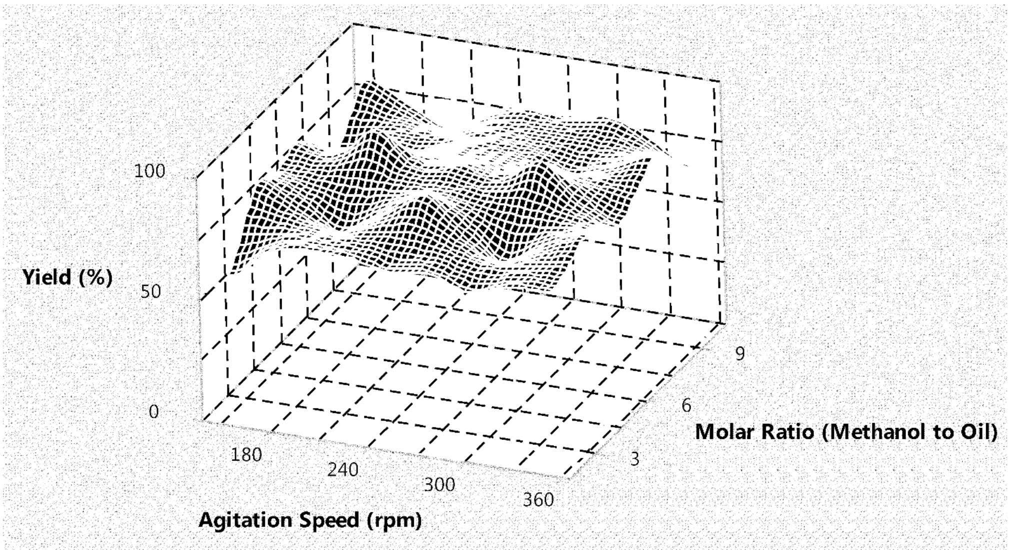


Figure 4.12. Surface Plot of Yield vs Molar ratio and Agitation speed

Since from Table 4.4 it was seen that time of reaction and temperature of reaction were the least contributing factors for biodiesel production. Therefore their relationship with one another for getting higher with yield is not very vibrant. From Figure 4.13 it was observed that at very high temperature and longer reaction duration, the yield was lowest. However, at other points below 60°C, higher yields can be obtained.

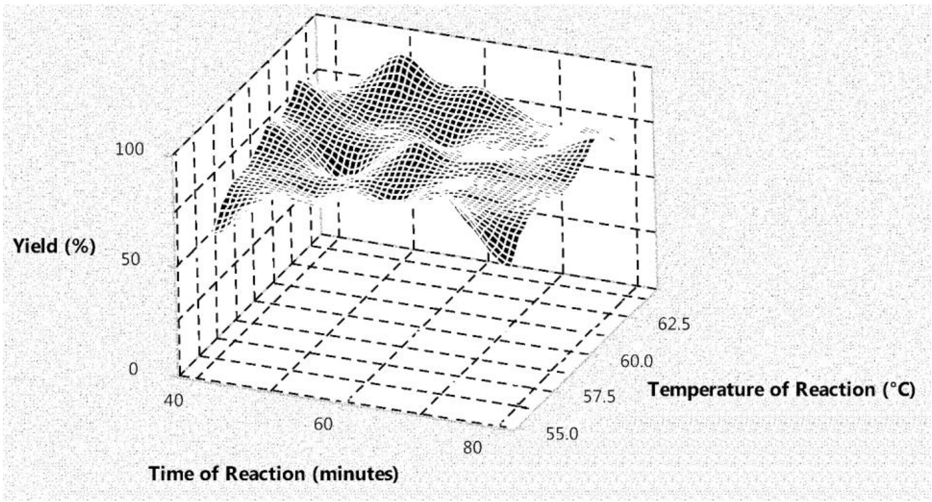


Figure 4.13. Surface Plot of Yield vs Temperature of Reaction and Time of Reaction

Figure 4.14 gives the relationship between the temperature of reaction and agitation speed.

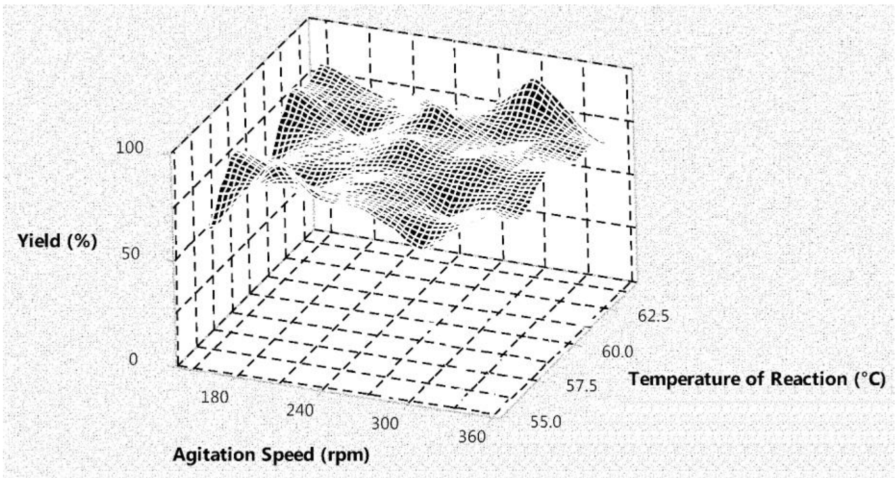


Figure 4.14. Surface Plot of Yield vs Temperature of Reaction and Agitation speed

It was observed from Figure 4.14 that yield percentage has a low affect with agitation speed and variation in temperature of reaction. Yield percentage for these inputs were near to each other.

It was seen from Figure 4.15 that maximum yield was obtained for lower agitation speed of nearly 200 rpm and longer time of reaction of 70 minutes. All other combinations of input parameters give a lower yield percentage.

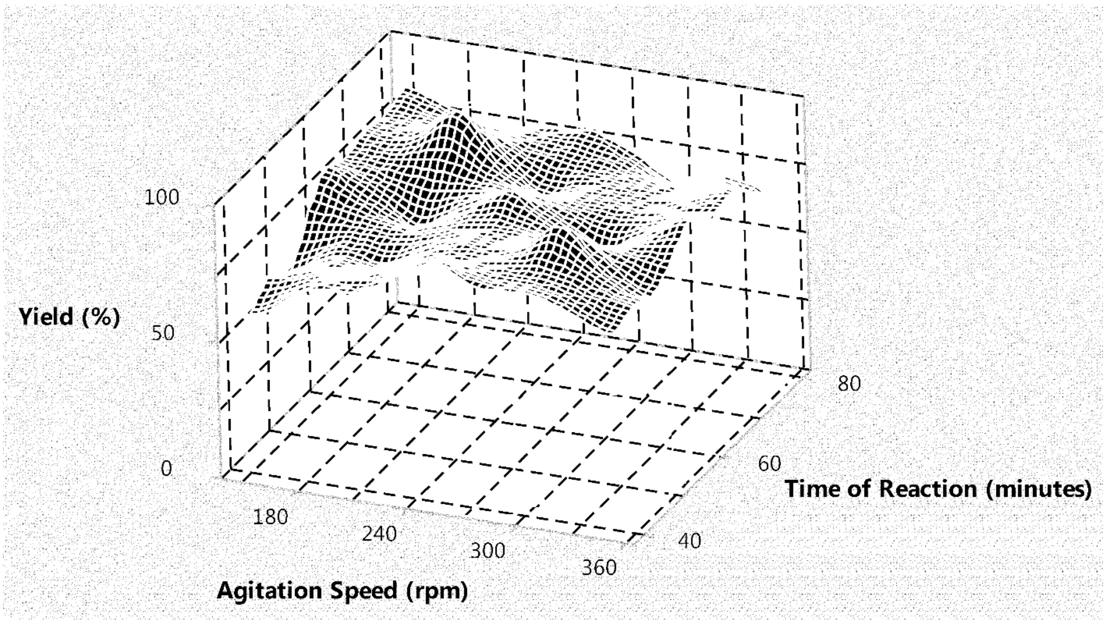


Figure 4.15. Surface Plot of Yield vs Time of Reaction and Agitation speed

4.3 Properties of biodiesel

Several tests were performed for determining the important properties of produced biodiesel. Apart from that, GC-MS test was also carried out for determining the constituents in methyl ester.

Table 4.5 summarizes the properties of the biodiesel determined using the equipment discussed in the previous chapter.

Table 4.5. Properties of Diesel and WCO biodiesel

Fuel property	Unit	Standard	Diesel	WCO Biodiesel
Density at 15°C	Kg/m^3	ASTM	838.3	891.1
Specific gravity at	-	-	0.839	0.892
Kinematic viscosity	cSt	ASTM D445	2.67	5.91
Calorific value	MJ/kg	ASTM D240	45.14	41.32
CFPP	°C	ASTM	-11	-2
Cloud point	°C	ASTM	-12	-3
Pour point	°C	ASTM D97	-15	-5
Flash point	°C	ASTM D93	58	165
Copper strip	Rating	ASTM D130	1a	1a
Acid Number	mgKOH/g	ASTM D664	-	0.17
Carbon residue	%m/m	ASTM D524	-	0.026
Saponification	mgKOH/g	ASTM D94	-	189
Cetane Index	-	ASTM	46.6	54.8
Ester content	Mass %	EN 14103	-	96.9

4.4 Fatty acid profile of biodiesel

Figure 4.16 shows the result of GC test of WCO biodiesel. Major constituents of the biodiesel found from the GC profile are Palmitoleic Acid (2.41%), Palmitic acid (31.24%), Linoleic acid (25.62%), Oleic acid (4.81%), Stearic acid (11.58%), Erucic acid (9.07%) and Behenic acid (6.39%).

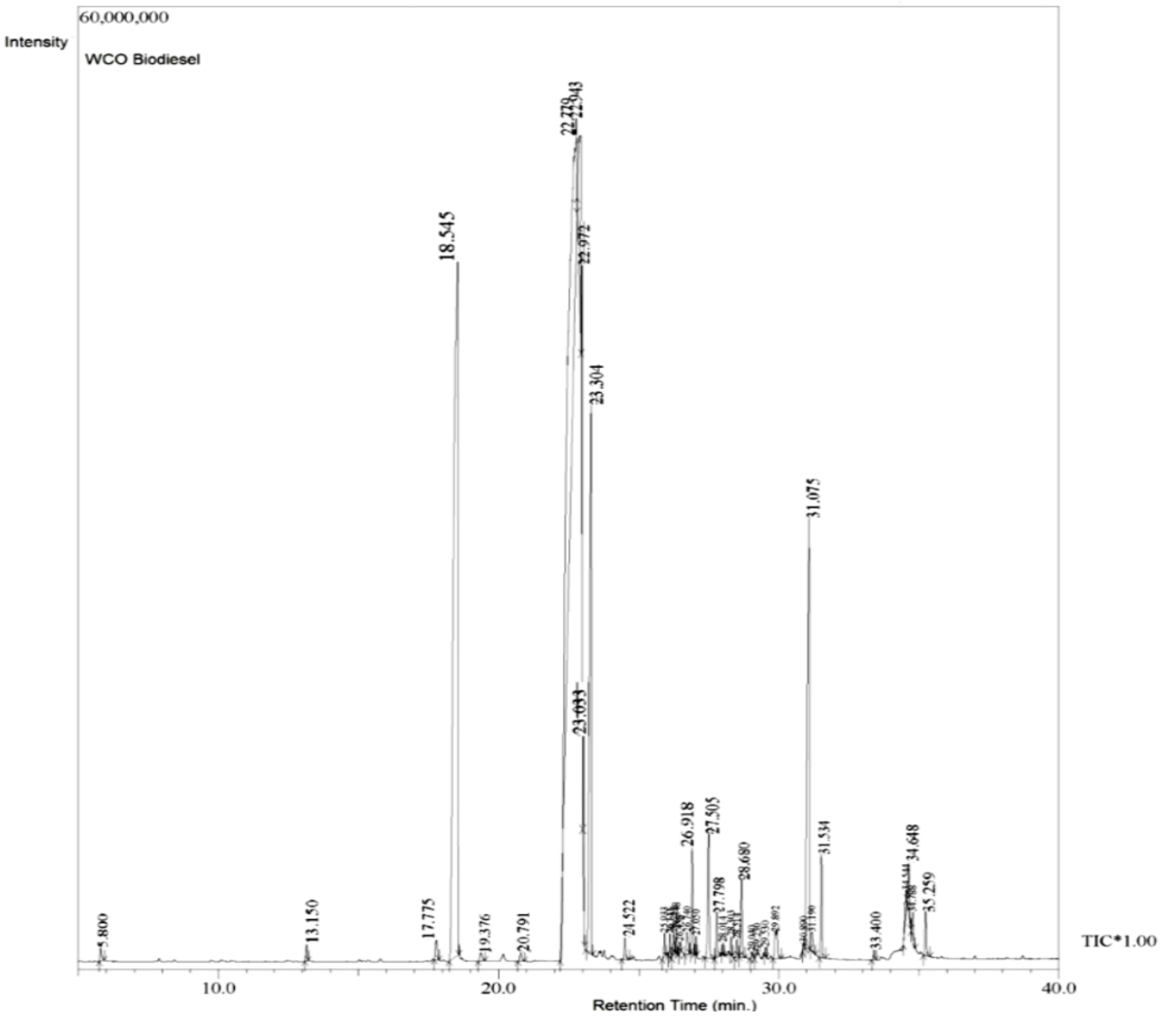


Figure 4.16. Fatty acid profile

Table 4.6 describes the main constituents in WCO methyl ester with their fatty acid name and chemical formula. These results were obtained from mass spectroscopy test. It was observed that the amount of saturated fatty acids in the biodiesel were 51.3% and unsaturated fatty acids in the biodiesel were 44.24%.

It has been found from the literature that the higher quantity of saturated fatty acids results in higher cetane number, oxidation stability and heating values (Saravanan et al., 2011) which results in improved fuel burning and reduced ignition delay (Pali and Kumar, 2016). Because of better burning, lower emissions and higher performance can be achieved.

Table 4.6. Mass spectroscopy test results of WCO biodiesel

S. No.	Fatty Acid Name	General Name	Chemical Formula	Percentage
1	9-Hexadecenoic acid, methyl ester, (Z)-	Palmitoleic Acid	$C_{17}H_{32}O_2$	2.41
2	Hexadecanoic acid, methyl ester	Palmitic acid	$C_{17}H_{34}O_2$	31.24
3	9,12-Octadecadienoic acid (Z,Z)-	Linoleic acid	$C_{18}H_{32}O_2$	25.62
4	9-Octadecenoic Acid (Z)-, methyl ester	Oleic acid	$C_{19}H_{36}O_2$	4.81
5	11-Octadecenoic acid, methyl ester	Vaccenic acid	$C_{19}H_{36}O_2$	1.46
6	9,12,15-Octadecatrienoic acid, methyl ester	Linolenic acid	$C_{19}H_{32}O_2$	0.87
7	Methyl stearate	Stearic acid	$C_{19}H_{38}O_2$	11.58
8	Methyl 18-methylnonadecanoate	-	$C_{21}H_{42}O_2$	2.09
9	13-Docosenoic acid, methyl ester, (Z)-	Erucic acid	$C_{23}H_{44}O_2$	9.07
10	Docosanoic acid, methyl ester	Behenic acid	$C_{23}H_{46}O_2$	6.39
Saturated fatty acids				51.30
Unsaturated fatty acids				44.24
Total				95.54

4.5 Blending of Diesel, biodiesel and octanol

After optimizing the parameters for biodiesel production, the WCO biodiesel was produced in large quantities using a 10 litre biodiesel reactor. WCO biodiesel was produced using transesterification in the reactor and then blended with octanol and diesel. The cost-effective splash blending method was used for preparing the test fuel samples. In splash blending a container was used in which all the fuels were added as per the required volume. Then rigorous stirring was carried out for a few minutes for making homogenous blends of test fuels. For forming the blends, diesel was added in volume proportion of 90%, 80% and 70%, biodiesel in 10% and 20% whereas octanol in 10% and 20%. Two binary fuel blend combinations and three ternary fuel blend combinations were used. No surfactant, cetane improver or solution was mixed in the blends. A light source was used for checking the phase separation of test fuel bends at regular intervals. Even after undergoing the centrifugal rotation of the blends, the samples were found to be completely homogeneous.

4.6 Study on phase separation of blends in different weather conditions of India

A long term study was carried out for the blends at different weather condition of New Delhi, India. Temperature variation in New Delhi is very extreme. It varies from 4°C in the winter season to 48°C in the summer season. Therefore it becomes necessary to assess the influence of a country's temperature on the fuel blends. On the basis of the evaluation of the blends, no change in any physical appearance was observed at different weathers conditions. Moreover, the blends were completely miscible for the entire duration. It was also observed that all the blends remained in the same phase and completely miscible during different weathers. Plates 4.1 to Plate 4.5 shows the photographs of the test fuels in different weather conditions. All the samples were kept in air tight glass bottles for observation. Samples were closely checked for homogeneity. Plate 4.1 shows the samples bottles kept during the spring season.

Plate 4.1. Test fuels in Spring Season (March-May)

Plate 4.2 and Plate 4.3 shows the test fuel samples bottles during summer and monsoon season. As discussed earlier no phase separation is observed in summer and monsoon season. This shows that the samples, when kept in close bottles in highly humid and hot weather, do not dissociate.

Plate 4.2. Test fuels in Summer Season (May-July)

Plate 4.3. Test fuels in Monsoon Season (July-September)

Plate 4.4 and Plate 4.5 shows the test fuel samples during autumn and winter season. New Delhi. During autumn and winter season no visibility of phase separation was there. Weather during winter is very cold where the temperature reaches 4 °C. During winters the temperature is very low and fuel cold flow properties may get worsened. Some fuels may form wax. However, in the current case, no phase separation was visible for low temperatures of 4 °C in any of the binary or ternary fuel blend.

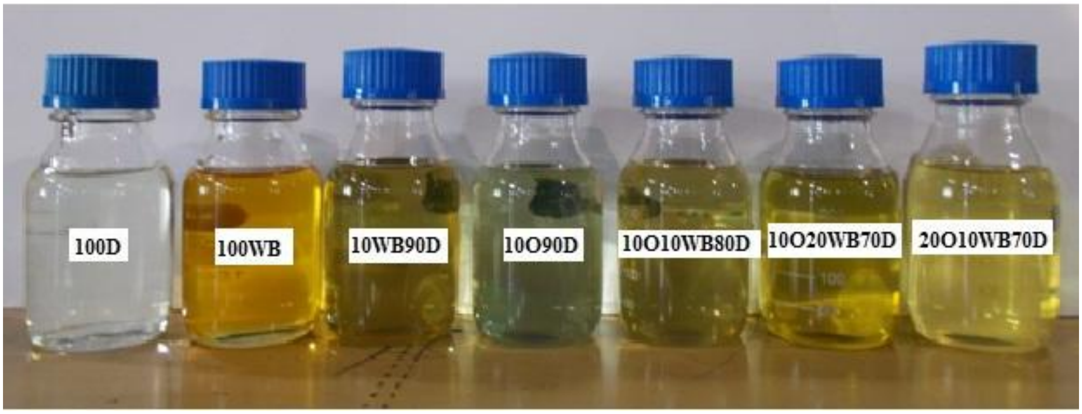


Plate 4.4. Test fuels in Autumn Season (September-November)

Plate 4.5. Test fuels in Heavy Winter Season (December-February)

4.7 Ternary liquid-liquid phase diagram

The study of temperature variation at different weathers formed the basis for studying the ternary liquid-liquid phase equilibrium diagram. It becomes evident to study the phase stability of the samples on lowering the temperature.

It was observed that at a high temperature of 50°C, room temperatures and even at a temperature of 0°C, phase separation does not occur in any blend. Figure 4.17 represents the no phase separation region in the blends. All the molecules of the three different fuels were having the attraction of liquid-liquid interfacial films and form homogeneous mixture. However, on further cooling the blends to a temperature of -2°C, -5°C and -8°C, some phase separation was observed because of lower cold flow properties of biodiesel.

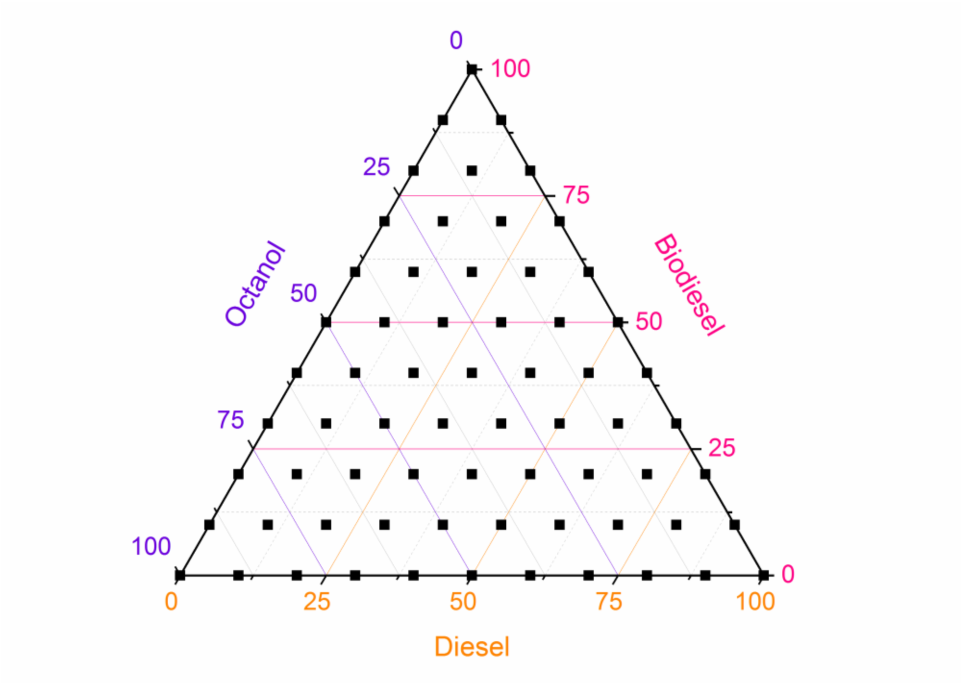


Figure 4.17. Ternary phase diagram at 0-50 °C

The low temperature causes a gel like formation in the fuels and separate layers were seen. Figures 4.18 to Figure 4.20 displays the effect of temperatures on different test fuel blends.

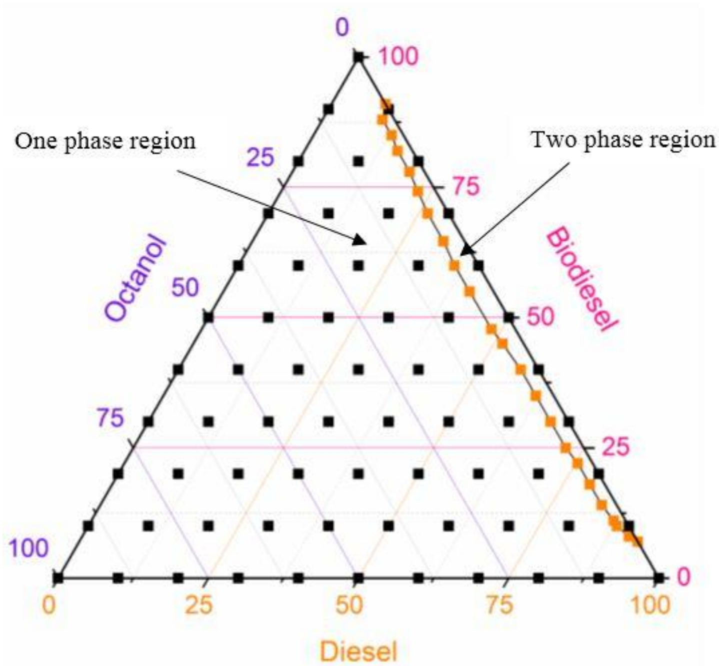


Figure 4.18. Ternary phase diagram at -2°C

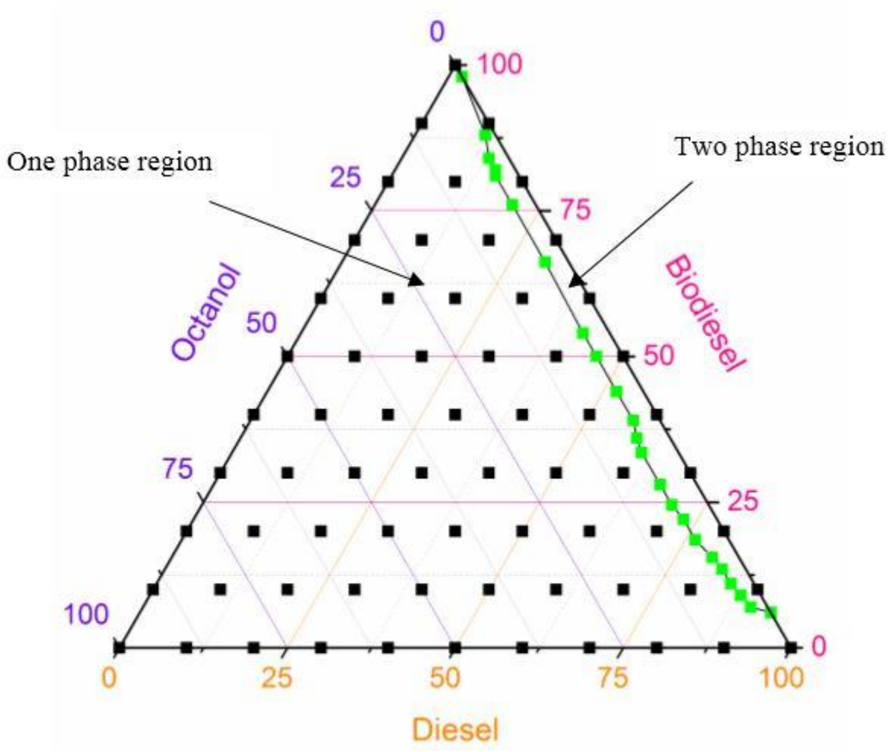


Figure 4.19. Ternary phase diagram at -5°C

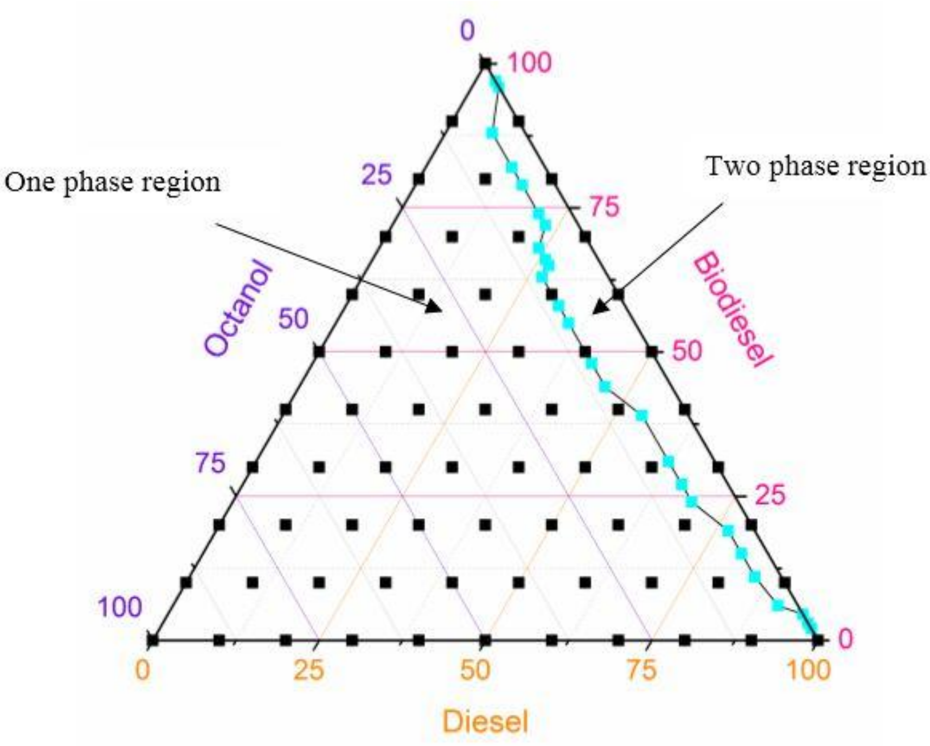


Figure 4.20. Ternary phase diagram at -8°C

It was found that the lower the temperature, greater was the region in the ternary phase diagram in which phase separation takes place.

