INFLUENCE OF GAS-TO-LIQUID FUEL IN THE COMBINED BLENDS OF BIODIESEL-DIESEL

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DISSERTATION SUBMITTED IN FULFILMENT OF THE REQUIRMENTS FOR THE DEGREE OF MASTER OF ENGINEERING SCIENCE

FACULTY OF ENGINEERING

UNIVERSITY OF MALAYA

KUALA LUMPUR

2015

UNIVERSITI MALAYA

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ABSTRACT

Energy security concerns and environmental sustainability issues have been increasing with the growth of civilization, which have developed the urge to increase energy efficiency with a diminution in environmental pollution. These situation have stimulated the researchers to focus on the alternative transportation fuels like Gas-to-liquid (GTL) fuel and biodiesel. GTL fuel is produced from Fischer–Tropsch synthesis and consists of some distinctive characteristics such as its paraffinic nature, very low sulfur and aromatic contents and a high cetane number. It can be used as an alternative to diesel and also with the blends of diesel and bio-diesel. Biodiesels are mono-alkyl esters of fatty acids, which can be produced from several widely available feedstock and consist of special features like renewability and diminution of engine emissions, which make those as one of the most potential substitutes for diesel or with the blends with diesel.

This study comprises of a comparative analysis of GTL fuel and three potential biodiesel feedstock from Palm, Jatropha and Calophyllum and their blends (20% by vol.) with diesel. Three ternary blends of GTL (20% by vol.), biodiesel (30% by vol.) and diesel (50% by vol.) had been introduced to aggregate the promising properties of these two alternative fuels with diesel, which is a pioneer study involving GTL fuel. The test results of these ternary blends were compared with their respective biodiesel blends (20% by vol.) to investigate the benefits of these blends. All of the fuel samples had been investigated in the context of major fuel properties and the experiments were performed to evaluate engine combustion and several engine performance-emission parameters in a four cylinder compression ignition engine at three different engine test conditions, such as, full load with variable speed, constant speed with variable load and constant torque with variable speed. Combustion analysis results showed that both the peaks of in-cylinder pressure and heat release rate (HRR) of the GTL blend (G20) were

slightly lower and occurred at later crank angles than those of the diesel, whereas, the biodiesel blends(B20) and ternary blends (DBG20) demonstrated higher peak values of these two parameters and advanced peak locations than those of diesel. Compared to the B20 blends, the DBG20 blends showed lower peak values of in-cylinder pressure and HRR and slightly retarded peak locations. Performance analysis results showed that both of the B20 and the DBG20 blends showed higher BSFC, BSEC and lower BTE, whereas GTL blend showed lower BSFC-BSEC but higher BTE than those of diesel. Exhaust emission test results demonstrated that all fuel blends showed reduced CO, HC and smoke than diesel. In case of NO_x, higher emission was observed for the B20 and DBG20 blends, whereas, GTL blend showed lower emission than diesel. The DBG20 blends showed improvement in all major fuel properties and engine performance parameters like lower BSEC (1.36-2.94%), higher BTE (1.18-3.09%), whereas, emission parameters like CO (4.69-15.48%), HC (2.75-11.89%), NOx (1.15-3.51%) and smoke (2.1-6.35%) than those of their respective B20 blends.

ABSTRAK

Dengan evolusi tamadun, pengurangan bahan api fosil, keinginan untuk meningkatkan kecekapan tenaga dan cabaran untuk memulihara kelestarian alam sekitar, para penyelidik telah memberi tumpuan kepada bahan api pengangkutan alternatif seperti Gas-ke-cecair (GTL) dan bahan api biodiesel. Bahan api GTL diperolehi daripada sintesis Fischer-Tropsch adalah ciri-ciri yang jelas berbeza daripada bahan api diesel fosil kerana sifat parafmik itu, hampir sifar sulfur, kandungan aromatik rendah dan nombor setana sangat tinggi pengganti diesel dan walaupun dengan campuran diesel dan bio-diesel. Biodiesels adalah ester mono-alkil asid lemak, yang boleh dihasilkan daripada beberapa bahan mentah dan terdiri daripada ciri-ciri istimewa seperti Pembaharuan, ketersediaan bahan mentah dan pengurangan emisi enjin, yang membuat mereka sebagai pengganti potensi diesel atau dengan campuran dengan diesel. Kajian ini terdiri daripada analisis perbandingan bahan api GTL dan tiga potensi bahan mentah biodiesel daripada sawit, Jatropha dan Calophyllum dan campuran mereka (20% oleh vol.) Dengan diesel. Tiga adunan pertigaan GTL (20% oleh vol.), Biodiesel (30% oleh vol.) Dan diesel (50% oleh vol.) Telah diperkenalkan untuk mengumpulkan sifat-sifat yang menjanjikan kedua-dua bahan api alternatif dengan diesel, yang merupakan perintis yang kajian yang melibatkan bahan api GTL. Keputusan ujian ini campuran pertigaan dibandingkan dengan campuran biodiesel masing-masing (20% oleh vol.) Untuk menyiasat manfaat campuran ini. Semua sampel bahan api telah disiasat dalam konteks hartanah bahan api utama dan eksperimen telah dijalankan untuk menilai pembakaran enjin dan beberapa parameter enjin berprestasi pelepasan dalam empat silinder enjin pencucuhan mampatan pada tiga keadaan ujian enjin yang berbeza, seperti, beban penuh dengan kelajuan boleh ubah, kelajuan malar dengan beban pembolehubah dan tork yang berterusan dengan kelajuan boleh ubah. Keputusan analisis pembakaran menunjukkan bahawa kedua-dua puncak kadar tekanan dan haba

dibebaskan dalam silinder (HRR) daripada gabungan GTL (G20) adalah lebih rendah sedikit dan berlaku pada sudut engkol kemudian berbanding dengan diesel, manakala, yang campuran biodiesel (B20) dan campuran pertigaan (DBG20) menunjukkan nilai puncak yang lebih tinggi daripada kedua-dua parameter dan lokasi puncak maju berbanding dengan diesel.

Berbanding dengan campuran B20, yang campuran DBG20 menunjukkan nilai puncak yang lebih rendah daripada tekanan dalam silinder dan HRR dan lokasi puncak sedikit akal. Keputusan analisis menunjukkan bahawa prestasi kedua-dua B20 dan campuran DBG20 menunjukkan BSFC yang lebih tinggi, dan lebih rendah BSEC BTE, manakala GTL gabungan menunjukkan lebih rendah BSFC-BSEC tetapi BTE lebih tinggi berbanding dengan diesel. Keputusan ujian pelepasan ekzos menunjukkan bahawa semua campuran bahan api dikurangkan menunjukkan CO, HC dan asap daripada diesel. Dalam kes NOx, pelepasan yang lebih tinggi diperhatikan bagi B20 dan DBG20 menggabungkan, manakala, GTL gabungan menunjukkan pelepasan lebih rendah daripada diesel. Campuran DBG20 menunjukkan peningkatan dalam semua sifat-sifat bahan api utama dan parameter prestasi enjin seperti BSEC lebih rendah (1,36-2,94%), lebih tinggi BTE (1,18-3,09%), manakala, parameter seperti pelepasan CO (4,69-15,48%), HC (2.75- 11.89%), NOx (1,15-3,51%) dan asap (2,1-6,35%) berbanding dengan campuran B20 masing-masing.

ACKNOWLEDGEMENT

First of all, I would like to thank to the **Almighty Allah s.w.t,** the creator of the world for giving me the fortitude and aptitude to complete this thesis in spite of many hurdles during the period of study.

I would like to convey sincere gratitude to my supervisors Professor Dr. Masjuki Hj. Hassan and Dr. Mahendra Varman A/L Munusamy for their insightful guidance, encouragement and assistance throughout the study. I also express my gratitude to Dr. Abul Kalam for sharing his expertise during the research. Without their persistent involvement in this research the completion of this study would not been an easy task.

I would also like to convey appreciation to all faculty members of the Department of Mechanical Engineering, University of Malaya, and all of my colleagues. In particular, I want to thank the members of "Centre for Energy Sciences" for their valuable ideas and discussions to enrich this research. Special thanks goes to my beloved parents Shah Md. Sahadat Hossain and Nazma Akter Chowdhury, my sister, Dr. Sajida Nahid, and my wife, Dr. Zobaida Edib for their endless love and encouragement.

I would like to extend my gratitude to Ministry of Higher Education (MOHE) for the financial support from University Malaya through project no. UM.C/HIR/MOHE/ENG/07. Last but no means the least, I express gratitude to the government of "Peoples Republic of Bangladesh" to enlighten me with high quality education from primary to university level, and for fostering my stay overseas to pursue this research.

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LIST OF ABBREVIATIONS

↑ Increase

↓ Decrease

ATDC- after top dead center

B10- 10% biodiesel + 90% diesel

B100- 100% neat biodiesel

B20- 20% biodiesel + 80% diesel

BCM- billion cubic meter

BOMF- biodiesel of mixed feedstock

BSEC- brake specific energy consumption

BSFC- brake specific fuel consumption

BSOY- soybean biodiesel

BTE- brake thermal efficiency

CFPP- Cold Filter Plugging Point

CI100- 100% CIBD

CI20- 20% CIBD + 80% diesel

CI50- 50% CIBD + 50% diesel

CIBD- Calophyllum inophyllum biodiesel

CN- cetane number

CO- carbon monoxide

CP- Cloud Point

DBG20- blends of 50% diesel + 30% biodiesel (PBD/JBD/CIBD) + 20% GTL fuel.

DI- direct injection

FCE- fuel conversion efficiency

FFAs- Free fatty acids

G + BD20- blend of 80% GTL fuel and 20% biodiesel

G + BD40- blend of 60% GTL fuel and 40% biodiesel

H/C ratio- hydrogen and carbon ratio

HC- hydrocarbons

HCV- higher calorific value

HSD- high speed diesel

IDI- indirect injection

IEA- International energy agency

IOP- injector opening pressure

J100- 100% Jatropha biodiesel

J20- 20% Jatropha biodiesel + 80% diesel

J50- 50% Jatropha biodiesel+ 50% diesel

JBD- Jatropha biodiesel

LCV- lower calorific value

MOD- Moringa oleifera biodiesel

NO_x- nitrogen oxides

P10- 10% palm biodiesel + 90% diesel

P100-100% palm biodiesel

P25-25% palm biodiesel+ 75% diesel

P5- 5% palm biodiesel + 95% diesel

P50- 50% palm biodiesel+ 50% diesel

P75-75% palm biodiesel+ 25% diesel

PBD- palm biodiesel

PD- plunger diameter

PHO- Preheated palm oils

PO - Palm oil-diesel blends

PO+WCO- methyl or ethyl esters of palm oil and waste cooking oil

PP- Pour Point

PPM - parts per million

REGR- regeneration of exhaust gas recirculation

ROHR- rate of heat release

SOC- start of combustion

SOI- start of injection

TC1- test condition 1 (Full load with variable speed)

TC2- test condition 2 (Variable load with constant speed of 2000 RPM)

TC3- test condition 3 (variable speed with constant torque of 80 Nm)

TCF- trillion cubic feet

TDC- top dead center

ULSD- Ultra low sulfur diesel

CHAPTER 1: INTRODUCTION

1.1 Overview

The evolution of human civilization has always been supported by a sustained growth of the usage of energy. The rapid advancement of energy utilization has been driven by the growth of population, industrialization, luxurious life style and applications of modern technology. It had been observed from the figure 1.1 that by 2040, the projected world population will increase up to 9 billion, which was about 7 billion in 2010. The estimated 30 percentage increase of world population will also result an increase in GDP about 140% in 2040 than that of 2010. Based on these circumstances, the estimated increase of global energy demand will increase approximately 35% in 2040 than that of 2010, with a mean growth rate of 1.1% (Colton, 2013). Moreover, about three quarters of this demand are expected to arise in the time range of 2010 to 2025. The upsurge in the demand of energy requires increased supply of fuels. Figure 1.2 presents the global demand of fuels by 2040. Overall, an average growth of about 1.0% per annum has been predicted from 2010-2040.

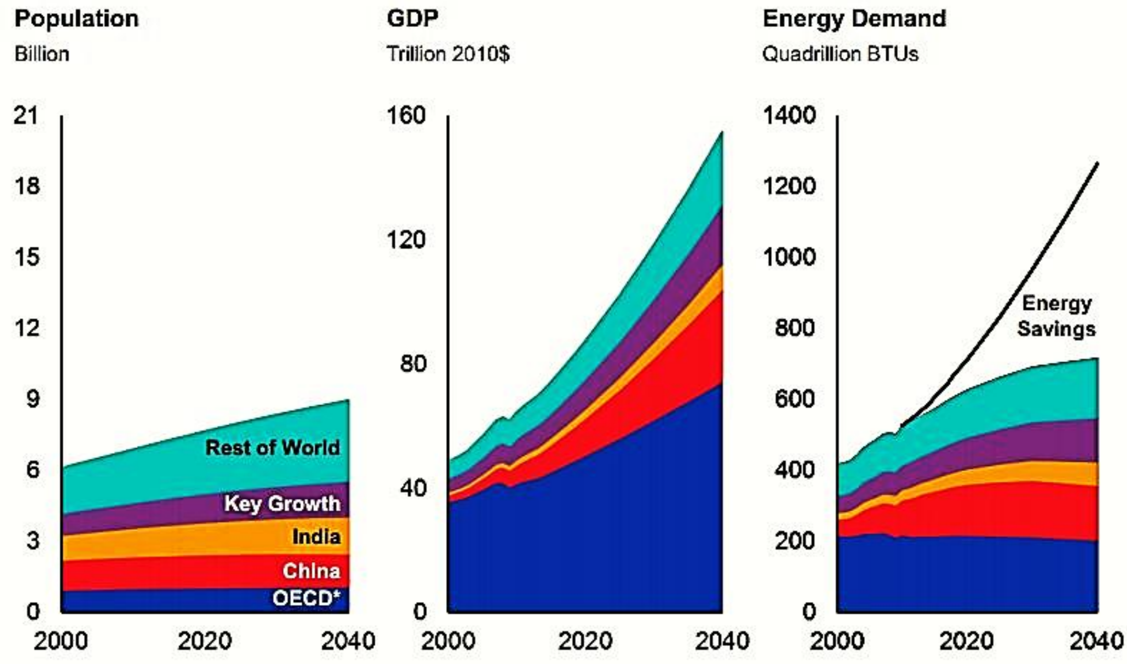

Figure 1.1: Forecast of worldwide population growth, GDP and energy demand (Colton, 2013).

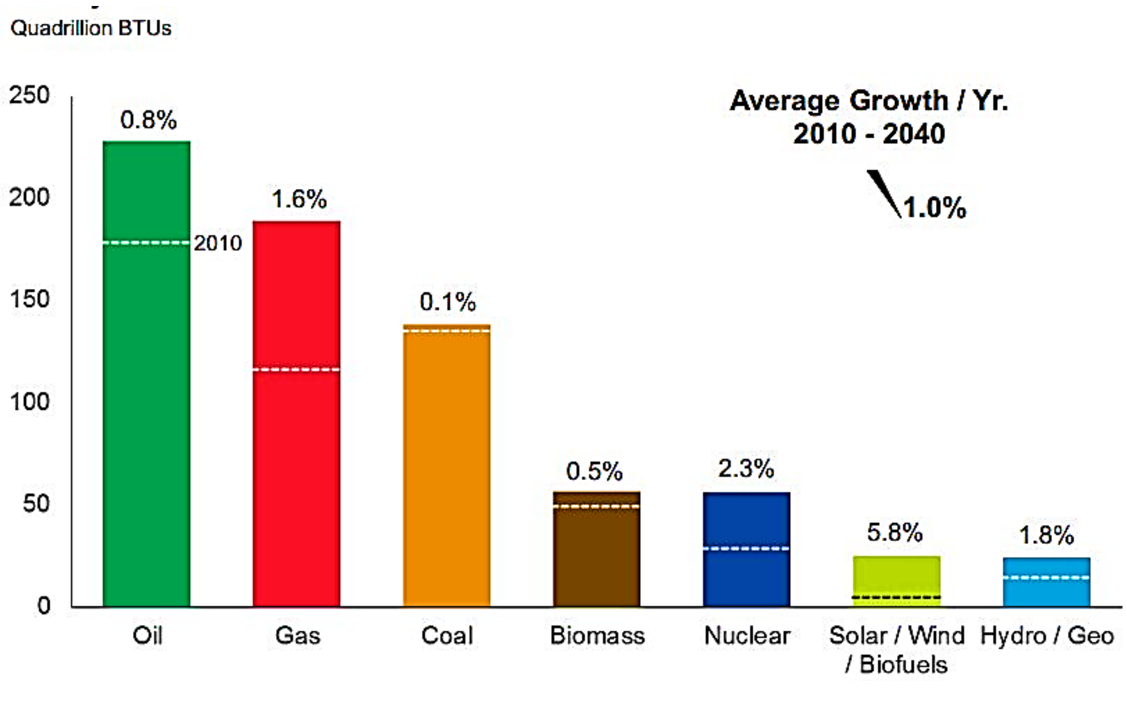

Figure 1.2: Worldwide demand of fuels by 2040 (Colton, 2013).

Fossil diesel is still regarded as the most popular fuel for heavy-duty vehicles because of its extensive availability, subsidies by the governments and the durability of diesel engines. The widespread application of diesel will increase substantially as per the projection till 2040, as it accounts for approximately 80% of the fuel requirement to sustain the advancement in heavy-duty transportation. Apart from diesel, natural gas has also become a prospective source of transport fuel. The international energy agency (IEA) has declared this era as "the golden age of natural gas," and the demand for natural gas has been estimated to increase by 65% from 2010 to 2040, which is definitely the highest volume growth of any energy source (EIAU, 2011). The production of natural gas seems to increase in a linear trend and by 2040, it will reach approximately 5400 billion cubic meter (bcm) (Colton, 2013). According to IEA, worldwide reserve of recoverable natural gas resources are approximately 28,500 trillion cubic feet (TCF) till 2013. With the projected demand and consumption, this reserve can definitely sustain more than 200 years (Colton, 2013).

The rapid growth of transportation sector has supported the advancement of civilization, but the excessive usage of these fossil fuels has initiated a confrontation of dual exigency between the abrupt depletion of fossil fuel and environmental degradation. The harmful exhaust emissions from the automotive engines have increased the pollution levels in terms of airborne pathogens (i.e. Infections, particles and chemicals), greenhouse effect in context of local, territorial and global spectrum. If no initiatives are taken now, the predicted emission from the fossil fuel can be increased up to 35% by 2035 (EIAU, 2011). Figure 1.3 presents the CO_2 emissions, starting from 1990 and projected up to 2035. The projection regarding CO_2 emission in Asia-Pacific Economic Cooperation (APEC) regions by 2035 will be about 25.1 billion ton, whereas in 2010 it was 19.0 billion ton, which illustrates an increase about 40%. Diesel and natural gas produce about 161.3 and 117 per million Btu of CO_2, and considering their share on global emission of fuels are about 35% and 21%, respectively (EIA, 2013).

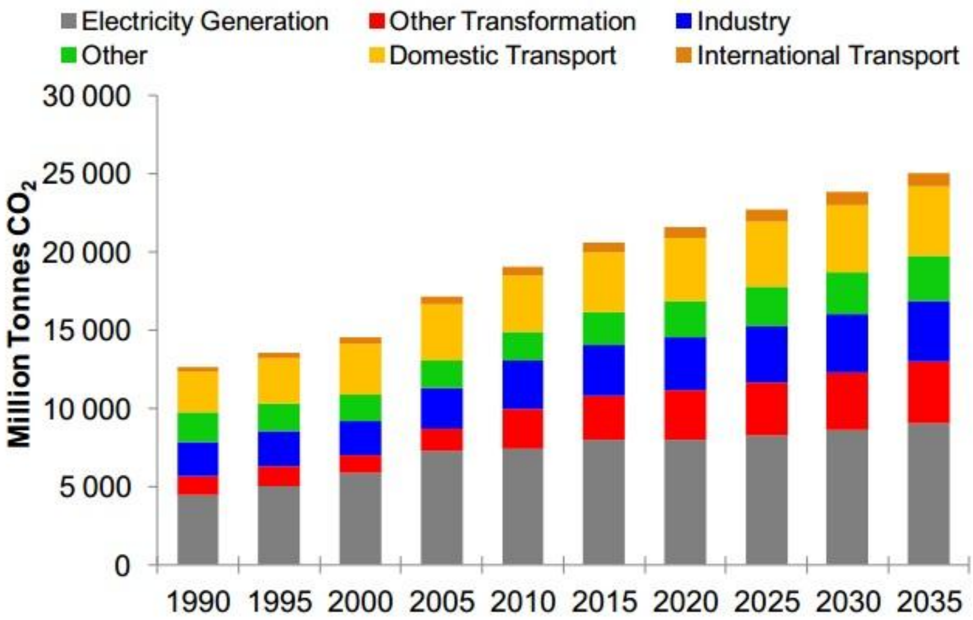

Figure 1.3 : Carbon di-oxide (CO_2) emission from different energy sources from 1990-2035 (EIA, 2013).

In these consequences, it can be concluded that with the dynamic progress of civilization, the requirements of transport fuel have been changing consistently considering issues like energy security, depletion of fossil fuel and foremost, the strict exhaust emission legislation to reduce and control the environmental pollution. Thus, the quest for alternative transport fuels have introduced biodiesel and gas-to-liquid (GTL) fuels. According to IEA, around 27% of total transportation fuel will be replaced completely by biofuels within 2050 (International Energy Agency, 2011). From the forecast of Organization of the Petroleum Exporting Countries (OPEC) it can be predicted that through 2035, the additional demand of transportation fuel will be 23 million barrels/day and GTL fuels can meet up to 57% of this demand (Wood et al., 2012). As a result, biodiesel and GTL fuel can be considered as prospective alternative fuels.

1.2 Background

A strong worldwide drive to introduce alternative liquid fuels for transportation has already been observed due to the urge of reducing automotive emissions, energy security concerns, volatility in the fuel price, and also for the demand of renewable and sustainable fuels in the current situation of dwindling world fuel supplies. Moreover, goals of improving air quality, and diversifying energy resources have intensified research into identifying suitable alternative fuels for internal combustion engines (Abedin et al., 2013; Nishiumi et al., 2009; Sanjid et al., 2013; Velaers & Goede, 2012).

Biodiesel is designated as the mono-alkyl esters of fatty acids, which can be extracted from vegetable oils, animal fats and alcohol. It has special features like, renewability, biodegradability and toxic-free; contains a high cetane number (CN), flash point and inherent lubricity, and demonstrates more diminution in emissions, when compared with fossil diesel (Lapuerta et al., 2010; Xue et al., 2011). Palm, Jatropha and Calophyllum Inophyllum can be regarded as three potential feedstocks for biodiesel production because of their high availability, higher oil yield than other feedstocks, and the compliance of the biodiesel yield from its crude oil with the US ASTM D6751 and European Union EN 14214 biodiesel standards (Atabani & César, 2014; I. Fattah et al., 2014).

GTL fuel is synthesized from natural gas through Fischer -Tropsch process (Bezergianni & Dimitriadis, 2013; Erturk, 2011; Swain et al., 2011). It has several distinguished beneficial properties as an alternative clean diesel fuel than conventional fossil diesel, including high CN, virtually zero sulfur, negligible amounts of aromatics and hetero atomic species like sulfur and nitrogen. Large GTL plants have been commissioned such as Shell plant in Bintulu, Malaysia, the PetroSA plant in Mossel Bay, South Africa, the ORYX GTL plant in Qatar (jointly owned by Qatar Petroleum and Sasol) and the Shell Pearl plant in Qatar and some others are in the design phase. It is foreseen that GTL fuel may become a more prominent player in the international market, driven by an increased projected future demand for diesel (Velaers & Goede, 2012).

1.3 Problem statement

Alternative fuels like biodiesel has some major constrains in fuel properties, which also affect the engine performance and exhaust emission parameters. Thus, the application of higher quantity (more than 20%, by vol.) of biodiesel blends have not been appreciated in present automotive engines. Considering the renewability and availability features of biodiesel, depletion of fossil fuel and energy security concerns, a higher quantity of biodiesel in blend will be much appreciated, if some effective measures can be applied to improve the overall quality of the blends. The additives that are used to improve a certain fuel property or performance parameter, so often makes a negative impact on other parameter and, are also expensive. The concept of the ternary blends of biodiesel with GTL fuel and diesel can be an effective strategy in this regard. The novelty of this study is to introduce three ternary blends of biodiesel, GTL and diesel with an aim to improve to the major fuel properties, and also the engine performance-emission features.

1.4 Objectives

The prime objectives of this study are as follows:

- To investigate the physicochemical properties of the blends of diesel, GTL fuel and three biodiesel from palm, jatropha and calophyllum feedstock.
- Comparative analysis of the engine combustion parameters by using all fuel blends at different engine test conditions.
- Evaluation of different engine performance and emission parameters by using all fuel blends at different engine test conditions.

1.5 Scopes of study

The target of this research work is to conduct a comparative study between the blends of four alternative fuels, such as Palm biodiesel (PBD), Jatropha biodiesel (JBD), Calophyllum biodiesel (CIBD) and GTL fuel. Initially, 20% (by vol.) blends of biodiesel-diesel (B20) and GTL-diesel (G20) were studied, and were also compared with diesel. Eventually, three ternary blends (DBG20) were prepared from three biodiesel with diesel and GTL fuel. The purpose of introducing these ternary blends is to study the feasibility of using high quantity (30% by vol.) of biodiesel in blends, and to observe the effect of GTL fuel, which can improvise the fuel blend properties to yield an improved engine performance-emission features of the ternary blends.

The incorporation of GTL fuel in ternary blends of biodiesel-diesel is a pioneer study. All of the major fuel properties of the blends like density, viscosity, calorific value, flash point, cetane number, and oxidation stability had been investigated. Combustion analysis was performed to study the in-cylinder pressure and heat release rate of all fuels. The in-depth analysis of engine performance parameters (BSFC, BSEC and BTE), and exhaust emission parameters (CO, HC, NO_x and smoke opacity) were performed in three engine test conditions, such as, full load-variable speed, constant speed-variable load and constant torque-variable speed.

1.6 Organization of thesis

This section provides a brief description on all chapters of this dissertation.

Chapter 1 contains the background of the current study, problem statement and scope of study. Based on these discussion, the selected objectives are also included in this chapter.

Chapter 2 consists of the literature review of GTL fuel, Palm, Jatropha and Calophyllum biodiesel. The literature review contains the outcome of the related previous studies of all these fuels in the context of fuel properties, engine performance and exhaust emission parameters.

Chapter 3 describes the methodology of this study. In this section, a brief illustration of all of the used equipment for fuel sample blending and characterization of fuel properties have been included. The engine test bed, test procedure and the analyzers for measuring exhaust emission and combustion data have been described in-details.

Chapter 4 comprises of the outcome of this study and the results have been discussed with reference to the previous studies.

Chapter 5 contains the conclusion and the further recommendation works that can be performed by the future researchers.

2 CHAPTER 2: LITERATURE REVIEW

2.1 Gas to liquid fuels

GTL fuel is the product of years of relentless research on gas to liquid technologies. In GTL technology, natural gas is transformed in to long chain hydrocarbon molecules, such as those consist crude oil (Gill et al., 2011). GTL technologies have provided a new way to monetize the stranded gas reserves (Wood et al., 2012). This section contains a brief description of the stages of GTL technology, in-detail analysis of previous research works with GTL fuel, and its blends with diesel and biodiesel in the context of fuel properties, and engine performance-emission features.

2.2 GTL technology

GTL process chain consists of three basic fundamental stages

1. Formation of synthesis gas.
2. Catalytic synthesis.
3. Post processing.

2.2.1 Formation of syngas

Syngas can be defined as a mixture of carbon monoxide, hydrogen, inert gas and many other combustibles. It is a significant intermediate for different synthesizing chemical elements and environmentally clean transportation fuels, like ammonia, methanol, dimethyl ether (DME), acetic acid and methyl-tertiary -butyl ether (MTBE), and also for production of synthetic liquid fuels by F-T synthesis.

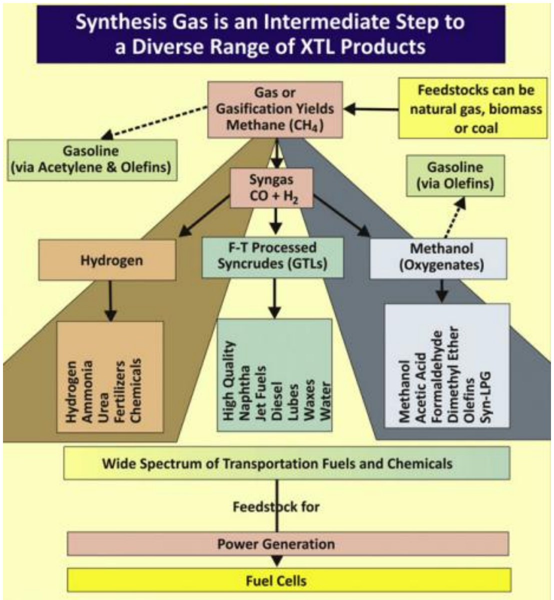

Figure 2.1: Improved Economics and Reduced Investment Risks for Integrated large-scale Gas/Ft-GTL Projects.

Syngas can be formed from any carbonaceous elements, such as natural gas, petroleum coke, coal or biomass etc. as seen in Figure 2.1. At present natural gas is the largest source of syngas, and its usage is rapidly increasing because of its better environmental performance, and lower cost than other sources (Wilhelm et al., 2001). Initially, the carbon and hydrogen are differentiated from methane molecule, coal and biomass. After that those are reconfigured in several processes, which are available for syngas production, such as partial oxidation, steam reforming, and auto thermal reforming (ATR), gasification, and (Enger et al., 2008; Smith & Shekhawat, 2011; Rafiq & Hustad, 2011; Christensen et al., 1998; Wood et al., 2012; Onsan & Avci, 2011) result in different hydrocarbon-carbon monoxide ratios (Henrici-Olivé & Olivé, 1976). The production of syngas can be capital intensive. About 70% of total capital and operating cost is devoted to Syngas production (Dry, 1999).

2.2.2 Catalytic synthesis

Most of the current commercial syngas conversion processes are on the basis of Fischer-Tropsch catalytic synthesis. The products depend on the types of reactors, choice of catalysts, and overall on the operating conditions. The gaseous mixture of CO and H_2 (syngas) is processed in various Fischer-Tropsch reactors and yields long-chain, waxy hydrocarbon, and considerable quantity of water as byproducts. The reactor for catalytic synthesis is specified by different design, targeting the technology to produce wide ranges of synthetic crude of paraffinic long-chain hydrocarbon (Jager, 1997).

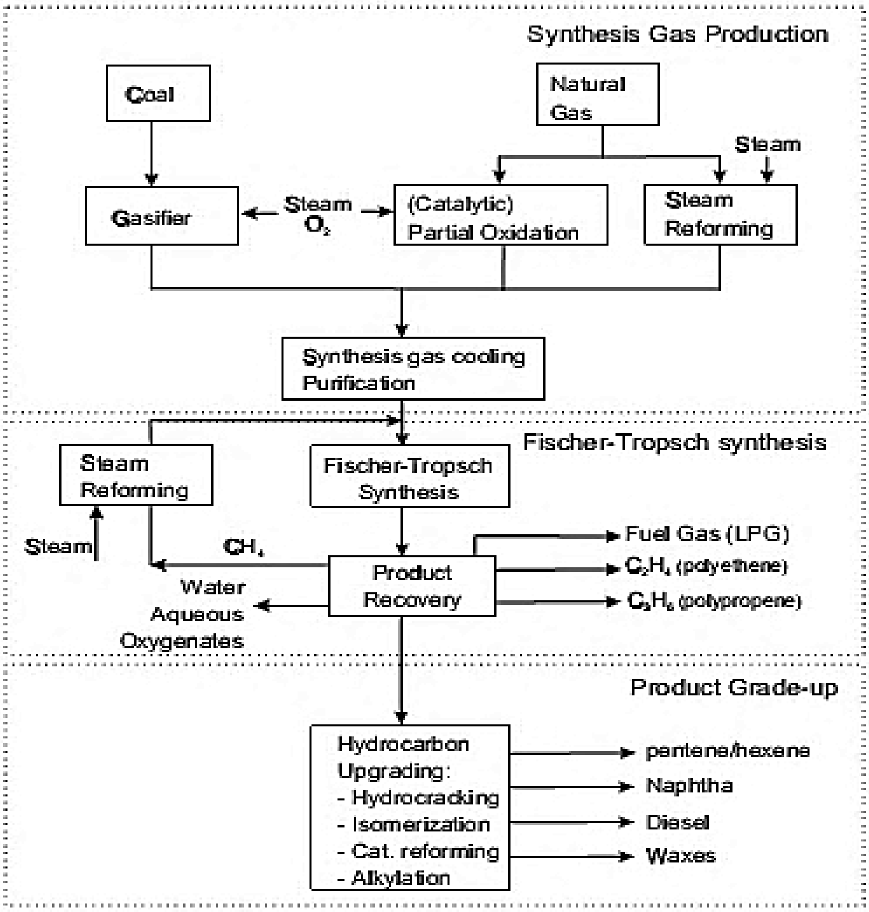

Figure 2.2: Overall process Schematic Fischer-Tropsch.

2.2.3 Post processing

The synthetic crude is produced either from HTFT or LTFT process, and is processed by means of traditional refinery cracking operations, in presence of zeolite catalysts and hydrogen to yield catalytically cracked shorter hydrocarbons. Finally, distillation leads to the production of a variety of fuel products ranging from kerosene to diesel, naphtha and lube oils (Agee, 2005). In most modern plants, Fischer-Tropsch GTL units are now designed and operated to obtain desired product distribution (Rahmim, 2005; Wood et al., 2012). Figure 2.2 presents a schematic diagram of the Fischer-Tropsch process.

2.3 Fuel property analysis of GTL fuel and its blends

Feasibility study of any alternative fuel, which will be used in existing engine, requires in-depth comparative analysis of the fuel properties of the concerned fuel. Table 2.1 contains the important properties of GTL fuel.

2.3.1 Kinematic viscosity

Viscosity effects on the fuel injection as well as spray atomization. Higher viscosity increase fuel pump power requirement, yields poor spray and atomization with increment in fuel consumption. ASTM D445 has widely been used to measure kinematic viscosity for engine fuels. In most of the previous study GTL showed lower kinematic viscosity values than Diesel which is advantageous on fuel spraying atomization (Armas et al., 2010; Gill et al., 2011; Kind et al., 2010; Soltic et al., 2009).

An increase in viscosity was observed for the blends of GTL and ULSD or EN590 diesel in most of the previous studies (Ng et al., 2008; Velaers & Goede, 2012), but (Huang, et al., 2007) reported unchanged viscosity till 50% volume ratio and abrupt increment in further GTL addition in blends. GTL- biodiesel blends showed higher viscosity compared to neat GTL due to the higher viscosity of biodiesel (Lapuerta et al., 2010; Moon et al., 2010).

2.3.2 Cetane number (CN)

Low CN causes an ignition delay that leads towards startup problems, poor fuel economy, unstable engine operation, noise and exhaust smoke. As a result an optimum higher CN is desired for all CI engine fuels. GTL has high paraffin content, and exhibits much higher CN (>74) than other CI engine fuels, which leads towards better combustion performance. Increasing quantity of GTL in blends of diesel (ULSD, EN 590 diesel and conventional) and biodiesel (Lapuerta et al., 2010; Moon et al., 2010) cetane number of blends shows increasing trends compared to diesel and biodiesel due to significantly higher CN of GTL fuels.

2.3.3 Density

A fuel of high density indicates high energy concentration that minimizes the chances of fuel leakage. However, high density yields high viscosity having significant influence in spray atomization efficiency, and results poor combustion with more exhaust emissions (Arbab et al., 2013; Atabani et al., 2012). Recent studies reported that GTL fuel contained approximately 7.2% of lower density than diesel, due to its higher hydrogen-carbon ratio than diesel (Mancaruso & Vaglieco, 2012; Velaers & Goede, 2012; Huang, et al., 2007). Previous studies showed that the presence of GTL fuel in blends with diesel (Ng et al., 2008; Velaers & Goede, 2012; Huang, et al., 2007; Zhang, et al., 2007), and bio-diesel (Lapuerta et al., 2010; Moon et al., 2010; Nabi et al., 2009) demonstrated lower density of the blends, when compared to diesel or biodiesel.

