Performance and Emissions of a DI Diesel Engine Fueled by Different Biodiesel Blends

By: Majed M. Alawi

Supervised by Dr. Wilson Wang, Department of Mechanical Engineering

Co-Supervised by Dr. Murari Roy, Department of Mechanical Engineering

Co-Supervised by Dr. Basel I. Ismail, Department of Mechanical Engineering

July, 2013

A thesis submitted in partial fulfillment of the requirement of

The M.Sc. Eng. Degree in

Control Engineering

Faculty of Engineering

Lakehead University

Thunder Bay, Ontario

Abstract:

Biodiesel has been a promising clean alternative fuel to fossil fuels, which reduces the emissions that are released by fossil fuels, and possibly reduces the energy crisis caused by the exhaustion of petroleum resources in the near future. Biodiesel is replacing diesel as an alternative fuel for internal combustion engines. Previous research studies have shown that biodiesel can greatly reduce carbon monoxide (CO), hydrocarbon (HC) and particulate matter (PM) emissions compared to diesel fuels, but very few studies have shown a reduction in total nitrogen oxides (NOx). At present, B20 (20% biodiesel in the total fuel mix) is being used commonly in the US due to its material compatibility to changing weather conditions, emission benefits and costs. Currently, Canada is planning to use 5% of biodiesel by 2015. The objective of this study is to test the feasibility of biodiesel in cold climates such as Canada. The biodiesel used is made of canola oil obtained from a local supermarket and winter diesel is used as a reference fuel. Three different series were used. The first series was biodiesel/diesel with six blends (B0, B5, B10, B20, B50 and B100). The second series was biodiesel/diesel plus 2% of a chemical additive (B0, B5A, B10A, B20A, B50A and B100A). The final was kerosene/biodiesel series (K0, K5, K10, K20, K50 and K100). Chemical additive (Wintron XC30) is used to lower the cloud point of the blends and this is the first attempt to investigate its effect on engine emissions. On the other hand, there are limited studies on kerosene being treated as a blending fuel, where it is mainly used to lower the cloud point of the blends to investigate the feasibility of biodiesel in a cold climate such as the winter season in Canada and suggest an appropriate solution for the future of biofuel. Engine performance and emission concentrations are investigated by determining the break specific fuel consumption (bsfc), fuel conversion efficiency and measuring emission concentrations of CO, HC, NO, NO_2 and NOx using gas analysers. Engine tests are performed on a constant rated speed at three different load conditions. A comparison is made for the three series. Most of the blends have shown improved emissions compared to fossil diesel. B5A demonstrated a lower cloud point than fossil diesel, and the kerosene series showed excellent results at high load conditions.

Acknowledgments:

I would like to express my deep and honest gratitude to my supervisor Dr. Wilson Wang and cosupervisor Dr. Murari Roy in the Department of Mechanical Engineering, for providing the support for my thesis research. Their immense range of knowledge in the area of Alternative Energy Engineering and biofuel emissions control has been of great value to me throughout the time towards completion of this thesis project. Their logical way of thinking, expertise, understanding, encouragement and guidance have provided a strong basis for the completion of this thesis.

Also, I would like to thank my another co-supervisor Dr. Basil Ismail for all the help and guidance related to this project. I would also like to thank my thesis reviewers, Dr. Hao Bai and Dr. Pedram Fatehi, for reviewing my thesis and their instructive suggestions.

I would also like to thank Mr. Joe Ripku and Ms. Stefanie Stangler for all the maintenance throughout the experiment. I also wish to thank Mr. Kallash Bhatia Bhatia from the mechanical workshop for his help and expertise.

Finally, I would like to sincerely thank my wife for the time and support she showed me during my thesis work and studies at Lakehead University.

Table of Contents

List of Tables:

List of figures:

Nomenclature

DI	Direct injection
CI	Compression ignition
B0	Pure diesel
B100	100% biodiesel
B5	5% biodiesel / 95% diesel
B10	10% biodiesel / 90% diesel
B20	20% biodiesel / 80% diesel
B50	50% biodiesel / 50% diesel
B5A	5% biodiesel / 95% diesel + 2% additives
B10A	10% biodiesel / 90% diesel+ 2% additives
B20A	20% biodiesel / 80% diesel+ 2% additives
B50A	50% biodiesel / 50% diesel+ 2% additives
B100A	10% biodiesel / 80% diesel+ 2% additives
K100	100% Kerosene
K5	5% kerosene / 95% biodiesel
K10	10% kerosene / 90% biodiesel
K20	20% kerosene / 80% biodiesel
K50	50% kerosene / 50% biodiesel
BP	Brake power
BTE	Brake thermal efficiency
BSFC	Brake specific fuel consumption
BSEC	Brake specific energy consumption
η	Brake fuel conversion efficiency
FAME	Fatty acid methyl ester
CO	Carbon monoxide
HC	Hydrocarbons
PM	Particulate matter
NO	Nitric oxide
NO2	nitrogen dioxide
NOx	Nitrous oxide
CFPP	Cold filter plugging point
ASTM	American Society of Testing and Materials

EPA	Environmental protection agency
FFA	Free fatty acids

Chapter 1
Introduction

1.1 Overview:

Over the last century, energy consumption has rapidly increased due to the significant growth of the world's population. The result of this rapid growth has caused high-energy demands among fossil fuel resources and has thus caused fossil fuel depletion. Because fossil fuels are limitable resources, there has been an increased demand for alternative sources of energy.

On the other hand, environmental pollution is becoming a big concern all over the globe due to the extensive use of fossil oil, which has given researchers and scientists even stronger motivation to look for an alternative sustainable energy source, which is more environmentally friendly. Renewable fuels, made from biomass, have the potential to substitute fossil fuels in stationary applications such as heat or electricity production as well as the transport sector [1]. It could solve several issues, such as the rising worldwide energy prices, the increased need for energy imports, the negative environmental consequences of fossil fuel combustion, and the security of national energy supply for many countries.

Biodiesel and alcohols have been proposed as alternative fuels in the market, which are derived from biomasses [2]. Biodiesel in particular has been proven to be one of the best alternatives for fossil fuel because it produces less pollutant emissions [3,4]. Most of the leading countries such as Germany, France and the United States of America have been conducting extensive Biodiesel research. Also, developing countries such as Brazil, Malaysia, India and Indonesia have been conducting similar research.

Diesel engines do not require modifications when using Biodiesel, and many countries have already converted to this fuel [5]. Biodiesel is actually good for diesel engines. It can provide improved lubrication than fossil diesel and has excellent solvent properties. Fossil diesel can leave deposits inside fuel lines and fuel tanks over time. Once fuel filters clogged with diesel sediments have been replaced, the biodiesel dissolves any leftover sediment while adding no deposits of its own, resulting in cleaner, more trouble-free fuel handling systems.

Biodiesel has been known for its renewable properties. Instead of making a fuel from a finite source such as crude oil, biodiesel can be produced from renewable resources such as organic oils and animal fats.

In 2008, the European Union (EU) set ambitious goals for using renewable energy. The integrated energy and climate change policy in 2008 states a general target of 20% greenhouse gas reduction, 20% reduced energy use through increased energy efficiency, and a 20% share of renewable energy by 2020 [6]. Increased production and use of bioenergy is promoted as a key to reaching the targets [7]. In order to make the shift to renewables in transportation possible, the EU Commission has set a mandatory target of 10% renewable energy in transport by 2020 [8], with a transitional target of 5.75% for 2010 [9]. The United States Environmental Protection Agency (US EPA) has done a comprehensive analysis of biodiesel impacts on exhaust emissions stating that pure biodiesel can reduce greenhouse gases compared to fossil diesel [4].

Biodiesel can be used in its pure form B100 (100% biodiesel) or blended with petroleum diesel. Commonly used blends include B2 (2% biodiesel with fossil diesel), B5 (5% biodiesel with fossil fuel), and B20 (20% biodiesel with fossil fuel).

Several countries have already started substituting fossil diesel with biodiesel. Canada started using 2% of biodiesel in diesel in 2012 and this percentage will increase to 5% by 2015. Both the US and Brazil use up to 20% biodiesel diesel blends, whereas Germany is using up to 100% biodiesel.

Biodiesel appears to be more environmentally friendly in comparison to fossil diesel. Engine emissions contain mainly carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), Nitric oxide (NO), nitrogen dioxide (NO_2), oxygen (O_2), particulate matter (PM) and nitrogen oxides (NO_x). Several analyses showed that using biodiesel would reduce HC, CO, CO_2 and PM significantly compared to fossil diesel [10]. These gases pose risks as they contribute to global warming.

One of the main challenges in using biodiesel in cold countries such as Canada is its high cloud point, which could lead to clogged filters during winter time. Some researchers have tackled this problem by introducing chemical additives to biodiesel to enhance its properties by lowering its cloud point, mainly to make it more feasible for cold climate. In this research, we have studied the effect of biodiesel on engine emissions, as well as the performance and effect of different additives on biodiesel properties.

1.2 CO_2 Cycle:

Biodiesel is made out from various vegetable oil, and produces 78% less CO_2 as compared to diesel [11]. This oil is extracted from plants, which absorbs CO_2 from the air to grow stems, leaves and seeds. The extracted oil (vegetable oil) is used for producing biodiesel. When burnt, the leftover plant material decomposes, returning the carbon from fuel and plant matter to the atmosphere as CO_2. However, this process of recycling carbon from CO_2 in the atmosphere to carbon in plant material and returning it to the atmosphere results in no accumulation of CO_2 in the atmosphere. Therefore, it does not contribute to the global climate change, which is unlike fossil fuels that release the CO_2 trapped underground for centuries to the atmosphere, thus disturbing the carbon dioxide cycle by adding excess CO_2 to the air. However, petroleum fuel is still used for fertilizer, farm equipment, and transportation during biodiesel production, and the CO_2 accumulates in the atmosphere year after year. Biodiesel produces 2661 grams of CO_2 per gallon, compared to 12,360 grams per gallon for petroleum diesel fuel, which represents 78% less CO_2 than diesel fuel. Figure 1.1 shows CO_2 cycle [12].

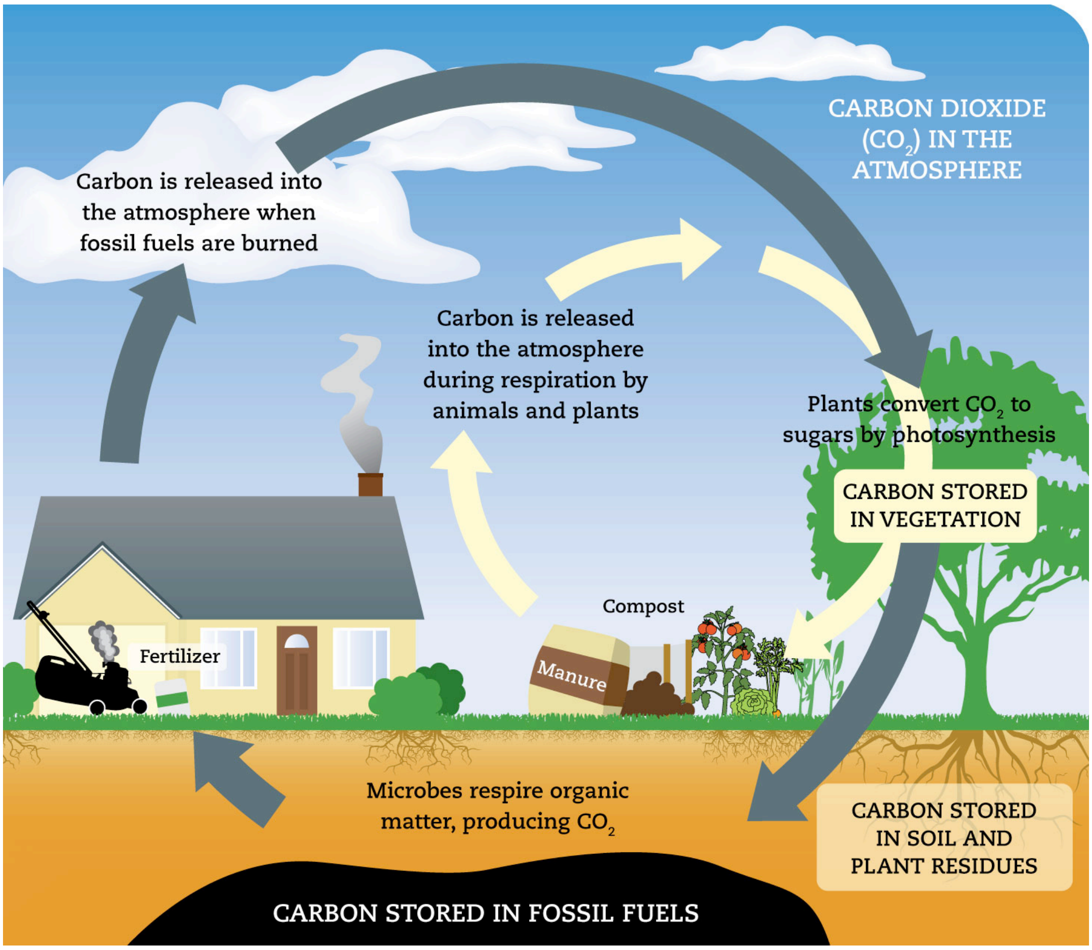

Figure 1.1: CO_2 cycle

1.3 History behind Biodiesel:

Diesel engines were named after their inventor, Rudolf Diesel, who was also the man coming up with the idea of using biofuels. The engine that he demonstrated at the World Exhibition in Paris in 1900 ran on biofuels extracted from peanuts. Despite technical feasibility, using vegetable oil as a fuel could not gain acceptance because it was more expensive than petroleum fuel. However, Diesel believed that vegetable oil had the potential to become a competitive alternative to fossil fuel one day.

After almost half a century of total reliance on fossil fuel, researchers discovered a simple chemical process that could reduce the viscosity of vegetable oils so that it could perform as well as diesel fuel in modern internal combustion engines. Since then, developers have paid more attention to biofuel research and the plant oil today has come a long way, becoming highly established.

1.4 Production of Biodiesel:

Biodiesel production is a very modern and technological area for researchers as an alternative fuel for diesel engines due to petroleum price increases, its renewability, and its environmental advantages. Biodiesel is produced mainly from animal fats or different types of vegetable oils (e.g., rapeseed, soybean, canola, sunflower, palm oil, etc.) depending on the most convenient source in the country. Currently, the cost of biodiesel is high compared to conventional diesel oil because most of the biodiesel is produced from pure vegetable oils. Waste cooking oil is considered more economical due to its cheaper price. Canola oil and animal fat are the leading feedstock for biodiesel production in Canada. The following (Table1.1) shows the feedstock of biodiesel in different countries around the world. [13]

Table 1.1: Sources for biodiesel (free acid methyl esters) around the world

Country	Feedstock
Australia	Waste oil, Animal fat
Brazil	Soybean oil, Palm oil, Castor oil, Cotton oil
Canada	Canola oil, Animal fat
China	Jatropha, Waste oil
Finland	Rapeseed oil, Animal fat
France	Rapeseed oil, Sunflower oil
Germany	Rapeseed oil
India	Jatropha
Japan	Waste oil
Korea	Waste oil
Malaysia	Palm oil
Mexico	Waste oil, Animal fat
New Zealand	Waste oil, Animal fat

Philippine	Coconut oil, Jatropha
Russia	Rapeseed, Sunflower, Soybean oil
Spain	Sunflower oil
Sweden	Rapeseed oil
Thailand	Palm oil, Coconut oil, Jatropha
U.K.	Rapeseed oil, Waste oil
U.S.A.	Soybean oil, Waste oil

The energy content of biofuels differs from that of fossil fuels. The total energy output per liter of biofuel is determined by the feedstock used.

1.5 Biodiesel Production Method:

Transesterification is regarded as one of the most efficient methods of producing biodiesel from vegetable oils due to its low cost and simplicity [14, 15]. Correspondingly, the study in this work will choose canola oil as feedstock and use the transesterification process to produce biodiesel. As illustrated in Figure 1.2, transesterification is a process of exchanging the Alkoxy Group of an ester compound by another alcohol. These reactions are often catalyzed by the addition of an acid or base, but here it is usually a base.

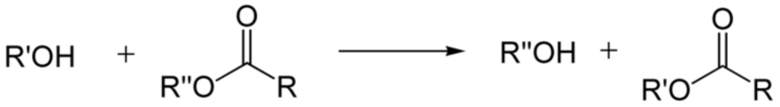

Figure 1.2: Chemical reaction of the transesterification

Basically, vegetable oil is treated in the presence of a catalyst with an alcohol to give the corresponding alkyl esters of the fatty acid mixture found in the parent vegetable oil or animal fat.

R is a mixture of various fatty acid chains. Methanol (methyl alcohol) or Ethanol (ethyl alcohol) is generally used in this chemical reaction. In this research, methanol is used due to its lower price compared to ethanol. Often the resulting products are also called fatty acid methyl esters (FAME) rather than biodiesel. The catalyst is generally a base and those most commonly used are sodium hydroxide (NaOH), potassium hydroxide (KOH) or sodium methoxide (CH_3NaO). NaOH is cheaper to use and it gives better results [16]

1.6 Biodiesel Properties:

1.6.1 Specific Gravity:

The specific gravity is the ratio of density of a substance compared to the density (mass of the same unit volume) of a reference substance. Biodiesel is slightly heavier than mineral diesel fuel. It is always better to add the biodiesel to the diesel when making blends, which can promote improved blending. Blending biodiesel with diesel reduces biodiesel density, which could contribute in improving fuel atomization during fuel injection inside the combustion chamber

1.6.2 Viscosity:

Viscosity is a measure of a fluid's resistance to flow. Biodiesel is more viscous than diesel fuel, which provides improved lubrication for the fuel pumps. Diesel fuel, in general, has low viscosity and does not provide sufficient lubrication for the fuel pumps. Improper viscosity could lead to poor combustion, resulting in a loss of power and excessive exhaust smoke. Also, high viscosity fuels could promote abnormal wear, injector pump leakage, and a decrease in power.

1.6.3 Flash Point:

The flash point of a fuel is defined as the temperature at which it will ignite when exposed to a flame or spark. The flashpoint of biodiesel is higher than petroleum diesel fuel, which is the reason why it increases in blends depending on the percentage of biodiesel in the mix [17]. Thus the increase in biodiesel flashpoint and its blends creates a safer storage environment compared to fossil diesel. On the other hand, the flashpoint can be reduced if the alcohol used in producing biodiesel is not removed properly, negatively affecting the fuel pumps, and also reducing the combustion quality.

1.6.4 Cloud Point:

Cloud point is the temperature at which a cloud or haze of crystals appears in the fuel under test conditions and thus becomes important for low temperature operations. Generally, biodiesel has a higher cloud point than diesel fuel.

1.6.5 Pour Point:

Pour point is the lowest temperature at which a petroleum product will begin to flow. Normally, pour point or Cold Filter Plugging Point (CFPP) is specified, since the pour point more accurately reflects the cold weather operation of fuel. However in the view of ASTM standards the CFPP and the pour point is not specified and The explanation is that the global climatic conditions vary significantly and therefore the needs of the biodiesel users vary accordingly [18]. Pour point depressants commonly used for diesel fuel do not work for biodiesel.

1.6.6 Cold Filter plugging point (CFPP):

CFPP is the lowest temperature at which fuel will still flow through a specific filter and it’s lower than cloud point. This is important as in cold weather countries like Canada a high cold filter plugging point will clog up diesel engine more easily. Also knowing the CFPP of biodiesel is important in relation to the use of additives, which helps the use of fuels at temperature below cloud point.

1.6.7 Cetane Number:

The cetane number of diesel engine fuel is indicative of its ignition characteristics. The higher the cetane number, the better its ignition properties are [19]. The cetane number affects a number of engine performance parameters like combustion, stability, drivability, white smoke, noise and emissions of CO and HC. Biodiesel has a higher cetane number than conventional diesel fuel, resulting in smoother combustion.

1.6.8 Calorific Value (Heating Value):

Calorie value is the total quantity of heat liberated by the complete burning one unit of mass of fuel. The calorific value of a substance is the amount of energy released when the substance is completely burned to a final state and has released all of its energy. Biodiesel has a lower heating value when compared to diesel.

1.6.9 Carbon Residue Content:

Carbon residue content correlates with respective amounts of glycerides, free fatty acids, soaps and catalyst residue. This parameter serves as a measure of the tendency of a fuel sample to produce deposits on injector tips and inside the combustion chamber. It is also influenced by a high concentration of polyunsaturated fatty acid methyl esters and polymers.

1.6.10 Volatility:

Volatility is a measure of the tendency of a substance to vaporize. Since biodiesel has a high flash point compared to fossil diesel, biodiesel has low volatility. Blending biodiesel with a fuel that has higher volatility will enhance the volatility properties of biodiesel.

Chapter 2
Literature Review and Thesis Objective

This chapter covers a summary of previous work on biodiesel. A brief literature for biodiesel performance and emissions is mentioned. Followed by a summary of biodiesel blends with chemical additive and kerosene. Finally highlighting the objective of this study concludes the chapter.

2.1 Biodiesel's Emissions and Performance:

Many investigations have been taken in literature for supporting our current results. Research results show that the use of biodiesel can result in a substantial reduction in PM, CO and HC emissions. Xue et al. [20] studied the effect of biodiesel on engine emissions and performance. They found the following:

- The use of biodiesel can reduce PM significantly due to the high oxygen content and the higher cetane number, which lead to a complete combustion. To this aspect, their results agreed with other researchers work on the idea that the higher the load, the higher the PM level and the higher the speed, the lower the PM level. This is mainly because reducing the air/fuel ratio in higher load can result in less efficient combustion.

- There is a substantial reduction in CO when using biodiesel due to two main reasons: 1) higher oxygen content in the biodiesel compared to diesel fuel; and 2) lower carbon to hydrogen ratio in biodiesel compared to diesel fuel. In addition, engine load was proved to have a big effect on CO emissions

- There was a noticeable reduction in HC when using biodiesel compared to diesel fuel, and researchers believed that the higher oxygen content of biodiesel could lead to more efficient fuel combustion.

- There was an increase in NO_x when biodiesel is used because its higher oxygen content and a higher cetane number can result in a higher combustion temperature compared to diesel fuel.

- BSFC (brake-specific fuel consumption) increases with biodiesel due to its lower heating value, higher density and viscosity. In higher loads, the BSFC decreases, possibly because of the higher percentage of increase in brake power at that load level compared to fuel consumption.

- Biodiesel decreases engine power due to its lower heating value and higher viscosity. High viscosity decreases combustion efficiency because of the related bad injection atomization, whereas high lubricity reduces friction loss and improves the brake effective power.

Di et al. [21] investigated a biodiesel made from waste cooking oil with ultra low sulphur diesel in a 4-cylinder DI diesel engine at a constant speed of 1800 RPM over five different load settings. They found that with the addition of biodiesel in the blended fuel, HC and CO emissions decreased due to improved combustion with oxygen enrichment of the fuel. The PM concentration decreased with the increase of biodiesel in the blended fuel, especially at higher engine loads, because of the increase in oxygen content and the decrease in carbon content in the fuel. However, NOx/NO emissions increased due to the higher combustion temperature and the increased oxygen level in the mixtures. The use of the ultra low sulfur diesel blended with biodiesel could lead to an increase in the BSFC, mainly due to the lower heat value of biodiesel compared to the ultra low sulfur diesel. On the other hand, the oxygen enrichment contributed to more complete combustion, while the improved lubricity reduced the friction loss, resulting in an increase in brake thermal efficiency [18].

Canakci [22] studied No. 2 diesel fuel, soybean biodiesel, and a B20 blend (20% biodiesel and 80% diesel) in a compression ignition (CI) engine. They found a significant reduction in the PM, CO and HC with biodiesel. However, the NO_x emissions increased by 11.2%. On the other hand, there was a 13.8% increase in BSFC due to the biodiesel's lower heating value. Based on combustion characteristics, the start of combustion for B20 and B100 was set earlier than in No. 2 diesel fuel, which resulted in shorter ignition delays than the No. 2 diesel when using B20 and B100 blends.

Buyukkaya [23] used standard diesel fuel, rapeseed biodiesel and blends of B5, B20, B70 on a 6-cylinder, 4-stroke, turbocharged DI diesel engine with different engine speeds (at full load). The results indicated a reduction in CO emissions for neat biodiesel and its blends compared to diesel. This decrease might be due to the high oxygen content in biodiesel. Also, the use of biodiesel and its blends reduced the HC emission. The reason could be related to a higher cetane number and an increase in gas temperature. The higher the temperature of the burned gases prevented condensation of the heaviest hydrocarbons in the sampling line, the higher cetane number decreased combustion delay. The use of biodiesel produced lowered smoke opacity (up to 60%). However there was an increase in NO_x due to the increase in combustion temperature; but it is known that NO_x formation is dependent upon volumetric efficiency, combustion duration and especially temperature arising from high activation energy. Although the exhaust gas temperatures increased, the NO_x emissions were observed to decrease with the increase in engine speed.

On the other hand, the BSFC increased with the use of biodiesel and its blends compared to diesel fuel. However, the brake thermal efficiency obtained with B100 and their blends was close to that obtained with the diesel fuel. From the combustion analysis, it was found that ignition delay was shorter for neat rapeseed oil and its blends tested than that of standard diesel. The combustion characteristics of rapeseed oil and its diesel blends closely followed those of standard diesel. They finally concluded that B20 and lower blends could be recognized as the potential candidates for use in diesel engines in terms of more environmentally friendly and increased performance efficiency.

Lin and Rong [24] used neat fish oil biodiesel, a waste cooking oil biodiesel, and 2D diesel on a DI 4-cylinder, 4-stroke engine (at constant load and different speeds). They noticed lower CO, and higher PM and NO_x emissions when using neat fish oil biodiesel than using waste cooking oil biodiesel. However, the two biodiesels showed lower CO, lower PM and higher NO_x emissions when compared to the diesel fuel. The neat fish oil biodiesel has higher brake fuel conversion efficiency and lower BSFC compared to the waste cooking oil biodiesel. The two biodiesels showed higher brake fuel conversion efficiency and higher BSFC compared to the diesel fuel. All the above comparisons were taken at speed of 1400 RPM and lower. At higher speeds, the diesel fuel showed higher brake fuel conversion efficiency than these two biodiesels.

Raheman and Phadatare [25] used diesel fuel and compared it to karanja methyl ester (biodiesel, B100) and its blends (B20, B40, B60 and B80) in a single cylinder, 4-stroke, DI, water-cooled diesel engine (at a constant speed and different load settings). They reported a noticeable reduction of CO and PM and determined that biodiesel had better combustion than diesel fuel. They also reported a reduction on NO_x but no detailed reason was stated for this phenomena. In addition, they compared the exhaust temperature of all fuels but no significant variations were reported. This could be due to a similar amount of fuel consumption per hour for both diesel and biodiesel blends at each load setting of the engine. The torque increased with the increase in load due to the increase in the fuel consumption. B20 and B40 showed higher torque than diesel, and B60 to B100 had a lower torque. This reduction could be because of the lower heat value of the latter blends. BSFC decreased with the increase in load due to the higher percentage of increase in brake power with load compared to the fuel consumption. B20 and B40 had a value lower than diesel, and B60 to B100 showed values higher than diesel; again this could be because of the lower heat of the latter blends. The brake thermal efficiency increased with the increase in load, which could be related to the increase in power and the decrease in heat loss. Furthermore, B20 and B40 showed better results than diesel fuel for the same reason as mentioned above. They finally concluded that B40 generated the best results and could the best substitute for diesel fuel.

Gokalp et al. [26] used marine diesel, soybean methyl ester and their blends B5, B20, B50 on 4-cylinder, 4-stroke, and DI diesel engine (at full load and different speeds). The CO emissions decreased with the addition of biodiesel thanks to the oxygen content in the biodiesel for more complete combustion. However, the highest values of CO emission were reported at low speed because the poor atomization and uneven distribution of small portions of fuel across the combustion chamber, along with low gas temperature, may cause local oxygen deficiency and poorer combustion. PM and HC were decreased with biodiesel compared to diesel fuel. Higher brake thermal efficiency (BTE) indicated better and completes combustion of fuel; that is, lesser amount of unburned hydrocarbons presented in the engine exhaust gases. Therefore, lower smoke opacity values were achieved with biodiesel blends compared to that of the diesel fuel. NO_x increased with biodiesel due to the resulting in higher temperatures. In general, all the reactions involved with atmospheric nitrogen are highly dependent on high temperature due to the high activation energy needed for the reactions.

On the other hand, B5 and diesel provided higher power and torque, which could be due to the lower calorific values of biodiesel with the other blends. In addition, the BSFC increased with biodiesel compared to diesel for the same reason as stated before. Biodiesel showed higher BTE due to the high oxygen content resulting complete combustion. However at full load, the BTE decreased due to the increase in friction loss at high speed, but biodiesel showed a better result than diesel because of the extra lubricity. High exhaust temperatures were observed with biodiesel due to the following two reasons:

- High ignition delay results in a delayed combustion;
- Biodiesel contains some constituents having a high boiling point, which are not sufficiently evaporated during the main combustion phase and continue to burn in the late combustion phase.

McCarthy et al. [27] used two types of biodiesel, diesel fuel and their blends (B5, B10, B20, B50 and B100) on a Kubota V3300 DI 4-cylinder, naturally aspirated engine. Type A biodiesel consisted of 80% tallow (beef, pork and sheep) and 20% canola oil methyl ester; and type B biodiesel consisted of 70% chicken tallow and 30% waste cooking oil methyl ester. Emissions of HC from the use of both biodiesels increased, but CO emissions decreased when compared to diesel fuel. Biodiesel A showed a lower trend for NO_x than biodiesel B. Biodiesel B had a higher fuel consumption than biodiesel A, indicative of a lower heating value for biodiesel B. In general, biodiesel A had lower exhaust emissions and better performance than biodiesel B due to its higher energy content associated with beef, pork, sheep and canola oil (compared to chicken tallow and waste cooking oil). They finally concluded that more investigation of fuel properties for both biodiesel A and B was needed in order to determine how the differences in properties affected performance and emissions.

Behcet [28] used anchovy fish oil biodiesel, petroleum diesel and their blends (B25, B50 and B75) in a single cylinder, DI compression ignition diesel engine (at full load and different engine speed). Emissions of CO and HC were low for the fish oil biodiesel and its blend fuels, but NOx emissions increased when biodiesel was used compared to the diesel fuel. BSFC increased for biodiesel blends compared to the diesel. The thermal efficiency for biodiesel was decreased in comparison to diesel fuel probably due to the lower heat value and higher fuel consumption of biodiesel-based fuels. A small power loss and an increase in fuel consumption were reported when biodiesel was used. This is probably due to the lower heating value of the fish oil biodiesel fuel blends. The high amount of saturated fatty acids enhanced the cetane number of biodiesel and led to shorter ignition delays in the combustion period, thus improving the combustion.