4.8 Results of Physico-chemical properties

Several properties of test fuels were evaluated by using equipment and methods which were discussed in the previous chapter. The properties which were determined for the test fuel samples are density, flash point, calorific value, kinematic viscosity, pour point, cloud point and cetane index, etc. for the binary and ternary fuel blends formed for the current study. These properties were compared to diesel and WCO biodiesel.

4.8.1 Density

It is one of the key property of the fuel that helps in understanding the fuels applicability in the engine. The energy content of the fuel increases with increasing density per unit volume (Ali et al., 2017). Therefore, with the increase in density, energy supplied to the engine also increases and thus the power delivered by it also increases. This results in a richer fuel-air mixture and so higher particulate matter emissions may be produced. Whereas, with a decrease in density, fuel consumption increases (Williams et al., 2016). In order to avoid both negative effects, the diesel fuel standards ASTM D1298 and EN 590 provide a very narrow tolerance range for the density as (820-860 kg/m^3) and (820-845 kg/m^3) respectively. Therefore, it will be beneficial to use diesel engines with fuels within these density ranges. As per the discussion in the previous chapter, the density of the fuels were determined using Anton Parr oscillating U-tube density meter.

The density of ternary fuel blend 10O10WB80D and binary fuel blend 10O90D were very lower than 100WB. The density of 100D, 100WB, 10WB90D, 10O90D, 10O10WB80D, 10O20WB70D and 20O10WB70D were 838.3 kg/m^3, 891.1 kg/m^3, 847.3 kg/m^3, 837.2 kg/m^3, 837.5 kg/m^3, 847.4 kg/m^3 and 836.7 kg/m^3 respectively. It was observed that 100WB has the highest density whereas 10O90D exhibited lowest and 10O10WB80D has the second lowest density among all the test fuels.

Figure 4.21 shows the comparison in density after blending.

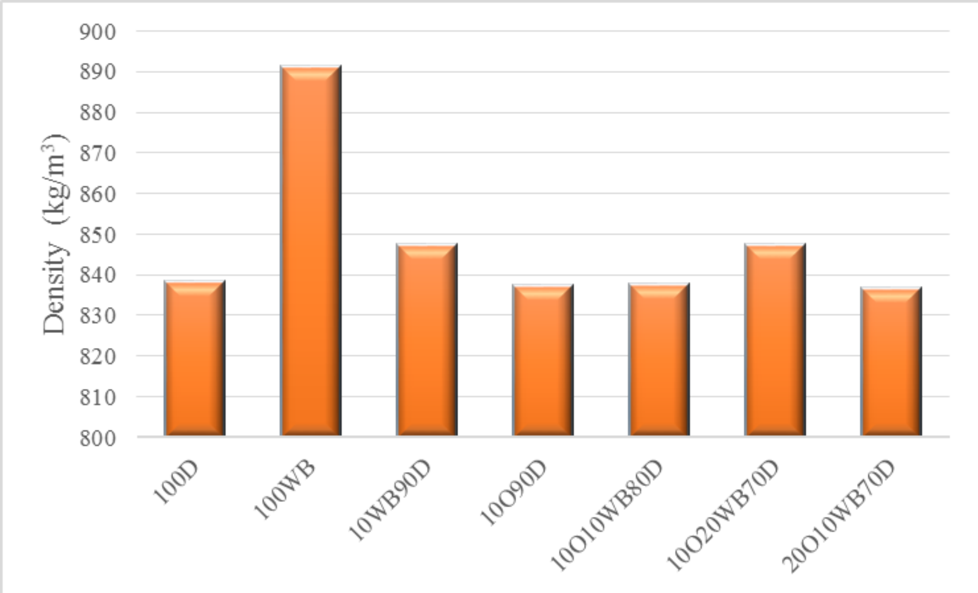


Figure 4.21. Variation in density for test fuel samples

4.8.2 Kinematic viscosity

It is known as the internal friction or flow resistanc of a fluide. According to ASTM D445 and EN 590, kinematic viscosity has a range of 2-4.5 cSt for a diesel like fuels to be utilized in a CI engine. This is a broad range for selecting a fuel for a diesel engine. However, the problem arises with higher viscosity which inturn applies higher pressure on the injection system (Chang and Farrell, 1997). Moreover, atomization of the fuel becomes difficult as the droplet of the fuel will be bigger causing poor burning. This leads to higher fuel consumption and hence produces lower BTE and higher emissions.

The viscosity of the fuel varies with temperature. At higher temperatures, the viscosity of the fuel is low and hence favors better combustion. However, the usage of straight vegetable oil is not recommended. Moreover, biodiesel also has nearly double kinematic viscosity compared to diesel which can affect the functionality of a diesel engine in the long run. Therefore, it is preferable to have a fuel having low kinematic viscosity and well within a range of ASTM/EN standards. The viscosity of the test fuels namely 100D, 100WB, 10WB90D, 10O90D, 10O10WB80D, 10O20WB70D and 20O10WB70D were 2.67 cSt, 5.91 cSt, 2.84 cSt, 2.69 cSt, 3.08 cSt, 3.4 cSt and 3.36 cSt, respectively.

The viscosity of all the ternary and binary fuel blends were lower than WCO biodiesel. However, on increasing the percentage of biodiesel and octanol composition in the blend, their viscosity also increases. It was also observed that the viscosity of 10O10WB80D ternary fuel blend is well within the EN and ASTM standards range making it suitable for running without a problem. Figure 4.22 shows the kinematic viscosity for test fuel samples.

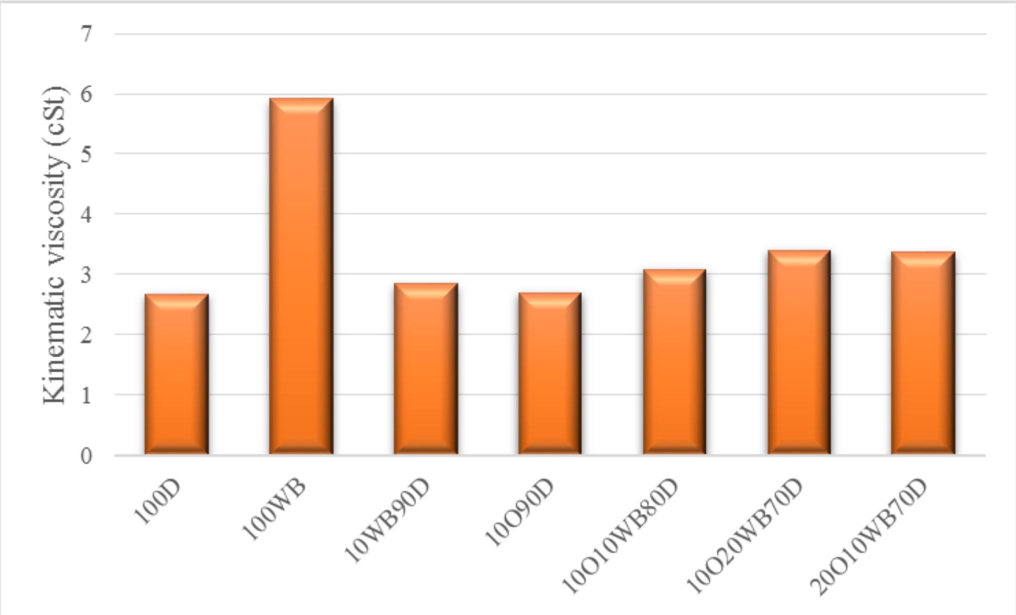


Figure 4.22. Variation in kinematic viscosity for test fuel samples

4.8.3 Calorific value

It represents the energy released by a unit mass of fuel due to the burning of fuel, to get CO_2 and water. This property directly affects the power of the engine. As per the discussions in the previous sections, a bomb calorimeter is used for measuring its heating value. It was analyzed that diesel is the best fuel in terms of its energy content. Lower calorific value is mainly determined for an IC engine as no heat loss was included because of side products. It was observed that all the ternary and binary test fuel blends exhibited lesser calorific value than diesel, however, for biodiesel, it was higher than octanol. This in turn offers low calorific value of the resulting blend. Therefore, it results in lowering the input energy during combustion. It was also found that the blends and diesel exhibited comparable calorific values. Figure 4.23 displays the calorific value of different fuel samples. The calorific values of 100D, 100WB, 10WB90D, 10O90D, 10O10WB80D, 10O20WB70D and 20O10WB70D were found to be 45.14 MJ/kg, 41.32 MJ/kg, 43.74 MJ/kg, 43.63 MJ/kg, 43.42 MJ/kg, 43.01 MJ/kg and 42.29 MJ/kg respectively.

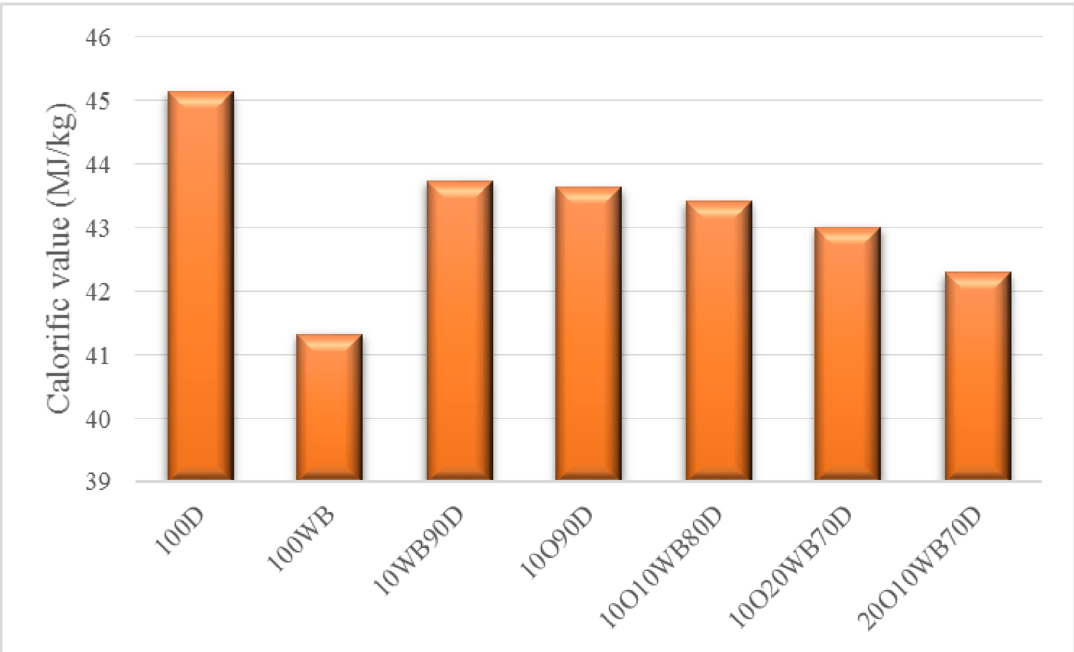


Figure 4.23. Variation in Calorific value for test fuel samples

4.8.4 Flash point

It is the minimum temperature when flammable vapours are produced. Here the fuel vaopurs will combine with oxygen in the air and then flash or ignites near the surface of the fuel. The fuel which has a low flash point can ignite easily (Stauffer et al., 2008). Generally, the flash point of diesel is much lower than biodiesel. This helps better storage and safety with biodiesel. However, it affects the ease of fuel burning.

Therefore flash point near to diesel is desirable. Since octanol has a very lower value of flash point than biodiesel and comparable to diesel, therefore, all the test fuels samples formed were well within the range of ASTM standards.

The flash point of diesel was 58 °C whereas for biodiesel was 165°C and for the 10O10WB80D blend was 73°C. This slightly higher flash point helps in providing better storage and handling. Figure 4.24 displays the variation in flash point for the test fuels.

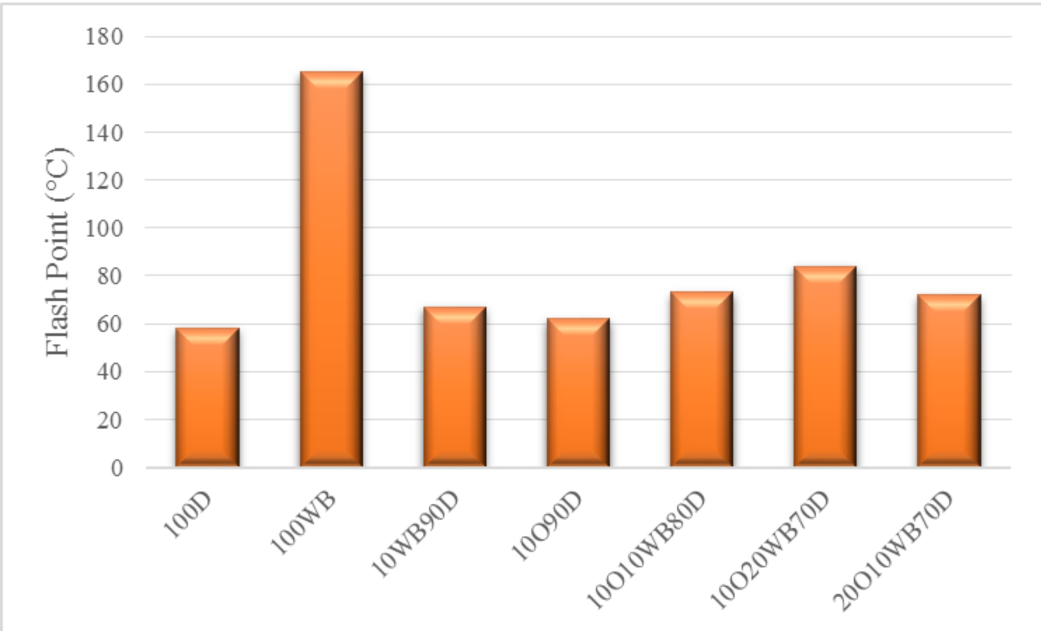


Figure 4.24. Variation in Flash point for test fuel samples

4.8.5 Cetane Index

Cetane number is one of the main indicators of quality of fuel in a CI engine. It helps in understanding the characterization of self-ignition of the fuel during injection into the combustion chamber. Since the cetane number is difficult to be determined, therefore, the cetane index is used for understanding the ignition characteristics of the fuel. Cetane index is determined from the volatility or distillation temperature of the fuel and its density. It gives a close approximation of the fuel quality equivalent to cetane number. The method used for the determination of cetane index is described in the previous chapter. Figure 4.25 shows the comparison of the cetane index of the test fuels.It was found from Figure 4.25 that the cetane index of biodiesel was higher than diesel. However, binary and ternary fuel blends of octanol have less value of cetane index owing to lower cetane index of octanol. Therefore it was found that higher the amount of octanol in the blend lower was the cetane index. Whereas, the addition of WCO biodiesel increases the cetane index of the blends. This higher cetane index shall help in better combustion of the fuel.

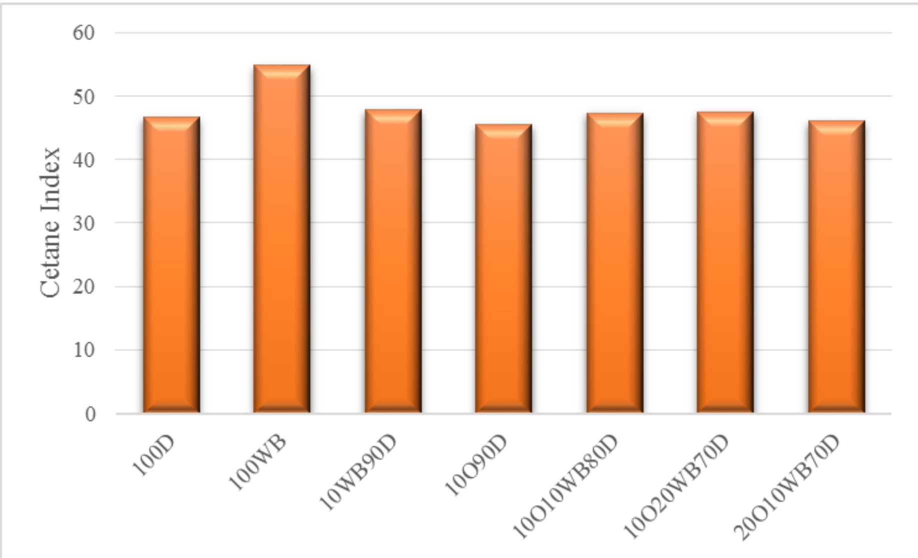


Figure 4.25. Variation in Cetane index for test fuel samples

The cetane index of 10O10WB80D is 47.3 whereas that of 100D is 46.6. This shows by the addition of biodiesel in blends smooth and proper combustion can take place.

4.8.6 Cold flow properties (Cold filter plugging point, cloud point and pour point)

Cold flow property is another key fuel parameter that helps in determining the suitability of fuels at low temperatures.

Paraffinic hydrocarbons are mainly suitable owing to their good auto-ignition temperature (Nolan, 2014). However, with decreasing temperatures, these fuels show the tendancy of forming of wax crystals. These fuels affect the pumping capacity of the fuel pump and can clog the fuel filter (Dabelstein et al., 2016). This leads to complete failure to start the engine. The cold flow properties are, therefore, a very important factor for knowing the low temperature application of fuel. Cold flow property mainly depends on several factors, such as ambient temperature, characteristics of the engine, fuel properties and storage conditions. So several factors contribute to affecting the cold flow properties and therefore it becomes necessary to determine the CFPP, cloud point and pour point of the fuel CFPP is the maximum temperature at which a given volume of fuel no longer flows through a fuel filter when it is cooled under standard conditions. In other words at a lower temperature, a limit is reached where-paraffin crystals are formed. These crystals cause wax/hazy like appearance and are big enough to choke or clog fuel filters. If the temperature reached at the test filter is clogged by crystal growth, so the CFPP value is reached.

Cloud point is the lowest temperature at which the molecules agglomerate. Whereas, pour point is the lowest temperature at which fuel will flow and below which it will not flow. Cloud point and pour points can be found by ASTM D97 standard. Pour point as per BS VI standard is minimum 3°C for winter. In the previous chapter the equipment used for determining CFPP, cloud point and pour point was discussed. Figures 4.26, Figures 4.27 and Figures 4.28 shows the trends of the cold flow properties of the test fuel blends. From the results it has been observed that 100WB has the poorest cold flow properties. Higher quantities of biodiesel in the blends also affects the cold flow properties greatly. It was observed that the CFPP of 100D, 100WB, 10WB90D, 10O90D, 10O10WB80D, 10O20WB70D and 20O10WB70D were -11°C, -2°C, -10°C, -12°C, -11°C, -9°C and -13°C respectively.A similar trend was seen for cloud point and pour point of the test fuels. Cloud point of 100D, 100WB, 10WB90D, 10O90D, 10O10WB80D, 10O20WB70D and 20O10WB70D were -12°C, -3°C, -9°C , -14°C, -11°C, -8°C and -12°C respectively.Pour point of 100D, 100WB, 10WB90D, 10O90D, 10O10WB80D, 10O20WB70D and 20O10WB70D were -15°C, -5°C, -11°C, -17°C, -14°C, -11°C and -15°C respectively. Binary and ternary fuel blends of octanol exhibit better cold flow properties and their values were in very close range of diesel fuel.

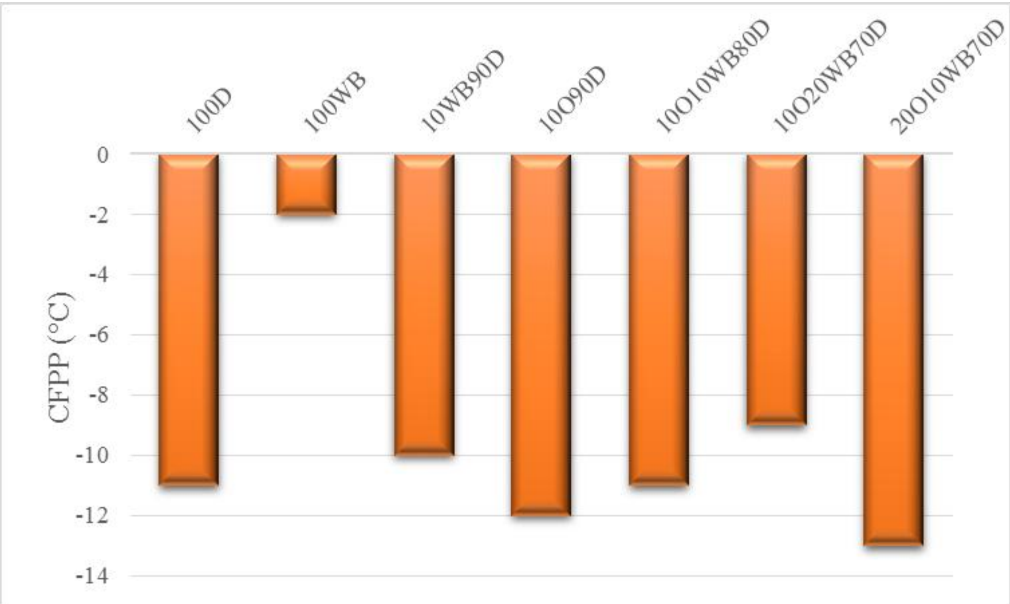


Figure 4.26. Variation in CFPP for test fuel samples

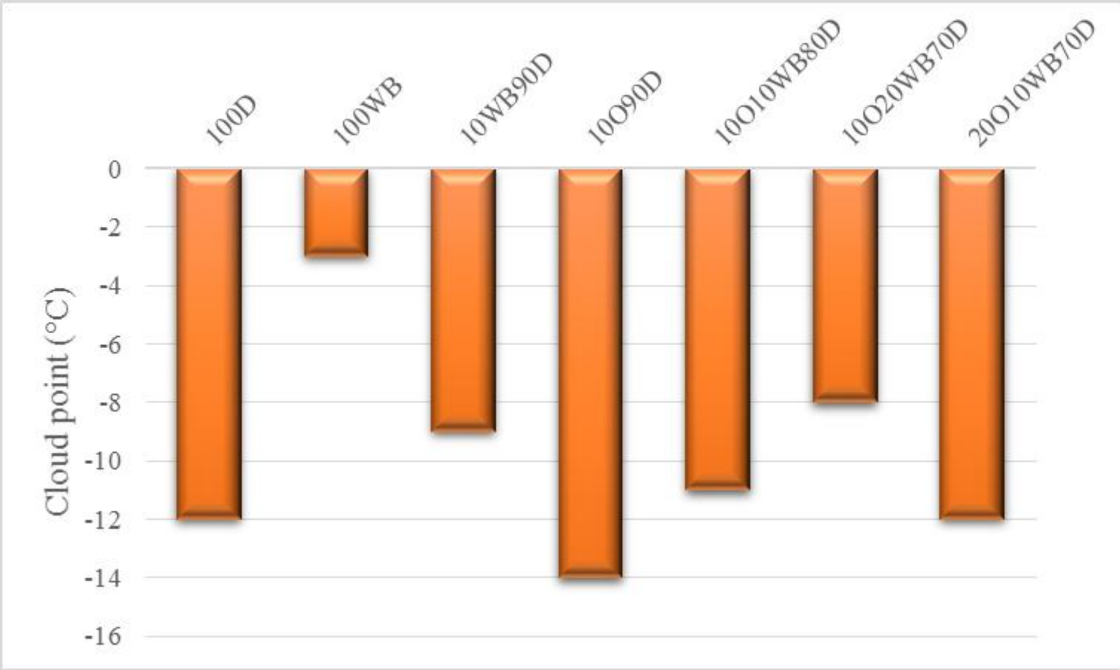


Figure 4.27. Variation in cloud point for test fuel samples

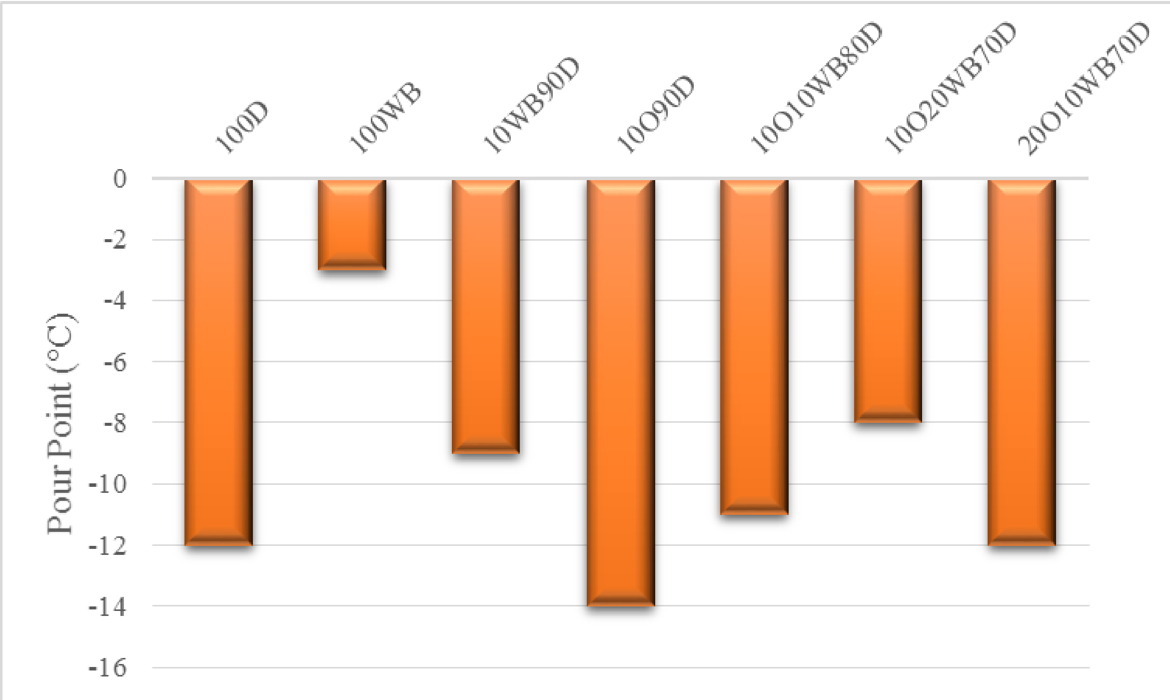


Figure 4.28. Variation in pour point for test fuel samples

4.8.7 Other physico chemical properties

Apart from these properties, some other properties like specific gravity, carbon and hydrogen percentage in the fuels were also determined. Table 4.7 shows the properties of different fuels. The method used for their determination was described in the previous chapter.

Table 4.7. Important physico-chemical properties of test fuels

Fuel Nomenclature/ Property	100D	100WB	10WB90D	10O90D	10O10WB80D	10O20WB70D	20O10WB70D
Density at 15°C (kg/m^3)	838.3	891.1	847.3	837.2	837.5	847.4	836.7
Specific gravity	0.839	0.891	0.848	0.838	0.838	0.848	0.837
Kinematic viscosity at 40°C (cSt)	2.67	5.91	2.84	2.69	3.08	3.4	3.36
Calorific value (MJ/kg)	45.14	41.32	43.74	43.63	43.42	43.01	42.29
Flash point (°C)	58	165	67	62	73	84	72
Cetane Index	46.6	54.8	47.8	45.4	47.3	47.5	46
Carbon (wt%.)	86.4	77.3	83.1	84.9	84.2	83.7	84.3
Hydrogen (wt%)	13.6	12.4	13.1	13.5	13.2	13	13.3
CFPP (°C)	-11	-2	-10	-12	-11	-9	-13
Cloud point (°C)	-12	-3	-9	-14	-11	-8	-12
Pour point (°C)	-15	-5	-11	-17	-14	-11	-15

4.9 Effect of storage on fuel properties

The test fuels on being stored for longer duration gets degraded. Three important properties namely density, kinematic viscosity and calorific value were evaluated over a period of one year and their corresponding effects were recorded. Samples were kept in a closed glass contained for the study.

