

THESIS

TESTING AND PERFORMANCE MEASUREMENT OF STRAIGHT VEGETABLE OILS
AS AN ALTERNATIVE FUEL FOR DIESEL ENGINES.

Submitted by

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ABSTRACT

TESTING AND PERFORMANCE MEASUREMENT OF STRAIGHT VEGETABLE OILS AS AN ALTERNATIVE FUEL FOR DIESEL ENGINES.

Rising fuel prices, growing energy demand, concerns over domestic energy security and global warming from greenhouse gas emissions have triggered the global interest in bio-energy and bio-fuel crop development. Backlash from these concerns can result in supply shocks of traditional fossil fuels and create immense economic pressure. It is thus widely argued that bio-fuels would particularly benefit developing countries by off-setting their dependencies on imported petroleum.

Domestically, the transportation sector accounts for almost 40% of liquid fuel consumption, while on-farm application like tractors and combines for agricultural purposes uses close to an additional 18%. It is estimated that 40% of the farm budget can be attributed to the fuel costs. With the cost of diesel continuously rising, farmers are now looking at using Straight Vegetable Oil (SVO) as an alternative fuel by producing their own fuel crops.

This study evaluates conventional diesel compared to the use of SVO like Camelina, Canola and Juncea grown on local farms in Colorado for their performance and emissions on a John Deere 4045 Tier-II engine. Additionally, physical properties like density and viscosity, metal/mineral content, and cold flow properties like CFPP and CP of these oils were measured using ASTM standards and compared to diesel. It was found that SVOs did not show significant differences compared to diesel fuel with regards to

engine emissions, but did show an increase in thermal efficiency. Therefore, this study supports the continued development of SVO production as a viable alternative to diesel fuels, particularly for on-farm applications.

The need for providing and developing a sustainable, economic and environmental friendly fuel alternative has taken an aggressive push which will require a strong multidisciplinary education in the field of bio-energy. Commercial bio-energy development has the potential to not only alleviate the energy concerns, but also to give renewed impetus to the agricultural sector and rural development.

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1. INTRODUCTION AND MOTIVATION FOR RESEARCH

The growth and development of a nation is heavily dependent on energy. From cars to cell phones, from health to pleasure, from air condition to heating, from exploring space to communication, energy plays an important role in our lives. Post industrial revolution, new technologies have been developed to help make life easier and better. Energy has played a great role in helping us perform various activities like farming, computing, manufacturing, construction, and health and social services. Each of the 7 billion people on this planet use energy to make their lives richer, more productive, healthier and safer. There are many energy players tapping into this market with an objective of bridging the gap between demand and supply.

1.1 ENERGY AND FUEL

Expansive use of technological advancements has resulted in an increased co-relation between the demands of coal, biomass, natural gas, oil and electricity. People have sought practical solutions with energy like increased fuel economy and efficiency. With the standard of living of people increasing and our lives becoming increasingly dependent on energy, it is estimated that we will see about a 35% increase in energy consumption over the next 5 years until 2019 [1].

According to the 2011 Annual Energy Review by the US Energy Information Administration (EIA), of the total energy consumption in the US, 36% comes from petroleum, 26% from natural gas, 20% from coal, 9% from renewable energy and 8% from nuclear-electric power. Classifying the energy consumption by sectors, transportation sector consumes about 28%, industrial sector about 21%, residential and commercial about 11% and electric power sector about 40% [2].

In 2012, the consumption of petroleum based liquid fuel saw a decrease by 2.1% followed by an increase of 1.7% in 2013. Amongst all sectors, transportation consumes the maximum share of liquid fuel. EIA expects a petroleum based liquid fuel decrease of 0.4% in the coming year 2014 [3]. It is estimated that in the US, the transportation sector consumes over 70% of the total liquid fuel totaling to approximately 220 billion gallons [4].