2.2 Biodiesel with Additives:

A key property of biodiesel limiting its application is its relatively poor low-temperature flow properties. Consequently, one of the major challenges is how to improve biodiesel low temperature flow characteristics so as to use it as an alternative fuel for diesel engines. The biodiesel fuels derived from fats or oils will contain significant amount of saturated fatty compounds (displaying higher cloud points and pour points) and therefore limit their applications. When ambient temperatures fall below the petroleum diesel fuel's cloud point, a growth of paraffin wax crystals starts taking place and these crystals could cause some problems such as filter clogging. While the cloud point of petroleum diesel is reported between -12 and -34°C, biodiesel typically has a cloud point of around 0°C, thereby limiting its use to ambient temperatures above freezing point [29]. Chemical additives are economical and could be used to improve the low-temperature properties of diesel fuels. Appropriate additives, referred to as pour point depressants, can be applied to a fuel to reduce growth and agglomeration rates as temperature decreases below cloud point.

Kwanchareon et al. [30] made diesel and biodiesel blends, using ethanol as an additive. They studied the phase diagram of diesel biodiesel and ethanol blends at different purities of ethanol and at different temperatures. They examined fuel properties of the selected blends such as density, heat of combustion, cetane number, flash point and pour point and their emissions performance in a diesel engine, and compared them with the fossil diesel fuel. It was found that CO and HC reduced significantly at high engine load, whereas NOx increased compared to those of diesel. Taking these facts into account, a blend of 80% diesel, 15% biodiesel, and 5% ethanol had the best results.

Zhu et al. [31] studied the emissions and performance of a 4-cylinder naturally aspirated DI diesel engine with Euro Vdiesel fuel, pure biodiesel and biodiesel with additives (ethanol and methanol separately in 5%, 10 % and 15% blends). They conducted experiments at a steady speed of 1800 RPM under five different load conditions. It was observed that compared to Euro Vdiesel fuel, the blended fuels could lead to reduction of both NOx and PM of a diesel engine, with the biodiesel–methanol blends being more effective than the biodiesel–ethanol blends. The effectiveness of NOx and particulate reductions were more effective with an increase of alcohol in the blends. The high percentage of alcohol in the blends helped reduce NOx and PM, but on the contrary the HC and CO emissions increased and the brake thermal efficiency slightly reduced. The 5% blends could reduce the HC and CO emissions as well.

The study conducted by Cheng et al. [32] also used a 4-cylinder naturally aspirated DI diesel engine operating at a constant speed of 1800 RPM with five different engine loads. In their experiment, they compared biodiesel from waste cooking oil with 10% blended methanol and 10% fumigation methanol to conventional diesel. The results indicated a reduction of CO_2, NOx, and particulate mass emissions, as well as a reduction in mean particle diameter (in both cases) compared with diesel fuel. It was also observed a slightly higher brake thermal efficiency at low engine load when blended methanol was used; similar results were observed at medium and high loads, when using fumigation methanol. When using fumigation methanol, there was an increase in CO, HC, NO_2 and particulate emissions in the engine exhaust compared to the blended methanol.

Metal-based additives such as cerium (Ce), cerium–iron (Ce–Fe), platinum (Pt), platinum–cerium (Pt–Ce), iron (Fe), manganese (Mn), barium, calcium and copper showed reduction in emissions, which may be due to the fact that the metals either react with water vapour to produce hydroxyl radicals, or serve as an oxidation catalyst, thereby reducing the oxidation temperature that results in increased particle burnout [33, 34].

Keskin et al. [35] used tall oil biodiesel with Mn and Ni-based additives in an unmodified DI diesel engine at full load condition. They found that specific fuel consumption of biodiesel fuels increased by 6%; but in comparison to 60% tall oil methyl ester and 40% diesel fuel, the trend showed a reduction after adding the additives. Exhaust emission profile of biodiesel fuels improved. CO emissions and smoke opacity decreased up to 64.28% and 30.91% respectively. It was also observed low NOx emission for the biodiesel fuels.

Kalam and Majuski [36] used palm biodiesel with a Nonylphenoxy acetic acid additive on diesel engine. They observed a reduction in NO, CO and HC emissions. They also noticed that a higher brake power and lower BSFC could be achieved compared to diesel.

Labeckas and Slavinskas [37] examined a 4-stroke, 4-cylinder, water-cooled, DI diesel engine using shale oil that had been treated with multi-functional fuel additives. The results revealed that there was a reduction in NO and HC emissions along with a slight increase in CO with the use of multi-functional fuel additives.

Metin et al. [38] studied the effect of waste chicken fat biodiesel with Mg-based additive on diesel engine. The tests results showed that the engine torque did not change significantly with the addition of 10% chicken fat biodiesel, while the specific fuel consumption increased by 5.2%. CO and smoke emissions decreased by 13% and 9% respectively, although NO emissions increased by 5%.

2.3 Biodiesel and Kerosene:

"On December 3 2008, 2-hour test flight was conducted on a Boeing 747-400 (belonging to Air New Zealand) in Auckland, New Zealand. The flight was a pioneering one, in which one of the plane's four engines ran on a 50:50 mix of kerosene and biodiesel. In February 2008, a Virgin Atlantic 747 flew a test flight between London and Amsterdam using the first generation 20% biofuel mix (using a product derived from coconut and babassu oil). The Air New Zealand flight used a second-generation biofuel, derived from jatropha oil. The fuel was developed by using a hydro treatment-based process. The jatropha resulted in a biokerosene with properties equal to or better than those of the standard kerosene used by commercial planes (such as a -47°C solidification point and a 38°C clear point) "[39].

Murthy et al. [40] conducted an experiment to test the feasibility of the burning of higher percentage non-edible straight vegetable oil blends with kerosene in horizontal-type pressurized kerosene stove. It also attempted to prompt the use of biomass fuel. They used thermal efficiency of pure kerosene in a pressurized kerosene stove at a pressure of 0.2kg/cm^2 as a reference value (53.6%). Then they used different blends on the modified pressurized kerosene stove and the highest thermal efficiency was obtained at the same pressure (48.6%) of a 30% vegetable oil and a 70% kerosene blend.

Liamas et al. [41] transesterified coconut and palm kernel oils and used two types of fossil kerosenes, a straightrun atmospheric distillation cut (hydrotreated) (K-1) and a commercial Jet A1 (K-2) for their blends. 5, 10 and 20% of biokerosene were blended with two types of fossil kerosenes. They studied the properties of those blends' smoke point, density, flash point, viscosity at -20°C, freezing point and the calorific value. it was concluded that it would be feasible to blend coconut and palm kernel biokerosenes prepared with commercial Jet A1 up to 10% of volume of the former as partial substitutes of fossil jet fuels.

Weber et al. [42] mentioned in their report that biojet fuel created from jatropha and camelina seeds showed, in more than one flight operation, that biokerosene could reduce carbon emissions (CO_2) by up to 85% compared to conventional petroleum jet fuel. The reduction was attributed to the high cetane number and the presence of oxygen in the molecular structure of the jatropha fuel. In addition, the biofuel was sulphur-free and jatropha based biokerosene demonstrated a much better environmental performance than fossil fuel.

Antonio et al. [43] obtained a US patent for their production process of biokerosene and aviation kerosene composition. The process ensured that the product having a freezing point lower than -10°C in the distilled light fraction, permited tedutilization thereof up to 20% by weight in the formulation of a finished semisynthetic aviation biokerosene.

2.4 Thesis Objective:

As discussed in the aforementioned literature review, although there have been a number of studies on biodiesel performance/emissions and biodiesel properties, their highlighted problems are the percentage of the NOx in the exhaust and the high cloud point for the biodiesel. The objective of this study is to test the feasibility of biodiesel in cold climate such as Canada and suggest an appropriate solution for the future of biofuel. In this study, the performance and emissions for three different blends will be tested with diesel used as a reference fuel. Furthermore, chemical additive (Wintron XC30) is used to lower the cloud point of the blends and this could be first time to study it is effect on engine emissions. On the other hand, there are limited studies on kerosene being treated as a blending fuel, where it's mainly used to lower the cloud point of the blends.

Chapter 3

Experiment and Methodology

This chapter discusses how the experiment was conducted, starting with the preparation of a single batch of biodiesel, concluding with the engine test. Also biodiesel standards were mentioned and a brief description of the chemical additive used in this study was included.

3.1 Biodiesel Production Process:

The basic biodiesel reaction and flow chart of biodiesel production is illustrated in Figure 3.1. The transesterification method to make biodiesel followed in this study is from ref. [44]. One-liter biodiesel is produced from one liter of canola oil and the final collection efficiency (after washing) was 86%.

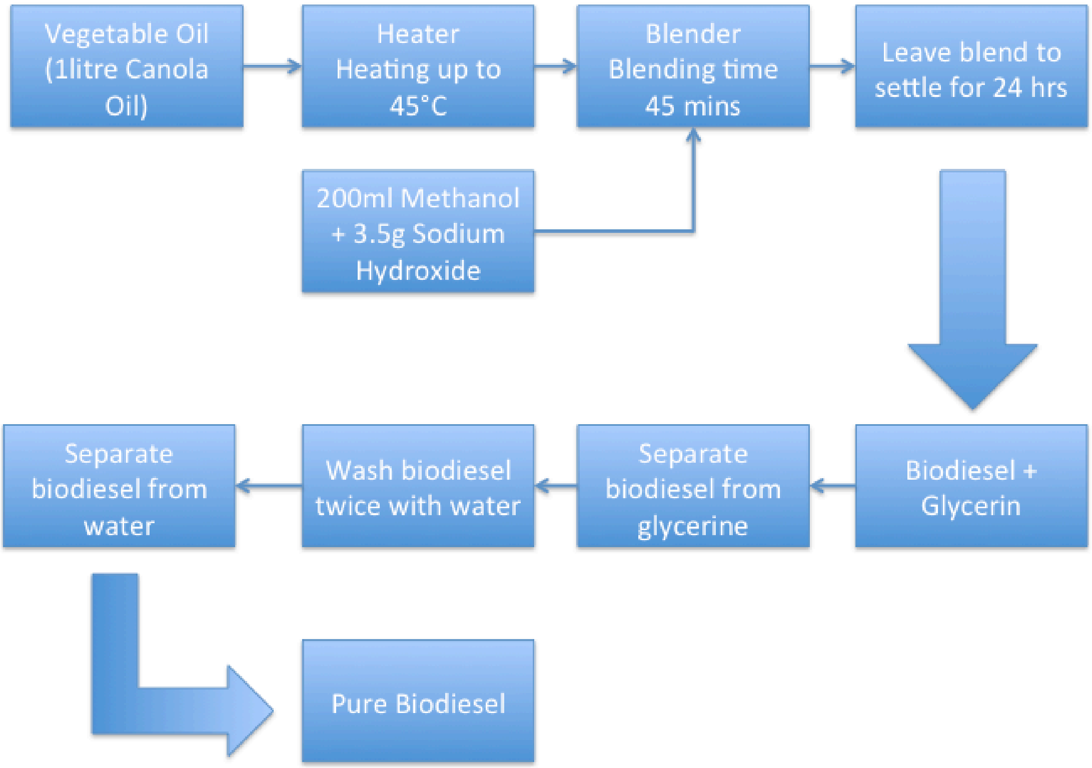

Figure 3.1: Biodiesel production process

3.1.1 Materials and Equipment Used for A single Batch Production:

- 1 liter of canola oil
- 200 ml of methanol (99% pure)
- 3.5 grams of sodium hydroxide (NaOH)
- Blender
- Scale accurate to 0.1 grams
- Small heater
- Half-liter capacity container with a cap
- 2 empty bottles (2- liters capacity each)
- Thermometer

3.1.2 Mixing of Alcohol and Catalyst:

The catalyst used is sodium hydroxide and the alcohol used is methanol. 200ml of the methanol is placed in a container then the 3.5 grams of the catalyst is added. The container is closed tightly and is shaken continuously until the catalyst has totally dissolved in the methanol.

3.1.3 Temperature Optimization:

Canola oil is heated to 40°C, 45°C, 50°C, 55°C and 60°C, and it is observed that canola oil produces more biodiesel when preheated to either 45°C or 60°C before the reaction takes place. 45°C was considered for the biodiesel production since it uses less heat.

3.1.4 Reaction:

The preheated canola oil is placed inside a blender, and alcohol/catalyst mix is added too. The blender is switched on after securing the lid tightly. Lower blending speeds should be high enough and the mix is left for 45 minutes of blending time. The reaction mix is constantly monitored during blending and is stopped when necessary to allow the mix to cool down since the methanol boiling point is around 64.5 °C.

3.1.5 Settling and Separation:

Once the reaction is completed, two major products exist: glycerine and biodiesel. The blend is placed in a 2-litre bottle and is left to settle at a room temperature for approximately 24 hours. The biodiesel and the glycerine are separated by gravity: glycerine will settle at the bottom, whereas biodiesel on top due the densities difference. Then, the biodiesel is carefully decanted into a separate bottle, taking care not to get any glycerine layer mixed with it.

3.1.6 Water Washing:

Once the biodiesel is separated from the glycerine, it is washed twice with warm water to remove residual catalyst or soaps to purify the biodiesel. The amount of water added is 50% of the biodiesel produced. The mixture is shaken for one minute and left to settle for a few hours. Once the water and foam at the bottom are separated from the biodiesel, the similar procedures are repeated except this time, the mixture is left to settle for about 24 hours. This is normally the end of the production process resulting in a clear amber-yellow liquid with a viscosity similar to petro diesel. In some systems, the biodiesel is distilled in an additional step to remove small amount of colour bodies to produce a colourless biodiesel.

3.1.7 Biodiesel Quality Test:

ASTM D6751 method is used to determine the quality of biodiesel [45]. Table 3.1 summarizes the properties of biodiesels tested by Bently Tribology Services [10]. The following points can explain the significance of the quality test:

- Methanol degrades some plastics and elastomers, corrosive and that could lower the flashpoint to unsafe levels.
- Unconverted/partly converted oils (bound glycerin) results in poor cold flow properties, injector and in-cylinder deposits and potential engine failure.

- Free Glycerin results in injector deposits, clogged fuel filters, deposit at bottom of fuel storage tank.
- Catalyst (NaOH) Excessive could affect the injector, fuel pump, piston, ring wear and lead filter plugging, issues with lubricant.

Therefore there are limits for all the mentioned parameters made by the ASTM to ensure the quality of the biodiesel.

Table 3.1: Properties of canola biodiesel

Test name	Test method	ASTM limit	Results
Free Glycerin (mass %)	ASTM D6584	Max. 0.020	0.000
Total Glycerin (mass %)	ASTM D6584	Max. 0.240	0.112
Flash Point, Closed Cup (°C)	ASTM D93	Min. 130	169
Water & Sediment (vol. %)	ASTM D2709	Max. 0.050	0
TAN (mg KOH/g)	ASTM D664	Max. 0.50	0.14
Sim. Dist., 50% Recovery (°C)	ASTM D2887	N/A	359.8
Cetane Index	ASTM D976 (2 variables formula)	N/A	50
Cloud Point (°C)	ASTM D2500	N/A	-3
Copper Corrosion, 3h @ 50°C (rating)	ASTM D130	Max. 3a	1a

3.1.8 Density Measurement:

A simple method is used to measure the density of the biodiesel and its blends. The procedure is as follows:

- The weight of a 100ml container (m_1) is taken on a scale accurate to 0.1 grams.
- 100ml of biodiesel (v) is added into the container and placed on the scale again, which will give the weight of the container filled with biodiesel (m_2)

- The weight of the 100ml of biodiesel can be determined by subtracting (m_2) and (m_1).

$$\boldsymbol{m_b = m_2 - m_1} \qquad (1)$$

m_1 = the weight of an empty 100ml container
m_2 = the weight of a 100 ml container filled with biodiesel
m_b = the weight of measured liquid

- Since the density is the mass per unit volume, it can be computed by using the following formula:

$$\boldsymbol{\rho} = \frac{\mathbf{m_b}}{\mathrm{V}} \qquad (2)$$

ρ = the density of the measured liquid
m_b = the weight of the measured liquid
v = the volume of the measured liquid

3.1.9 Viscosity Measurement:

Ostwald viscometer is used for the viscosity measurement at 40°C complying with ASTM D445 [46]. The procedure is as follow:

- Water tank with a fixed heater to maintain water temperature at 40°C.
- A small external heater to preheat the sample prior adding it into the viscometer.
- Viscometer is fixed by a clip and submerged underwater with keeping the two top ends outside the water surface.
- Viscometer filled to the lower red mark.
- Time is measured when the liquid passes the two top red marks.
- Time is measured as well for a known viscosity liquid, i.e., water for calculation purposes.
- First, the dynamic viscosity (η_s) for the tested liquid is calculated by:

$$\boldsymbol{\eta_s} = \boldsymbol{\eta_w} \frac{\boldsymbol{t_s \rho_s}}{\boldsymbol{t_w \rho_w}} \tag{3}$$

η_s = the dynamic viscosity of the measured liquid

η_w = the dynamic viscosity of water

t_s = time elapsed until the liquid passes the red marks

t_w = time elapsed until the water passes the red marks

ρ_s = the density of the measured liquid

ρ_w = the density of water

- Since the kinematic viscosity (v_s) is the dynamic viscosity (η_s) divided by the liquid density, then it can be obtained by using the following equation:

$$\boldsymbol{v_s} = \frac{\boldsymbol{\eta_s}}{\boldsymbol{\rho_s}} \tag{4}$$

v_s = the kinematic viscosity of the measured liquid

η_s = the dynamic viscosity of the measured liquid

ρ_s = the density of the measured liquid

3.2.9 Heating Value Measurement:

Heating value measurement test is conducted using a calorimeter. The specification of the calorimeter is listed in Table 3.2. The test procedures are as follows complying with ASTM standards [47]:

- The pump and heater are turned on to heat up the jacket water up to 30°C inside the calorimeter.
- A fuel sample is prepared by weighing it to the nearest 0.0001g.
- The sample was placed on the head of the bomb and a fuse wire was attached touching a solid pellet.
- The head was placed inside a cylinder bomb.
- Filled the bomb with oxygen.
- The bomb was placed in the pail and the pail was placed inside the calorimeter,
- Ignition wires was attached to the bomb head

- The pail was filled with a 2L of water using a water handling system that pumps accurately because using the same amount of water for every test is very critical. Water temperature was between 25-27°C
- After observing the bomb for any leaks the lid was closed.
- Then the test went through three steps: pre-period cycle, firing the sample, and finally the post-period cycle.
- Once the test was done the results were printed out on the printer.

Table 3.2: Calorimeter specifications

Specifications:
Isoperibolcalorimetry
Removable 1108P Oxygen Vessel and Bucket
4-7 tests per hour
Operator time per test is approximately 6 minutes
0.05 – 0.1% precision class instrument
0.01 ºC Temperature Resolution 0.02
52 – 12000 calorie sample range dependent on vessel selected
0.05% Linearity across operating range
SD memory and TCP/IP network communications
USB Port for balance and printer connections
Updates via the Internet
Dimensions (in) 23w x 16d x 17h
Dimensions (cm) 57w x 40d x 43h

3.2 Biodiesel Standards:

Biodiesel fuel has to meet certain criteria to ensure its quality. In the US, "ASTM D6751" has all biodiesel standards; and in Europe, biodiesel standards are compiled in the "Norm CEN EN 142144". The biodiesel ASTM testing panel (D6751) is required to be performed on biodiesel if it is going to be used for commercial purposes to use a fuel in on-road vehicles, for example. The environmental protection agency (EPA) should receive all the results from these tests before biodiesel can be mass-produced and sold commercially [48]. The internal revenue service IRS also requires proof that biodiesel passes these tests before allowing the manufacturer to take certain tax credits. The most important aspects of biodiesel production that is specified in ASTM D6751 to ensure trouble-free operation in diesel engines are as follows:

- Complete Reaction
- Removal of Glycerine
- Removal of Catalyst
- Removal of Alcohol
- Absence of Free Fatty Acids.

The National Biodiesel Board (NBB) has recently formed the National Biodiesel Accreditation Commission that has put into place an accreditation program for companies selling biodiesel and biodiesel blends [49].

However, biofuel cannot be used as raw or refined vegetable oils that are unprocessed, as Rudolf Diesel stated after his experiment. According to the National Renewable Energy Laboratory (NREL), raw or unrefined vegetable oils and greases used in CI engines at levels as low as 10% can cause problems including long-term engine deposits, ring sticking, and lube oil gelling, which can reduce the engine's useful life [50]. These problems generally stem from these oils' greater thickness or viscosity, compared to that of typical diesel fuels for which the engines are designed. These problems can be avoided through the refinement of these oils in the biodiesel production process.

3.3 Different Blends Used In Engine Test:

As stated on Chapter 2, the main objective of this study was to investigate the emissions and performance of biodiesel and the effect of different additives on biodiesel properties (mainly cloud point). Therefore, three different series were prepared to achieve this goal.

- The first one is biodiesel and diesel Series.
- The second one is biodiesel and diesel with 2% of chemical additive series.
- The third one is kerosene and biodiesel series.

The results and discussions of the three series will be covered in Chapter 4.

3.4 WintroneXC30:

WintroneXC30 is a chemical additive used in the biodiesel additive series. It is a low cost biodiesel pour point depressant (PPD) effective for biodiesel produced from a wide range of feedstock's. Treat rate varies, which is largely dependent on the feedstock used to produce the biodiesel. Typically treat rate is 0.1% - 2% by volume. The additive modifies the viscosity compounds, which reduces the tendency of viscosity to increase as the fuel is cooled. This alters the low temperature crystallization process - lowering the temperature at which biodiesel is able to flow and lowering the temperature at which wax crystals become large enough to block the pores of the fuel filter [51].

3.5 Engine Test

Figure 3.2 shows the schematic diagram of engine experiment [52]. The engine used in this study is a Peter diesel engine (model PH2W), which is a 4-stroke 2-cylinder naturally aspirated DI diesel engine and its specifications are summarized in Table 3.3. All experimental data are taken after engine warm-up (about 20 minutes after start-up). In this condition, there is almost no fluctuation of emissions. Tests are carried out at the warmed up condition of the engine under three engine loads at the rated speed of 1800 RPM. Table 3.4 lists engine-operating conditions for different fuels. Loads are measured by a water brake dynamometer. The fuel supply system is modified to switch between the diesel fuel used as a standard and the test fuels. The engine is started using diesel; once the engine warmed up, it is switched to biodiesel-diesel blends. After concluding the tests, the engine is switched back to diesel, and keeps running until the blends are purged from the fuel line, injection pump and injector. Engine load and fuel consumption are measured to calculate BSFC and fuel conversion efficiency of the engine.

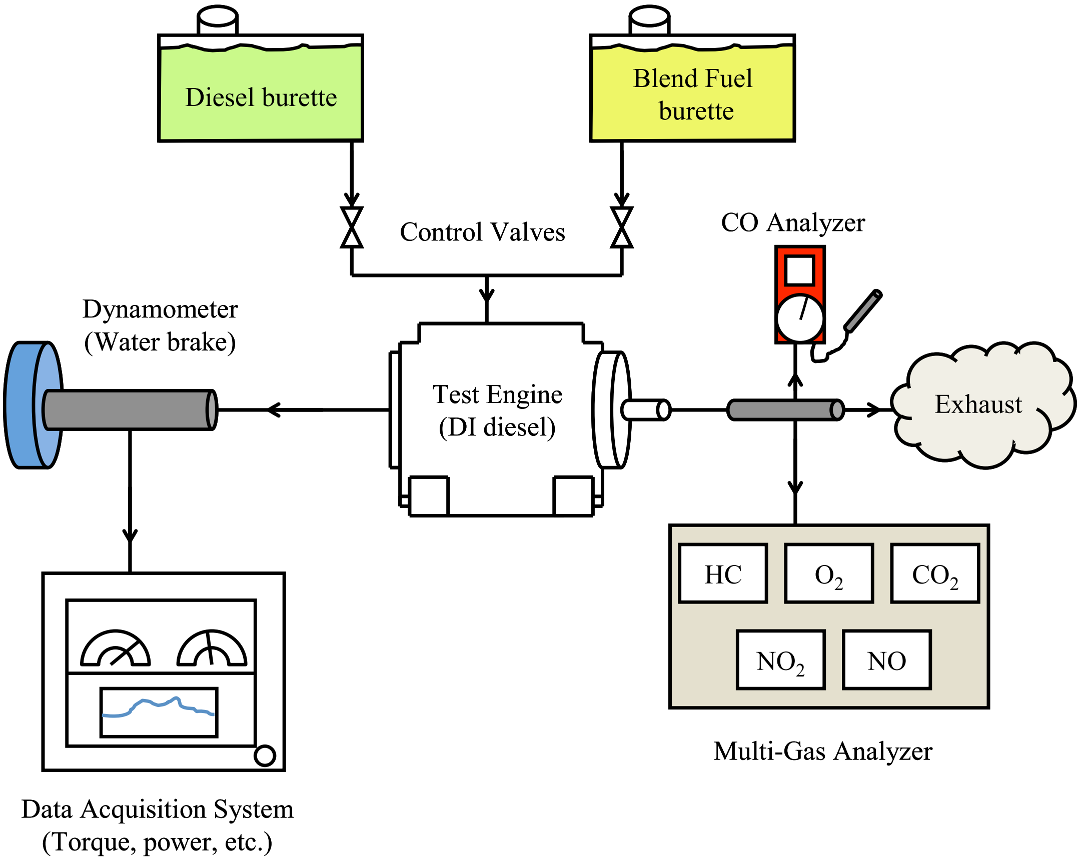

Figure 3.2: Schematic diagram of engine experiment

Table 3.3: Engine specification

Engine make and model	Lister Peter; PH2W
Engine type	4-stroke DI diesel engine
Number of cylinder	Two
Bore × Stroke	87.3 × 110 mm
Swept volume	1318 cc
Bore stroke ratio	1:1.3
Rated power	11.2 kW @ 1800 rpm
Fuel injection timing	24ºBTDC (below 1650 rpm); 28ºBTDC (above 1650 rpm)

Table 3.4: Engine operating condition

Engine speed (rpm)	Rated power (kW)	Load	Actual power (kW)	bmep (kPa)	Load (%)
1800	11.2	Low	0.34	16	3
		Medium	5.38	272	48
		High	10.75	545	96

A multi-gas analyser (NOVA Model 7466 PK) and a CO analyser (Dwyer 1205A) are used to measure the CO, NO, NO_2, HC, CO_2 and O_2 of exhaust gases corresponding to each data point. Gas analysers' specifications with resolution, range and accuracy are summarized in Table 3.5.

Method of detection	Species	Measured unit	Range	Resolution	Accuracy
NDIR	CO_2	%	0-20%	0.1%	±1%
NDIR	HC	ppm	0-20000 ppm	10 ppm	±1%
Electrochemical	CO	ppm	0-2000 ppm	1 ppm	±10 ppm<100 ppm ±5% of reading>100 ppm
Electrochemical	O_2	%	0-25%	0.1%	±1%
Electrochemical	NO	ppm	0-5000 ppm	1 ppm	±1%
Electrochemical	NO_2	ppm	0-800 ppm	1 ppm	±1%

Table 3.5: Gas analyser's specifications

At every test point, different data are recorded at least three times, but a single point (average of data) is shown to present the results graphically with ± standard error of average value. Similar conditions are maintained for all the tests for better comparison of the results.

3.6 CALCULATION

bsfc: Engine bsfc is calculated from fuel consumption, engine torque and speed data. Fuel consumption is measured as millilitre (ml) per second and torque T as N.m. The following formula is used to calculate engine bsfc:

$$\text{bsfc (g/kWh)} = \text{Fuel mass flow rate (g/h)} / \text{Engine power (kW)} \tag{5}$$

$$\text{Fuel mass flow rate (g/h)} = 3600 \times [\text{fuel volume flow rate (ml/s)} \times \text{fuel density (g/ml)}] \tag{6}$$

$$\text{Engine power } P \text{ (kW)} = 2\pi N \text{ (rev/s) } T \text{ (N.m)} \times 10^{-3} \tag{7}$$

Fuel conversion efficiency: This is also known as engine efficiency or thermal efficiency of the engine, which is computed by:

Fuel conversion efficiency (%) = 3600/[bsfc (g/kWh) × Heating value of fuel (MJ/kg)] (8)

Brake specific energy consumption: it's also known as the brake specific energy conversion and its calculated by:

Brake specific energy consumption (MJ/kWh) = bsfc (g/kWh)* [Heating value of fuel (MJ/kg) / 1000] (9)

The fuel consumption in (L/h) can be obtained by the following equation:

Fuel consumption (L/h) = {[bsfc (g/kWh) * Engine power (kW)] / Fuel denstity (g/m^3)}*1000 (10)

Conversion of ppm to g/kWh: The used gas analysers measure the emissions in ppm unit. This is converted to g/kWh according to the following formulas. However before preceding the air volume flow rate has to be obtained first:

Air mass flow rate (kg/s) = (Volumetric efficiency * Air density (kg/cm^3)* Engine displacement (cm^3) * rpm/60)/2 (11)

Air volume flow rate (m^3/h) = (Air mass flow rate (kg/h) / Air density (kg/m^3) *3600 (12)

For CO:

CO (mg/m^3) = CO (ppm) × A_{CO}; where A_{CO} = 1.25 is conversion factor. (13)

CO (g/kWh) = [CO (mg/m^3) × Air volume flow rate (m^3/h)]/1000P (kW) (14)

For HC: The analyser measures HC as propane (C_3H_8):

HC (mg/m^3) = HC (ppm) × A_{HC}; where A_{HC} = 1.965 is conversion factor. (15)

HC (g/kWh) = [HC (mg/m^3) × Air volume flow rate (m^3/h)]/1000P (kW) (16)

For NO:

$NO\ (mg/m^3) = NO\ (ppm) \times A_{NO}$; where $A_{NO} = 1.34$ is conversion factor. (17)

$NO\ (g/kWh) = [NO\ (mg/m^3) \times \text{Air volume flow rate}\ (m^3/h)]/1000P\ (kW)$ (18)

For NO_2:

$NO_2\ (mg/m^3) = NO_2\ (ppm) \times A_{NO2}$; where $A_{NO2} = 2.056$ is conversion factor. (19)

$NO_2\ (g/kWh) = [NO_2\ (mg/m^3) \times \text{Air volume flow rate}\ (m^3/h)]/1000P\ (kW)$ (20)

NOx: The absolute mass concentration of NOx is calculated as a simple sum of measured NO and NO_2 mass concentrations:

$NOx\ [g/kWh] = NO\ [g/kWh] + NO_2\ [g/kWh]$ (21)

Chapter 4
Results and Discussion

In our experiment, we will use three different series biodiesel/diesel series (B100, B50, B20, B10, B5), biodiesel/diesel + 2% additives series (B100A, B50A, B20A, B10A, B5A), and kerosene/biodiesel series (K100, K50, K20, K10, K5). Discussion and comparison of the performance and emissions for all blends is included. Cloud point of different blends comparisons is also discussed.