Figure 4.29 shows that the density of binary and ternary fuels changed with time. Diesel and diesel-octanol binary fuel blends showed the least deterioration whereas all other binary and ternary fuel blends due to biodiesel exhibited the highest variation. These variations were observed owing to gumming and oxidation of test fuels (Beranek et al., 1987; Czarnocka et al., 2015; Karavalakis et al., 2011, 2010).

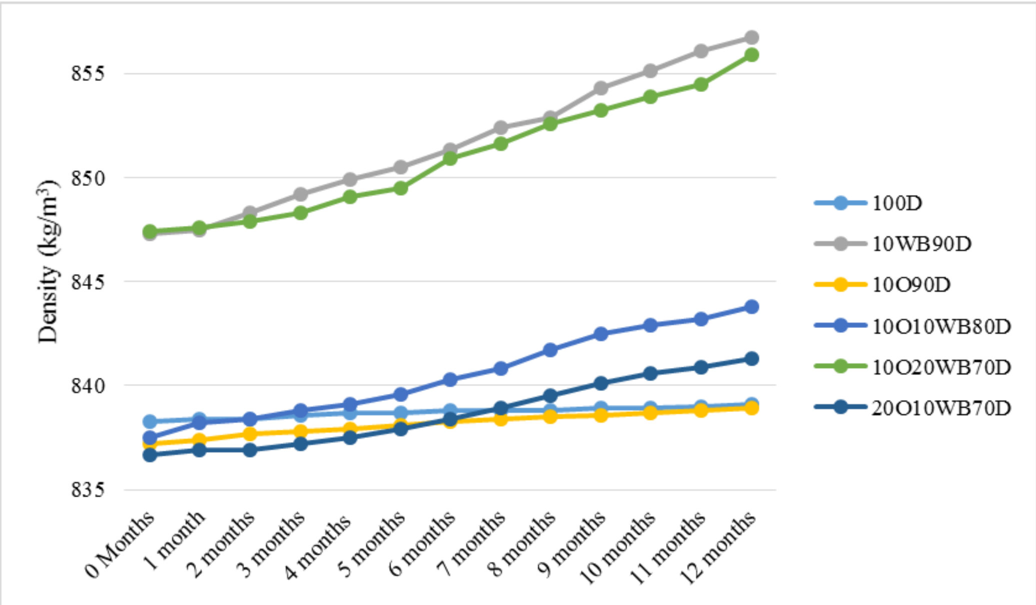


Figure 4.29. Change in the density of test fuels over 12 month's period

Figure 4.30 and Figure 4.31 shows the change in kinematic viscosity and calorific values of binary and ternary fuels compared to diesel over one year period. It was observed that the viscosity was higher after 12 month period whereas calorific value was lower.

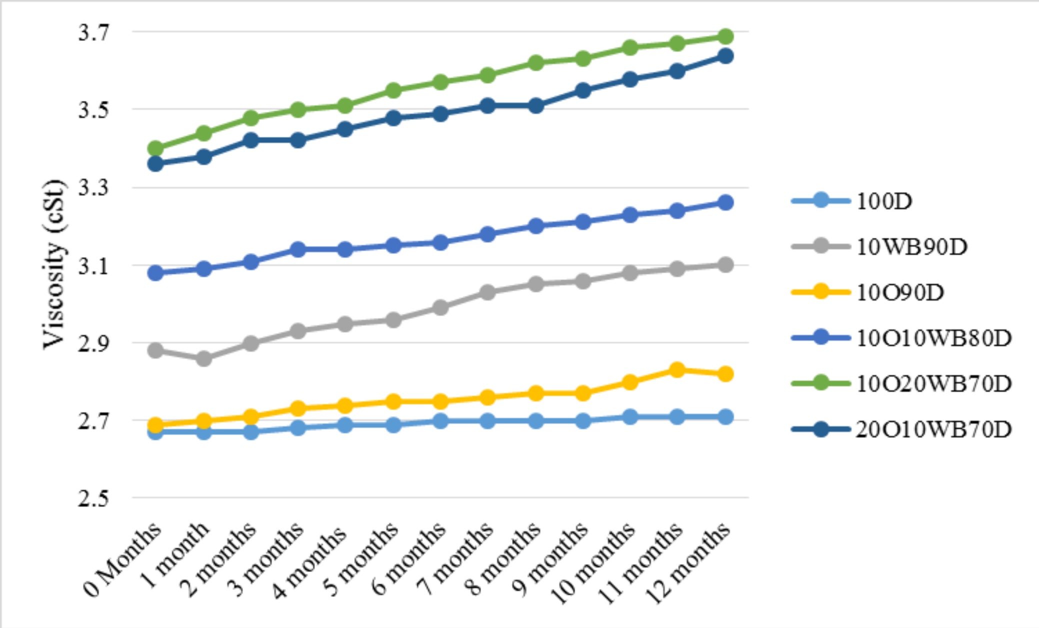


Figure 4.30. Change in Kinematic viscosity of test fuels over 12 months period

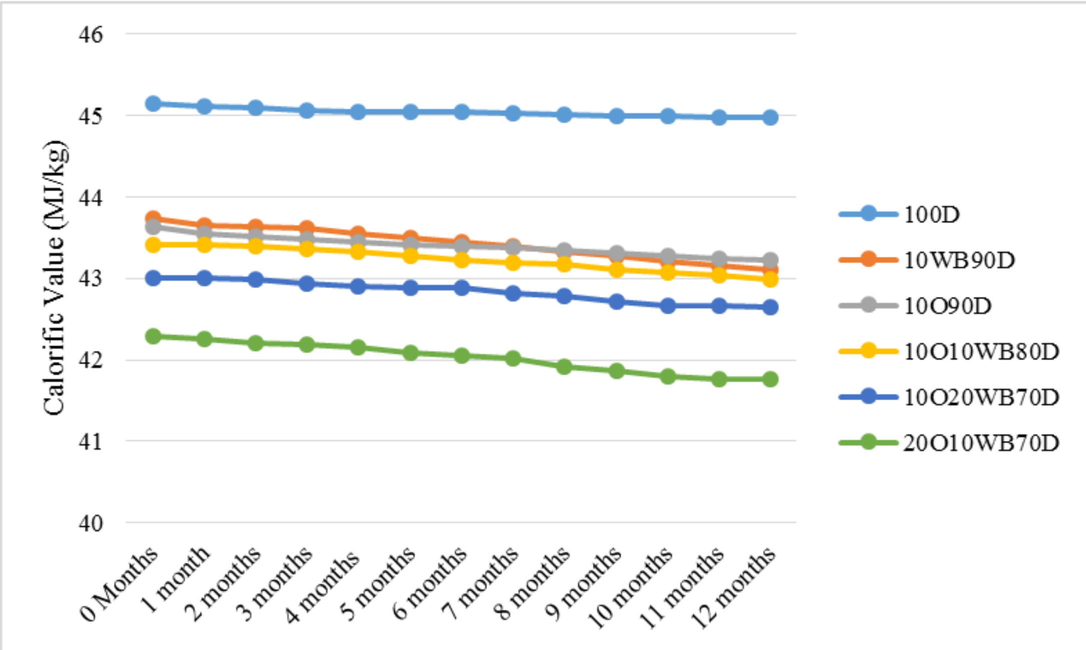


Figure 4.31. Change in calorific value of test fuels over 12 months period

It was found that the viscosity of the test fuels increased whereas its calorific value decreased. However, the changes in density, viscosity and calorific values of the test were very small making them suitable for operating in a diesel engine.

4.10 Oxidation stability

To analyze the effect of long term storage stability on the test fuels, their oxidation stability was also determined in the present study. The induction period of over 6 hours is required as per EN 14214 standard and over 3 hours as per ASTM D6751 standard. From this study, it was found that the oxidation stability of biodiesel was lower than that of octanol and diesel. From Figure 4.32, it was seen that 100WB has an induction time of nearly 6.5 hours.

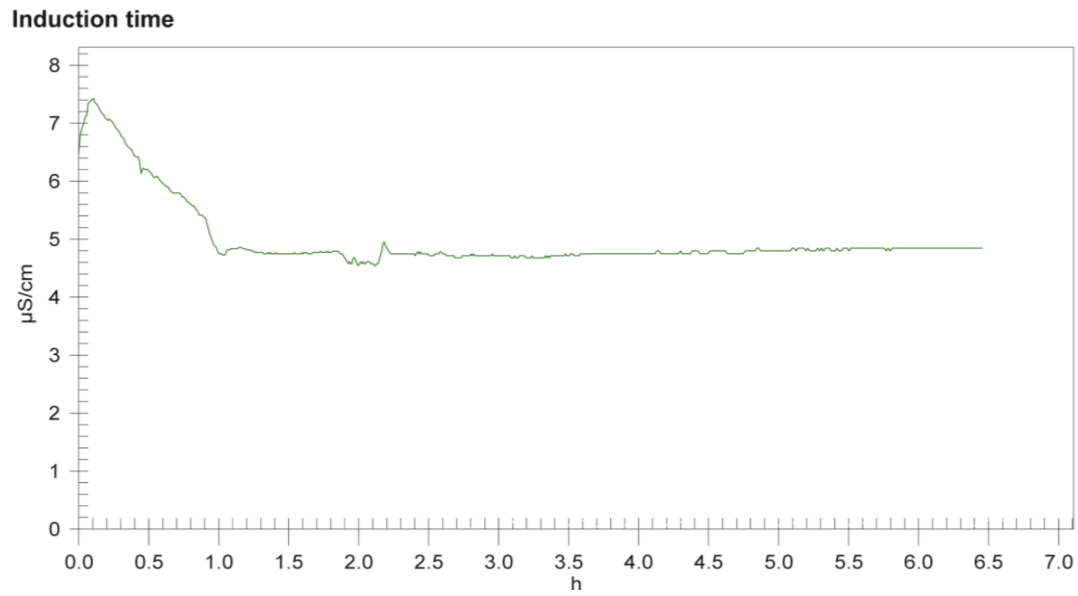


Figure 4.32. Oxidation stability test result of WCO biodiesel (100WB)

It was seen from Figure 4.33 and 4.34 that on adding 10% biodiesel or 10% octanol to diesel, oxidation stability of the blend was higher compared to 100WB. The induction time of the two binary fuels 10WB90D and 10O90D was nearly 8 hours and 10 hours, respectively.

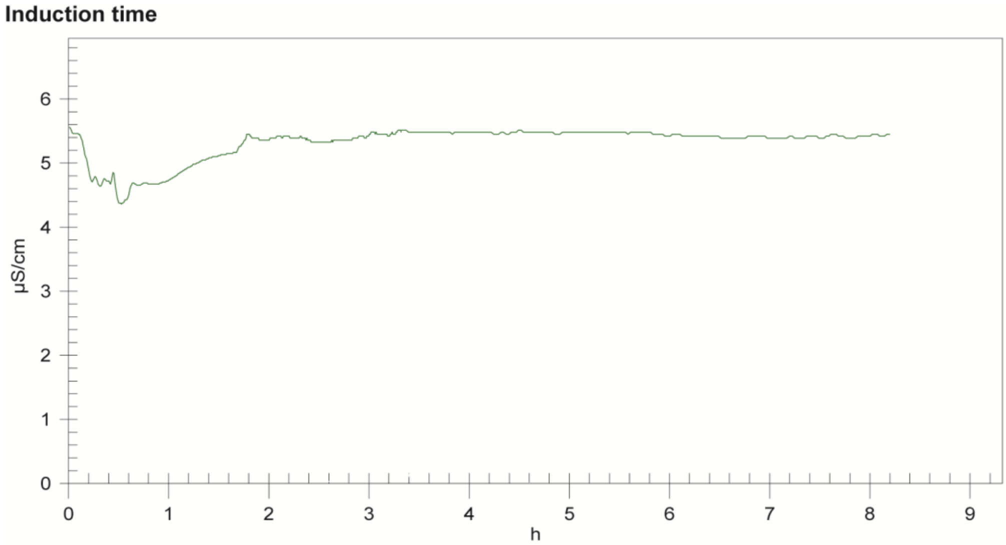


Figure 4.33. Oxidation stability test result of the 10WB90D binary fuel blend

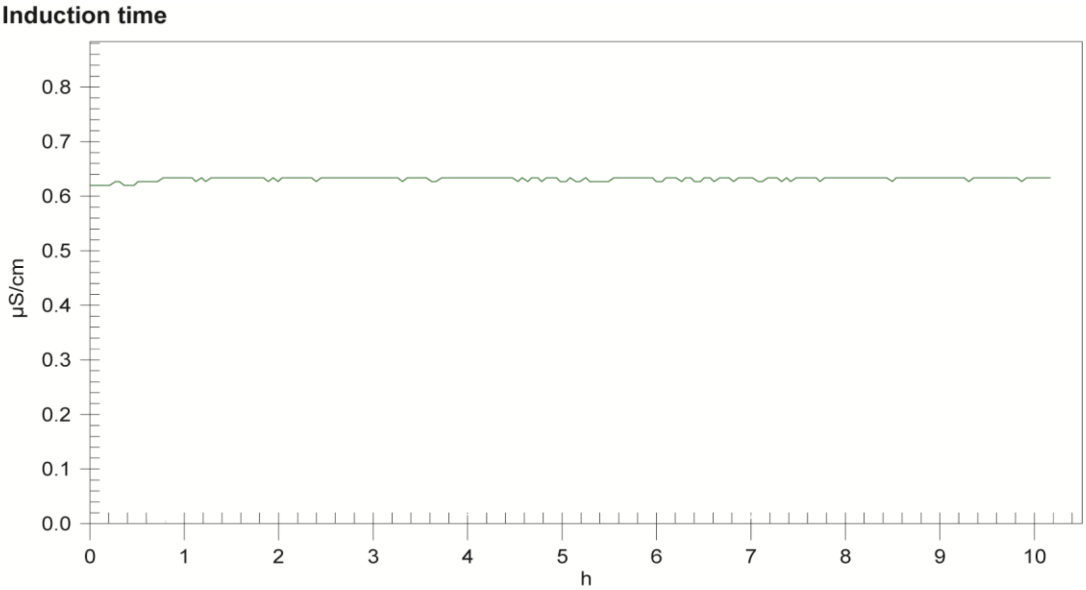


Figure 4.34. Oxidation stability test result of the 10O90D binary fuel blend

A similar trend was observed for the ternary fuel blends of octanol, biodiesel and diesel. Since diesel has the highest oxidation stability, it helps in forming a better blend for increasing the shelf life of the fuels. Moreover, octanol also has better oxidation stability than biodiesel. Therefore, the ternary blend 10O10WB80D has superior oxidation stability of nearly 8 hours compared to 6.75 hours of 10O20WB70D.

Also, the ternary fuel blend 20O10WB70D has more oxidation stability than 20% biodiesel ternary fuel blend. Its oxidation stability was found to be nearly 7 hours.

Figure 4.35, Figure 4.36 and Figure 4.37 show the results of oxidation stability tests of the ternary test fuel blends.

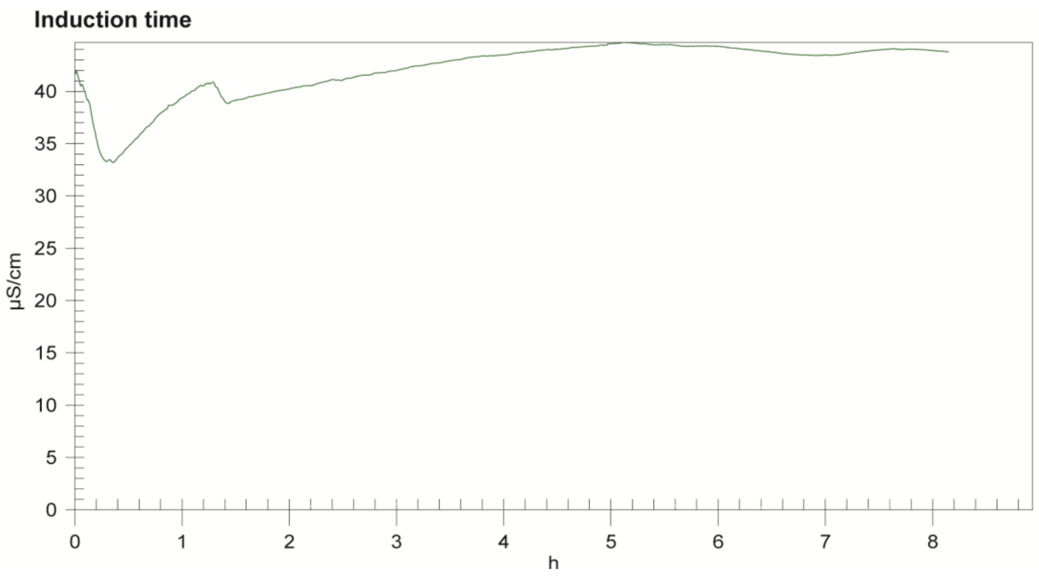


Figure 4.35. Oxidation stability test result of the 10O10WB80D ternary fuel blend

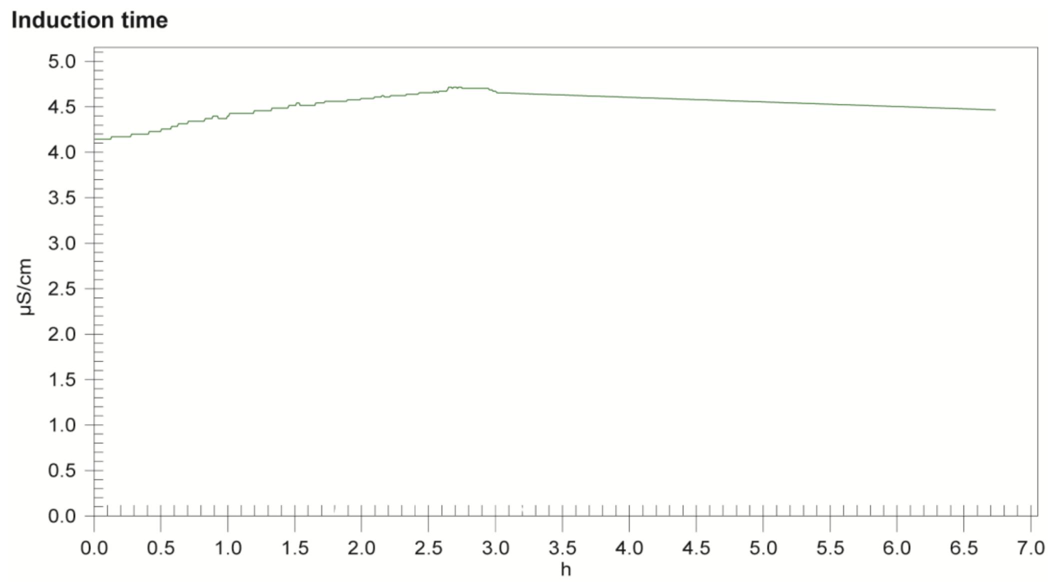


Figure 4.36. Oxidation stability test result of the 10O20WB70D ternary fuel blend

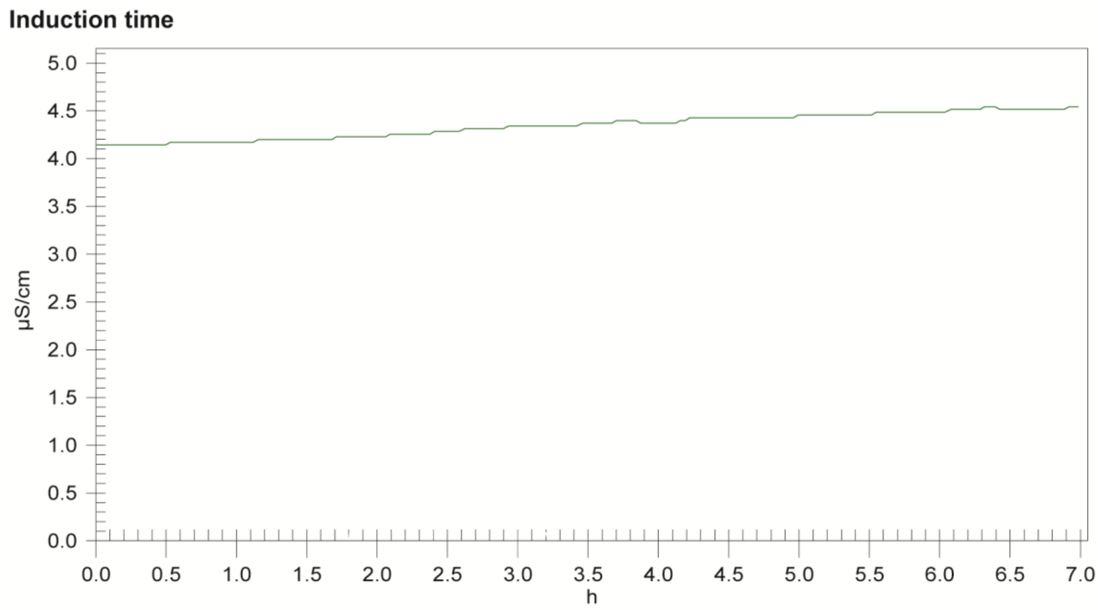


Figure 4.37. Oxidation stability test result of the 20O10WB70D ternary fuel blend

4.11 Infrared spectroscopy

FTIR graphs were obtained from the instrument discussed in the earlier chapter. A known quantity of the sample was used for determining the infrared spectroscopy of the test fuel samples. The graphs were plotted by the instrument between transmittance percentage and wave number (cm^{-1}).

The FTIR analyses show the regions where samples absorb the infrared spectrum containing specific molecular bonds.

The wave number and transmittance percentage for C-O bonds are 600 cm^{-1} to 1400 cm^{-1}, C = O bonds are 1500 cm^{-1} to 1800 cm^{-1} , C-H bonds are 2700 cm^{-1} to 3000 cm^{-1} and O-H bonds are 3000 cm^{-1} to 3700 cm^{-1}.

In FTIR, ester groups are represented by C-O and C=O bonds spectrum. Figure 4.38, Figure 4.39 and Figure 4.40 show the FTIR of 10WB90D, 10O90D and 10O10WB80D.

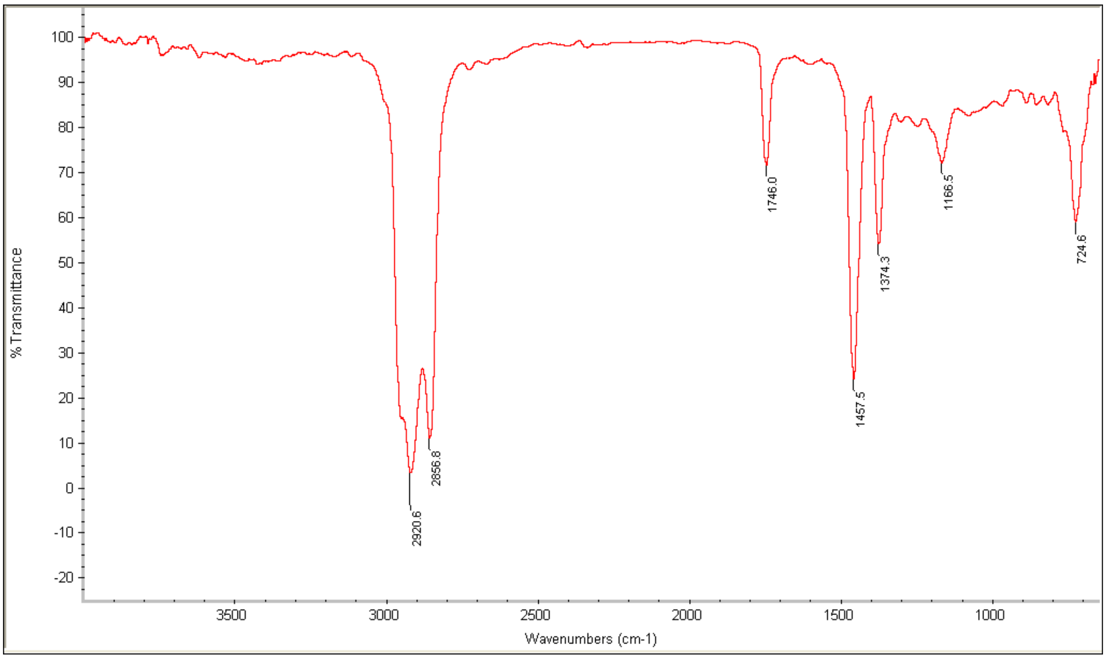


Figure 4.38. FTIR test of the 10WB90D binary fuel blend

The presence of methyl ester at a wavelength of approximately 1750 cm^{-1} for 10WB90D and 10O10WB80D is clearly seen from Figure 4.38 and Figure 4.40. This peak was absent in 10O90D binary fuel blends.

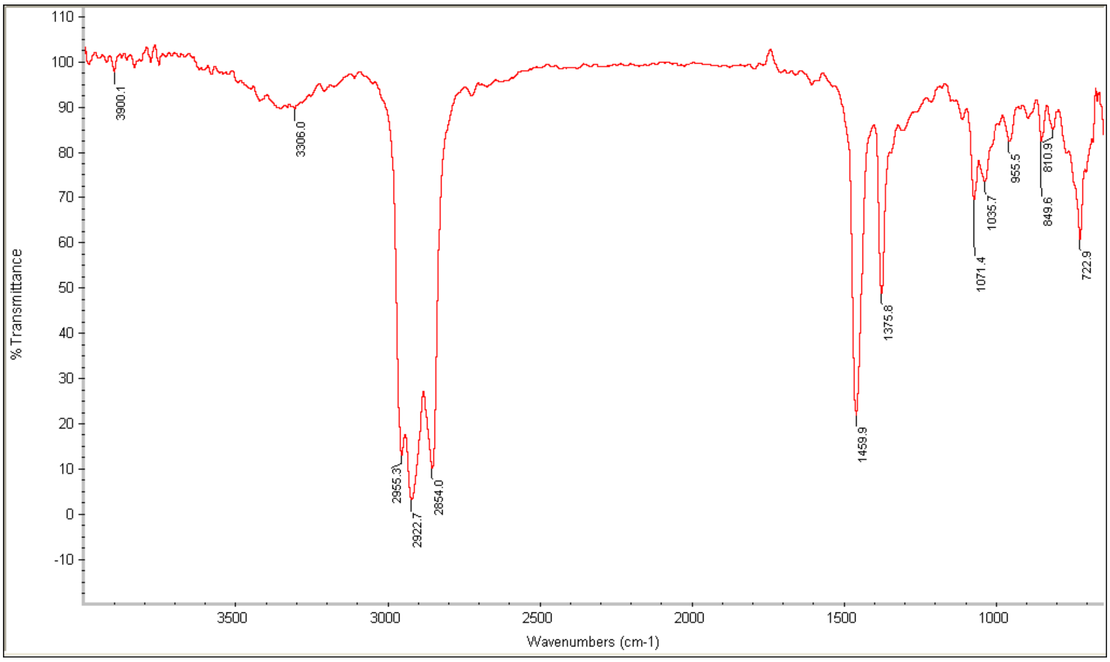


Figure 4.39. FTIR test of the 10O90D binary fuel blend

Similarly, from Figure 4.39 and Figure 4.40, a peak at 3300 cm^{-1} is observed for 10O90D and 10O10WB80D fuel blends confirming the presence of the alcoholic group. This peak is absent for 10WB90D blend. Blend 10O10WB80D shows the peak of both alcohol and methyl ester confirming their presence in the test fuel blend.