2.3.4 Calorific Value

The high calorific value of any fuel is desired because it favors the heat release during combustion and improves engine performance. GTL fuel demonstrates slightly higher HCV and LCV than diesel. The heating value of GTL is about 2.8% higher by weight, and the density is 5.7% lower than diesel. So, the heating value is lower on a volumetric basis, which leads to the less power for a fixed volume injection (Azimov & Kim, 2008; Hao et al., 2010; Rodríguez-Fernández et al., 2009; Soltic et al., 2009). As GTL fuel contains a higher heating value than most of the biodiesel, conventional diesel and

ULSD, blends of these fuels with GTL fuel have demonstrated an improvement in the heating value (Lapuerta et al., 2010; Ng et al., 2008; Velaers & Goede, 2012; Huang, et al., 2007).

2.3.5 Flash Point

A high flash point ensures safety of fuel for handling, storage and prevention from unexpected ignition during combustion. Flash point contains an inverse relation with the volatility of fuel. Several studies reported that GTL has around 20 °C higher flash point than Diesel (Tsujimura et al., 2007; Huang, et al., 2007; Yehliu et al., 2010).

2.3.6 Cloud Point, Pour Point and Cold Filter Plugging Point

The characteristics of any fuel in low temperature zones are significant to investigate engine performance in cold atmosphere. Partial or complete solidification of fuel may incur blockage of the fuel system such as fuel lines, filters etc. It results interruption in fuel supply associated with inadequate lubrication resulting problems in driving or even damage to the engine. CP, PP and CFPP are used to explain the cold flow characteristics of any fuel.

CP and PP are measured applying ASTM D2500, EN ISO 23015 and D97 procedures. GTL fuel has slightly higher CP and PP than conventional diesel fuel. Blending with biodiesel and diesel, showed an improvement of the CP and PP (Lapuerta et al., 2010; Moon et al., 2010; Schaberg et al., 2005).

CFPP defines the temperature at which fuel flows freely through a fuel filter, approximately halfway between the CP and the PP. Usually at low temperature, fuel may become denser, which degrades the flow property, resulting a poor performance of the fuel system (fuel line, pumps, and injectors). CFPP is measured using ASTM D6371. GTL fuel shows marginally higher CFPP than diesel and biodiesel. Thus, blends with diesel and biodiesel demonstrates improved CFPP (Lapuerta et al., 2010; Moon et al., 2010; Ng et al., 2008; Schaberg et al., 2005).

2.3.7 Acid value

It indicates the proportion of free fatty acids (FFAs) present in a fuel. A high portion of free fatty acid contents in a fuel exhibits high acid value, and makes the fuel severely corrosive. High acid value also leads to corrosion in the fuel supply system, and degrades the longevity and performance of the engine. Acid value for GTL fuel and diesel is measured by ASTM D 974 and ASTM D3242, respectively. GTL fuel exhibits significantly lower acid value than diesel and biodiesel (Alleman et al., 2004; Velaers & Goede, 2012). With the increase in the percentage of GTL fuel in the consecutive blends of ULSD, EN 590 and conventional diesel, a linear decrease of acid number was observed in the previous studies (Ng et al., 2008; Velaers & Goede, 2012; Huang, et al., 2007).

2.3.8 Iodine Number (IN)

Iodine number is used to determine the definitive amount of unsaturation in fatty acids in the form of double bonds, which reacts with iodine compounds. The higher the iodine number, the more C=C bonds are present in the fuel. According to EN 14111 standards

GTL has IN of 1.22 (Nabi et al., 2009) which is comparatively lower than biodiesel (Atabani et al., 2012).

2.3.9 Lubricity

Lubricity reduces the damage caused by friction. It is a significant parameter for using low and ultra-low sulphur fuels. Lubricity can be adjusted with additives, which are compatible with the fuel, and with any additives that already exists in the fuel. High frequency reciprocating rig (HFRR) ASTM D6079 and SLBOCLE ASTM D6078 are used to describe lubricity values. GTL fuel showed same or slightly lower level of lubricity than diesel (Velaers & Goede, 2012). Addition of biodiesel (Moon et al., 2010) and ULSD (Ng et al., 2008) in GTL blends, significantly improves the lubricity of the blends.

2.3.10 Carbon residue

A high carbon residue indicates poor combustion of fuel. ASTM D524 and ASTM D4530 procedures are applied to determine the carbon residue mass percentage of GTL and diesel. Previous studies showed that GTL contains lower carbon residue than diesel (Soltic et al., 2009; Velaers & Goede, 2012).

2.3.11 Aromatics

Aromatics improve seal-swell characteristics, but also enhance engine soot emissions. Particulate matter (PM) emissions increase with increasing aromatic molecular weight and concentration, which can be attributed to an increase in soot precursors. ASTM

D5186 procedure is used to measure the content of aromatics in fuel. Previous studies showed that GTL fuel contained negligible aromatic compounds, compared to diesel (Gill et al., 2011; Hassaneen et al., 2012; Nishiumi et al., 2009; Velaers & Goede, 2012). Total aromatics as well as poly aromatics of the blended fuels decrease gradually, when the GTL fraction increases in the blends (Ng et al., 2008; Velaers & Goede, 2012; Huang, et al., 2007).

2.3.12 Distillation properties

This property demonstrates the temperature range over which a fuel sample volatilize. It is determined by ASTM D 975 standard. As it is quite difficult to have precise measurements of the highest temperature obtained during distillation (known as end point) with good repeatability, 90% (T90) or 95% (T95) distillation point of a fuel is commonly used. Engine manufacturer association (EMA) prefers T95, because of its acceptable reproducibility, and being nearer to the fuel's end point than T90. The T90 of GTL fuel is about 6.3% lower than diesel. This distillation characteristic of GTL fuel also improves the atomization and dispersion of fuel spray, and also ensures ease of evaporation of fuel, which accelerates the fuel-mixing with air to constitute a more combustible air-fuel mixture. Several studies reported that lowering distillation characteristics of GTL fuel reduce smoke and PM emission, in spite of its high CN (Koji Kitano et al., 2005-10-24; Wu, Huang, et al., 2007). During operation at low loads and frequent idle periods, a lower end point is desirable to reduce smoke and combustion deposits.

Previous studies showed that GTL-diesel (ULSD, EN590 or conventional) blends demonstrated lower initial and intermediate boiling point, but slightly higher end boiling point compared to neat GTL (Ng et al., 2008; Velaers & Goede, 2012; Wu, Huang, et al., 2007), whereas GTL-biodiesel blends showed higher distillation temperature throughout the distillation range than neat GTL fuel (Magín Lapuerta et al., 2010; M. Nabi et al., 2009).

2.3.13 Sulfur Content

Presence of sulfur in fuel has a hazardous effect on engine performance and the environment. During combustion, sulfur reacts with water vapor to produce sulfuric acid and other corrosive compounds, which deteriorate the longevity of the valve guides and the cylinder liners, and cause premature engine failure. When these corrosive compounds are mixed with atmospheric air, it results in acid rain, and pollutes vast areas of arable land. ASTM D5453 and ASTM D2622 standards are used to determine sulfur contents as parts per million. Virtually, GTL fuel has zero sulfur, but the maximum level of sulfur observed in real scenario was 0.005 ppm. On the contrary, ULSD and conventional diesel showed maximum sulfur content about 0.0034 ppm and 11ppm, respectively (Nishiumi et al., 2009; Soltic et al., 2009; Velaers & Goede, 2012). It had been observed that the presence of high percentage of GTL fuel in blend, results lower sulfur contents of that blend. As ULSD and EN 590 diesel possess low sulfur content, their 20% and 50% blends with GTL fuel showed a reduction in sulfur approximately 15% and 28%, respectively than that of conventional diesel (Ng et al., 2008; Velaers & Goede, 2012; Huang, et al., 2007).

Table 2.1 : Technical Attributes of GTL Properties (Abu-Jrai et al., 2009; Alleman et al., 2005; T.L. Alleman et al., 2004; Cowart et al., 2008; Kind et al., 2010; Lu et al., 2009; Mancaruso & Vaglieco, 2012; Nabi et al., 2009; Ng et al., 2008; Nishiumi et al.,

2009; Oguma et al., 2002; Schaberg et al., 2005; Soltic et al., 2009; Tsujimura et al., 2007; Ushakov et al., 2013; Velaers & Goede, 2012; Huang, et al., 2007).

Properties	Test Standard	Units	GTL fuel	Diesel
Acid Number	ASTM D 974, ASTM D3242	mg/KOH/g	0.00167~0.001	0.026
Ash Content	ASTM D482	mass %	<0.001	<0.01
Cloud Point	ASTM D2500	°C	-17~3	-26~1
Calorific value or Heat of Combustion	ASTM D240 ASTM D4868	MJ/Kg	34.5~49.3	42.95
CFPP	ASTM D6371	°C	-19~ -8	-20 ~ -25
Density @15,deg.C	ASTM D4052	Kg/m^3	768~785	830
Distillation				
Initial Boiling Point			162~212	198.5
10%			173~260	224.5
20%			177~262	234.0
30%			183~274	242.0
40%			190~286	250.5
50%			198~298	259.5
60%	ASTM D86	°C	210~308	270.5
70%			222~317	285.5
80%			235~327	304.0
90%			247~343	329.5
95%			254~363	350.0
Final Boiling Point			258~369	360.0
Flash point	ASTM D93	°C	63~99	61~71
H / C ratio	ASTM D5291		2.10~2.15	1.89
Hydrocarbon Types				
Carbon content		mass %	84.9~85.4	86.0
Hydrogen content	ASTM D1319	mass %	13.99~15.1	14.0
Oxygen content		mass %	0.0	0.00
Nitrogen Content		mass %	0.67	
Aromatic hydrocarbon		vol %	0.3~1.1	24.0~35.3
Olefins		vol %	0.6~1.1	3.0
Saturates		vol %	97.8	61.7
Iodine number	EN 14111		1.22	
Kinetic viscosity @30 deg.C	ASTM D445	mm^2/s	4.441	3.76
Pour point	ASTM D97	°C	-27 ~ -2.5	-32 ~ -35
Sulfur content	ASTM D5453 ASTM D2622	mass ppm	0.005~1	0.034~11.6
SFC Aromatics				
Mono Aromatics	ASTM D5186	mass %	1.3~2.1	
Poly nuclear Aromatics			0.2~1.7	
Total Aromatics			2.3~3.0	24.0
Viscosity	ASTM D445	cSt	2.19	2.35

2.4 Engine performance features of GTL fuel and its blends

Featured parameters for in depth analysis regarding engine performance factors like brake specific fuel consumption (BSFC) and brake thermal Efficiency (BTE) are discussed in this section.

As GTL fuel possesses higher LCV in gravimetric basis, lower BSFC of GTL fuel and its blends was observed in several studies than conventional diesel and biodiesel (Abu-Jrai et al., 2006; Hassaneen et al., 2012; Huang, et al., 2007). Significant improvement of fuel economy was observed in lower speed than in mid-higher speed (Abu-Jrai et al., 2006; Ng et al., 2008; Schaberg et al., 2005; Huang, et al., 2007). At lower load and speed conditions, BSFC of GTL-biodiesel (soybean oil and waste cooking oil volume ratio of 3:7) blends was appreciable, but at higher load and speed, an increase in BSFC was observed, due to the lowering LHV of the blends. LHV of G + BD20 and G + BD40 was lower about 3.7% and 7.3%, respectively than GTL fuel. As a result, extra fuel was required at a given speed and load for the compensation of different LHV values. Since fuel conversion efficiency (FCE) has an inverse relation with the BSFC and LHV, increased BSFC of biodiesel blends with GTL had been compromised by decreasing LHV. As a result, addition of biodiesel in GTL blends yields higher FCE, and with the combination of high oxygen content of biodiesel, the blends towards a complete combustion (Lapuerta et al., 2010; Moon et al., 2010). High CN of GTL fuel yields a shorter ignition delay, which induces lower decreasing rate of BTE of GTL fuel than diesel at the retarding injection timing condition. The shortened premixed combustion stage of GTL fuel permits advanced injection timing, which provides better engine efficiency constraining $NO_{x,}$ and combustion noise at low load levels (Oguma et al., 2002). GTL fuel showed higher BTE than ULSD in medium load conditions than low-load operations due to the less requirement of fuel to overcome the mechanical losses at increasing load (Abu-Jrai et al., 2009). The influence of REGR on the BTE seemed to vary with the load. Increased REGR at lower load showed a decrease in BTE because of the incomplete combustion, but at higher load, increased BTE was observed due to a faster flame velocity, associated with an increase in the expansion work (Abu-Jrai et al., 2009).

2.5 Engine emission features of GTL fuel and its blends

GTL fuel has advantages as a clean alternative diesel fuel in the context of lower emissions of CO, HC, NO_x and smoke, owing to its unique fuel properties. It contains the potential to achieve low emissions without any major engine modifications (Alleman et al., 2004; Myburgh et al., 2003; Oguma et al., 2004; Oguma et al., 2002; Steinbach et al., 2006; WU et al., 2006).

Most of the previous studies showed that GTL fuel exhibited lower CO emission compared to diesel and biodiesel, irrespective of all loading conditions and injection timings (Armas et al., 2010; Wang et al., 2009; Xinling & Zhen, 2009; Yehliu et al., 2010). Some studies showed increased CO emission at retarded injection timing; however, the increasing rate of GTL fuel was lower than that of diesel (Oguma et al., 2002). The reasons of CO emission reduction of GTL fuel lie within the fuel properties and the combustion phenomena. A high H/C ratio and very low aromatic content provides improved combustion that favors CO reduction. The high CN of GTL fuel induces shortening of ignition delay that prevents less over-lean zones. The lower distillation temperature of GTL fuel results in rapid vaporization, which reduces the probability of flame quenching, and ensures lower CO emission (Moon et al., 2010; Yongcheng et al., 2006). Previous studies regarding GTL- diesel blends showed a reduction of CO emission with the increased ratio of GTL fuel in the blend (Ng et al., 2008; Schaberg et al., 2005; Huang, et al., 2007; Zhang, et al., 2007). A significant decrease of CO emission approximately 16–52% was observed for GTL-biodiesel blends, when compared to diesel (Moon et al., 2010; Nabi et al., 2009; Rounce et al., 2009; Theinnoi et al., 2009). With the presence of biodiesel in GTL blends, the additional oxygen content and high CN of GTL fuel yielded better combustion, and thus, it lead towards reduction in CO emission (Miyamoto et al., 1998; Rakopoulos et al., 2004; Xing-cai et al., 2004). A low ratio of biodiesel (within the range of 20%~30%) in GTL-biodiesel blends showed less CO reduction than higher ratio of biodiesel in blends (Moon et al., 2010).

Several studies reported that GTL fuel showed a lower HC emission in the range of 31–60%, compared to conventional diesel (Wang et al., 2009; Xinling & Zhen, 2009). With the advanced injection timing, the trend of lower HC emission existed, but in the retarded injection timing, a slight increase was observed within a range of 100-130 ppm, which was still lower than that of diesel (Oguma et al., 2002). Alike CO emission, HC emission reduction can also be explained regarding the fuel properties and combustion phenomena of GTL fuel. The high CN of GTL fuel shortens the ignition delay, which prevents the formation of over-lean regions. Lower distillation temperature characteristic of GTL ensures the proper pace of evaporation and mixing with air to constitute a more effective combustible charge which results less unburned HC in exhaust emission (Wang et al., 2009; Xinling & Zhen, 2009; Yongcheng et al., 2006). Previous studies regarding the GTL-diesel blends demonstrated significant reduction in HC emission with the increased ratio of GTL fuels in blends (Abu-Jrai et al., 2006; Ng et al., 2008; Schaberg et al., 2005; Wu, Huang, et al., 2007). In case of GTL-biodiesel blends, significant reduction of HC emissions were observed at low-load conditions, compared to diesel and neat GTL fuel (Armas et al., 2010; Lapuerta et al., 2010; Moon et al., 2010; Nabi et al., 2009; Theinnoi et al., 2009). The reduction of HC emission in blends was possible because of the increased oxygen content in the blends due to the addition of biodiesel, which led towards proper combustion. Several studies suggested to maintain a low ratio (within range of 20~30%) of biodiesel in blends with GTL fuel to ensure the lower HC emission (Lapuerta et al., 2010; Moon et al., 2010).

Previous studies showed that GTL fuel demonstrated lower NO_x emission than diesel and biodiesel in all loading conditions and injection timing (Armas et al., 2010; Oguma et al., 2002; Wang et al., 2009; Xinling & Zhen, 2009; Yehliu et al., 2010). With the advanced and retarded SOI, GTL fuel showed lower NO_x emission about 22% and 33%, respectively than that of diesel (Armas et al., 2010). The high CN of GTL fuel produced short ignition delay; followed by less premixed charge, which led towards low combustion temperature and pressure, and resulted less NO_x formation (Wang et al., 2009). Significant low aromatic contents of GTL fuel favored local adiabatic flame temperature, which also assisted in NO_x reduction (Kidoguchi et al., 2000; Xinling & Zhen, 2009; Yongcheng et al., 2006). GTL-diesel blends showed improved NO_x emission than diesel, but higher values than neat GTL fuel (Abu-Jrai et al., 2006; Ng et al., 2008; Schaberg et al., 2005; Szybist et al., 2005; Huang, et al., 2007; Zhang, et al., 2007). GTL-biodiesel blends demonstrated higher NO_x than neat GTL, but lower values than individual biodiesel like JBD, BSOY (Lapuerta et al., 2010; Moon et al., 2010; Nabi et al., 2009). The high bulk modulus of biodiesel advanced the injection timing in blends, which yields earlier combustion, followed by a long residence time, and resulted high NO_x emissions (Boehman et al., 2004; Nuszkowski et al., 2008; Tat et al., 2000). In GTL-biodiesel blends, the temperature of the premixed combustion phase is quite high due to the high ROHR values. In addition, high percentages of unsaturated fatty acids, which contain double bonds, could also be responsible for higher NO_x emission up to 12% in GTL-JBD blended fuels than diesel (Ban-Weiss et al., 2007; Moon et al., 2010; Nabi et al., 2009). On the contrary, a study reported an improvement in NO_x emission for biodiesel, but higher NO_x was observed for GTL–biodiesel blends, compared to biodiesel (Lapuerta et al., 2010).

GTL fuel contains properties like zero sulfur, low aromatics and high H/C ratio, which might suppress the formation of particulate precursors, whereas, the rapid progress of diffusion combustion also assist in lowering the smoke emission about 22-73% than diesel (Yongcheng et al., 2006). Several studies illustrated that GTL-biodiesel blends resulted reduction of smoke opacity than neat diesel and GTL fuel (Lapuerta et al., 2010; Nabi et al., 2009). The presence of bonded oxygen and the absence of aromatics in biodiesel ensured local fuel rich mixture to fuel lean mixture, and associated with enhanced combustion efficiency, which yielded low smoke emission in blends (Lapuerta et al., 2008; Nabi et al., 2000).

2.6 Summary of engine performance-emission parameters of GTL fuel and its blends

This section presents a summary of engine performance and emission results of all previous studies of GTL fuel in Table 2.2 and Table 2.3, respectively.

Table 2.2: Engine performance feature of GTL and GTL blended fuels.

Engine Specifications	**Operating Conditions**	**Test results**			**References**
		Power/Torque	Efficiency , **η**	BSFC	
Lister-Petter TR1 Engine 1-Cylnider, 0.773L, DI, NA	Variation of Speed: 1200,1500RPM, Variation of load: 25%,50% Injection timing : 22°CA BTDC Fuel: ULSD,GTL EGR, REGR	N/A	@1200 RPM : It showed ↓trend @1500RPM it showed ↑ trend. Overall ↑ At medium load than lower load.	N/A	(Abu-Jrai et al., 2009)

Engine 1: **4-cylinder in line, 2L** **DI, CR:18.2:1, TC, 1400rpm** **Common rail** **Engine 2:** **4-cylinder in line,4L,** **DI, CR:18.0:1, TC, 1800rpm** **Common rail** **Engine 3:** **8L, 6-cylinder in line,** **DI, CR:18.0:1, TC, 1620rpm** **Common rail**	Variation in RPM and BMEP Fuels: 3 categories of GTL and a reference Diesel fuel	**At full load** About 2-5 %↓ in maximum power output & About 4-7 % ↓ in peak torque was exhibited by GTL than ref. DF	In case of each RPM data set and with ↑BMEP all fuels showed ↓trend without variation among them,	N/A	(Uchida et al., 2008)
Cummins Euro III diesel engine, **6-cylinder ,5.9L, CR: 17.5** **TC , Inter Cooled,** **RP: 136KW, RS: 2500rpm** **common rail,**	Full load, Variation of Speeds, Variations of power, Fuels used: GTL fuel, Diesel Fuel(DF)	Both fuels demonstrated ↑trend with ↑speed. GTL showed marginally ↓ than DF. GTL exhibited respectively 1.9%↓ and 1.3% ↓ max power and peak torque than ref. DF	Both fuel showed common ↑trend with ↑power GTL showed ↓ **η** than DF. Highest thermal efficiency ↓ from 39.6% of diesel to 38.7% of GTL.	**Volume basis analysis(VBA):** both fuels showed ↓trend with ↑ power. GTL showed 3.8% ↑ than diesel **Mass basis analysis(MBA)s:** both fuels showed ↓trend with ↑ power. Overall, BSFC in MBA was ↑than VBA for GTL.	(Wang et al., 2009)

CRDI diesel engine, 4-cylinder, 2L, CR:17.7 TC, Inter-cooled, , Common Rail	Variation of speed: 1500,2000,2500 RPM, Variation of Load **Fuels used:** Diesel and GTL fuel; **Fuel blends:** D+BD20 **(** 80% diesel +20% biodiesel by vol**)**; G + BD20 **(** 80% GTL + 20% biodiesel by vol **)**; G + BD40 **(**60% GTL + 40% biodiesel by vol**)**.	N/A	N/A	Overall ↑ with + of GTL in biodiesel blend except In low speed and load conditions (1500 and 2000 rpm and BMEP of 0.4 MPa). G + BD40 showed the highest at all operating conditions.	(Moon et al., 2010)
Diesel Engine , 4-Cylinder, 2L ,CR:16:1 TC ,Intercooled Common rail,	Fuel Used: EURO 4 DF and GTL fuels of two types: J series(higher cetane number) N series(lower cetane number)	@100% load Maximum torque for all GTL samples is similar with DF.	N/A	All fuel showed ↓ BSFC with ↑ load.	(Koji Kitano et al., 2005-10-24)

Lister-Petter TR1 Engine **1-Cylnider , 0.773L, CR: 15.5** **DI, NA,** **RP: 8.6KW RS: 2500RPM**	Variation in Load and EGR Fuel used: GTL ULSD GD50: ULSD-GTL blend (50/50 by vol %) and GTL adv (advanced injection 4°CA)	N/A	**Without EGR:** With ↑ load all fuels showed ↑ **η** GTL showed ↑ **η** than ULSD. ++ GTL in blend also ↑ efficiency. **With EGR:** @lower load(IMEP 2bar): GTL showed highest **η followed by** GTL adv,GD50 and DF @medium load(IMEP 3-4bar) and higher load(IMEP 5bar): GTL adv. showed highest **η** followed by GTL,GD50 and DF	**Without EGR:** With ↑ load all fuels showed ↓BSFC. GTL showed ↓BSFC than ULSD. ++ GTL in blend also↓ BSFC.	(Abu-Jrai et al., 2006)
Mitsubishi Diesel Engine, **1-cylinder, 2L, 4S ,** **CR: 17.5,** **DI , NA** **RS:1500rpm**	Constant Speed: 1500rpm Variation in injection timing**(IT)** Fuels Used: DF and GTL	N/A	**@Fixed injection timing:** **(-15° ATDC)** **η** ↑ in all fuels with ↑load @↓ load, GTL and DF showed similar values. @ ↑ load, GTL showed 3% ↓ than DF. **@Variable injection timing:** ↓ IT BSFC ↓linearly for all fuels. For GTL ↓ rate was ↓than DF.	N/A	(Oguma et al., 2002)
Nissan diesel engine **4-cylinder, 2L, 4S ,** **CR: 18.1 ,** **DI, TC, Intercooled** **RP: 82KW** **RS:4000rpm**	Variation of Speed and load Fuels used: Diesel fuel(DF) GTL fuel Soybean Biodiesel	Torque ↑ with ↑ speed for all fuels.	**η** ↑ with ↑ load. observed for all fuels.	BSFC ↓ with ↑ load. GTL showed lowest among all fuels. G30B70 was ↑ than GTL and DF but ↓ than BSOY.	(Lapuerta et al., 2010)

Common Rail, Pilot injection	(BSOY) GTL-Biodiesel blend (G30B70)				
Diesel engine **6-cylinder ,8.27L, 4S ,** **CR: 18 , , DI, TC, Intercooled** **RP: 184 KW,RS: 2200rpm** **Common Rail**	9° CA, @ full load. Fuel used**:** Diesel ,GTL(G100) GTL blends: G10(10%GTL + 90% DF) G20 (20%GTL + 80% DF) G30 (30%GTL + 70% DF) G50 (50%GTL + 50% DF) G70 (70%GTL + 30% DF)		**η** ↑ with ↑ load for all fuels. G100 showed slightly ↑ by 1.2% than DF @ all engine operating conditions.	BSFC ↓ for GTL and GTL blends than DF. G100 showed 2.7%↓ than DF.	(Huang, et al., 2007)
Diesel engine **6-cylinder ,6.37L, 4S** **CR: 17.4, DI, NA, water-cooled** **RP: 205 KW,RS: 2300rpm** **Common Rail**	Variation in load and speed. Fuels used: GTL RME DF			BSFC ↑ @ higher speed but no variation @mid-lower speed. GTL showed ↓BSFC than other fuels.	(Hassaneen et al., 2012)

Medium-duty Diesel Engine 6-cylinder, 8.27L, 4S, CR: 18.1, DI, TC, Intercooled RP: 184KW,RS: 2200rpm Common Rail	Variation in speed @full load. Fuels used: GTL,DME and DF	Power ↑ with ↑ speed for all fuels. @ low speed GTL showed ↓ power than DME but same power rating @ mid-higher speed.			(Xinling & Zhen, 2009)
Light-duty Diesel Engine 4-cylinder, 8.27L, 4S CR: 17.5 , DI, TC, RP: 103 kW, RS: 4000rpm Common Rail	Constant Torque (64Nm) and Speed (2400RPM). Variation @ start of Injection (SOI) Single and Pilot Injection. Fuel Used**:** Low sulfur diesel (BP15) Bio-diesel(B100) and GTL		**@single and spilt injection:** All fuels showed ↓**η** for -SOI (advanced) but ↑ **η** observed for +SOI(retarded). GTL showed ↓ 2.5% **η** for **-**SOI but ↑4.2% for +SOI.	**@single and split injection:** All fuels showed ↑BSFC for +SOI but ↓BSFC observed for -SOI. GTL showed ↓ BSFC about 2% for **-**SOI, 8% for +SOI compared to BP15.	(Armas et al., 2010)
Light-duty Diesel Engine, 4-cylinder, 2.5L, 4S , CR: 17.5 , DI, TC RP: 103 kW, RS: 4000rpm Common Rail	Variation in speed(1850rpm, 2400rpm) Fuel Used: Ultra Low Sulfur diesel fuel(BP15), Soybean Methyl Ester (B100), GTL	**@single and split injection:** All fuels showed almost similar trends. GTL demonstrated slightly ↑ BMEP than all.	**@single injection:** In all test mdiesele GTL showed ↑ or similar η as BP15 and B100 was the lowest. **@split injection:** About 5%↑ **η** demonstrated by GTL compared to BP15 than single injection.	**@single injection:** GTL showed ↓BSFC among all fuels. **@split injection:** @load ↓, BSFC ↑1.4% but in ↑load 2%-5% BSFC↓ observed compared to BP15 than single injection.	(Yehliu et al., 2010)
Diesel Engine, 6-cylinder, 10.6L, 4S CR: 18:1 , DI,TC RP: 280kW, RS: 1800rpm	Optimum speed 1450rpm, 20° CA BTDC **Fuels Used:** DF and GTL,	**N/A**	All fuels showed ↑ η with ↑load. GTL,DF showed identical **η in** all load but BD 50 showed ↓ **η** @ higher load.	All fuels showed ↓ BSFC with ↑load. GTL showed lowest BSFC. +GTL % in blend exhibited	(Nabi et al., 2009)

common rail	GTL-Jatropha biodiesel (JB) blends**:** B25 (25% JB+75% GTL), B50(50% JB+ 50% GTL)		↓BSFC but +JB% in blend resulted ↑BSFC.

Table 2.3 : Engine emission features of GTL and GTL blended fuels.

Engine Specifications	**Operating Conditions**			**Test results**			**Reference**
		CO	HC	NO_x	Smoke ,Noise/ SOOT	PM	
Lister-Petter TR1 Engine, 1-Cylnider ,0.773 L DI, NA	Variation of speed and load .1200,1500RPM, 25% ,50% Load Injection timing 22°CA BTDC, EGR, REGR Fuel: ULSD and GTL	**@low load** ↑with REGR **@medium load** ↓ with REGR Overall CO↑ for GTL than ULSD.	**@low load** ↑with REGR **@ medium load** ↓ with REGR	**@low load** With (GTL+EGR) NO_x ↓ and (GTL +30%REGR) exhibited 75% ↓ NO_x than ULSD. **@medium load** With (GTL +10%REGR) 40%↓ NO_x than ULSD.	**@ low load** With (GTL+EGR) ↑↑ but (GTL+30% REGR) exhibits 60% ↓ than ULSD. **@medium load** (GTL +10%REGR) 10%↓ than ULSD.	**N/A**	**(Abu -Jrai et al., 2009)**
Mercedes-Benz Euro 3 engine, 6-Cylnider, 6.37L, CR: 17.4, TC, IC, RS: 2300RPM RP: 205KW	13-mdiesele European Stationary Cycle; Fuels: Diesel(DF),GTL RME and RSO	All fuels exhibited below Euro 3 limits. GTL showed ↑ CO compared to other fuels.	All fuels were within Euro 3 marginal limit. GTL showed similar values with other fuels.	Except GTL and DF other fuels were beyond Euro 3 limit. GTL was lowest.	**N/A**	All fuels were within Euro 3 marginal limit. GTL showed second lowest.	**(Krahl et al., 2009)**

Engine 1: **4-cylinder in line,2L DI, CR:18.2:1, TC, 1400rpm Common rail** **Engine 2:** **4L, 4-cylinder in line,** **DI, CR:18.0:1, TC, 1800rpm Common rail** **Engine 3:** **8L, 6-cylinder in line,** **DI, CR:18.0:1, TC, 1620rpm Common rail**	Variation in speed and power **Fuels:** GTL A (similar distillation temp. with DF), GTL B(↑distillation temp. than DF), GTL C(↓distillation temp. than DF) and Diesel **Test Mdiesele:** Steady State and Transient emission test (engine out + aftertreatment)	**N/A**	**Steady State:** **With pilot injection:** All GTL exhibited ↓HC than DF except GTL C which showed marginally higher HCs than DF. **Without pilot injection:** CO ↓ for all GTL fuels than DF.	**Steady State:** All fuels demonstrated ↓trend @ low-medium load but ↑trend @higher load. Exception: In engine 1 GTL C showed slight ↑ NO_x @ low-medium load. **Transient state:** Both (engine out + aftertreatment) mdieseles showed similar trend with steady state.	**Steady State:** **With pilot injection:** GTL exhibited ↓ smoke than DF. GTL C showed 50% NO_x ↓in all engines than DF. **Without pilot injection:** ↓ NO_x for each fuel than with pilot injection.	**Steady State:** ↓PM for all GTL fuels in all test engines than DF. **Transient state :** ↓↓PM significantly in all GTL fuels than in DF irrespective of all test engines. SOF, IOF both were ↓ in GTLs than DF. Overall Transient PM emission was ↑ than steady state.	**(Uchida et al., 2008)**
Cummins Euro III diesel engine, 6-cylinder, 5.9L CR:17.5,TC,IC RP:136KW, RS:2500rpm common rail,	European Steady-State test Cycle (ESC) FUELs Used: GTL fuel, Diesel Fuel(DF)	CO ↓ for GTL than DF about 38% in avg . In ESC cycle maximum 19.3% ↓ observed with GTL than DF	**Total HC for GTL ↓** than DF in a range of 31–55%. In ESC cycle maximum 19.8% ↓ observed with GTL than DF.	maximum 13% NO_x ↓ for GTL than DF In ESC cycle maximum 5.2% ↓ observed with GTL than DF.	**N/A**	In ESC cycle maximum 33% ↓ observed with GTL than DF.	**(Wang et al., 2009)**
CRDI diesel engine, 4-cylinder ,2L CR:17.7 ,TC,IC, Common Rail,	Variation of speed Variation of Load Fuels used: DF and GTL fuel; Blends: D+BD20 (80% diesel + 20% biodiesel by vol); G + BD20 (80% GTL+ 20%	Significantly CO ↓ for GTL than DF. ++ BD in GTL blends ↓↓ CO observed. G + BD40 showed 30% ↓ than DF.	Significant HC↓ for GTL than DF. ++ BD in GTL blends further ↓↓ HC observed. G + BD40 showed 40% ↓ HC than DF.	NO_x ↓ observed for GTL than DF under all conditions. With ++ Biodiesel concentration in blends NO_x ↑↑.	**N/A**	**With EGR:** <u>Nucleation mdiesele:</u> PM ↑ for GTL than DF <u>Accumulation mdiesele:</u> Significant PM ↑ for GTL than DF **Without EGR:** <u>Nucleation mdiesele:</u> about 30%, 18%, 27%, and 40% ↓in D + BD20, GTL, G + BD20, and	**(Moon et al., 2010)**

	biodiesel by vol); G + BD40 (60% GTL + 40% biodiesel by vol).					G + BD40 respectively than DF <u>Accumulation mdiesele:</u> About 36%, 29%, 43%, and 52% ↓ for D + BD20, GTL,G + BD20, and G + BD40, respectively than DF.	
Diesel Engine , 4-Cylinder ,2L, CR:16:1, TC,IC Common rail,	Variation of load, speed and EGR rating. Fuel Used: EURO 4 DF and GTL fuels : J series(higher CN), N-series(Lower CN)	**Transient state:** GTL fuels exhibited about 60-70% ↓CO than DF.	**Steady state :** @ low load(0.19MPa) HC↑, with %EGR ↑ but all GTL showed ↓ HC than DF. J series showed ↓ HC than N series. **Transient state:** GTL fuels exhibited about 60-70% ↓ than DF.	**Steady state :** With ↑EGR at ↑CN NO_x ↓ **Transient state:** ↓EGR leaded to NO_x ↑.	**@medium load** (0.6MPa) With %EGR ↑, smoke ↑ but noise ↓; All GTL fuels showed significant ↓smoke than DF .	**Steady state :** **@max EGR,** PM ↓ observed by lowering T90 of GTL in all loads. N2 showed 50% ↓ than DF. **Transient state:** PM ↓↓ than steady state. N2 showed 70 % ↓than DF.	**(Koji Kitano et al., 2005-10-24)**
Lister-Petter TR1 Engine 1-Cylnider ,0.7L, , CR: 15.5, DI, NA, RP: 8.6KW RS: 2500RPM	Variation in Load and EGR Fuels used: GTL ULSD GD50 :ULSD-GTL blend (50/50 by vol% and GTL adv. (advanced injection 4°CA)	N/A	N/A	**Without EGR:** NO_x ↑for all fuels With ↑load <u>@Lower load</u> GTL showed least NO_x followed by GD50, DF and GTL adv. <u>@Higher load</u> GTL showed least NO_x followed by GD50,GTL adv. and DF **With EGR:** ↑EGR % all fuels show ↓NO_x	**Without EGR:** With ↑load, smoke ↑for all fuels. **With EGR:** ↑EGR % all fuels show ↑smoke <u>@all load (with and without EGR) :</u> GTL adv. showed	N/A	**(Abu-Jrai et al., 2006)**