4.1 Biodiesel/Diesel series:

As discussed in literature review, numerous studies were done on biodiesel / diesel series by researchers. However, our main goal in this chapter is to simulate the results in the related literature and to further investigate the biodiesel behaviour in low temperature conditions corresponding to Canada's cold weather. Data in Appendix A will be used for the following analysis.

4.1.1 Engine performance:

Figure 4.1 shows the variation of bsfc of the engine with different canola biodiesel-diesel blends at different load settings. At all load-setting conditions, there is an increase in bsfc with higher biodiesel-diesel blends than with neat diesel. The bsfc of B100 increases to approximately 4.5% at low load condition and increases to about 8.5% at high load operation. B100 has approximately 12% less heating value than diesel fuel as illustrated in Table 4.1, but it has less bsfc increase (e.g., 4.5%-8.5% at different loads). This indicates that biodiesel has higher fuel conversion efficiency than that of diesel fuel.

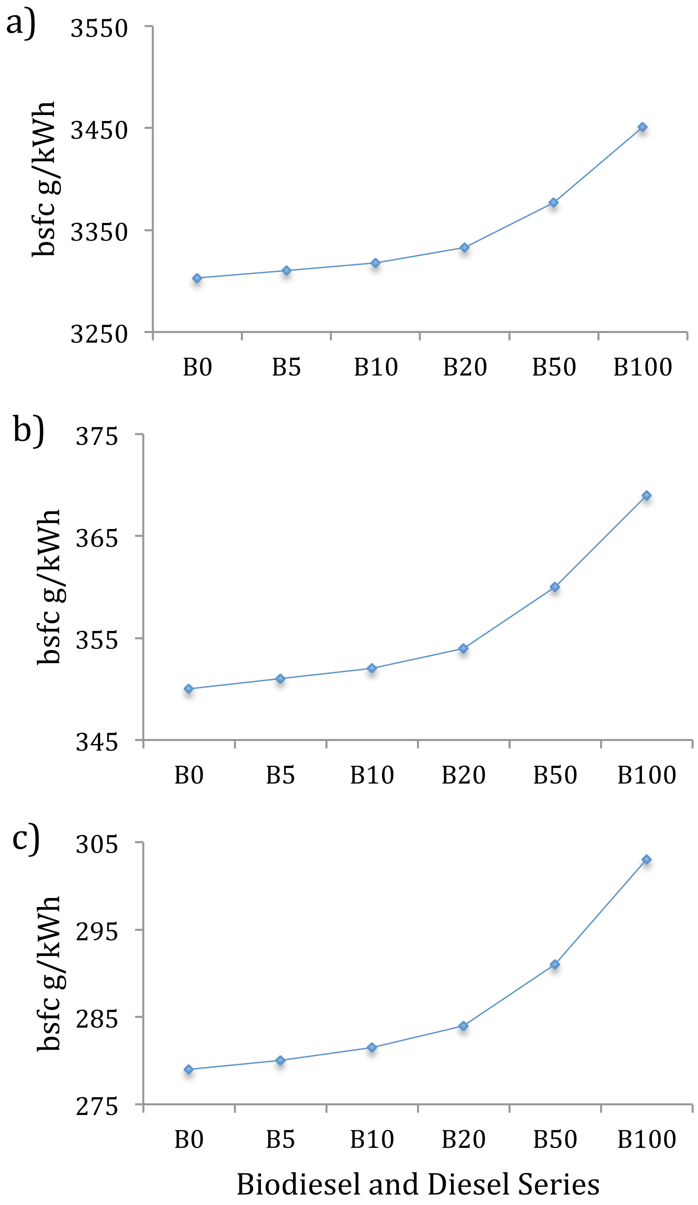

Figure 4.1: bsfc for biodiesel/diesel blends a) low load, b) medium load, c) high load

Table 4.1: Fuel properties of biodiesel/diesel blends

Fuel	Density (kg/m^3)	Viscosity (cSt @ 40ºC)	Heating value (kJ/kg)	Cloud point (ºC)
B0	830	1.86	45573	-41
B5	832.5	2.13	45293	-37
B10	835.1	2.19	45016	-34
B20	840.2	2.5	44466	-25
B50	855.5	2.8	42855	-16
B100	881	4.2	40296	-4

The variation of fuel conversion efficiency of the engine with different fuels is demonstrated in Figure 4.2. B100 shows about 8% higher efficiency than diesel at low and medium load conditions, and about 5% under high load operation. A higher efficiency with B100 at each engine load supports less bsfc increase of B100 than it should have, according to its calorific value. Other biodiesel-diesel blends show similar trends. Furthermore, the higher efficiency with biodiesel-diesel blends than diesel indicates that with blended fuels, combustion is better than diesel fuel combustion. This is attributed to oxygen content (about 9%) of biodiesel. Due to better combustion with biodiesel, less emission of CO and HC is expected. The CO and HC emission results will be discussed in the following subsection.

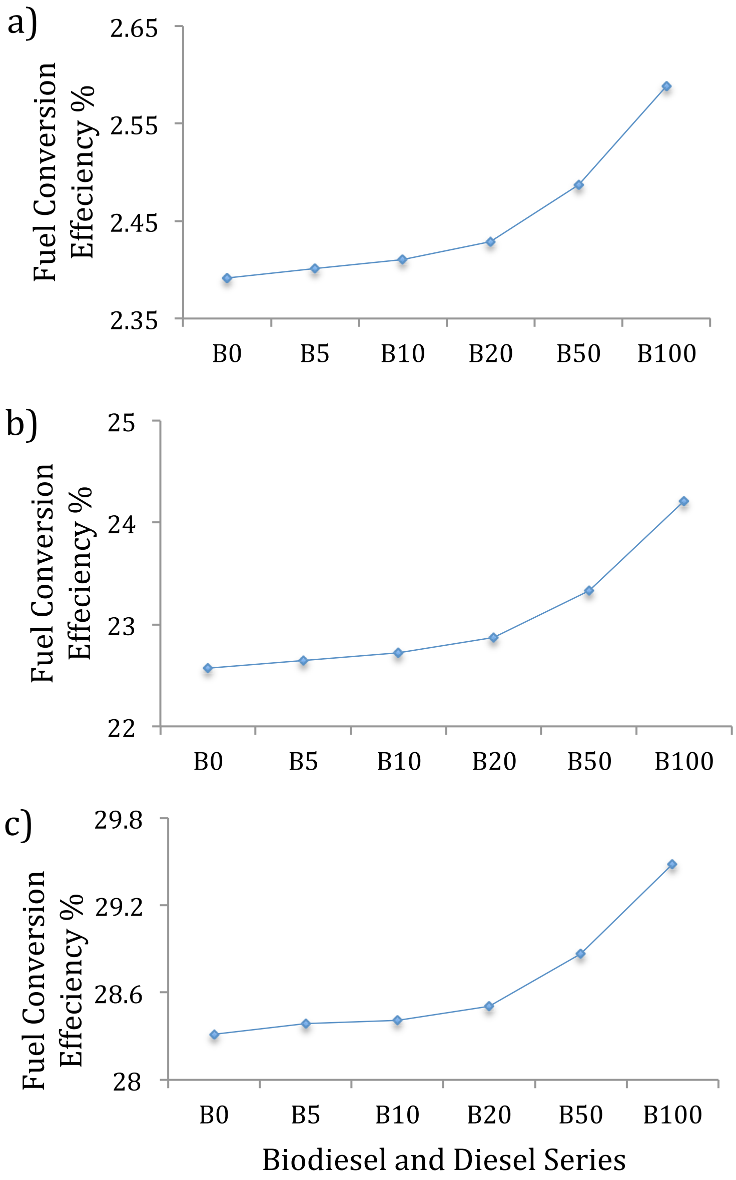

Figure 4.2: Fuel conversion efficiency for biodiesel/diesel blends a) low load, b) medium load, c) high load

4.1.2 Emissions:

Figure 4.3 shows CO emissions at different engine loads for various fuels. At low load setting, diesel fuel produces the maximum CO (about 200 g/kWh), which decreases gradually with biodiesel-diesel blends and becomes the lowest (about 123 g/kWh) for B100, which is approximately 39% lower. At medium load, diesel fuel again produces the maximum CO (7.83 g/kWh). With B100, it is approximately 18% lower than that of diesel. At high load, on the other hand, diesel fuel produces 2.67 g/kWh and B100 shows a slight increase in CO (about 5%).

The main observations from CO emission results are as follows:

1) The higher the engine load, the lower the CO emissions for all fuels. This is due to better evaporation and mixing of air and fuels at higher loads for higher in-cylinder temperatures.

2) The higher the biodiesel percentage in biodiesel-diesel blends, the lower the CO emissions at low and medium load conditions. This is thought to be due to higher O_2 concentration in the air-fuel mixture, which can improve combustion and enhance further CO oxidation.

3) At high load operation, biodiesel no longer reduces the CO emissions compared to diesel. At this condition, the in-cylinder temperature with diesel is higher than that of biodiesel (this claim is supported by higher exhaust gas temperature of 360ºC for diesel and 304ºC for biodiesel). The mixture is still leaner than stoichiometric for both the fuels (excess oxygen in exhaust gases supports this claim). The higher in-cylinder temperature seems to dominate over fuel-bound O_2 effect in biodiesel at high load operation. Therefore, it may be concluded that biodiesel is superior over diesel in terms of CO emissions up to a certain engine load.

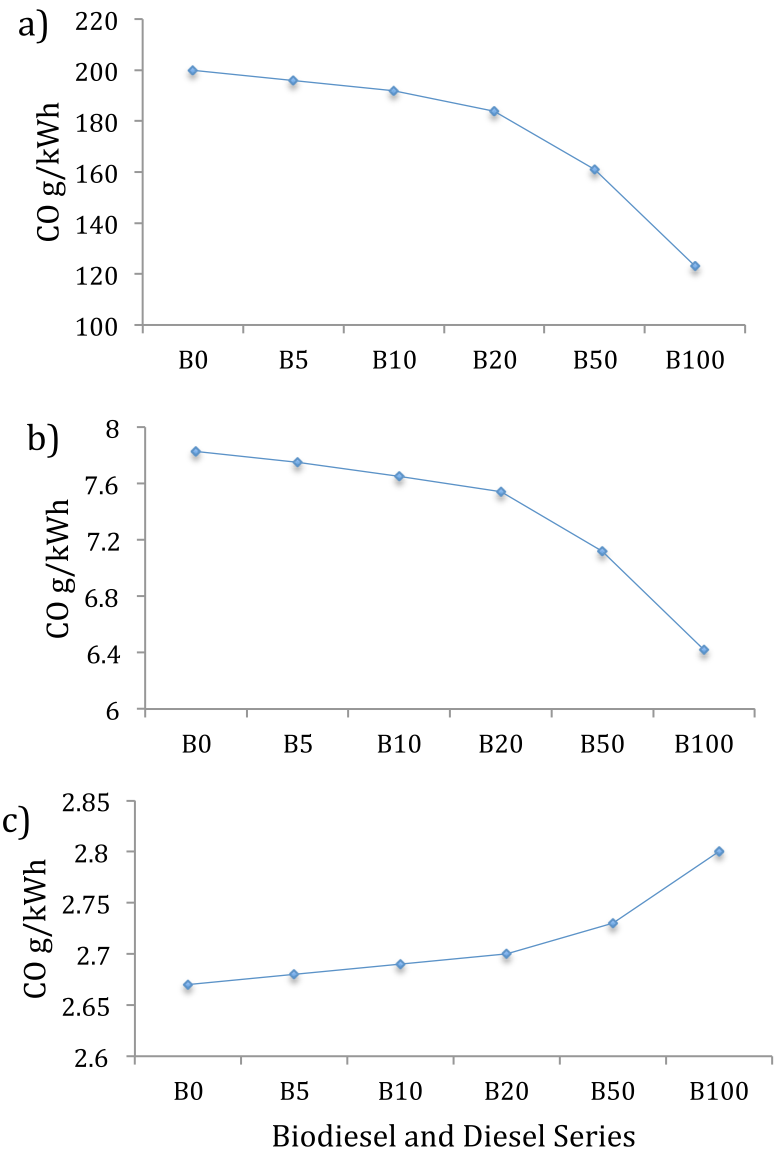

Figure 4.3: CO emissions for biodiesel/diesel blends a) low load, b) medium load, c) high load

Figure 4.4 demonstrates HC emissions at different engine loads for various fuels. At low load, diesel fuel produces 30.47 g/kWh of HC; it decreases gradually with biodiesel-diesel blends and becomes about 56% lower for B100. At medium load, diesel fuel produces 1.04 g/kWh HC, and then decreases to 0.63 g/kWh for B100 (about 39% reduction). At high load, diesel fuel produces 0.52 g/kWh of HC; B100 shows only about 12% reduction. Here, the observations are summarized as follows:

1) The higher the engine load, the lower the HC emissions for all fuels. This phenomenon can be attributed to better mixing of air and fuel due to higher evaporation at higher engine loads for higher in-cylinder temperatures.

2) The higher the biodiesel percentage in biodiesel-diesel blends, the lower the HC emissions. This occurrence is due to higher O_2 concentration in the air-fuel mixture that can help enhance oxidation of unburned hydrocarbons.

3) At high load, HC reduction with biodiesel is lower than at lower loads. The beneficial effect of O_2 presence in biodiesel is not very significant at high load operation.

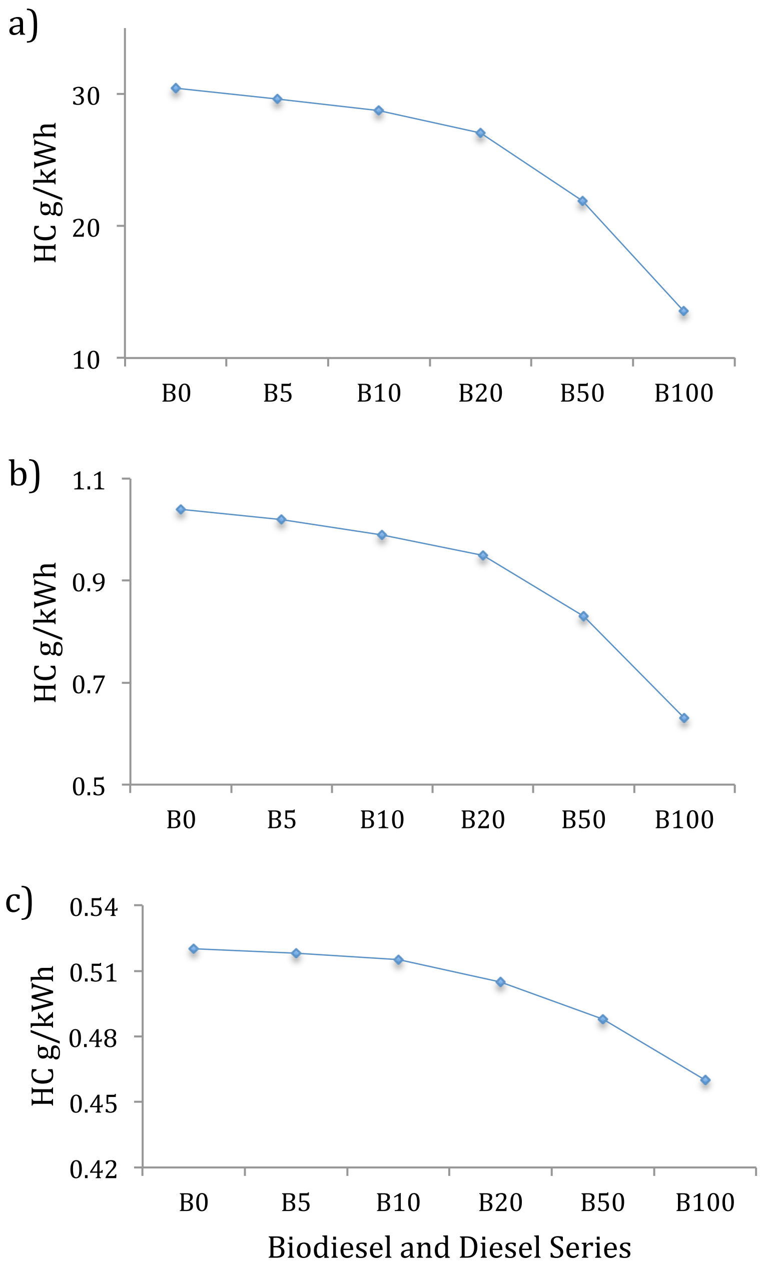

Figure 4.4: HC emissions for biodiesel/diesel blends a) low load, b) medium load, c) high load

Figures 4.5, 4.6 and 4.7 illustrate NO, NO_2 and NOx emissions at different loads for various fuels. At low load, diesel fuel produces 7.16 g/kWh of NO, 15.58 g/kWh NO_2 and 22.74 g/kWh of total NOx. B100 increases NO emissions by about 58%, whereas NO_2 emissions are only about 25% higher. At medium load, diesel fuel produces 7.58 g/kWh of NO, 2.28 g/kWh NO_2 and 9.86 g/kWh of NOx. B100 shows only about a 5% NO increase than that of diesel. However, the NO_2 emissions with diesel and biodiesel are fairly similar at this load condition. At high load, diesel fuel produces 15.29 g/kWh of NO, about 1.4 g/kWh NO_2 and 16.72 g/kWh of NOx. B100 produces only about 1% higher NO, NO_2 and NOx to that of diesel. The following observations are made from the results of NO, NO_2 and NOx emissions:

1) NO emissions at low and medium loads are relatively similar, however high load produces the highest NO with different fuels. This may be attributed to the maximum in-cylinder temperature at high load condition;

2) The higher the load, the lower the NO_2 emissions with different fuels. This suggests that NO_2 formation is not dependant on temperature condition;

3) NO_2 production at low load is significant and even higher than NO production and its share in total NOx is more than 60%. This is ignored most of the time as in [53, 54] in describing that in most high-temperature combustion processes, the majority (95%) of NOx produced is in the form of NO. Even some gas analyzers have used the same principle to calculate the NOx emissions from NO measurements and considering that NO is 95% of total NOx. This might be true for high load (this study shows about 8% NO_2 in total NOx), however, diesel engine at low load emits much higher NO_2 [55]. NO formed in the flame zone can be rapidly converted to NO_2 via reactions such as:

$$NO + HO_2 = NO_2 + OH \qquad (22)$$

Subsequently, conversion of this NO_2 to NO occurs via

$$NO_2 + O = NO + O_2 \qquad (23)$$

unless the NO_2 formed in the flame is quenched by mixing with cooler fluid. At low load operation, there are many cooler regions and NO_2 formed in the flame is quenched and could not be converted back to NO. Consequently, higher amount of NO_2 is produced at light load operations. This suggests that a proper care is needed to report NOx emissions from biodiesel combustion, especially at low load operation. This also suggests that NOx abatement technology must include a system to address both NO_2 and NO reduction

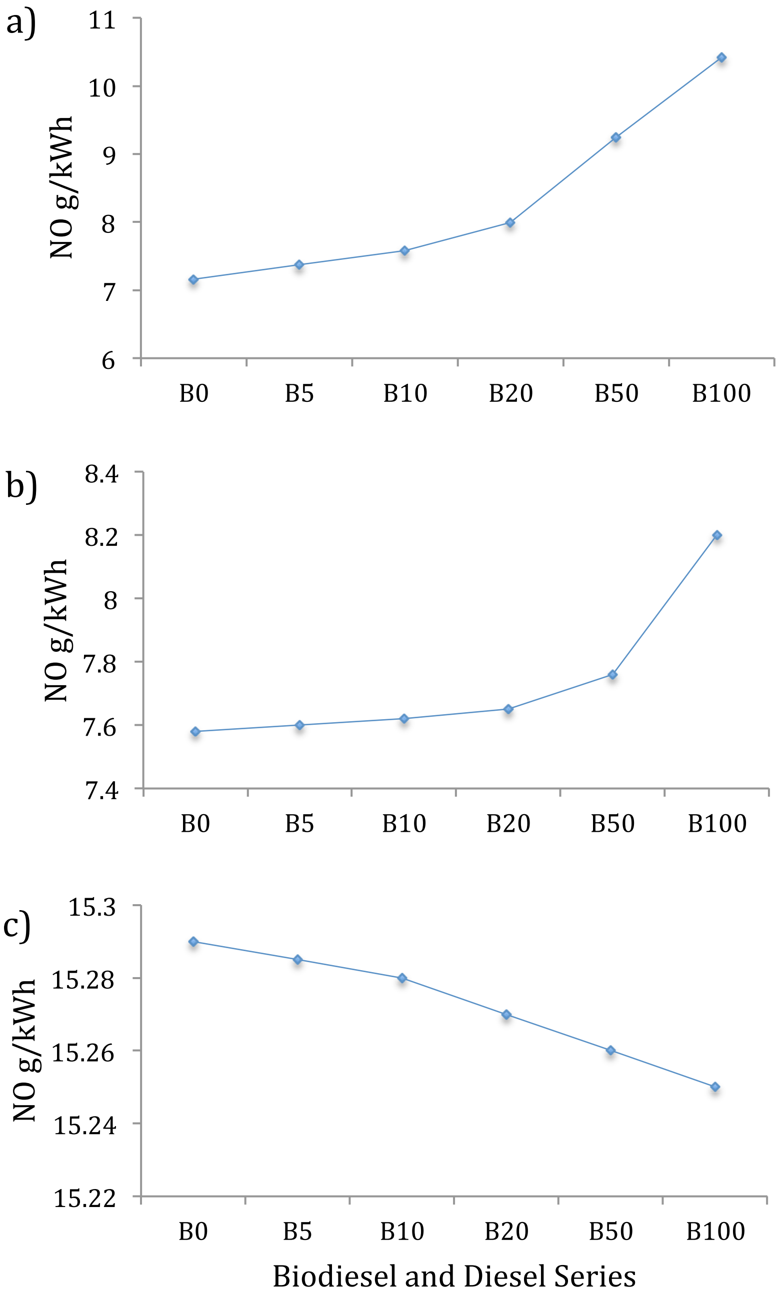

Figure 4.5: NO emissions for biodiesel/diesel blends a) low load, b) medium load, c) high load

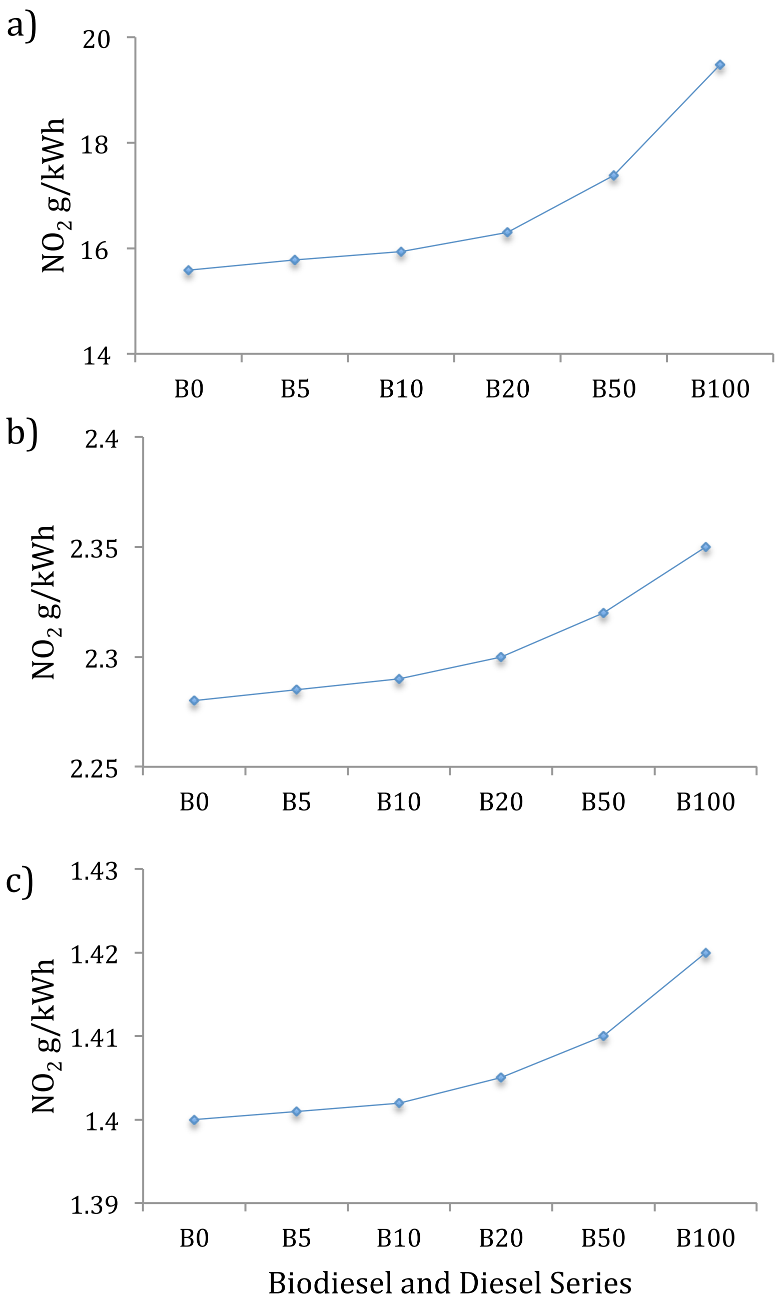

Figure 4.6: NO_2 emissions for biodiesel/diesel blends a) low load, b) medium load, c) high load

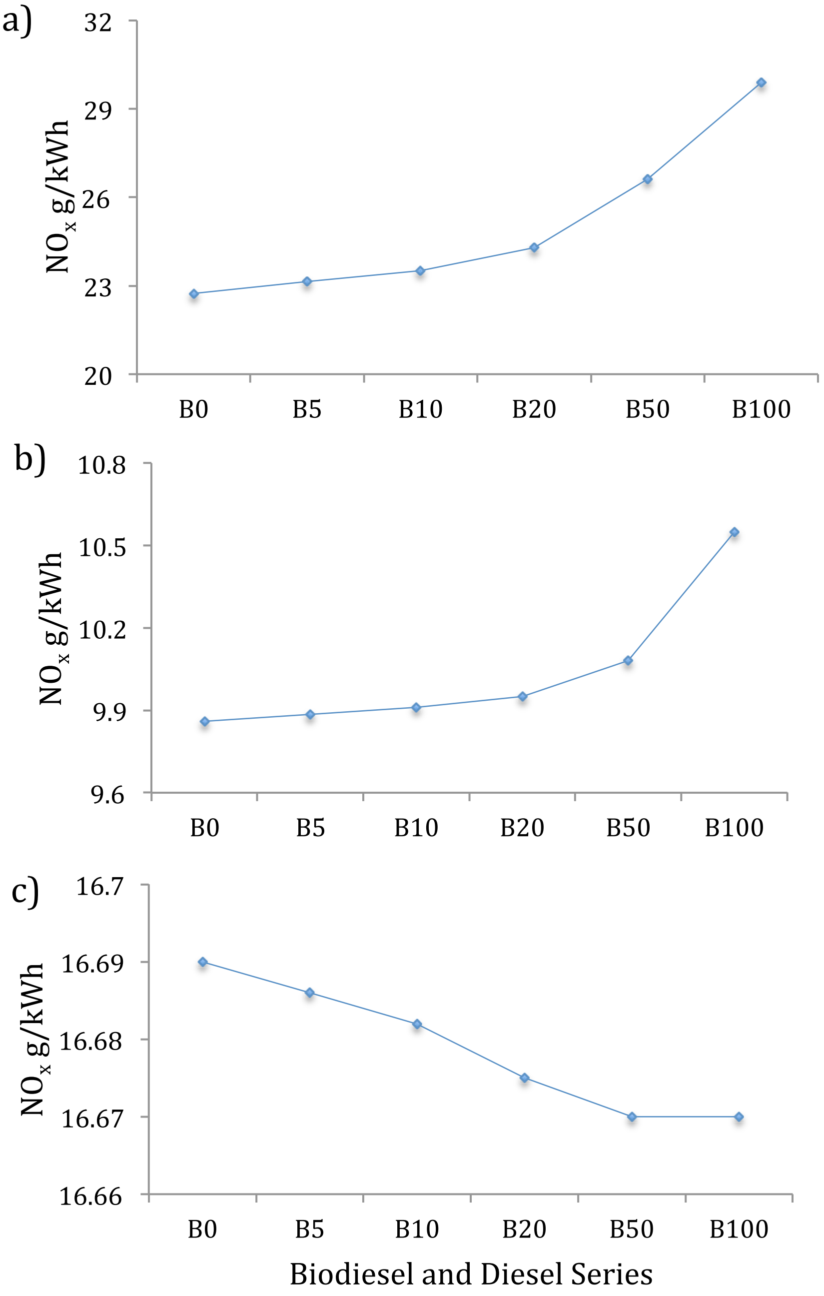

Figure 4.7: NOx emissions for biodiesel/diesel blends a) low load, b) medium load, c) high load

4.2 Biodiesel/ Diesel + 2% Additives series:

2% of Wintron XC30 is added to the biodiesel series to lower the cloud points of the blends. Also a further investigation will be taken to study the impact of the chemical additive on the engine performance and emissions. Our main goal is to promote biodiesel blends in cold weather. Data in Appendix B are used for the following analysis.

4.2.1 Engine Performance:

Figure 4.8 illustrates the variation of bsfc with different engine load for different biodiesel blends with diesel and 2% additives. The curve shows that bsfc is higher at low load and decreases with the increase in load for different biodiesel blends. In higher loads, the bsfc decreases because of the higher percentage of an increase in brake power with load compared to fuel consumption. It is also showing that the bsfc increases with the increase of biodiesel percentage in the blends. This is mainly due to the relationship among volumetric fuel injection systems, specific gravity, viscosity and heating value of the fuel (see Table 4.2). As a result, more biodiesel blend is needed to produce the same amount of energy due to its higher density and lower heating value in comparison to diesel. Again, as biodiesel blends have a different viscosity, biodiesel causes poor atomization and mixture formation and thus increases the fuel consumption rate to maintain the power. Also, the difference in bsfc as the load increases for low load B100A shows 5% increase compared to B0. Where at half and high load, it shows 7% and 10% increase respectively.