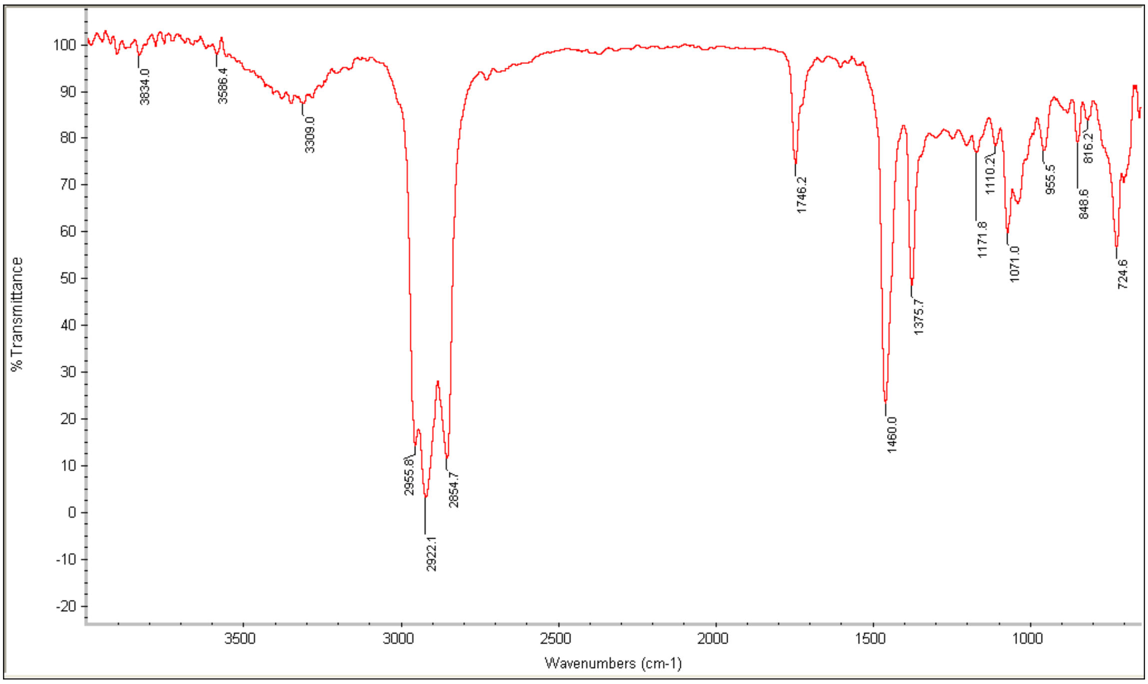


Figure 4.40. FTIR test of the 10O10WB80D ternary fuel blend

4.12 Sauter mean diameter

To understand the process of fuel spray through an injector nozzle, that helps in forming a mixture that easily ignites in the combustion chamber a knowledge of Sauter mean diameter is very necessary. Sauter mean diameter was found on the basis of the relation between the spatial distribution of the fuel and the spray evaporation. SMD is the ratio of the volume of fuel sprays to the surface area of fuel sprays (L. Chen et al., 2018) and helps in determining the level of atomization of the fuel from the injector.

The aim of measuring the droplet size helps in understanding the actual conditions similar to a spray from an injection inside a diesel combustion chamber. In this setup, collimated light was absorbed by the fuel and the detector detects the average particle size or average droplet size.

Figure 4.41 shows the SMD values of all the test fuels. It was observed from the investigation that the SMD of 100WB (29.36 µm) was the highest and diesel (20.41 µm) was the lowest. Since SMD is related to the atomization of fuel and diesel exhibits very good atomization, therefore fuels having SMD near to diesel are preferred. It was also observed that the SMD of 10O10WB80D blend has the lowest value of 21.58 µm among all ternary fuel blends. Its value is also very near to diesel making it fit for use in a CI engine to attain good burning characteristics.

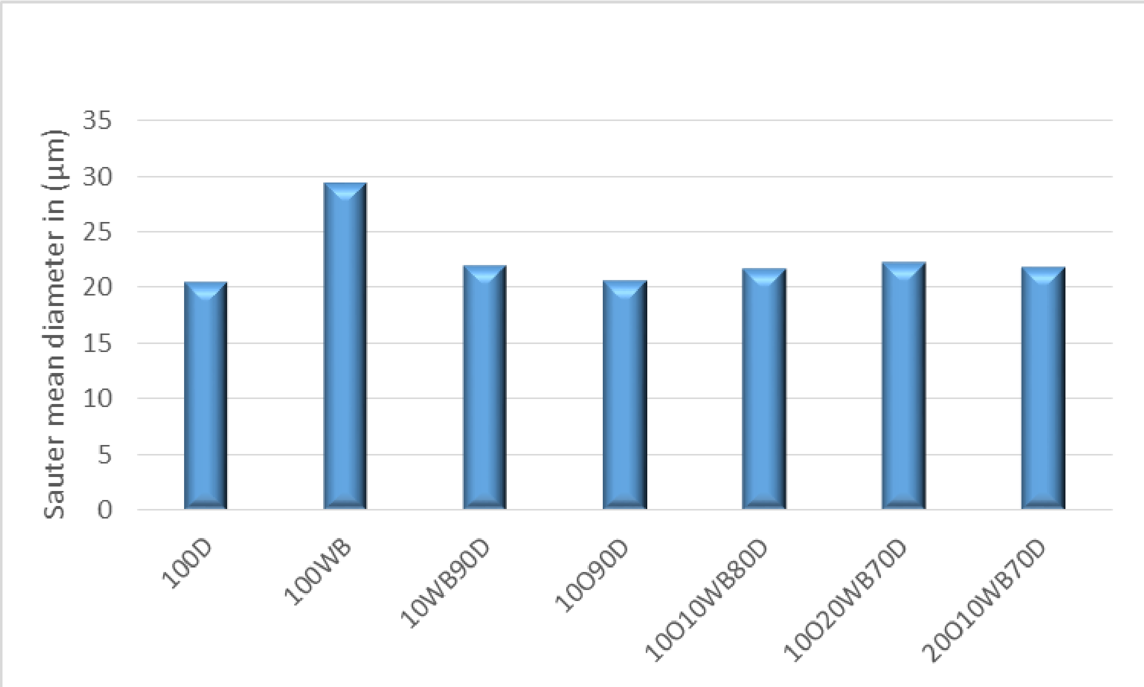


Figure 4.41. SMD values of test fuels

4.13 Performance characteristics

In this section three important parameters namely BTE, BSEC and EGT were analyzed and compared to diesel. Firstly the comparison is made for binary fuel blends with diesel and biodiesel. Then a comparison is made for ternary fuel blends with diesel and biodiesel. In the end, a cumulative comparison was carried out taking diesel as a baseline.

4.13.1 Brake thermal efficiency

BTE helps in estimating the conversion of fuel to mechanical energy. It gives the ratio of the output power to the input of the fuel's chemical energy. BTE variation with BMEP for the binary fuel blends was shown in Figure 4.42. From the results, it was seen that the 10% binary fuel blends of diesel/biodiesel have higher BTE than diesel. It was mainly because of added oxygen in both WCB and octanol that helps in proper combustion of the fuel and hence gives superior BTE.

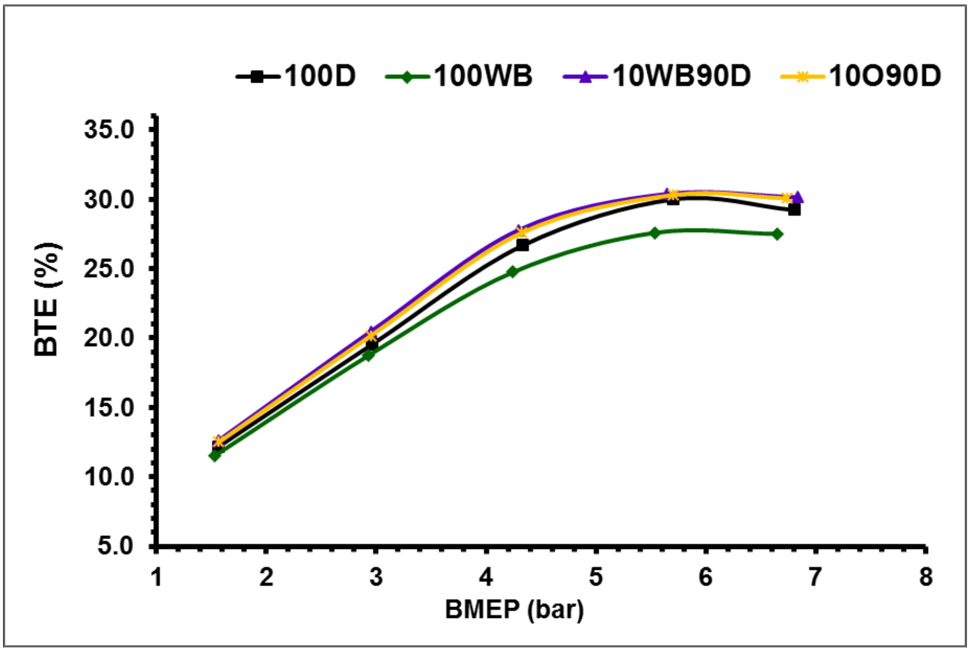


Figure 4.42. Comparison of BTE with BMEP of binary fuel blends

It was seen from Figure 4.43 that only ternary fuel blend 10O10WB80D has the highest BTE compared to all the ternary fuel blends, diesel and WCO biodiesel. It is attributed to the presence of oxygen in biodiesel/octanol and slightly higher cetane number of the 10O10WB80D (Imdadul et al., 2016a, 2016b; Li et al., 2015). All other ternary fuel blends show similar SMD values. Therefore ternary test fuels exhibited similar atomization to that of 100D. However, due to lower heating values and higher viscosity for the blends 10O20WB70D and 20O10WB70D, slightly lower BTE was observed.

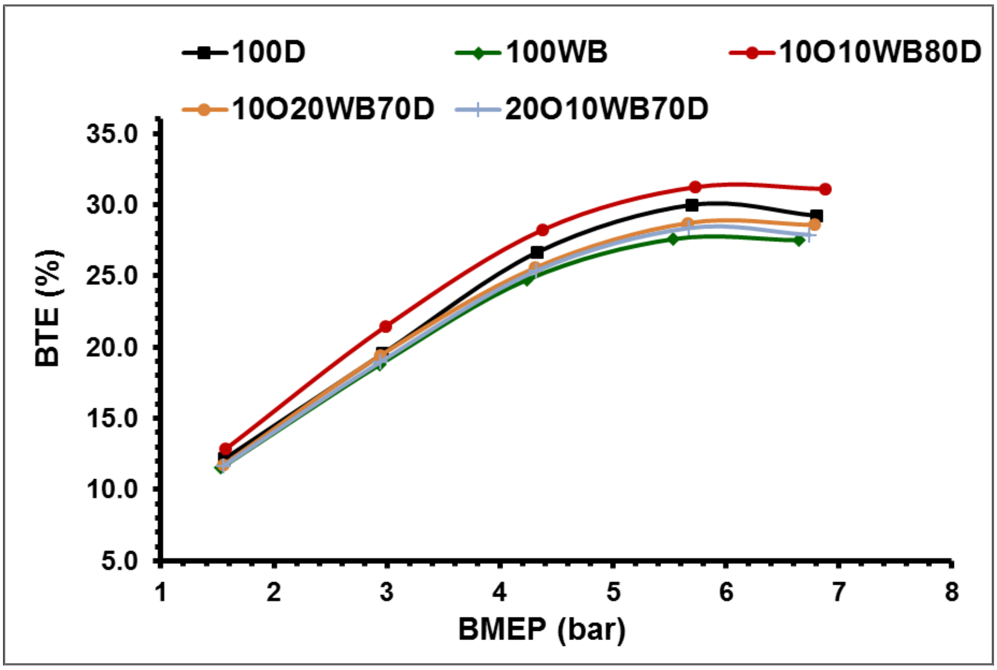


Figure 4.43. Comparison of BTE with BMEP of ternary fuel blends

Figure 4.44 compares all the results of binary and ternary fuel blends.

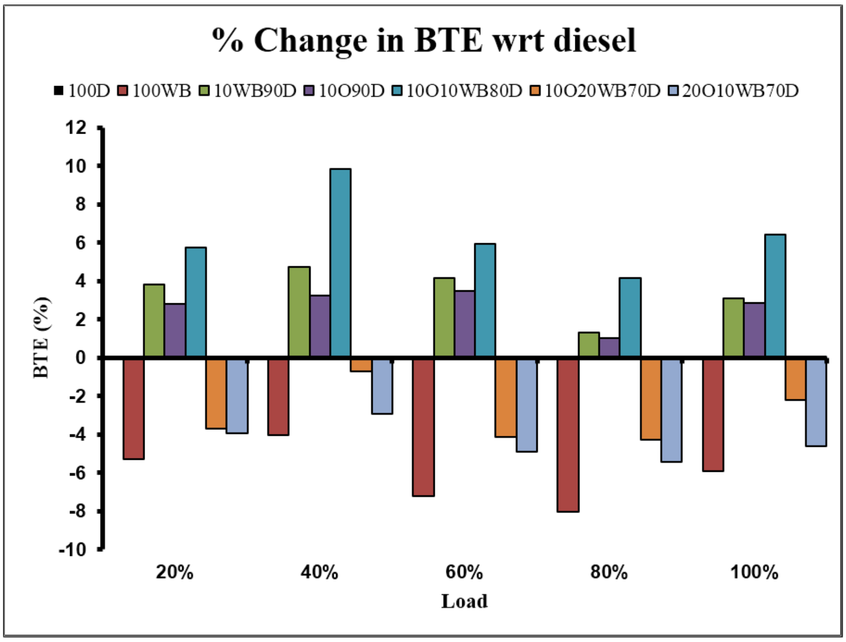


Figure 4.44. Variation of BTE of all test fuel blends with baseline diesel

It was observed that 10O10WB80D showed the highest BTE among all fuels. It happened due to the presence of biodiesel and octanol together in the test fuel blends. Since the SMD, calorific value and viscosity were comparable to diesel with added oxygen and slightly better cetane index, better combustion leads to higher BTE.

4.13.2 Brake specific energy consumption

BSEC gives an understanding of the energy gained by the burning of the fuel inside the engine. Since BSFC compares the efficiency of an engine with shaft output and lacks in comparing two separate engines. Therefore BSEC is a parameter that also helps in comparing different types of engines. It has been observed from the results that BTE and BSEC were inversely proportional.

Figure 4.45 shows the variation of BSEC with BMEP for binary fuel blends. It was seen that BSEC of 100WB was highest and for 10WB90D it was lowest. It was showing an inverse trend to BTE.

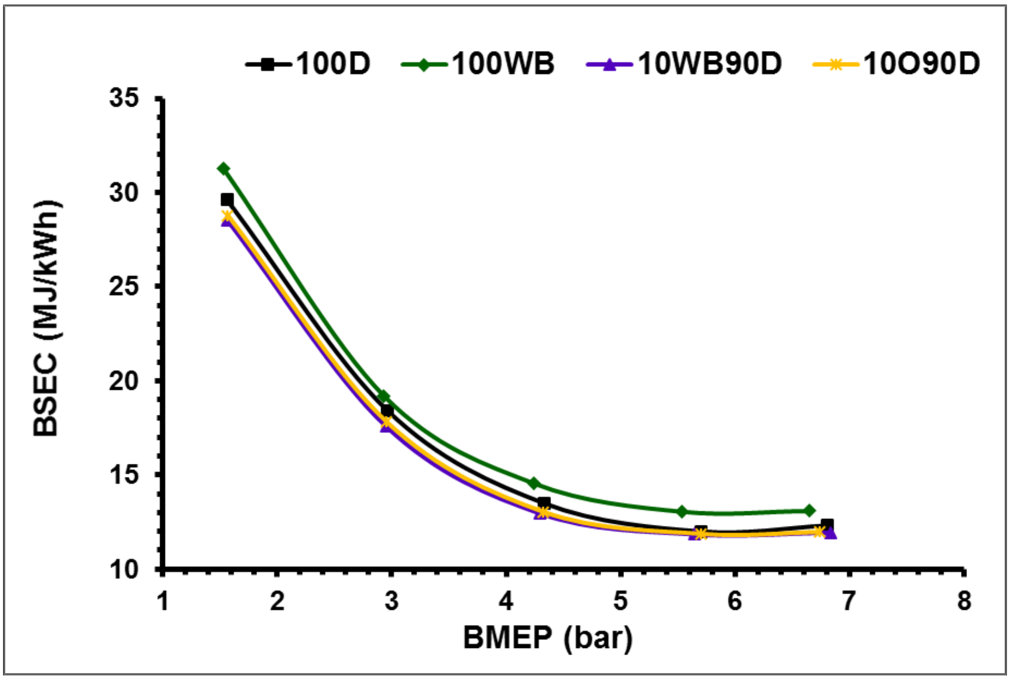


Figure 4.45. Comparison of BSEC with BMEP of binary fuel blends

Similarly, Figure 4.46 shows the variation of BSEC with BMEP for ternary fuel blend. It was found that the BSEC of 10O10WB80D was the lowest whereas for 100WB was the highest.

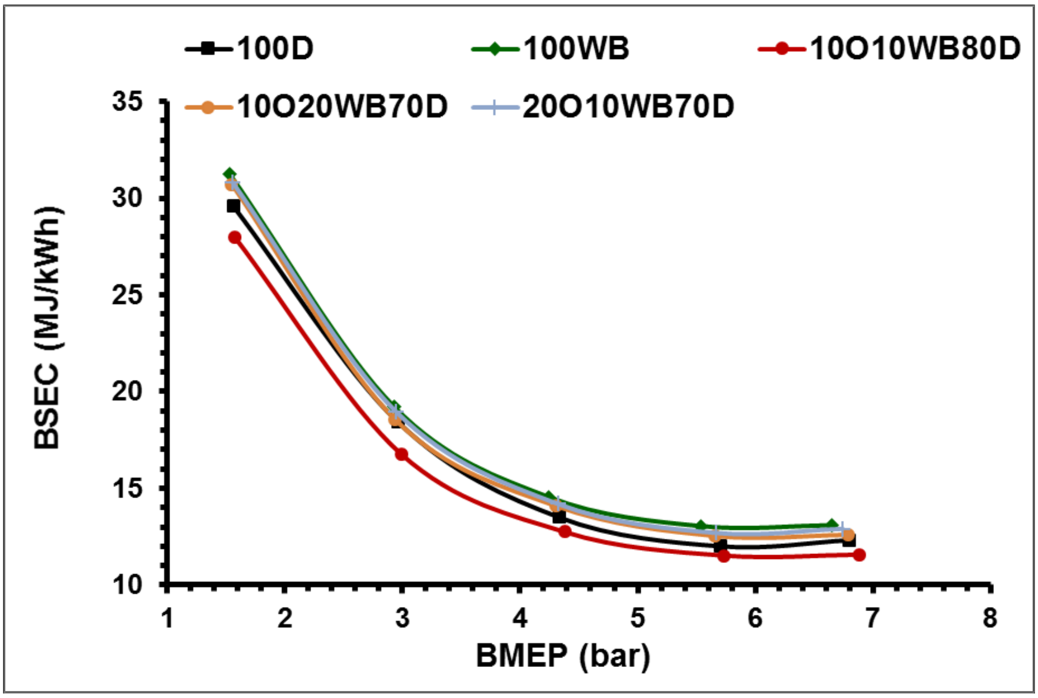


Figure 4.46. Comparison of BSEC with BMEP of ternary fuel blends

Also on the basis of the cumulative comparison shown in Figure 4.47, it was found that the BSEC of ternary fuel blend 10O10WB80D was lowest due to lower viscosity, higher heating value and better burning when compared with other ternary and binary fuel blends.

100WB has the highest BSEC owing to higher viscosity, lower heating value and higher SMD that results in improper burning and higher energy consumption.

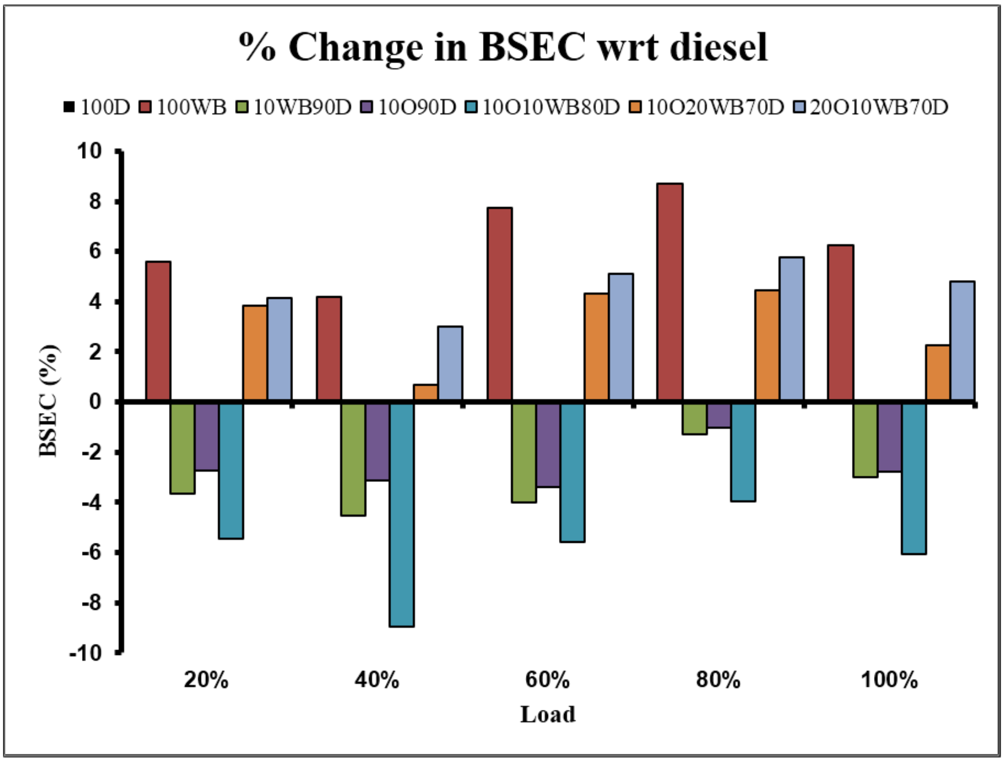


Figure 4.47. Variation of BSEC of all test fuel blends with baseline diesel

4.13.3 Exhaust gas temperature

EGT represents the type of burning in the engine cylinder. It mainly depends upon the calorific value of fuel, compression ratio and ignition delay and slight dependent upon latent heat of vaporization of fuels. EGT increases with increase in engine load. At higher loads since additional fuel is fed therefore EGT increases.

From Figure 4.48 it was found that EGT of 100WB was highest. EGT reduces drastically on using octanol due to its higher latent heat of vaporization. 10O90D shows the lowest EGT emissions. This reduction shall also help in reduction in NO_X emissions as both were related since NO_X emissions form at higher temperatures.

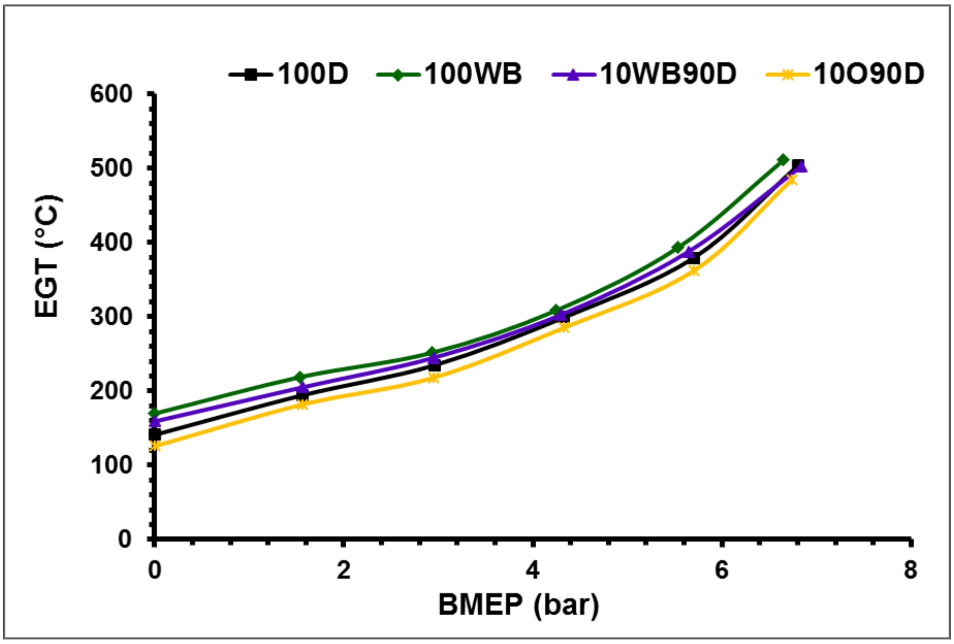


Figure 4.48. Comparison of EGT with BMEP of binary fuel blends

As per the trend seen for binary fuel blends, Figure 4.49 shows a similar trend for ternary fuel blends. Greater the amount of octanol, lower is the EGT. 20O10WB70D exhibited the lowest EGT owing to more quenching or cooling of the cylinder walls that decreases the in-cylinder temperature to some extent.

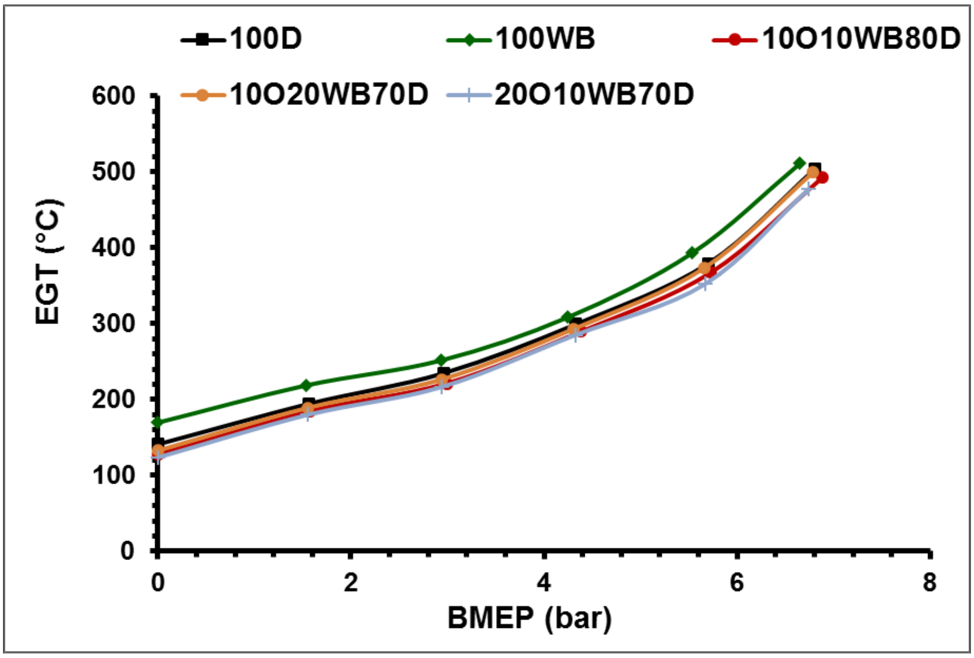


Figure 4.49. Comparison of EGT with BMEP of ternary fuel blends

Similarly, for the reasons explained above, on comparing both binary and ternary fuel blends shown in Figure 4.50, 20O10WB70D exhibited a significant drop in EGT whereas 10WB90D and 100WB exhibited slightly higher EGT.