				<u>@Lower load</u> GTL showed least NO_x followed by GD50, DF and GTL adv. <u>@Medium load</u> GTL showed least NO_x followed by GD50,GTL adv. and DF <u>@Higher load</u> GTL showed least NO_x followed by GTL adv. , GD50 and DF.	min^m NO_x followed by DF, GD50 and GTL.		
Mitsubishi Diesel Engine, 1-cylinder,2L, 4S , CR:17.5, NA ,DI RS:1500rpm	Constant speed 1500rpm Variation in injection timing(IT) Fuels Used: DF GTL Exhaust Gas Analyzer	CO ↑ for both fuels with ↑load. @low load (0.55MPa) GTL showed ↓ emission than DF but with ↑load CO emission of GTL was comparable to DF. **@variable injection timing:** ↑ CO with ↓IT. ↑ Rate was ↓ for GTL than DF.	HC ↑ for both fuels with ↑load. @medium load, GTL showed 60% ↓ HC than DF. **@variable injection timing:** Both fuels were in range of 100 to 130ppm.	NO_x ↑ for both fuels with ↑ load. @higher load, NO_x ↓ for GTL than DF. **@variable injection timing:** NO_x ↓ for GTL than DF with ↓ IT.	Soot ↑ for both fuels with ↑load . GTL showed ↓ soot than DF except @low load. **@variable injection timing:** Soot ↑ for both fuels with ↓ IT. ↑rate was ↓ for GTL than DF	**N/A**	**(Oguma et al., 2002)**
Nissan diesel engine 4-cylinder, 2L, 4S , CR: 18. ,DI,TC,IC RP: 82KW RS:4000rpm Common Rail,	Variation of Speed and Load; Pilot injection Fuels used: Diesel Fuel(DF) GTL, Soybean Biodiesel (BSOY) GTL-Biodiesel blend (G30B70)	CO ↓ for GTL than other fuels.	HC ↓ with ↑ load for all fuels. GTL showed lowest emission. G30B70 ↑ at higher load than other fuels.	**@lower and higher load** NO_x ↓ trend but **@medium load** NO_x ↑ observed for all fuels.	Smoke ↑ with ↑ load for all fuels. + +bio-diesel in GTL blends ↓smoke. Neat GTL showed ↓smoke than DF but ↑than others.	**@lower and higher load** PM ↑ **@medium load** PM↓ was observed for all fuels. GTL and BSOY showed the lowest emission but G30B70 was only ↓than DF.	**(Lapuerta et al., 2010)**

Diesel engine **6-cylinder, 8.27L, 4S** **CR:18 ,DI,TC,IC** **RP: 184 KW** **RS: 2200rpm** **Common Rail**	Two test mdiesele **@9° CA,BTDC** (i)@ 1400rpm with variation of load. (ii)@full load with variation of speed **and @different pump timings** Fuel used: Diesel and GTL(G100) GTL blends: G10 (10%GTL + 90% DF) G20 (20%GTL + 80% DF) G30 (30%GTL + 70% DF) G50 (50%GTL + 50% DF) G70 (70%GTL + 30% DF)	**@1400rpm,varying load** CO ↑ for all fuels in ↑load ++ GTL % in blends ↓CO G100 showed 26.7% ↓ CO emission than DF. **@full load, varying speed** All fuels showed ↑CO with ↓speed; ↓↓CO @mid-high speed ; @lower speed GTL blends showed higher ↓rate than higher speed than DF. Avg. 38.6%↓CO for GTL observed than DF. **@different pump timings and GTL%:** @all pump timing ++GTL% in blends ↓ CO emissions; ↓ pump timings ↓ emissions. @ at 6°CA G100 emitted ↓ CO by 22.6% and 42.5% than at 9°CA and 12°CA, respectively	**@1400rpm, varying load** @all loading all fuels showed ↓ HC. ++GTL % in blends ↓ emissions. G100 showed 20.2%↓ HC than DF. **@full load ,varying speed:** G100 showed 9.9% ↓ HC emissions than DF. **@different pump timings and GTL%:** @all pump timing ++GTL% ↓HC @ at 6°CA G100 emitted ↓ HC by 3.4% and 8% than at 9°CA and 12°CA, respectively	**@1400rpm varying load** NO_x ↑ for all fuels with ↑load. @all condition ++GTL% in blends ↓ NO_x. G30,G70,G100 respectively showed 4.3%, 9.1%, and 12.1%↓ NO_x than DF. **@full load ,varying speed:** NO_x ↓ for all fuels with ↑speed. ++GTL% in blends↓ NO_x. G30,G70,G100 respectively showed 1.1%, 3.5%, and 8.4% ↓ NO_x than DF. **@different pump timings and GTL%:** @all pump timing +GTL% ↓ emissions; ↓ pump timings ↓ emissions. @ at 6°CA G100 emitted ↓ NO_x by 25.7% and 42.5% than at 9°CA and 12°CA, respectively	**@ 1400rpm varying load** Soot ↑ for all fuels with ↑load. @↑ load GTL showed ↓ soot than DF. @all load conditions G30,G70 and G100 showed↓4.8%,12.2%, 15.6% respectively than DF **@full load ,varying speed:** Soot ↓ for all fuels with ↑ speed. On avg, ++GTL % in blends ↓ soot. G100 ↓15.4% than DF.	**@different pump timings and GTL%** ↓ PM with ↑ pump timings. G100 showed ↓PM by 3.4% and 5.5% at 9°CA and 12°CA than that @6° CA BTDC, respectively.	**(Huang, et al., 2007)**

Diesel engine 6-cylinder, ,6.37L, 4S CR: 17.4, DI,NA, RP: 205 KW RS: 2300rpm Common Rail	Variation in load and speed. Fuels used: GTL RME and DF	All fuels showed CO <EURO 5. @ low and high load ↑CO @ medium load. ↓CO @ ↑speed all fuels emitted ↑CO GTL showed ↑CO than other fuels	All fuels emitted HC < EURO 5. for all fuels ↓HC @↑load ↑HC @ ↑speed GTL showed ↓HC than DF but ↑than RME.	All fuels exhibited ↑ NO_x than EURO 5 limit. ↑NO_x @lower speed than mid-higher ones. GTL showed ↓ NO_x than other fuels.	N/A	GTL showed ↓PM than DF but ↑than RME. Except RME no other fuel matched EURO 5 limits.	**(Hassaneen et al., 2012)**
Medium-duty Diesel Engine 6-cylinder, 8.27L, 4S CR:18.1, DI,TC,IC RP: 184KW RS: 2200rpm Common Rail	Variation in speed (1400rpm & 2200rpm) and load Fuels used: GTL DME and DF	**@low speed:** ↓CO for all fuels @ lower load. Drastic ↑CO @higher load for GTL and DF. But GTL showed ↓CO than DF. **@higher speed:** GTL showed ↓CO than all other fuels @ all load.	@ all speed range no significant variations observed by tested fuels. @higher loads all fuels showed ↓HC. Overall, GTL showed ↓HC than DF but ↑ than DME.	All fuels showed , ↑ NO_x with ↑load. and ↑ NO_x @ lower speed than @mid-higher speed. Overall, GTL showed ↓ NO_x than DF but ↑ than DME.	All fuels showed , ↑smoke with ↑ load. and ↑ Smoke @ lower speed than @higher speed. Overall, GTL showed 22.1 % ↓smoke than DF but ↑ than DME.	N/A	**(Xinling & Zhen, 2009)**
Light-duty Diesel Engine 4-cylinder,8.27L, 4S , CR:17.5 , DI, TC, RP: 103 kW, RS: 4000rpm Common Rail	Constant Torque (64Nm) and Speed (2400RPM). Variation @ start of Injection (SOI) Single injection and Pilot Injection. Fuel Used: Low sulfur diesel (BP15) Bio-diesel(B100) and GTL	**@single injection:** Significant ↑ CO while +SOI (retarding) for BP15 and B100. GTL showed ↓ CO than BP15 by 56%, 70% and 81% for -SOI (advanced), SOI (baseline) and +SOI (retarding) respectively. **@split injection:** B100, BP15 showed ↓CO than previous test mdiesele. No impact for	**@single injection:** Significant ↑ HC while +SOI (retarding) for BP15 and B100. GTL showed ↓ HC than BP15 by 38%, 67% and 78% for -SOI (advanced), SOI(baseline) and +SOI (retarding) respectively. **@split injection:** B100, BP15 showed	GTL showed ↓NO_x than ref. fuel by 22% for –SOI (advanced) and 33% for +SOI(retarding).	N/A	**@single and split injection:** Except B100 all fuels showed similar trends irrespective of SOI variations. GTL showed the lowest emission than other fuels in all SOI variation.	**(Armas et al., 2010)**

		GTL	↓HC than previous test mdiesele. No impact for GTL.				
Light-duty Diesel Engine, DI 4-cylinder, 2.5L, 4S CR: 17.5 ,DI,TC RP: 103 kW, RS: 4000rpm Common Rail	Variation in speed (1850rpm,2400rpm) Variation in injection: split, single. Fuel Used: Ultra Low Sulfur diesel fuel (BP15), Soybean Methyl Ester (B100) and GTL fuel	**@single injection:** In all test mdieseles GTL showed lowest CO than any other fuel.	**@single injection:** In all test mdieseles GTL showed lowest HC than other tested fuels.	**@single injection:** In all test mdieseles GTL showed lowest NO_x. **@split injection:** GTL showed ↑NO_x In some test mdieseles than single injection.	N/A	**@single and split injection:** Among all test mdieseles GTL exhibited lowest PM emission than other fuels.	**(Yehliu et al., 2010)**
Diesel Engine, 6-cylinder,10.6L, 4S CR: 18:1,DI, TC, RP: 280kW, RS: 1800rpm, common rail	Optimum speed 1450rpm and 20° CA BTDC **Fuels Used:** DF, GTL, GTL-Jatropha biodiesel (JB) blends: B25 (25% JB+75% GTL), B50(50% JB+ 50% GTL),	**@medium load**: ↑CO for all fuels than @lower and higher load. With ↑ load: GTL showed 15%↓ CO emission than DF . GTL biodiesel blends B25,B50 showed 7%↓ and 24% ↓ emission than neat GTL	**@lower to higher load** ↓HC for GTL was 5-20% than DF. **@higher load:** GTL blends B25, B50 showed respectively 16%↓ and 54% ↓ HC emission than neat GTL.	↑NO_x with ↑load for all fuels. **@higher load** GTL showed ↓10% emission than DF. GTL biodiesel blends B25, B50 showed 6%↓ and 20% ↓ NO_x emission than neat GTL.	↑smoke with ↑load for all fuels. **@↑ load:** , GTL showed 19%↓ smoke than DF. GTL biodiesel blends B25, B50 showed 25%↓ and 44% ↓ smoke than neat GTL.	GTL showed 21%↓ PM emission than DF. GTL biodiesel blends B25, B50 showed 15%↓ and 24% ↓ emission than neat GTL.	**(M. Nabi et al., 2009)**

2.7 Features of Palm biodiesel

Palm is regarded as a significant feedstock in biodiesel production. In this section the scope of a palm as a potential feedstock and the previous research work performed involving palm biodiesel are discussed.

2.7.1 Feedstock description

The palm plants can be classified in 2600 species and most of those are widely available in the tropical regions. The palm oil is extracted from the *Elaeis guineensis* species, which belongs to the family of *Palmae* (Singh et al., 2010). The origin of palm tree is in wild forest of West Africa. The usage palm oil has been started from 5000 years ago. With the increasing potential of palm oil in transportation and financial aspects, the commercial cultivation had been commenced gradually almost in all tropical areas (Ong et al., 2011; Tan et al., 2009). *Elaeis Guineensis* is the most high-yielding of all species and eligible for mass production in all regions that has hot and humid weather, such as Malaysia and Indonesia. The annual production capacity of this plant is approximately 10-35 tonnes/ha. The palm plants are usually single stemmed with a height of 20-30 m (Edem, 2002). The pinnate leaves are about (3-5) meter in length with small but densely clustered flowers, each of those contains three sepals and petals (Abdullah, 2003). The palm fruit kernel is covered with a fleshy and soft pulpy outer layer. The kernel contains about 20-21% oil (Borugadda & Goud, 2012). Palm oil can be extracted from the pulp and the seed. South East Asia is known as the maximum palm production region in the world. The total production of palm oil in the world is approximately 45 million tonnes/year, and about 87% of total produced oil is supplied by Malaysia, Indonesia and Thailand (as shown in figure 2.3). Comparing the situation from 1990 to 2013, the cultivation area of palm trees in Malaysia have been increased from 2.03 to 4.49, in million hectares, respectively, which results an increase of 121.2% (Indonesia: palm oil pro-duction prospects continue to grow. Washington; United States Department of Agriculture; Palm oil: world supply and distribution. Washington). Figure 2.4 presents a comparative statistics of per hectare oil yield for palm with other prospective biodiesel.

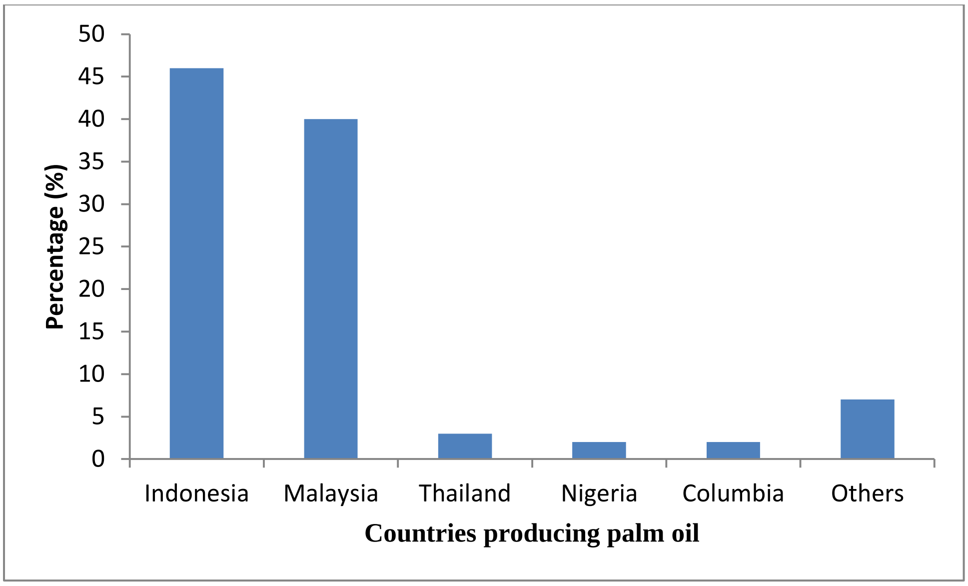

Figure 2.3: World palm oil production 2009 (Bazmi et al., 2011; USDA (United States Department of Agriculture), Palm oil: world supply and distribution. Washington)

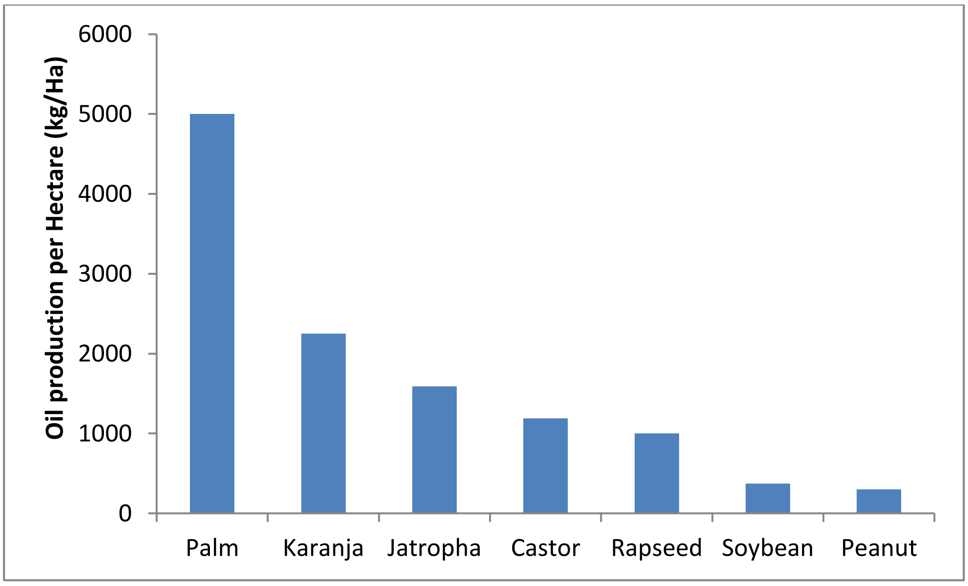

Figure 2.4: Comparison of oil production, per hectare of Palm with other biodiesel feedstock (Gui et al., 2008).

2.7.2 Engine performance

Ndayishimiye & Tazerout (2011) studied performance parameters of different types of palm oil based biofuel, such as palm oil-diesel blends (PO), preheated palm oils (PHO) and methyl or ethyl esters of palm oil and waste cooking oil (PO+WCO) in a single cylinder diesel engine at constant speed with variable loading and compared the results with diesel. A higher BSFC was observed for all of the fuel samples than diesel. On average, PO blends, PHO blends and PO+WCO blends demonstrated lower BSFC about (2-6%), (14-17%) and (17-25%), respectively than those of diesel. The BTE was found marginally higher for the PO blends, whereas, the rest of the blends showed slightly lower values of BTE when compared to diesel. Ng et al. (2012) studied blends (P50, P100) of palm biodiesel with diesel by using a single cylinder diesel engine at different load-speed test conditions. The authors reported higher fuel consumption for the P50 and P100 than diesel due to the lower calorific value of PBD. Besides, the BSFC values showed a proportional trend with speed whereas an inverse trend was observed for variation of load. Sharon et al. (2012) investigated three blends (P25, P50, P75) of PBD-diesel in a single cylinder diesel engine at constant speed with variable load condition. It had been observed that with addition of PBD in the blend, both of the BTE and BSFC values degraded. The authors reported that the decrease of BSFC for P25, P50, P75 and P100 were about 2.59%, 8.93%, 9.25% and 14.55%, respectively than those of diesel. Regarding the BTE, the analysis resulted approximately 30.895%, 30.56%, 29.22%, 29.58% and 28.65%, for diesel, P25, P50, P75 and P100, respectively at full load condition. Ozsezen et al., (2008) studied PBD from waste frying oil and their blends with diesel in an unmodified IDI diesel engine. The authors reported higher fuel consumption of the blends than diesel. It had been observed that BSFC values were increased with the higher quantity of biodiesel in the blends. Ozsezen et al. (2009) also conducted a comparative study between PBD (sourced from waste frying oil) and canola biodiesel in a multi-cylinder diesel engine. It had been observed that PBD showed higher fuel consumption than diesel and canola biodiesel. On average, the BSFC of PBD were about 10% higher than that of diesel. Mofijur et al. (2014) investigated the engine performance of the blends (B5, B10) of diesel-biodiesel using two different feedstock, such as PBD and Moringa oleifera (MOD) at full load with variable speed test conditions in a multi-cylinder diesel engine. The test results showed higher BSFC for the PBD-diesel blends (P5, P10) than diesel, but lower than that of MOD-diesel blends. On average, P5 and P10 showed increase of BSFC about 0.69% and 2.02%, respectively than diesel.

2.7.3 Engine exhaust emission

The emission analysis results of Ndayishimiye & Tazerout (2011) demonstrated reduced CO, HC but increased NO_x emission. The CO emissions were reduced up to 7% for the (PO + WCO) blends, whereas, an increase of 30% was observed for the PO and PHO blends. PHO and (PO + WCO) blends showed about (30-65%) reduction in HC emission, but the PO blends showed an increase of approximately (13-17%), when compared to that of diesel. In case of the NO_x emissions, (PO + WCO) showed higher values than those of the PO blends. Ng et al. (2012) investigated the emission parameters of P50 and P100 blends in several test conditions and reported lower emission of all examined parameters, such as, CO, HC, NO and smoke when compared to diesel. As illustrated by the authors, the maximum reduction achieved by the fuel samples for CO, HC, NO and smoke were approximately 0.89%, 26.2%, 5.35 and 66.7%, respectively, than those of diesel. Sharon et al. (2012) investigated emission parameters of three blends (P25, P50, P75) of PBD-diesel in a single cylinder diesel engine at constant speed with variable load condition. It had been observed that all blends showed lower CO emission and higher NO_x emission than diesel, whereas, variation of results were found for HC and smoke emission. All blends demonstrated lower CO emission in the range of (21.4-52.9%) than that of diesel. Regarding HC emission, only P25 showed higher value about 9.52%, whereas, the other blends showed lower values approximately (9.53- 38.09%) than diesel. Alike HC emission, P25 also showed higher smoke emission about 9.8%, whereas, the other blends demonstrated (10-19%) lower emission than diesel. In case of NO_x emission, the authors reported high emission values for all blends, including neat PBD, due to the high exhaust gas temperature. Ozsezen et al. (2008) studied the emission parameters of PBD and their blends with diesel in an unmodified IDI diesel engine. The authors reported lower CO, HC and smoke emissions of the blends than diesel. The maximum reduction of CO, HC and smoke emissions showed by sample blends were approximately 57%, 40% and 23%, respectively, when compared to those of the diesel. Regarding NO_x emission, the biodiesel blends demonstrated different trends with the variation of engine speed. At lower and medium speed (1500, 2000 and 2500 rpm), all blends showed higher $NO_{x,}$ but lower NO_x at higher speed (3000 rpm) than that of diesel. The emission analysis results from Ozsezen et al. (2009) in a multi-cylinder DI diesel engine were quite similar to the previous study of the authors. It was observed that PBD showed lower values of all emission parameters except $NO_{x,}$ than those of diesel. On average, the reduction of CO, HC and smoke were approximately 67%, 26% and 63%, respectively than diesel. In case of $NO_{x,}$ an increase about 11% was reported for PBD than that of diesel. Compared to canola biodiesel, PBD showed improvement in all emission parameters. The emission analysis results from M. Mofijur et al. (2014) by using blends (B5, B10) of PBD and MOD with diesel at different load-speed condition. PBD-diesel blends (P5, P10) showed a decrease in CO and HC emission, but increase of NO, when compared to diesel. These blends showed overall improvements in all emission parameters than MOD-diesel blends. On average, P5 and P10 showed lower emissions of CO and HC about 13.17% and 17.36%; 14.47% and 18.42%, whereas, higher NO about 1.96% and 3.38%, respectively than those of diesel.

2.8 Features of Jatropha biodiesel

2.8.1 Feedstock description

Jatropha curcus belongs to genus of Jatropha with more than 170 species and a member of the Euphorbiaceae family. It is regarded as a drought-resistant plant, which is originated from Mexico or other neighboring regions of Central America. Gradually, it had been introduced to Africa, Asia and now is being cultivated world-wide. It has been observed that Jatropha cultivation is most successful in tropical regions at low altitudes of 0-500 m, with an average annual rainfall and temperature of 300-1000 mm and 20°C, respectively. It can also thrive in high altitude and moderate frost. The plant is a large shrub or small tree with smooth gray bark and grows up to 5-8 m. The green leaves appear with a petiole of 3–20 cm, and has an orientation of spiral phyllotaxis with 3-5 lobes. Jatropha fruits are ellipsoid in shape, fleshy and green and eventually turns to yellow and at last becomes dry and black when the seeds become mature. Each fruit contains 3 seeds, which are ellipsoid in shape and coarsely pitted. The Jatropha plant seeds have an average oil content of 37%. The oil can be used directly in adapted engines to run in grain mills, biofuel generators, several types of oil press, water pumps, etc. Besides, the trans-esterified oil can be used as a single or blend fuel in diesel engines (Mofijur et al., 2013).

2.8.2 Engine performance

Three blends (J100, J50 and J20) of Jatropha biodiesel (JBD) were used by of Sahoo et al. (2009) to investigate the performance parameters in a CI tractor engine. The blends showed an increase of BSEC about 2.86- 12.37 % than diesel. Bora et al. (2012) prepared a biodiesel (BOMF), and mixed blend (BOMF20) by mixing biodiesel from three feedstock such as, Calophyllum (CIBD), Koroch and Jatropha to conduct a comparative study of the performance parameters of a CI engine, with B100 and B20 blends, prepared from these three biodiesel. All fuel samples showed a decrease of BSFC with the increase of load. At full load condition, BOMF and BOMF20 showed improvement of BSFC and BTE than their respective B100 and B20 blends. In case of BSFC, JBD showed higher values about 3.64%, but J20 showed lower values about 2.44%, respectively than those of BOMF and BOMF20. Regarding BTE, JBD and J20 showed lower values about 0.53% and 0.92%, respectively than BOME and BOMF20. Mofijur et al. (2013) studied two blends (J10, J20) of JBD-diesel in a single cylinder diesel at full load with variable speed test condition. They found higher fuel consumption for the blends than diesel. The BSFC trend was proportional to the biodiesel content of the blends. On average, J10 and J20 showed higher BSFC about 6.75% and 11.4%, respectively, than that of diesel. Rahman et al. (2013) investigated the engine performance of the blends (B10) of diesel-biodiesel using JBD and MOD, at full load with variable speed test conditions in a multi-cylinder diesel engine. The test results showed higher BSFC values for the JBD-diesel blend (J10) than diesel, but lower values than that of MOD-diesel blend. On average, J10 showed an increase of BSFC about 15.12% than diesel. Huang et al. (2010) conducted a comparative study of two biodiesel from Jatropha oil and Chinese pistache oil feedstock in a single cylinder diesel engine, at a constant speed of 1500 rpm and 2000 rpm, with variation of engine power conditions. It had been observed that with the increase in speed, the average fuel consumption was reduced and the BTE was increased. The average decrease of BSFC for JBD was about 9.3% and 6.8% at 1500rpm and 2000rpm, respectively than those of diesel. In case of BTE, JBD showed an average increase about 0.2–3.5% and 0.1–6.7%, respectively for 1500 rpm and 2000 rpm, than those of diesel.

2.8.3 Engine exhaust emission

Bora et al. (2012) studied emission analysis by using a mixed biodiesel (BOMF) and blend (BOMF20), which were prepared from three biodiesel feedstock such as, CIBD, Koroch and JBD. The result demonstrated lower values of CO, HC and smoke emissions than those of their respective B100 and B20 blends. At full load conditions, both BOMF and BOMF20 showed lower emissions than their respective B100 and B20 blends. Regarding CO, HC and smoke emissions, JBD and J20 showed higher values about 11.11% and 17.39%; 10.34% and 4.0%; 16.77% and 13.39%, respectively, than those of BOMF and BOMF20. The investigation of Sahoo et al. (2009) by using 8-mode cycle test illustrated an overall reduction in smoke opacity, HC and PM, but increase in CO and NO_x emission for the three blends of JBD-diesel. The blends showed a reduction of smoke at full throttle condition about 28.57-64.28% than diesel. Besides, the blends demonstrated an increase in CO and NO_x emission about 5.57-35.21% and 15.65-20.54%, respectively, whereas, a decrease was observed in HC and PM emission about 18.19-32.28% and 16.53- 42.06%, respectively than those of diesel.

Mofijur et al. (2013) showed lower CO and HC emission, but higher NO_x emission from the JBD-diesel blends, when compared to diesel. On average, J10 and J20 demonstrated lower values of CO about 16% and 25%, HC about 3.84% and 10.25%, whereas higher NO_x about 3% and 6% than those of diesel. Rahman et al. (2013)

investigated the engine exhaust emission by using blends of JBD and MOD with diesel at different speed with full load condition. The result showed that JBD-diesel blend (J10) showed a decrease of CO and HC emission, but an increase of NO, when compared to diesel. J10 showed overall improvements in all emission parameters than MOD-diesel blend. On average, J10 showed lower emissions of CO and HC about 14% and 16%, whereas, higher NO was observed about 7%, respectively than those of diesel. Huang et al. (2010) showed that JBD and Chinese pistache biodiesel demonstrated lower values of all emission parameters than diesel. At 1500rpm, the average reduction of CO, HC, NO_x and smoke emission for JBD were approximately 20-25 %, 17–23%, 0.3 - 4.5% and 8-35%, respectively than those of diesel. Referring to the same parameters, the emission results of 2000rpm demonstrated reduction of emission about 19-66%, 37–42%, 4.4- 14.5% and 12–57%, respectively than diesel.

2.9 Features of *Calophyllum inophyllum* biodiesel

2.9.1 Feedstock description

Calophyllum inophyllum L. belongs to the Clusiaceae family, and widely grows in warm coastal areas throughout the Pacific and Indian oceans from Madagascar to Tahiti and Marquesas Island (Friday JB, 2006.). The Greek word *Calophyllum* refers to “beautiful leaf” and *inophyllum* denotes to the straight line like veins in the leaves. It was first discovered in the Marianas Island at north, the Ryukyu Islands in southern Japan and Polynesia (Friday JB, 2006). In different regions, *Calophyllum inophyllum* is known as different names, which are presented in Table 2.4.

The plant Calophyllum is a large tree, can be as high as 12-20 m. The grown trees can become wider than height, often leaning with broad and spreading crowns. The bark is grey in colour with flat ridges, and sap is milky white and sticky. The leaves are glossy, oval shaped with elliptical tips and light green in colour, but turn to dark green with aging. Its white flowers has yellow stamens, blooms in a cluster on long stalks in leaf axils. Young fruits are like round green balls, and around 2-5 cm in diameter. Matured fruits are yellow in colour and wrinkled when ripe. A single seed kernel is surrounded by a thin inner layer and this layer is surrounded by a hard shell as shown in Figure 2.5. Kernels of Calophyllum have a very high oil content (75%) and most of them (71%) are unsaturated oleic and linoleic acid. Once grown, a Calophyllum tree produces up to 100 kg of fruits, and about 18 kg of oil. There are about 100-200 fruits/kg in shell with the skin and pulp removed (Dweck AC, 2002).

Table 2.4 : Dialectal names of *Calophyllum inophyllum* in different regions of the world (Friday JB, 2006; Michel, 2005).

Country	Common names
Bangladesh	Punnang
Cook Island	Tamanu
Cambdieselia	Kchyong, Khtung.
English	Beach mahogany, Alexandrian laurel, Beauty leaf, Ball nut.
Fiji	Dilo
Guam	Da’ok, Da’og
Hawaii	Kamanu, Kamani
India	Poon, Polanga, Undi, Sultan champa.
Indonesia	Bintangur, Nyamplung
Kiribati	Te itai
Malaysia	Bintangor, Penang laut
Marquesas	Tamanu
Myanmar	Ponnyet
Northern Marianas	Da’ok, Da’og
Nauru	Tomano
Palau	Btaches
Papua New Guinea	Beach calophyllum
Philippines	Bitaog, Butalau, Palo maria

Solomon Islands	Dalo
Society Islands	Tamanu
Tahiti	Tamanu
Thailand	Naowakan, Krathing, Saraphee

Figure 2.5 : Calophyllum inophyllum plant and seed (Friday JB, 2006).

2.9.2 Engine performance

Three blends (CI100, CI50 and CI20) of Calophyllum inophyllum biodiesel (CIBD) were used by Sahoo et al. (2009) to investigate the performance parameters in a CI tractor engine. The blends showed an increase of BSEC about 2.59-13.31% than diesel. Though all of the blends demonstrated deterioration of BSEC, CI20 showed improvement of BSEC values than the other two blends. Overall, CI20 was declared as the optimum blend. Venkanna & Reddy, (2011) also investigated CIBD and diesel in a DI diesel engine in different range (200-260 bar) of injector opening pressure (IOP). It had been perceived that with the increase of IOP, the BSFC values of CIBD showed decreasing trend, but overall BSFC was marginally higher than that of diesel. With the increase of load percentage, CIBD showed an improvement in BTE values, but alike BSFC, the overall BTE was lower than diesel. Belagur & Reddy, (2010) investigated the variation of injection rate and ignition delay as a function of plunger diameter (PD) on a DI diesel engine by using diesel and a blend (50% by vol.) of diesel-CIBD. With the variation of the PD, both of the injection rate and the ignition delay was synchronized. It had been observed that with the increase of the rate of injection and PD, both diesel and the blend demonstrated high BTE values. Bora et al. (2012) prepared a biodiesel (BOMF) and mixed blend (BOMF20) by mixing biodiesel from three feedstock such as, Calophyllum, Koroch and Jatropha to conduct a comparative study of the performance features of a CI engine with respect to B100 and B20 blends of these three biodiesel. All fuels showed decrease of BSFC with the increase of load. At full load condition, BOMF and BOMF20 showed improved BSFC and BTE than the respective B100 and B20 blends. CIBD and CI20 showed higher BSFC about 2.06% and 2.24%, respectively than those of BOMF and BOMF20. Regarding BTE, CIBD and CI20 showed lower values about 0.61% and 3.57%, respectively than BOME and BOMF20. Mohanty et al. (2011) investigated engine emission-performance features by using three blends (CD10, CD30 and CD50) of Calophyllum oil with diesel. The result showed improvement of BSEC and BTE of the blends than diesel. The results obtained at full load engine test condition showed that diesel, CD10, CD30 and CD50 demonstrated BTE values approximately 28.6%, 28.96%, 28.73% and 28.28%, respectively. In case of BSEC, CD10 and CD30 showed lower values than that of diesel. Sahoo et al. (2007) investigated CIBD, high speed diesel (HSD) and their blends of 20%, 40%, 60%, 80%, and 100% in a single cylinder diesel engine at different engine load-speed condition. The study results revealed that the performance parameters of CIBD and its blends were better than diesel. Overall, neat CIBD showed best BTE (about 0.1% improvement) and BSEC than other fuel blends. Fattah et al. (2014) conducted experiments on IDI diesel engine by using various blends (10% and 20%) of Alexandrian laurel biodiesel (also known as CIBD) at constant load-variation of speed conditions. The analyses showed higher BSFC about 2.42–3.20% and lower BTE about 0.87-1.14% of the CIBD blends than diesel.

2.9.3 Engine Exhaust Emission

Sahoo et al. (2009) applied 8-mode cycle test to study emission parameters of the three blends of CIBD-diesel. The study reported an overall reduction in smoke opacity, HC and PM, but an increase in CO and NO_x. A diminution of smoke opacity of CIBD blends was observed with the increase of CIBD quantity in blends, while testing at full and part throttle positions than those of diesel. Neat CIBD showed maximum reduction of smoke opacity of all fuel samples, which was about 1/9th of diesel. Besides, a discernible diminution of HC emission about 4.3–32.28%, and PM emission about 9.88–45.48% was observed for CIBD and the blends, whereas, an increase of NO_x about 4.15–22.5% and CO about 5.57–35.21% were observed than those of diesel. Emission analysis results from the investigation of Sahoo et al. (2007) showed that the blends of CIBD-HSD, and neat CIBD showed reduction in smoke opacity, NO_x and HC emission. Considering the maximum reduction of emission parameters, B60 showed about 65% lower smoke emission, and B100 showed about 4% reduced NO_x emissions than those of diesel. The exhaust emissions analysis results from Fattah et al. (2014) showed diminution of CO, HC and smoke emission, except NO_x. On average, the CIBD blends demonstrated reduced CO about 15.12–26.84%, HC about 9.26–17.04%, and smoke about 7.78-13.28%, whereas, higher NO_x about 2.12–8.32% was observed than those of diesel. Bora et al. (2012) studied the exhaust emission parameters by using a mixed biodiesel (BOMF) and blend (BOMF20), which were prepared from three feedstock such as, Calophyllum, Koroch and Jatropha. The reported lower values of CO, HC and smoke emissions than that of their respective B100 and B20 blends. At full load conditions, both BOMF and BOMF20 showed lower emissions than their respective B100 and B20 blends. Regarding CO, HC and smoke emissions, CIBD and CI20 showed higher values about 15.79% and 19.72%; 13.33% and 5.26%; 19.89% and 16.98%, respectively, than those of BOMF and BOMF20. Venkanna & Reddy, (2011) reported a reduction in CO, HC and smoke emissions by CIBD blends, when compared to diesel. It was observed that an increase in injection rate could result proper combustion, which assisted to attain higher injection pressure and suitable spray formation. All of these resulted the diminution in CO and HC emission. Approximately 11%-20% diminution of smoke opacity was observed for CIBD than that of diesel at higher load. Belagur & Reddy, (2010) reported that both of the CO and HC emission were reduced while using PD of 10 mm than PD of 8mm for the CI50 blend. The authors predicted that the increase of NO_x emission might be related with the increase of temperature and the in-cylinder pressure, which were dependent on PD and other operating conditions. Unlike HC and CO emission, CI50 showed an increase in NO_x, while increasing the PD. The maximum NO_x was observed for PD of 10 mm, but the NO_x emission of CI50 was less than that of diesel. The results of emission analysis from the study of Mohanty et al. (2011) illustrated an increase in CO and HC emission, but lower NO_x emission from the sample fuel blends (CI10, CI30, CI50) than those of diesel. It was observed that CI30 showed less HC formation than the two other blends. In case of NO_x emission, CI10 and CI50 demonstrated much lower values than diesel.