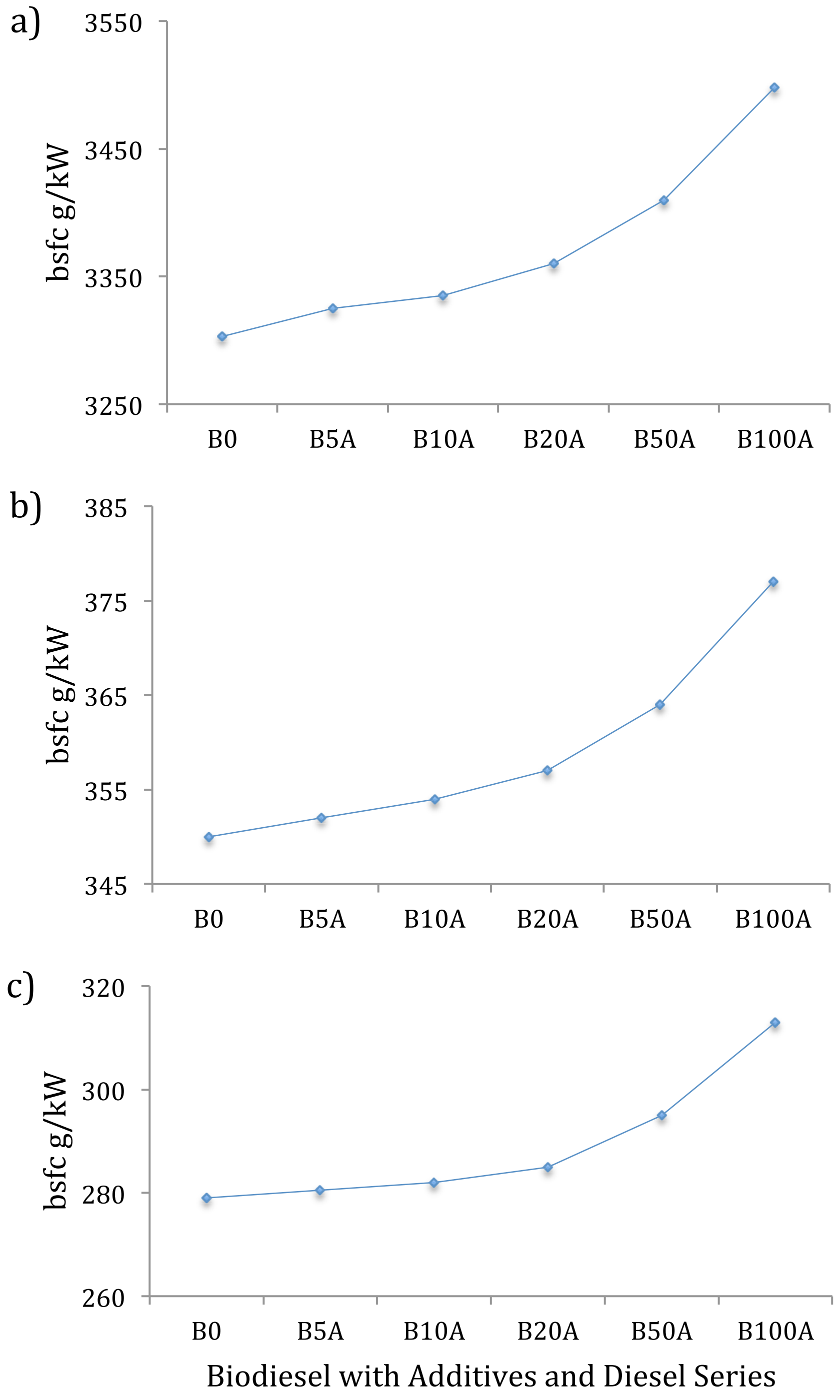

Figure 4.8: bsfc for biodiesel/diesel + 2% additives blends a) low load, b) medium load, c) high load

Table 4.2: Fuel properties of biodiesel/diesel + 2% additives blends

Fuel	Density (kg/m^3)	Viscosity (cSt @ 40ºC)	Heating value (kJ/kg)	Cloud point (ºC)
B0	830	1.86	45573	-41
B5A	859	3.41	45236	-43
B10A	861	3.67	44965	-38
B20A	864	3.93	44427	-29
B50A	873	4.28	42852	-16
B100A	888	7.87	40346	-7

Figure 4.9 shows the variation of fuel conversion efficiency with different engine loads. The fuel conversion efficiency of the engine was observed to increase with the increase in the load, and also increases with the increase of biodiesel percentage in the blend. The highest overall thermal efficiency has been found in B100A for all load conditions and the lowest thermal efficiency is found in B0 for all load conditions. This could be due to oxygen enrichment, which contributes to more complete combustion, while the improved lubricity reduces the friction loss, leading to an increase of fuel conversion efficiency for biodiesel. The increase in efficiency between B100A and B0 for different loads starting from low to high is approximately 6%, 0.4% and 0.7%, respectively.

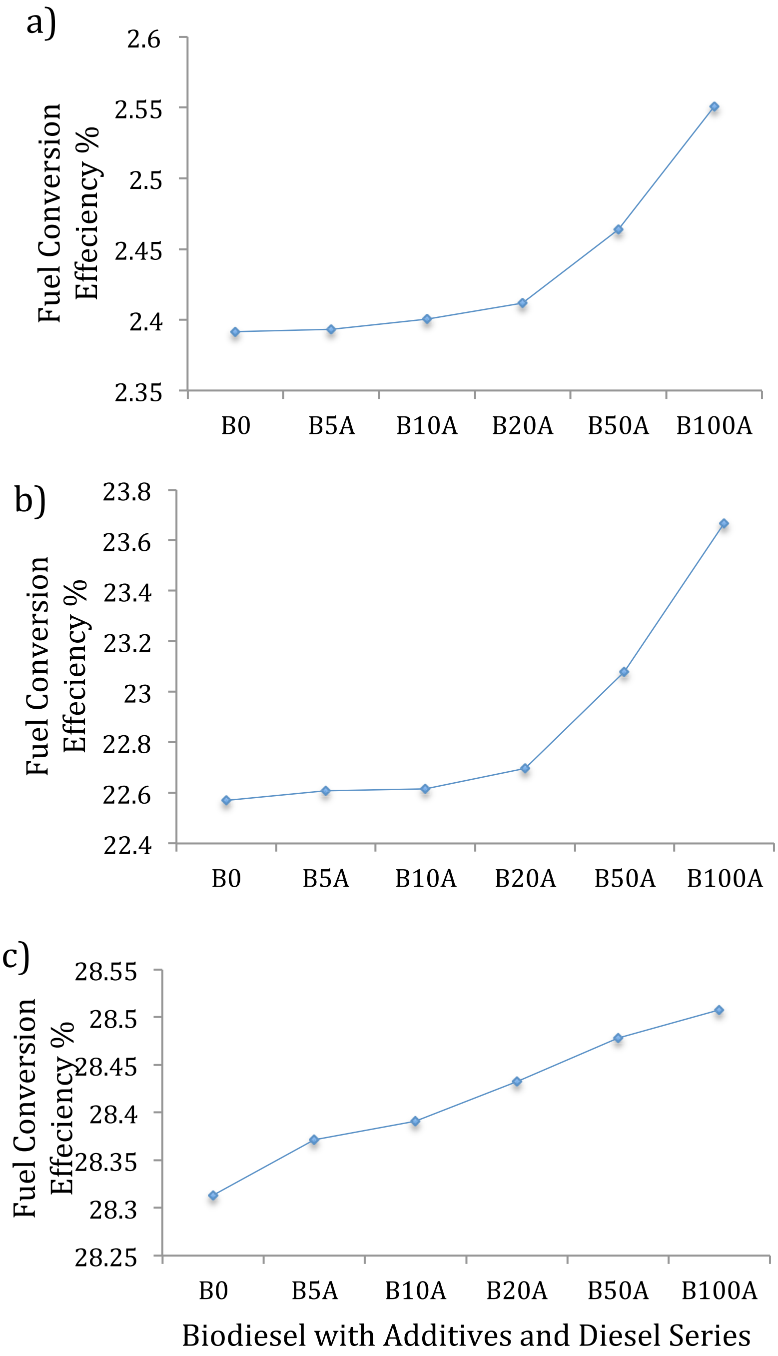

Figure 4.9: Fuel conversion efficiency for biodiesel/diesel +2% additives blends a) low load, b) medium load, c) high load

4.2.2 Emissions:

Figure 4.10 shows CO emissions at different engine loads for various fuels. At low load, half load and high load conditions, B0 produces the highest amount of CO (200, 7.83, and 2.62 g/kWh) respectively starting from low to high load, which decreases gradually with the increase of biodiesel percentage in diesel. Where B100A shows the lowest values of CO at all load conditions (120, 6.38 and 2.65 g/kWh) respectively, it also increases with the increase of diesel percentage in biodiesel. B100A shows a decrease in CO from low to high load conditions compared to B0 by 40%, 18.5% and 0.7%, respectively.

It has been observed by the results that the higher the engine load, the lower the CO emissions for all fuels. This is possibly due to the more complete combustion by a better air/fuel mixing that leads to a higher temperature inside the cylinder. Also, it can be observed that the higher the biodiesel percentage in the blends, the lower the CO emissions at low, medium and high load conditions. This could be due to the oxygen enrichment that leads to a more complete combustion, which, in turn, enhances the CO oxidation.

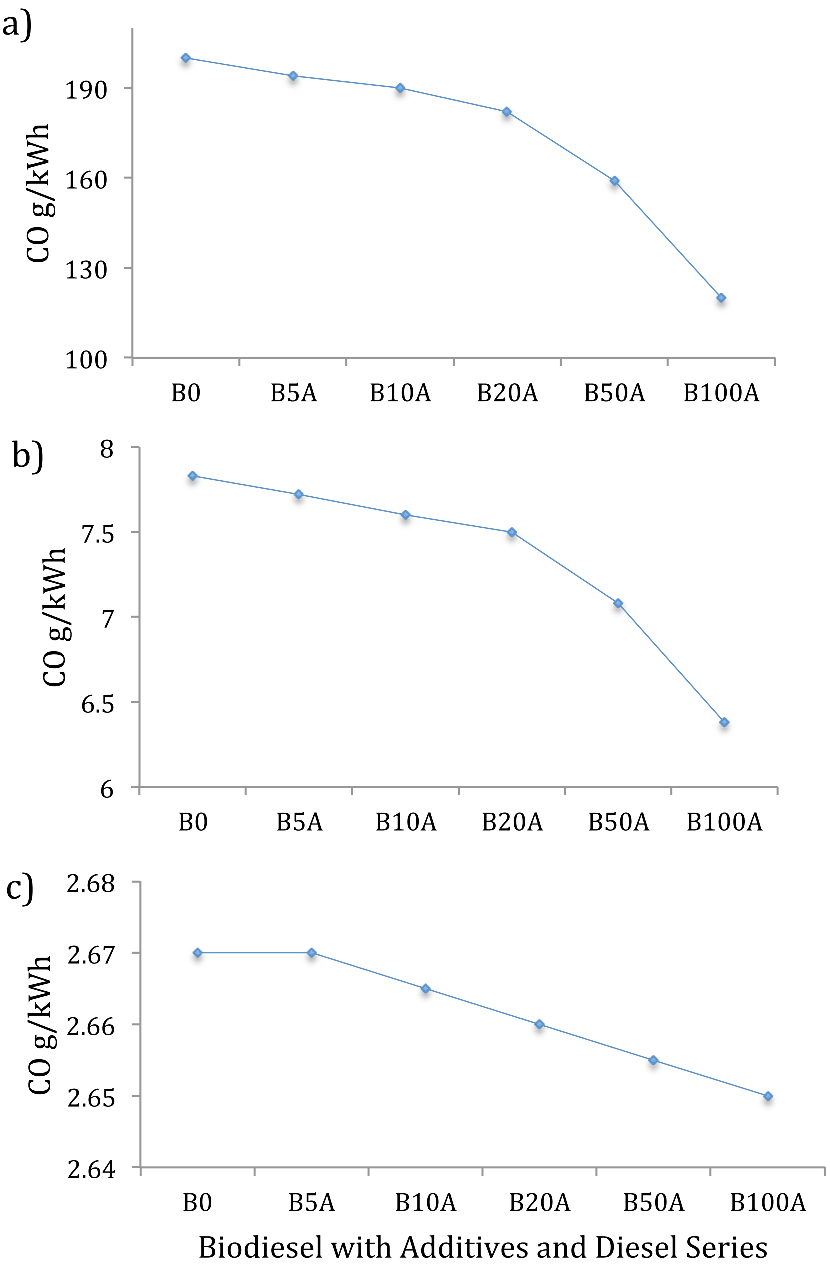

Figure 4.10: CO for biodiesel/diesel + 2% additives blends a) low load, b) medium load, c) high load

Figure 4.11 demonstrates HC emissions at three different engine loads for various fuels. At low, medium and high loads B100A shows the lowest of values of HC compared to the rest of the blends (10.56, 0.43, 0.3 g/kWh) respectively, where B0 has the highest values of HC at all load conditions (30.47, 1.04, 0.52 g/kWh) respectively.

It can be observed that the HC level decreases dramatically with the increase in load. This could be because of a better mixing of air and fuel due to higher evaporation at higher engine loads for higher in-cylinder temperatures. It is also observed that the increase of biodiesel percentage in the blends reduces the HC values. That could be caused by the higher O_2 concentration in the air-fuel mixture, which can help enhance oxidation of unburned hydrocarbons.

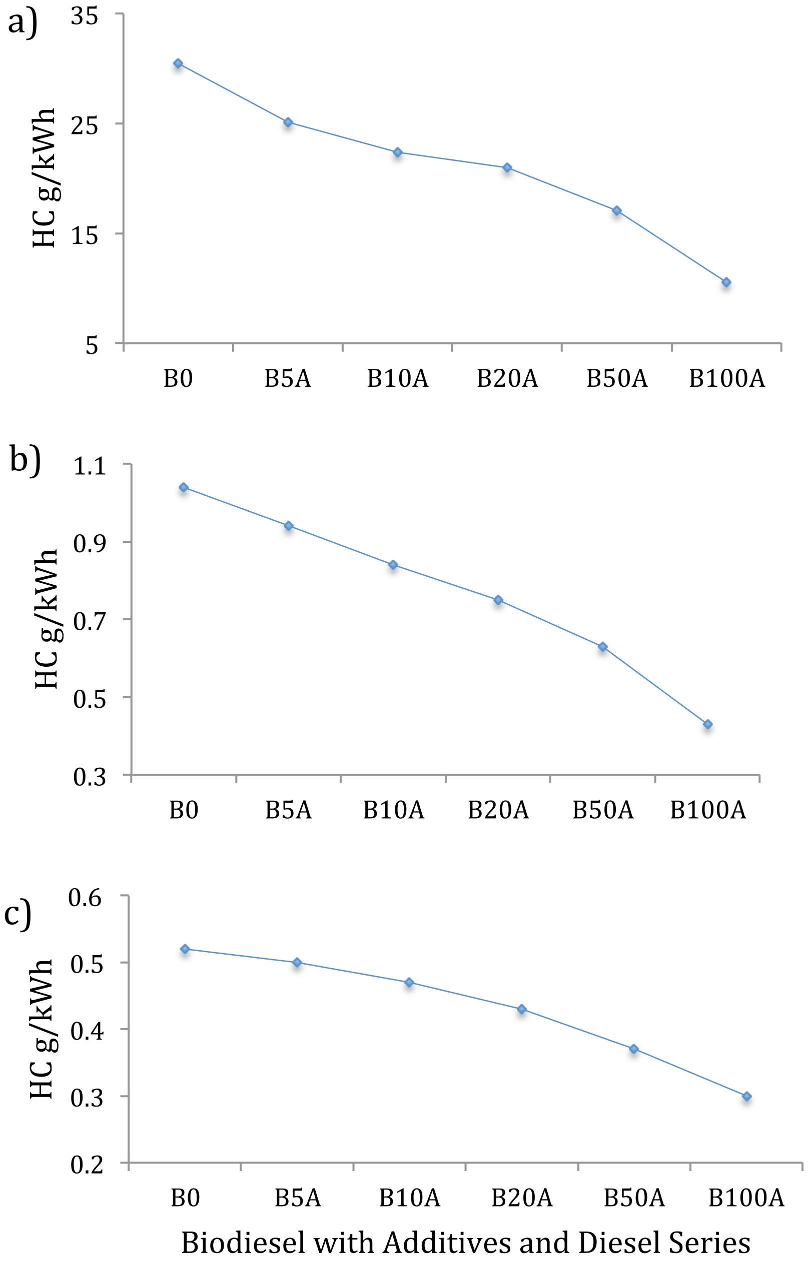

Figure 4.11: HC emissions for biodiesel/diesel + 2% additives a) low load, b) medium load, c) high load

Figure 4.12 shows the amount of NO produced by different fuels at different load conditions. At low load and medium load B0 shows the lowest values of NO (7.16 and7.58 g/kWh) respectively, where B100A value is 47% and 10.6% higher respectively.

At full load, B100A shows the lowest value of NO (14.87 g/kWh), whereas B0 value is around (2.7 %) higher.

Looking at the pattern, it can be seen that high temperature has a noticeable impact on the increase of NO. As the load increases, the NO emitted is also increased. At low load condition and medium load, the NO increases as the percentage of biodiesel increase in the blend because of the higher oxygen content in biodiesel. At high load condition, it is the opposite: the NO decreases as the percentage of biodiesel in blend increases. The higher oxygen content in biodiesel and the less cool regions can help convert NO_2 back to NO.

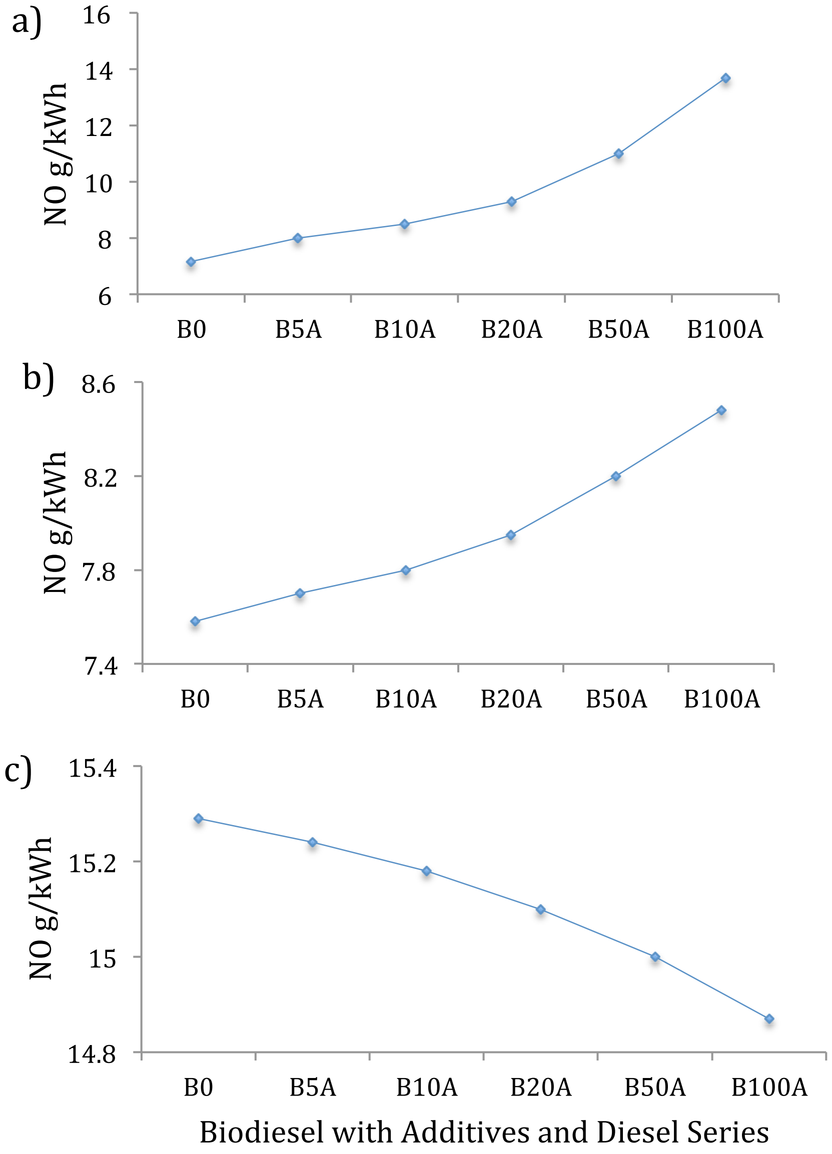

Figure 4.12: NO emissions for biodiesel/diesel + 2% additives a) low load, b) medium load, c) high load

Figure 4.13 shows the amount of NO_2 produced by different fuels at different load conditions; at low load B0 generates the lowest value of NO_2 (15.58 g/kWh) where B100A value is 24.73% higher. At medium load, B0 generates the lowest value of NO_2 (2.28 g/kWh, where B100A value is 5.4% higher. At high load, B100A gives the lowest value of NO_2 (1.27 g/kWh) with 9.2% reduction compared to B0.

It can be observed that the higher the load, the less NO_2 is emitted for all fuels. This suggests that NO_2 formation is not dependent on temperature conditions. Also at low and medium loads, the NO_2 increases as the biodiesel percentage increases in the blend, which could be due to the higher oxygen content in biodiesel. However in high load, the oxygen content with the aid of the high temperature regions helps decrease the amount of NO_2

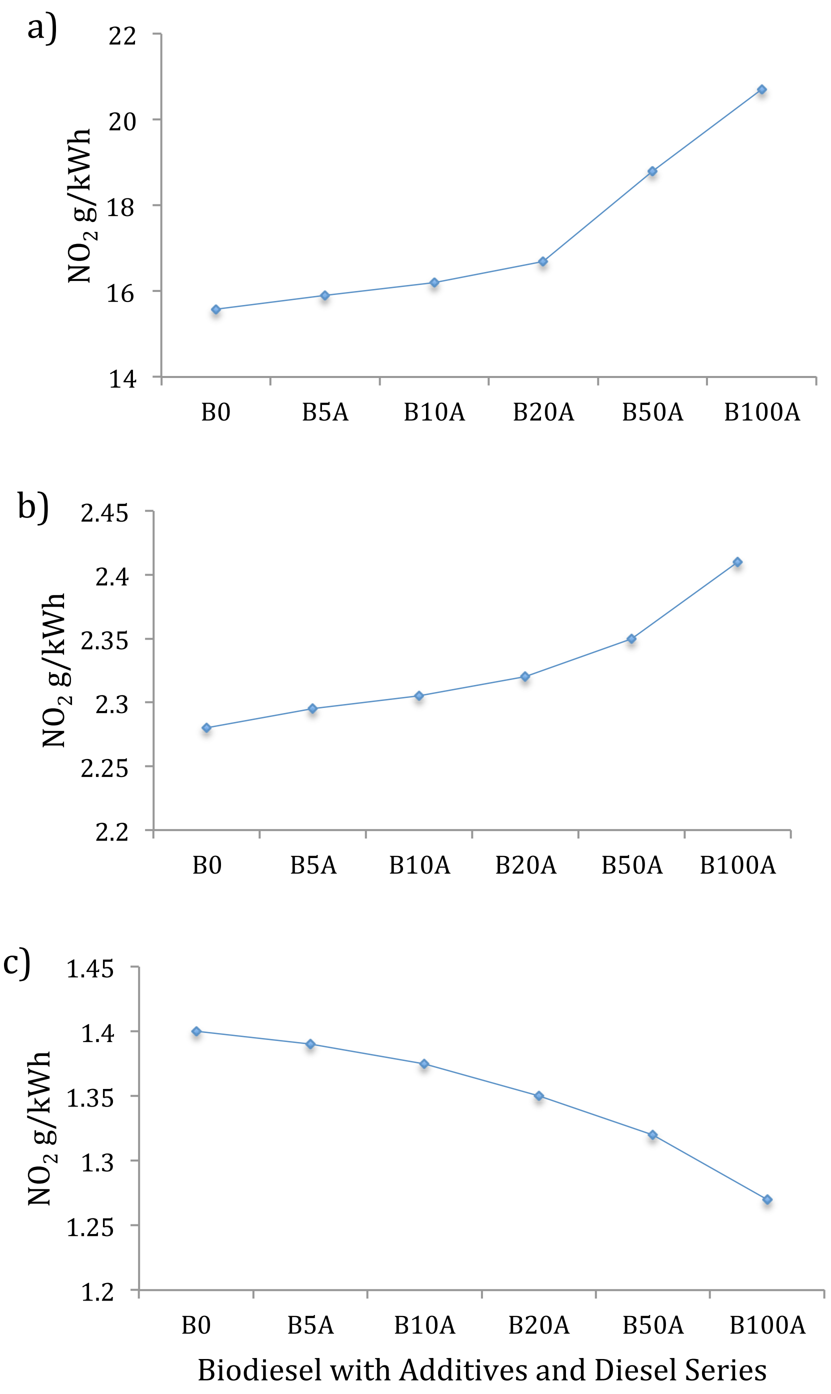

Figure 4.13: NO_2 emissions for biodiesel/diesel + 2% additives a) low load, b) medium load, c) full load

Figure 4.14 demonstrates the total NOx produced by different fuels at different load conditions at low load; B0 shows the lowest value of NOx (22.74 g/kWh), where the B100A value is 33.8% higher. At medium load, again B0 has the lowest value of NOx (9.86 g/kWh), whereas B100 value is 9.45% higher. At high load B100A gives the lowest value of NOx (16.14 g/kWh) with 3.3% reduction compared to B0.

It can be observed from the curves that NO_2 has the higher percentage in total NOx at low load by around 60%. However at medium and high load conditions, the NO percentages are much higher 77% and 92% respectively. This supports the possibility that NO_2 formation is not dependent on temperature change.

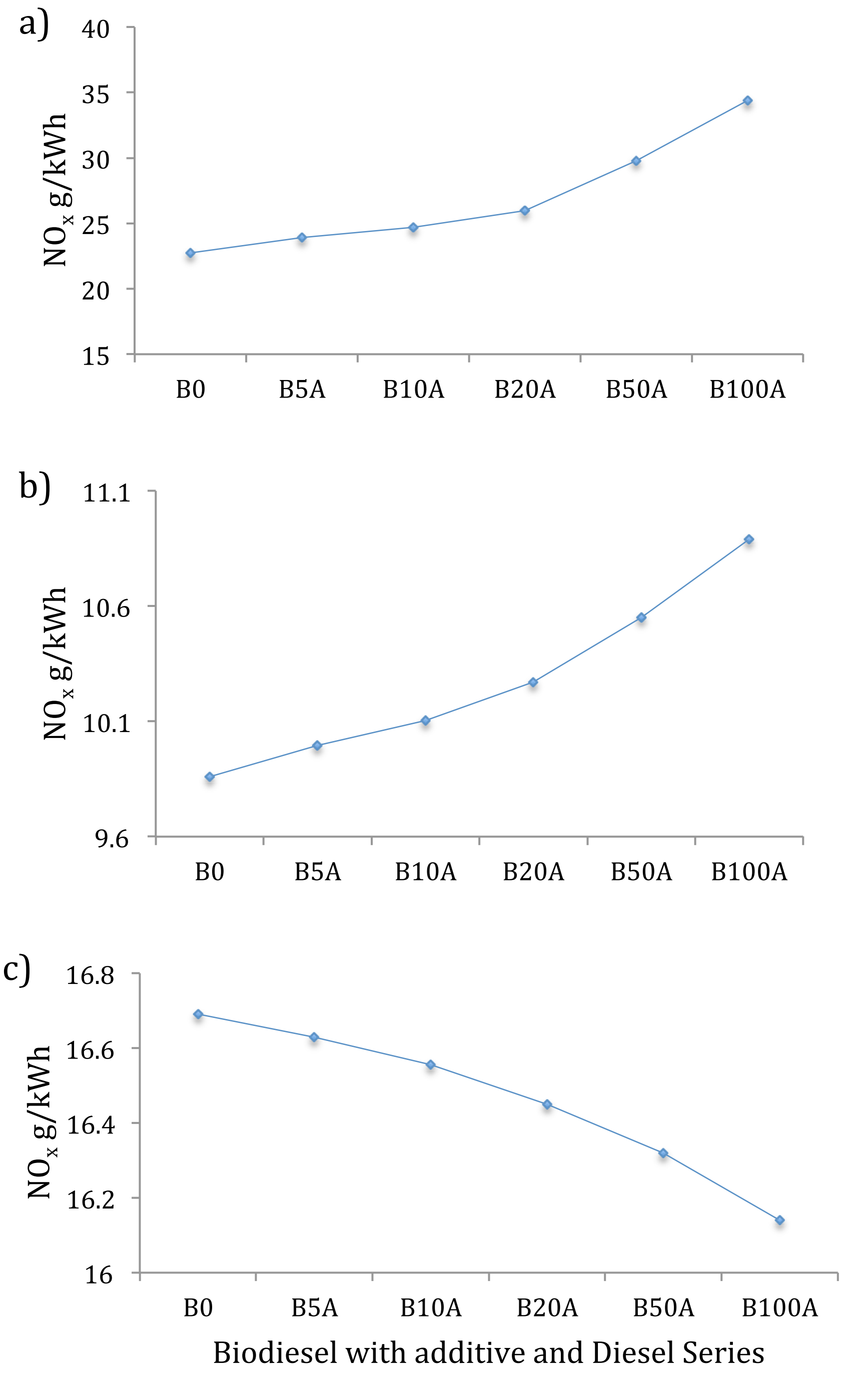

Figure 4.14: NOx emissions for biodiesel/diesel + 2% additives a) low load, b) medium load, c) high load

4.3 Kerosene/ Biodiesel Series:

Kerosene fuel has a high heating value, low viscosity and a very low cloud point, which makes kerosene a good additive candidate to enhance biodiesel characteristic by lowering its cloud point and boost up its heating value. Our main goal is make biodiesel feasible in cold weather. Data in (Appendix C) was used for the following analysis.