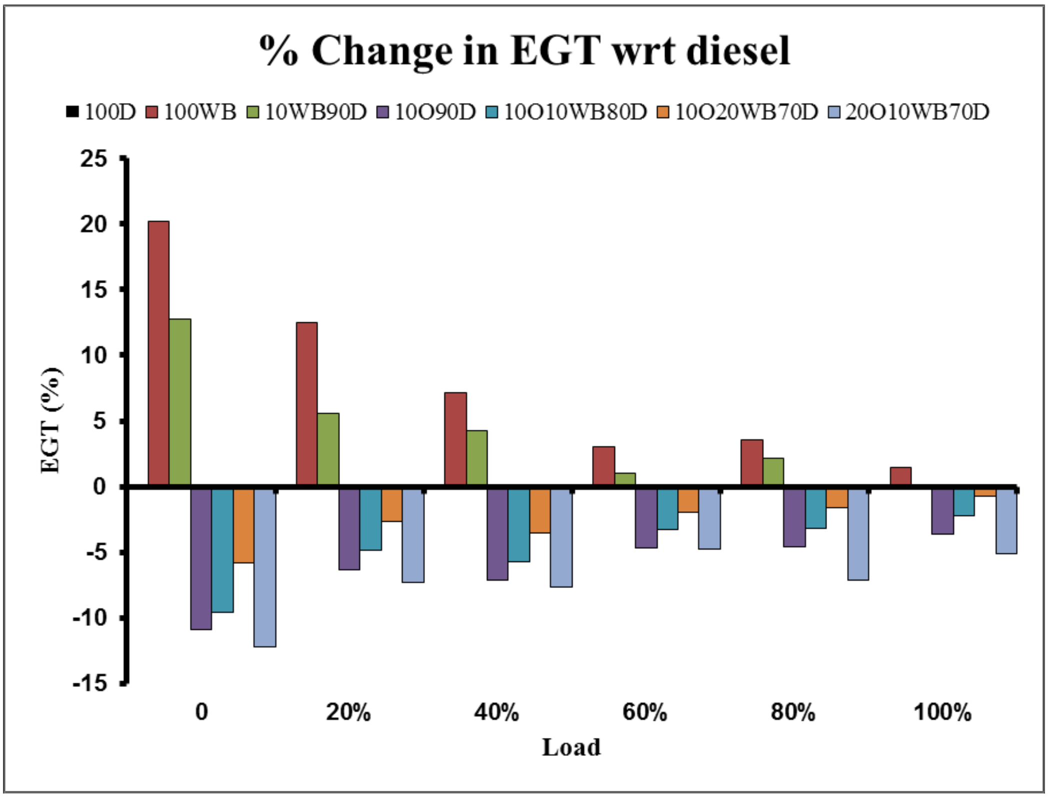


Figure 4.50. Variation of EGT of all test fuel blends with baseline diesel

10O90D exhibited the lowest EGT for binary fuel blend. Blend 10O10WB80D also exhibited a large drop in EGT but was not as much significant as for 20O10WB70D ternary fuel blend.

4.14 Emission characteristics

In this section, emissions liberated from the engine exhaust were discussed for binary and ternary fuel blends. Results were compared with neat diesel and neat WCO biodiesel. Emissions like CO, HC, NO_X and smoke opacity were analyzed in detail. All the test fuel samples i.e. 100D, 100WB, 10O90D, 10WB90D, 10O10WB80D, 20O10WB70D and 10O20WB70D were observed for the possible increase or decrease in emissions.

4.14.1 Carbon Monoxide

As CO is related to incomplete combustion of fuel, its knowledge is essential to understand the burning of fuel. Absence of oxygen increases CO emissions from the engine. Since in the present study WCO biodiesel and octanol both are oxygen rich fuels, hence their blending may be beneficial. Due to higher latent heat of vaporization of octanol, CO emissions shall be higher, however, its effect will not be very prominent as seen from the previous studies showing a reduction in CO with the addition of octanol (Nour et al., 2019b; De Poures et al., 2019). From Figure 4.51 an estimation for the burning of binary fuel blend is made.

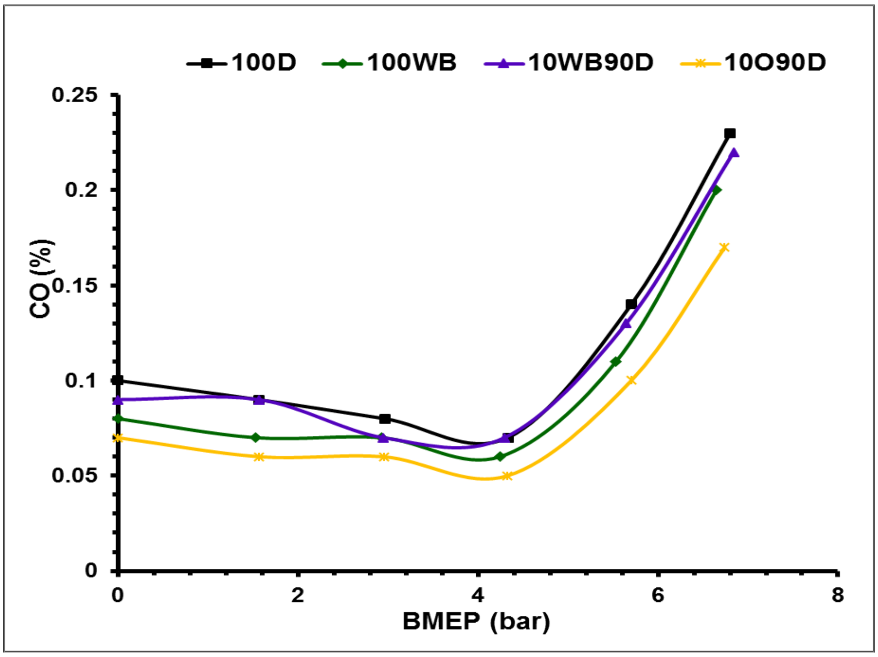


Figure 4.51. Comparison of CO emissions with BMEP of binary fuel blends

It was found from Figure 4.51 that binary fuel blends containing octanol and biodiesel exhibited lower CO emissions than diesel. Moreover, 10O90D exhibited the lowest CO emissions owing to better burning as its viscosity was lower and also octanol contains more oxygen. This benefits in better burning and hence less CO emissions.

From Figure 4.52, for ternary fuel blends, both 100D and 100WB exhibited higher CO emissions. All the ternary fuel blends exhibited lower CO emissions owing to added oxygen in them. Among all the ternary fuel blends 10O10WB80D has the lowest viscosity and SMD. This promotes better burning and due to added oxygen, CO emissions get reduced.

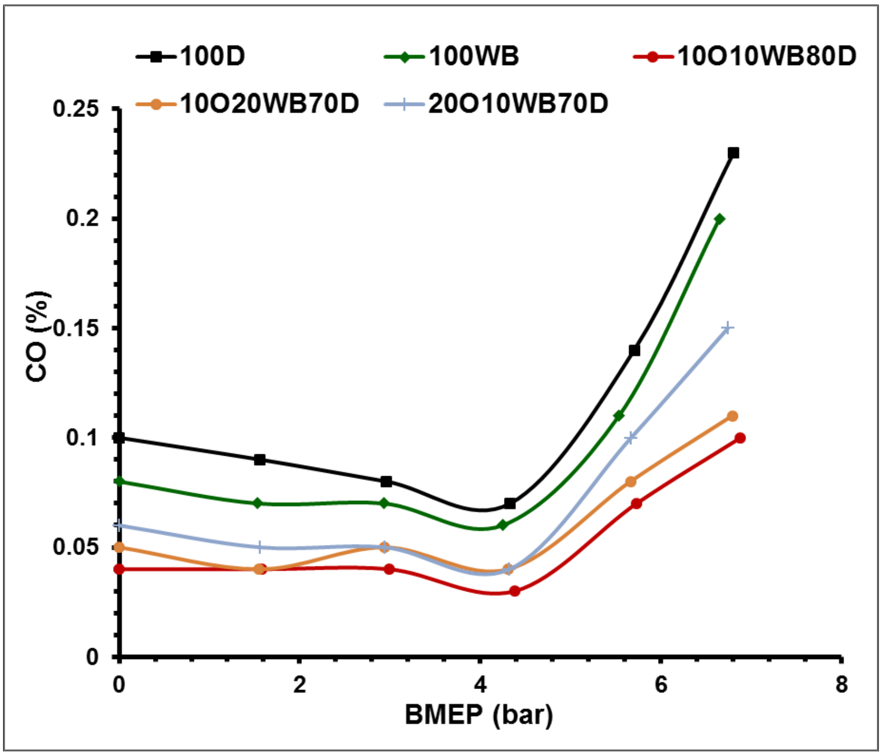


Figure 4.52. Comparison of CO emissions with BMEP of ternary fuel blends

It was observed from Figure 4.53 that for all the test fuels CO emissions were lower comparable to 100D. Owing to oxygen present in both octanol and biodiesel their addition decreases the CO formation. Moreover, elevated temperature burning is achieved at higher loads due to this oxygen. Also, due to higher in-cylinder of biodiesel, more combustion temperature was attained leading to slightly better burning and therefore lesser CO emissions were liberated. Due to octanol i.e. 20% octanol in the blend 20O10WB70D, some cooling or quenching inside the cylinder walls takes place resulting in slightly inferior burning. Therefore, CO emissions were higher with 20O10WB70D than 10O20WB70D. It was also observed that for 100D, CO emissions were highest whereas 10O10WB80D emits lowest CO emissions.

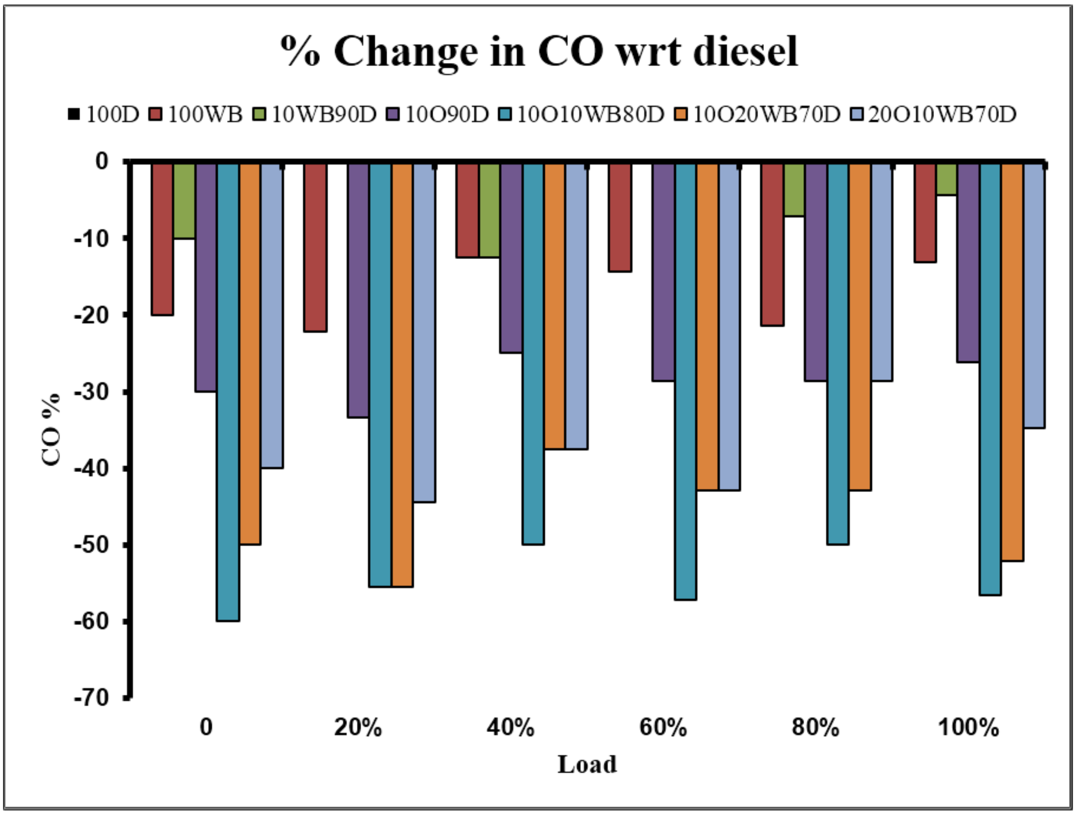


Figure 4.53. Variation of CO emissions of all test fuel blends with baseline diesel

4.14.2 Oxides of nitrogen emissions

NO_X emissions are formed at a very high temperature of nearly 1500°C. This is the main problem with the usage of biodiesel and diesel. Several investigations determined higher NO_X emissions for biodiesel (Hoekman and Robbins, 2012; Thangaraja et al., 2016). Since alcohols have higher latent heat of vaporization, this brings some cooling effect in the cylinder that reduces the temperature and hence helps in lowering NO_X emissions.

It was observed that nitrogen oxide emissions from the engine increase with an increase in load due to rise in temperature with load. For the same reasons, it was witnessed in Figure 4.54 that NO_X emissions of 100WB and 10WB90D were higher than diesel. However, the addition of octanol reduces the temperature and hence lowers the NO_X emission

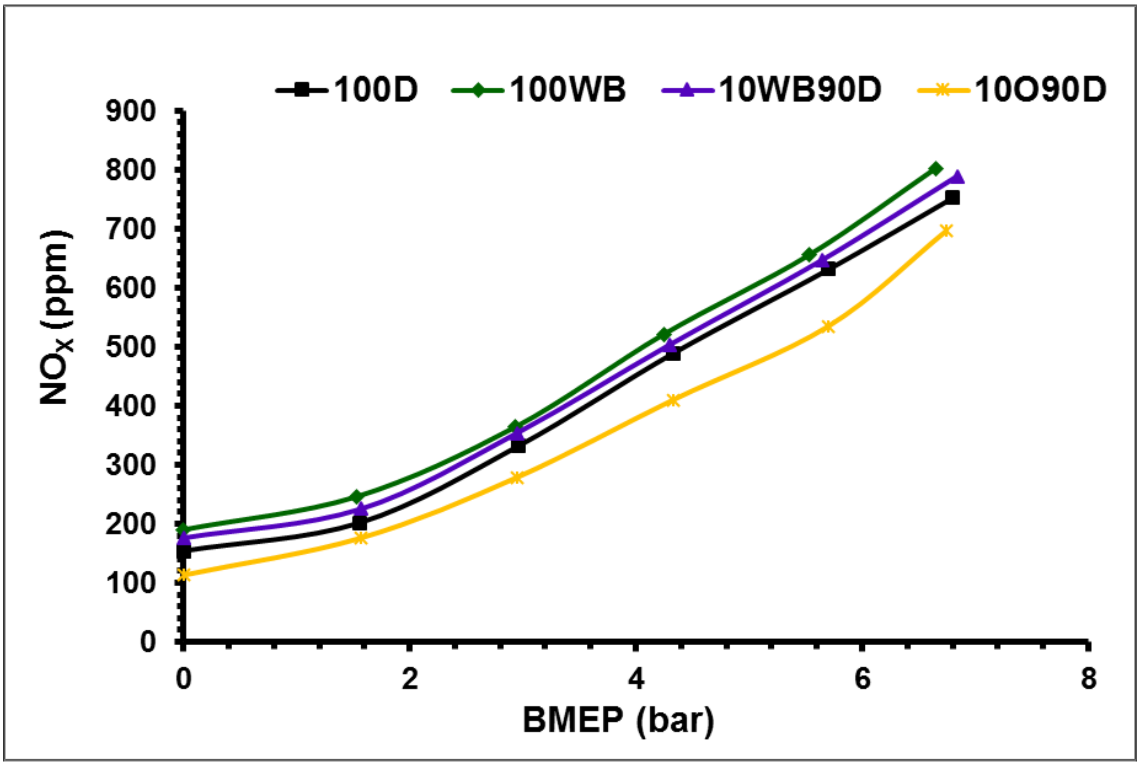


Figure 4.54. Comparison of NO_X emissions with BMEP of binary fuel blends

From Figure 4.55, it was observed that the NO_X emissions of 20O10WB70D were the lowest due to maximum octanol content in the blend. This lowers in-cylinder temperature and lowers NO_X emission.

Moreover, it was also found that more the quantity of biodiesel in the blend, more were the NO_X emissions. Therefore having higher biodiesel content in the blend is not preferable as it leads to higher NO_X.

Among all ternary fuel blends, 20O10WB70D produces lowest NO_X emissions whereas 10O20WB70D produces highest NO_X emissions. NO_X emissions for 10O10WB80D are in between both the ternary fuel blends.

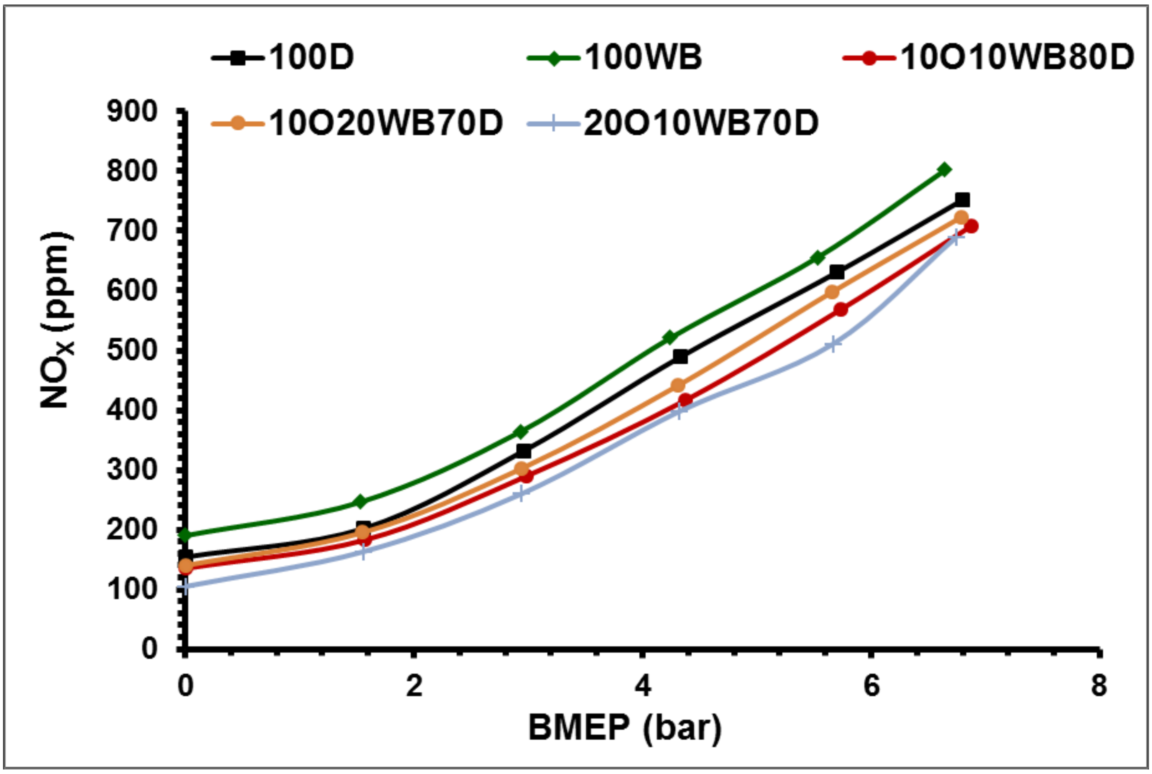


Figure 4.55. Comparison of NO_X emissions with BMEP of ternary fuel blends

Figure 4.56 depicts the comparison of NO_X emissions for both binary and ternary fuel blends of octanol, diesel and biodiesel. NO_X emissions were found highest for 100WB.

Exhaust gas temperature of 100WB was much higher than other test fuels. As discussed earlier, octanol due to nearly 60% higher latent heat of vaporization, reduces the cylinder peak temperature and lowers NO_X emissions.

20O10WB70D emits minimum NO_X emissions because of higher octanol content whereas NO_X emissions from 10O10WB80D were second lowest.

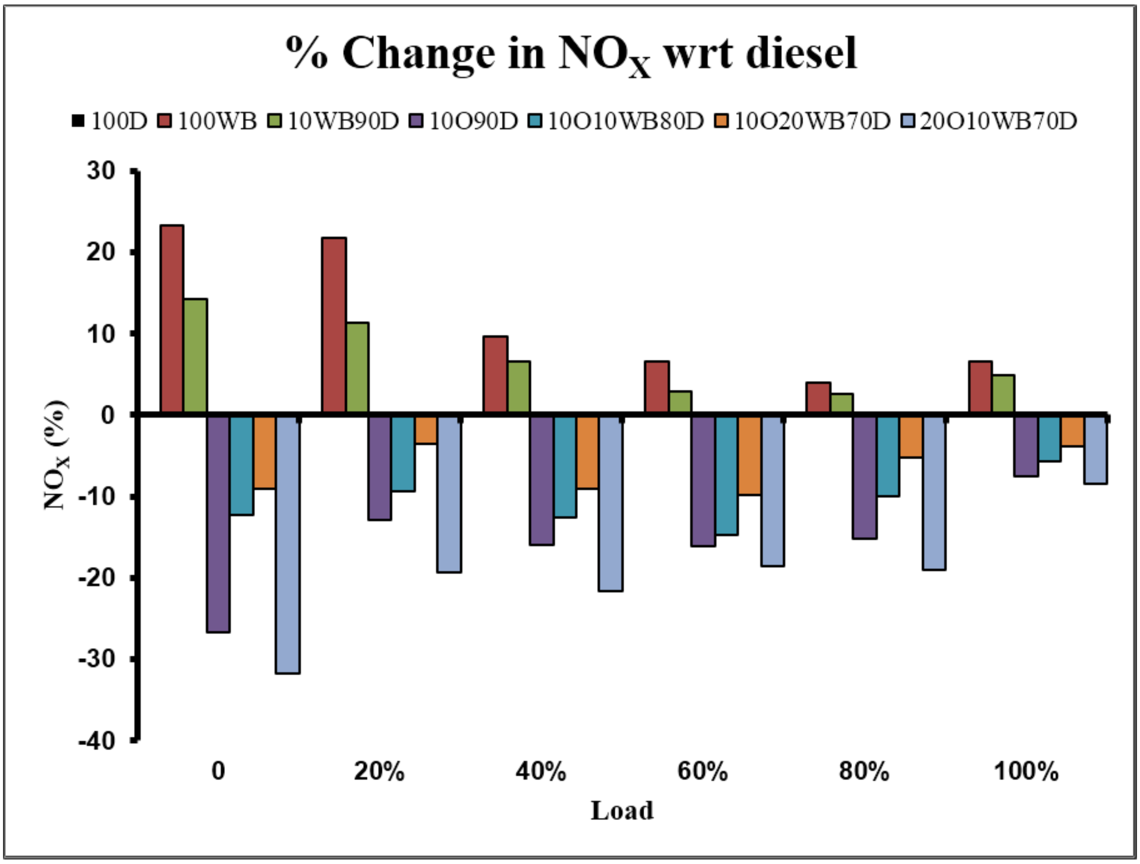


Figure 4.56. Variation of NO_X emissions of all test fuel blends with baseline diesel

4.14.3 Unburnt Hydrocarbon emissions

Unburnt HC emissions are the emissions that do not take part in the combustion and exit from the exhaust in unburnt form. It represents the quality of burning of a fuel. It depends upon many parameters like fuel composition, combustion temperature, engine type, oxygen concentration, etc., however, the proper reason for its formation is still under study (Reşitoğlu et al., 2015).

Figure 4.57 shows the variation of unburnt HC emissions with BMEP. The HC emissions increase with the load for all the test fuel samples. It has been observed from the results that 100WB produces lower HC emissions compared to diesel and binary fuel blends.

It may be attributed to better burning of fuel due to its higher cetane number and inflame temperature.

However, for octanol blends, quenching in the cylinder takes place that increases HC emissions. Also, improper mixing of octanol blends also increases HC emissions for 10O90D to some extent. 10WB90D has the second highest value of unburnt HC emissions.

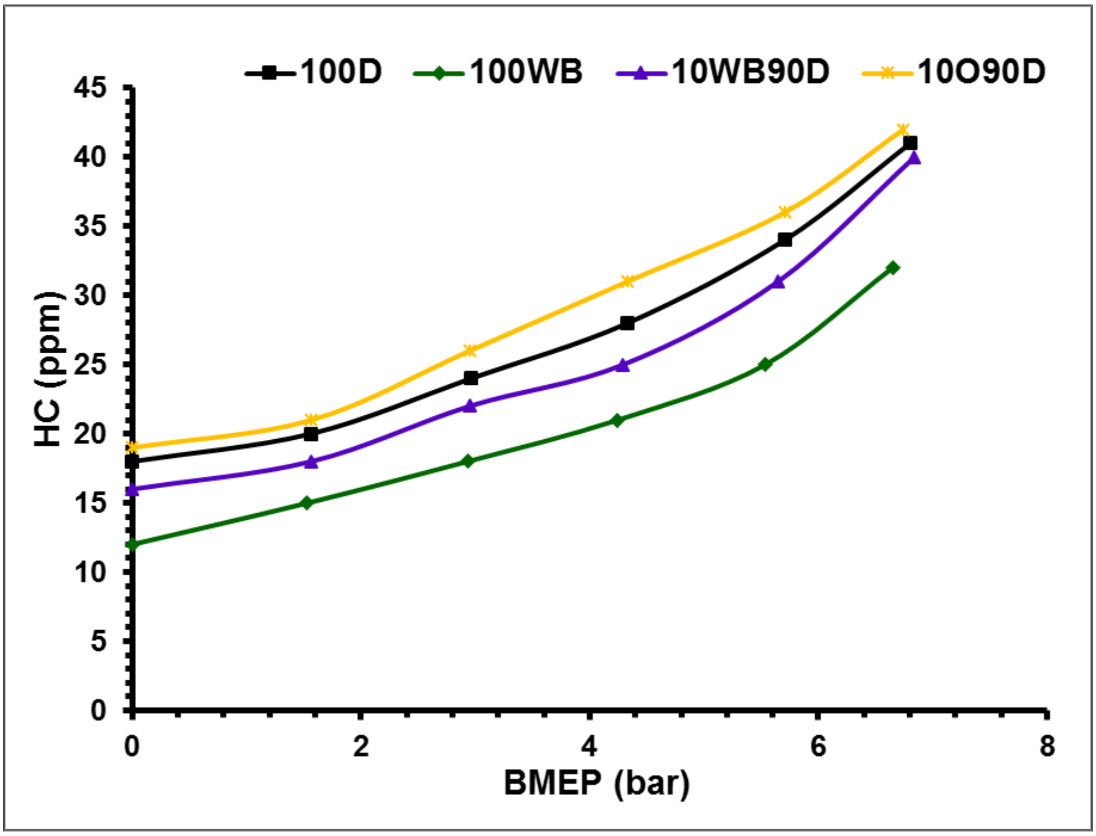


Figure 4.57. Comparison of unburnt HC emissions with BMEP of binary fuel blends

Similar to the reason explained for binary fuel blends, the same trend was observed for ternary fuel blends also. From Figure 4.58 it was observed that 20O10WB70D showed the highest values whereas 10O20WB70D exhibited the lowest unburnt HC emissions among all the three ternary fuel blends.