1.2 RENEWABLE ENERGY IN THE US

The prime focus for governments across the globe is towards energy security. The quest for finding alternative energies to achieve energy independence is on the increase. Renewable energy as an alternative to petroleum is the focus so as to achieve Energy Independence. The Energy Independence and Security Act – 2007 (EISA-2007) was signed on 19-December 2007 establishing energy management goals and requirements while amending portions of the National Energy Conservation Policy Act (NECPA). Section 142 mandates federal agencies reduce their annual petroleum consumption by 20% and increase annual alternative fuel consumption by 10% by 2015 from a 2005 baseline. DOE and other allied organizations have established interim milestones that will monitor their implementation and progress [5, 6].

Renewable Fuel Standards (RFS) were established by the US Department of Energy (US DoE). This policy measures and monitors the minimum fuel usage, tariff and taxes, blending limits and research grants. Currently, the RFS-II standards mandate an increase in use of 9 billion gallons of biofuel fuel in 2008 to a proposed use of 36 billion gallons in 2022. RFS-II has divided biofuel into four categories – (i) total renewable fuels, (ii) advanced bio-fuels, (iii) bio-mass based diesel and (iv) cellulosic biofuel; each with

specific volume and Greenhouse Gas (GHGs) mandates compared to the 2005 baseline of gasoline or diesel that the proposed biofuel will displace [7, 8].

First generation biofuels – biodiesel, bioethanol and biogas are characterized by their ability to be blended with petroleum based fuels for use in engines and distributed by existing infrastructure. Second generation biofuels are defined as the fuels derived from plant bio-mass referring largely to lingo-cellulosic materials of plants. Cellulosic ethanol is an example of second generation biofuel [9, 10].

1.3 FARM FUEL

Agricultural sector consumes a significant amount of energy for producing field crops. Agriculture and allied activities account for approximately 17% of liquid fuel consumption in the US [11]. This roughly translates to about 38 billion gallons per year. In the years 2005 to 2008, fuel costs were about 6.6 % of the total production costs. The costs have since then gone up three times [12]. Increases in the prices of fuel and energy directly affect the cost of producing a crop which in turn affects the farmer's net farm profitability. This in turn affects the prices of food commodities.

1.4 FOOD VS FUEL

There is a growing skepticism and debate over the Food versus Fuel scenario where crops are used as fuel sources. Some people argue that using agricultural land to grow fuel crops will shrink our food supply and have negative economic impacts [13]. Some studies suggest that biofuel production using food crops like corn and soybean led to an increase in commodity food price by 3–30% during the years 2006 to 2008 [14]. However, the crop intensifying programs to increase the crop yield over the long run might help mitigate some of this debate [15]. Thus, co-existence of biofuel and food production

seems possible for 2nd generation biofuels. It is also important to consider sustainability criteria seriously. Despite this, if all crops, forests and grasslands that are not currently used were used for biofuel production, it would still be impossible to substitute biofuel for all fossil fuel used today in transport [16, 17].

1.5 SVOS – DIESEL ALTERNATIVE?

Agriculture has held an extremely coveted position in this new arena as the stock for many on the new "alternatives" have their base in animals or crops raised on the farm. Using straight vegetable oils (SVOs) as an alternative to diesel fuel is not a new concept. It is predicted that second generation biofuels would fill the void for both personal consumption and powering generation industry as they would be able to balance the need to grow more food crops while also their biomass could be used for producing fuels. This reduces some of the dependence on fossil fuel [18, 19].

Biodiesel is increasingly gaining importance and interests as an alternative fuel for diesel. It is made from vegetable oils or animal fats through a chemical process called transesterification. This involves a chemical reaction with methanol using sodium or potassium hydroxide as a catalyst [20-22].

The process of making fuel from crops consists of various conversion steps and requires basic knowledge of chemistry. Three energy metrics are commonly used to summarize the energy flow in a system- [23, 24]

- (i) Net Energy Balance (NEB): Output energy minus the input energy (MJ^{-1})
- (ii) Net Energy ratio (NER): Ratio of output energy to input energy
- (iii) Net Energy Yield (NEY): Output energy minus the input energy measured in terms of feedstock production area (MJ ha^{-1})

As of today, we have come a long way to understand the formation of biodiesel. It has in fact opened the door and new avenues to the direct use of vegetable oils as straight vegetable oil (SVO).