4.3.1 Engine Performance:

Figure 4.15 demonstrates the variation of bsfc with different engine loads for different biodiesel blends with kerosene. The curve shows that bsfc is higher at low load and decreases with the increase of load for different kerosene-biodiesel blends. In higher loads, the bsfc decreases because of the higher percentage of an increase in brake power with load compared to fuel consumption. It also shows that the bsfc increases with the increase of biodiesel percentage in the blends for medium and high loads, due to the relationship among specific gravity, viscosity and heating value of the fuel (see Table 4.3). As a result, more biodiesel blend is needed to produce the same amount of energy due to its higher density and lower heating value in comparison to kerosene. However at low load, the bsfc increases as the kerosene percentage in the blends increased. This could be due to kerosene's high volatility characteristic. For a complete combustion an intimate air fuel mixing should take place but if the mixture is too lean due to excess air that may cause an inhomogeneous air fuel mixture in the cylinder resulting in poor combustion. However at higher load kerosene seems to reach a state close to stoichiometric, which improves the combustion.

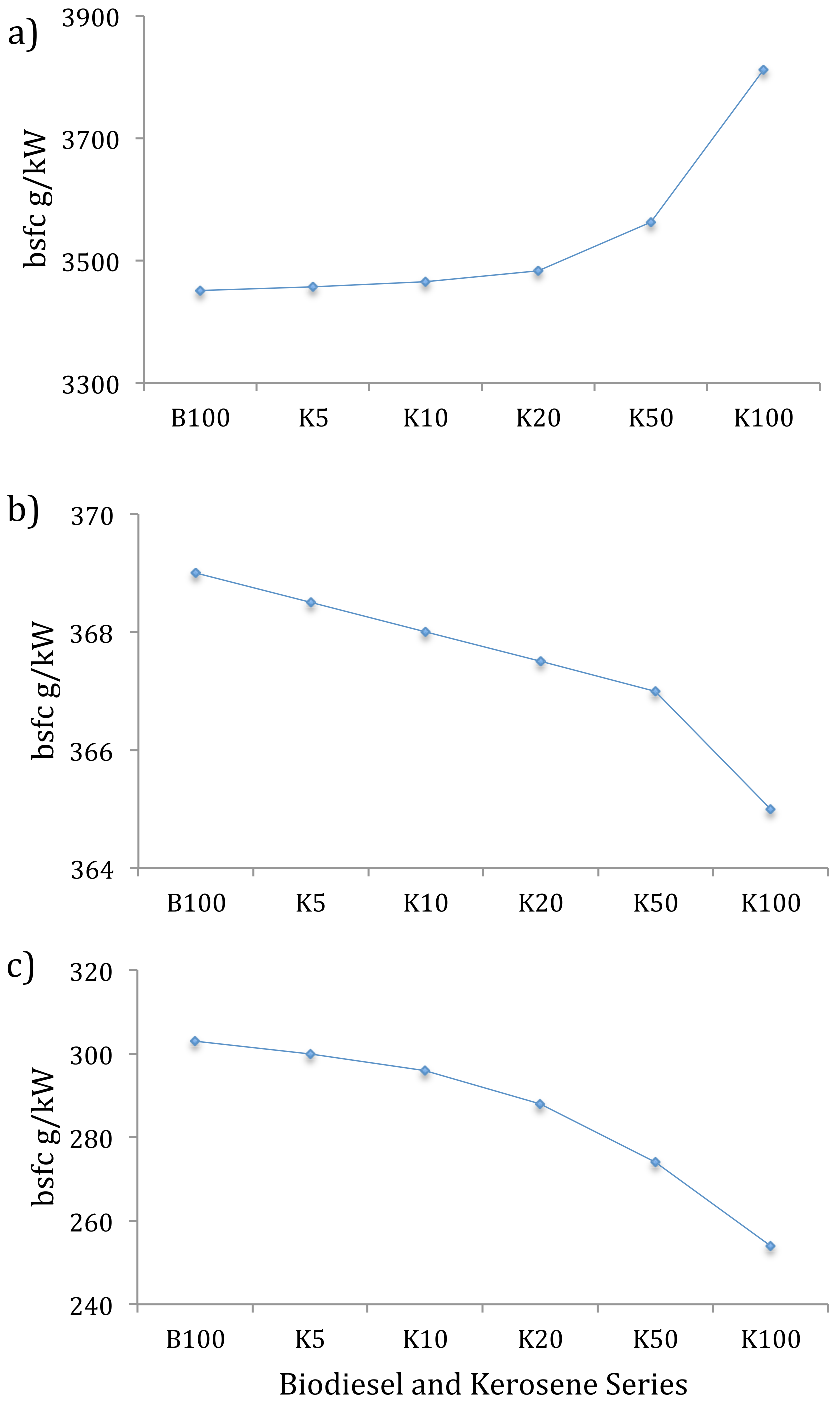

Figure 4.15: bsfc for kerosene/biodiesel a) low load, b) medium load, c) high load

Table 4.3: Fuel properties of biodiesel/diesel + 2% additive blends

Fuel	Density (kg/m^3)	Viscosity (cSt @ 40ºC)	Heating value (kJ/kg)	Cloud point (ºC)
B100	881	4.2	40296	-4
K5	866	4.1	40568	-7
K10	862	3.6	40839	-8
K20	854	3.07	41390	-9
K50	830	2.12	43113	-23
K100	790	1.02	46250	-78

Figure 4.16 shows the variation of break thermal efficiency with different engine loads. The break thermal efficiency of the engine is observed to increase with an increase in the load. Similarly, it increases with the increase of biodiesel blends with kerosene for low and medium loads. That could be due the oxygen enrichment, which contributes to more complete combustion, while the improved lubricity reduces the friction loss and leads to an increase of the brake thermal efficiency for biofuels. However at high load conditions, kerosene seems to reach a state close to stoichiometric that improves kerosene combustion and makes kerosene superior to biodiesel at this load. K100 is better than B100 at high load by around 3.5%.

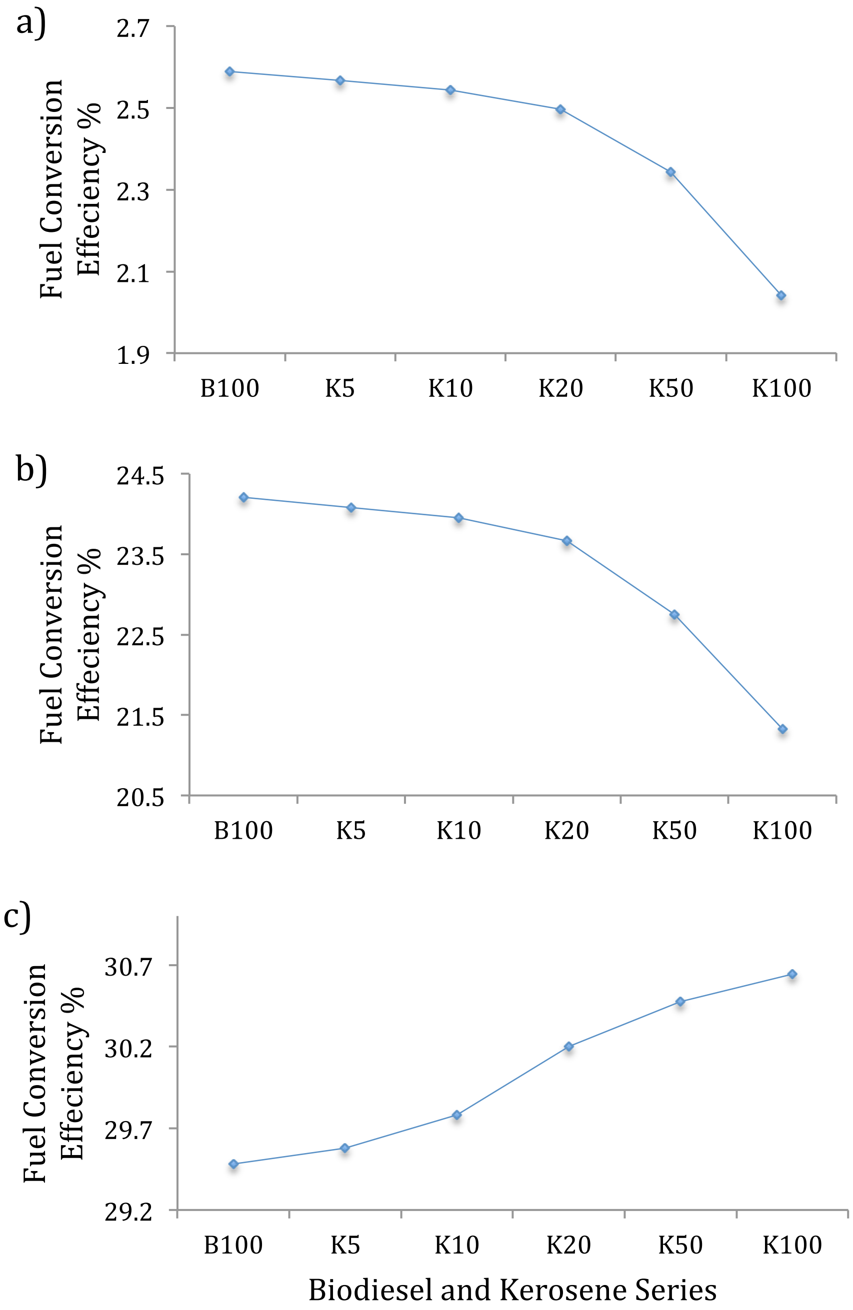

Figure 4.16: Fuel conversion efficiency values kerosene/biodiesel a) low load, b) medium load, c) high load

4.3.2 Emissions:

Figure 4.17 shows CO emissions at different engine loads for various fuels. At low load and half load, kerosene fuel produces the highest amount of CO (123, and 6.42 g/kWh), respectively, which decreases gradually with the increase of biodiesel percentage with kerosene. B100 shows a reduction of CO at low and medium loads compared to K100 by (49% and 38.7%) respectively. At high load K100 generates the lowest values compared to the rest of blends (2.52 g/kWh), where B100 exhibits the highest value of CO by 10.3% higher than K100.

It can be observed from these results that the higher the engine load, the lower the CO emissions for all fuels. This is possibly due to the more complete combustion by a better air/fuel mixing, which leads to a higher temperature inside the cylinder. Also, it has been observed that the higher the biodiesel percentage in the blends, the lower the CO emissions at low and medium load conditions. This could be due to the oxygen enrichment that leads to a more complete combustion, which, in turn, enhances the CO oxidation. However, at high loads, K100 has the lowest CO value and again that could due to a more complete combustion compared to the lower load conditions.

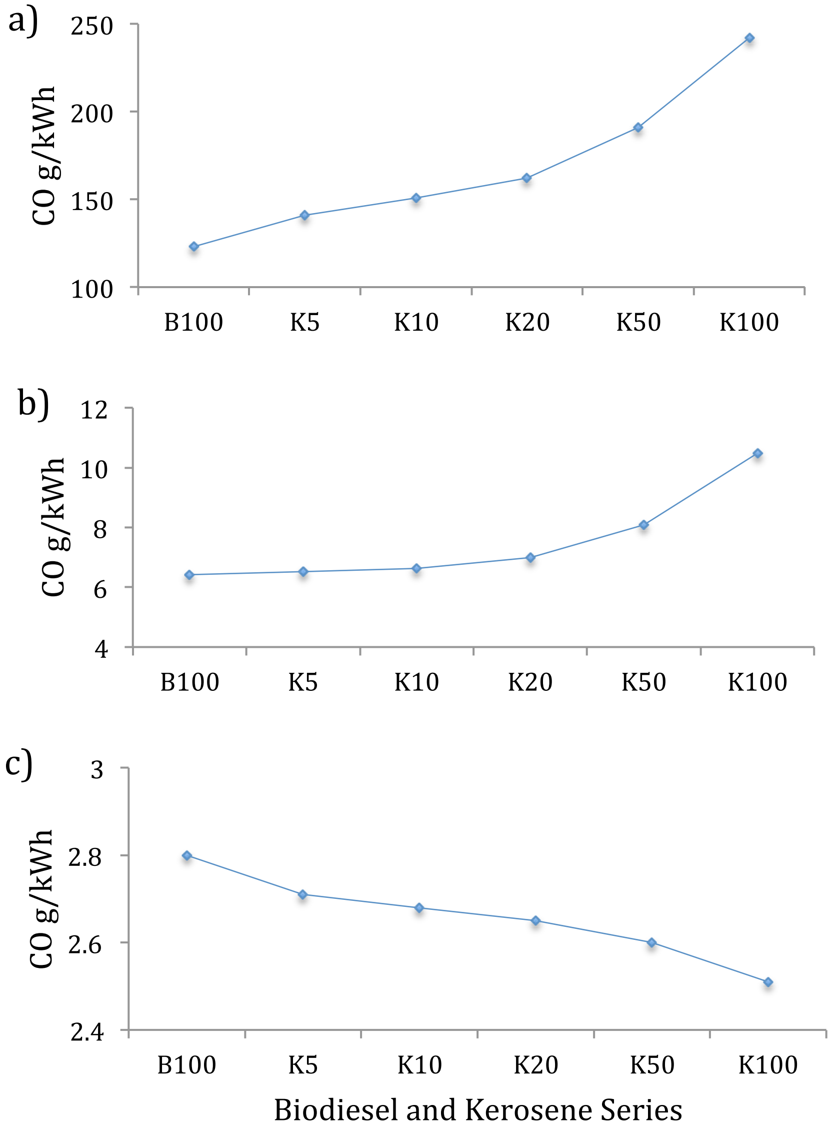

Figure 4.17: CO emissions for kerosene/biodiesel a) low load, b) medium load, c) high load

Figure 4.18 demonstrates HC emissions at different engine loads for various fuels. At low and medium loads, K100 shows the highest value of HC higher than B100 by (71.4% and 30.7%) respectively. This difference could be explained, by kerosene's high volatility characteristic. For a complete combustion an intimate air fuel mixing should take place but if the mixture is too lean due to excess air that may cause an inhomogeneous air fuel mixture in the cylinder resulting in poor combustion, and hence the amount of HC increases (from overlean regions). Also, the higher oxygen content in the biodiesel improves the oxidation on unburned hydrocarbons. However, K100 emits the least HC at high load condition with 32% reduction compared to B100, which could be due to a more complete combustion by a better air/fuel mixing.

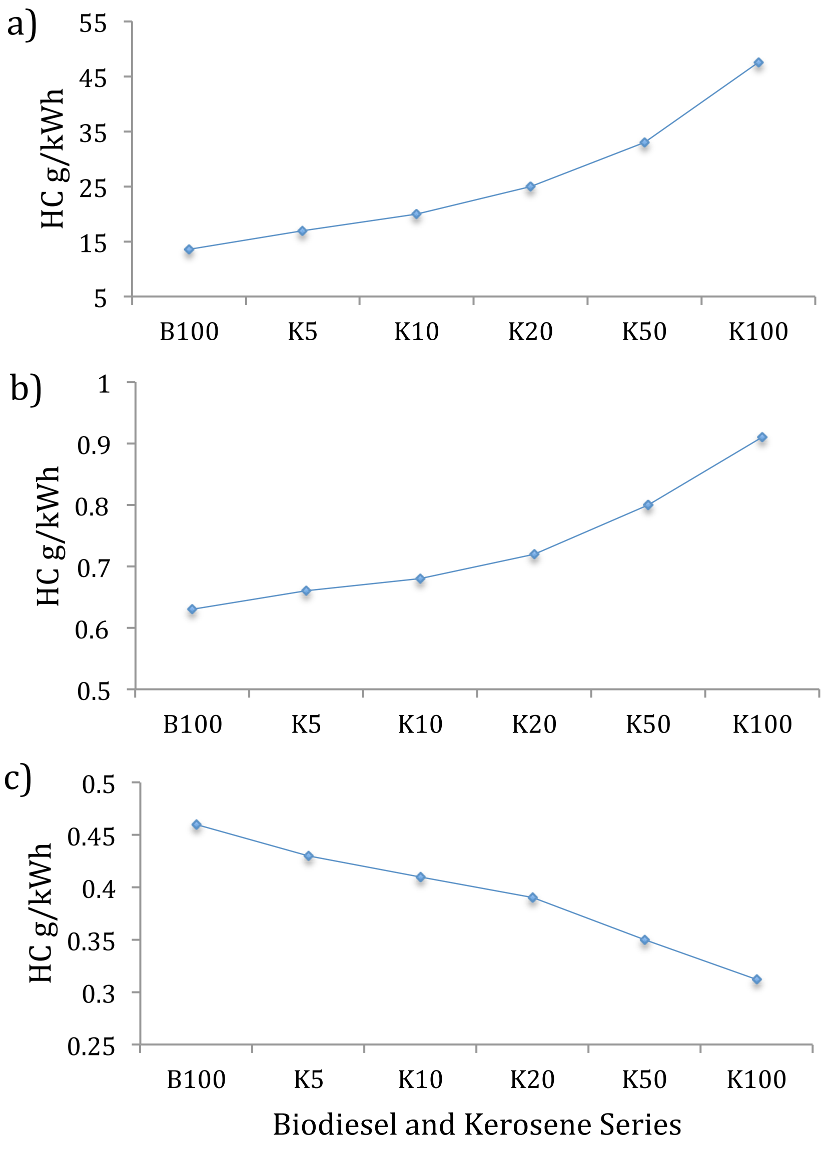

Figure 4.18: HC emissions for kerosene/biodiesel a) low load, b) medium load, c) high load

Figure 4.19 shows the amount of NO produced by different fuels at different load conditions. At low load, K100 emits the lowest value of NO (5.62 g/kWh), where the NO value of B100 is 46% higher. At medium load, again K100 generates the lowest value of NO (6.11 g/kWh), where B100's NO value was 25% higher. At high load, K100 gives the lowest value again of NO (14.8 g/kWh) with a 2.9% reduction compared to B100.

Looking at the pattern, it can be observed that high temperature has a noticeable impact on the increase of NO. At low and medium load conditions, there is a significant difference between the amount emitted by B100 and K100 due to their higher oxygen content in biodiesel. However at high load, they emit almost the same amount of NO. This can be explained by, the higher the load, the better the air/fuel mixing, and the more complete combustion and a higher temperature inside the cylinder for all fuels

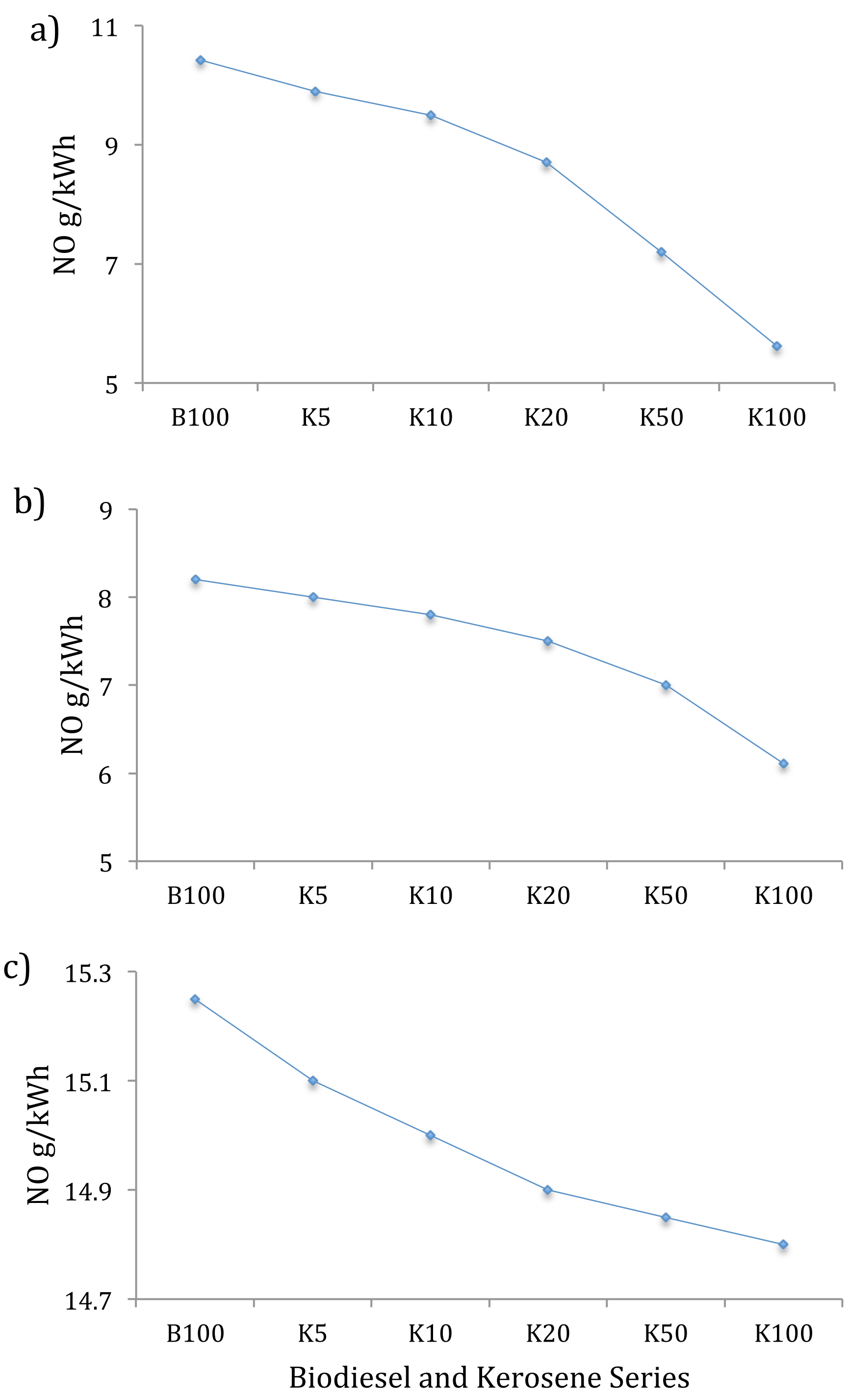

Figure 4.19: NO emissions for kerosene/biodiesel a) low load, b) medium load, c) high load

Figure 4.20 shows the amount of NO_2 produced by different fuels at different load conditions at low load K100 show the lowest value of NO_2 (7.46 g/kWh), where B100's NO_2 value is 66% higher than K100. At medium load, B100 generates the lowest value of NO_2 (2.2 g/kWh), but the NO_2 value of K100 is 20.5% higher than B100. At high load B100 gives the highest value of NO_2 (1.41 g/kWh) with a 7.8% increase compared to K100. At this load, the lowest value showed is for K100 (1.3 g/kWh). It can be observed that the higher the load, the less NO_2 is emitted for all fuels. It can be concluded that temperature condition is not the main factor for NO_2 formation.

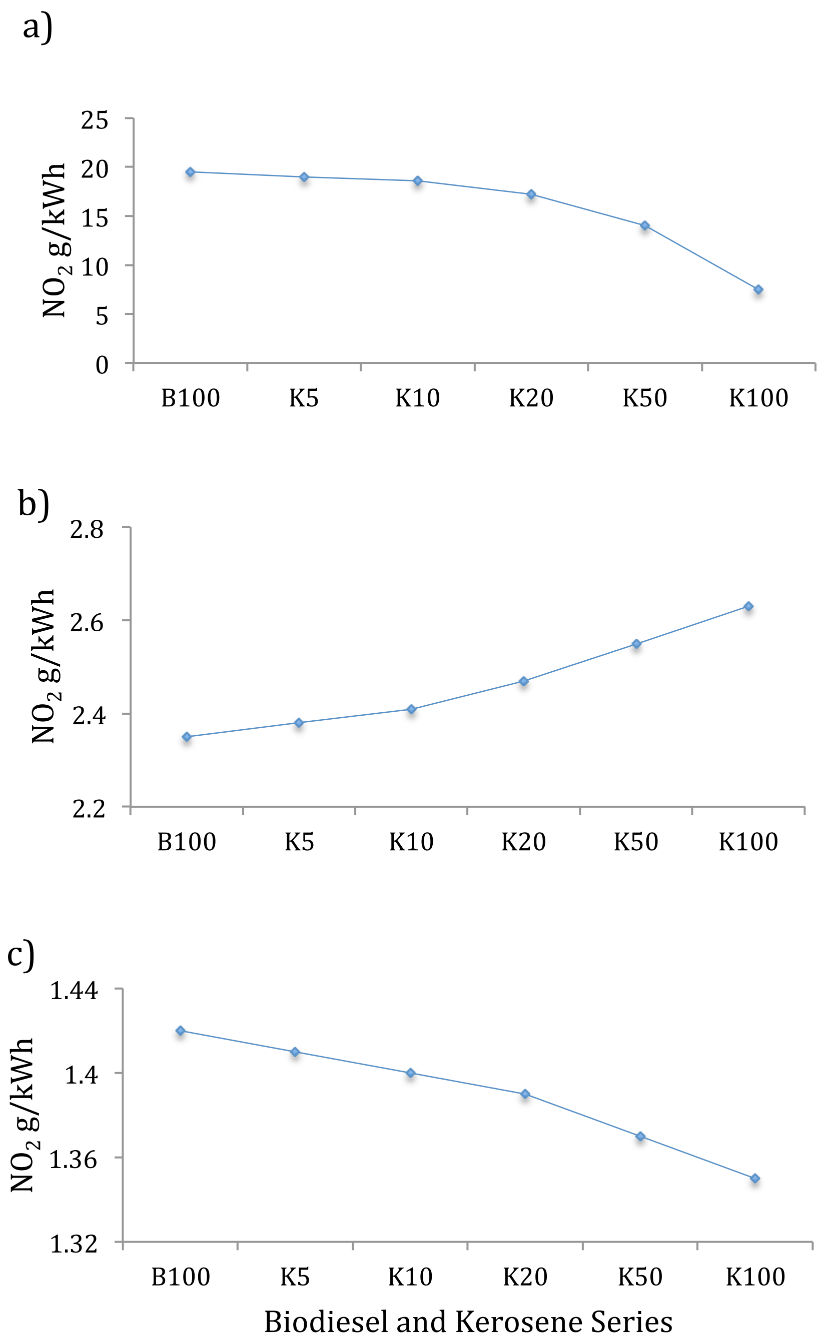

Figure 4.20: NO_2 emissions for kerosene/biodiesel a) low load, b) medium load, c) high load

Figure 4.21 illustrates the amount of NOx produced by different fuels at different load conditions at low load; K100 shows the lowest value of NOx (13.08

g/kWh), where B100 value was 56% higher. At medium load, again K100 has the lowest value of NOx (8.74 g/kWh), where B100 value was 17.15% higher. At high load, B100 emits the highest value of NOx (16.67 g/kWh) with a 3.11% increase compared to K100. It can be seen from the curves that NO_2 has the higher percentage in total NOx at low load by 61.6%. However at medium and high load conditions, the NO percentages are much higher by about 81% and 92% respectively. This possibly could mean that the change in temperature is not the main reason for forming NO_2.

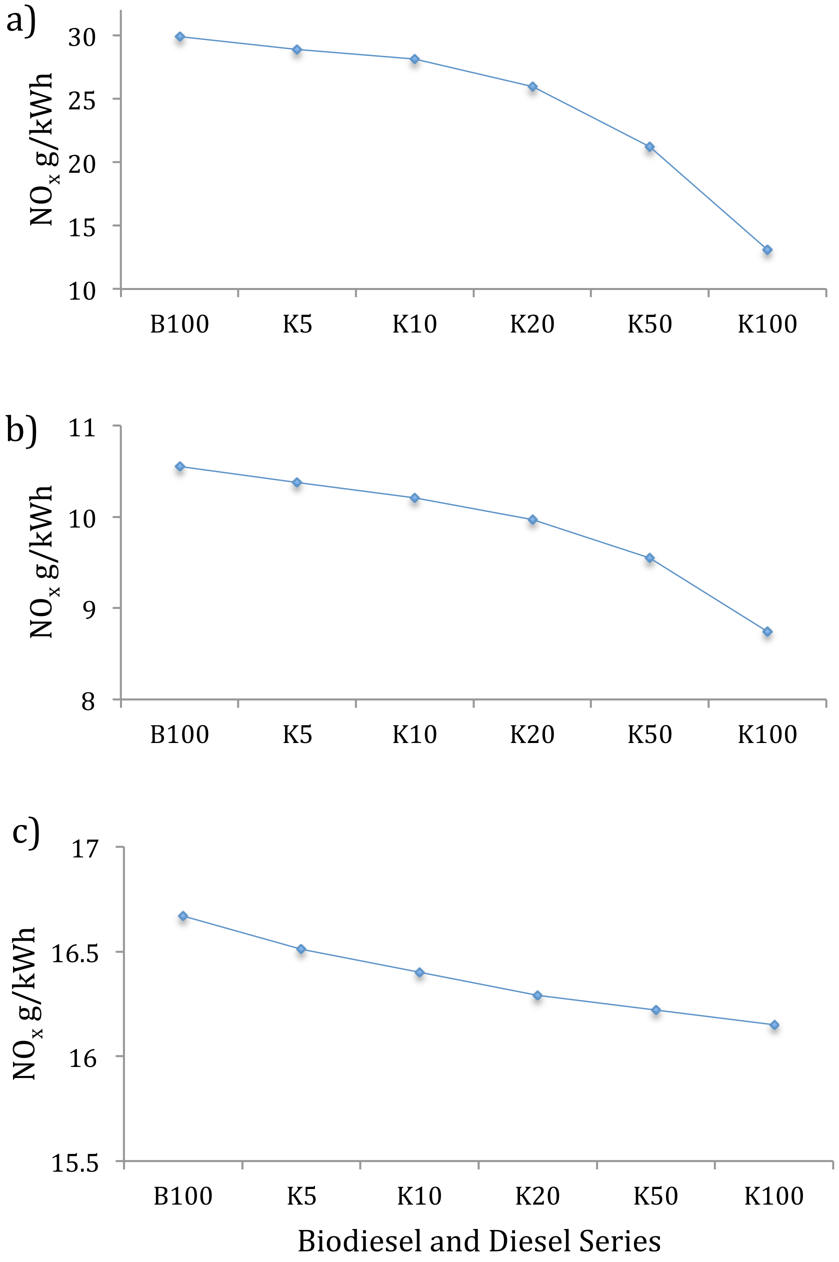

Figure 4.21: NO_2 emissions for kerosene/biodiesel a) low load, b) medium load, c) high load

4.4 Results Comparison:

In this section a comparison of engine performance and emissions results for all three series (biodiesel/diesel series, biodiesel/diesel + 2% additives and kerosene/biodiesel series) are discussed.

4.4.1 Engine Performance:

The brake specific energy consumption (bsec) will be included in this section in order to show the relation between the power, fuel consumptions and the heating values for each blend.

Figure 4.22 shows the bsfc for all three series at three different load conditions.

- At low load, the kerosene/biodiesel series has the highest bsfc values for all blends, where the biodiesel/diesel series has the lowest values for all blends. This can be explained by the high volatility of kerosene with the presence of excess air; which causes an inhomogeneous air fuel mixture in the cylinder resulting in poor combustion. Biodiesel/diesel + 2% additives series values are very close to the biodiesel/diesel series but slightly higher. This could be due to the fact that the 2% additives decrease the heating value of the blends by around 0.1%. Diesel fuel has the lowest bsfc values at this load.