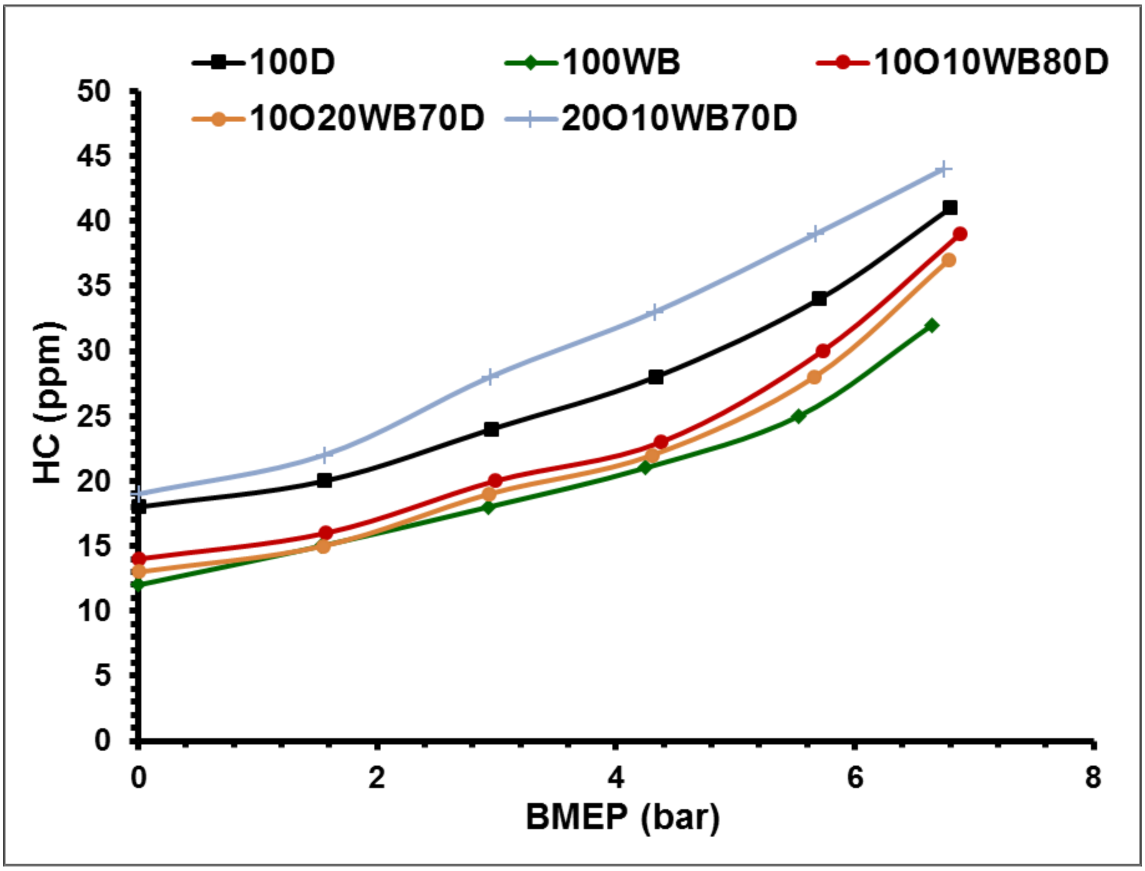


Figure 4.58. Comparison of unburnt HC emissions with BMEP of ternary fuel blends

Figure 4.59 shows the percentage change in unburnt hydrocarbon emissions compared to baseline diesel for all the test fuels**.** Unburnt HC emissions for the biodiesel blend emitted from the engine exhaust were lower compared to octanol blends because of the higher cetane number of biodiesel. This reduces the ignition delay and hence promotes full burning of fuel.

Due to lower auto-ignition temperature of octanol, the lean outer flame zone is formed with its blends reducing the flame. Higher HC emissions were seen with the use of octanol in the test fuel blends, however, biodiesel is negating this to some extent.

Lowest HC emissions were exhibited for 100WB. 10O20WB70D and 10O10WB80D emit the second lowest and third lowest value of HC emissions respectively.

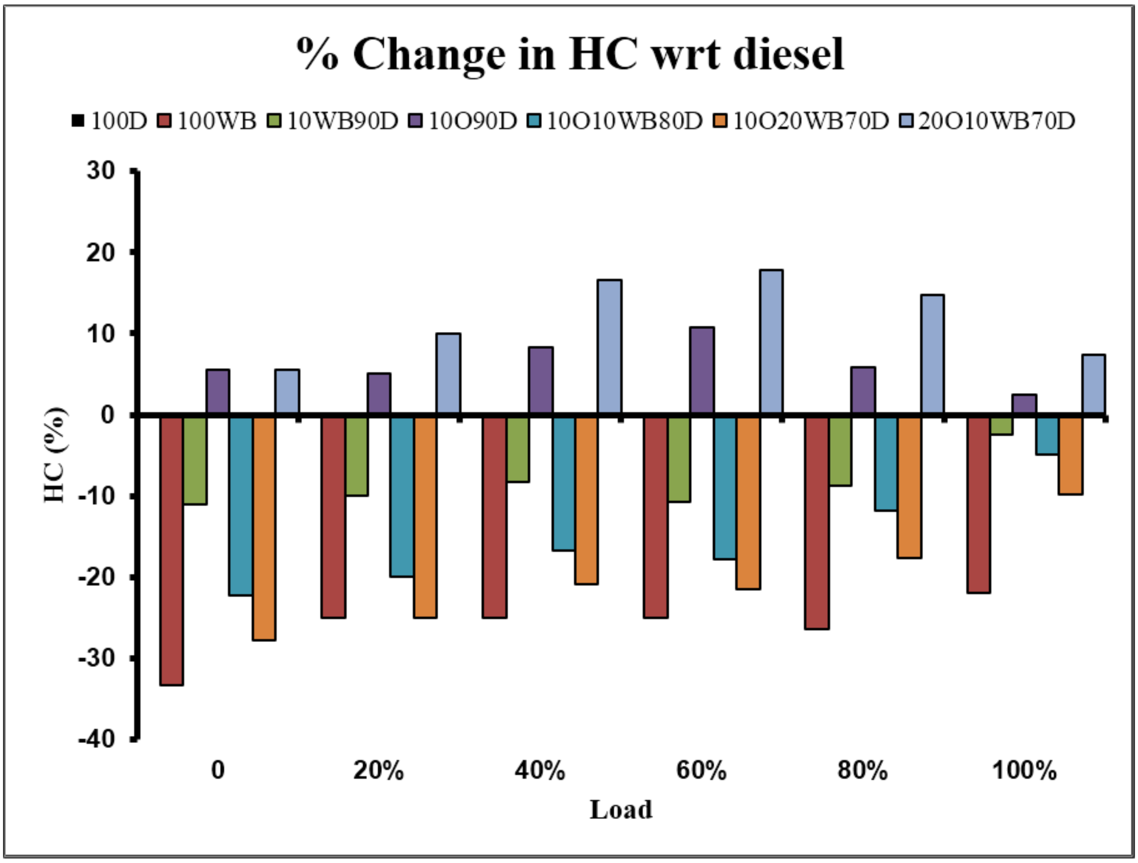


Figure 4.59. Variation of unburnt HC emissions of all test fuel blends with baseline diesel

4.14.4 Smoke Opacity

Smoke is liberated from CI engines mainly due to lack of oxygen, incomplete combustion and fuel rich zones. Therefore, promoting better burning and combustion shall lead to lower smoke emissions.

For determining the smoke from the engine, its smoke opacity is measured. It represents the percentage of blackness in the smoke i.e. the level upto which smoke blocks light. Since at higher loads more fuel is injected. This leads to an increase in smoke emissions with the load. A similar trend was seen for all fuels.

Figure 4.60, displays that by the addition of oxygen-rich fuels like octanol and biodiesel, smoke emissions were lower. Octanol has lower carbon content compared to biodiesel.

So, blend 10O90D emits the lowest smoke compared to blend 10WB90D. Also, due to the higher oxygen content in octanol compared to biodiesel, smoke emissions of 10O90D were the lowest compared to all three test fuels 100D, 100WB and 10WB90D.

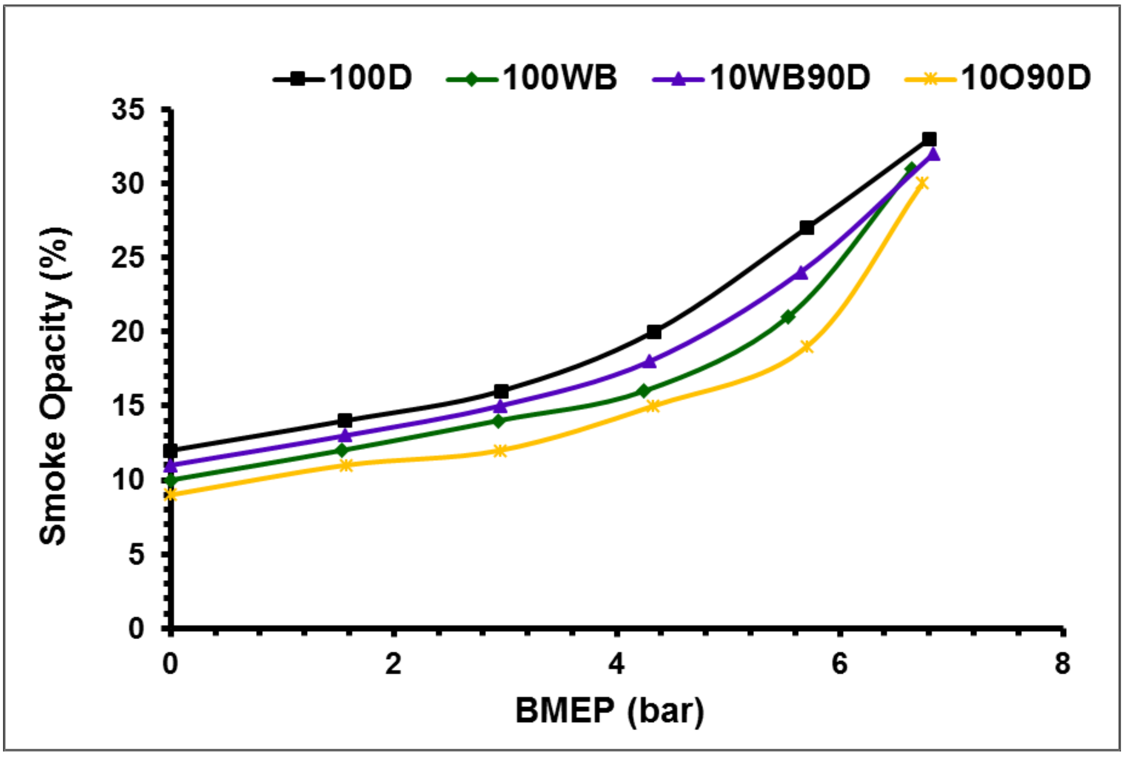


Figure 4.60. Comparison of smoke opacity with BMEP of binary fuel blends

Similar trends were seen in Figure 4.61 for smoke opacity of ternary fuel blends. More the octanol percentage in the fuel blends lower was the smoke emission.

20O10WB70D exhibited minimum smoke opacity due to higher octanol content. 100D exhibited the highest smoke opacity whereas 10O10WB80D displayed the second lowest.

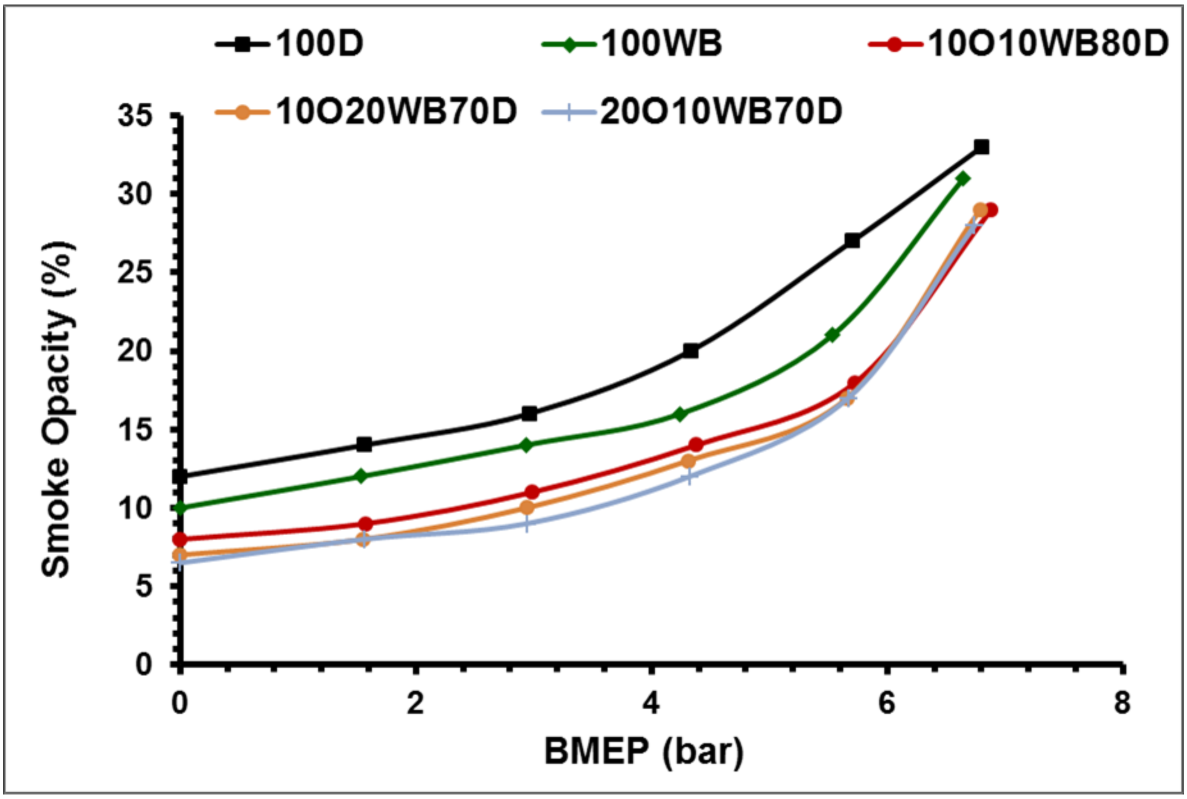


Figure 4.61. Comparison of smoke opacity with BMEP of ternary fuel blends,

From Figure 4.62, a detailed comparison of smoke opacity of test fuels with baseline diesel was seen. All the test fuels displayed lower smoke opacity compared to diesel. Lowest emissions were observed for 20O10WB70D and it was observed that the addition of octanol in the blends shows more decrease in smoke emissions compared to diesel. 100WB shows marginal drop in smoke emissions whereas for both binary fuel blends much lower smoke than diesel and slightly lower than biodiesel was observed.

All the ternary fuel blends showed a drastic reduction in smoke opacity compared to 100D, 100WB, 10O90D and 10WB90D. It was also observed that smoke opacity variation decreased with increase in load for all test fuels.

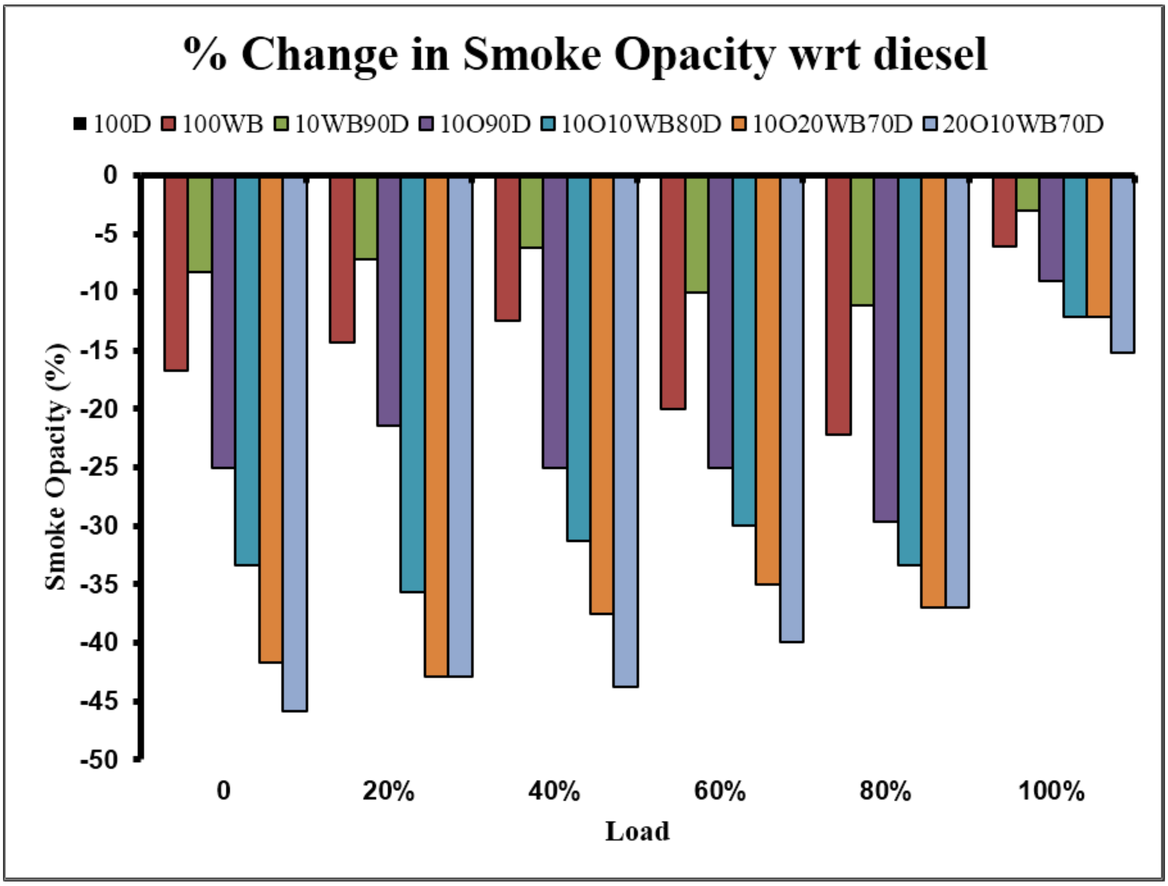


Figure 4.62. Variation of smoke opacity of all test fuel blends with baseline diesel

4.15 Combustion characteristics

Several processes take place simultaneously one after another in a diesel engine. These processes interact with one another and are very complex in nature.

(Heywood, 2011) distinguishes the diesel combustion process (compression ignition) as:

- The ignition delay
- Premixed combustion
- Diffusion combustion or mixing controlled combustion
- Late combustion

Even though diesel engine technology has evolved significantly over the years, this sequence remains globally valid for conventional diesel combustion.

In this section important combustion characteristics like HRR, in-cylinder pressure and mass fraction burnt has been studied at full load using the data obtained from the computer software. The results have been analysed for 100WB, 10O90D, 10WB90D, 10O10WB80D, 20O10WB70D and 10O20WB70D at full load. All the results were compared to 100D.

4.15.1 Heat release rate

HRR is a very significant parameter to learn about burning and combustion phenomenon in the engine. It provides heat energy released after combustion of fuel. HRR is plotted with the crank angle for test fuels shown in Figure 4.63. Due to the lower calorific value of 100WB, HRR was found to be lowest and it was highest for 10O10WB80D.

Since the blends have comparable viscosity and SMD values, good atomization of the fuel took place resulting in higher values of HRR. However, due to the low calorific value of 10O90D and 20O10WB70D blend, lower heat release was observed. Also owing to lower latent heat of vaporization and poor atomization of the 10O20WB70D and 10WB90D blend, improper burning was seen leading to lower values of HRR. The results have shown that the maximum peak HRR values for 10O90D, 10WB90D, 10O10WB80D, 10O20WB70D and 20O10WB70D were 59 J/°CA, 61.2 J/°CA, 62.9 J/°CA, 55.2 J/°CA, 53.1 J/°CA, respectively.

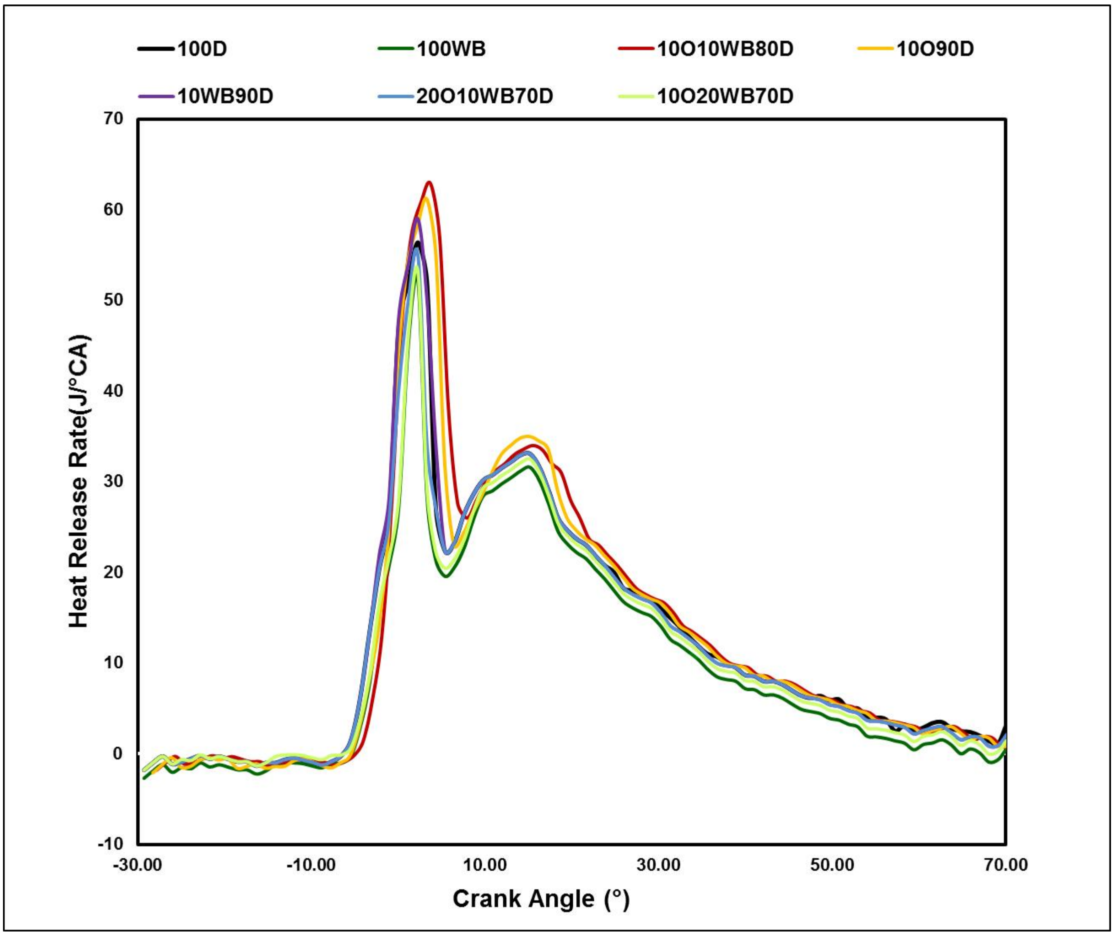


Figure 4.63. HRR variation with crank angle

4.15.2 In Cylinder pressure

In-cylinder pressure helps in learning fuel's combustion. Figure 4.64 shows in-cylinder pressure variation for different test fuels blends. This curve shows the starting of fuel injection in the combustion chamber. Due to the commencement of combustion the slope of curves changes suddenly. After reaching the TDC, the slope of the in-cylinder pressure curve increases and then it reverses showing the beginning of diffused combustion. This change in pressure lasts until the end of the expansion stroke. The same trend was followed by all the test fuels. Due to the better calorific value, cetane index and oxygen content of the blend 10O10WB80D, higher in-cylinder pressure was achieved, showing better combustion with the ternary fuel blend. 10O10WB80D exhibited higher in-cylinder pressure than diesel. Due to lower cetane index and absence of oxygen in diesel slightly inferior combustion was observed. However, higher density, SMD and viscosity of other ternary fuel blends leads to difficulty in fuel atomization. This inturn leads to inferior combustion when compared to 10O10WB80D and hence lower peak in-cylinder pressure. In-cylinder pressure results also confirm with the BTE results (shown in Figure 4.44).

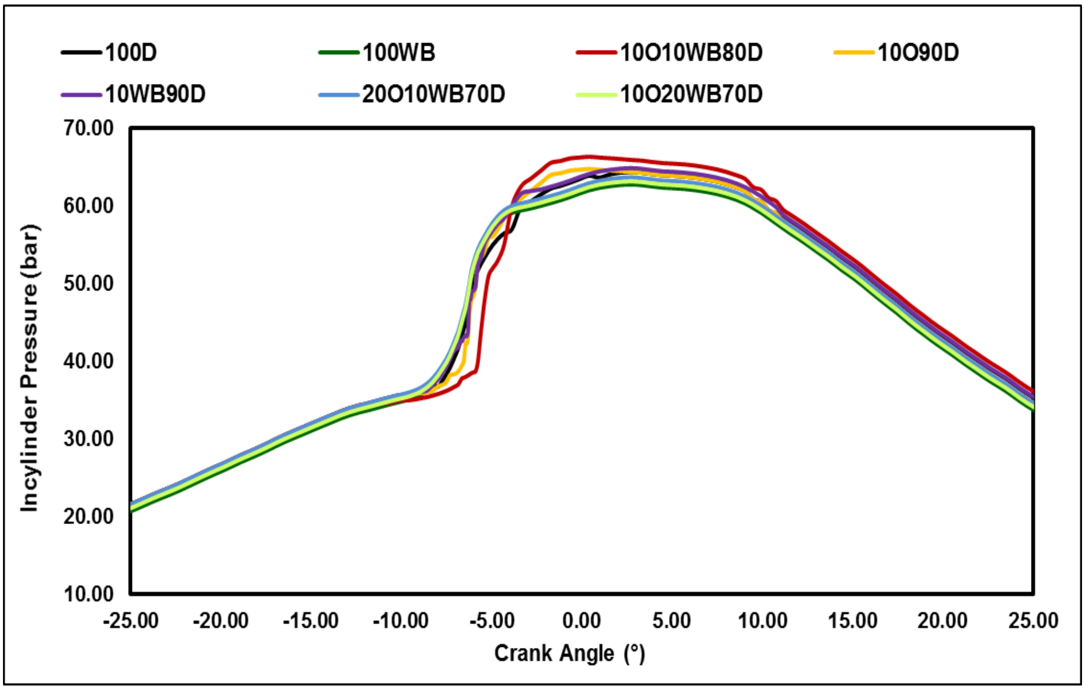


Figure 4.64. In-cylinder pressure variation with crank angle

4.15.3 Mass fraction burnt

Mass fraction burnt gives the amount or quantity of fuel burnt in the factor of 0 to 1. During the combustion phase, the volume of exhaust or flue gases increases whereas that of fuel charge decreases gradually. The mass fraction burned increases with the advancement of combustion to reach its maximum value of 1 at the end of combustion phase, which means that the entire mass of the fuel is burned and then stabilizes at this level.

From Figure 4.65 it was observed that mass fraction of all the test fuels reaches near 1 and gets stabilized there. Also, all the fuels show a very similar profile of mass fraction burnt. Moreover, 10O10WB80D ternary fuel blend exhibited higher mass fraction indicating more fuel volume fraction, smoother and better combustion confirming the performance characteristics also.

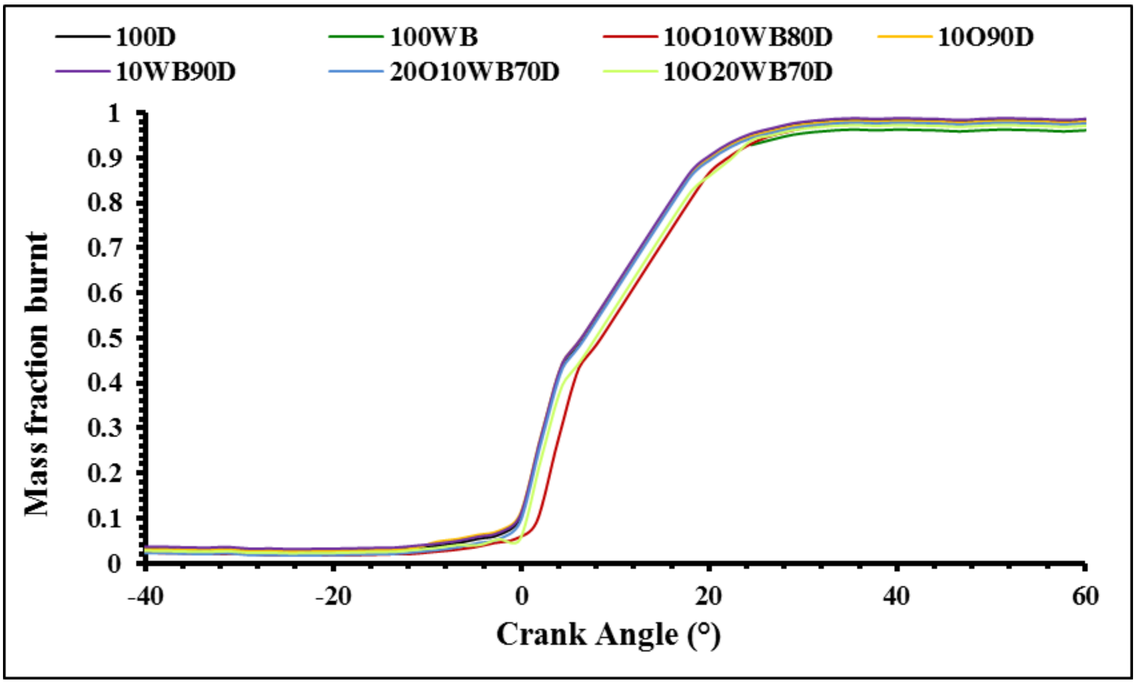


Figure 4.65. Mass fraction burnt variation with crank angle

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusions

The objective of the current research is to find cleaner alternative fuels that can successfully run in the current engine setups. It is found that using ternary fuel blends is a very vital approach to tackle the problem of environmental pollution and higher crude oil prices. Also, it will help in making a country self-reliant without looking to get fuel from external sources.