1.6 SVO KITS

A variety of kits are available in the market to supplement the current conventional diesel fuel system in automotive vehicles. These kits help run the vegetable oil in a parallel loop to diesel with dedicated filters and pump. There are three criteria for the SVO kit plumbing [25]:

1. Looped fuel return system.
2. Purging of the SVOs when stopping.
3. Start and stop of diesel as default.

The SVO kits are usually suited for long distance driving. The vehicle must start and stop on diesel. Since engine operating temperature plays an important role in proper combustion, the engine would be required to be warmed up to its operating temperature before switching to SVO as fuel [26]. The following figure shows a schematic of a two fuel system set up.

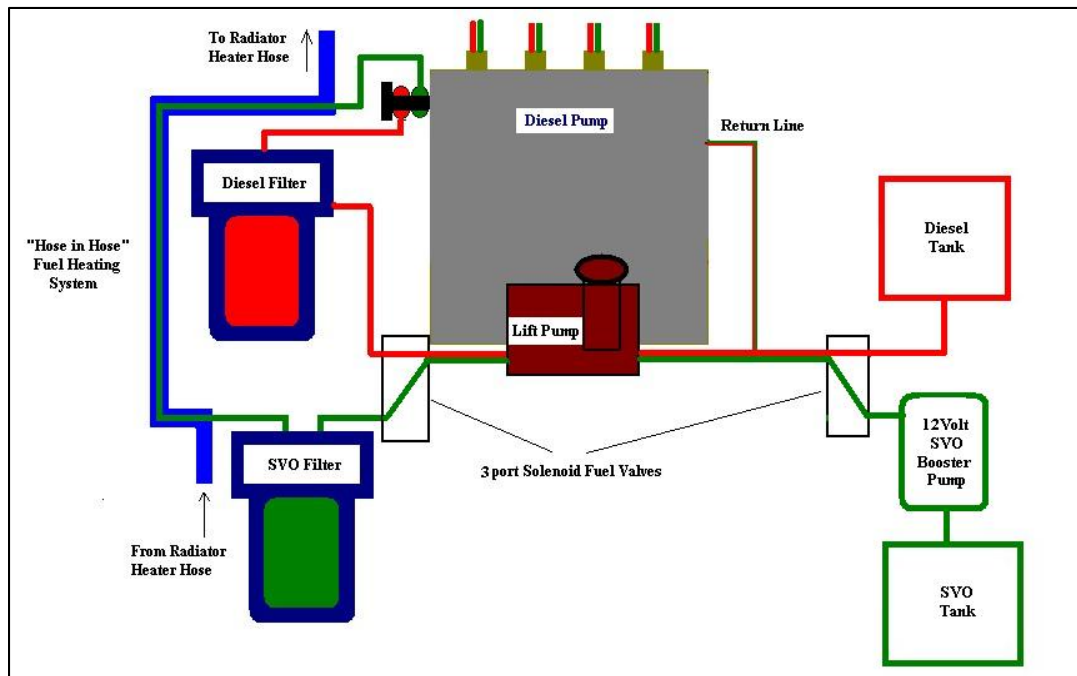


Figure 1: SVO conversion kit schematic diagram [28]

The main components of vegetable oil kits are Controller, Supplemental tank, switching unit, electrical fuel preheater, heat exchanger, control electronics and cables [27]. The engine starts on diesel fuel and switches to SVO once the operating temperature is attained. The heat exchanger helps heat the vegetable oil to an optimum temperature. A small buzzer signal will remind the driver to switch back to diesel fuel and purge the SVO before stopping.