- Medium load condition shows a similar trend to low load condition. Biodiesel/diesel + 2% additives series values are very close to the biodiesel/diesel series but slightly higher. The decrease in heating value of the blends by around 0.1% after adding the 2% of additive could be the reason for the slight increase. However the results of K100 are slightly different. K100 has the lower bsfc compared to B100 and B100A. This could be due to the previously mentioned fact that kerosene has a lower flash point and the higher the temperature inside the chamber, the more complete combustion the kerosene will make. Diesel fuel has the lowest bsfc values at this load.

- At full load biodiesel/diesel series has the lowest values for all blends. Biodiesel/diesel + 2% additives series values are very close to the biodiesel/diesel series but slightly higher. This is possibly the effect of the 2% additives that decreased the heating value of the blends by around 0.1%. However K50 and K100 show the lowest bsfc values 1.7% and 8.9% lower than fossil diesel, respectively. Dismissing the fact that kerosene has the highest heating value, it seems that kerosene burns much better at higher loads when the temperature is higher.

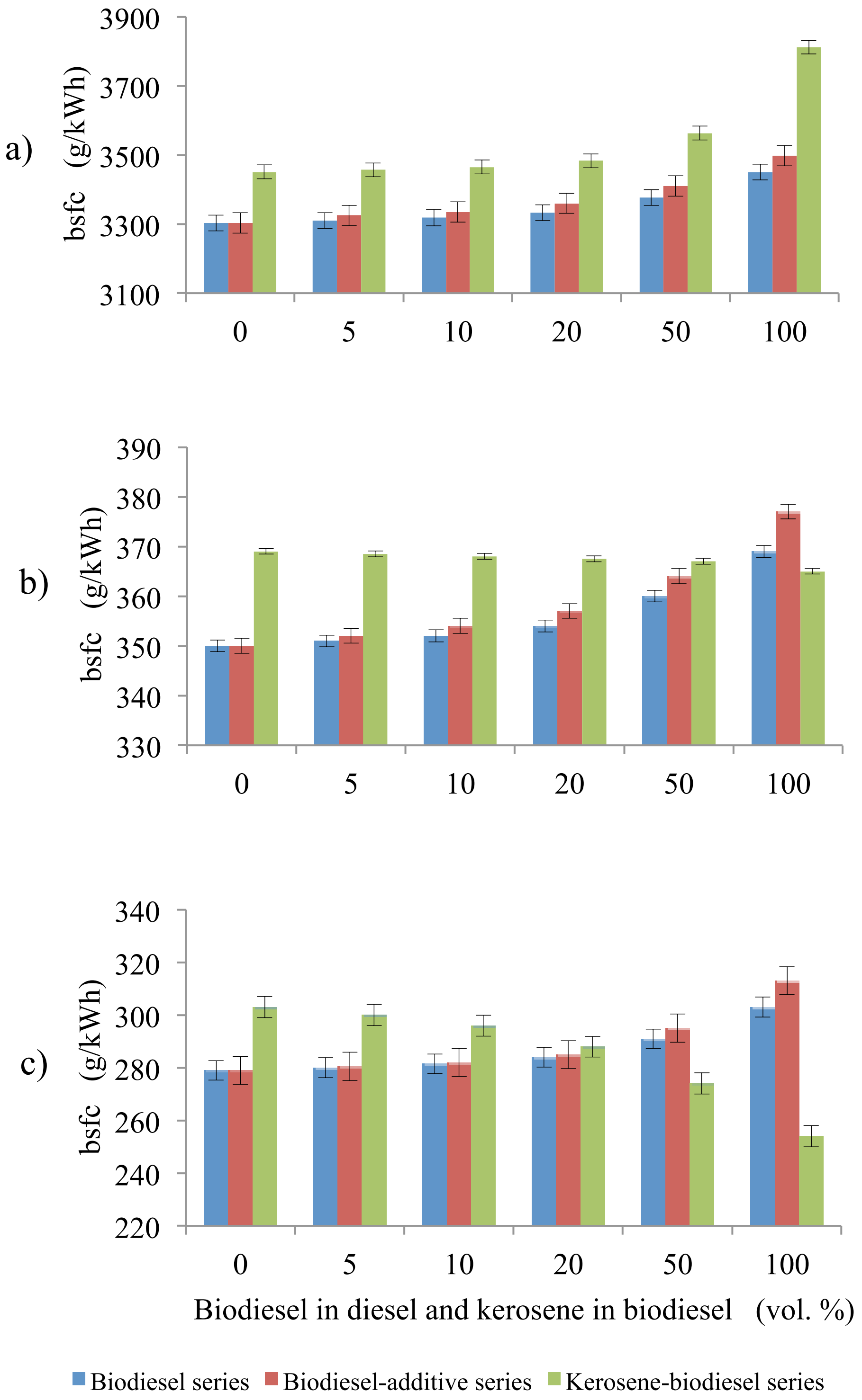

Figure 4.22: Comparison of bsfc for all three series a) low load, b) medium load c) high load

Figure 4.23 shows ratio between the bsfc for biodiesel blends and additive blends to the bsfc of fossil diesel and kerosene-biodiesel blends to neat biodiesel. The following properties can be observed:

- Biodiesel series: the trend shows a linear correlation and the ratio increases at high loads. bsfc ratios for B100 from low to high load are 1.03, 1.04 and 1.09 respectively.
- Biodiesel additive: the trend exhibits a similar trend to the biodiesel series. Bsfc ratio for B100A from low to high load is 1.04, 1.06 and 1.13 respectively.
- Kerosene biodiesel series: it demonstrates a non-liner trend and the ratio decreases as the load increases. Bsfc ratios for K100 from low to high load are 1.06, 0.98 and 0.86.

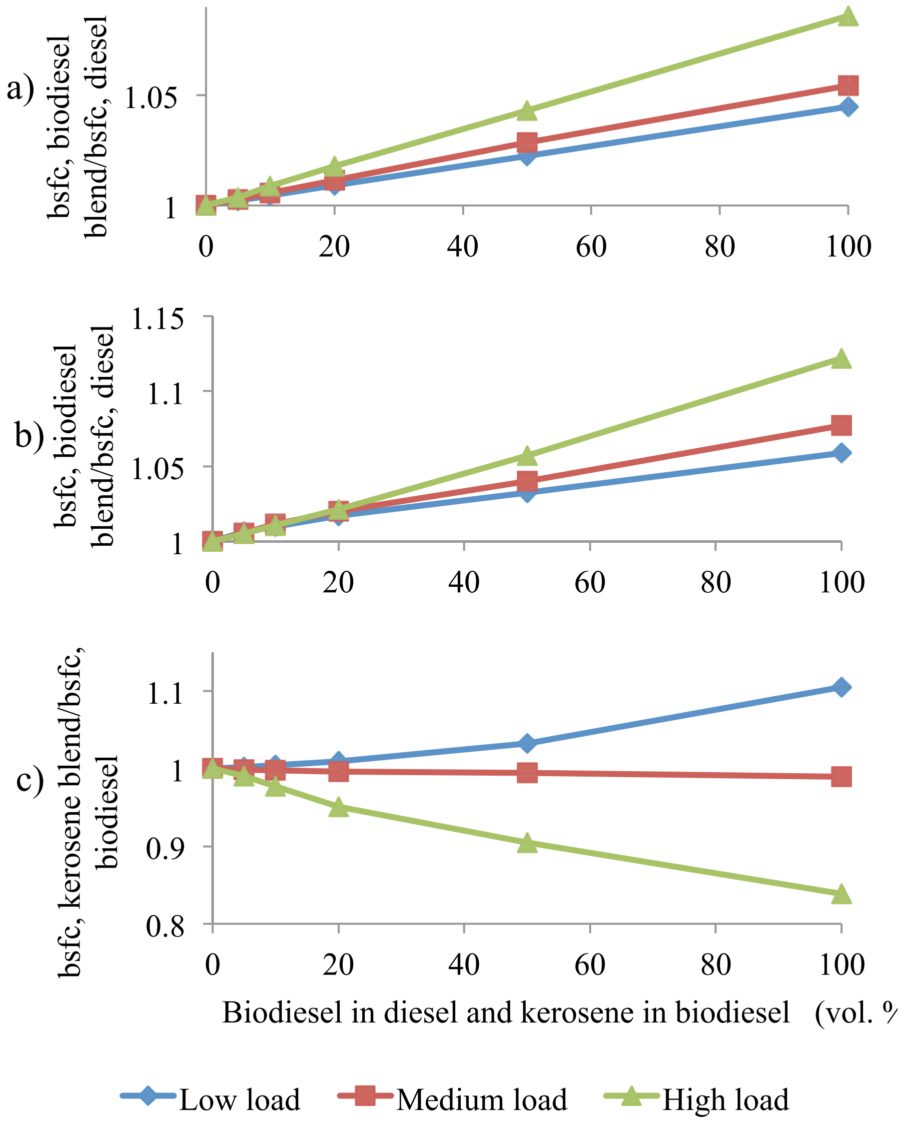

Figure 4.23: a) Ratio of bsfc of biodiesel blends to fossil diesel, b) ratio of bsfc of additive series and fossil diesel, c) ratio of bsfc of kerosene biodiesel blends to neat biodiesel

Figure 4.24 shows the values of the fuel conversion efficiency for all three series at three different load conditions. The following observations can be derived.

- At low load, the kerosene/biodiesel series shows the highest efficiency results up to 20/80 blends, but the 50/50 blends and neat fuels are slightly different. K50 and K100 have the lowest efficiency values compared to the rest of the blends. They are 2% and 15% lower than fossil diesel respectively. This could be due to the decrease in biodiesel percentage and to the fact that kerosene does not burn well at low load conditions. Biodiesel/diesel series and additive series have very similar values but the fuel conversion efficiency for biodiesel-additive series is slightly lower due the lower heating value. In general, biodiesel blends show better values compared to fossil diesel, and B100 exhibit the highest efficiency compared to the rest of the blends.

- At medium load, all the blends showed a similar trend to the low load condition. K50 is superior to B50 and B50A. K100 has the lowest value compared to the rest of the blends 5.5% lower than the efficiency of fossil diesel. B100 showed the highest fuel conversion efficiency value. This could be due to the poor combustion kerosene produces at lower loads and the more complete combustion neat biodiesel produces. Again, the biodiesel-diesel series results are slightly higher than the biodiesel-additive series. In general, biodiesel blends provide better efficiency compared to diesel fuel and that could be due to the higher oxygen content biodiesel has compared to diesel.

- At high load, the kerosene-biodiesel series show the best results and the highest values compared to the rest of the blends. K100 has the highest efficiency, where diesel efficiency is 7% lower than K100. Again, kerosene can give better results at higher load. Still, biodiesel-diesel series provides better results than biodiesel-additive series.

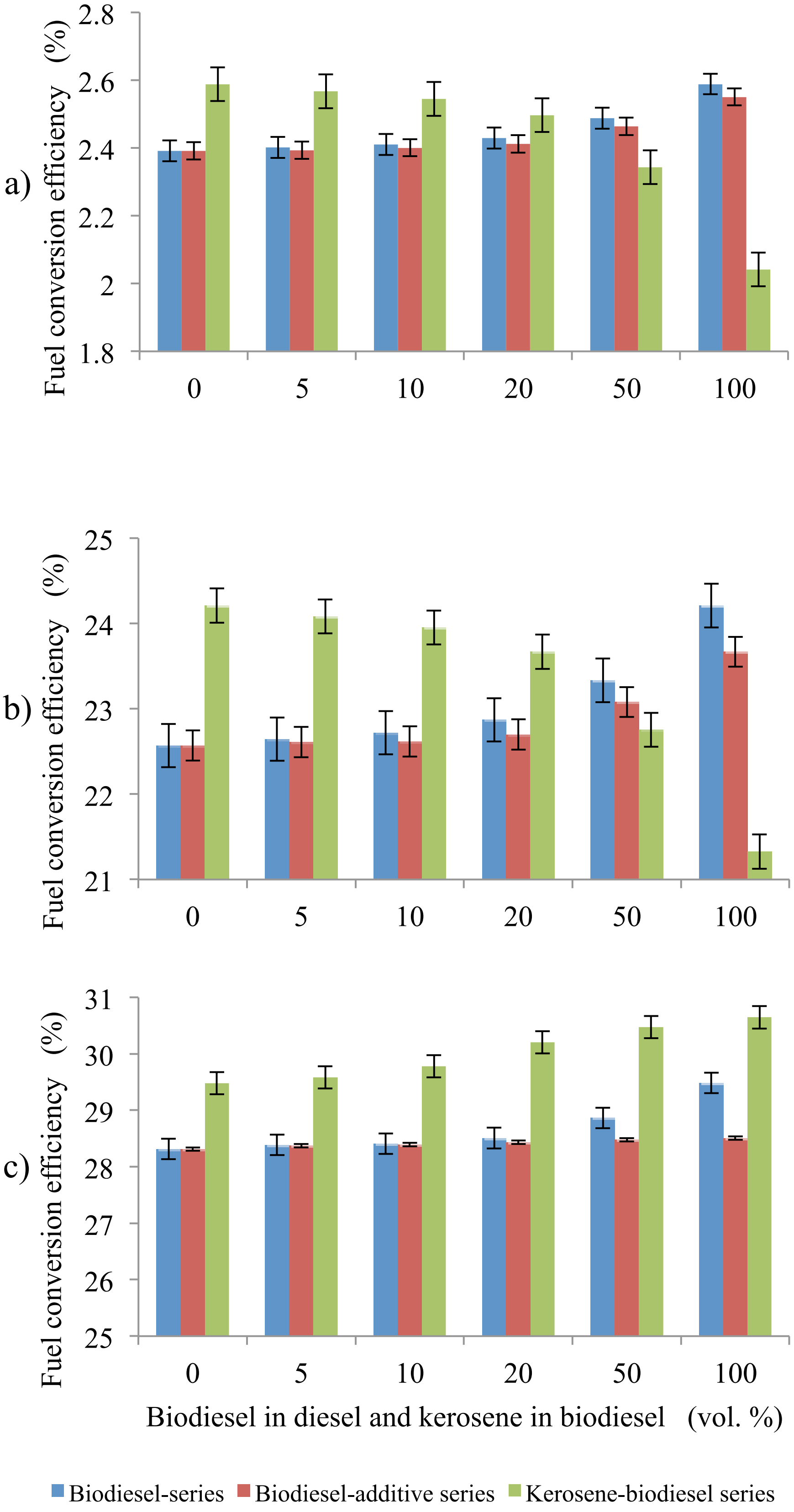

Figure 4.24: Comparison of fuel conversion efficiency for all three series, a) low load, b) medium load, c) high load

Figure 4.25 demonstrates the ratio between the efficiency for biodiesel blends and additive blends to the efficiency of fossil diesel and kerosene -biodiesel blends to neat biodiesel. Similarly, the following points can be obtained:

- Biodiesel series: shows a linear trend and the ratio increase at lower load. Efficiency ratios for B100 from low to high load are 1.08, 1.07 and 1.04.
- Biodiesel additive: has a similar trend to biodiesel series. Efficiency ratios for B100A from low to high load are 1.06, 1.05 and 1.01.
- Kerosene series: the ratio increases at high loads. Efficiency ratios for K100 from low to high load are 0.8, 0.9 and 1.04.

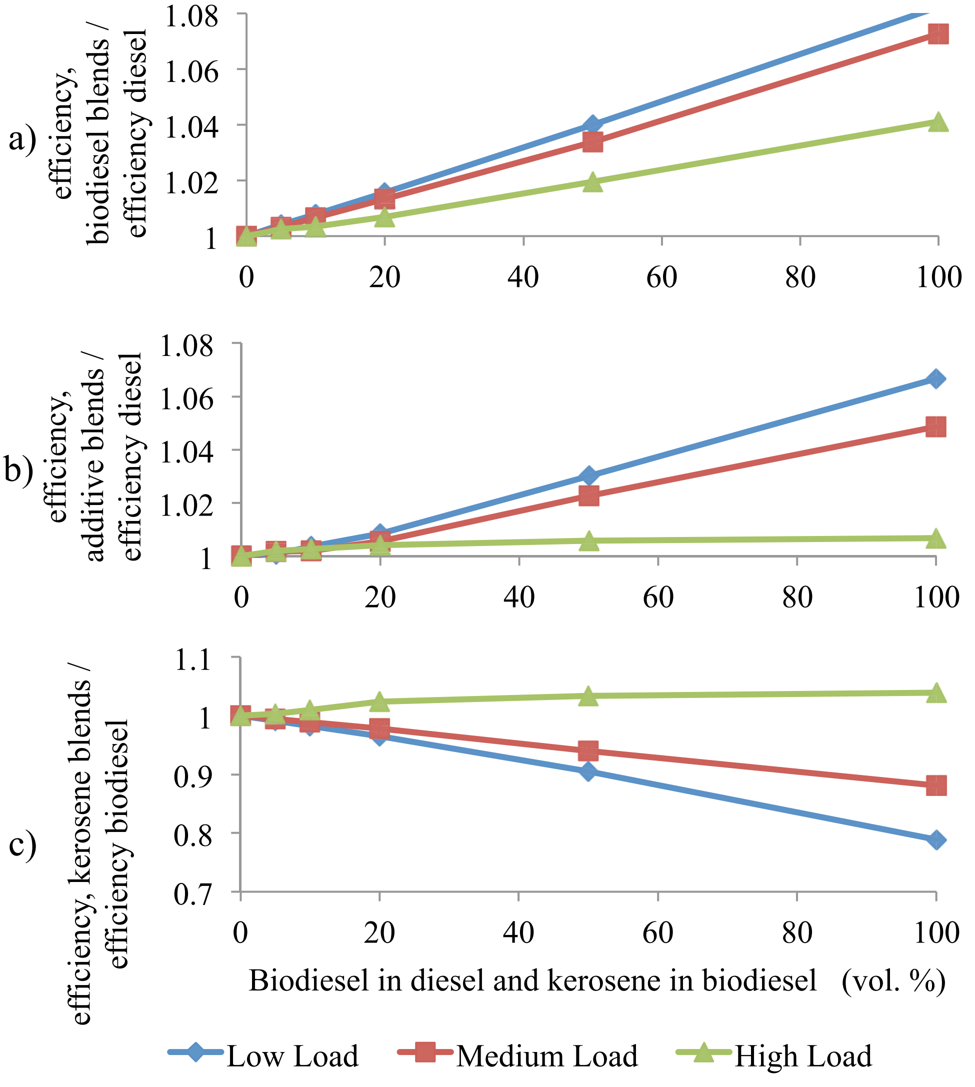

Figure 4.25: a) Efficiency ratio between biodiesel blends and fossil diesel, b) efficiency ratio of the additive blends to fossil diesel, c) efficiency ratio of kerosene biodiesel blends to neat biodiesel

Figure 4.26 compares the bsec for different blends at three different loads. The following observations can be obtained:

- At low load, the kerosene biodiesel series has the lowest bsec up to 20/80 blends. However K50 and K100 show an increase of 1.9% and 14% compared to fossil diesel. This is due the high volatility nature of kerosene and with presence of excess air that may cause an inhomogeneous air fuel mixture in the cylinder resulting in poor combustion. Biodiesel and additive series exhibit lower bsec compared to fossil diesel. B100 and B100A have 7.6% and 6.2% lower bsec compared to fossil diesel. This could be due to the high oxygen content in biodiesel that makes a more complete combustion.

- At half load, all blends have lower bsec compared to the low load but they give a very similar trend to the low load condition. However K50 at this load has a lower bsec compared to fossil diesel by 0.6%. K100 shows a 5.3% increase compared to fossil diesel where B100 and B100A have 7% and 4.4% decrease compared to fossil diesel.

- At high load, the blends have a different trend. The kerosene-biodiesel has the lowest bsec values compared to the rest of the blends. K100 shows 8% decrease compared to fossil diesel. This is possibly caused by the closer state to stoichiometric the kerosene series reaches at high load condition, resulting in a complete combustion. Biodiesel series again have lower values compared to the additive series. B100 and B100A demonstrate lower values compared to fossil diesel by 4% and 0.7%.

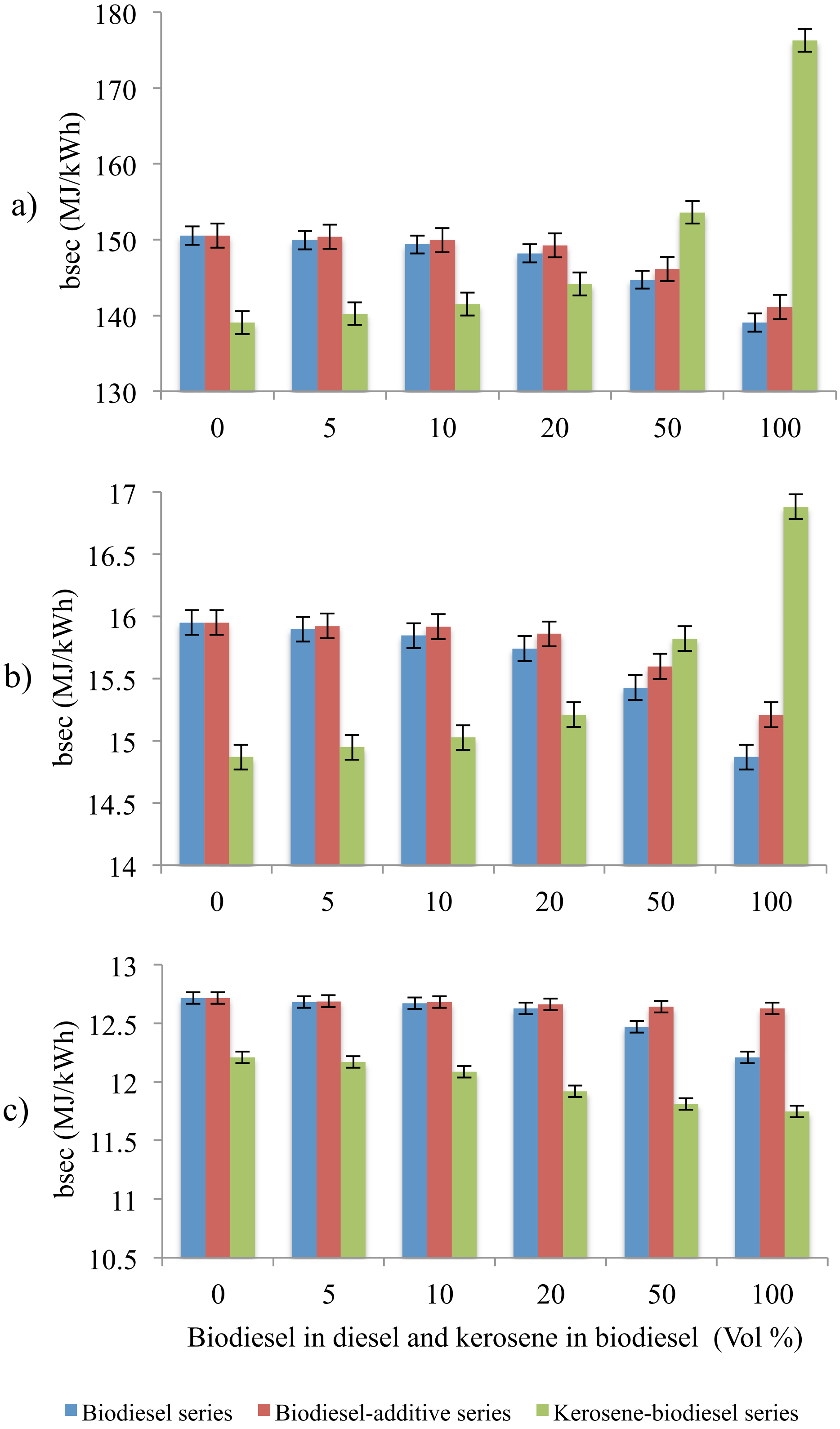

Figure 4.26: Comparison of bsec for all the blends at three different loads, a) low load, b) medium load, c) high load

4.4.2 Emissions:

Figure 4.27 compares the CO emitted from different blends at three different loads. The related properties are summarized as follows:

- At low load, the kerosene-biodiesel series emitted the least CO up to 20/80 blends. At 50/50 blends, B50A emits the least, but just slightly lower than B50. K100 emits the most CO compared to the rest of the blends, which again supports the fact that kerosene burns poorly at lower loads. However the biodiesel-additive series does not exhibit a bit of difference compared to the biodiesel-series. In general, biodiesel blends have less CO than fossil diesel.

- At medium load, the blends show a similar trend to the low load condition. Again K100 has the most CO compared to the rest of the blends and that again supports the fact that kerosene gives poorer combustion at lower loads compared to high load. However, the biodiesel-additive series shows similar results compared to the biodiesel-series. Overall, biodiesel blends have less CO than fossil diesel.

- At high load, B100 emits the most CO compared to the rest of the blends, whereas K100 emits 6% CO lower than fossil diesel. This further proves that kerosene is very efficient at higher loads. The CO biodiesel-additive series emits is slightly lower than the biodiesel series. However, B100A gives 5% less CO compared to B100, which could be due to the chemical composition of the additive.

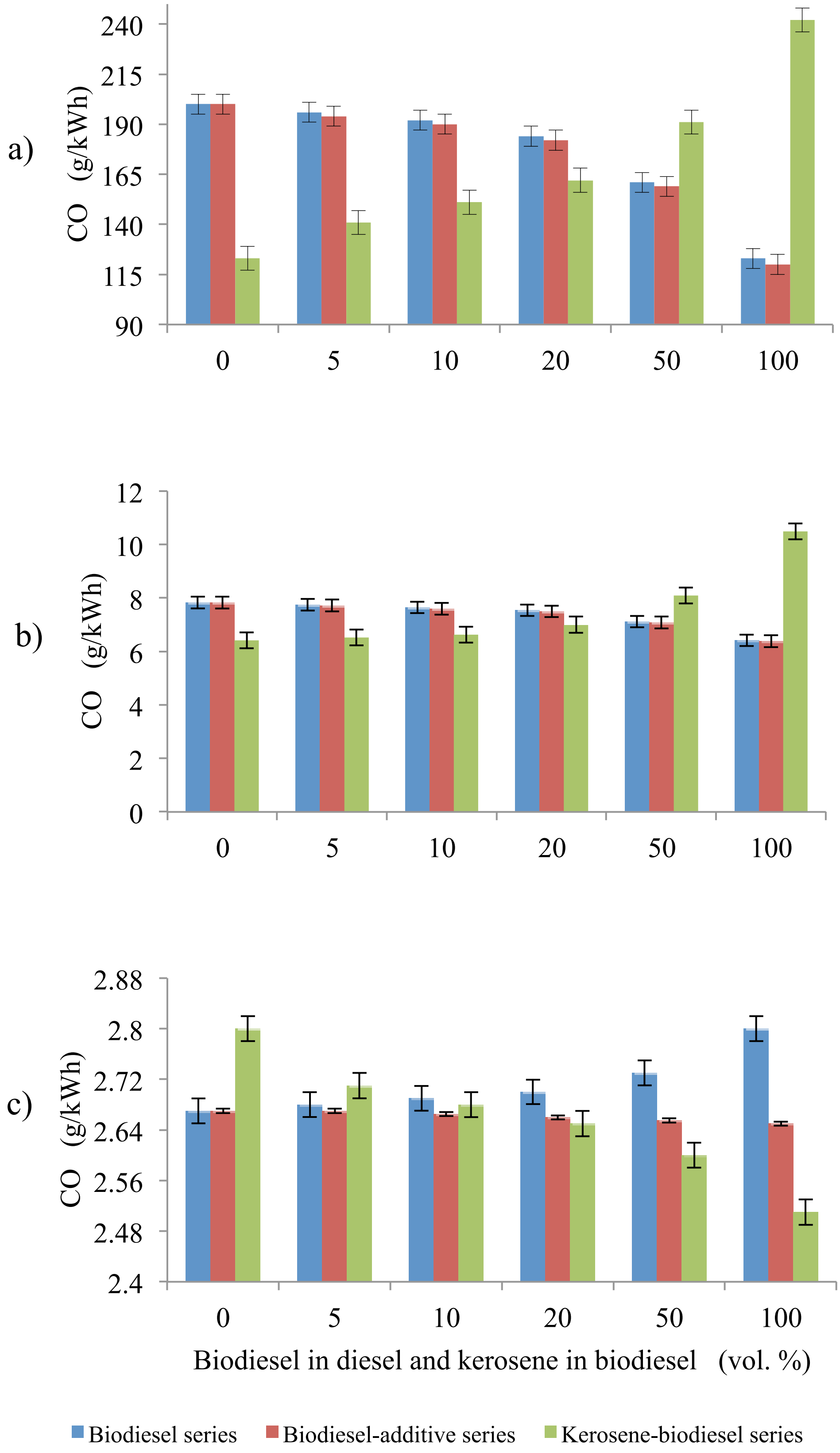

Figure 4.27: Comparison of the CO emissions by different blends a) low load, b) medium load, c) high load

Figure 4.28 shows the ratio between CO emissions ratio for biodiesel blends and additive blends to fossil diesel and kerosene -biodiesel blends to neat biodiesel. The following properties can be recognized:

- Biodiesel series has a linear trend and the ratio increases at high loads. CO ratios for B100 from low to high load are 0.62, 0.82 and 1.05 respectively.
- Biodiesel additive shows similar trend. CO ratios for B100A from low to high load are 0.6, 0.81 and 0.99 respectively.
- Kerosene- biodiesel series exhibits the ratio increase at low loads. CO ratios for K100 from low to high load are 1.97, 1.63 and 0.9 respectively.