From the point of view of the authors, the combined effect of the higher CN and lower calorific values of CI10 and CI50 blends resulted this decrease in NO_x emission

2.10 Summary of engine performance-emission parameters of biodiesel

Table 2.5 : Research findings of different performance parameters for Palm, Jatropha and Calophyllum inophyllum biodiesel.

Performance parameter	Palm biodiesel	Jatropha Biodiesel	Calophyllum inophyllum biodiesel
BSFC increase	(Lin et al., 2006); (Yusaf et al., 2011); (Ndayishimiye & Tazerout, 2011); (Almeida et al., 2002); (Leevijit & Prateepchaikul, 2011);	(Sahoo et al., 2009); (Bora et al., 2012); (Mofijur et al., 2013); (Rahman et al., 2014);	(Sahoo et al., 2009); (Venkanna & Reddy, 2011); (Bora et al., 2008); (Fattah et al. 2014);
BSFC decrease		(Huang et al., 2010);	(Mohanty et al., 2011); (Sahoo et al. 2009);
BTE increase	(Almeida et al., 2002); (Ndayishimiye & Tazerout, 2011)	(Huang et al., 2010);	(Mohanty et al., 2011); (Sahoo et al. 2009);

BTE decrease	(Leevijit & Prateepchaikul, 2011); (Ndayishimiye & Tazerout, 2011);	(Bora et al., 2012);	(Belagur & Reddy, 2010); Bora et al., 2008). (Fattah et al. 2014);

Table 2.6 : Research findings of different emission parameters for palm, jatropha and calophyllum biodiesel.

Emissions	Palm biodiesel	Jatropha biodiesel	Calophyllum inophyllum biodiesel
Smoke opacity increase			(Belagur & Reddy, 2010);
Smoke opacity decrease	(Leevijit & Prateepchaikul, 2011); (Ozsezen & Canakci, 2011);	(Bora et al., 2012); (Sahoo et al., 2009); (Huang et al., 2010);	(Venkanna & Reddy, 2011) ;(Sahoo et al., 2009); (Bora et al., 2008);
CO increase	(Almeida et al., 2002); (Yusaf et al., 2011); (Ndayishimiye & Tazerout, 2011);	(Sahoo et al., 2009)	(Mohanty et al., 2011); (Belagur & Reddy, 2010); (Sahoo et al., 2009);
CO decrease	(Leevijit & Prateepchaikul, 2011); (Kalam & Masjuki, 2002); (Ozsezen & Canakci, 2011); (Kalam & Masjuki, 2004);	(Bora et al., 2012); (Mofijur et al., 2013); (Rahman et al., 2014); (Huang et al., 2010);	(Venkanna & Reddy, 2011); (Bora et al., 2008);

HC increase	(Almeida et al., 2002); (Ndayishimiye & Tazerout, 2011);		(Mohanty et al., 2011); (Belagur & Reddy, 2010); (Venkanna & Reddy, 2011);
HC decrease	(Ndayishimiye & Tazerout, 2011); (Kalam & Masjuki, 2002); (Ozsezen & Canakci, 2011); Kalam & Masjuki, 2004).	(Bora et al., 2012); (Sahoo et al., 2009); (Mofijur et al., 2013); (Rahman et al., 2014); (Huang et al., 2010);	(Sahoo et al., 2009); (Bora et al., 2008);
NO_x increase	(Leevijit & Prateepchaikul, 2011); (Kalam & Masjuki, 2004); (Ozsezen & Canakci, 2011); (Ndayishimiye & Tazerout, 2011);	(Sahoo et al., 2009); (Mofijur et al., 2013); (Rahman et al., 2014);	(Belagur & Reddy, 2010); (Sahoo et al., 2009); (Bora et al., 2008);
NO_x decrease	(Yusaf et al., 2011); (Almeida et al., 2002); (Kalam & Masjuki, 2002); (Ndayishimiye & Tazerout, 2011); (Kalam & Masjuki, 2004);	(Huang et al., 2010);	(Mohanty et al., 2011); (Venkanna & Reddy, 2011).

CHAPTER 3: METHODOLOLOGY

3.1 Fuel Blend preparation

All of the fuel blends were prepared in University Malaya heat engine laboratory before the characterization of fuel blends and engine test. A calculated volume of two fuels were taken into a glass jar, which was attached with a homogenizer device. The homogenizer device consists of an electrical stirrer with adjustable arm and variable rpm settings. With the adjustable arm it can be positioned within the level of sample fuels in glass jar. For preparing each sample fuel blend the homogenizer was set at 2000RPM for 30 minutes. After that the stirred blend was placed in the digital shaker for more 30 minutes at 400rpm. The blend sample was removed from the shaker and observed for 12hrs to ensure that no phase separation was occurring. All blend compositions are listed in the Table 3.1.

Table 3.1: Blend fuel compositions (% vol.).

No.	Fuel Samples	Samples description
01	Diesel	100% diesel fuel
02	GTL	100% Gas-to-liquid fuel
03	P20	20% PBD + 80% Diesel
04	J20	20% JBD +80% Diesel
05	CI20	20% CIBD +80% Diesel
06	G20	20% GTL fuel + 80% diesel fuel
07	G30	30% GTL fuel + 70% diesel fuel
08	G50	50% GTL fuel + 50% diesel fuel
09	DPG20	50% diesel + 30% PBD + 20% GTL fuel
10	DJG20	50% diesel + 30% JBD + 20% GTL fuel
11	DCIG20	50% diesel + 30% CIBD + 20% GTL fuel

3.2 Equipment and property characterization methods of fuel samples

The instruments required for the characterization of all sample fuels are in the Energy Laboratory and the Engine Tribology Laboratory, Department of Mechanical Engineering, University of Malaya. Table 3.2 shows the in-detail specification of the equipment and method used to determine fuel properties.

Table 3.2: Equipment used to test fuel properties.

Property	Equipment	Method	Manufacturer	Standard method	Accuracy
Kinematic viscosity and density	Stabinger Viscometer	SVM 3000	Anton Paar	ASTM D7042	± 0.1 mm^2/s
Flash point	Pensky–martens flash point tester	NPM 440	Normalab, France	ASTM D93	± 0.1°C
Cloud and pour point	Cloud and pour point tester	NTE 450	Normalab, France	ASTM D2500	± 0.1°C
Calorific value	Semi auto bomb calorimeter	6100EF	Perr, USA	ASTM D240	± 0.1% of reading
Oxidation stability	Rancimat testing machine	873 Rancimat	Metrohm, Switzerland	EN 14112	± 0.01 h
Calorific Value	Auto bomb calorimeter	C2000 basic calorimeter	IKA, UK	ASTM D240	±.0.1%

3.2.1 Density and viscosity measurement

The digital Stabinger viscometer (SVM 3000), manufactured by Anton-Paar, was used to measure the viscosity and density simultaneously. The equipment as shown in figure 3.1 operates on ASTM D7042 method and measures dynamic viscosity (mPa-s) and density (kg/cm^3) to provide kinematic viscosity (mm^2/s) values equivalent to ISO 3104 or ASTM D445 standard.

Figure 3.1: SVM 300 Stabinger viscometer.

This equipment can be used for 10 predefined standard to measure values by selection of mode from menu. An automated initial test starts after switching on the instrument. When it becomes ready for test, a window appears to insert the sample fuel. To calculate density and viscosity of any sample fuel, approximately 3 ml of fuel needs to be inserted in the test chamber. For every sample test, it compares two consecutive data to maintain the accuracy level within 5%. After every successful test, the machine chamber was purged with toluene in order to clean and prepare for the next test sample. This machine can measure viscosity from less than 1 up to 20,000 mm^2/s.

3.2.2 Flash point measurement

To measure the flash point of the sample fuels, the HFP 380 Pensky–Martens flash point tester as shown in Figure 3.2, was used in this study. It operates on ASTM D93 standard. This instrument measures the flash point by increasing the temperature of fuel sample placed in a closed cavity, while a small flame is kept passing over the fuel at a regular interval to make the fuel vapour ignite.

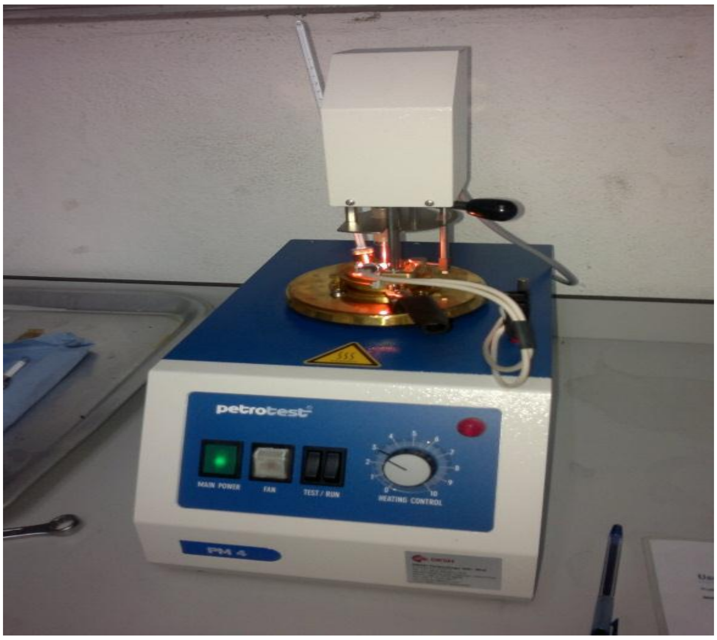

Figure 3.2: HFP 380 Pensky–Martens flash point tester.

The temperature at which the produced fuel vapour is about to ignite by the incorporated small flame, is recorded by the flash point tester. For each test, about 60 ml of the sample fuel were placed in the test cavity, and closed with the cork, which was equipped with required sensors and igniter. At the beginning of the test, a guess value of the flash point was required to start the spark igniter from that temperature. After launching the test, the temperature starts to rise from the room temperature, and when it reaches at the given spark igniter value, the sparking procedure is initiated by the tester until the flash point was found. After the test of a sample, the tester cavity was cleaned properly to ensure that no residue of the previous sample was left, which could corrupt the next test sample.

3.2.3 Calorific value measurement

The IKA C2000 Auto bomb calorimeter (as shown in Figure 3.3) was used to find the calorific values of the sample fuels.

Figure 3.3: IKA C2000 Auto bomb calorimeter.

This is a constant volume type instrument, which calculates the heat generated from a definite chemical reaction. The burning of the sample is initiated electrically. While burning, the surrounded air gets heated and escapes through the copper tube. Thus, the temperature of the water surrounded by the tube increases and the sensors in calorimeter record this to calculate the calorific content of the fuel sample. It requires 0.5 gm of a fuel sample to run the test. At first, each fuel sample was weighed in a digital micro balance. After that it was placed in to the insulated container of the bomb calorimeter. Then the hatch is closed and test starts. When the test is finished the alarm beeps, the hatch opens automatically and the result appears at the digital screen. The residue of the sample fuel is cleaned and the system was prepared again for the next test. The system is fully automated and much convenient to use.

3.2.4 Cloud point (CP) and pour point (PP) measurement

In this study NTE 450 (Normalab, France) was used to test the cloud and pour point of fuel samples. As shown in the Figure 3.4, this machine measures CP and PP according to ASTM D2500 and ASTM D93 standard, respectively. At first, the test assembly was checked for the appropriate level of the methanol to perform the test. To initiate the test, the tester need to attain the temperature approximately, -45 degree Celsius.

Figure 3.4: NTE 450 (Normalab, France) CP. PP tester.

Then the fuel sample was poured in to the test tube and positioned in the system. After closing the hatch, a guess value was entered for the cloud point. When the temperature reached at the guess value the hatch opened at an interval of 5 minutes to check that the cloud point was reached or not. After the cloud point result, the tester continued to find out the pour point. The results of CP and PP were displayed in the digital screen after the completion of tests.

3.2.5 Oxidation stability testing

Oxidation stability of samples was evaluated with commercial appliance Rancimat 743 (as shown in Figure 3.5) according to EN 14112 specification. The end of the induction period (IP) was determined by the formation of volatile acids measured by a sudden increase of conductivity during a forced oxidation of ester sample at 110 °C with airflow of 10 L/h passing through the sample.

Figure 3.5: Rancimat 743 tester.

However, during the experiment following procedure was followed:

- The heating block is heated up to the 110° C temperature.

- The measuring vessel is filled with 60 mL deionized water and placed on the Rancimat together with the measuring vessel cover. For long analysis times (> 72 h), it is recommended to increase the volume to compensate evaporation loss.

An evaporation rate of 5-10 mL water per day has to be taken into account. It has to be ensured that the electrode is immersed into the measuring solution at any time.

- For each determination, a new reaction vessel is used. To remove particles, the reaction vessel is air-cleaned inside and outside by a sharp stream of nitrogen. Then sample is weighed directly into the reaction vessel. For liquid samples and for samples that melt at elevated temperatures a sample size of 3.0 ± 0.1 g is used. For samples with significant water content (> 5%) the sample size has to be increased to compensate the decrease in volume when the water evaporates. Ensure that the air inlet tube always immerses in the sample. Solid samples which do not melt should only cover the bottom of the reaction vessel. In this case, 0.5-1 gm of the powdered sample is weighed into the reaction vessel.

- The reaction vessel is closed with a cover, assembled with an air inlet tube.

- Before the determination can be started, the temperature of the heating block has to be stable. The two tubing's between Rancimat and reaction vessel, and between reaction vessel and measuring vessel are connected. Then the reaction vessel is placed in the heating block and the measurement is started immediately.

3.2.6 Determination of the saponification number, iodine value and cetane number

Saponification number (SN), iodine value (IV) and cetane number (CN) were calculated by using the fatty acid composition results and the following empirical equations (3.1), (3.2) and (3.3) respectively (Devan and Mahalakshmi, 2009).

$$\mathrm{SN} = \sum \frac{(560 \times \mathrm{Ai})}{\mathrm{MWi}} \dots\dots\dots\dots\dots (3.1)$$

$$\mathrm{IV} = \sum \frac{(254 \times \mathrm{D} \times \mathrm{Ai})}{\mathrm{MWi}} \dots\dots\dots\dots\dots (3.2)$$

$$\mathrm{CN} = 46.3 + \frac{5458}{\mathrm{SN}} - \frac{0.225}{\mathrm{IV}} \dots\dots\dots.. (3.3)$$

Where A_i is the weight percentage of each fatty acid component, D is the number of double bond present in each fatty acid; MW_i is the molecular weight of each fatty acid component.

3.3 Engine test assembly

A four cylinder, four stroke, water cooled, diesel engine was used for this study. The test engine was directly coupled to the AG250 Froude-Hofmann eddy current dynamometer. The test rig schematic is depicted in Figure 3.6. There was no special modification of the test engine to operate with the fuel samples. The specifications of the test engine and experimental conditions are depicted in Table 3.3. A number of safety rules were followed before starting the test procedures. The test bed controller was switched on to initiate the circulation of cooling water in the test assembly from cooling tower. It had been ensured that the cooling tower water level was enough to run the tests. The lubricating oil level was checked by the dipstick indicator. All of the tests were performed under steady-state condition with adequately warmed up exhaust gas and water coolant temperature. The initial engine run was performed with diesel before starting the tests with the fuel blends.

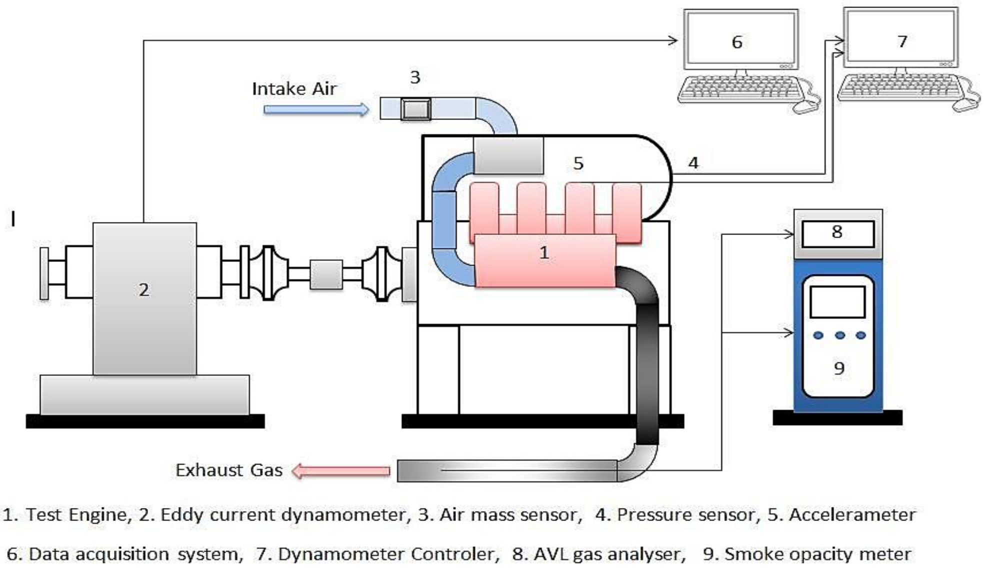

Figure 3.6: Experimental set-up.

To remove the residual diesel from the fuel line, the engine was kept running for ten minutes prior to the starting of the test with sample fuels. After the test of each fuel blend, the fuel line was purged with diesel again to remove that sample and to make it ready for the next sample. This procedure had been maintained for testing in all test conditions. The operations were performed at the same injection timing for all fuels.

Table 3.3: Engine specification.

Engine type	**4 Stroke diesel engine**
Number of cylinders	4 in-line, longitudinal
Cylinder bore * stroke	91.1 x 95 mm
Displacement	2477 cc
Compression ratio	21:1
Combustion chamber	Swirl type
Rated Power	65 kW at 4200 rpm
Torque	185 Nm, at 2,000 rpm
Valve mechanism	Single overhead camshaft (SOHC)

Injection pressure (bar)	157 bar
Connecting rod (mm)	1.58
Aspiration	Turbo charged
Fuel system	Distributor type injection pump
Cooling system	Radiator cooling
Lubrication system	Pressure feed, full flow filtration

In this study, three test conditions were selected. At first, engine test was performed at full load and with variable speed within the range of 1000-4000 rpm, at an interval of 500 rpm. This test condition was termed as TC1. In the second test condition, the engine speed was fixed at 2000 rpm, while varying the load percentage (25%, 50%, 75% and 100%), and termed as TC2. In third test condition, the engine torque was constant (80Nm), while varying the speed from 1000 rpm to 3000 rpm, with an interval of 500 rpm. This condition is presented as TC3. To maintain accuracy, each test point was repeated three times and the mean value was obtained to plot graphs. In addition, each and every test data series (i.e. test point with the same fuel type and at various engine speeds) were recorded on the same day to minimize substantial day-to-day variation in the experimental results. To measure the fuel flow rate, a positive-displacement type flow meter (KOBOLD ZOD) was installed. For recording the engine test data, REO-dCA data acquisition system was incorporated. For engine performance test, the data recorded by the computer-dyno interface are: engine speed, load applied by dynamometer, throttle position, fuel flow rate, air flow rate, temperature readings of fuel, lube oil and air, engine torque, brake power and brake specific fuel consumption.

3.4 Exhaust emission analyzer

For exhaust emission analysis, an AVL-DICOM 4000 gas analyzer was used to measure the concentration of CO, HC and NO_x. Smoke opacity was measured with AVL Di-Smoke 4000 analyzer. This automated emission analyzer recorded emission data with microprocessor control. Auto calibration was performed prior to test with individual fuel samples. After the analyzer was switched ON, the warm up sequences start and takes three minutes to get itself prepared. Before each measurement, the zero point of the analysis system is automatically adjusted with zero gas after the pump is switched on. During the first 15 seconds of the 30 seconds adjustment, zero is indicated in the indicator panels for the gases, and the particular upper limit of the effective range is indicated for 15 seconds. During the emission test, the water condensed in the hose connecting the probe, which was collected in the condensate container, and automatically sucked out. However, a new condensate filter has to be installed by switching of the measured-gas pump, if the current filter condition is badly fouled. All emissions were measured during steady state engine operation. The measurement range and resolution of both of the instruments are given in Table 3.4.

Table 3.4: Specification of Exhaust Gas Analyzer.

	Method	**Measured component**	**Range**	**Resolution**
AVL Exhaust Gas Analyzer	Non-dispersive infrared	CO	0-10% vol.	0.01 vol.%
	Non-dispersive infrared	Unburned HC	0-20000 ppm Vol	1 ppm
	Electrochemical	NO_x	0-5000 ppm Vol	1 ppm
Smoke opacimeter	Photodiode detector	Opacity %	0-100%	0.10%

3.5 Combustion analysis unit

To investigate the combustion phenomena, the engine test assembly was equipped with adequate sensors. The RIE-360 crank angle encoder was installed to measure the crank angle position at different combustion phases. For the measurement of the in-cylinder pressure data, the Kistler 6058A type pressure sensor was installed in the swirl chamber by means of a glow plug. The Kistler 2614B type amplifier was used, which could feed an amplified output of the pressure sensor to the data acquisition system (DAS). A high precision and robust Leine & Linde incremental encoder was selected to determine the TDC position and the adjacent signal from crank angle in each rotation. The DEWE-30-8-CA data acquisition unit was installed for concurrent samplings of the in-cylinder pressure and encoder signals. To eliminate the variability of cycle to cycle data, one hundred consecutive combustion cycle of pressure data were recorded, and then the average value was considered in the analysis of sample fuels in each test. Besides, Savitzky-Golay (Savitzky & Golay, 1964) smoothing-filtering tool was used to reduce the noise effects on the average pressure data. MATLAB® R2009a software was used to calculate the heat release rate (HRR) and the commencement of combustion.

The heat release rate analysis is regarded as an appropriate approach to acquiring in-detail insightful information, concerning the combustion phenomena in C.I. engines. In this study, the main combustion chamber and the pre-combustion chamber were considered to be combined into a single zone thermodynamic model (Li et al., 1995; Ozsezen et al., 2008). It has been assumed that no passage throttling losses within these two chambers. Moreover, vaporization and mixing of fuel, presences of temperature gradients and pressure waves, non-equilibrium conditions etc. have not been considered during the calculation. An average in-cylinder pressure data of hundred successive cycles with a 0.25° CA resolution were used for calculation in HRR analysis. This analysis had been deduced from the first law of thermodynamics, as presented in Eq. (1), assuming no heat loss through cylinder walls.

$$\frac{\mathbf{dQ}}{\mathbf{d\theta}} = \frac{\mathbf{V}\frac{\mathbf{dP}}{\mathbf{d\theta}} + \boldsymbol{\gamma}\mathbf{P}\frac{\mathbf{dV}}{\mathbf{d\theta}}}{\boldsymbol{\gamma}-\mathbf{1}} \qquad \textbf{(3.4)}$$

Where**,** V = instantaneous cylinder volume, units: m^3,

θ= crank angle (°CA),

P= instantaneous cylinder pressure, units: Pa,

γ =specific heat ratio, which is considered as 1.35 (Heywood, 2002),

$\frac{dQ}{d\theta} =$ rate of heat release, unit: J/ ° CA,

The V and $\frac{dV}{d\theta}$ were obtained from the equations 2 and 3, respectively.

$$\boldsymbol{V = V_c + A.r\left[1 - \cos\left(\frac{\pi\theta}{180}\right) + \frac{1}{\lambda}\left\{1 - \sqrt{1 - \lambda^2 \sin^2\left(\frac{\pi\theta}{180}\right)}\right\}\right]} \quad \textbf{(3.5)}$$

$$\boldsymbol{\frac{dV}{d\theta} = \left(\frac{\pi A}{180}\right) \times r\left\{\sin\left(\frac{\pi\theta}{180}\right) + \frac{\lambda^2 \sin^2\left(\frac{\pi\theta}{180}\right)}{2\times\sqrt{1-\lambda^2 \sin^2\left(\frac{\pi\theta}{180}\right)}}\right\}} \qquad \textbf{(3.6)}$$

Here $\boldsymbol{\lambda = \frac{l}{r}}$**,** $\boldsymbol{A = \frac{\pi D^2}{4}}$**,** r = 0.5 x stroke where l = connecting rod length , r = crank radius ,D = cylinder bore , and V_c = clearance volume.

4 CHAPTER 4: RESULTS AND DISCUSSION

4.1 Characterization of fuel properties

Fuel property analysis was conducted as a part of investigation to have a prediction about the quality of sample fuel blends prior to the engine combustion, performance and emission test. Table 4.1 and Table 4.2 present the major fuel properties of the fuel blends and biodiesel, respectively.

Table 4.1: Physiochemical properties of all fuel blends.

Properties	Diesel	GTL	P20	J20	CI20	G20	DPG20	DJG20	DCIG20
Density kg/m^3	829.6	761.9	837	835.1	840.1	815.8	826.2	827.4	830.4
Kinematic viscosity at 40°C (mm^2/sec)	3.07	2.74	3.68	3.35	3.85	3.03	3.58	3.25	3.73
Calorific Value (MJ/kg)	44.46	46.78	43.71	43.40	43.35	45.02	43.88	43.60	43.47
Flash Point (°C)	69.5	103.5	78.5	79.5	76.5	83.5	90.5	95.5	93.5
Oxidation stability at 110°C , (hr)	59.1	-	20.6	36.7	13.5	48.2	40.2	48.9	37.2

Properties	ASTM D6751	EN 14214	Crude Palm oil	PBD	Crude Jatropha oil	JBD	Crude CI oil	CIBD
Density@ 40°C (gm/cc)	Not specified	860–900	920	870	918.9	878.8	921.6	877.0
Kinematic viscosity @ 40°C (mm^2/sec)	1.9–6.0	3.5–5.0	38.1	4.62	34.072	4.2684	53.136	5.6872
Flash Point (°C)	>130	>120	174	188.5	210.5	176.5	218.5	141.5
Calorific Value (MJ/Kg)	Not specified	Not specified	39.4	39.90	39.420	40.899	38.51	39.39
Cetane NO.	≥47	>51	-	61	-	53.5	-	56.3
CP,(°C)	Report	Not specified	17	13	12	3	8	7
PP,(°C)	Not specified	Not specified	5	15	1	2	8	7
CFPP,(°C)	Not specified	Not specified		12	22	1	27	8
Acid value (mg KOH/g)	<0.50	<0.50	0.41	0.28	16	0.18	40	0.34
Saponification number	Not specified	Not specified	-	196.4	-	192.6	-	191.6
Iodine value	Not specified	Not specified	54	58	-	93.8	-	82.1
Oxidation stability at	>3	>6	1.8	6.59	1.2	8.41	2.43	3.58

110°C , (hr)	

Table 4.2: Physiochemical properties of Palm, Jatropha and Calophyllum inophyllum biodiesel.

4.1.1 Kinematic viscosity

Excessive density of any fuel yields high viscosity, which has significant influence in spray atomization efficiency, resulting poor combustion with formation of engine deposits and high exhaust emissions. Among the sample fuels, P20, J20, CI20, DPG20, DJG20 and DCIG20 showed higher density and viscosity, whereas, G20 showed lower values of these two parameters, than those of diesel. P20, DPG20, J20, DJG20, CI20 and DCIG20 demonstrated increased kinematic viscosity about 19.8%, 16.61%, 14.4% and 5.86% 25.4% and 21.5%, respectively, whereas, G20 showed 1.66% lower value than diesel. DPG20, DJG20 and DCIG20 showed decreased kinematic viscosities about 2.72%, 2.98% and 3.12%, respectively, than those of P20, J20 and CI20. All of the sample blends fulfil the ASTM D7467 specification. Low kinematic viscosity of fuel ensures less resistance while flows through the fuel system and also leads to better fuel atomization (Arbab et al., 2013). Hence, better combustion efficiency can be observed for G20 and the three ternary blends than the B20 blends, which will yield improved performance and emission characteristics. Figure 4.1 shows the variation of kinematic viscosities of all fuel blends when compared to diesel.

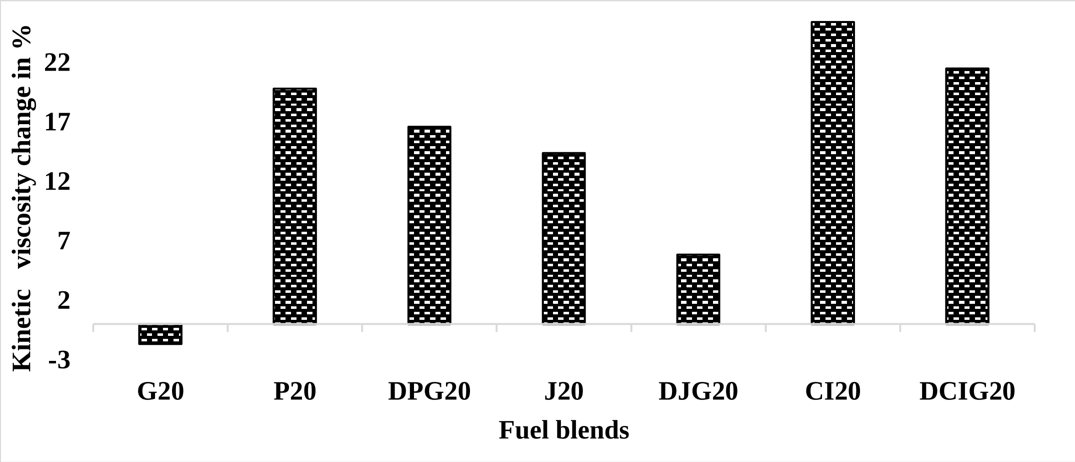

Figure 4.1: Variation of kinematic values of fuel blends compared to diesel.

4.1.2 Flash point

The flash point maintains an inverse relation to fuel volatility (Arbab et al., 2014). Higher flash point ensures safety of fuel for handling, storage and prevention from unexpected ignition during combustion. As PBD, JBD and CIBD primarily consists of methyl palmitate, methyl stearate, methyl oleate and methyl lineolate, it demonstrated higher flash point than diesel, which meet the ASTM D6751 specification of 130°C. G20, P20, DPG20, J20, DJG20, CI20 and DCIG20 showed higher flash point about 20.1%, 13.1%, 30.22%, 14.4%, 37.41%, 10.1% and 34.5%, respectively than diesel. DPG20, DJG20 and DCIG20 showed increased flash point about 15.28%, 20.13%, 22.22%, respectively, when compared to P20, J20 and CI20. All of these fuel samples meet the ASTM D7467 specification of fuel blends. Figure 4.2 shows the variation of flash points of all fuel blends, when compared to diesel.

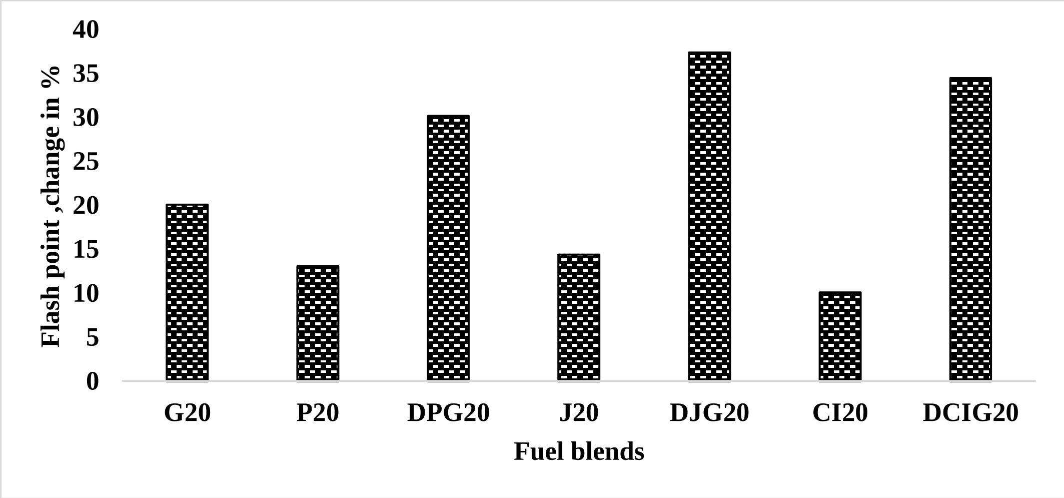

Figure 4.2: Variation of flash points of fuel blends compared to diesel.

4.1.3 Calorific value

In case of the calorific value, P20, DPG20, J20, DJG20, CI20 and DCIG20 exhibited reduction in calorific values about 2.34%, 1.31%, 2.37%, 1.93%, 2.48% and 2.22%, respectively, whereas, G20 showed about 1.27% higher values than diesel. The higher calorific value of any fuel is desired because it favors the heat release during combustion and improves engine performance. Figure 4.3 shows the variation of calorific values of all fuel blends when compared to diesel.

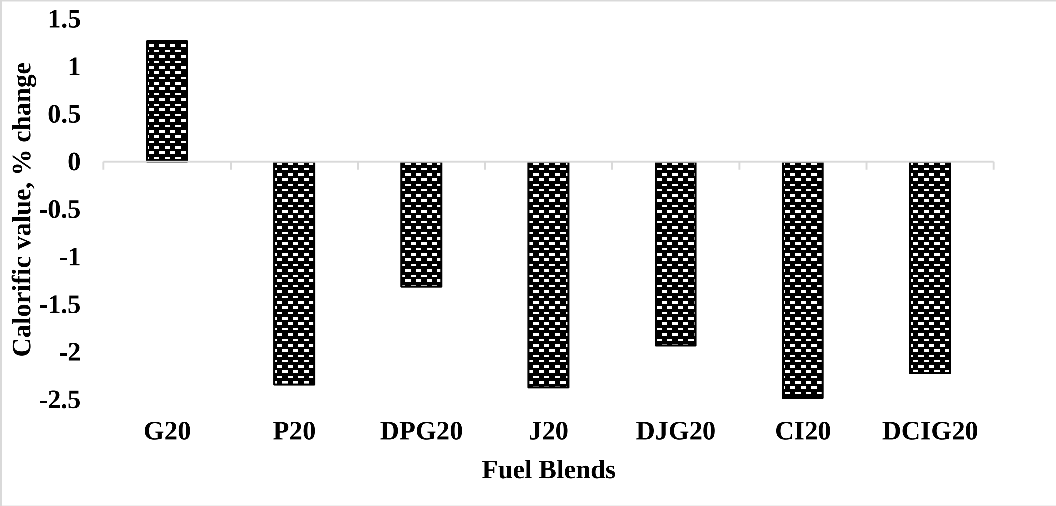

Figure 4.3: Variation of calorific values of fuel blends compared to diesel.

4.1.4 Oxidation stability

Due to the inherent high unsaturation percentage, CIBD exhibited low oxidation stability of 3.58 hour, but due to the presence of saturated fatty acid esters in PBD and JBD their oxidation stability was found 6.6 hour and 8.4 hour, respectively, and all of these biodiesel met the ASTM D6751 standard. All of the fuel blends showed an increase in oxidation stability. The oxidation stability values for G20, P20, DPG20, J20, DJG20, CI20 and DCIG20 were 48.5hr, 20.6hr, 40.3hr, 36.9hr, 48.9hr, 13.55hr and 37.26hr, respectively, which meet the ASTM D7467 specification. Figure 4.5 shows the variation of oxidation stability values of all fuel blends, when compared to diesel.