2. BACKGROUND

Vegetable oils apparently have good potential as alternative fuels for maintaining crop production during periods of fuel shortages. Among the advantages of vegetable oils as fuel are: their physical nature as liquids and, hence, their portability; their heat content (88% of diesel oil); their ready availability and the fact that they are renewable resources [29, 30].

However, vegetable oil fuels that have been used on farm tractors introduced a large number of problems that can be attributed to their high viscosity, low volatility and the oxidative stability of the unsaturated hydrocarbon chains [31]

The feasibility of an alternative farm fuel depends on the amount of land required to produce the crop. For example, the average sunflower yield in the United States is 1390 kg/ha. The oil content of the seed is approximately 40%, which could be recovered using commercial techniques. The on-farm fuel required to produce one hectare of sunflower or small grain in North Dakota ranges from 56 to 84 L. Thus, one hectare of sunflower could produce enough fuel to grow 7-11 hectares of small grain or sunflower.

2.1 WHAT IS SVO?

Straight Vegetable Oils (SVO) are basically the oils contained in the seed of various edible and non-edible crops. These seeds are crushed in a seed crusher with a set temperature and pressure to get this oil. This oil then undergoes filtration and further purification as necessary for human consumption. Canola, peanut and corn oils that are available in stores are examples of de-waxed and de-gummed vegetable oils that are

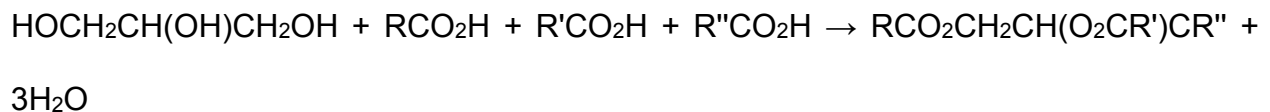
deemed fit for human consumption, while Brassica Juncea and Camelina Sativa oils are unapproved for human consumptions in the US.

The oil content of these seeds varies from one species to another. They range between 10% to 40 % with the majority of them centering around 33%.

2.2 TRIGLYCERIDES

Vegetable fats and oils are lipid materials derived from plants. Physically, oils are liquid at room temperature, and fats are solid. Chemically, both fats and oils are composed of triglycerides, in contrast to wax, that lack glycerin in their structure. Though many plant parts may yield oil, in commercial practice, seeds are the primary source of oil.

Triglycerides are formed by combining glycerol with three molecules of fatty acid. Alcohols have a hydroxyl (HO-) group while Organic acids have a carboxyl (-COOH) group. Alcohols and organic acids join to form esters. The glycerol molecule has three hydroxyl (HO-) groups. Each fatty acid has a carboxyl group (-COOH). In triglycerides, the hydroxyl groups of the glycerol join the carboxyl groups (R, R', R'') of the fatty acid to form ester bonds:



2.3 DOWNSIDE OF SVO

The use of SVOs as a fuel for compression ignition engines is restricted by certain unfavorable properties, particularly their viscosity. This high viscosity is a result of the high molar mass and the presence of saturated and unsaturated fatty acids in the oil. At

high temperatures polymerization of these unsaturated fatty acids may cause some problems. Cross-linking starts to occur between molecules, causing large agglomerations and gumming. The higher viscosities of SVOs cause poor fuel atomization, incomplete fuel combustion, and carbon deposition on the injector and valve seat, resulting in engine fouling. When direct injection engines are run with SVOs, injectors choke very soon. This choking may also lead to poor fuel atomization and incomplete combustion. As a result, the partially burnt vegetable oil runs down the cylinder walls and dilutes the lubricating oil and thickens the lubricating oil.

Despite these limitations of SVOs, it could be possible to use them for certain low-end applications like single cylinder diesel engines which are widely used in rural/agricultural applications. But, this would still call for an additional fuel supply, since starting and stopping of the engine has to be done on diesel to avoid deposition of oil on various engine parts, affecting the cold starting and engine performance.