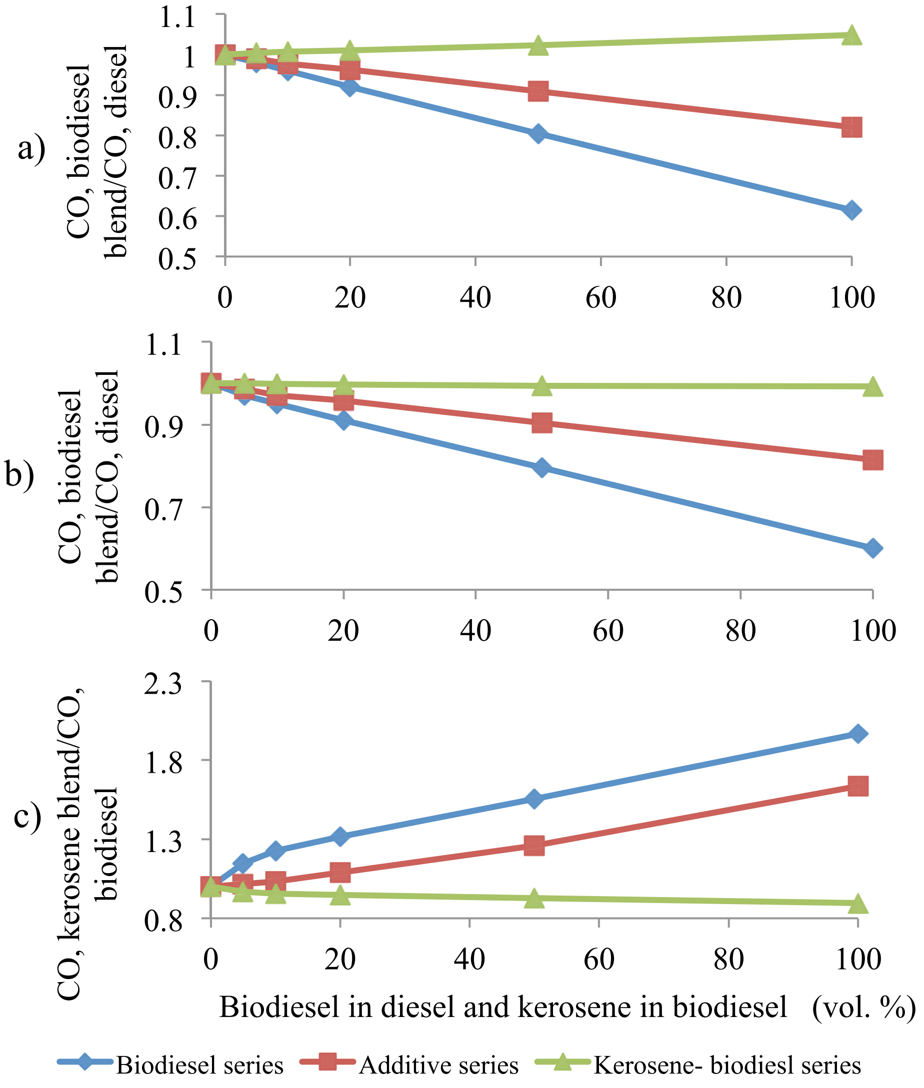

Figure 4.28: a) CO emissions ratio between biodiesel blends to fossil diesel, b) CO emissions ratio between additive blends to fossil diesel, c) CO emissions ratio between kerosene biodiesel blends to neat biodiesel

Figure 4.29 compares HC values for different blends at three different loads. Correspondingly, the following observations can be obtained:

- At low loads, K50 and K100 emits the highest value of HC 7.6% and 36% higher than fossil diesel, respectively, which is again due to the poor combustion of kerosene at lowers loads. The biodiesel-additive series shows better results compared to the biodiesel series, which possibly due to the change in the chemical properties of biodiesel after blending it with the chemical additive. Generally, Biodiesel blends emit less HC compared to fossil diesel.

- At medium loads, diesel fuel generates the highest amount of HC; and again up to 20/80 blends, the kerosene-biodiesel series emits the least but more than the other two series at 50/50 blends. The biodiesel-additive series is superior to biodiesel series since it gives less HC. B100A has 31% less HC compared to B100. It can be concluded that, biodiesel blends emit less HC than fossil diesel.

- At high loads, kerosene-biodiesel produces the least HC and again, the better combustion kerosene produces at higher loads could explain the reduction in HC. K100 and K50 have 40% and 32% less HC compared to fossil diesel. Still, the biodiesel-additive series is superior to biodiesel series since B100A emitted 34% less HC compared to B100.

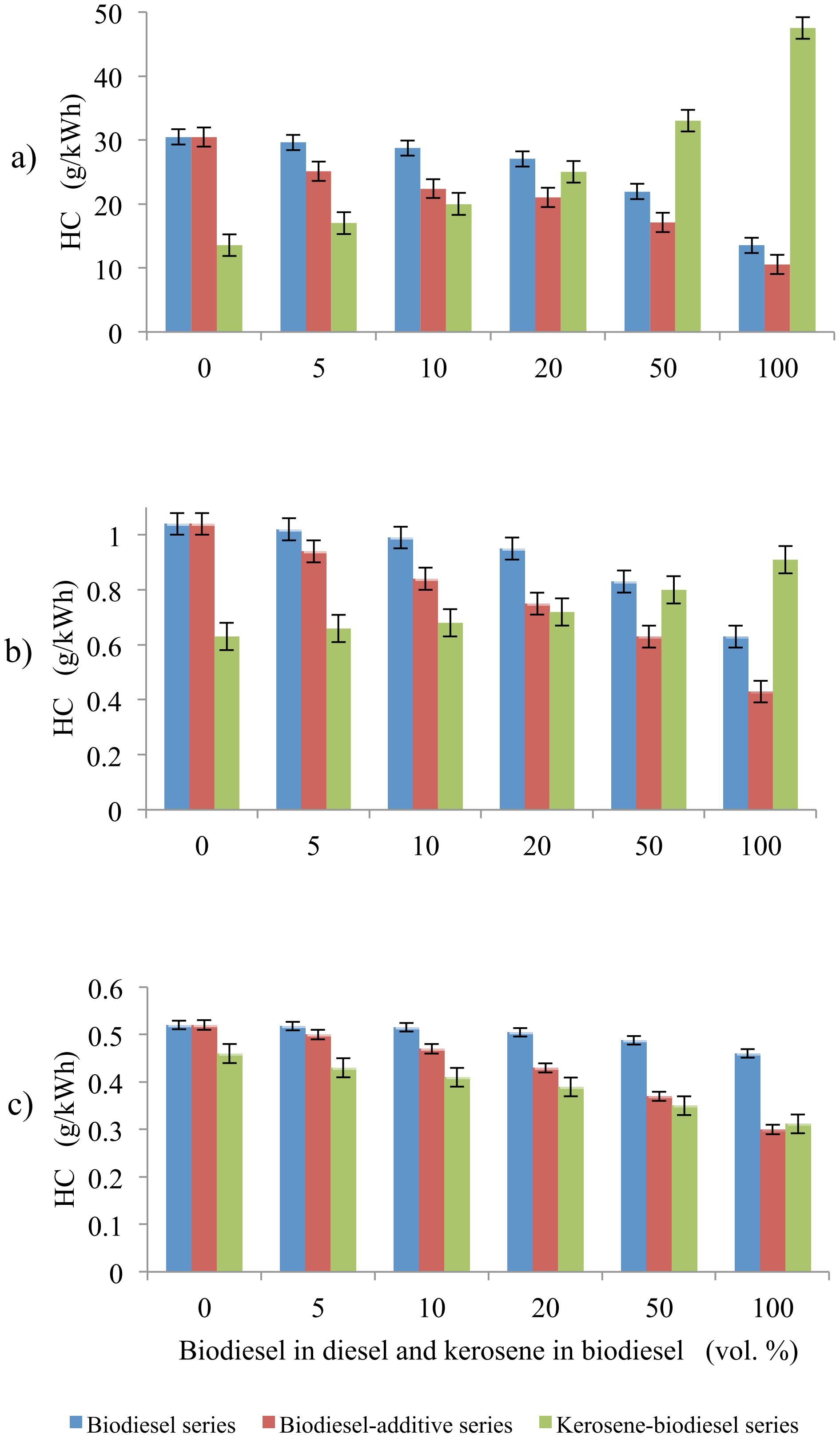

Figure 4.29: Comparison of HC emissions for different blends a) low load, b) medium load, c) high load.

Figure 4.30 demonstrates the HC emissions ratio between for biodiesel blends and additive blends to fossil diesel and kerosene-biodiesel blends to neat biodiesel, with the following observations:

- Biodiesel series shows a linear trend and the ratio increase at high loads. HC ratios for B100 from low to high load are 0.45, 0.6 and 0.88 respectively.
- Biodiesel additive exhibits a nonlinear trend. HC ratios for B100A from low to high load are 0.35, 0.41 and 0.58 respectively.
- Kerosene-biodiesel has the ratio increase at low loads. HC ratios for K100 from low to high load are 3.5, 1.45 and 0.68 respectively.

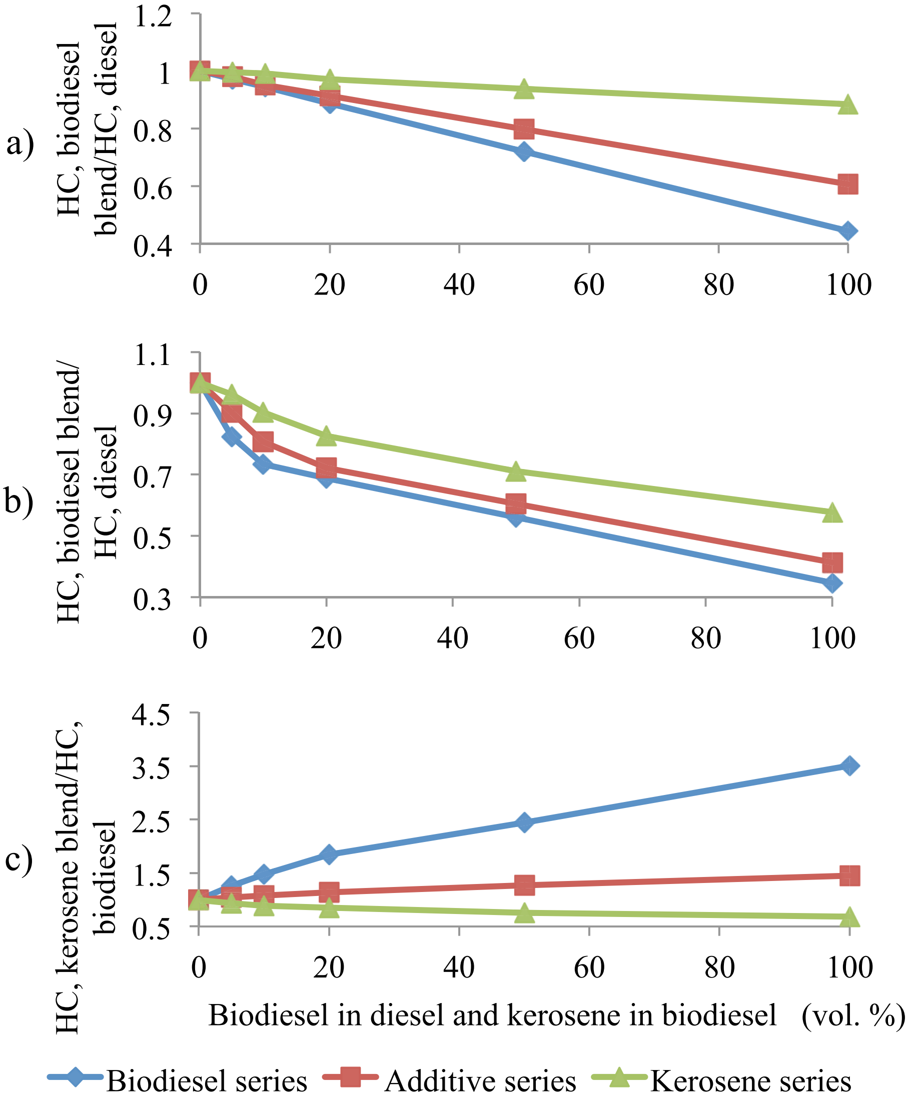

Figure 4.30: a) HC emissions ratio between of biodiesel blends to fossil diesel, b) HC emissions ratio between additive blends and fossil diesel, c) HC emissions ratio of kerosene biodiesel blends to neat biodiesel

Figure 4.31 compares NO, NO_2 and total NOx for all blends at low load condition. The following summarizes the related observations:

- NO: biodiesel series emits the least NO compared to the other series. However in the kerosene-biodiesel series, it seems the higher the percentage of kerosene in the blends, the less NO is emitted. K50 has a comparable amount of NO to fossil diesel, but K100 gives the least compared to the rest of the blends and 21% less than fossil diesel. The biodiesel-additive series is superior to the kerosene series up to 10/90 blends. The biodiesel series is superior to the additive series since B100 emits 23% less NO than B100A. That could be related to the chemical composition of the additive. B5, B10 and B20 generate 2.8%, 5.5% and 10% respectively, more NO compared to fossil diesel.

- NO_2: The biodiesel and additives series emits the least NO_2, up to 20/80 blends, but the biodiesel series has slightly lower values compared to the additive series. K50 and K100 have the least among all the other blends and 10% and 52% less than fossil diesel respectively. K50 gives less NO_2 compared to B50A and B50 by 25% and 20%, respectively. B100A emits around 5% more compared to B100. B5, B10 and B20 generate 1.2%, 2.2% and 4.6%, respectively more NO_2 compared to fossil diesel.

- Total NOx: The biodiesel series emits the least amount of NOx compared to the other series. However, K50 and K100 have the least amount of NOx compared to the other blends. K100 and K50 exhibit 42% and 6.7% less NOx than fossil diesel. B5, B10 and B20 have 1.7%, 3.3% and 8% respectively, more of total NOx compared to fossil diesel.

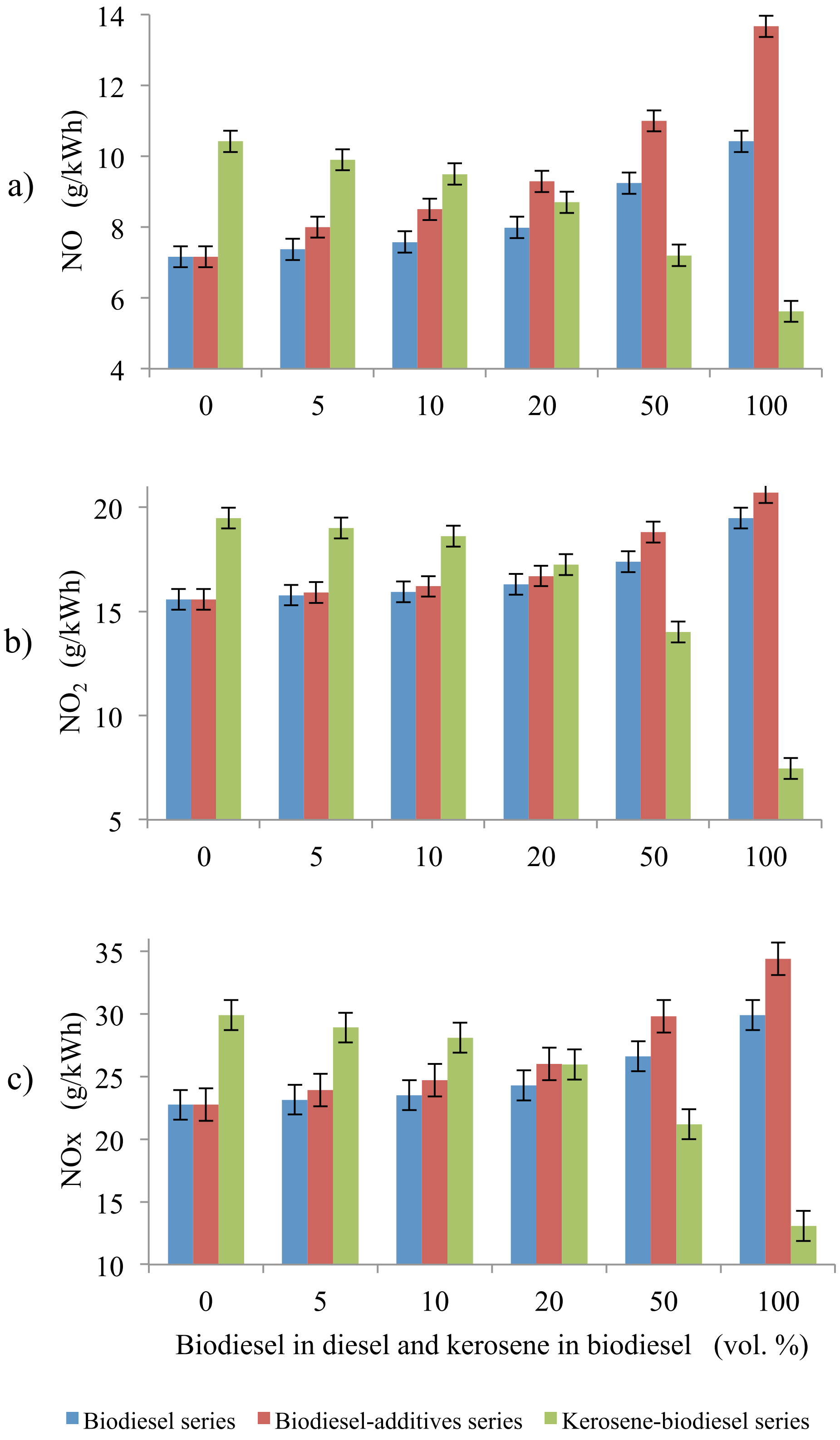

Figure 4.31: Comparison of NO, NO_2 and NOx for all blends at low load conditions a) NO values, b) NO_2 values, c) NOx values

Figure 4.32 compares the emitted NO, NO_2 and total NOx for all blends at medium load condition with the following properties:

- NO: The biodiesel series emits a similar amount of NO compared to fossil diesel. However K20, K50 and K100 generate the least NO among all other blends including fossil diesel. K20 and K50 have 1% and 7% less NO compared to fossil diesel and K100 has 19% less than fossil diesel. B50 emits 2.3% more NO than fossil diesel, whereas blends up to B20 have similar values of NO compared to fossil diesel.

- NO2: The biodiesel series emits the least NO_2 compared to the other two series. The biodiesel-additive series has very similar values but slightly higher than the biodiesel series. B100A emits about 2% more NO_2 than B100. The kerosene-biodiesel series is the worst series for NO_2. The biodiesel series generates a comparable amount of NO_2 to fossil diesel. B100 has 2.9% more NO_2 than fossil diesel.

- Total NOx: The biodiesel series is the best series compared to fossil diesel. However K50 and K100 emit 3.1% and 11.3% less NOx compared to fossil diesel. The NOx emissions for B5, B10 and B20 have similar values compared to fossil diesel, whereas K20 generates 1.7% more NOx than fossil diesel. B100A emits 3% more NOx compared to B100.

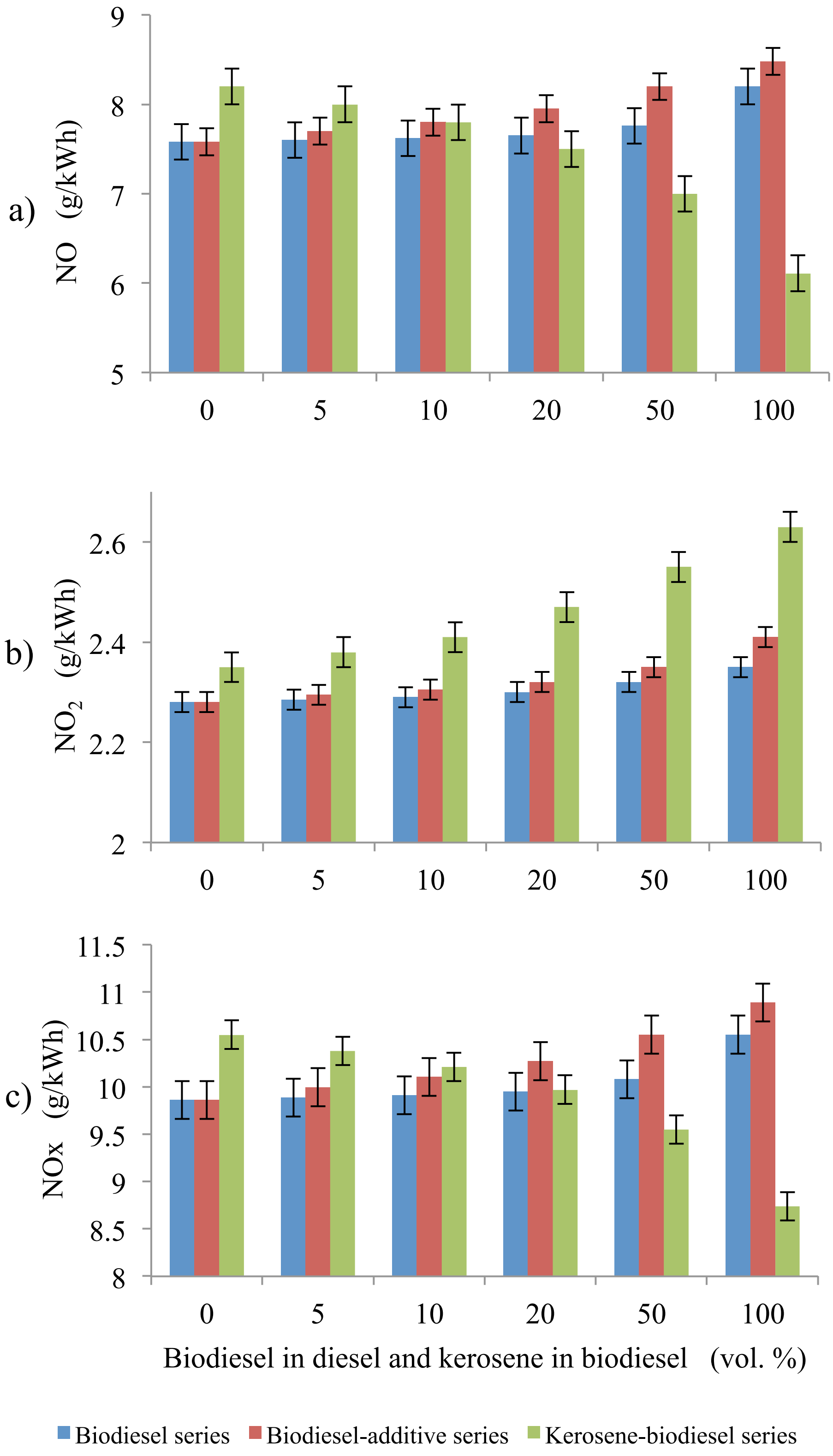

Figure 4.32: Comparison of NO, NO_2 and NOx for all blends at medium load condition, a) NO emissions, b) NO_2 emissions, c) NOx emissions.

Figure 4.33 compares NO, NO_2 and total NOx for all blends at high load conditions. The following observations can be recognized:

- NO: all three series are superior to fossil diesel at this load. The kerosene-biodiesel series emits the least NO compared to the other two series. K100 generated 3.2% less than diesel. The biodiesel-additive series is superior to the biodiesel series. B100A has 2.5% less NO compared to B100. B100 emits 0.26% less NO than fossil diesel.

- NO2: The biodiesel-additive series has the least NO_2 compared to fossil diesel and the other two series. B100A emits 9.2% less NO_2 than fossil diesel, whereas B100 emitted 1.4% more than fossil diesel. K10, K20, K50 and K100 are superior to B10, B20, B50 and B100.

- Total NOx: The kerosene-biodiesel series emits the least compared to the other two series. B100A gives similar amount of NOx compared to K100 and 3.17% less than B100. The biodiesel-additive series is better than the biodiesel series.

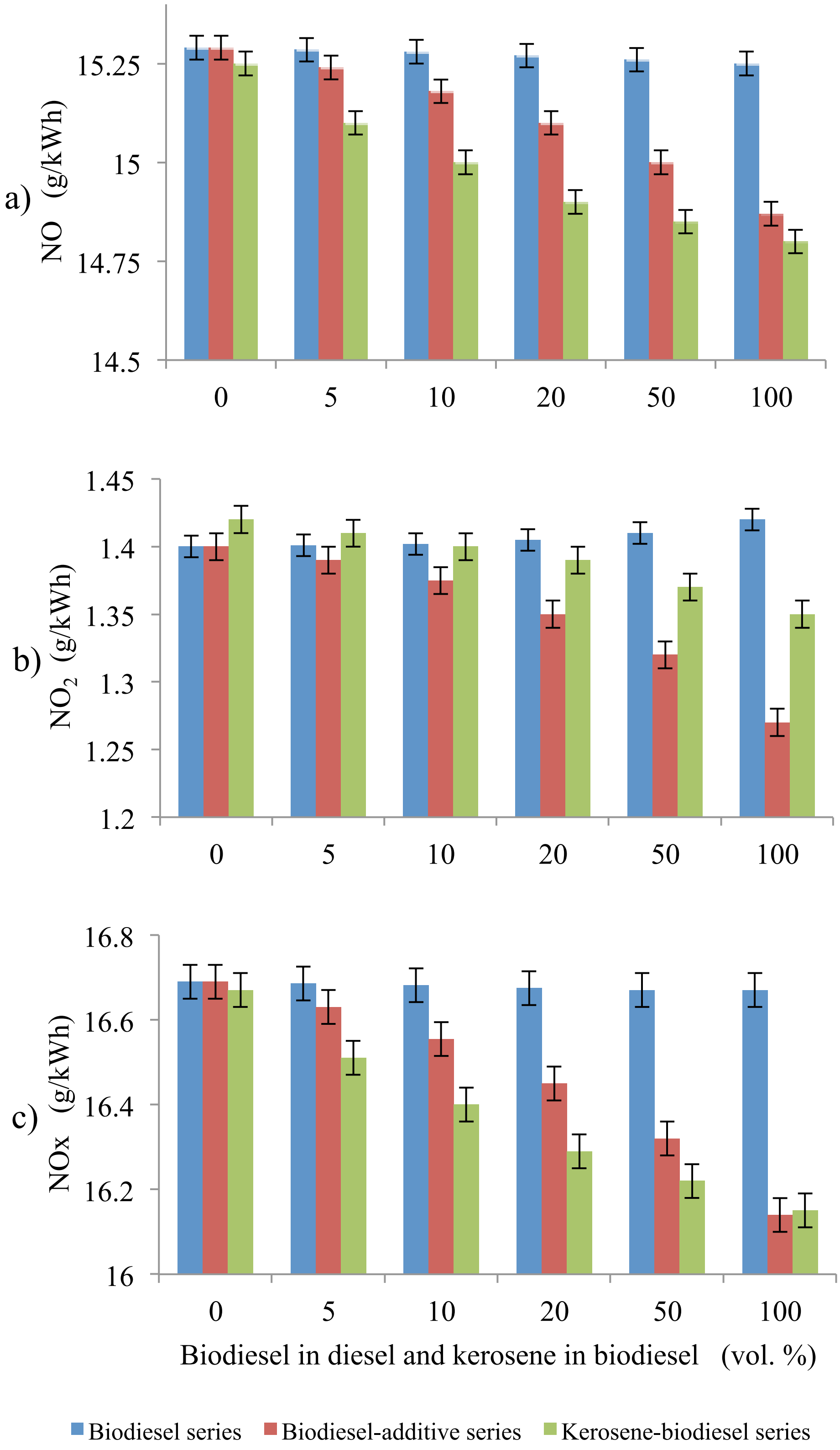

Figure 4.33: Comparison of NO, NO_2 and NOx for all blends at high load conditions, a) NO emissions, b) NO_2 emissions, c) NOx emissions

Figure 4.34 shows the ratio of NOx for biodiesel blends and additive blends to fossil diesel and kerosene-biodiesel blends to neat biodiesel, with the following specific points:

- Biodiesel series shows a linear relation and the ratio increases at low load. NOx ratios for B100 at low and medium loads are 1.3 and 1.06 respectively. There is no increase in NOx with B100 than diesel at high load condition.
- Biodiesel additive exhibits similar trend. NOx ratios for B100A for low and medium loads are 1.5 and 1.1 respectively. There is a slight decrease in NOx with B100A than diesel at high load condition.
- Kerosene-biodiesel has the ratio increase at high load. NOx ratios for K100 at low and medium loads are 0.43 and 0.82 respectively. There is a slight decrease in NOx with K100 than K0 at high load operation

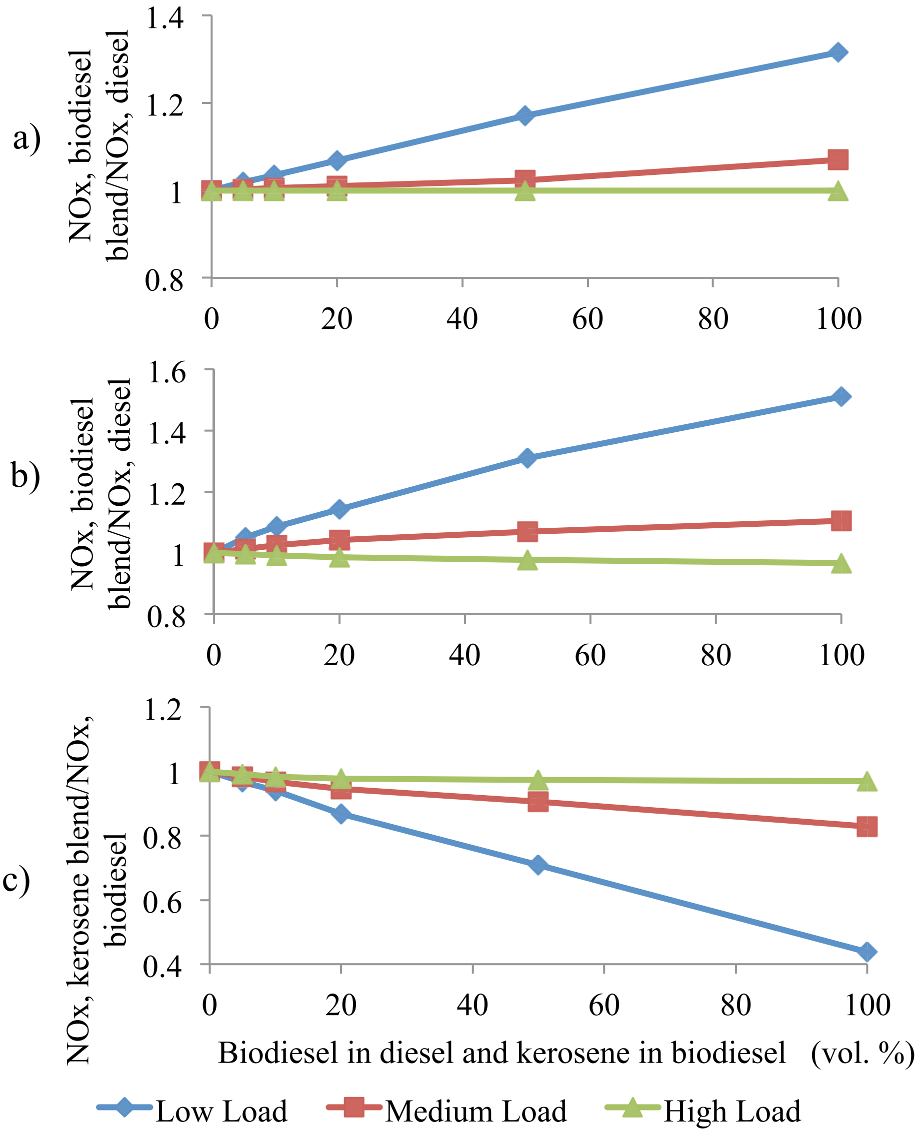

Figure 4.34: a) Ratio of NOx of biodiesel series to fossil diesel, b) ratio of NOx in additive blends to fossil diesel, c) ratio of NOx in kerosene blends to neat biodiesel

4.4.3 Fuel Consumption (L/h):

Comparing the fuel consumption for each blend is significant for consumers to know how many litters they are using to make a proper budget when considering biodiesels. Figure 4.35 compares the fuel consumptions for all the blends at three different load conditions. The following properties can be obtained from the related test results and analysis.