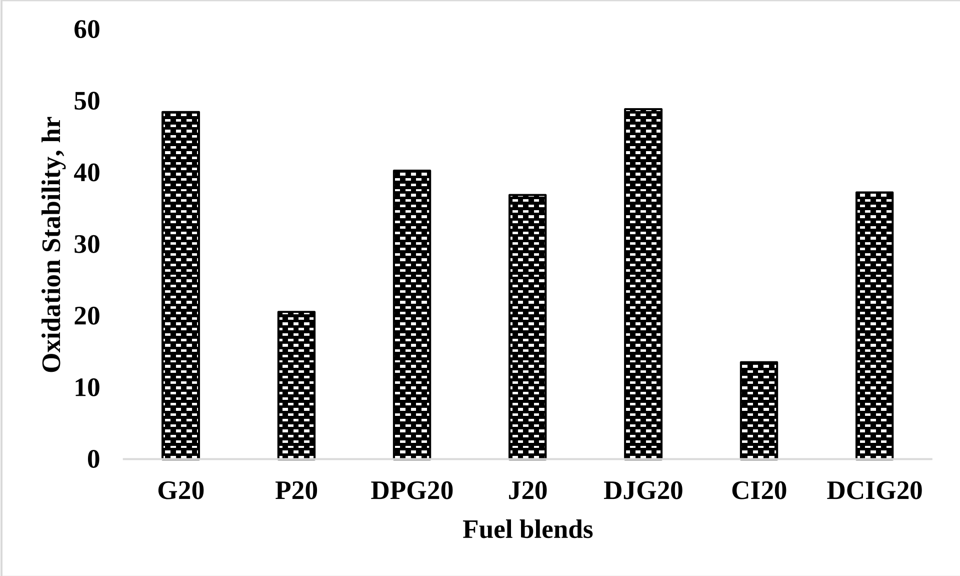

Figure 4.4: Variation of oxidation stability of fuel blends compared to diesel.

4.2 Combustion characteristics analysis

In this study, the in-cylinder pressure and heat release rate (HRR) of all fuels were measured at two conditions: full load at 2000 rpm, and constant torque (80Nm) at 2000 rpm. The results of the comparative analysis of in-cylinder pressure are presented in figure 4.5(a-c) and figure 4.6 (a-c). The HRR values of all test conditions are depicted in figure 4.7 (a-c) and 4.8 (a-c).

4.2.1 In-cylinder pressure analysis

Figure 4.5 (a-c) present the in-cylinder pressure values of all fuel samples at 2000 rpm and constant torque condition. The peak in-cylinder pressure developed by diesel, G20, P20, DPG20, J20, DJG20, CI20 and DCIG20 was 72.38 bar, 72.25bar, 73.01bar, 72.73bar, 72.58bar, 72.45bar, 73.19bar and 72.78bar respectively, and occurred at 8.7°

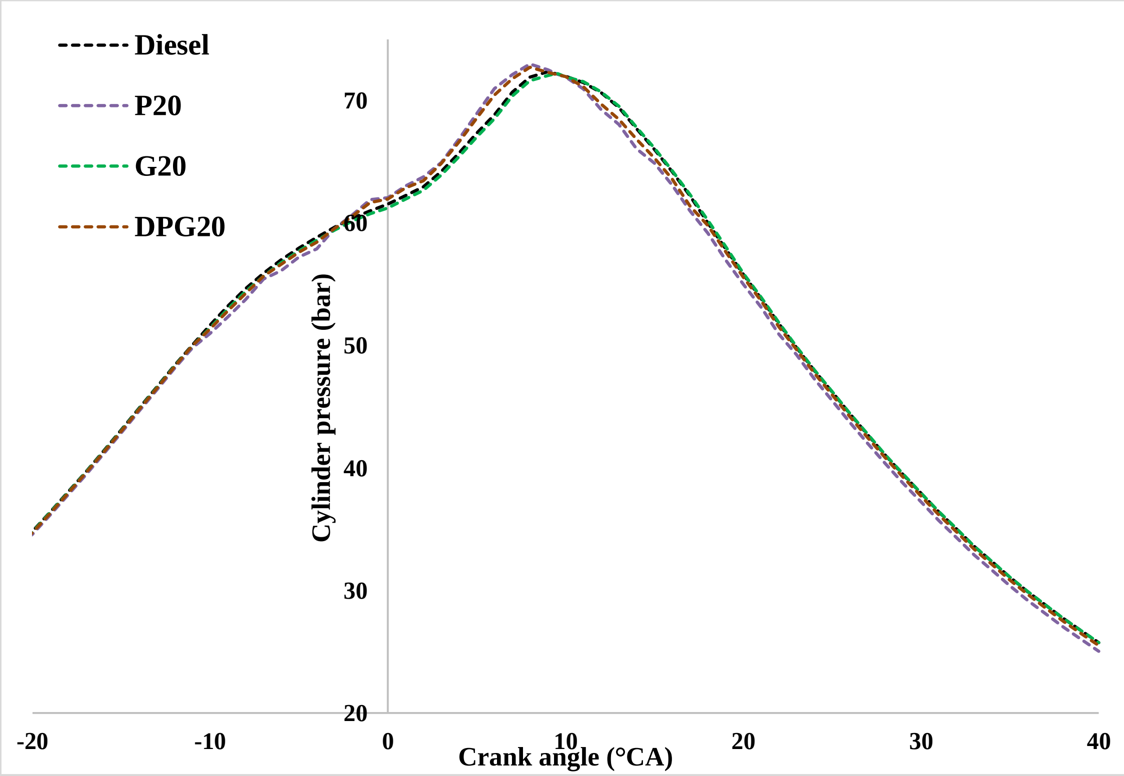

Figure 4.5 a) In-cylinder pressure of the diesel, P20, G20 and DPG20 at constant torque-2000rpm condition.

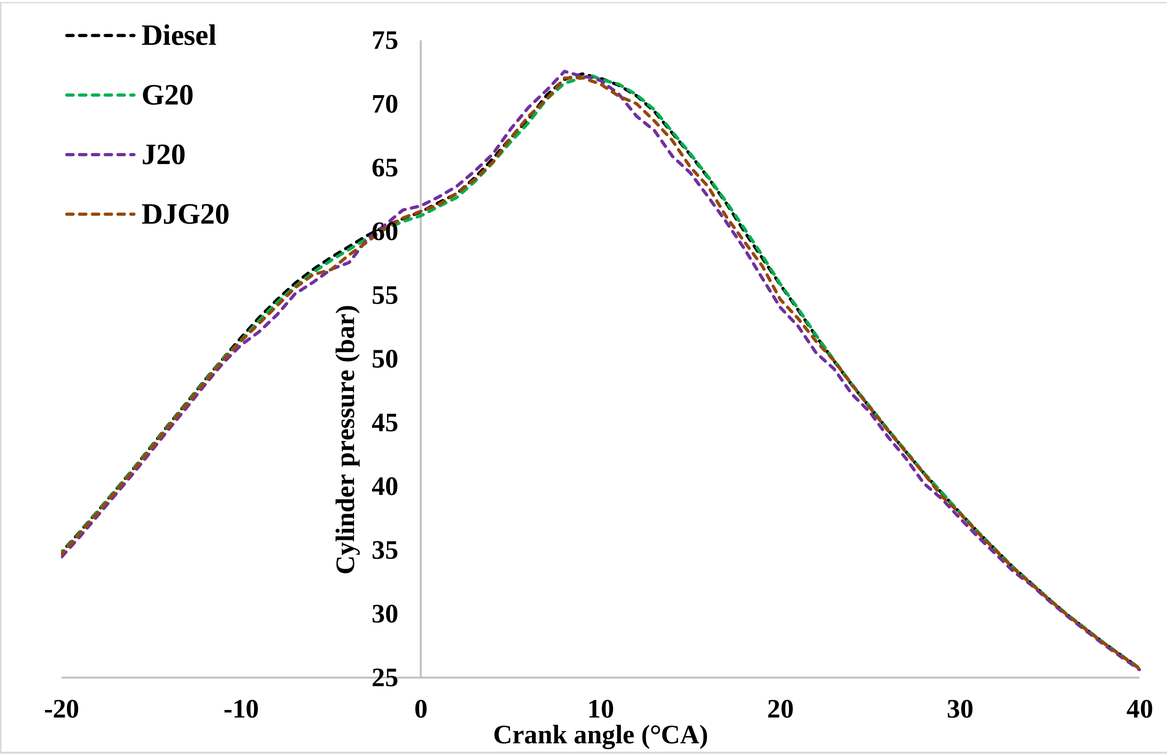

Figure 4.5 b) In-cylinder pressure of the diesel, J20, G20 and DJG20 at constant torque-2000 rpm condition.

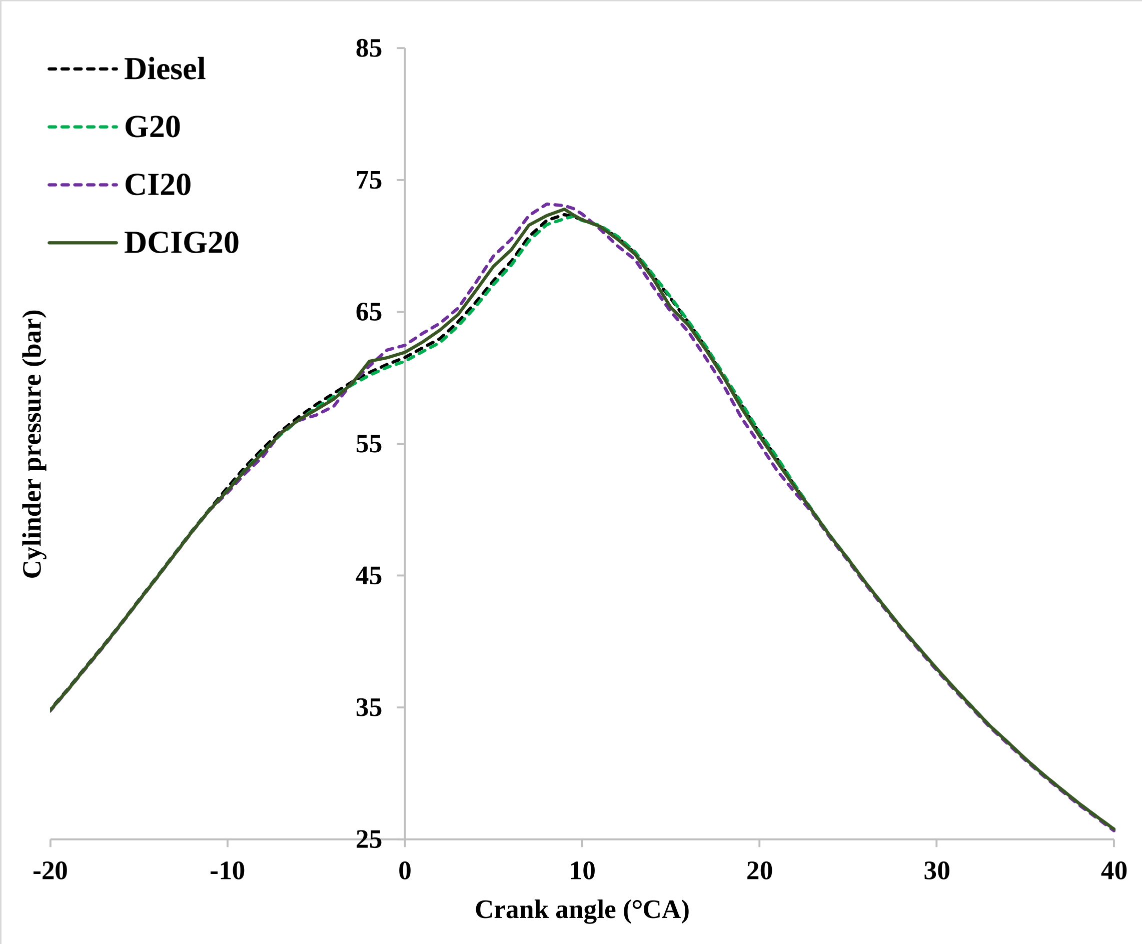

Figure 4.5 c) In-cylinder pressure of the diesel, CI20, G20 and DCIG20 at constant torque-2000 rpm condition.

ATDC, 9.5° ATDC, 8.1° ATDC, 8.3° ATDC, 8.3° ATDC, 8.5° ATDC, 8.4° ATDC, and 8.6° ATDC, respectively.

Figure 4.6 (a-c) present the in-cylinder pressure values of all fuel samples at full load-2000 rpm speed condition. The peak in-cylinder pressure obtained by diesel, G20, P20, DPG20, J20, DJG20, CI20 and DCIG20 was 96.59bar, 95.91bar, 97.18bar, 96.92bar, 97.28bar, 96.57bar, 98.41bar and 97.66bar respectively, and occurred at 5.7° ATDC, 6.2° ATDC, 4.9° ATDC, 5.1° ATDC, 5.1° ATDC, 5.3° ATDC, 5.4° ATDC, and 5.6° ATDC, respectively.

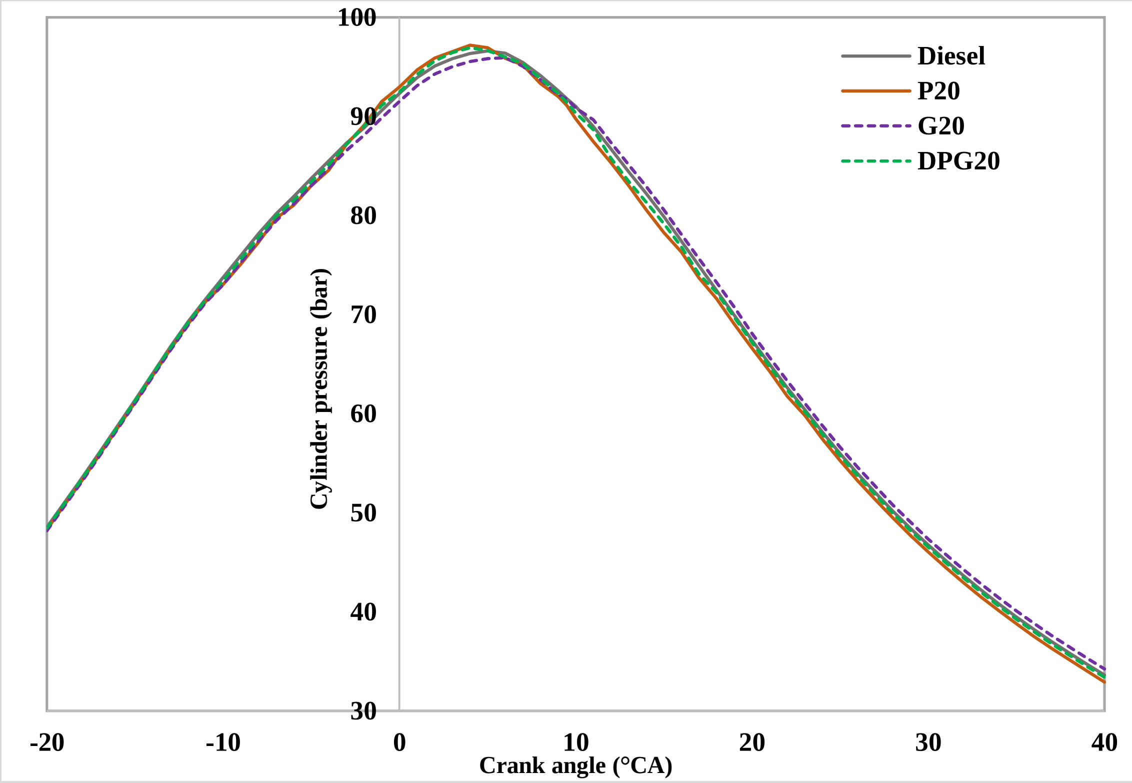

Figure 4.6 a) In-cylinder pressure of the diesel, P20, G20 and DPG20 at full load-2000 rpm condition.

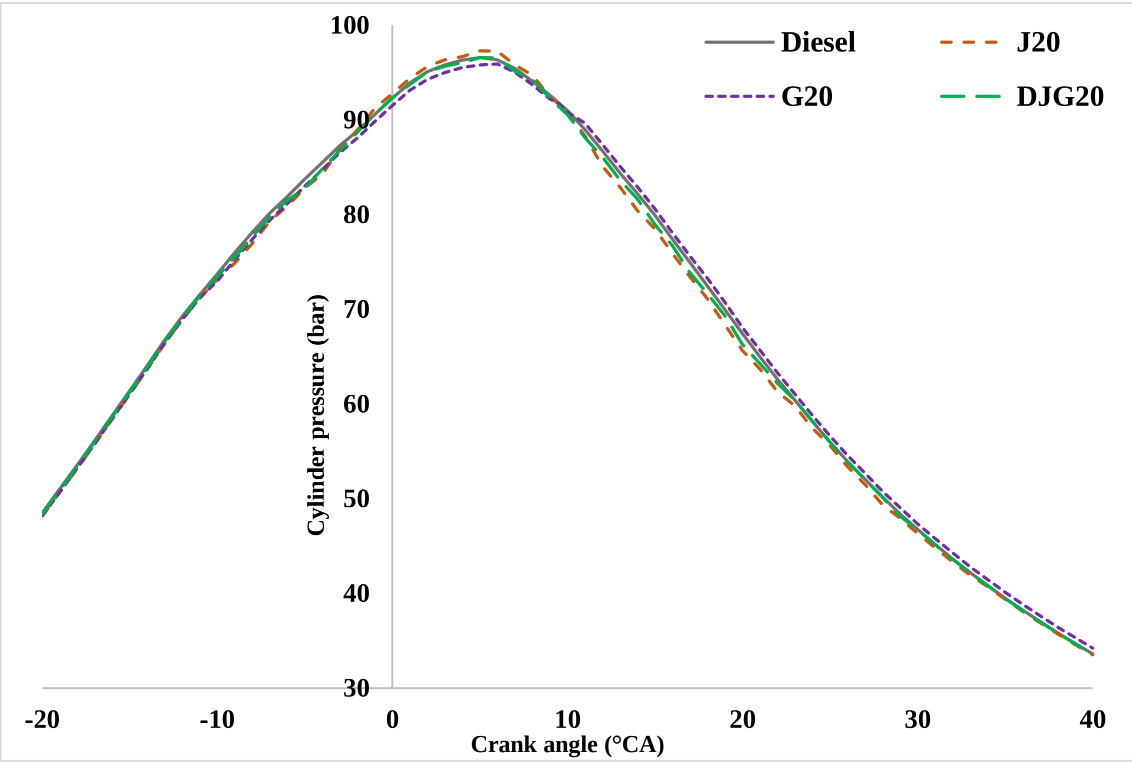

Figure 4.6 b) In-cylinder pressure of the diesel, J20, G20 and DJG20 at full load-2000rpm condition.

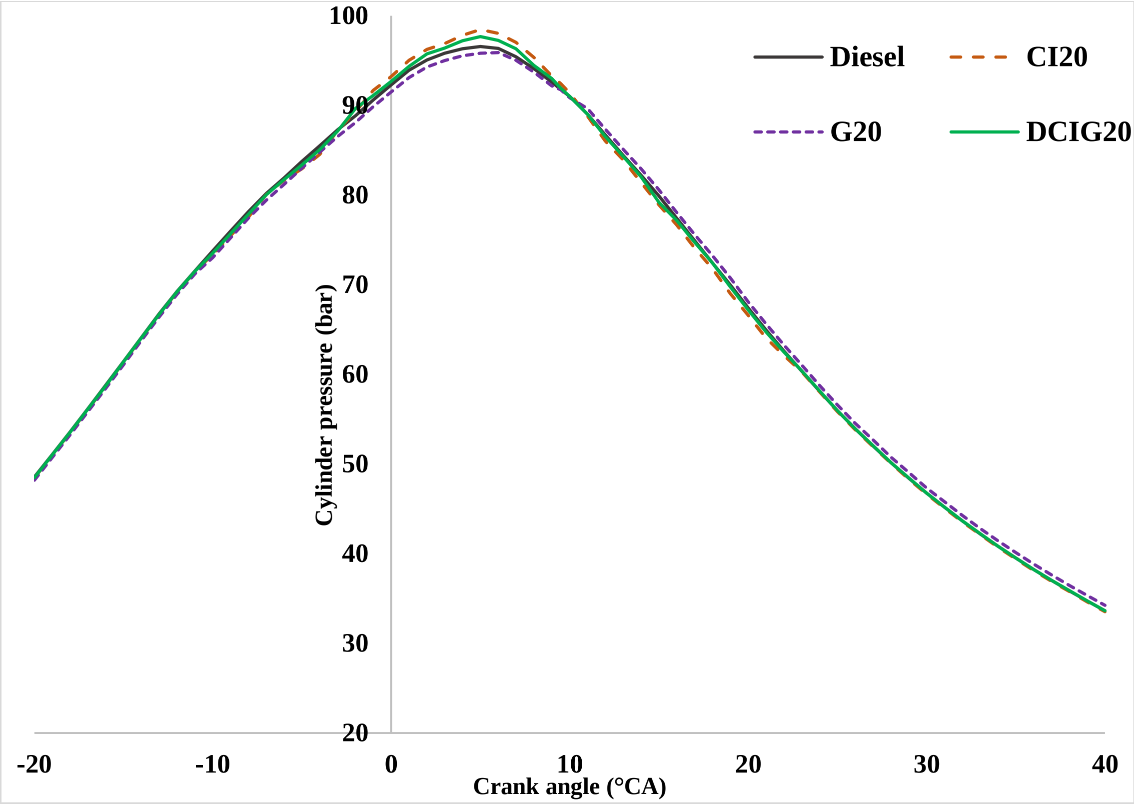

Figure 4.6 c) In-cylinder pressure of the diesel, CI20, G20 and DCIG20 at full load-2000rpm condition.

There was no significant variation in the peak in-cylinder pressure values of all test fuels. Thus, it can be deduced that the chemical to mechanical energy conversion efficiency of the test fuels was similar to the reference fuel. All biodiesel blends and the ternary blends showed higher peak pressure than diesel fuel, which can be attributed to the combined effects of high CN, high BSFC values and the advancement of the SOI timings of the biodiesel (Imtenan et al., 2014; Ozsezen & Canakci, 2011; Ozsezen et al., 2009). The high bulk modulus of biodiesel initiated the advancement of the nozzle opening, and thus, it results earlier injection compared to diesel (Palash et al., 2014). In case of G20, the peak in-cylinder pressure was quite lower, and occurred at an advanced crank angle than those of diesel and the other blends. The reason can be explained with the high CN of GTL fuel, which induced substantially short ignition delay, and led towards a diminution of premixed combustion zone (Huang et al., 2007). Thus, a decrease was observed in the peak combustion pressure. It can be deduced that the decreased maximum pressure of G20 can initiate a smooth combustion, which resulted a diminution in combustion noise (Yongcheng et al., 2006).

4.2.2 Heat release rate analysis

The HRR analysis is regarded as a suitable parameter for in-detail illustration of the combustion phenomena in C.I. engine. Figure 4.7 (a-c) and 4.8 (a-c) illustrate the HRR values of all fuel samples at all test conditions. It was observed that all fuel blends demonstrated a prompt premixed burning, which led towards the diffusion combustion zone. From the HRR diagrams it can be observed that SOC of the biodiesel occurred earlier than diesel, on account of their earlier SOI timings. As the test engine had a pump-line nozzle injection system, fuels with high density and high bulk modulus of compressibility, demonstrated advanced SOI. The SOC values were obtained from the HRR vs crank angle diagram. At constant torque-2000 rpm test conditions, the SOC timings for diesel, G20, P20, DPG20, J20, DJG20, CI20 and DCIG20 were -3.5°ATDC, -2.7° ATDC, -4.2° ATDC, -3.6° ATDC, -4.7° ATDC, -3.8° ATDC, -4.5° ATDC, and -3.7°ATDC, respectively. At full load- 2000 rpm test conditions, the SOC timings for diesel, G20, P20, DPG20, J20, DJG20, CI20 and DCIG20 were -3.4°ATDC, -2.5° ATDC, -4.1° ATDC, -3.7° ATDC, -4.4° ATDC, -3.6° ATDC, -4.3° ATDC and -3.8°ATDC, respectively. The earlier SOC timings of the biodiesel blends also provide the justification of the slight advanced peak of the in-cylinder pressure, compared to the other test fuels. At constant torque-2000rpm test condition, the HRR peak values of diesel, G20, P20, DPG20, J20, DJG20, CI20 and DCIG20 were 35.48 J/°CA, 35.23

J/°CA, 36.15 J/°CA, 35.80 J/°CA, 35.82 J/°CA, 35.65 J/°CA, 35.78 J/°CA, and 35.46 J/°CA, respectively, and

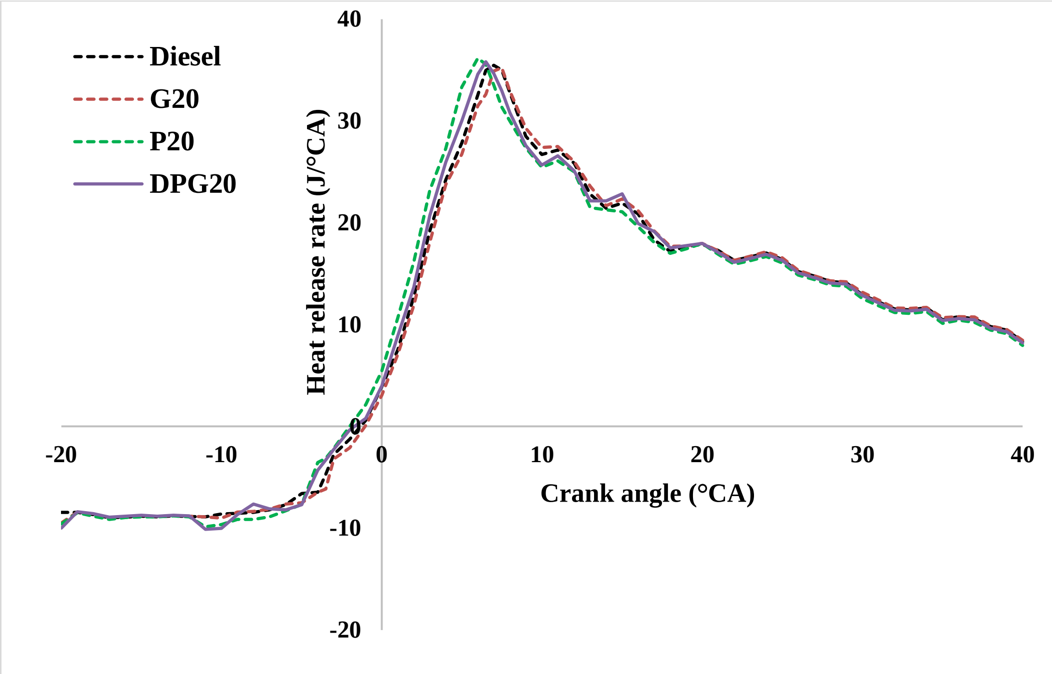

Figure 4.7 a) HRR values of the diesel, P20, G20 and DPG20 at constant torque-2000rpm condition.

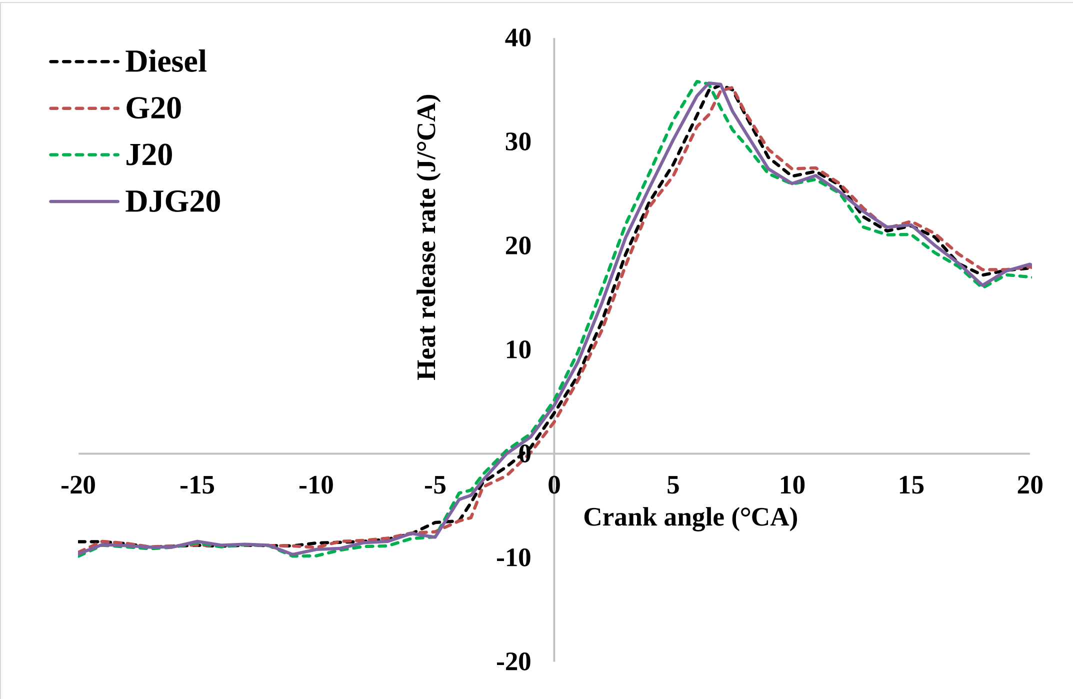

Figure 4.7 b) HRR values of the diesel, J20, G20 and DJG20 at constant torque-2000rpm condition.

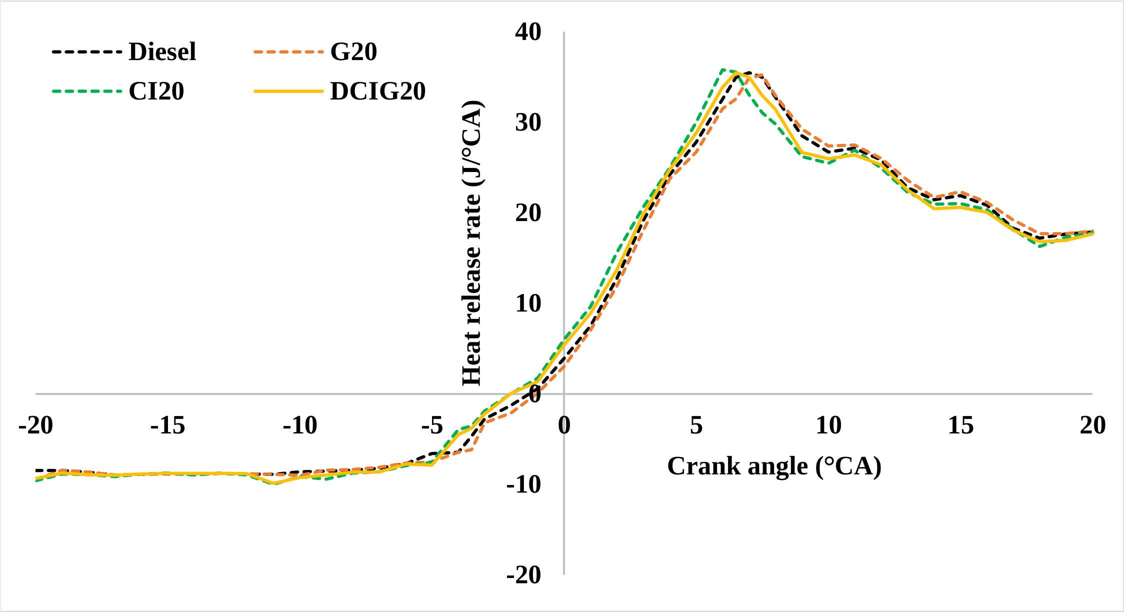

Figure 4.7 c) HRR values of the diesel, CI20, G20 and DCIG20 at constant torque-2000rpm condition.

occurred at 7.3° ATDC, 7.7° ATDC, 6.3° ATDC, 6.7° ATDC, 6.5° ATDC, 6.8° ATDC, 6.8° ATDC, and 7.1° ATDC, respectively. At full load-2000rpm test condition, the HRR peak values of diesel, G20, P20, DPG20, J20, DJG20, CI20 and DCIG20 were 23.79 J/°CA, 22.84 J/°CA, 24.08 J/°CA, 23.95 J/°CA, 24.27 J/°CA, 23.84 J/°CA, 24.53 J/°CA, and 23.97 J/°CA, respectively, and occurred at 7.1° ATDC, 7.5° ATDC, 6.1° ATDC, 6.4° ATDC, 6.3° ATDC, 6.5° ATDC, 6.2° ATDC, and 6.7° ATDC, respectively.

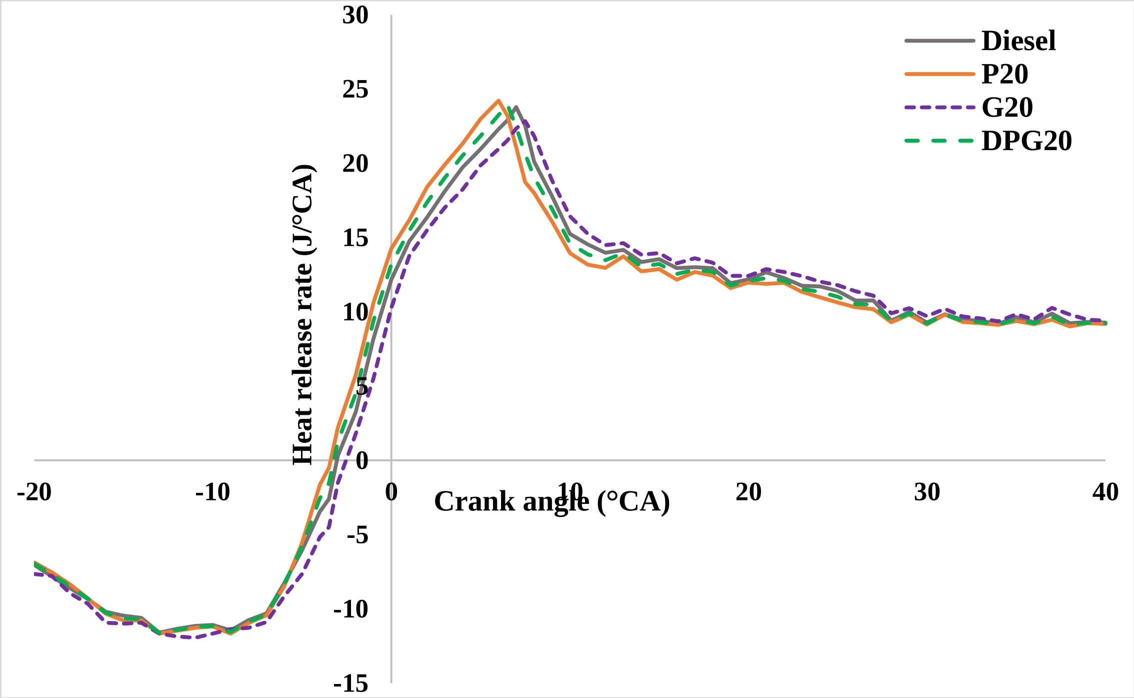

Figure 4.8 a) HRR values of the diesel, P20, G20 and DPG20 at full load-2000rpm condition.