2.4 COMBUSTION STUDIES OF SVO

Vegetable oils are mainly constituted of triglycerides that consist of one molecule of glycerol combined with three molecules of fatty acids. These fatty acids contain a long chain of carbon atoms linked by single bonds and combined with hydrogen, ending with a carboxyl group. Fatty acids can be further divided into two classes: saturated and unsaturated. In the unsaturated, one or more adjacent carbon atoms are linked by a double bond. If there is more than one double bond, the fatty acid is polyunsaturated, as compared to monounsaturated when there is only one double bond. Fatty acid composition varies principally in relation to the crop used [32, 33]. There have been numerous problems associated with the use of vegetable oils in conventional diesel

engines. Most of these are associated with the fuel oil properties and the local climatic and geographical conditions [34]. The fuel injection, combustion and atomization characteristics of vegetable oils are very different than those of diesel fuel. The high viscosity of vegetable oils interferes with the injection process in the engine resulting in poor and improper atomization. Poor and improper mixing of fuel oils with air in the engine leads to improper combustion, lower power output and high emissions often leading to deposit formations in the combustion chamber, piston head and injectors. The combination of high viscosity associated with vegetable oils and their low viscosity causes poor cold start of the engine and misfires. Over a long period of operations, vegetable oils start gumming, chocking of injectors and valve sticking which can result in engine breakdowns [35, 36]

The exhaust smoke density (opacity) is generally found to be more as compared to diesel. The ignition delay is also found to be lower than diesel fuels from 1 to 3 degrees crank angle [30, 34]

Some studies conclude that the SVO chemistry in addition to viscosity affects the atomization of the fuel. Polyunsaturated lipids (linolenic and linoleic) chains were most affected during the injection process often resulting in unexpected injector spray characteristics[37]

Structural indices - saponification value (SV) and iodine value (IV) are used to describe the lipid qualities in SVOs. The SV is a measure of the average molecular weight or chain length of the fatty acids present in oil. It represents the quantity in grams of potassium hydroxide required to saponify 1 g of oil. The IV is the measure of the unsaturated quality, the amount of double bonds, of oil. An IV is assigned to an SVO

based on the amount of iodine that can be absorbed by the double bonds. It corresponds to the number of grams of iodine absorbed by 100 g of oil [33] The IV neglects the differentiation between polyunsaturated acids and monounsaturated acids[37]

2.5 IMPORTANT FUEL PROPERTIES

- **Ignition quality:**

Cetane number (CN) is related to ignition and combustion behavior and is a prime indicator of the quality of diesel fuels, including those derived from renewable resources such as biodiesel. Satisfactory diesel combustion would mean self-ignition of the fuel as it is being sprayed near TDC into the hot and turbulent compressed air in the cylinder. Long ignition delay is not efficient and it leads to knock. The Cetane number, a dimensionless number, is the measure of the tendency to knock of the fuel. Higher Cetane number corresponds to shorter ignition delay while lower Cetane number might result in engine knock. SVOs have a relatively low Cetane number around 32 to 40 [38], while the optimal number should be between 40 and 60 [39]

The table below shows the cetane numbers prescribed in fuel standards[40, 41]:

Table 1:Cetane numbers prescribed in standards

Standard	Type	Cetane number(Minimum)
ASTM D975	Petrodiesel	40
EN 590	Petrodiesel	51
ASTM D6751	Biodiesel	47
EN 14214	Biodiesel	41

The structural composition of the fuel has been related to the cetane number. Presence of double bonds, aromatic compounds and saturated esters would lower the cetane

number while increase of the chain length of saturated fatty acid alkyl esters would increase the cetane number. In cases where double bonds are present, the cetane number could increase if the double bond is towards the end of the chain [42]. Some studies indicate that isomers of a compound would have an impact on cetane number. “cis” compounds are known to have a slightly higher cetane number than “trans”. Triple bonds have little or no effect on the cetane number [43].