- At low load condition biodiesel series has the lowest fuel consumption compared to the rest of the blends. B100 fuel consumption is 6.2% higher than fossil diesel but B5 shows a similar fuel consumption compared to fossil diesel. The additive series fuel consumption is slightly higher than the biodiesel series. The fuel consumption of B100A is 2.22% higher than B100. Kerosene series shows a considerably high fuel consumption compared to the other two series. The fuel consumption of K100 is 30.7% higher than fossil diesel.

- At half load condition, similarly the biodiesel-diesel series has the best fuel consumption but slightly lower than fossil diesel. K100 is superior to B100 and B100A at this load. K100 shows a 1% reduction compared to B100. B100 fuel consumption is 6.8% higher than fossil diesel.

- At high load biodiesel series trend and additive trend are similar to the low and half load conditions trend. However K50 and K100 show a significant improvement where their fuel consumption is 0.82% and 5.5% lower than fossil diesel, respectively. B100 fuel consumption is higher than fossil diesel consumption by 5.5%.

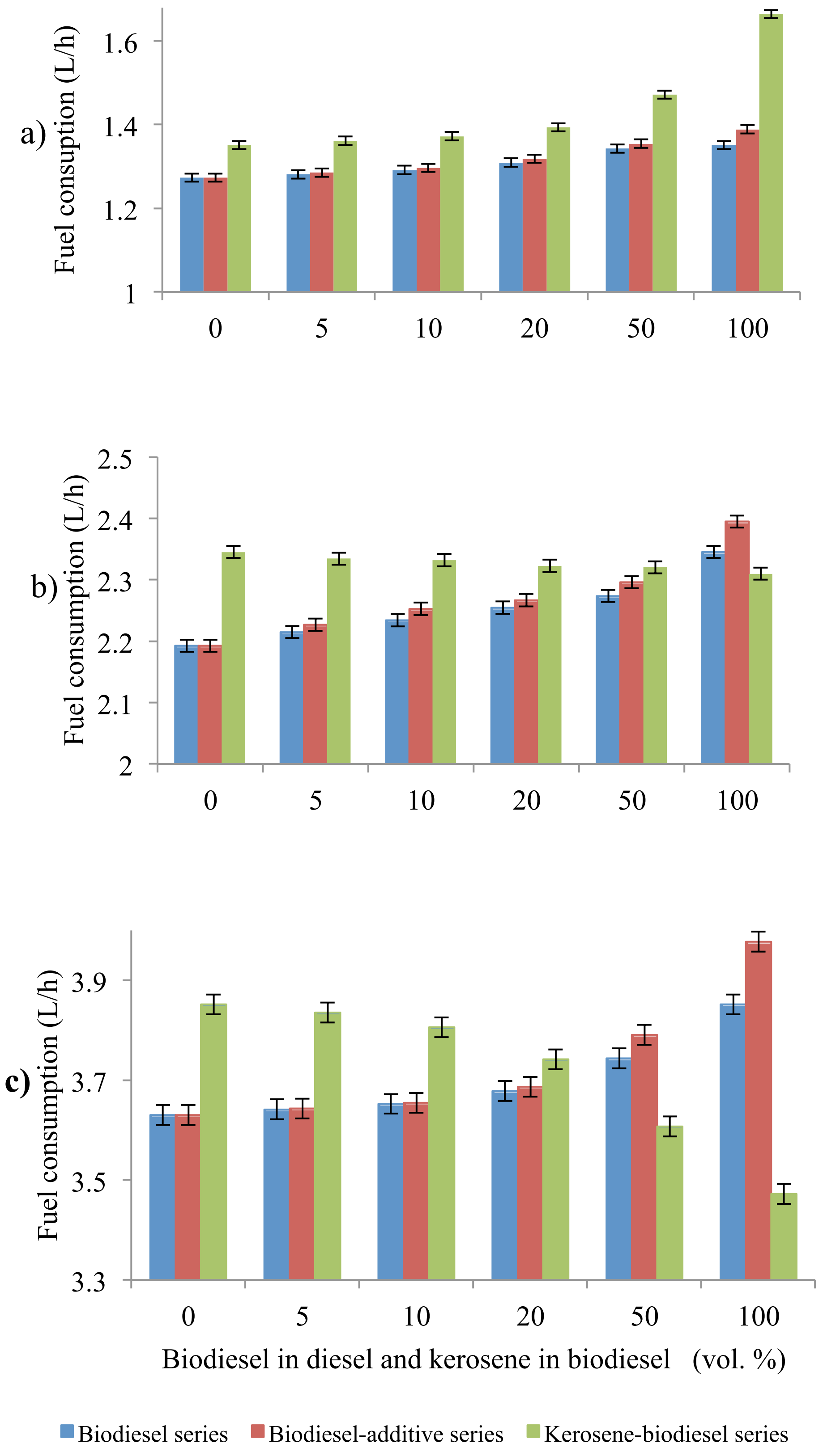

Figure 4.35: Comparison of the fuel consumption in L/h for all blends a) low load, b) medium load, c) high load

4.4.3 Cloud Points:

Figure 4.36 shows different cloud points for all the blends. Kerosene-biodiesel series had the highest cloud points at 5/95, 10/90 and 20/80 blends this could be due to the fact that biodiesel doesn't blend very well with kerosene. The biodiesel and biodiesel additive series had very similar cloud points, where the additive series cloud points are slightly lower, by almost 2 degrees. B5A was the only blend to show a lower cloud point compared to fossil diesel.

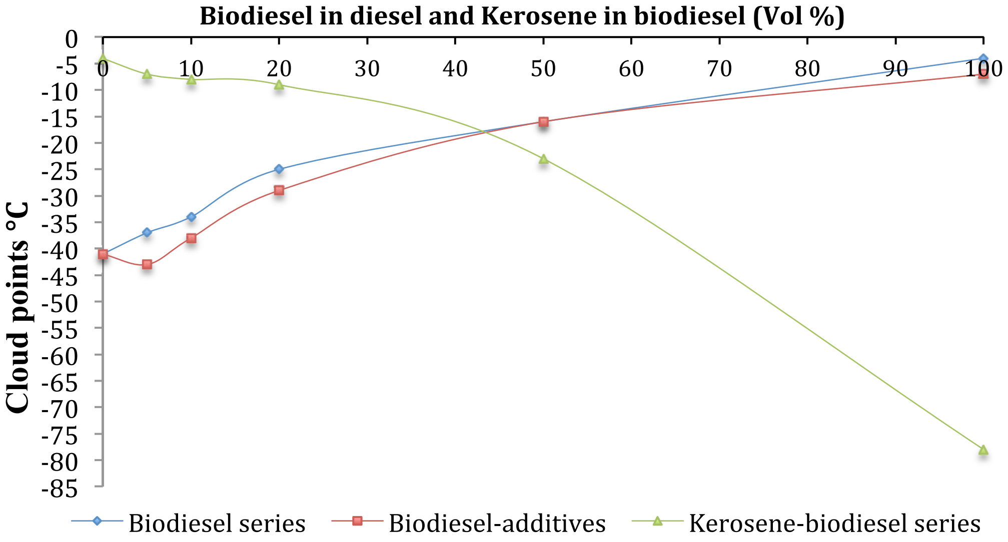

Figure 4.36: Comparison of cloud points for all the blends

Chapter 5

Conclusion and Future Work

5.1 Conclusion:

The objective of this work was to test the feasibility of biodiesel in cold climate such as Canada and suggest an appropriate solution for the future of biofuel. Canola biodiesels is produced and their quality and fuel characteristics are investigated. An experimental investigation is conducted to explore the performance and emissions of biodiesel blends on a small DI diesel engine. Also, chemical additive (Wintron XC30) is used to lower the cloud point of the blends, which could be the first time to study its effect on engine emissions in the literature. On the other hand, there are limited studies on kerosene as a blending fuel, where it is mainly used to lower the cloud point of the blends. The results obtained suggest the following conclusions:

1) Quality biodiesels are produced from canola oil by base catalyst transesterification process that satisfies ASTM standard. The conversion rate is 100% and collection efficiency 86%. Its cetane index is about 50 and heating value about 10% less than diesel fuel.

2) B100A (100% biodiesel + 2% chemical additive) viscosity exceeded the ASTM limit of 6 Cst by 23%.

3) The cloud points for the Kerosene-biodiesel series are higher than expected, which could indicate a poor mixing between the two fuels. Whereas the cloud points for additive series are less than biodiesel series by 4°C to 5°C. However B5A (5% biodiesel/95% diesel + 2% additive) shows a lower cloud point compared to winter diesel. Fossil diesel cloud point is -41°C and B5A cloud point is -43°C.

4) Break specific fuel consumption (bsfc) decreases as the load increases as the biodiesel increases in the blend. Biodiesel series generates the best results compared to the other two series. At low, medium and high load B100 gives 4.2%, 5.1% and 8% increase compared to fossil diesel respectively. B100A shows 5%, 7.1% and 11% increase

compared to fossil diesel respectively. However K50 generates a 2% less bsfc compared to fossil diesel at high load.

5) Fuel conversion efficiency kerosene-biodiesel series gives the best values at low and medium load up to 20/80 blends, but at high load the kerosene series outperforms compared to the other two blends. B100 at low, medium and high load shows an increase in efficiency compared to fossil diesel by 7.6%, 6.7% and 3.9% respectively. B100A has 6.2%, 4.6% and 0.7% increase, respectively. However K50 at high load gives 7.12% increase compared to fossil diesel.

6) CO emissions for all fuels are lower at high load condition. The higher the biodiesel percentage in biodiesel-diesel blends, the lower the CO emissions at low to medium load conditions. B100 generates about 39% and 18% CO reduction than diesel at low and medium load conditions, respectively and B100A provides about 40% and 19% reduction. At high load condition B100 shows about 5% increase in CO emissions than that of diesel whereas B100A has about 1% reduction in CO. Furthermore, K20 at high load has a similar result to B100A but the CO value for K50 is slightly lower.

7) HC emissions for all fuels are also lower at higher loads. The higher the biodiesel percentage in biodiesel-diesel blends, the lower the HC emissions, a similar trend to that of CO emissions. B100 shows about 56%, 40% and 12% HC reduction than diesel at low; medium and high load conditions, respectively, whereas B100A gives 22%, 31% and 35% less than B100 respectively. At high load condition kerosene-series emits the least HC compared to the rest of the blends and K50 generates 33% less than fossil diesel.

8) The highest NO is emitted at high load condition for all fuels; however, NO_2 emissions are the lowest at high load operation. B100 NOx emissions for low and medium loads are 24% and 6.5% higher than fossil diesel, respectively. B100A shows 33.8% and 9.4% increase, respectively. K50 produces 6.7% and 3.14% less NOx than fossil diesel. However at high load B100, B100A and K50 generate 0.1%, 3.2% and 2.8% decrease compared to fossil diesel. The shares of NO_2 in total NOx are approximately 8% and 23% at high and medium loads, respectively. It is also found that NO_2 production at low load operation is very significant (even higher than NO production) and its share in total NOx around 60%.

5.2 Future Work Recommendation:

A further study would be conducted on the chemical additive Wintron XC30 by lowering the amount (less than 2%) with the blends. That perhaps would improve the results of the additive series.

The experimental work for the kerosene-biodiesel series showed that kerosene and biodiesel do not mix well together. However there could be ways to get over that by instantly adding a third fuel into the blend such as fossil diesel. A kerosene/diesel/biodiesel series may have a great potential to make a good blend in terms of cold weather feasibility, performance and emissions.

An Exhaust Gas Recirculation (EGR) system could be used in conducting biodiesel experiment, which may help reduce the NOx emitted to the atmosphere.

Scanning weather of different cities in Canada, I would foresee biodiesel blends could be used on a seasonal base or through out the year in some areas. For example,

- **Vancouver:** The average lowest temperature throughout the year is about 1°C. The lowest cloud point obtained in this study is -4°C for B100, which could promote the common use of different biodiesel blends in such areas.

- **Toronto:** The average lowest temperature throughout the year is around -7°C. It is possible to use biodiesel/diesel blends up to 50% since B50 cloud point is -16°C.

- **Halifax:** The average lowest temperature throughout the year is around -9°C. Similarly, biodiesel/diesel blends up to 50% can be used in these areas.

- **Ottawa**: The average lowest temperature throughout the year is around -15°C. The biodiesel series and the additive series up to 20% mix can be used in these areas, for example, B20 cloud point is as low as -25°C.

Appendices

Appendix A: (Biodiesel series)

Diesel/biodiesel

bsfc (g/kWh)		Low load	Med load	High load
B0	0	3303	350	279
B5	5	3310	351	280
B10	10	3318	352	281.5
B20	20	3333	354	284
B50	50	3377	360	291
B100	100	3451	369	303

Efficiency %		Low load	Med load	High load
B0	0	2.39	22.56	28.31
B5	5	2.40	22.64	28.38
B10	10	2.41	22.72	28.40
B20	20	2.43	22.86	28.50
B50	50	2.47	23.33	28.86
B100	100	2.58	24.21	29.48

CO (g/kWh)		Low load	Med load	High load
Diesel	0	200	7.83	2.67
B5	5	196	7.75	2.68
B10	10	192	7.65	2.69
B20	20	184	7.54	2.71
B50	50	161	7.12	2.73
B100	100	123	6.42	2.80

HC (g/kWh)		Low load	Med load	High load
Diesel	0	30.47	1.04	0.52
B5	5	29.62	1.02	0.518

B10	10	28.76	0.99	0.515
B20	20	27.05	0.95	0.505
B50	50	21.93	0.83	0.488
B100	100	13.54	0.63	0.46

NO (g/kWh)		Low load	Med load	High load
Diesel	0	7.16	7.58	15.29
B5	5	7.37	7.6	15.28
B10	10	7.58	7.62	15.28
B20	20	7.99	7.65	15.27
B50	50	9.24	7.76	15.26
B100	100	10.42	8.20	15.25

NO2 (g/kWh)		Low load	Med load	High load
Diesel	0	15.58	2.28	1.4
B5	5	15.78	2.285	1.41
B10	10	15.94	2.29	1.41
B20	20	16.30	2.30	1.41
B50	50	17.38	2.32	1.41
B100	100	19.48	2.35	1.42

NOx (g/kWh)		Low load	Med load	High load
Diesel	0	22.74	9.86	16.69
B5	5	23.15	9.88	16.66
B10	10	23.52	9.91	16.68
B20	20	24.29	9.95	16.675
B50	50	26.62	10.08	16.67
B100	100	29.90	10.55	16.67

Appendix B: (biodiesel-additive)

biodiesel-additive

bsfc (g/kWh)		Low load	Med load	High load
B0	0	3303	350	279
B5A	5	3325	352	280.5
B10A	10	3335	354	282
B20A	20	3360	357	285
B50A	50	3410	364	295
B100A	100	3498	377	313

Efficiency %		Low load	Med load	High load
B0	0	2.39	22.56	28.31
B5A	5	2.39	22.60	28.37
B10A	10	2.40	22.61	28.39
B20A	20	2.41	22.69	28.43
B50A	50	2.46	23.09	28.47
B100A	100	2.55	23.66	28.50

CO (g/kWh)		Low load	Med load	High load
B0	0	200	7.83	2.67
B5A	5	194	7.72	2.67
B10A	10	190	7.6	2.665
B20A	20	182	7.5	2.66
B50A	50	159	7.08	2.655
B100A	100	120	6.38	2.65

HC (g/kWh)		Low load	Med load	High load
B0	0	30.47	1.04	0.52
B5A	5	25.1	0.94	0.5
B10A	10	22.4	0.84	0.47

B20A	20	21	0.75	0.43
B50A	50	17.1	0.63	0.37
B100A	100	10.56	0.43	0.3

NO (g/kWh)		Low load	Med load	High load
B0	0	7.16	7.58	15.29
B5A	5	8	7.7	15.24
B10A	10	8.5	7.8	15.18
B20A	20	9.29	7.95	15.1
B50A	50	11	8.2	15
B100A	100	13.67	8.48	14.87

NO_2 (g/kWh)		Low load	Med load	High load
B0	0	15.58	2.28	1.4
B5A	5	15.9	2.295	1.39
B10A	10	16.2	2.305	1.375
B20A	20	16.7	2.32	1.35
B50A	50	18.8	2.35	1.32
B100A	100	20.7	2.41	1.27

NOx (g/kWh)		Low load	Med load	High load
B0	0	22.74	9.86	16.69
B5A	5	23.9	9.995	16.63
B10A	10	24.7	10.105	16.555
B20A	20	25.99	10.27	16.45
B50A	50	29.8	10.55	16.32
B100A	100	34.37	10.89	16.14

Appendix C: (Kerosene/biodiesel)

Kerosene/biodiesel

bsfc (g/kWh)		Low load	Med load	High load
B100	0	3451	369	303
K5	5	3457	368.5	300
K10	10	3465	368	296
K20	20	3483	367.5	288
K50	50	3563	367	274
K100	100	3812	365	254

Efficiency %		Low load	Med load	High load
B100	0	2.58	24.20	29.48
K5	5	2.56	24.08	29.57
K10	10	2.54	23.95	29.78
K20	20	2.49	23.66	30.20
K50	50	2.34	22.754	30.47
K100	100	2.04	21.35	30.64

CO (g/kWh)		Low load	Med load	High load
B100	0	123	6.42	2.8
K5	5	141	6.53	2.71
K10	10	151	6.63	2.68
K20	20	162	7	2.65
K50	50	191	8.09	2.6
K100	100	242	10.49	2.51

HC (g/kWh)		Low load	Med load	High load
B100	0	30.47	1.04	0.52
K5	5	25.1	0.94	0.5
K10	10	22.4	0.84	0.47

K20	20	21	0.75	0.43
K50	50	17.1	0.63	0.37
K100	100	10.56	0.43	0.3

NO (g/kWh)		Low load	Med load	High load
B100	0	10.42	8.2	15.25
K5	5	9.9	8	15.1
K10	10	9.5	7.8	15
K20	20	8.7	7.5	14.9
K50	50	7.2	7	14.85
K100	100	5.62	6.11	14.8

NO2 (g/kWh)		Low load	Med load	High load
B100	0	19.48	2.35	1.42
K5	5	19	2.38	1.41
K10	10	18.6	2.41	1.4
K20	20	17.24	2.47	1.39
K50	50	14	2.55	1.37
K100	100	7.46	2.63	1.35

NOx (g/kWh)		Low load	Med load	High load
B100	0	29.9	10.55	16.67
K5	5	28.9	10.38	16.51
K10	10	28.1	10.21	16.4
K20	20	25.94	9.97	16.29
K50	50	21.2	9.55	16.22
K100	100	13.08	8.74	16.15

References:

[1] E.C. Quaye, “Energy demand in the 21st century: The role of biofuels in a developing country,” Renewable Energy, Vol. 9, No. 6, pp.1029-1032; 1996.

[2] G. Knothe, R.O. Dunn, M.O. Bagby, “Biodiesel: the use of vegetable oils and their derivatives as alternative diesel fuels,” Fuels and chemical from biomass, Vol. 666, Chapter. 10, pp. 172-208; 1997.

[3] J. Cvengros, F. Povazanec, “Production and treatment of rapeseed oil methyl esters as alternative fuels for diesel engines,” Bioresource Technology Vol. 55, No. 2, pp.145–52; 1996.

[4] USEPA, “A comprehensive analysis of biodiesel impacts on exhaust emissions,” EPA420-P-02-001; 2002.

[5] UNCATD, “The biofuel market: current scenario and alternative scenarios,” UNCTAD/DITC/BCC; 2009.

[6] European Commission. “20 20 by 2020: Europe’s climate change opportunity,” Brussels Belgium; 2008.

[7] European Commission, “Biomass action plan,” Brussels Belgium; 2005.

[8] T. Wiesenthal, G. Leduc, P. Christidis, B. Schade, L. Pelkmans, L. Govaerts,“Biofuel support policies in Europe: lessons learnt for the long way ahead,” Renewable and Sustainable Energy Reviews, Vol. 13, No. 4, pp. 789-800; 2009.

[9] European Commission, “Accompanying document to the EC Communication,“ Renewable energy progress report, 503 final; 2009.

[10] M.M. Roy, W. Wang, J. Bujold, “Biodiesel production and comparison of emissions of a DI diesel engine fueled by biodiesel–diesel and canola oil–diesel blends at high idling operations,” Applied Energy, Vol. 106, pp. 198-208; 2013.

[11] I.M. Atadashi, M.K. Aroua, A. Abdul Aziz, “High quality biodiesel and its diesel engine application: A review,” Renewable and Sustainable Energy Reviews, Vol. 14, No. 7, pp. 1999-2008; 2010.

[12]www.ucsusa.org/food_and_agriculture/what_you_can_do/the-climate-friendly-gardener.html.

[13] L. Lin, Z Cunshan, S. Vittayapadung, S. Xiangqian, D. Mingdong, “Opportunities and challenges for biodiesel fuel,” Applied Energy, Vol. 88, No. 4, pp.1020–1031; 2011.

[14] Y.C. Sharma, B. Singh, “Development of biodiesel current scenario,” Renew Sustain

Energy, Vol. 13, No. 6–7, pp. 1646–51; 2009.

[15] M. Balat, H. Balat, "Progress in biodiesel processing," Applied Energy, Vol. 87, No. 6, pp. 1815–1835; 2010.

[16] D.Y.C Leung, Y. Guo, 'Transesterification of neat and used frying oil: Optimization for biodiesel production," Fuel processing Technology, Vol. 87, No. 10, pp. 883-890; 2006.

[17] A. S. Ramadhas, C. Muraleedharan, S. Jayaraj, "Performance and emission evaluation of a diesel engine fueled with methyl esters of rubber seed oil," Renewable Energy, Vol. 30, No. 12, pp. 1789-1800; 2005.

[18] F. Anwar, U. Rashid, M. Ashraf, M. Nadeem, "Okra Hibiscus esculentus seed oil for biodiesel production," Applied Energy, Vol. 87, No. 3, pp. 779-785; 2010.

[19] M. Jesús, R. Carmen, M. Fernández, A. Casas, L. Rodríguez, Á. Pérez, "Influence of fatty acid composition of raw materials on biodiesel properties," Bioresource Technology, Vol. 100, No. 1, pp. 261-268; 2009.

[20] J. Xue, E.Y. Grift, C.A. Hansen, "Effect of biodiesel on engine performances and emissions," Renewable and Sustainable Energy, Vol. 15, No. 2, pp. 1098–1116; 2011.

[21] Y. Di, C.S. Cheung, Z.H. Huang, "Experimental investigation on regulated and unregulated emissions of a diesel engine fueled with ultra-low sulfur diesel fuel blended with biodiesel from waste cooking oil," Science of The Total Environment, Vol. 407, No. 2, pp. 835–46; 2009.

[22] M. Canakcı, "Combustion characteristics of a turbocharged DI compression ignition engine fueled with petroleum diesel fuels and biodiesel," Bioresour Technol, Vol. 98, No. 6, pp. 1167–75; 2007.

[23] E. Buyukkaya, "Effects of biodiesel on a DI diesel engine performance, emission and combustion characteristics," Fuel, Vol. 89, No.10, pp. 3099–3105; 2010.

[24] C.Y. Lin, J.L. Rong, "Engine performance and emission characteristics of marine fish-oil biodiesel produced from the discarded parts of marine fish," Fuel Processing Technology, Vol. 90, No. 7-8, pp. 883–888; 2009.

[25] H. Raheman, A.G. Phadatare, "Diesel engine emissions and performance from blends of karanja methyl ester and diesel," Biomass and Bioenergy, Vol. 27, No. 4, pp. 393–397; 2004.

[26] B. Gokalp, E. Buyukkaya , H.S. Soyhan, "Performance and emissions of a diesel tractor engine fueled with marine diesel and soybean methyl ester," Biomass and bioenergy, Vol. 35, No. 8, pp. 3575-3583; 2011.

[27] P. McCarthy, M.G. Rasul, S. Moazzem, “Analysis and comparison of performance and emissions of an internal combustion engine fuelled with petroleum diesel and different bio-diesels,” Fuel, Vol. 90, No. 6, pp. 2147–2157; 2011.

[28] R. Behcet, “Performance and emission study of waste anchovy fish biodiesel in a diesel engine,” Fuel Processing Technology , Vol. 92, No. 6, pp. 1187–1194; 2011.

[29] R.O. Dunn, MW Shockley, MO Bagby, “Improving the low-temperature properties of alternative diesel fuels: vegetable oil-derived methyl esters,” J Am Oil Chem Soc, Vol. 73, No. 12, pp. 1719–28; 1996.

[30] P. Kwanchareon, A. Luengnaruemitcha, S. JaiIn, “Solubility of a diesel–biodiesel–ethanol blend its fuel properties, and its emission characteristics from diesel engine,” Fuel, Vol. 86, No. 7-8, pp. 1053-61; 2007.

[31] L. Zhu, C.S. Cheung, W.G. Zhang, Z. Huang, “Emissions characteristics of a diesel engine operating on biodiesel and biodiesel blended with ethanol and methanol,” Sci Total Environ, Vol. 408, No. 4, pp. 914-21; 2010.

[32] C.H. Cheng, C.S. Cheung, T.L. Chan, S.C. Leec , C.D. Yao, K.S. Tsang, “Comparison of emissions of a direct injection diesel engine operating on biodiesel with emulsified and fumigated methanol,” Fuel, Vol. 87, No. 10-11, pp. 1870-9; 2008.

[33] H.H. Yang, W.J. Lee, H.H. Mi, C.H. Wong, C.B. Chen, “PAH emissions influenced by Mn-based additive and turbo charging from a heavy-duty diesel engine,” Environ Int, Vol. 24, No. 4, pp. 389–403;1998.

[34] M. Kasper, K. Sattler, K. Siegmann, U. Matter, H.C. Siegmann, “Particulate emissions from a low-speed marine diesel engine,” Aerosol Science and Technology, Volume 41, No 1, pp. 24-32; 2007.

[35] A. Keskin, M. Gürü, D. Altıparmak, “Biodiesel production from tall oil with synthesized Mn and Ni based additives: effects of the additives on fuel consumption and emissions,” Fuel, Vol. 86, No. 7-8, pp. 1139–43; 2007.

[36] M.A. Kalam, H.H. Majuski, “Testing palm biodiesel and NPAA additives to control NO_x and CO while improving efficiency in diesel engines,” Biomass Bioenergy, Vol. 32, No. 12, pp. 1116–1122; 2008.

[37] G. Labeckas, S. Slavinskas, “Influence of fuel additives on performance of direct-injection diesel engine and exhaust emissions when operating on shale oil,” Energy Convers Manage, Vol. 46, No. 11-12, pp. 1731–1744; 2005.

[38] G. Metin, K. Atilla, C. özer, C. Can, S. Faith, “Biodiesel production from waste chicken fat based sources and evaluation with Mg based additive in a diesel engine,” Renewable

Energy, Vol. 35, No. 3, pp. 637–643; 2010.

[39] C.P. Hebdo, “Biokerosene takes off in aviation sector,” Focus on Catalysts, Vol. 2009, No. 1, pp 2; 2009.

[40] M.S.Murthy, S.A.Agiwal, M.A.Bharambe, A. Mishra, A. Raina, “Modified kerosene stove for burning high percentage non-edible straight vegetable oil blends,”Conference of Clean Energy and Technology, pp. 145-150; 2011.

[41] A. Llamas, M. Jesús, G. Martínez, A. María A. Lal, L. Canoira, M. Lapuerta, “Biokerosene from coconut and palm kernel oils: Production and properties of their blends with fossil kerosene,” Fuel, Vol. 102, pp. 483–490; 2012.

[42] C. Weber, CEO JATRO AG, Frankfurt & Mitchell Hawkins, CEO BioJet Corp, Santa Barbara, CA, “Bio-kerosene GHG emission cocktail: fast forward into clean air – Against all odds,” 1 July 2012.

[43] J. Antonio, M. Rocha, R. Lopez, M. Vieira, “Process for the production of aviation biokerosene and aviation kerosene composition,” US patent 20130055624 A1. Mar 7, 2013.

[44] K. Addison, www.journeytoforever.org/biodiesel_make.html#process.

[45] R. Burton, “An Overview of ASTM D6751:Biodiesel Standards and Testing Methods,”Alternative Fuels Consortium, Central Carolina Community College; 2008.

[46] J.L. Lane, K.O. Henderson, http://www.astm.org/SNEWS/JUNE_2004/lanhen_jun04.html, ;2004.

[47] Parr instrument company, “instruction manual,” http://www.scimed.co.uk/wp-content/uploads/2013/03/6200-with-1108-Operation.pdf.

[48] EPA Office of Transportaion and Air quality, “Biodoesel standards EPA background and objectives, http://www.epa.gov/oar/caaac/mstrs/March2007/Simon.pdf.

[49] NBB, “BQ 9000 quality management system marketers requirement” www.bq-9000.org/documents/Marketer%20Req%20Rev%206%20Final.pdf ; 2011.

[50] A Biodiesel Primer: Market & Public Policy Developments, Quality, Standards & Handling. Report prepared by Methanol institute and International fuel quality center. April 2006.

[51] Biofuel Systems group limited, “Wintronxc30,” www.biofuelsystems.com/other/wintronxc30.pdf.

[52] M.M. Roy, M. Alawi, W. Wang, “Effects of canola biodiesel on a DI diesel engine performance and emissions,” IJMME-IJENS, Vol. 13 No. 2; 2013.

[53] K. Varatharajana, M. Cheralathan, “Influence of fuel properties and composition on NOx emissions from biodiesel powered diesel engines a review,” Renew Sustain Energy, Vol. 16, No. 6, pp. 3702– 10; 2012.

[54] US Environmental Protection Agency, Nitrogen oxides (NOx), why and how they are controlled. http://www.epa.gov/ttn/catc/dir1/fnoxdoc.pdf.

[55] J.B. Heywood, “Internal combustion engine fundamentals,” McGraw-Hil Inc; pp. 577-78; 1988.