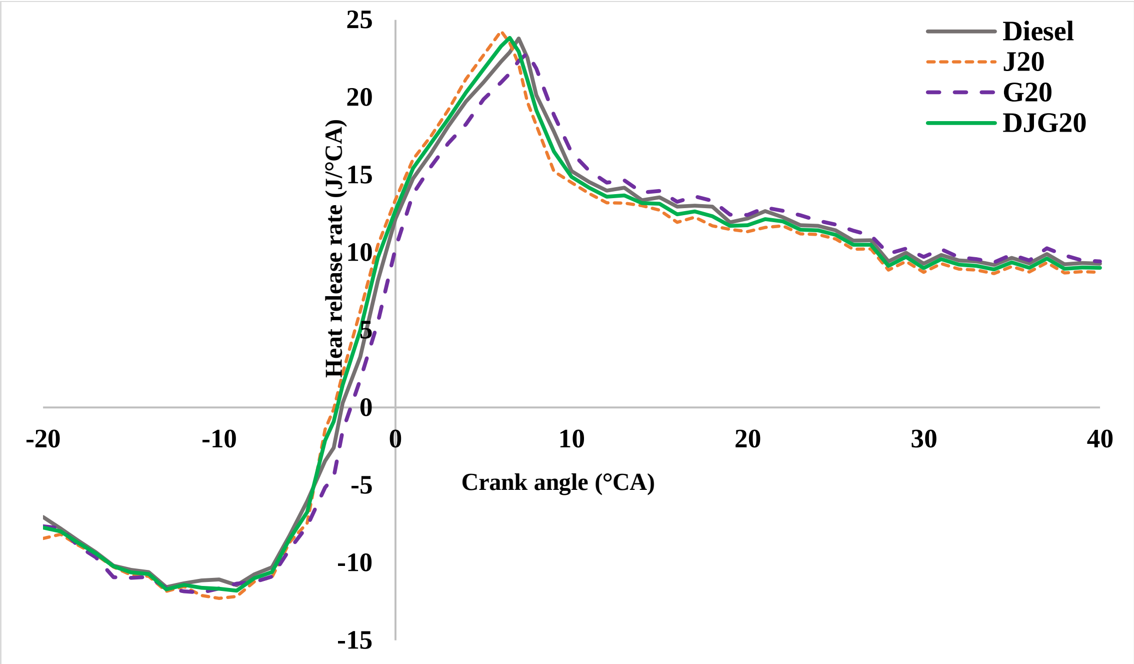

Figure 4.8 b) HRR values of the diesel, J20, G20 and DJG20 at full load-2000rpm condition.

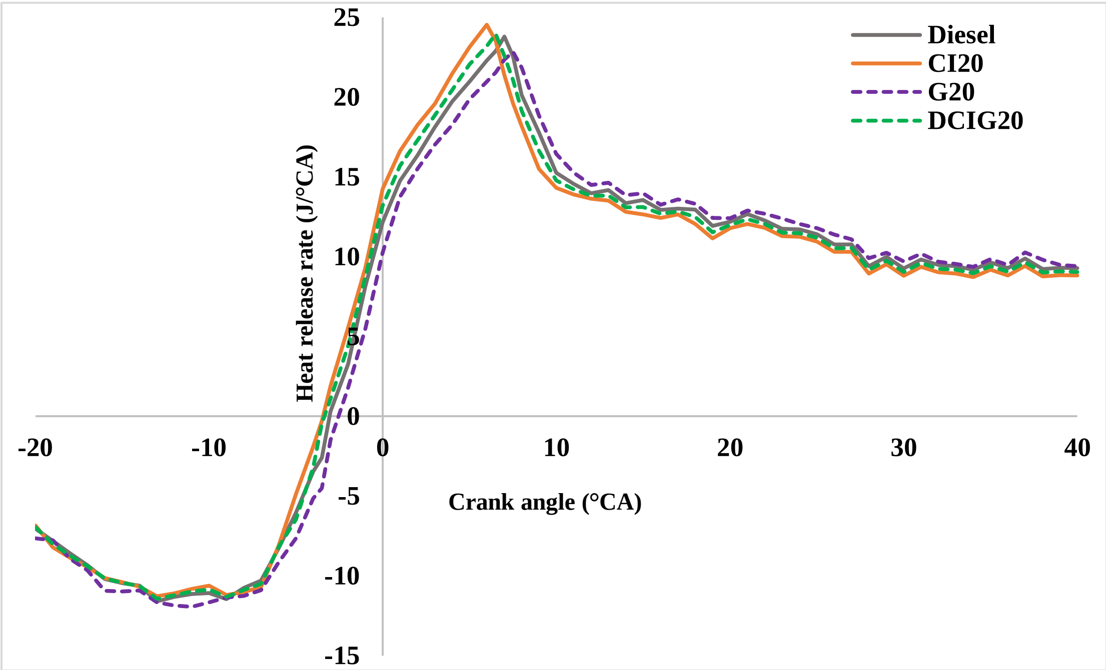

Figure 4.8 c) HRR values of the diesel, CI20, G20 and DCIG20 at full load-2000rpm condition.

Compared to diesel, the premixed combustion stages for both of the biodiesel blends and ternary blends were quite higher and sharper, which also resulted the higher peak of the in-cylinder pressure. In case of G20, the peak value of HRR during premixed combustion was much lower, and the duration of this phase was also shorter, whereas, in diffusion burning zone, the peak was higher, and the duration was longer when compared with those of diesel. The high CN of GTL fuel resulted a smaller ignition delay, which yielded a diminution in both of the mass of injected fuel, and the evaporation rate of fuel prior to ignition (Huang, et al., 2007; Yongcheng et al., 2006). As a result, G20 demonstrated a lower burning rate and smaller amount of energy released during the premixed combustion phase than other sample fuels. Since the amount of energy released during the premixed combustion phase was smaller, the diffusion-controlled combustion exhibited more energy (Park et al., 2014). Due to the low boiling point of GTL fuel, it promptly vaporized and mixed with the in-cylinder air, which yielded a faster diffusion-mixing, accompanied with a high rate of diffusion combustion. Thus, G20 showed a higher peak value of the diffusion burning rate than those of other sample fuels.

4.3 Analysis of engine performance parameters

This section illustrates the results of the engine performances parameters of all fuel samples at different engine test conditions. In this study, four performance parameters were chosen, such as, brake specific fuel consumption (BSFC), brake specific energy consumption and brake thermal efficiency (BTE).

4.3.1 Brake Specific Fuel Consumption (BSFC)

The experiment results of BSFC values for all fuel samples at three different test conditions are discussed in this section. The BSFC values of three ternary blends were compared with their respective B20 blends, G20 and diesel in all test conditions. The results are depicted in Figure 4.9(a), 4.9(b) and 4.9(c).

4.3.1.1 Full load with variable speed condition

Figure 4.9 (a) shows the variation of BSFC values among all fuel samples at full load with variable speed condition. Higher values of BSFC had been observed for all B20 blends and the ternary blends, but G20 showed lower BSFC, when compared to diesel. On average, P20, DPG20, J20, DJG20, CI20 and DCIG20 showed higher BSFC about 3.38%, 2.46%, 3.91%, 2.55%, 4.21% and 3.31%, respectively, whereas, G20 showed lower BSFC about 2.1% than diesel. Compared to P20, J20 and CI20, the improvement of BSFC values for the three ternary blends DPG20, DJG20 and DCIG20 were approximately 1.02%, 1.33% and 1.18%, respectively.

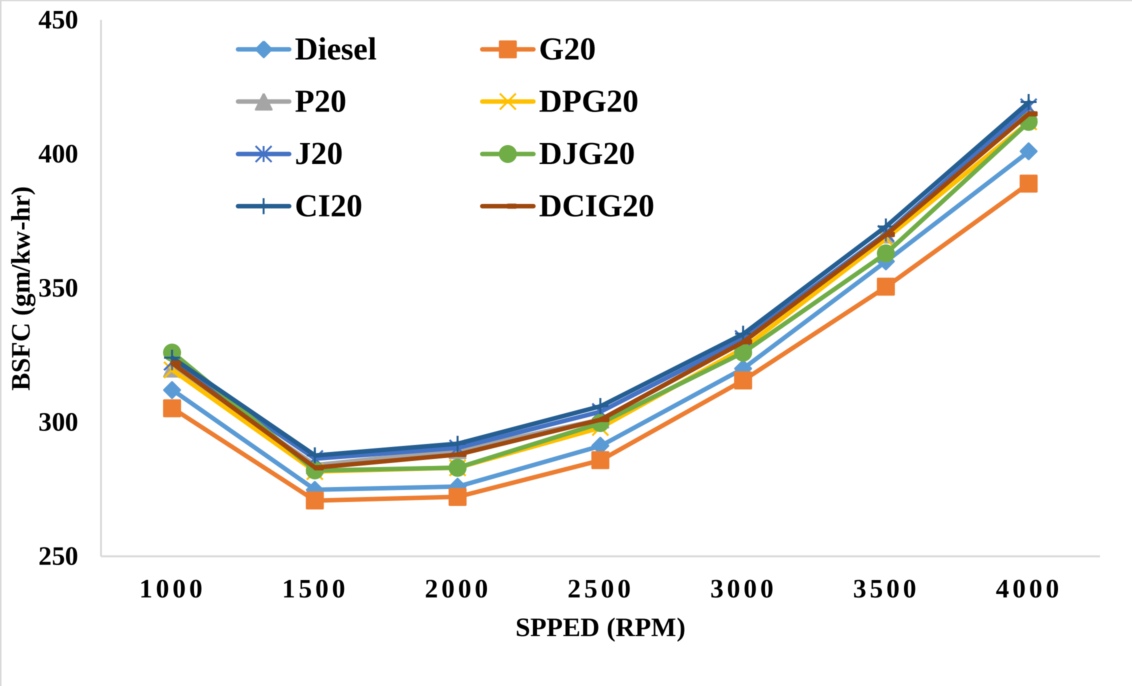

Figure 4.9(a) Variation of BSFC of all fuel blends within the test speed range at full load condition.

4.3.1.2 Constant speed with variable load condition

Figure 4.9 (b) shows the variation of BSFC values among all fuel samples at constant speed of 2000rpm with variable load condition. Except G20, all B20 and ternary blends demonstrated higher BSFC values, when compared to diesel. On average, P20, DPG20, J20, DJG20, CI20 and DCIG20 showed higher BSFC about 4.09%, 2.56%, 5.05%, 2.53%, 5.92% and 3.06%, respectively, whereas, G20 showed lower BSFC about 3.7% than diesel. In comparison to P20, J20 and CI20, the improvement of BSFC values for the three ternary blends DPG20, DJG20 and DCIG20 were approximately 1.48%, 2.41% and 2.71%, respectively.

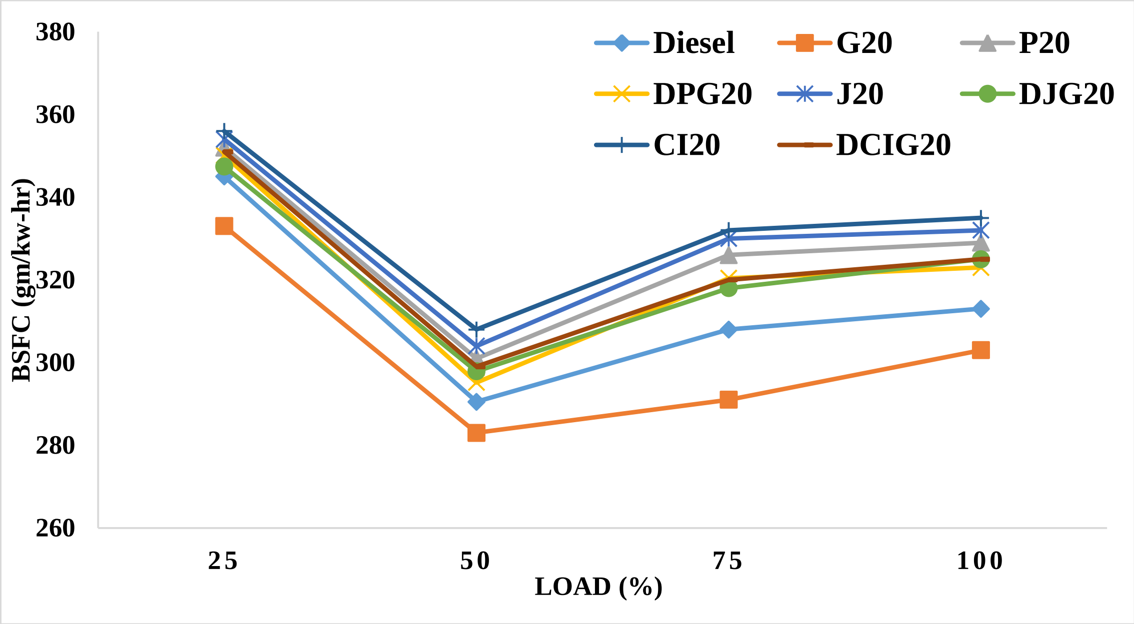

Figure 4.9 (b) Variation of BSFC values of all fuel blends at 2000 rpm at variable load condition.

4.3.1.3 Constant torque with variable speed condition

Figure 4.9 (c) shows the variation of BSFC values among all fuel samples at constant torque of 80 Nm with variable speed condition. It can be deduced that the B20 blends and the ternary blends demonstrated higher BSFC values, whereas, G20 showed lower BSFC, when compared to diesel. On average, P20, DPG20, J20, DJG20, CI20 and DCIG20 showed higher BSFC about 4.68%, 3.36%, 3.57%, 2.51%, 4.18% and 2.71%, respectively, whereas, G20 showed lower BSFC about 2.25% than diesel. In comparison to P20, J20 and CI20, the improvement of BSFC values for the three ternary blends DPG20, DJG20 and DCIG20 were approximately 1.26%, 1.1% and 1.41%, respectively.

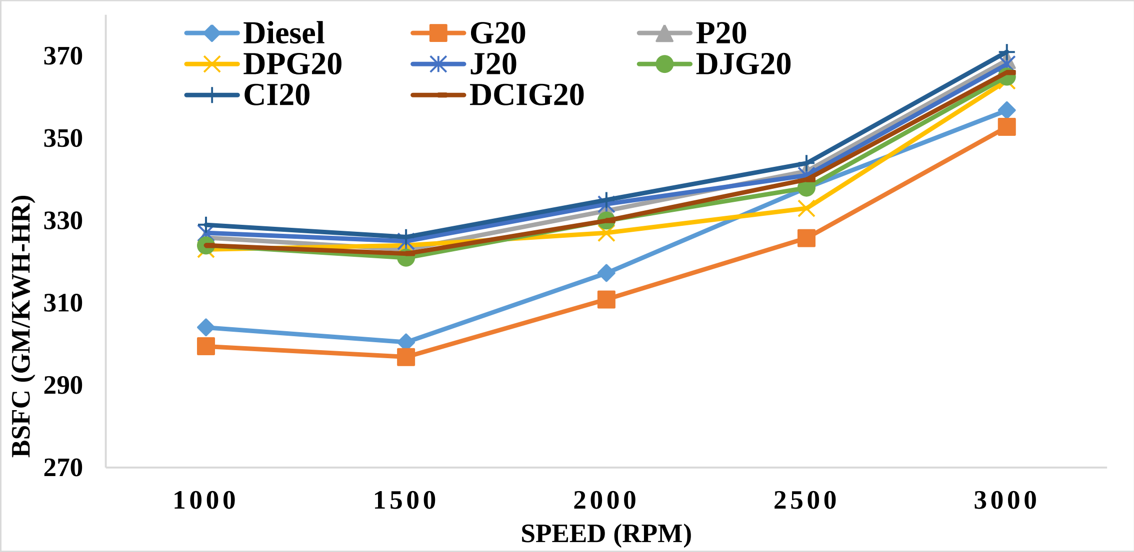

Figure 4.9 (c): Variation of BSFC values of all fuel blends within the test speed range at constant torque condition.

The improvement in BSFC for G20 can be illustrated by the combustion phenomena and fuel characteristics. As fuel was delivered on the fixed volumetric basis, the amount of fuel injected in a single stroke was same for all fuel samples. Since G20 had a higher calorific value than other fuel samples, it required comparatively small quantity of fuel per stroke to produce the same power than diesel and the other blends (Abu-Jrai et al., 2006; Yehliu et al., 2010). Besides, G20 demonstrated lower in-cylinder pressure and lower pressure rise rate than other fuel samples, which could assist compensating mechanical losses, and led towards better combustion (Yongcheng et al., 2006). The high BSFC values of the B20 blends and the ternary blends can be ascribed to the volumetric effect of the constant fuel injection rate, associated with their high kinematic viscosity values. Several studies (Buyukkaya, 2010; Lapuerta et al., 2008) confirmed that the fuel consumption of these blends increases with the decrease of the calorific value. The overall improvement of the BSFC of the ternary blends than their respective B20 blends can be justified for the presence of GTL fuel in the blend, which improved the density and kinematic viscosity of the ternary blend. Figure 4.9(d) shows a comparison of the improvements of BSFC values of all ternary blends than the 20% biodiesel blends.

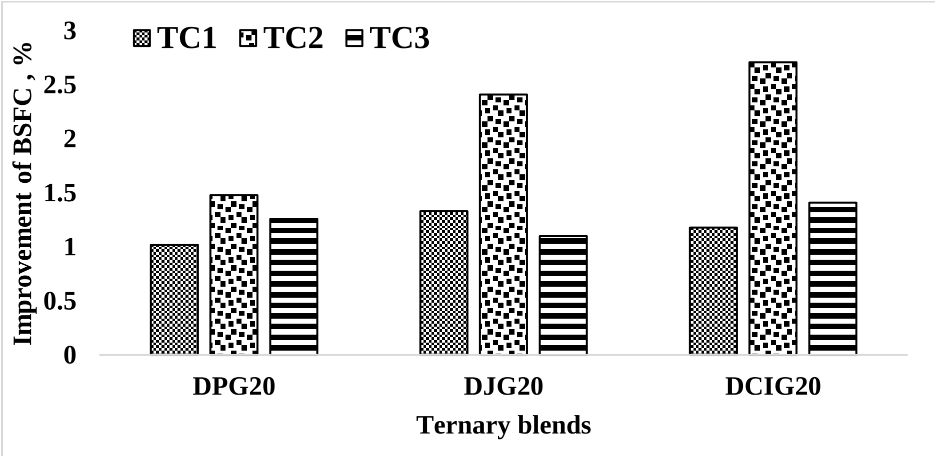

Figure 4.9 (d): Improvements of BSFC values of all ternary blends than the 20% biodiesel blends.

4.3.2 Brake Specific Energy Consumption (BSEC)

Apart from BSFC, another significant performance parameter is the brake specific energy consumption (BSEC). Generally, BSEC is introduced to compare the performance of the fuels with different calorific values. It can be defined as the product of the BSFC and calorific value of the fuel. It indicates the amount of energy consumed to produce a unit output power in one hour. Usually, the value of BSEC decreases in line with an increase in energy consumption efficiency. In this section, the BSEC values of three ternary blends were compared with their respective B20 blends, G20 and diesel in all test conditions. The comparative results are presented in Figure 4.10(a), 4.10(b) and 4.10(c).

4.3.2.1 Full load with variable speed condition

Figure 4.10(a) shows the variation of BSEC values among all fuel samples at full load with variable speed condition. All B20 blends and the ternary blends demonstrated higher values of BSEC, but G20 showed lower value, when compared to diesel. On average, P20, DPG20, J20, DJG20, CI20 and DCIG20 showed higher BSEC about 1.17%, 0.17%, 1.59%, 0.16%, 1.95% and 0.57%, respectively, whereas, G20 showed lower BSEC about 1.29% than diesel. Compared to P20, J20 and CI20, the improvement of BSEC values for the three ternary blends DPG20, DJG20 and DCIG20 were approximately 1.02%, 1.48% and 1.36%, respectively.

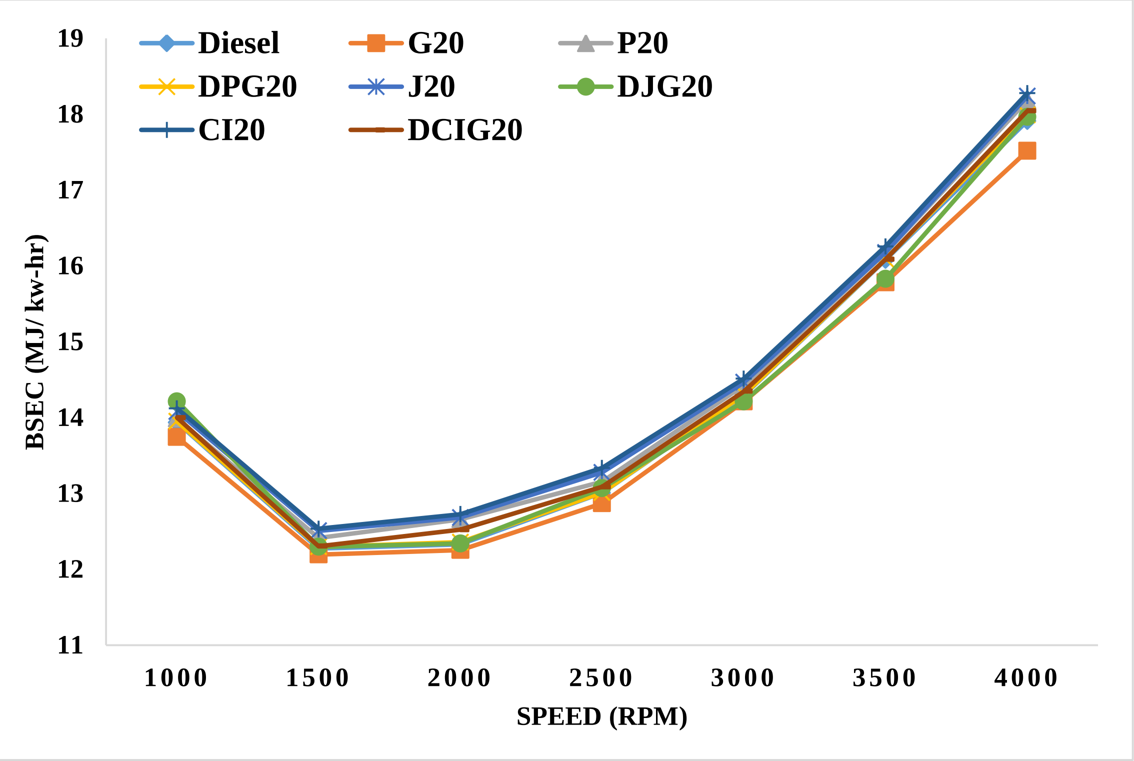

Figure 4.10 (a) Variation of BSEC of all fuel blends within the test speed range at full load condition.

4.3.2.2 Constant speed with variable load condition

Figure 10(b) shows the variation of BSEC values among all fuel samples at constant speed of 2000 rpm with variable load condition. Unlike BSFC, it had been observed that all B20 blends and the ternary blends demonstrated higher BSEC values, but G20 showed lower BSEC value than diesel. On average, P20, DPG20, J20, DJG20, CI20 and DCIG20 showed higher values of BSEC about 1.87%, 0.26%, 2.72%, 0.11%, 3.35% and 0.33%, respectively, whereas, G20 showed lower BSEC value about 2.92% than diesel. In comparison to P20, J20 and CI20, the improvement of BSEC values for DPG20, DJG20 and DCIG20 were approximately 1.59%, 2.56% and 2.94%, respectively.

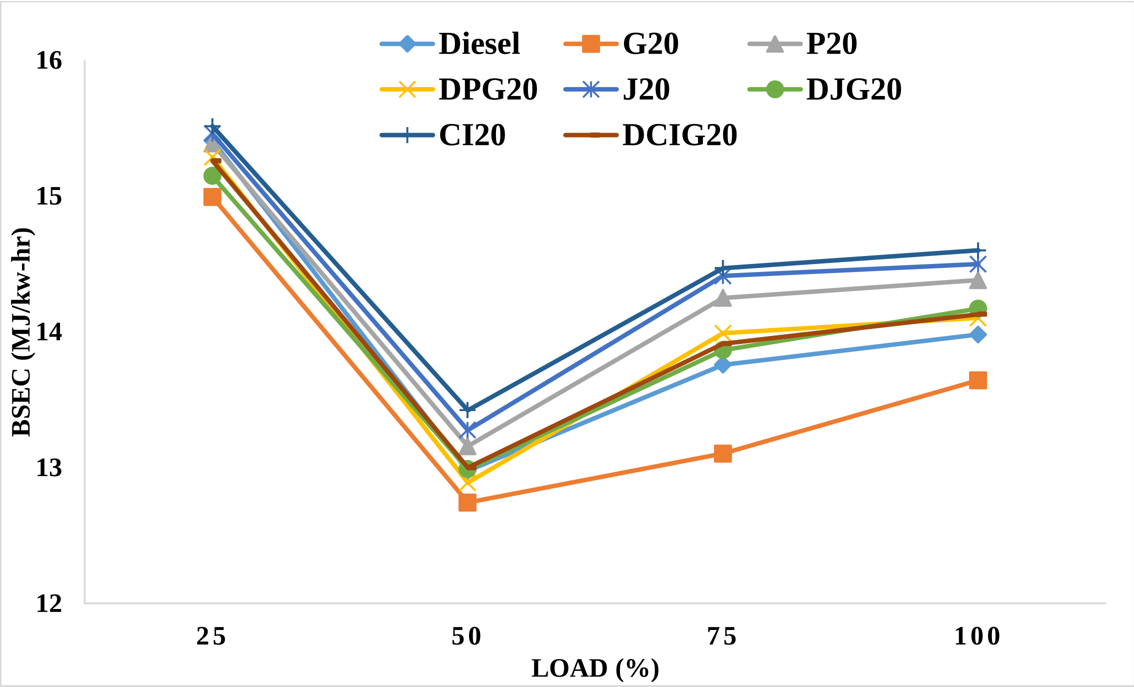

Figure 4.10(b) Variation of BSEC values of all fuel blends at 2000 rpm at variable load condition.

4.3.2.3 Constant torque with variable speed condition

Figure 4.10 (c) shows the variation of BSEC values among all fuel samples at constant torque of 80 Nm with variable speed condition. It was observed that like previous two test conditions, the B20 blends and the ternary blends demonstrated higher values of BSEC, but G20 showed lower values, when compared to diesel. On average, P20, DPG20, J20, DJG20, CI20 and DCIG20 showed higher values of BSEC about 2.44%, 1.04%, 1.26%, 0.08%, 1.66% and 0.04%, respectively, whereas, G20 showed lower BSEC values about 1.48% than diesel. In comparison to P20, J20 and CI20, the improvement of BSEC values for DPG20, DJG20 and DCIG20 were approximately 1.37%, 1.18% and 1.61%, respectively.

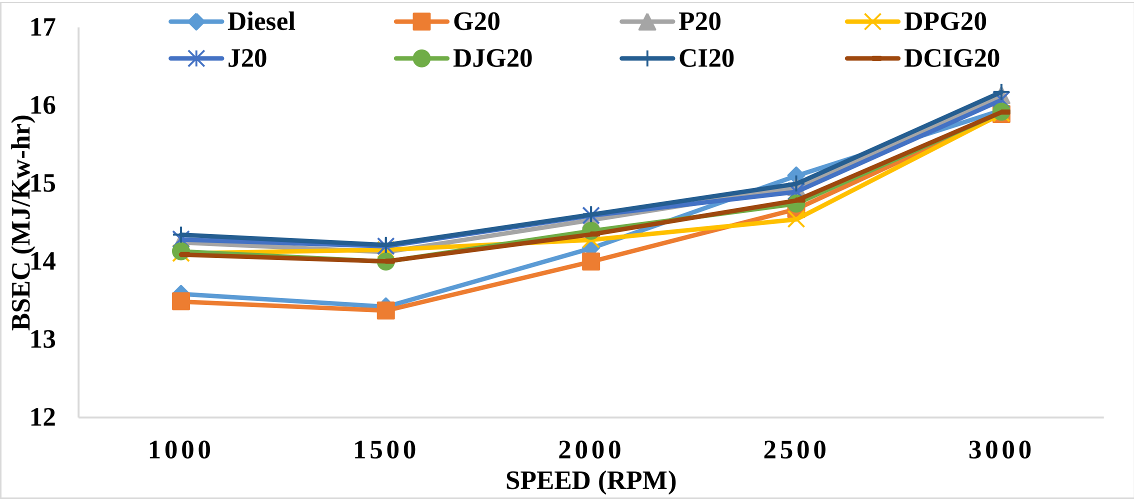

Figure 4.10(c): Variation of BSEC values of all fuel blends within the test speed range at constant torque condition.

Alike BSFC, the improvement of the BSEC of the ternary blends than their respective B20 blends can be justified for the presence of GTL fuel, which improved the density and kinematic viscosity of the ternary blend. Figure 4.10(d) shows a comparison of the improvements of BSFC values of all ternary blends than their respective B20 blends.

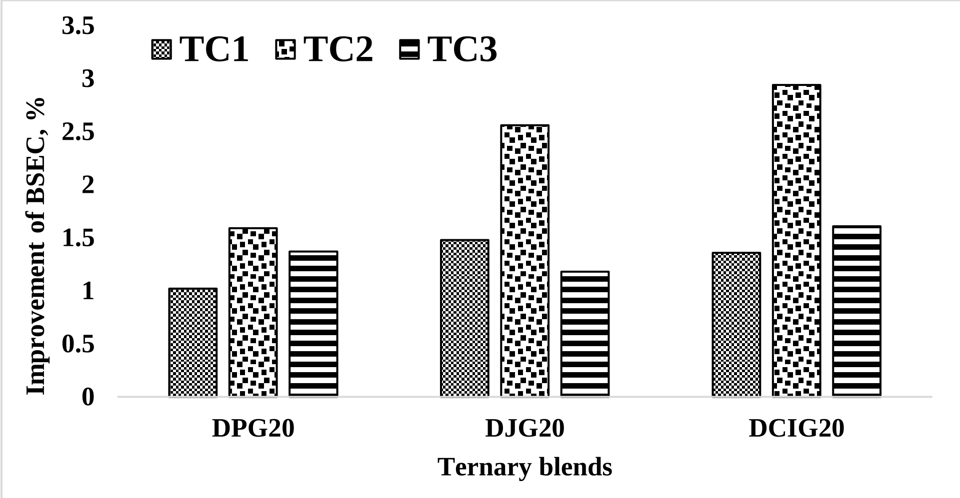

Figure 4.10(d): Improvements of BSEC values of all ternary blends than the 20% biodiesel blends.

4.3.3 Brake Thermal Efficiency

Engine brake thermal efficiency is regarded as a significant performance parameter, which can be measured by the product of mechanical efficiency and net indicated thermal efficiency. Due to the effect of various loss mechanisms, such as combustion inefficiency, heat transfer and mechanical friction, the BTE of a real operating diesel cycle is usually under 50% and often far below it (Heywood, 2002). In this section, the BTE of the three ternary blends were compared with their respective B20 blends, G20 and diesel at all engine test condition. The comparative results are presented in Figure 4.11(a), 4.11(b) and 4.11(c). The BTE was calculated by equation 4.1 where η_{bt} is the BTE (%), fc is the BSFC (g/kWh) and H_v is the lower heating value of the fuel (MJ/kg).

$$\eta \mathrm{bt} = \left[\frac{3.6 \times 10^3}{fc \times Hv}\right] \times 100\% \dots\dots\dots\dots\dots\dots.(4.1)$$

4.3.3.1 Full load with variable speed condition

Figure 4.11 (a) shows the variation of BTE values among all fuel samples at full load with variable speed condition. All of the B20 blends and the ternary blends demonstrated lower BTE values, but G20 showed higher BTE, when compared to diesel. On average, P20, DPG20, J20, DJG20, CI20 and DCIG20 showed lower BTE about 1.21%, 0.15%, 1.66%, 0.16%, 1.98% and 0.59%, respectively, whereas, G20 showed higher BTE about 1.15% than diesel. Compared to P20, J20 and CI20, the improvement of BTE values for the three ternary blends DPG20, DJG20 and DCIG20 were approximately 1.07%, 1.53% and 1.43%, respectively.

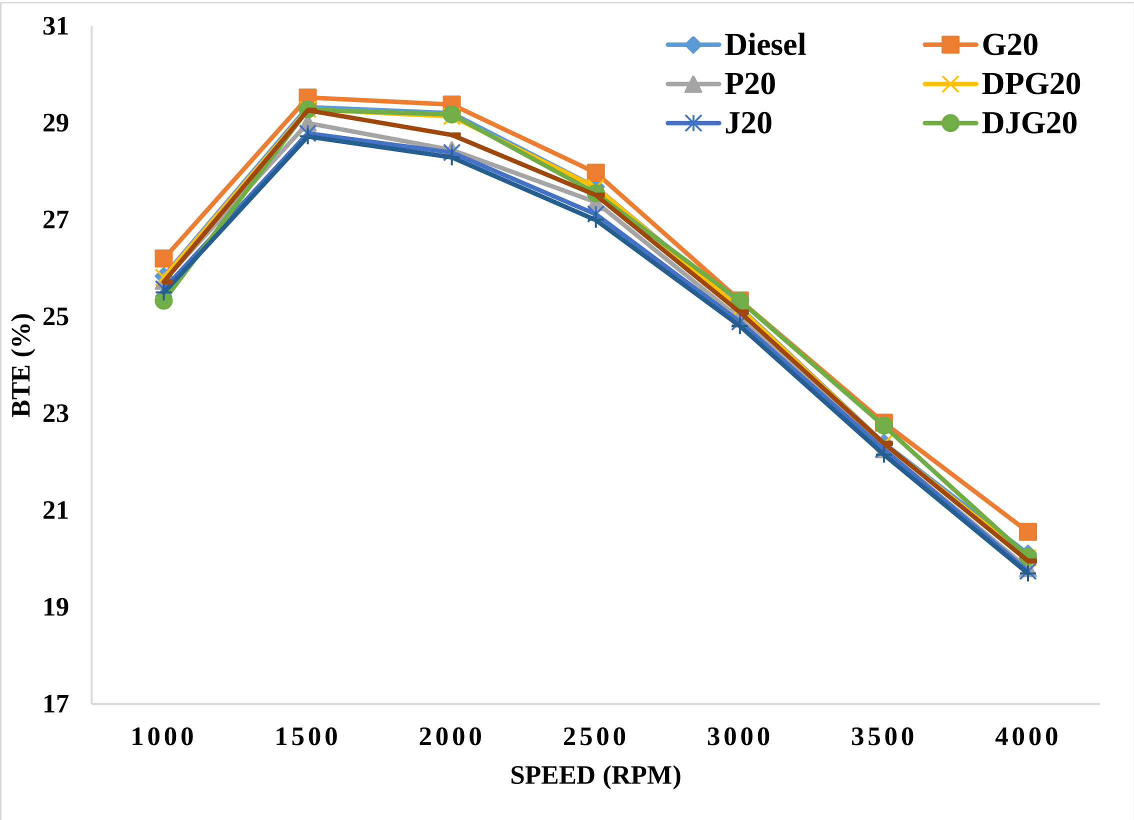

Figure 4.11 (a) Variation of BTE values of all fuel blends within the test speed range at full load condition.

4.3.3.2 Constant speed with variable load condition

Figure 4.11 (b) shows the variation of BTE values among all fuel samples at constant speed of 2000 rpm with variable load condition. It was observed that not only the B20 blends but also the ternary blends demonstrated lower BTE values, but G20 showed higher BTE than diesel. On average, P20, DPG20, J20, DJG20, CI20 and DCIG20 showed lower BTE values about 1.91%, 0.28%, 2.73%, 0.17%, 3.36% and 0.38%, respectively, whereas, G20 showed higher values of BTE about 3.12% than that of diesel. In comparison to P20, J20 and CI20, the improvement of BTE values for DPG20, DJG20 and DCIG20 were approximately 1.66%, 2.63% and 3.09%, respectively.