The main conclusion of physico-chemical properties of fuels, biodiesel production, optimization, determination of sauter mean diameter, ternary phase diagrams, oxidation stability, etc. are summarized as follows:

1. Biodiesel production is carried out experimentally from waste cooking oil and Taguchi approach is utilized for optimizing the production process. Using the Taguchi approach, the maximum yield of biodiesel is predicted to be 97.13% and using the same optimized parameters, the maximum yield obtained experimentally is 96.9%.
2. Many physico-chemical properties including flash point, cloud point, cold filter plugging point, density, pour point, kinematic viscosity, cetane index and calorific value are measured for the ternary fuel blends of diesel-biodiesel-octanol. Almost all the properties of the blends are comparable to diesel and are within ASTM standards. The properties of 10O10WB80D blend are nearly equal to diesel.

3. Sauter mean diameter of ternary fuel blends are comparable to diesel. Sauter mean diameter of 10O10WB80D is lowest for ternary fuel blends and shall give best fuel atomization.
4. Ternary fuel blends will work effectively at temperatures as low as 0°C. This increases their adaptability in colder regions.
5. Oxidation stability of ternary fuels is within ASTM standards.
6. Gas chromatography–mass spectrometry and Fourier transform infrared spectroscopy tests confirm the presence of biodiesel and biodiesel/alcohols respectively in the blends

Below are the conclusion drawn for the engine's combustion, emission and performance working with different fuels

1. Brake thermal efficiency of 10O10WB80D is higher than diesel due to both biodiesel and octanol present in the test fuel blends. Since the sauter mean diameter, calorific value and viscosity are comparable to diesel with added oxygen and slightly better cetane index, better combustion leads to a higher percentage increase in brake thermal efficiency.
2. Brake specific energy consumption varies inversely to brake thermal efficiency. Brake specific energy consumption of 100D is lower than 10O10WB80D whereas all other ternary fuel blends have higher brake specific energy consumption.
3. 20O10WB70D exhibited the lowest exhaust gas temperature owing to quenching or cooling of the cylinder walls that decreases the in-cylinder temperature to some extent. Greater the amount of octanol, lower is the exhaust gas temperature found.

4. All the ternary fuel blends exhibited lower carbon monoxide emissions owing to added oxygen in them. Among all the ternary fuel blends 10O10WB80D has the lowest viscosity and sauter mean diameter. This promotes better burning and due to added oxygen, carbon monoxide emissions get reduced.
5. Higher the quantity of biodiesel in the blend, more are the nitrogen oxide emissions liberated. Therefore having higher biodiesel content in the blend is not preferable as it leads to higher nitrogen oxide emissions. Among all ternary fuel blends, 20O10WB70D produces lowest nitrogen oxide emissions whereas 10O20WB70D produces the highest nitrogen oxide emissions. Nitrogen oxide emissions for 10O10WB80D are in between both the ternary fuel blends whereas it is lower than 100D.
6. 20O10WB70D shows the highest unburnt hydrocarbon emissions whereas 10O20WB70D exhibited the lowest unburnt hydrocarbon emissions among all the three ternary fuel blends. Unburnt hydrocarbon emissions for 10O10WB80D are in between both the ternary fuel blends
7. 100WB shows marginal drop in smoke emissions whereas, both binary fuel blends exhibit much lower emission than diesel and slightly lower than biodiesel. All the ternary fuel blends showed a drastic reduction in smoke opacity compared to 100D, 100WB, 10O90D and 10WB90D.
8. Due to the lower calorific value, the heat release rate was found lowest for 100WB and highest for 10O10WB80D. Since the blends have comparable viscosity and sauter mean diameter values, the atomization of the fuel was good which results in higher values of heat release rate.

9. Due to the better calorific value, cetane index and oxygen content of the blend 10O10WB80D, higher in-cylinder pressure was achieved, showing better combustion for the ternary fuel blend.
10. 10O10WB80D ternary fuel blend exhibited higher mass fraction burnt indicating higher fuel volume fraction, smoother and better combustion. These results also confirm the performance characteristics.

5.2 Future work

On the basis of the experimentation conducted, the knowledge gained from the current study, the following future recommendations are underlined:

1. The current study focused on using octanol. There is a need to check other higher alcohols in the fuel blends.
2. Waste cooking oil biodiesel is studied for use as one of the ternary fuel. Other unexplored fuels like tyre oil and plastic oil as a ternary fuel blend needs to be carried out for reducing waste and increasing self-dependence.
3. Advanced sustainability assessment tools (like life cycle analysis) should be studied for knowing the environmental sustainability of the fuels.
4. Vibration and sound analysis need to be carried out to get a detailed effect of fuels on engine operation.

REFERENCES

Abed KA, Gad MS, El Morsi AK, Sayed MM, Elyazeed SA. Effect of biodiesel fuels on diesel engine emissions. Egypt J Pet 2019. doi:10.1016/j.ejpe.2019.03.001.

Abed KA, El Morsi AK, Sayed MM, Shaib AA El, Gad MS. Effect of waste cooking-oil biodiesel on performance and exhaust emissions of a diesel engine. Egypt J Pet 2018;27:985–9. doi:10.1016/j.ejpe.2018.02.008.

Agarwal AK. Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. Prog Energy Combust Sci 2007;33:233–71. doi:10.1016/j.pecs.2006.08.003.

Agarwal AK, Khurana D, Dhar A. Improving oxidation stability of biodiesels derived from Karanja, Neem and Jatropha: step forward in the direction of commercialisation. J Clean Prod 2015;107:646–52. doi:10.1016/j.jclepro.2015.05.055.

Akhtar MK, Dandapani H, Thiel K, Jones PR. Microbial production of 1-octanol: A naturally excreted biofuel with diesel-like properties. Metab Eng Commun 2015;2:1–5. doi:10.1016/j.meteno.2014.11.001.

Al-Hamamre Z, Al-Salaymeh A. Physical properties of (jojoba oil+biodiesel), (jojoba oil+diesel) and (biodiesel+diesel) blends. Fuel 2014;123:175–88. doi:10.1016/j.fuel.2014.01.047.

Ali B, Yusup S, Quitain AT, Kamil RNM, Sumigawa Y, Ammar M, et al. Pretreatment and Bentonite-based Catalyzed Conversion of Palm-rubber Seed Oil Blends to Biodiesel. Procedia Eng 2016;148:501–7. doi:10.1016/j.proeng.2016.06.539.

Ali MH, Mashud M, Rubel MR, Ahmad RH. Biodiesel from Neem Oil as an Alternative

Fuel for Diesel Engine. Procedia Eng 2013;56:625–30. doi:10.1016/j.proeng.2013.03.169.

Ali OM, Mamat R, Rasul MG, Najafi G. Potential of Biodiesel as Fuel for Diesel Engine. Clean Energy Sustain. Dev., Elsevier; 2017, p. 557–90. doi:10.1016/B978-0-12-805423-9.00018-1.

Anand K, Sharma RP, Mehta PS. Experimental investigations on combustion, performance and emissions characteristics of neat karanji biodiesel and its methanol blend in a diesel engine. Biomass and Bioenergy 2011;35:533–41. doi:10.1016/j.biombioe.2010.10.005.

Le Anh T, Reksowardojo IK, Wattanavichien K. Utilisation of biofuels in diesel engines. Handb. Biofuels Prod., Elsevier; 2011, p. 611–46. doi:10.1533/9780857090492.4.611.

Annual Statistical Bulletin, OPEC. 2018:26.

Aravind A, Joy ML, Nair KP. Lubricant properties of biodegradable rubber tree seed (Hevea brasiliensis Muell. Arg) oil. Ind Crops Prod 2015;74:14–9. doi:10.1016/j.indcrop.2015.04.014.

Armendáriz J, Lapuerta M, Zavala F, García-Zambrano E, del Carmen Ojeda M. Evaluation of eleven genotypes of castor oil plant (Ricinus communis L.) for the production of biodiesel. Ind Crops Prod 2015;77:484–90. doi:10.1016/j.indcrop.2015.09.023.

Ashok B, Jeevanantham AK, Nanthagopal K, Saravanan B, Senthil Kumar M, Johny A, et al. An experimental analysis on the effect of n-pentanol- Calophyllum Inophyllum Biodiesel binary blends in CI engine characteristcis. Energy 2019a;173:290–305.

doi:10.1016/j.energy.2019.02.092.

Ashok B, Nanthagopal K, Anand V, Aravind KM, Jeevanantham AK, Balusamy S. Effects of n-octanol as a fuel blend with biodiesel on diesel engine characteristics. Fuel 2019b;235:363–73. doi:10.1016/j.fuel.2018.07.126.

Ashok B, Nanthagopal K, Sakthi Vignesh D. Calophyllum inophyllum methyl ester biodiesel blend as an alternate fuel for diesel engine applications. Alexandria Eng J 2018;57:1239–47. doi:10.1016/j.aej.2017.03.042.

Atabani AE, Mahlia TMI, Masjuki HH, Badruddin IA, Yussof HW, Chong WT, et al. A comparative evaluation of physical and chemical properties of biodiesel synthesized from edible and non-edible oils and study on the effect of biodiesel blending. Energy 2013;58:296–304. doi:10.1016/j.energy.2013.05.040.

Atmanli A. Comparative analyses of diesel–waste oil biodiesel and propanol, n-butanol or 1-pentanol blends in a diesel engine. Fuel 2016;176:209–15. doi:10.1016/j.fuel.2016.02.076.

Atmanli A, Yilmaz N. A comparative analysis of n-butanol/diesel and 1-pentanol/diesel blends in a compression ignition engine. Fuel 2018;234:161–9. doi:10.1016/j.fuel.2018.07.015.

Atmanlı A, İleri E, Yüksel B. Effects of higher ratios of n-butanol addition to diesel–vegetable oil blends on performance and exhaust emissions of a diesel engine. J Energy Inst 2015;88:209–20. doi:10.1016/j.joei.2014.09.008.

Babu D, Anand R. Effect of biodiesel-diesel-n-pentanol and biodiesel-diesel-n-hexanol blends on diesel engine emission and combustion characteristics. Energy 2017;133:761–76. doi:10.1016/j.energy.2017.05.103.

Balat M, Balat H. A critical review of bio-diesel as a vehicular fuel. Energy Convers Manag 2008;49:2727–41. doi:10.1016/j.enconman.2008.03.016.

Bello EI, Fatimehin Daniel. Optimization of Groundnut Oil Biodiesel Production and Characterization. Appl Sci Reports 2015;9. doi:10.15192/PSCP.ASR.2015.9.3.172180.

Beranek LA, Baran IJ, McVea G, Solly RK. The Formation of Gums in Aged Automotive Diesel Fuel - Their Effects Upon Engine Performance, 1987. doi:10.4271/871275.

Betiku E, Adepoju TF. Methanolysis optimization of sesame (Sesamum indicum) oil to biodiesel and fuel quality characterization. Int J Energy Environ Eng 2013;4:9. doi:10.1186/2251-6832-4-9.

Betiku E, Omilakin OR, Ajala SO, Okeleye AA, Taiwo AE, Solomon BO. Mathematical modeling and process parameters optimization studies by artificial neural network and response surface methodology: A case of non-edible neem (Azadirachta indica) seed oil biodiesel synthesis. Energy 2014;72:266–73. doi:10.1016/j.energy.2014.05.033.

Bhandarkar S. Vehicular Pollution , Their Effect on Human Heatlh and Mitigation Measures. Veh Eng 2013;1:33–40.

Bora BJ, Saha UK. Experimental evaluation of a rice bran biodiesel – biogas run dual fuel diesel engine at varying compression ratios. Renew Energy 2016;87:782–90. doi:10.1016/j.renene.2015.11.002.

BP Energy Outlook BEO. BP Energy Outlook 2019 edition 2019.

Canoira L, Alcántara R, Jesús García-Martínez M, Carrasco J. Biodiesel from Jojoba oil-wax: Transesterification with methanol and properties as a fuel. Biomass and Bioenergy 2006;30:76–81. doi:10.1016/j.biombioe.2005.07.002.

Cardoso AL, Augusti R, Da Silva MJ. Investigation on the Esterification of Fatty Acids Catalyzed by the H3PW12O40 heteropolyacid. J Am Oil Chem Soc 2008;85:555–60. doi:10.1007/s11746-008-1231-0.

Ceviz MA, Koncuk F, Küçük Ö, Gören AC, Yüksel F. Analysis of Combustion Stability and Its Relation to Performance Characteristics in a Compression Ignition Engine Fueled with Diesel-biodiesel Blends. Energy Sources, Part A Recover Util Environ Eff 2011;33:990–1003. doi:10.1080/15567030903261790.

Chang CT, Farrell P V. A Study on the Effects of Fuel Viscosity and Nozzle Geometry on High Injection Pressure Diesel Spray Characteristics, 1997. doi:10.4271/970353.

Chauhan BS, Kumar N, Cho HM. Performance and emission studies on an agriculture engine on neat Jatropha oil. J Mech Sci Technol 2010a;24:529–35. doi:10.1007/s12206-010-0101-5.

Chauhan BS, Kumar N, Cho HM, Lim HC. A study on the performance and emission of a diesel engine fueled with Karanja biodiesel and its blends. Energy 2013;56:1–7. doi:10.1016/j.energy.2013.03.083.

Chauhan BS, Kumar N, Du Jun Y, Lee KB. Performance and emission study of preheated Jatropha oil on medium capacity diesel engine. Energy 2010b;35:2484–92. doi:10.1016/j.energy.2010.02.043.

Chaurasiya PK, Singh SK, Dwivedi R, Choudri R V. Combustion and emission characteristics of diesel fuel blended with raw jatropha, soybean and waste cooking oils. Heliyon 2019;5:e01564. doi:10.1016/j.heliyon.2019.e01564.

Che F, Sarantopoulos I, Tsoutsos T, Gekas V. Exploring a promising feedstock for biodiesel production in Mediterranean countries: A study on free fatty acid esterification of olive pomace oil. Biomass and Bioenergy 2012;36:427–31. doi:10.1016/j.biombioe.2011.10.005.

Chen H, Xie B, Ma J, Chen Y. NOx emission of biodiesel compared to diesel: Higher or lower? Appl Therm Eng 2018;137:584–93. doi:10.1016/j.applthermaleng.2018.04.022.

Chen L, Li G, Ma X, Lim J, Sivathanu Y. A method for measuring planar Sauter mean diameter of multi-component fuel spray based on the combined statistical extinction tomography and particle imaging velocimetry. Fuel 2018;214:154–64. doi:10.1016/j.fuel.2017.10.110.

Chinnamma M, Bhasker S, Madhav H, Devasia RM, Shashidharan A, Pillai BC, et al. Production of coconut methyl ester (CME) and glycerol from coconut (Cocos nucifera) oil and the functional feasibility of CME as biofuel in diesel engine. Fuel 2015;140:4–9. doi:10.1016/j.fuel.2014.09.057.

Chisti Y. Biodiesel from microalgae. Biotechnol Adv 2007;25:294–306. doi:10.1016/j.biotechadv.2007.02.001.

Choi B, Jiang X, Kim YK, Jung G, Lee C, Choi I, et al. Effect of diesel fuel blend with n-butanol on the emission of a turbocharged common rail direct injection diesel engine. Appl Energy 2015;146:20–8. doi:10.1016/j.apenergy.2015.02.061.

Christiansen B, Shuwaikh F, editors. Theoretical and Applied Mathematics in International Business. IGI Global; 2019. doi:10.4018/978-1-5225-8458-2.

Corsini A, Marchegiani A, Rispoli F, Sciulli F, Venturini P. Vegetable Oils as Fuels in

Diesel Engine. Engine Performance and Emissions. Energy Procedia 2015;81:942–9. doi:10.1016/j.egypro.2015.12.151.

Czarnocka J, Matuszewska A, Odziemkowska M. Autoxidation of Fuels During Storage. Storage Stab. Fuels, InTech; 2015. doi:10.5772/59807.

Czerwinski J, Zimmerli Y, Mayer A, D'Urbano G, Zürcher D. Emission Reduction with Diesel Particle Filter with SCR Coating (SDPF). Emiss Control Sci Technol 2015;1:152–66. doi:10.1007/s40825-015-0018-7.

Dabelstein W, Reglitzky A, Schütze A, Reders K, Brunner A. Automotive Fuels. Ullmann's Encycl. Ind. Chem., Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA; 2016, p. 1–41. doi:10.1002/14356007.a16_719.pub3.

Demirbas. Biodiesel: A Realistic Fuel Alternative for Diesel Engines. London: Springer London; 2008. doi:10.1007/978-1-84628-995-8.

Desmond E. Winterbone and Ali Turan. Advanced Thermodynamics for Engineers. Elsevier; 2015. doi:10.1016/C2013-0-13437-X.

Devarajan Y, Munuswamy DB, Nagappan B, Pandian AK. Performance, combustion and emission analysis of mustard oil biodiesel and octanol blends in diesel engine. Heat Mass Transf 2018;54:1803–11. doi:10.1007/s00231-018-2274-x.

Devarajan Y, Munuswamy DB, Radhakrishnan S, Mahalingam A, Nagappan B. Experimental Testing and Evaluation of Neat Biodiesel and Heptanol Blends in Diesel Engine. J Test Eval 2019;47:20170307. doi:10.1520/JTE20170307.

Dhanasekaran R, Ganesan S, Rajesh Kumar B, Saravanan S. Utilization of waste cooking oil in a light-duty DI diesel engine for cleaner emissions using bio-derived propanol. Fuel 2019;235:832–7. doi:10.1016/j.fuel.2018.08.093.

Dixit S, Kanakraj S, Rehman A. Linseed oil as a potential resource for bio-diesel: A review. Renew Sustain Energy Rev 2012;16:4415–21. doi:10.1016/j.rser.2012.04.042.

Efe Ş, Ceviz MA, Temur H. Comparative engine characteristics of biodiesels from hazelnut, corn, soybean, canola and sunflower oils on DI diesel engine. Renew Energy 2018;119:142–51. doi:10.1016/j.renene.2017.12.011.

EL_Kassaby M, Nemit_allah MA. Studying the effect of compression ratio on an engine fueled with waste oil produced biodiesel/diesel fuel. Alexandria Eng J 2013;52:1–11. doi:10.1016/j.aej.2012.11.007.

EL-Seesy AI, Hassan H. Combustion Characteristics of a Diesel Engine Fueled by Biodiesel-Diesel-N-Butanol Blend and Titanium Oxide Additives. Energy Procedia 2019;162:48–56. doi:10.1016/j.egypro.2019.04.006.

Emiroğlu AO, Şen M. Combustion, performance and emission characteristics of various alcohol blends in a single cylinder diesel engine. Fuel 2018;212:34–40. doi:10.1016/j.fuel.2017.10.016.

Fadhil AB, Abdulahad WS. Transesterification of mustard (Brassica nigra) seed oil with ethanol: Purification of the crude ethyl ester with activated carbon produced from de-oiled cake. Energy Convers Manag 2014;77:495–503. doi:10.1016/j.enconman.2013.10.008.

Fang Q, Fang J, Zhuang J, Huang Z. Effects of ethanol–diesel–biodiesel blends on combustion and emissions in premixed low temperature combustion. Appl Therm Eng 2013;54:541–8. doi:10.1016/j.applthermaleng.2013.01.042.

Fernández JC, Arnal JM, Gómez J, Dorado MP. A comparison of performance of higher alcohols/diesel fuel blends in a diesel engine. Appl Energy 2012;95:267–75. doi:10.1016/j.apenergy.2012.02.051.

Ganapathy T, Gakkhar RP, Murugesan K. Influence of injection timing on performance, combustion and emission characteristics of Jatropha biodiesel engine. Appl Energy 2011;88:4376–86. doi:10.1016/j.apenergy.2011.05.016.

Gnanamoorthi V, Devaradjane G. Effect of compression ratio on the performance, combustion and emission of DI diesel engine fueled with ethanol – Diesel blend. J Energy Inst 2015;88:19–26. doi:10.1016/j.joei.2014.06.001.

Godiganur S, Suryanarayana Murthy CH, Reddy RP. 6BTA 5.9 G2-1 Cummins engine performance and emission tests using methyl ester mahua (Madhuca indica) oil/diesel blends. Renew Energy 2009;34:2172–7. doi:10.1016/j.renene.2008.12.035.

Hernández JJ, Rodríguez-Fernández J, Calle-Asensio A. When diesel NOx aftertreatment systems meet advanced biofuels. Results Eng 2019;2:100009. doi:10.1016/j.rineng.2019.100009.

Heywood J. Internal Combustion Engine Fundamental. 2011.

Hoekman SK, Robbins C. Review of the effects of biodiesel on NOx emissions. Fuel Process Technol 2012;96:237–49. doi:10.1016/j.fuproc.2011.12.036.

How HG, Masjuki HH, Kalam MA, Teoh YH, Chuah HG. Effect of Calophyllum Inophyllum biodiesel-diesel blends on combustion, performance, exhaust particulate matter and gaseous emissions in a multi-cylinder diesel engine. Fuel 2018;227:154–64. doi:10.1016/j.fuel.2018.04.075.

Huang H, Teng W, Liu Q, Zhou C, Wang Q, Wang X. Combustion performance and emission characteristics of a diesel engine under low-temperature combustion of pine oil–diesel blends. Energy Convers Manag 2016;128:317–26. doi:10.1016/j.enconman.2016.09.090.

Huang W-C, Hou S-S, Lin T-H. Combustion characteristics of a 300 kW th oil-fired furnace using castor oil/diesel blended fuels. Fuel 2017;208:71–81. doi:10.1016/j.fuel.2017.07.007.

IEA. Domestic Crude Oil First Purchase Prices by Area 2019. http://api.eia.gov/series/?api_key=YOUR_API_KEY_HERE&series_id=PET.F000000__3.M.

Ileri E, Atmanli A, Yilmaz N. Comparative analyses of n-butanol–rapeseed oil–diesel blend with biodiesel, diesel and biodiesel–diesel fuels in a turbocharged direct injection diesel engine. J Energy Inst 2016;89:586–93. doi:10.1016/j.joei.2015.06.004.

Imdadul HK, Masjuki HH, Kalam MA, Zulkifli NWM, Alabdulkarem A, Kamruzzaman M, et al. A comparative study of C4and C5alcohol treated diesel-biodiesel blends in terms of diesel engine performance and exhaust emission. Fuel 2016a;179:281–8. doi:10.1016/j.fuel.2016.04.003.

Imdadul HK, Masjuki HH, Kalam MA, Zulkifli NWM, Alabdulkarem A, Rashed MM, et al. Higher alcohol-biodiesel-diesel blends: An approach for improving the performance, emission, and combustion of a light-duty diesel engine. Energy Convers Manag 2016b;111:174–85. doi:10.1016/j.enconman.2015.12.066.

Indian PNG Statistics. 2018.

Jaichandar S, Annamalai K. Emission and Combustion Characteristics of Pongamia Oil

Methyl Ester and Its Diesel Blends in a CI Engine. Energy Sources, Part A Recover Util Environ Eff 2015;37:1473–8. doi:10.1080/15567036.2011.631090.

Joy N, Devarajan Y, Nagappan B, Anderson A. Exhaust emission study on neat biodiesel and alcohol blends fueled diesel engine. Energy Sources, Part A Recover Util Environ Eff 2018;40:115–9. doi:10.1080/15567036.2017.1405119.

Julis J, Leitner W. Synthesis of 1-Octanol and 1,1-Dioctyl Ether from Biomass-Derived Platform Chemicals. Angew Chemie Int Ed 2012;51:8615–9. doi:10.1002/anie.201203669.

Kadiyala S, Harris J, Headey D, Yosef S, Gillespie S. Agriculture and nutrition in India: mapping evidence to pathways. Ann N Y Acad Sci 2014;1331:43–56. doi:10.1111/nyas.12477.

Karabas H. Application of the Taguchi Method for the Optimization of Effective Parameters on the Safflower Seed Oil Methyl Ester Production. Int J Green Energy 2014;11:1002–12. doi:10.1080/15435075.2013.829475.

Karabas H. Biodiesel production from crude acorn (Quercus frainetto L.) kernel oil: An optimisation process using the Taguchi method. Renew Energy 2013;53:384–8. doi:10.1016/j.renene.2012.12.002.

Karavalakis G, Hilari D, Givalou L, Karonis D, Stournas S. Storage stability and ageing effect of biodiesel blends treated with different antioxidants. Energy 2011;36:369–74. doi:10.1016/j.energy.2010.10.029.

Karavalakis G, Stournas S, Karonis D. Evaluation of the oxidation stability of diesel/biodiesel blends. Fuel 2010;89:2483–9. doi:10.1016/j.fuel.2010.03.041.

Karmee SK, Chadha A. Preparation of biodiesel from crude oil of Pongamia pinnata. Bioresour Technol 2005;96:1425–9. doi:10.1016/j.biortech.2004.12.011.

Kaya C, Hamamci C, Baysal A, Akba O, Erdogan S, Saydut A. Methyl ester of peanut (Arachis hypogea L.) seed oil as a potential feedstock for biodiesel production. Renew Energy 2009;34:1257–60. doi:10.1016/j.renene.2008.10.002.

Killol A, Reddy N, Paruvada S, Murugan S. Experimental studies of a diesel engine run on biodiesel n-butanol blends. Renew Energy 2019;135:687–700. doi:10.1016/j.renene.2018.12.011.

Kim S-T, Yim B-B, Park Y-T. Application of Taguchi Experimental Design for the Optimization of Effective Parameters on the Rapeseed Methyl Ester Production. Environ Eng Res 2010;15:129–34. doi:10.4491/eer.2010.15.3.129.

Kong W, Kang Q, Feng W, Tan T. Improving the solvent-extraction process of rice bran oil. Chem Eng Res Des 2015;104:1–10. doi:10.1016/j.cherd.2015.06.001.

Kremer F, Blank LM, Jones PR, Akhtar MK. A Comparison of the Microbial Production and Combustion Characteristics of Three Alcohol Biofuels: Ethanol, 1-Butanol, and 1-Octanol. Front Bioeng Biotechnol 2015;3. doi:10.3389/fbioe.2015.00112.

Kumar JTS, Sharma TK, Murthy KM, Rao GAP. Effect of reformed EGR on the performance and emissions of a diesel engine: A numerical study. Alexandria Eng J 2018;57:517–25. doi:10.1016/j.aej.2017.01.008.

Kumar N, Mohapatra SK, Ragit SS, Kundu K, Karmakar R. Optimization of safflower oil transesterification using the Taguchi approach. Pet Sci 2017;14:798–805. doi:10.1007/s12182-017-0183-0.

Kumar P, Sharma MP, Dwivedi G. Impact of ternary blends of biodiesel on diesel engine performance. Egypt J Pet 2016;25:255–61. doi:10.1016/j.ejpe.2015.06.010.