- **Viscosity**

The viscosity of the fuel plays an important role in the combustion of fuel. The ease of combustion and thermal efficiency of the engine is directly related to the injected fuel in the combustion chamber through the nozzle and pattern of fuel spray. Lower viscosity may lead to excessive internal pump leakage and the system pressure reaches an unacceptable level. Higher viscosity will block the fuel passage through the pump, affect the flow ability of fuel. These will affect injection during the spray atomization. The effect of viscosity is critical at low speed or light load conditions. In general, SVOs have a higher viscosity than diesel by a magnitude of 10-15 [44, 45]. The kinematic viscosity is usually associated with the degree of unsaturation and the molecular size. An increase in double bonds leads to decrease in kinematic viscosity. This is due to the fact that presence of double bonds does not allow the fatty acid molecules to stack closely. Hence the molecule does not have a rigid structure and is loosely packed [46]. Studies have also shown that larger molecules result in higher viscosity [47, 48]. Overall, an increase in Temperature, SV and IV lead to decrease in viscosity.

- **Heating value**

The heating value or calorific value is the measure of the energy content of a fuel; it is also called as heat of combustion. This heating value is obtained by the complete combustion of a known quantity of solid fuel in an oxygen-bomb calorimeter under defined conditions. The gross heat of combustion or higher heating value (GHC or HHV) is obtained by oxygen-bomb calorimeter method as the latent heat of moisture in the combustion products is recovered. The higher heating value is one of the most important properties of a fuel.

Heating value of the fuel can also be calculated by using data from saponification and the iodine value [49, 50]. Studies have shown that the higher heating values increase with an increase in the carbon number and the ratio of hydrogen and carbon to oxygen to nitrogen increases [51]. Although the diesel engines can accept wide variations in heating value, practical systems are only suitable with higher calorific value of the fuel. This helps to reduce the quality and quantity of fuel being handled and maximizes the equipment operating efficiency. It is desirable for the vegetable oils to have a calorific value nearer to that of diesel.

- **Important temperatures**

Pour point and cloud point are important properties for fuels used in an IC engine. At lower temperatures, crystals start to appear in the fuel affecting its use in engines during cold weather operations. ASTM Standards are prescribed for the ideal properties of fuel - D 2500 for the cloud point, D 2386 for the freezing point and D 97 for the pour point [52]. Cloud point is the starting temperature of wax appearance. CFPP is the temperature that

the oil cannot flow across the filters in diesel engines and PP refers to the temperature at which the diesel fuel loses its fluid properties. The concentration of polyunsaturated fatty acids (PUFAs) was found to be a predominant parameter that influences the low-temperature properties of vegetable oil-based lubricants. The molecules of saturated fatty acids are usually packed very effectively into crystalline forms and hence have higher waxy temperature than unsaturated fatty acids of the same chain-length. In addition, the unsaturated hydrocarbon chains have C=C bonds [53]. In biofuels, the constituents of water, monoglycerides, free fatty acids, alcohol, sodium or potassium salts of fatty acids (soaps), antioxidants, sterols and other unsaponifiable matter has a significant impact on these properties [54]. The values of both should be well below the freezing point of the oil used. Flash point is another important temperature from a safety point of view. This temperature should be practically as high as possible. Vegetable oil–diesel blend should not decrease the flash point temperature.

- **Metals**

The sulphur content, carbon residue, ash content and various metals like sodium, potassium are responsible for corrosion and residue formation on the engine parts which in turn affects the engine life. These values should be as small as possible. Practical values are 0.5% sulphur, 0.27% carbon residue and 0.01% ash. The presence of Ca and Mg in exhaust gases can poison catalytic converters, reducing the benefits for the environment and for human health [55] The phosphorus content in the fuel indicates the presence of phospholipids (or mucilage), which are undesirable constituents. They come from the cell membranes of seeds and kernels. It is an essential concern in the quality of

vegetable oil as a fuel, as using oil with a high level of phospholipids results in the formation of deposits, which coke in hot engine sections - combustion chamber and nozzle holes [32] The phosphorus content of seeds mainly depends on the temperature during processing, but it is also highly variable from one species to another. For example, it is around 70 ppm for sunflower oil, 200 ppm for jatropha oil, 270 ppm for crude soybean oil and 620 ppm for crude cotton oil [55, 56]