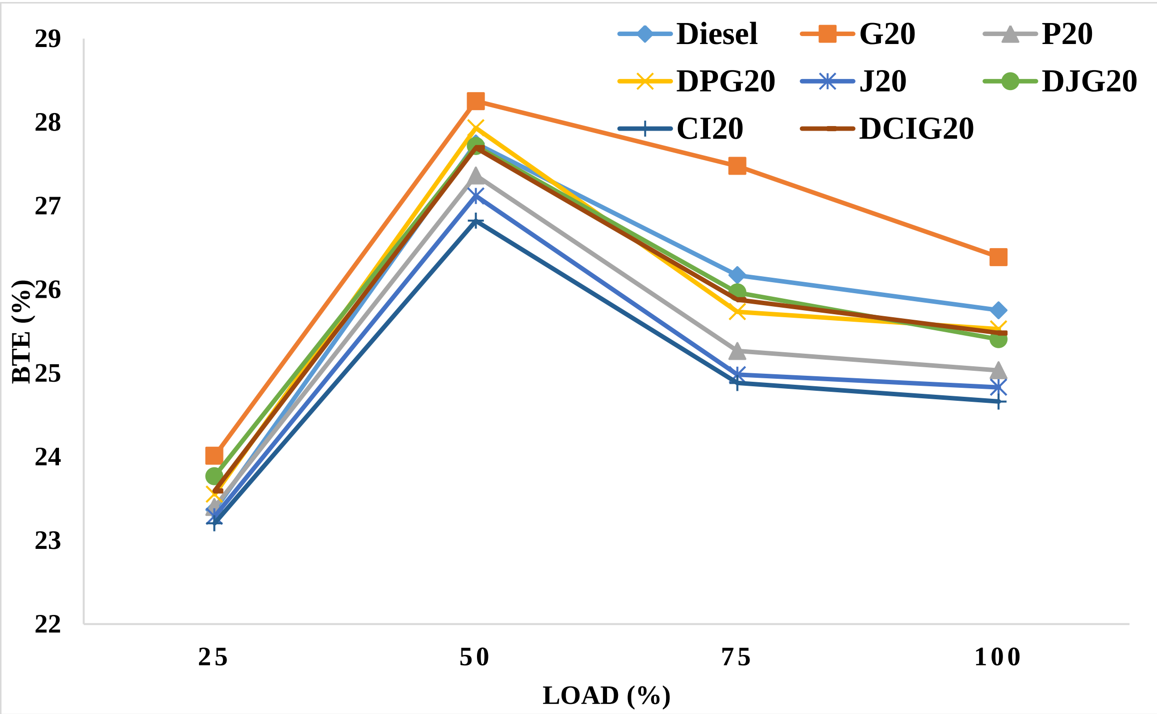

Figure 4.11 (b) Variation of BTE values of all fuel blends at 2000 rpm at variable load condition.

4.3.3.3 Constant torque with variable speed condition

Figure 4.11 (c) shows the variation of BTE values among all fuel samples at constant torque of 80 Nm with variable speed condition. It was observed that like the other test conditions, the B20 blends and the ternary blends demonstrated lower BTE values, but the G20 showed higher BTE, when compared to diesel. On average, P20, DPG20, J20, DJG20, CI20 and DCIG20 showed lower BTE about 2.57%, 1.25%, 1.29%, 0.12%, 1.65% and 0.07%, respectively, whereas, G20 showed higher BTE about 1.61% than diesel. In comparison to P20, J20 and CI20, the improvement of BTE values for the three ternary blends DPG20, DJG20 and DCIG20 were approximately 1.35%, 1.18% and 1.62%, respectively.

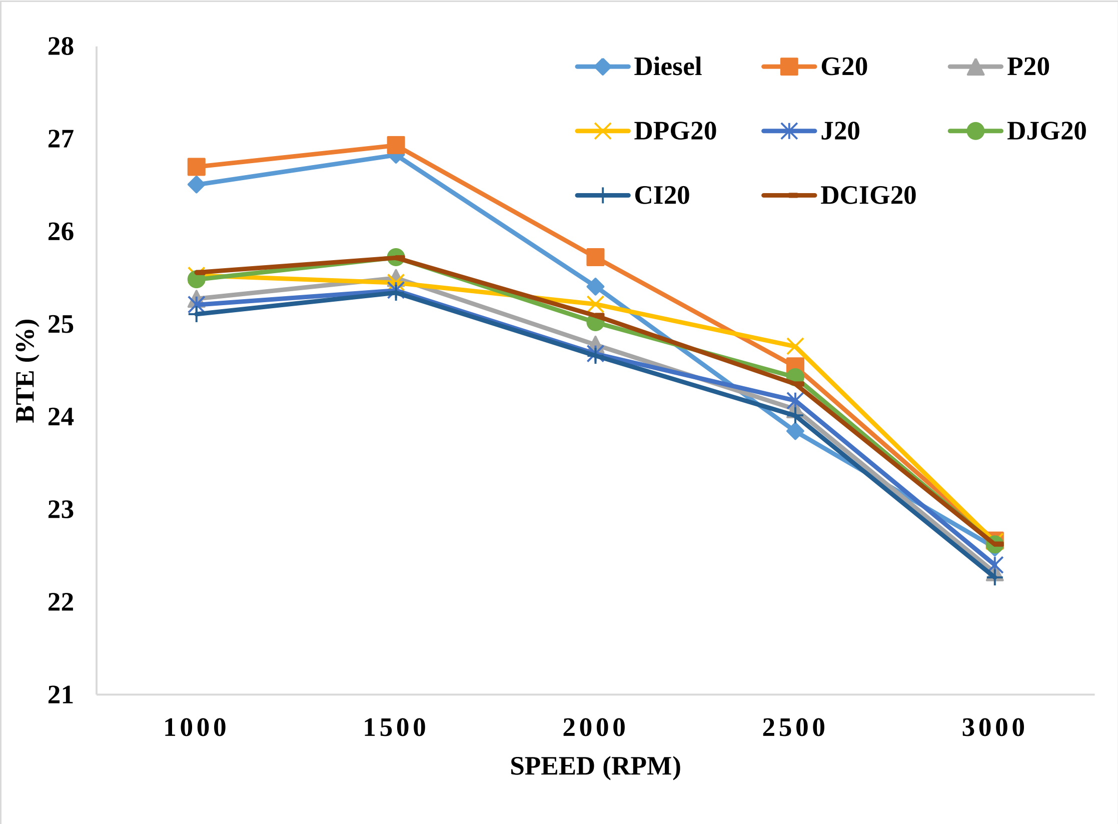

Figure 4.11(c): Variation of BTE values of all fuel blends within the test speed range at constant torque condition.

It was observed that all of the fuel blends showed higher BTE in the medium-speed conditions compared to low speed operation. Since lower fuel consumption is required to overcome the mechanical losses associated with engine during medium-higher speed operating zone compared to the lower speed zone. At the top dead center, a higher level of spontaneous premixing occurs, which induces a faster rate of combustion (Yongcheng et al., 2006). At high speed, all fuels demonstrated low BTE. This can be attributed to insufficient air, causing incomplete combustion of the fuel (Buyukkaya, 2010). Considering efficient energy consumption, this improved BTE of G20 and the ternary blends over the B20 blends are of significant advantages. Moreover, the high brake thermal efficiency is beneficial to the automobile manufacturer as improved BTE widens the range of opportunities to comply with the upcoming strict pollutant regulations and after-treatment system requirements by modifying the injection parameters. Figure 4.11 (d) shows a comparison of the improvements of BTE values of all ternary blends than their respective B20 blends.

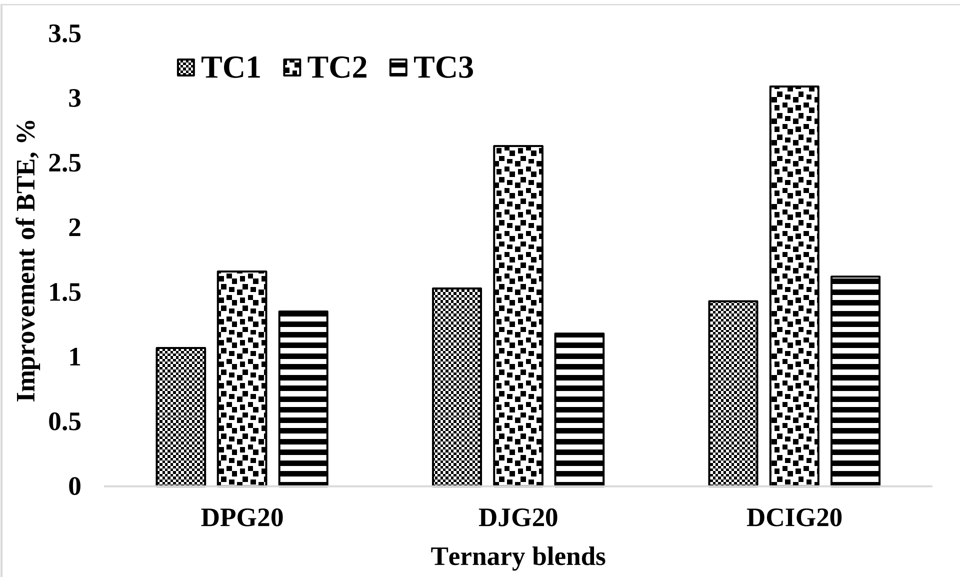

Figure 4.11 (d): Improvements of BTE values of all ternary blends than the 20% biodiesel blends.

4.4 Analysis of exhaust emission parameters

This section illustrates the results of the engine exhaust emission parameters of all fuel samples at different engine test conditions. In this study, four emission parameters were chosen, such as, carbon monoxide (CO), hydrocarbon (HC), nitrogen oxides (NO_x) and smoke opacity.

4.4.1 CO Emission

The presence of higher CO content in exhaust emissions is definitely an indicator of incomplete combustion. Occurrence of rich combustion mixture on account of lower air-fuel proportion can be regarded as the prime reason that induces CO emission (Abu-Jrai et al., 2006). Besides, the occurrence of flame quenching in the midst of the over-lean zone and in the wall impingement quenching zone, also favor CO emission. Moreover, presence of aromatic hydrocarbons in fuel, can be responsible for the additional CO formation (Heywood, 2002). In this section, the reduction of CO emission for the ternary blends were compared with their respective B20 blends, G20 and diesel at all test conditions. The comparative results are presented in Figure 4.12(a), 4.12(b) and 4.12(c).

4.4.1.1 Full load with variable speed condition

Figure 4.12(a) depicts the CO emission values of all fuel blends at full load with variable engine speed test conditions. It was observed that all of the fuel blends showed lower CO emission than diesel. On average, G20, P20, DPG20, J20, DJG20, CI20 and

DCIG20 showed diminution in CO emission approximately 25.96%, 19.21%, 23.47%, 18.31%, 24.23%, 16.84% and 23.37%, respectively than diesel. In comparison to P20, J20 and CI20, the ternary blends DPG20, DJG20 and DCIG20 demonstrated further reduction in CO emission about 5.53%, 6.57% and 7.83%, respectively.

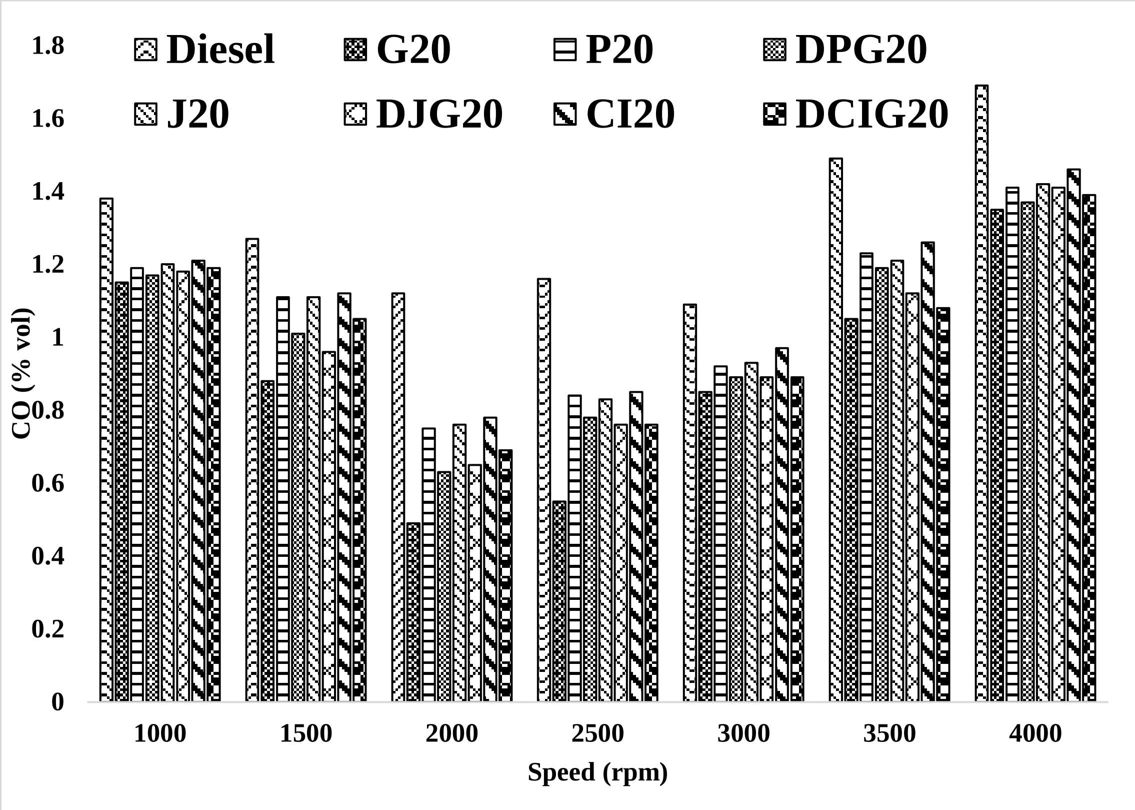

Figure 4.12(a) Variation of CO emission of all fuel blends within the test speed range at full load condition.

4.4.1.2 Constant speed with variable load condition

Figure 4.12(b) presents the CO emission values of all fuel blends at a constant speed of 2000 rpm with variable engine load test conditions. All of the fuel blends demonstrated lower CO emission than diesel. On average, G20, P20, DPG20, J20, DJG20, CI20 and DCIG20 showed diminution in CO emission approximately 33.36%, 18.1%, 27.16%, 12.34%, 25.93%, 8.79% and 19.75%, respectively than diesel. In comparison to P20, J20 and CI20, their ternary blends DPG20, DJG20 and DCIG20 demonstrated further reduction in CO emission about 10.61%, 15.48% and 12.16%, respectively.

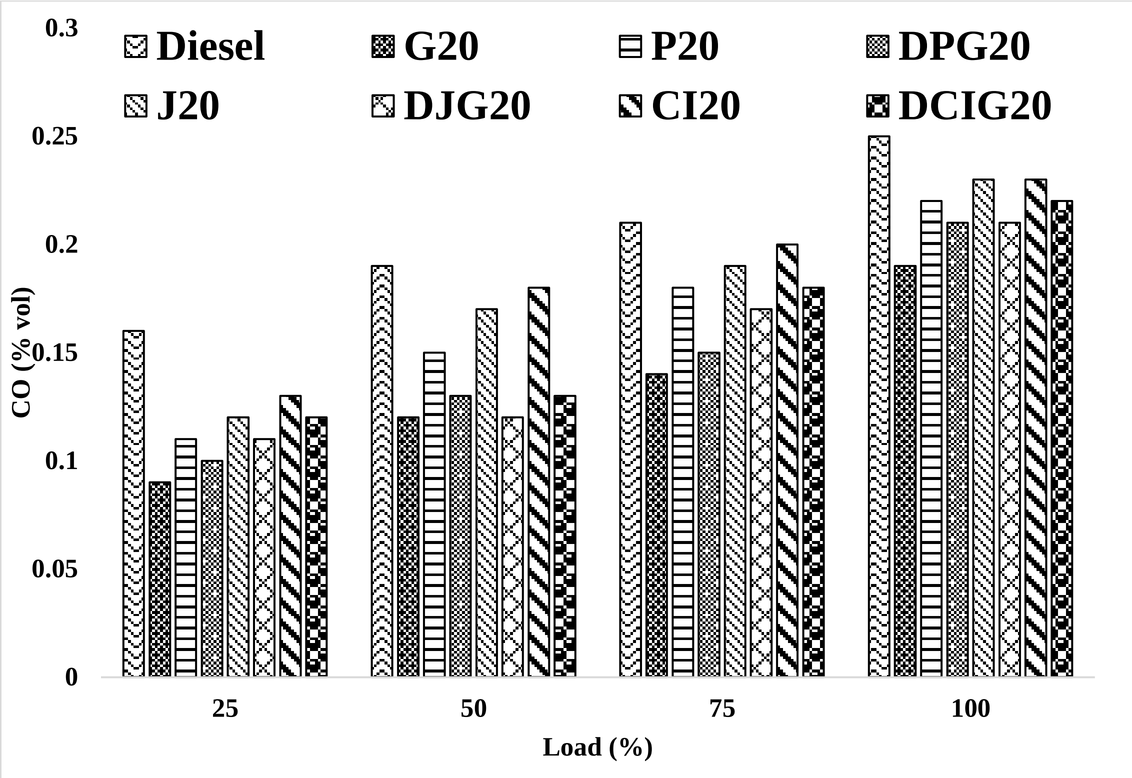

Figure 4.12(b): Variation of CO emission of all fuel blends at 2000 rpm at variable load condition.

4.4.1.3 Constant torque with variable speed condition

Figure 4.12(c) presents the CO emission values of all fuel blends at a constant torque of 80 Nm with variable engine speed test conditions. Alike the other two test conditions, all fuel blends demonstrated lower CO emission than diesel. Considering the average emission values, G20, P20, DPG20, J20, DJG20, CI20 and DCIG20 showed diminution in CO approximately 26.13%, 17.58%, 21.61%, 14.76%, 18.96%, 11.74% and 17.48%, respectively than diesel. When compared to P20, J20 and CI20, their respective ternary blends DPG20, DJG20 and DCIG20 demonstrated further reduction in CO emission about 4.87%, 4.69% and 6.19%, respectively.

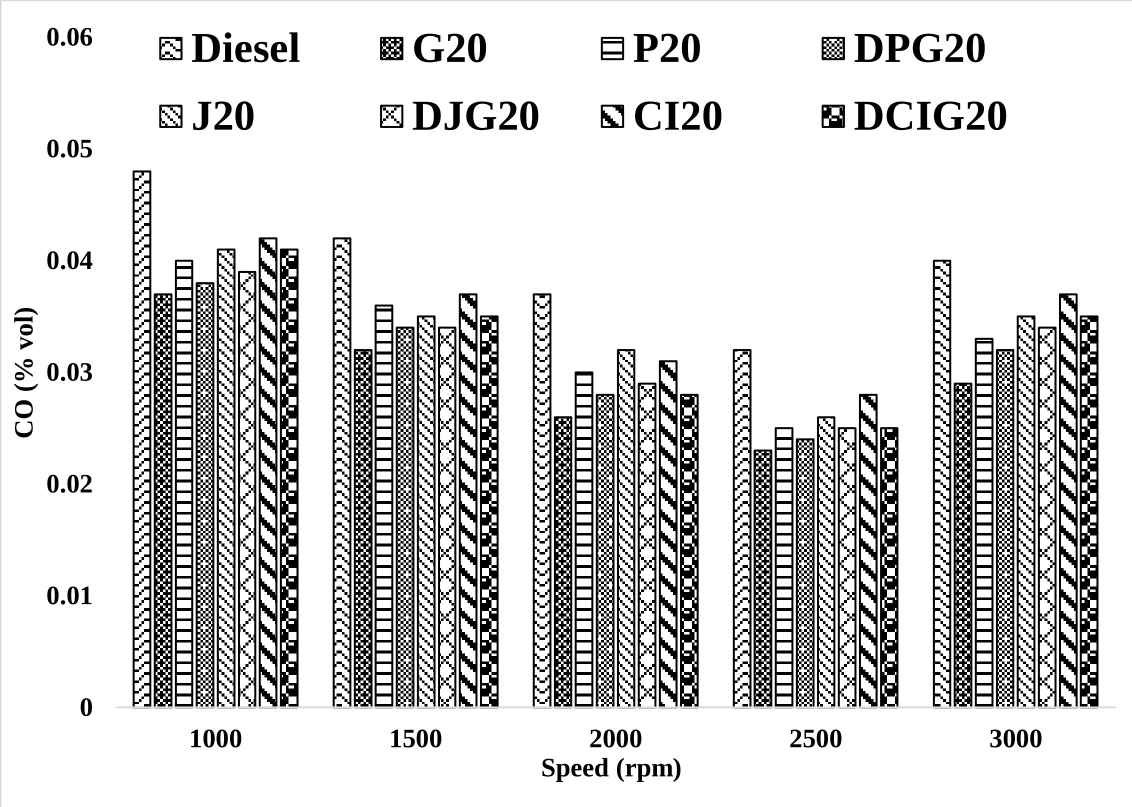

Figure 4.12(c): Variation of CO emission of all fuel blends within the test speed range at constant torque condition.

The reasons of CO emission reduction for G20 can be explained by the fuel properties and combustion phenomena. G20 exhibited good thermal efficiency (as described in section 4.3.3), which resulted an increase in air-fuel ratio. Fuel characteristics of G20, like high hydrogen-carbon ratio, high CN and very low aromatic content resulted better combustion, which also contributed to CO reduction. The high CN of G20 induces shortening of ignition delay that prevented the formation of less over-lean zones. Besides, the lower distillation temperature of GTL fuel induced rapid vaporization, which reduced the probability of flame quenching and thus ensured lower CO emission (Huang, et al., 2007; Yongcheng et al., 2006). In case of the B20 blends, lower CO emissions can be explained by the combined effect of the high oxygen content and high CN (Hirkude & Padalkar, 2012). High CN resulted short ignition delay, which led towards better combustion. Moreover, the short ignition delay can also be induced by the longer chain length of biodiesel, and thus improves combustion process (Xue et al., 2011). High oxygen content ensured proper in-cylinder temperature, which also facilitated complete combustion (Cecrle et al., 2012; Di et al., 2009). In case of the ternary blends, the combined presence of GTL fuel and biodiesel resulted more reduction of CO emission than diesel and their respective B20 blends. Figure 4.12(d) shows a comparison of the reductions of CO emission values of all ternary blends than the B20 blends.

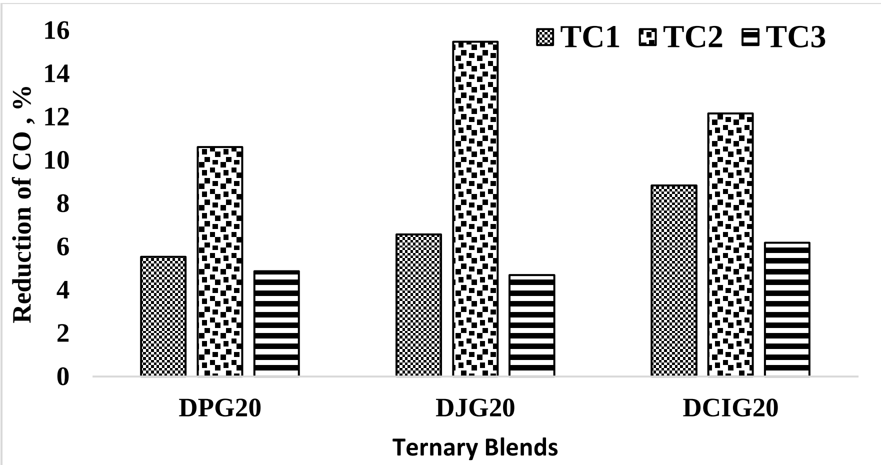

Figure 4.12(d): Percentage of CO emission reductions of all ternary blends than their respective 20% biodiesel blends.

4.4.2 HC Emission

The major reasons behind the formation of HC emission in CI engines are the over-lean fuel mixture (excessive air-fuel ratio) throughout the ignition delay period, improper mixing of fuel adjacent to the spray core at the time of combustion and specially the occurrence of wall quenching of flames due to the impingement of fuel spray on the peripheral areas of the combustion chamber (Yongcheng et al., 2006). In this section, the effect of the ternary blends in HC emission reduction has been compared with their respective B20 blends, G20 and diesel. The results are presented in the Figure 4.13(a), 4.13(b) and 4.13(c).

4.4.2.1 Full load with variable speed condition

Figure 4.13(a) presents the HC emission values of all fuel blends at full load with variable engine speed test conditions. It had been observed that all of the blends showed lower HC emission than diesel. On average, G20, P20, DPG20, J20, DJG20, CI20 and DCIG20 showed diminution in HC emission approximately 27.94%, 15.74%, 23.62%, 14.7%, 24.41%, 12.39% and 20.47%, respectively than diesel. In comparison to P20, J20 and CI20, their ternary blends DPG20, DJG20 and DCIG20 demonstrated further reduction in HC emission about 9.35%, 11.89% and 9.1%, respectively.

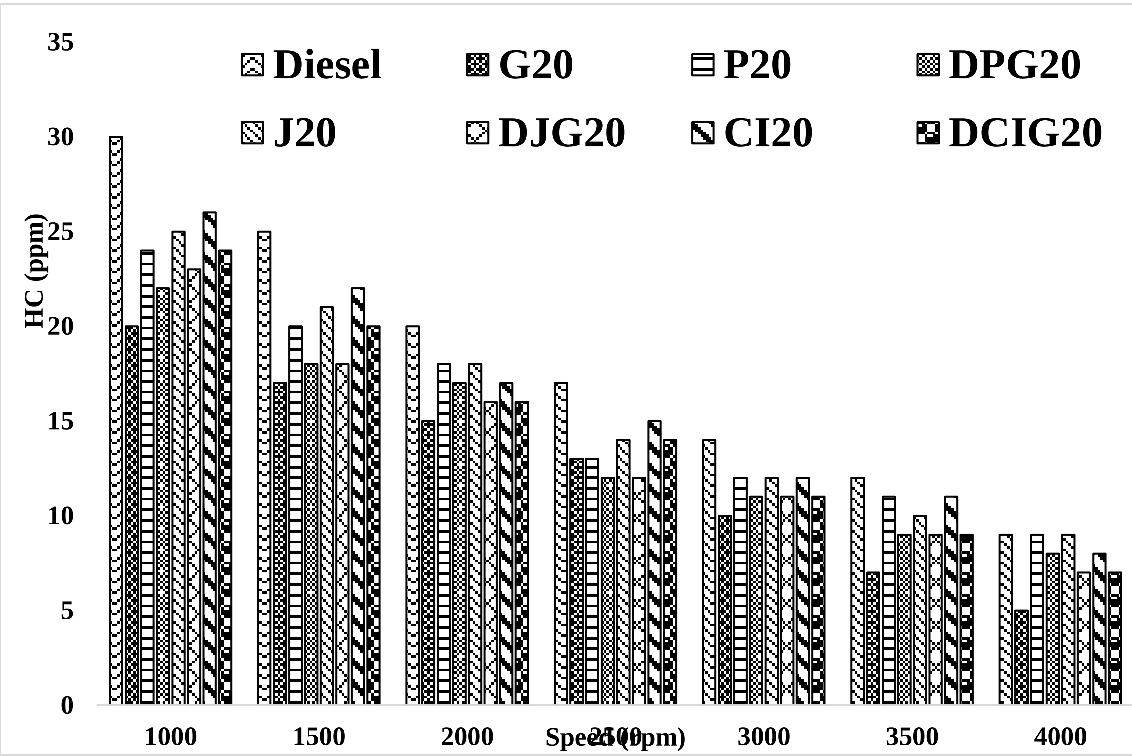

Figure 4.13(a) Variation of HC emission of all fuel blends within the test speed range at full load condition.

4.4.2.2 Constant speed with variable load condition

Figure 4.13(b) represents the HC emission values of all fuel blends at a constant speed of 2000 rpm with variable engine load test conditions. All of the fuel blends demonstrated lower HC emission than diesel. On average, G20, P20, DPG20, J20, DJG20, CI20 and DCIG20 showed diminution in HC emission approximately 25.64%, 11.58%, 20.51%, 15.38%, 21.79%, 12.82% and 21.81%, respectively than diesel. In comparison to P20, J20 and CI20, their ternary blends DPG20, DJG20 and DCIG20 demonstrated further reduction in HC emission about 10.14%, 7.58% and 10.29%, respectively.

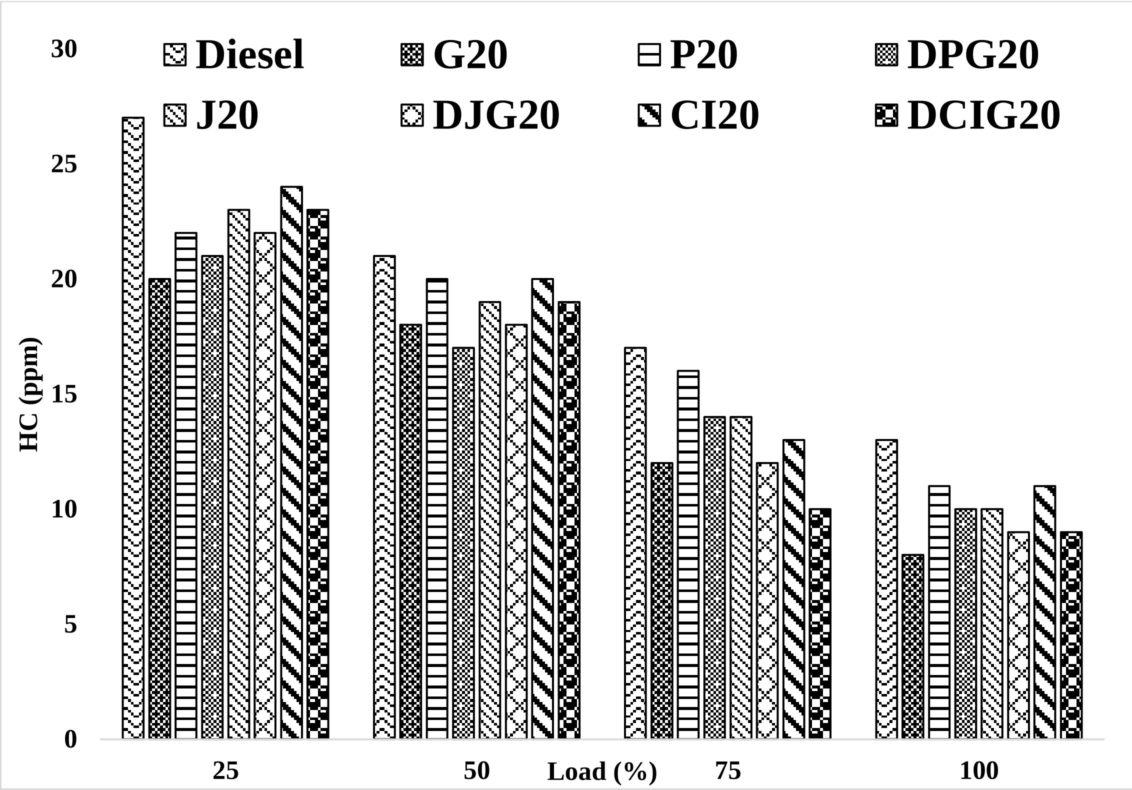

Figure 4.13(b): Variation of HC emission of all fuel blends at 2000 rpm at variable load condition.

4.4.2.3 Constant torque with variable speed condition

Figure 4.13(c) presents the HC emission values of all fuel blends at a constant torque of 80 Nm with variable engine speed test conditions. Alike the other two test conditions, all fuel blends demonstrated lower HC emission than diesel. Considering the average values, G20, P20, DPG20, J20, DJG20, CI20 and DCIG20 showed diminution in HC emission approximately 24.48%, 19.83%, 22.45%, 15.16%, 16.28%, 11.21% and 19.61%, respectively than diesel. When compared to P20, J20 and CI20, their ternary blends DPG20, DJG20 and DCIG20 demonstrated further reduction in HC emission about 3.95%, 2.75% and 8.41%, respectively.

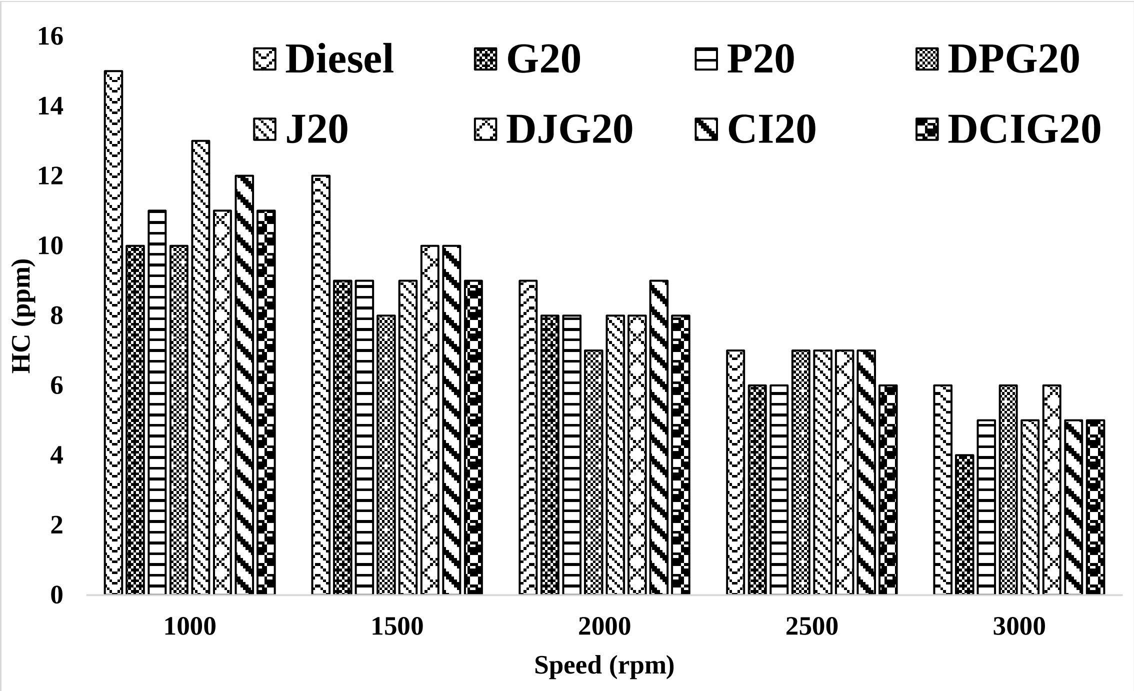

Figure 4.13(c): Variation of HC emission of all fuel blends within the test speed range at constant torque condition.

Alike CO emission, reduction of HC emission can be explained regarding the fuel properties and combustion phenomena of GTL fuel. The high CN of GTL fuel shortened the ignition delay, which prevented the formation of the over-lean regions. Moreover, low distillation temperature of GTL fuel ensured the proper pace of evaporation, and mixing with air to constitute a more effective combustible charge, which resulted less unburned HC in exhaust emission (Wang et al., 2009; Huang, et al., 2007). In case of the B20 blends, their inherent higher oxygen content induced some advantageous conditions throughout the air–fuel interactions, such as, post flame oxidation, high flame speed, etc., especially in the fuel-rich regions, which ensured the proper oxidation of the unburned HC, and thus resulting significant HC emission reduction (Ozsezen et al., 2009). For the ternary blends, the combined presence of GTL fuel and biodiesel yield additional reduction of HC emission than diesel and B20 blends. Figure 4.13(d) shows a comparison of the diminution of HC emission values of all ternary blends than their respective B20 blends.

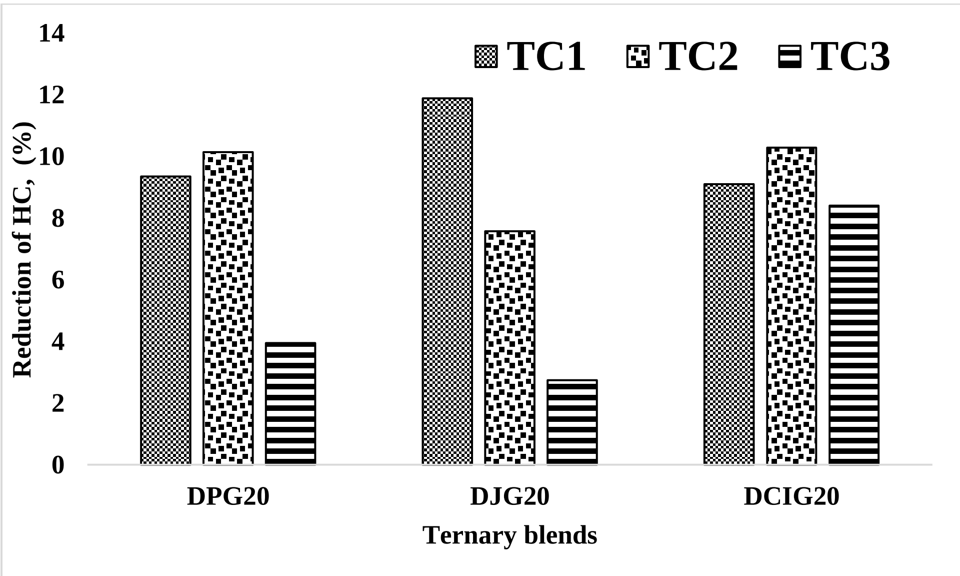

Figure 4.13(d): Percentage of HC emission reductions of all ternary blends than their respective 20% biodiesel blends.