Kumar R, Tiwari P, Garg S. Alkali transesterification of linseed oil for biodiesel production. Fuel 2013;104:553–60. doi:10.1016/j.fuel.2012.05.002.

Kumar S, Cho JH, Park J, Moon I. Advances in diesel–alcohol blends and their effects on the performance and emissions of diesel engines. Renew Sustain Energy Rev 2013;22:46–72. doi:10.1016/j.rser.2013.01.017.

Kumar Tiwari A, Kumar A, Raheman H. Biodiesel production from jatropha oil (Jatropha curcas) with high free fatty acids: An optimized process. Biomass and Bioenergy 2007;31:569–75. doi:10.1016/j.biombioe.2007.03.003.

Lama-Muñoz A, Álvarez-Mateos P, Rodríguez-Gutiérrez G, Durán-Barrantes MM, Fernández-Bolaños J. Biodiesel production from olive–pomace oil of steam-treated alperujo. Biomass and Bioenergy 2014;67:443–50. doi:10.1016/j.biombioe.2014.05.023.

Lapuerta M, García-Contreras R, Campos-Fernández J, Dorado MP. Stability, Lubricity, Viscosity, and Cold-Flow Properties of Alcohol−Diesel Blends. Energy & Fuels 2010;24:4497–502. doi:10.1021/ef100498u.

Leevijit T, Prateepchaikul G, Maliwan K, Mompiboon P, Eiadtrong S. Comparative properties and utilization of un-preheated degummed/esterified mixed crude palm oil-diesel blends in an agricultural engine. Renew Energy 2017;101:82–9. doi:10.1016/j.renene.2016.08.047.

Li L, Wang J, Wang Z, Xiao J. Combustion and emission characteristics of diesel engine fueled with diesel/biodiesel/pentanol fuel blends. Fuel 2015;156:211–8.

doi:10.1016/j.fuel.2015.04.048.

Liu H, Hu B, Jin C. Effects of different alcohols additives on solubility of hydrous ethanol/diesel fuel blends. Fuel 2016;184:440–8. doi:10.1016/j.fuel.2016.07.037.

López I, Quintana CE, Ruiz JJ, Cruz-Peragón F, Dorado MP. Effect of the use of olive–pomace oil biodiesel/diesel fuel blends in a compression ignition engine: Preliminary exergy analysis. Energy Convers Manag 2014;85:227–33. doi:10.1016/j.enconman.2014.05.084.

Ma F, Hanna MA. Biodiesel production: a review1Journal Series #12109, Agricultural Research Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln.1. Bioresour Technol 1999;70:1–15. doi:10.1016/S0960-8524(99)00025-5.

Ma F, Zhao C, Zhang F, Zhao Z, Zhang Z, Xie Z, et al. An Experimental Investigation on the Combustion and Heat Release Characteristics of an Opposed-Piston Folded-Cranktrain Diesel Engine. Energies 2015;8:6365–81. doi:10.3390/en8076365.

Ma X, Zhang F, Han K, Zhu Z, Liu Y. Effects of Intake Manifold Water Injection on Combustion and Emissions of Diesel Engine. Energy Procedia 2014;61:777–81. doi:10.1016/j.egypro.2014.11.963.

Mahalingam A, Devarajan Y, Radhakrishnan S, Vellaiyan S, Nagappan B. Emissions analysis on mahua oil biodiesel and higher alcohol blends in diesel engine. Alexandria Eng J 2018;57:2627–31. doi:10.1016/j.aej.2017.07.009.

Mihaela P, Josef R, Monica N, Rudolf Z. Perspectives of safflower oil as biodiesel source for South Eastern Europe (comparative study: Safflower, soybean and rapeseed). Fuel 2013;111:114–9. doi:10.1016/j.fuel.2013.04.012.

Millo F, Debnath BK, Vlachos T, Ciaravino C, Postrioti L, Buitoni G. Effects of different biofuels blends on performance and emissions of an automotive diesel engine. Fuel 2015;159:614–27. doi:10.1016/j.fuel.2015.06.096.

Ming C, Rizwanul Fattah IM, Chan QN, Pham PX, Medwell PR, Kook S, et al. Combustion characterization of waste cooking oil and canola oil based biodiesels under simulated engine conditions. Fuel 2018;224:167–77. doi:10.1016/j.fuel.2018.03.053.

MohamedMusthafa M, Sivapirakasam SP, Udayakumar M. Comparative studies on fly ash coated low heat rejection diesel engine on performance and emission characteristics fueled by rice bran and pongamia methyl ester and their blend with diesel. Energy 2011;36:2343–51. doi:10.1016/j.energy.2010.12.047.

Moser BR, Vaughn SF. Evaluation of alkyl esters from Camelina sativa oil as biodiesel and as blend components in ultra low-sulfur diesel fuel☆. Bioresour Technol 2010;101:646–53. doi:10.1016/j.biortech.2009.08.054.

Muthaiyan P, Gomathinayagam S. Combustion Characteristics of a Diesel Engine Using Propanol Diesel Fuel Blends. J Inst Eng Ser C 2016;97:323–9. doi:10.1007/s40032-016-0229-x.

Nanthagopal K, Ashok B, Saravanan B, Ramesh Pathy M, Sahil G, Ramesh A, et al. Study on decanol and Calophyllum Inophyllum biodiesel as ternary blends in CI engine. Fuel 2019;239:862–73. doi:10.1016/j.fuel.2018.11.037.

No S-Y. Inedible vegetable oils and their derivatives for alternative diesel fuels in CI engines: A review. Renew Sustain Energy Rev 2011;15:131–49. doi:10.1016/j.rser.2010.08.012.

Nolan DP. Physical Properties of Hydrocarbons and Petrochemicals. Handb. Fire Explos. Prot. Eng. Princ., Elsevier; 2014, p. 55–77. doi:10.1016/B978-0-323-31301-8.00004-0.

Nour M, Attia AMA, Nada SA. Combustion, performance and emission analysis of diesel engine fuelled by higher alcohols (butanol, octanol and heptanol)/diesel blends. Energy Convers Manag 2019a;185:313–29. doi:10.1016/j.enconman.2019.01.105.

Nour M, Attia AMA, Nada SA. Improvement of CI engine combustion and performance running on ternary blends of higher alcohol (Pentanol and Octanol)/hydrous ethanol/diesel. Fuel 2019b;251:10–22. doi:10.1016/j.fuel.2019.04.026.

Al Omari SAB, Hamdan MO, Selim MY, Elnajjar E. Combustion of jojoba-oil/diesel blends in a small scale furnace. Renew Energy 2019;131:678–88. doi:10.1016/j.renene.2018.07.009.

Onoji SE, Iyuke SE, Igbafe AI, Nkazi DB. Rubber seed oil: A potential renewable source of biodiesel for sustainable development in sub-Saharan Africa. Energy Convers Manag 2016;110:125–34. doi:10.1016/j.enconman.2015.12.002.

Özçelik AE, Aydoğan H, Acaroğlu M. Determining the performance, emission and combustion properties of camelina biodiesel blends. Energy Convers Manag 2015;96:47–57. doi:10.1016/j.enconman.2015.02.024.

Öztürk E. Performance, emissions, combustion and injection characteristics of a diesel engine fuelled with canola oil–hazelnut soapstock biodiesel mixture. Fuel Process Technol 2015;129:183–91. doi:10.1016/j.fuproc.2014.09.016.

Pali HS, Kumar N. Combustion, performance and emissions of Shorea robusta methyl ester blends in a diesel engine. Biofuels 2016;7:447–56. doi:10.1080/17597269.2016.1153363.

Pandian AK, Munuswamy DB, Radhakrishanan S, Devarajan Y, Ramakrishnan RBB, Nagappan B. Emission and performance analysis of a diesel engine burning cashew nut shell oil bio diesel mixed with hexanol. Pet Sci 2018;15:176–84. doi:10.1007/s12182-017-0208-8.

Panigrahi N, Mohanty MK, Acharya SK, Mishra SR, Mohanty RC. Experimental Investigation of Karanja Oil as a Fuel for Diesel Engine-Using Shell and Tube Heat Exchanger 2014;8:89–96.

Panwar NL, Shrirame HY, Rathore NS, Jindal S, Kurchania AK. Performance evaluation of a diesel engine fueled with methyl ester of castor seed oil. Appl Therm Eng 2010;30:245–9. doi:10.1016/j.applthermaleng.2009.07.007.

Patil V V, Patil RS. Effects of partial addition of n-butanol in rubber seed oil methyl ester powered diesel engine. Proc Inst Mech Eng Part A J Power Energy 2017;231:607–17. doi:10.1177/0957650917708695.

Paul A, Panua R, Debroy D. An experimental study of combustion, performance, exergy and emission characteristics of a CI engine fueled by Diesel-ethanol-biodiesel blends. Energy 2017;141:839–52. doi:10.1016/j.energy.2017.09.137.

Pinzi S, Garcia IL, Lopez-Gimenez FJ, Luque de Castro MD, Dorado G, Dorado MP. The Ideal Vegetable Oil-based Biodiesel Composition: A Review of Social, Economical and Technical Implications. Energy & Fuels 2009;23:2325–41. doi:10.1021/ef801098a.

De Poures MV, A.P. S, Rana D, Babu RK, Subramani S, Sethuramasamyraja B, et al.

Using renewable n-octanol in a non-road diesel engine with some modifications. Energy Sources, Part A Recover Util Environ Eff 2019;41:1194–208. doi:10.1080/15567036.2018.1544997.

De Poures MV, Sathiyagnanam AP, Rana D, Rajesh Kumar B, Saravanan S. 1-Hexanol as a sustainable biofuel in DI diesel engines and its effect on combustion and emissions under the influence of injection timing and exhaust gas recirculation (EGR). Appl Therm Eng 2017;113:1505–13. doi:10.1016/j.applthermaleng.2016.11.164.

Prakash T, Geo VE, Martin LJ, Nagalingam B. Effect of ternary blends of bio-ethanol, diesel and castor oil on performance, emission and combustion in a CI engine. Renew Energy 2018;122:301–9. doi:10.1016/j.renene.2018.01.070.

Raheman H, Phadatare AG. Diesel engine emissions and performance from blends of karanja methyl ester and diesel. Biomass and Bioenergy 2004;27:393–7. doi:10.1016/j.biombioe.2004.03.002.

Rajesh Kumar B, Saravanan S. Effects of iso-butanol/diesel and n-pentanol/diesel blends on performance and emissions of a DI diesel engine under premixed LTC (low temperature combustion) mode. Fuel 2016;170:49–59. doi:10.1016/j.fuel.2015.12.029.

Rajesh Kumar B, Saravanan S, Rana D, Anish V, Nagendran A. Effect of a sustainable biofuel – n-octanol – on the combustion, performance and emissions of a DI diesel engine under naturally aspirated and exhaust gas recirculation (EGR) modes. Energy Convers Manag 2016a;118:275–86. doi:10.1016/j.enconman.2016.04.001.

Rajesh Kumar B, Saravanan S, Rana D, Nagendran A. A comparative analysis on combustion and emissions of some next generation higher-alcohol/diesel blends in a direct-injection diesel engine. Energy Convers Manag 2016b;119:246–56.

doi:10.1016/j.enconman.2016.04.053.

Rakopoulos DC. Combustion and emissions of cottonseed oil and its bio-diesel in blends with either n-butanol or diethyl ether in HSDI diesel engine. Fuel 2013;105:603–13. doi:10.1016/j.fuel.2012.08.023.

Ramadhas A, Jayaraj S, Muraleedharan C. Biodiesel production from high FFA rubber seed oil. Fuel 2005;84:335–40. doi:10.1016/j.fuel.2004.09.016.

Raman LA, Deepanraj B, Rajakumar S, Sivasubramanian V. Experimental investigation on performance, combustion and emission analysis of a direct injection diesel engine fuelled with rapeseed oil biodiesel. Fuel 2019;246:69–74. doi:10.1016/j.fuel.2019.02.106.

Ramírez AI, Aggarwal SK, Som S, Rutter TP, Longman DE. Effects of blending a heavy alcohol (C 20 H 40 O with diesel in a heavy-duty compression-ignition engine. Fuel 2014;136:89–102. doi:10.1016/j.fuel.2014.06.039.

Reitz RD, Duraisamy G. Review of high efficiency and clean reactivity controlled compression ignition (RCCI) combustion in internal combustion engines. Prog Energy Combust Sci 2015;46:12–71. doi:10.1016/j.pecs.2014.05.003.

Reşitoğlu İA, Altinişik K, Keskin A. The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems. Clean Technol Environ Policy 2015;17:15–27. doi:10.1007/s10098-014-0793-9.

Reumuth G, Alharbi Z, Houschyar KS, Kim B-S, Siemers F, Fuchs PC, et al. Carbon monoxide intoxication: What we know. Burns 2019;45:526–30. doi:10.1016/j.burns.2018.07.006.

Rosa HA, Wazilewski WT, Secco D, Chaves LI, Veloso G, de Souza SNM, et al. Biodiesel produced from crambe oil in Brazil—A study of performance and emissions in a diesel cycle engine generator. Renew Sustain Energy Rev 2014;38:651–5. doi:10.1016/j.rser.2014.07.013.

Ryan TW, Bagby MO. Identification of Chemical Changes Occurring During the Transient Injection of Selected Vegetable Oils, 1993. doi:10.4271/930933.

Sahoo PK, Das LM, Babu MKG, Arora P, Singh VP, Kumar NR, et al. Comparative evaluation of performance and emission characteristics of jatropha, karanja and polanga based biodiesel as fuel in a tractor engine. Fuel 2009;88:1698–707. doi:10.1016/j.fuel.2009.02.015.

Saleh HE. Experimental study on diesel engine nitrogen oxide reduction running with jojoba methyl ester by exhaust gas recirculation. Fuel 2009;88:1357–64. doi:10.1016/j.fuel.2009.01.023.

Sánchez N, Sánchez R, Encinar JM, González JF, Martínez G. Complete analysis of castor oil methanolysis to obtain biodiesel. Fuel 2015;147:95–9. doi:10.1016/j.fuel.2015.01.062.

Sanjid A, Masjuki HH, Kalam MA, Abedin MJ, Rahman SMA. Experimental Investigation of Mustard Biodiesel Blend Properties, Performance, Exhaust Emission and Noise in an Unmodified Diesel Engine. APCBEE Procedia 2014;10:149–53. doi:10.1016/j.apcbee.2014.10.033.

Sanli H. An experimental investigation on the usage of waste frying oil-diesel fuel blends with low viscosity in a Common Rail DI-diesel engine. Fuel 2018;222:434–43. doi:10.1016/j.fuel.2018.02.194.

Saravanakumar A, Avinash A, Saravanakumar R. Optimization of biodiesel production from Pungamia oil by Taguchi's technique. Energy Sources, Part A Recover Util Environ Eff 2016;38:2524–9. doi:10.1080/15567036.2015.1098746.

Saravanan S, Gupta S, Chidambaram R, Jain A, Vora K. Assessment on Performance, Combustion and Emission Characteristics of Diesel Engine Fuelled with Blends of Diesel, Algae Biodiesel and Heptanol, 2019. doi:10.4271/2019-26-0091.

Saravanan S, Nagarajan G, Sampath S. Investigation on combustion characteristics of crude rice bran oil methyl ester blend as a heavy duty automotive engine fuel. Int J Oil, Gas Coal Technol 2011;4:282. doi:10.1504/IJOGCT.2011.040840.

Saravanan S, Pitchandi K, Suresh G. An experimental study on premixed charge compression ignition-direct ignition engine fueled with ethanol and gasohol. Alexandria Eng J 2015;54:897–904. doi:10.1016/j.aej.2015.07.010.

Sarve A, Sonawane SS, Varma MN. Ultrasound assisted biodiesel production from sesame (Sesamum indicum L.) oil using barium hydroxide as a heterogeneous catalyst: Comparative assessment of prediction abilities between response surface methodology (RSM) and artificial neural network (ANN. Ultrason Sonochem 2015;26:218–28. doi:10.1016/j.ultsonch.2015.01.013.

Sarve AN, Varma MN, Sonawane SS. Ultrasound assisted two-stage biodiesel synthesis from non-edible Schleichera triguga oil using heterogeneous catalyst: Kinetics and thermodynamic analysis. Ultrason Sonochem 2016;29:288–98. doi:10.1016/j.ultsonch.2015.09.016.

Sathish Kumar R, Sureshkumar K, Velraj R. Combustion, performance and emission characteristics of an unmodified diesel engine fueled with Manilkara Zapota Methyl

Ester and its diesel blends. Appl Therm Eng 2018;139:196–202. doi:10.1016/j.applthermaleng.2018.04.107.

Sathish Kumar R, Sureshkumar K, Velraj R. Optimization of biodiesel production from Manilkara zapota (L.) seed oil using Taguchi method. Fuel 2015;140:90–6. doi:10.1016/j.fuel.2014.09.103.

Selvaraj K, Thangavel M. The experimental study on the performance, combustion and emission characteristics of a diesel engine using diesel – biodiesel – diethyl ether blends. Energy Sources, Part A Recover Util Environ Eff 2019:1–15. doi:10.1080/15567036.2019.1623950.

Senthur Prabu S, Asokan MA, Prathiba S, Ahmed S, Puthean G. Effect of additives on performance, combustion and emission behavior of preheated palm oil/diesel blends in DI diesel engine. Renew Energy 2018;122:196–205. doi:10.1016/j.renene.2018.01.068.

Shahir SA, Masjuki HH, Kalam MA, Imran A, Ashraful AM. Performance and emission assessment of diesel–biodiesel–ethanol/bioethanol blend as a fuel in diesel engines: A review. Renew Sustain Energy Rev 2015;48:62–78. doi:10.1016/j.rser.2015.03.049.

Sharma YC, Singh B. An ideal feedstock, kusum (Schleichera triguga) for preparation of biodiesel: Optimization of parameters. Fuel 2010;89:1470–4. doi:10.1016/j.fuel.2009.10.013.

Sheet EAE. Effect of preheating waste cooking oil on biodiesel production and properties. Energy Sources, Part A Recover Util Environ Eff 2018;40:207–13. doi:10.1080/15567036.2017.1410594.

Silitonga AS, Masjuki HH, Ong HC, Sebayang AH, Dharma S, Kusumo F, et al. Evaluation of the engine performance and exhaust emissions of biodiesel-bioethanol-diesel blends using kernel-based extreme learning machine. Energy 2018;159:1075–87. doi:10.1016/j.energy.2018.06.202.

Sindhu R, Amba Prasad Rao G, Madhu Murthy K. Effective reduction of NOx emissions from diesel engine using split injections. Alexandria Eng J 2018;57:1379–92. doi:10.1016/j.aej.2017.06.009.

Singh G, Mohapatra SK, S. Ragit S, Kundu K. Optimization of biodiesel production from grape seed oil using Taguchi's orthogonal array. Energy Sources, Part A Recover Util Environ Eff 2018;40:2144–53. doi:10.1080/15567036.2018.1495778.

Song C-L, Bin F, Tao Z-M, Li F-C, Huang Q-F. Simultaneous removals of NOx, HC and PM from diesel exhaust emissions by dielectric barrier discharges. J Hazard Mater 2009;166:523–30. doi:10.1016/j.jhazmat.2008.11.068.

Song C, Zhao Z, Lv G, Song J, Liu L, Zhao R. Carbonyl compound emissions from a heavy-duty diesel engine fueled with diesel fuel and ethanol–diesel blend. Chemosphere 2010;79:1033–9. doi:10.1016/j.chemosphere.2010.03.061.

Stauffer E, Dolan JA, Newman R. Chemistry and Physics of Fire and Liquid Fuels. Fire Debris Anal., Elsevier; 2008, p. 85–129. doi:10.1016/B978-012663971-1.50008-7.

Stewart J, Clarke A. A Three-Zone Heat-Release Rate Model for Dual-Fuel Combustion. Proc Inst Mech Eng Part C J Mech Eng Sci 2010;224:2423–34. doi:10.1243/09544062JMES1955.

Suthisripok T, Semsamran P. The impact of biodiesel B100 on a small agricultural diesel engine. Tribol Int 2018;128:397–409. doi:10.1016/j.triboint.2018.07.042.

Thangaraja J, Anand K, Mehta PS. Biodiesel NOx penalty and control measures - a review. Renew Sustain Energy Rev 2016;61:1–24. doi:10.1016/j.rser.2016.03.017.

Thiyagarajan S, Geo VE, Martin LJ, Nagalingam B. Selective Non-catalytic Reduction (SNCR) of CO2 and NO Emissions from a Single-Cylinder CI Engine Using Chemical Absorbents. Emiss Control Sci Technol 2017;3:233–42. doi:10.1007/s40825-017-0076-0.

Tippayawong N, Sittisun P. Continuous-flow transesterification of crude jatropha oil with microwave irradiation. Sci Iran 2012;19:1324–8. doi:10.1016/j.scient.2012.08.004.

Tüccar G, Özgür T, Aydın K. Effect of diesel–microalgae biodiesel–butanol blends on performance and emissions of diesel engine. Fuel 2014;132:47–52. doi:10.1016/j.fuel.2014.04.074.

Tutak W, Jamrozik A, Pyrc M, Sobiepański M. A comparative study of co-combustion process of diesel-ethanol and biodiesel-ethanol blends in the direct injection diesel engine. Appl Therm Eng 2017;117:155–63. doi:10.1016/j.applthermaleng.2017.02.029.

Usta N, Aydoğan B, Çon AH, Uğuzdoğan E, Özkal SG. Properties and quality verification of biodiesel produced from tobacco seed oil. Energy Convers Manag 2011;52:2031–9. doi:10.1016/j.enconman.2010.12.021.

Vallinayagam R, Vedharaj S, Yang WM, Roberts WL, Dibble RW. Feasibility of using less viscous and lower cetane (LVLC) fuels in a diesel engine: A review. Renew Sustain Energy Rev 2015;51:1166–90. doi:10.1016/j.rser.2015.07.042.

Vallinayagam R, Vedharaj S, Yang WM, Saravanan CG, Lee PS, Chua KJE, et al.

Emission reduction from a diesel engine fueled by pine oil biofuel using SCR and catalytic converter. Atmos Environ 2013;80:190–7. doi:10.1016/j.atmosenv.2013.07.069.

Veljkovic V, Lakicevic S, Stamenkovic O, Todorovic Z, Lazic M. Biodiesel production from tobacco (Nicotiana tabacum L.) seed oil with a high content of free fatty acids. Fuel 2006;85:2671–5. doi:10.1016/j.fuel.2006.04.015.

Verma P, Sharma MP, Dwivedi G. Evaluation and enhancement of cold flow properties of palm oil and its biodiesel. Energy Reports 2016;2:8–13. doi:10.1016/j.egyr.2015.12.001.

Wazilewski WT, Bariccatti RA, Martins GI, Secco D, Souza SNM de, Rosa HA, et al. Study of the methyl crambe (Crambe abyssinica Hochst) and soybean biodiesel oxidative stability. Ind Crops Prod 2013;43:207–12. doi:10.1016/j.indcrop.2012.07.046.

Wei L, Cheung CS, Ning Z. Effects of biodiesel-ethanol and biodiesel-butanol blends on the combustion, performance and emissions of a diesel engine. Energy 2018;155:957–70. doi:10.1016/j.energy.2018.05.049.

Williams R, Hamje H, Zemroch PJ, Clark R, Samaras Z, Dimaratos A, et al. Effect of Fuel Properties on Emissions from Euro 4 and Euro 5 Diesel Passenger Cars. Transp Res Procedia 2016;14:3149–58. doi:10.1016/j.trpro.2016.05.255.

Woodyard D. Exhaust emissions and control. Pounder’s Mar. Diesel Engines, Elsevier; 2004, p. 64–87. doi:10.1016/B978-075065846-1/50004-3.

World Oil Outlook 2040, Organization of the Petroleum Exporting Countries. 2017.

Xia Q, Xia Y, Xi J, Liu X, Wang Y. Energy-efficient production of 1-octanol from biomass-derived furfural-acetone in water. Green Chem 2015;17:4411–7. doi:10.1039/C5GC01119A.

Xu YX, Hanna MA. Synthesis and characterization of hazelnut oil-based biodiesel. Ind Crops Prod 2009;29:473–9. doi:10.1016/j.indcrop.2008.09.004.

Yang J, Caldwell C, Corscadden K, He QS, Li J. An evaluation of biodiesel production from Camelina sativa grown in Nova Scotia. Ind Crops Prod 2016;81:162–8. doi:10.1016/j.indcrop.2015.11.073.

Yang, Lin KC, Lin Y-C, Jhang S-R, Chen S-C. Emission evaluation of a diesel engine generator operating with a proportion of isobutanol as a fuel additive in biodiesel blends. Appl Therm Eng 2016;100:628–35. doi:10.1016/j.applthermaleng.2016.01.118.

Yasin MHM, Mamat R, Yusop AF, Aziz A, Najafi G. Comparative Study on Biodiesel-methanol-diesel Low Proportion Blends Operating with a Diesel Engine. Energy Procedia 2015;75:10–6. doi:10.1016/j.egypro.2015.07.128.

Yerrennagoudaru H, Manjunatha K, Raza A, Kantharaj BR, Mujahed A, Irshad K. Analysis and comparison of performance and emissions of compression ignition engine fuelled with diesel and different bio-fuels blended with Methanol. Mater Today Proc 2018;5:5175–85. doi:10.1016/j.matpr.2017.12.099.

Yesilyurt MK, Eryilmaz T, Arslan M. A comparative analysis of the engine performance, exhaust emissions and combustion behaviors of a compression ignition engine fuelled with biodiesel/diesel/1-butanol (C4 alcohol) and biodiesel/diesel/n-pentanol (C5 alcohol) fuel blends. Energy 2018;165:1332–51.

doi:10.1016/j.energy.2018.10.100.

Yilmaz N, Vigil FM, Benalil K, Davis SM, Calva A. Effect of biodiesel–butanol fuel blends on emissions and performance characteristics of a diesel engine. Fuel 2014;135:46–50. doi:10.1016/j.fuel.2014.06.022.

Žaglinskis J, Lukács K, Bereczky Á. Comparison of properties of a compression ignition engine operating on diesel–biodiesel blend with methanol additive. Fuel 2016;170:245–53. doi:10.1016/j.fuel.2015.12.030.

Zhang T, Munch K, Denbratt I. An Experimental Study on the Use of Butanol or Octanol Blends in a Heavy Duty Diesel Engine. SAE Int J Fuels Lubr 2015;8:2015-24–2491. doi:10.4271/2015-24-2491.

Zhang X, Wang H, Zheng Z, Reitz RD, Yao M. Effects of late intake valve closing (LIVC) and rebreathing valve strategies on diesel engine performance and emissions at low loads. Appl Therm Eng 2016;98:310–9. doi:10.1016/j.applthermaleng.2015.12.045.

Zhu J, Huang H, Zhu Z, Lv D, Pan Y, Wei H, et al. Effect of intake oxygen concentration on diesel–n-butanol blending combustion: An experimental and numerical study at low engine load. Energy Convers Manag 2018;165:53–65. doi:10.1016/j.enconman.2018.03.045.

Zhu L, Xiao Y, Cheung CS, Guan C, Huang Z. Combustion, gaseous and particulate emission of a diesel engine fueled with n-pentanol (C5 alcohol) blended with waste cooking oil biodiesel. Appl Therm Eng 2016;102:73–9. doi:10.1016/j.applthermaleng.2016.03.145.

Zou C, Zhao Q, Zhang G, Xiong B. Energy revolution: From a fossil energy era to a new energy era. Nat Gas Ind B 2016;3:1–11. doi:10.1016/j.ngib.2016.02.001.

Zubel M, Heuser B, Pischinger S. 1-Octanol Tailor-made Fuel for Lower Soot Emissions. MTZ Worldw 2017;78:58–61. doi:10.1007/s38313-016-0178-z.