3. EXPERIMENTAL SET-UP

Three species: Brassica Juncea (hereafter referred to as Juncea), Camelina sativa (Camelina) and B. Napus (Canola) varieties were grown Colorado State University in different climatic, genetic and agricultural conditions. These seeds were then harvested, crushed and filtered to obtain the Straight Vegetable Oils. In addition to these SVOs, de-gummed and de-waxed canola, corn and coconut oils were procured from the store. Table 2 shows the various Straight Vegetable Oils that were used for testing.

Table 2: SVOs Tested

SVO Mix	SVO Sample Name
10+214	Camelina 1
202+44	Camelina 2
117+227+148	Camelina 3
244	Camelina 4
25	Camelina 5
V1037	Canola 1
V2018	Canola 2
JC002	Juncea 1
JC001	Juncea 2
Refined	Corn - Albertsons
Refined	Canola- Great Value
Refined	Coconut - Nutiva

These Oils were then used as fuels in a Tier 2 John Deere 4.5 liter 4 cylinder engine at the Engines and Energy Conversion Laboratory (EECL). The engine was loaded with an eddy-current dynamometer (Mid West Induction Dynamometer Model 1014A).

Exhaust samples were extracted and flowed through heated sample lines to emissions analyzers. Emissions analyzers used a 5-gas analyzer (CO, THC, NO_x, O₂, and CO₂) and a dilution tunnel (particulate matter). Fuel flow was measured either with Coriolis meters (diesel) or an electronic scale (SVO). More details on each system are provided in subsequent sections.

3.1 FUEL SYSTEM

The fuel system schematic is shown in Figure 1. Two different fuel systems, one for diesel and one for SVO, were necessary. This was due to the viscous nature of SVO, which imposed too high of backpressure on the engine when a return flow meter was used. Diesel and SVO fuels were stored in separate fuel tanks and were supplied to the engine with dedicated fuel lift pumps.

SVO was supplied from a tank on an electronic scale that was interfaced to a data acquisition system. The SVO return from the engine went into the SVO tank on the electronic scale. The SVO net flow rate was determined by taking the time derivative of the time resolved SVO weight readings from the electronic scale. The SVO fuel was passed through a shell-tube heat exchanger utilizing engine coolant to heat the SVO. The SVO then flowed through a section of tubing wrapped with heat tape for more precise

temperature control. The fuel was then supplied to the engine mounted fuel injection pump, which pressurized the fuel common rail that supplied the fuel injectors.