4.4.3 NO_x Emission

In CI engine, the formation of NO_x can be illustrated by zeldovich mechanism (Fattah et al., 2014). During the combustion process, high temperature disengages molecular bonds of nitrogen, which initiates a series of reactions with oxygen and thus accounted for the occurrence of thermal NO_x. Formation of NO_x in the flame front and in the post flame gases depends on the oxygen contents, in-cylinder temperature and residence time (Heywood, 2002). In this section, the NO_x emission of the ternary blends were compared with their respective B20 blends, G20 and diesel. The results are presented in the figure 4.14(a), 4.14(b) and 4.14(c).

4.4.3.1 Full load with variable speed condition

Figure 4.14(a) represents the NO_x emission values of all fuel blends at full load with variable engine speed test conditions. It had been observed that all B20 blends and the ternary blends showed higher NO_x emission, whereas, G20 showed lower emission than diesel. On average, P20, DPG20, J20, DJG20, CI20 and DCIG20 showed higher NO_x emission approximately 3.51%, 1.63%, 4.29%, 1.41%, 4.53% and 2.1%, respectively, but G20 showed about 9.1% lower values, when compared to diesel. In comparison to P20, J20 and CI20, the respective ternary blends DPG20, DJG20 and DCIG20 demonstrated reduction in NO_x emission about 1.87%, 2.71% and 2.34%, respectively.

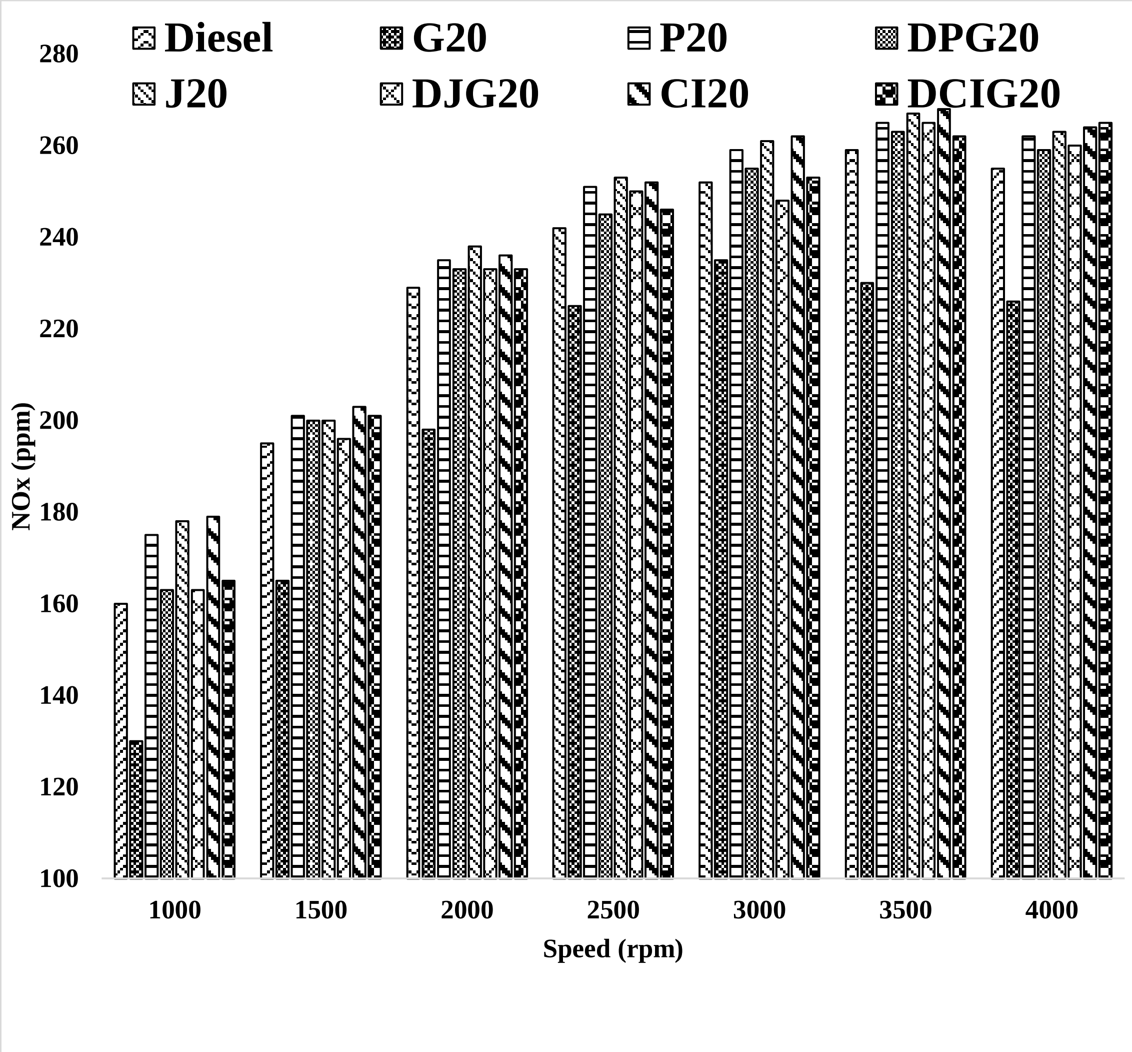

Figure 4.14(a) Variation of NO_x emission of all fuel blends within the test speed range at full load condition.

4.4.3.2 Constant speed with variable load condition

Figure 4.14(b) presents the NO_x emission values of all fuel blends at a constant speed of 2000 rpm with variable engine load test conditions. Higher NO_x emission had been observed for both of the B20 blends and the ternary blends, whereas, G20 showed lower emission than diesel. On average, P20, DPG20, J20, DJG20, CI20 and DCIG20 showed higher NO_x emission approximately 2.33%, 1.13%, 2.57%, 1.32%, 3.11% and 1.62%, respectively, but G20 showed about 7.74% lower values, when compared to diesel. In comparison to P20, J20 and CI20, their ternary blends DPG20, DJG20 and DCIG20 demonstrated reduction in NO_x emission about 1.15%, 1.19% and 1.35%, respectively.

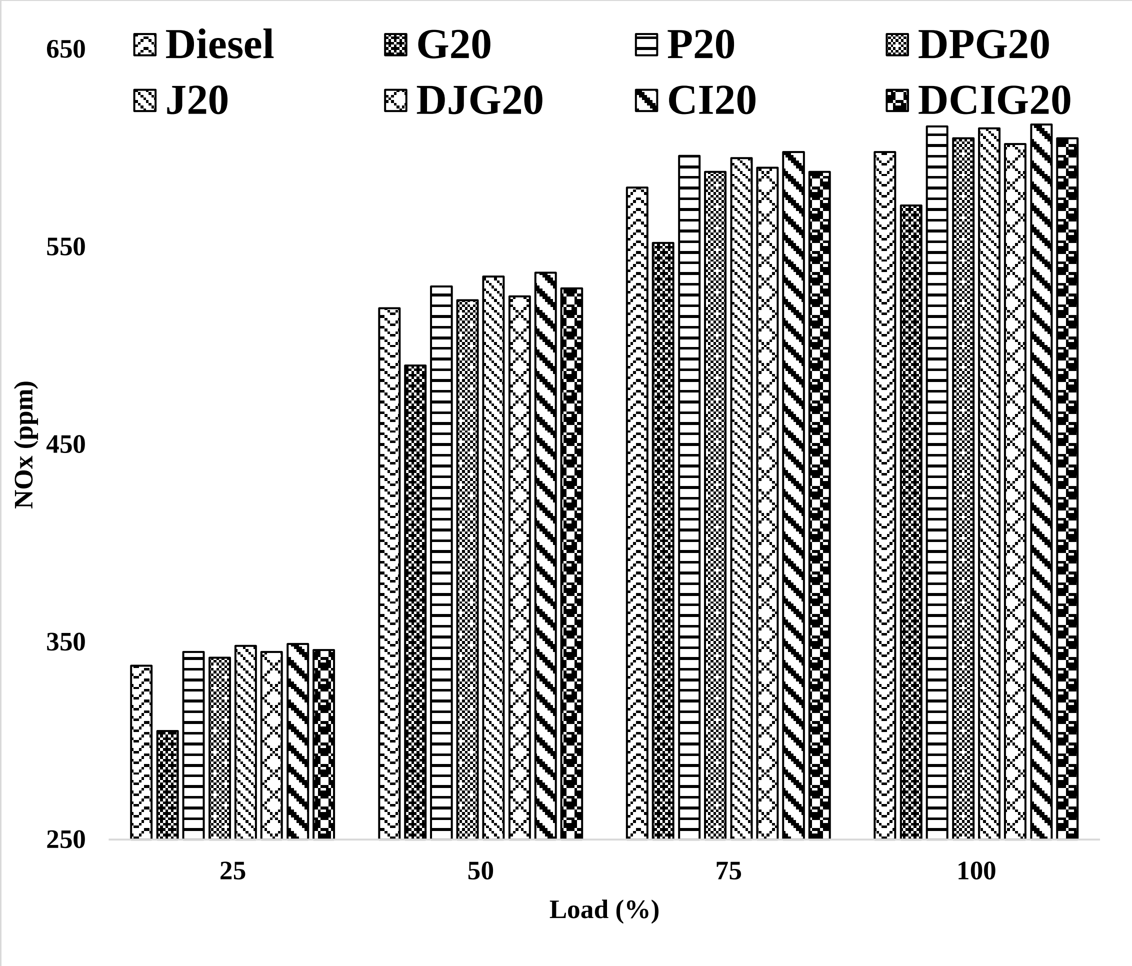

Figure 4.14(b): Variation of NO_x emission of all fuel blends at 2000 rpm at variable load condition.

4.4.3.3 Constant torque with variable speed condition

Figure 4.14(c) represents the NO_x emission values of all fuel blends at a constant torque of 80 Nm with variable engine speed test conditions. Alike the other two test conditions, higher NO_x emission was observed for both of the B20 and the ternary blends, whereas, G20 showed lower emission than diesel. On average, P20, DPG20, J20, DJG20, CI20 and DCIG20 showed higher NO_x emission approximately 5.66%, 2.61%, 5.43%, 2.63%, 5.69% and 2.1%, respectively, but G20 showed about 7.19% lower values, when compared to diesel. In comparison to P20, J20 and CI20, the respective ternary blends DPG20, DJG20 and DCIG20 demonstrated reduction in NO_x emission about 2.89%, 2.77% and 3.51%, respectively.

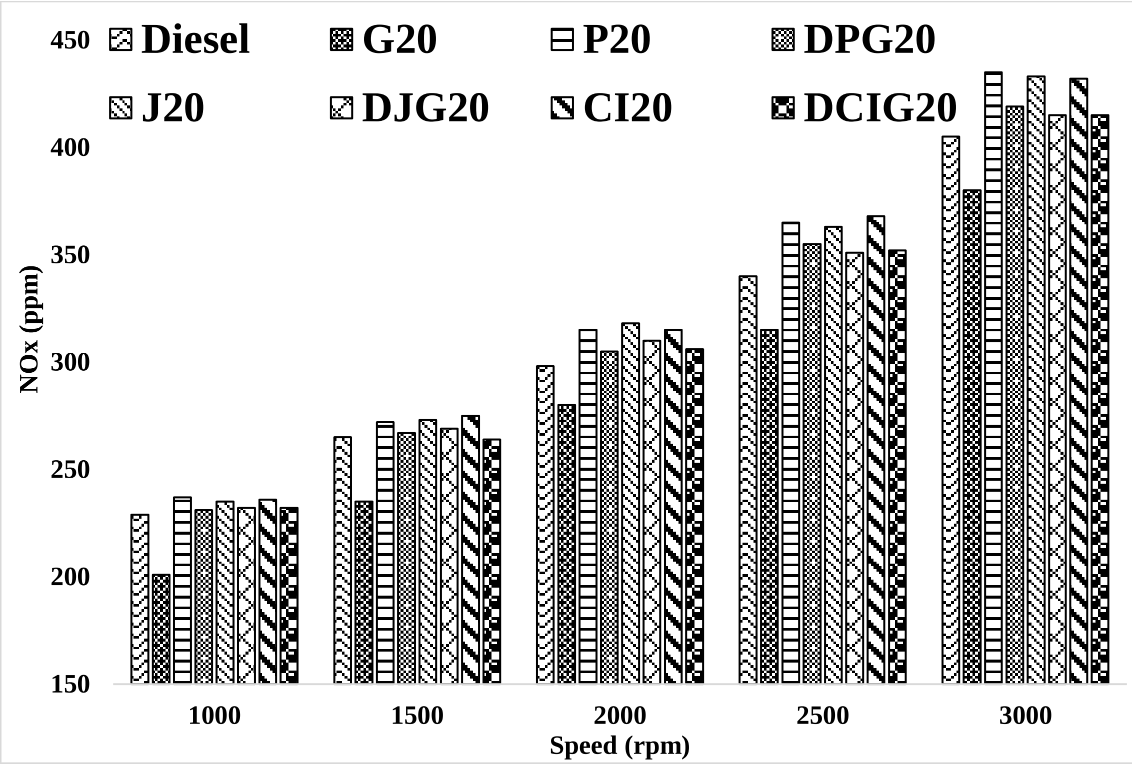

Figure 4.14(c): Variation of NO_x emission of all fuel blends within the test speed range at constant torque condition.

The diminution of NO_x emission of G20 can be illustrated by the influence of fuel properties in combustion phenomena and exhaust emission. The high CN of G20 induced shorter ignition delay, followed by a lesser premixed charge, which resulted the low combustion temperature and pressure (Huang, et al., 2007; Yongcheng et al., 2006). It led towards less thermal NO_x formation. Significant lower aromatic contents of GTL fuel also influenced G20, which prompted to maintain a lower local adiabatic flame temperature, and thus assists in NO_x reduction (Abu-Jrai et al., 2006; Xinling & Zhen, 2009). Several research studies revealed that NO_x emission in biodiesel or diesel-biodiesel blends demonstrated higher emission with the increase in unsaturation percentage and with the decrease of the chain length (Hoekman & Robbins, 2012; Knothe, 2005). In case of the biodiesel blends, high NO_x was observed in all test modes because of their high oxygen content and a high "premixed part" during combustion, where NO_x primarily formed (Rakopoulos, 2013). In case of the ternary blends, the presence of GTL fuel in blend resulted additional reduction of NO_x content in exhaust emission than their respected B20 blends in all three test conditions. Figure 4.14(d) shows a comparison of the improvements of NO_x emission values of all ternary blends than their respective B20 blends.

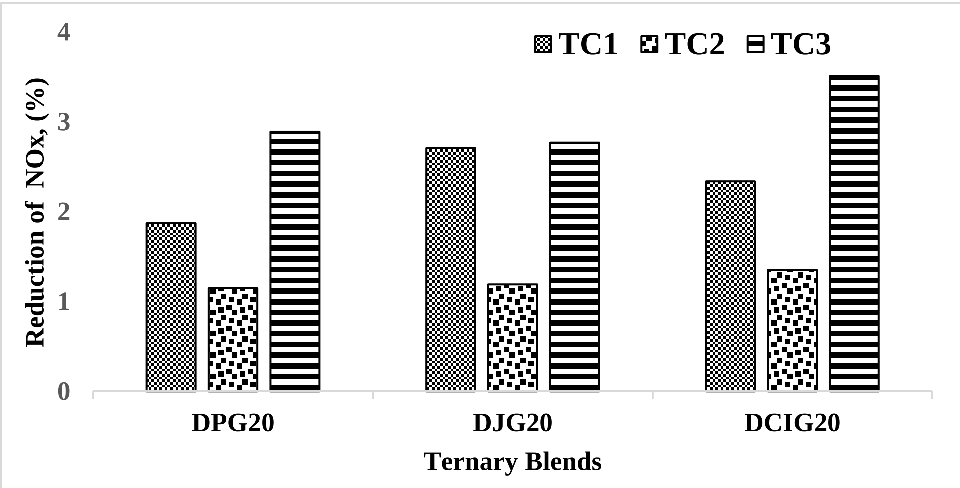

Figure 4.14(d): Percentage of NO_x emission reductions of all ternary blends than the 20% biodiesel blends.

4.4.4 Smoke emission

Smoke is an undesirable by-product of the combustion process in C.I. engines. It is constituted because of the incomplete combustion of hydrocarbon fuel. Usually, the smoke from the engine exhaust can be seen in the form of dark black smoke. "Smoke opacity” is one of the most common terms to identify soot formation in the exhaust gas. Moreover, this term can also be applied to forecast the tendency of soot formation during combustion of any test fuel (Imtenan et al., 2014). The composition of the smoke depends upon the fuel characteristics and the engine test conditions. In this section, the variation in smoke opacity of the ternary blends were compared with their respective B20 blends, G20 and diesel at different engine test conditions. The results are presented at Figure 4.15(a), 4.15(b) and 4.15(c).

4.4.4.1 Full load with variable speed condition

Figure 4.15(a) represents the smoke opacity values of all fuel blends at full load with variable engine speed test conditions. It had been observed that all of the blends showed lower smoke than diesel. On average, G20, P20, DPG20, J20, DJG20, CI20 and DCIG20 showed diminution in smoke emission approximately 19.18%, 15.28%, 18.89%, 13.18%, 17.96%, 11.28% and 15.98%, respectively than diesel. In comparison to P20, J20 and CI20, their respective ternary blends DPG20, DJG20 and DCIG20 demonstrated further reduction in smoke about 4.26%, 5.51% and 5.31%, respectively.

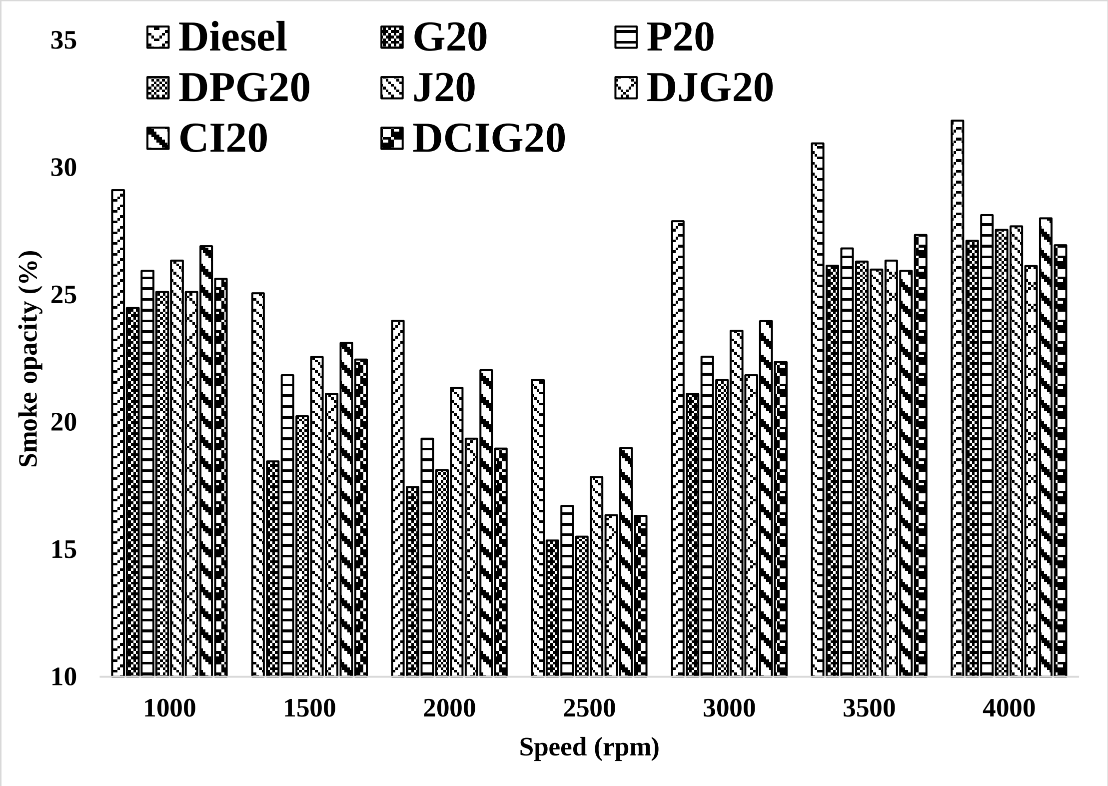

Figure 4.15(a) Variation of smoke emission of all fuel blends within the test speed range at full load condition.

4.4.4.2 Constant speed with variable load condition

Figure 4.15(b) represents the smoke opacity of all fuel blends at a constant speed of 2000 rpm with variable engine load test conditions. All of the fuel blends demonstrated lower smoke than diesel. On average, G20, P20, DPG20, J20, DJG20, CI20 and DCIG20 showed reduction in smoke emission approximately 19.4%, 11.1%, 15.81%, 11.58%, 16.97%, 11.86% and 16.57%, respectively than diesel. In comparison to P20, J20 and CI20, their ternary blends DPG20, DJG20 and DCIG20 demonstrated further reduction in smoke opacity about 5.56%, 6.35% and 5.35%, respectively.

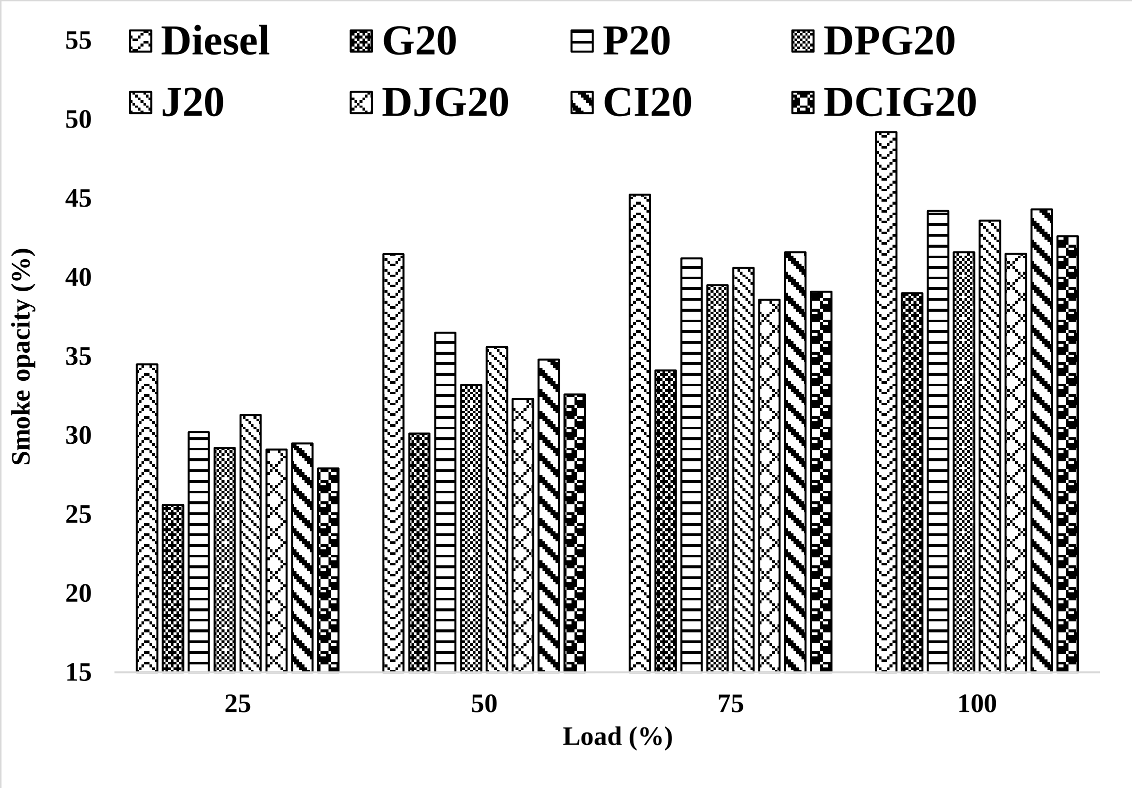

Figure 4.15(b): Variation of smoke emission of all fuel blends at 2000 rpm at variable load condition.

4.4.4.3 Constant torque with variable speed condition

Figure 4.15(c) represents the smoke opacity values of all fuel blends at a constant torque of 80 Nm with variable engine speed test conditions. Alike the other two test conditions, all fuel blends demonstrated lower smoke than diesel. Considering the average values, G20, P20, DPG20, J20, DJG20, CI20 and DCIG20 showed diminution in smoke emission approximately 9.74%, 6.65%, 8.55%, 4.79%, 8.1%, 5.46% and 7.83%, respectively than diesel. When compared to P20, J20 and CI20, their ternary blends DPG20, DJG20 and DCIG20 demonstrated further reduction in smoke opacity about 2.1%, 3.5% and 2.62%, respectively.

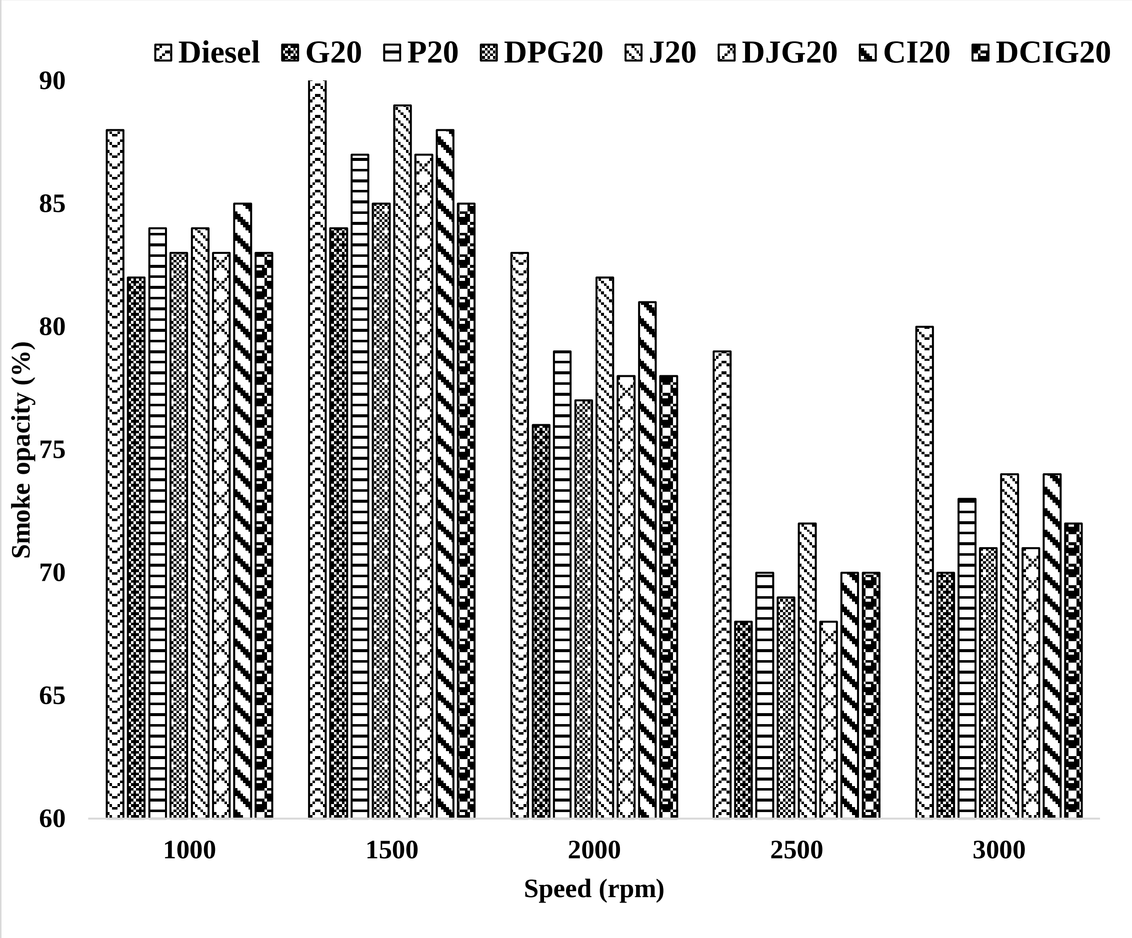

Figure 4.15(c): Variation of smoke emission of all fuel blends within the test speed range at constant torque condition.

This reduction in smoke emissions in G20, which is in accordance with that observed in the literature (Lapuerta et al., 2010; Yongcheng et al., 2006), can be illustrated by the combined effect of the absence of aromatics (regarded as soot predecessors), low sulfur content and high hydrogen to carbon ratio of GTL fuel. Regarding the smoke emission reduction of the biodiesel blends, it can be deduced that the high oxygen content, associated with low sulfur content and impurities, can be attributed to such diminution of smoke emission (Imtenan et al., 2014). In case of the ternary blends, the incorporation of GTL fuel and biodiesel with diesel demonstrated additional reduction of smoke emission than diesel and their respective B20 blends. Figure 4.15(d) shows a comparison of the reductions of smoke emission values of all ternary blends than their respective B20 blends.

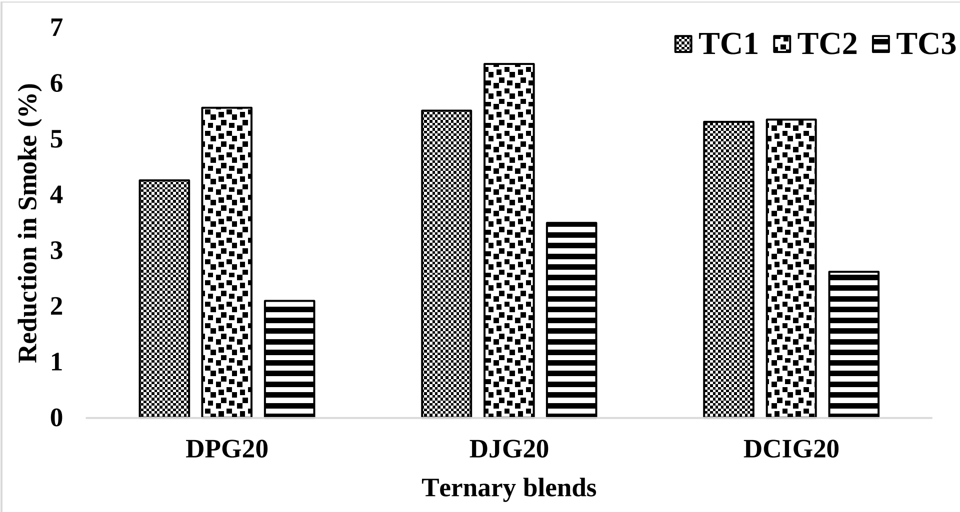

Figure 4.15(d): Percentage of smoke emission reductions of all ternary blends than their respective 20% biodiesel blends.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

This research consists of a comparative study regarding four alternative fuel blends and three ternary blends. GTL fuel and three prospective biodiesel such as, palm, jatropha and calophyllum were used in this study. All of the fuel samples were investigated in the context of major fuel properties and engine performance and exhaust emission parameters. All engine tests were carried out in a multi-cylinder diesel engine and the parameters were evaluated at three different engine test conditions. Based on the results of the investigation the conclusions are illustrated here.

1. All B20, G20 and DBG20 blends showed higher flash point and CN than reference fuel diesel. Regarding the three major properties like density, viscosity and calorific value, G20 showed lower values of for the first two properties, but higher value for the third one, whereas, all B20 blends demonstrated higher values of first two properties, and lower values for the third one than those of diesel. It was observed that all DBG20 blends showed improvement of fuel properties than their respective B20 blends.

2. Considering the fuel consumption and energy consumption of all fuel samples, G20 showed the lowest BSFC and BSEC values in all test conditions. All B20 blends demonstrated higher BSFC and BSEC values than diesel. All DBG20 blends showed promising improvements in BSFC and BSEC than those of their respective B20 blends.

3. The analysis of BTE showed that of all fuel samples, G20 had the best BTE in all test conditions. The B20 blends had lower BTE than diesels, whereas all DBG20 showed slight improvement than their respective B20 blends.

4. The emission analysis results of all test conditions revealed that G20, B20 and DBG20 blends showed lower CO, HC and smoke emissions than those of diesel. In case of NO_x emission, only G20 showed lower values, whereas, the B20 and DBG20 blends showed higher values, when compared to those of diesel.

5. Regarding the emission analysis of the ternary blends, it was observed that all DBG20 blends showed significant lower values of CO, HC, NO_x and smoke opacity than those of their respective B20 blends.

6. Combustion analysis result demonstrated that all B20 and DBG20 blends had higher peak values of the in-cylinder pressure, whereas, G20 shower lower peak pressure than those of diesel. The peak locations of B20 and DBG20 were slightly advanced, but G20 showed retarded peak position, when compared to diesel.

7. In case of HRR analysis, both of the B20 and DBG20 blends showed higher peak of HRR, but G20 had lower peak value, when compared to diesel. The HRR peak positions of B20 and DBG20 occurred at advanced crank angle, but for G20, it occurred at later crank angle, when compared to diesel.
8. It was observed that all DBG20 blends showed lower peak for both of the in-cylinder pressure and HRR values than those of their respective B20 blends. The

peak locations for both of these parameters positioned at later crank angles when compared to their respective B20 blends.

5.2 Recommendations

Referring to the conclusions of this study, the following recommendations can be proposed:

1. As the present study was confined to engine performance-emission parameters, the effect of wear, corrosion and material compatibilities by using these sample fuels can be studied further.

2. Variation of combustion parameters like, changing the compression ratio, nozzle diameter and nozzle fouling performance of these alternative fuel blends can be another prospective research scope.

3. The heat transfer and heat loss of diesel engine can be investigated while operating with these alternative fuels to justify the application of these blends in future transport sector.

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APPENDIX

LIST OF PUBLICATIONS

Journal Publications

- Sajjad, H., Masjuki, H. H., Varman, M., Kalam, M. A., Arbab, M. I., Imtenan, S., & Ashraful, A. M. (2015). Influence of gas-to-liquid (GTL) fuel in the blends of Calophyllum inophyllum biodiesel and diesel: An analysis of combustion–performance–emission characteristics. *Energy Conversion and Management, 97*(0), 42-52. doi: http://dx.doi.org/10.1016/j.enconman.2015.02.037.

- Sajjad, H., Masjuki, H. H., Varman, M., Kalam, M. A., Arbab, M. I., Imtenan, S., & Rahman, S. M. A. (2014). Engine combustion, performance and emission characteristics of gas to liquid (GTL) fuels and its blends with diesel and bio-diesel. *Renewable and Sustainable Energy Reviews, 30*(0), 961-986. doi: http://dx.doi.org/10.1016/j.rser.2013.11.039.

- Sajjad, H., Masjuki, H., Varman, M., Kalam, M., Arbab, M., Imtenan, S., & Rashedul, H. (2015). Influence of gas-to-liquid (GTL) fuel in the combined blend of Jatropha biodiesel and diesel: an analysis of engine combustion–performance–emission parameters. *RSC Advances, 5*(38), 29723-29733.

- Sajjad, H., Masjuki, H., Varman, M., Kalam, M., Arbab, M., Imtenan, S., & Rashed, M. (2014). Comparative study of gas-to-liquid fuel, B5 diesel and their blends with respect to fuel properties, engine performance and exhaust emissions. *RSC Advances, 4*(84), 44529-44536.

Conference Publications

- Sajjad, H., Masjuki, H., Varman, M., Khan, M. M. R., Arbab, M., Imtenan, S., & Sanjid, A. (2014). Comparative Study of Biodiesel, GTL Fuel and Their Blends in Context of Engine Performance and Exhaust Emission. 10th International Conference on Mechanical Engineering (ICME 2013), *Procedia Engineering, 90*, 466-471.

- Sajjad, H., Masjuki, H., Varman, Kalam, A., Arbab, M., & Imtenan, S. (2015) Experimental investigation on the influence of Gas-to-liquid (GTL) fuel in reduction of the hazardous emission parameters of the combined blend of diesel-

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