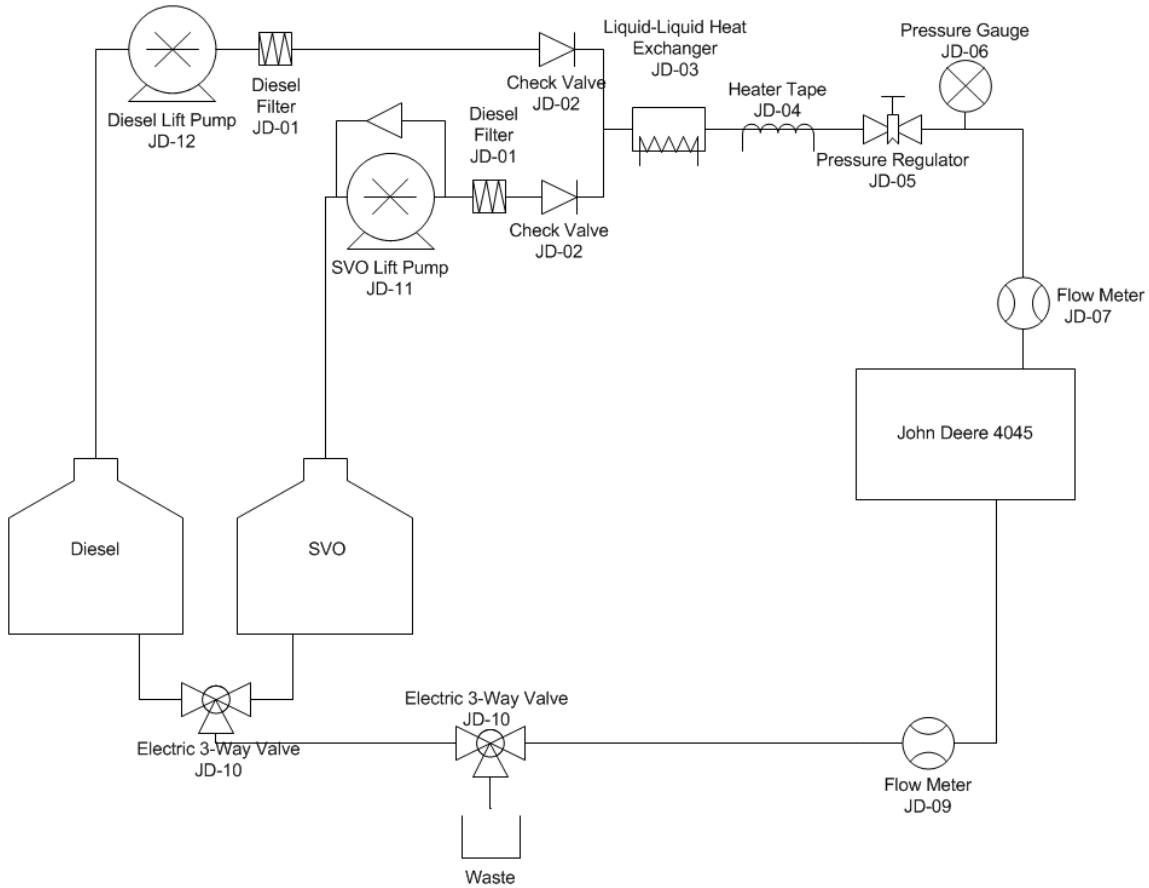


Figure 2 Schematic Diagram of the Engine Test Set UP

The diesel consumption was measured by a Micro Motion - Coriolis flow meter (Model Number 2700R11BBCEZZZ & 2700C11ABUEXZZ) on the supply and return lines. Two 3-way manual valves were used to control the flow of the SVO and diesel from the fuel tanks into engine and the flow of waste return into the waste bucket.



Figure 3: Engine Test Set UP

3.2 EXHAUST SETUP

Two different probes extracted exhaust for emissions measurements. An averaging probe was used for gaseous emissions and an isokinetic probe was used for particulate measurement. The gas analysis was performed with a 5-gas analyzer and particulate matter was measured using a dilution tunnel.

3.2.1 GAS ANALYZERS



Figure 4: 5 - Gas Analyzer

Criteria pollutants, CO₂ and O₂ are determined with our exhaust gas analyzers shown in Figure 2. The Rosemount 5-gas emissions bench measures CO, CO₂, THC, NO_x and O₂ concentrations. A Peltier-type condenser removes water from the exhaust sample before the gas enters the analyzers. The analyzer to determine relative CO concentrations uses infrared radiation (IR) adsorption. IR detection is also used to measure CO₂ concentrations in the exhaust. Total hydrocarbon compounds (THCs) are detected using a flame ionization detection (FID) method. A regulated flow of sample gas passes through a flame sustained by regulated flows of fuel gas and air. Within the flame, the hydrocarbon sample stream undergoes a complex ionization that produces electrons and positive ions, which are collected by an electrode, causing a measurable current flow.

The ionization current is proportional to the rate at which carbon atoms enter the burner and is therefore a measure of the concentration of hydrocarbons in the sample. The NGA 2000 CLD uses the chemiluminescence method of detection for NO_x. All NO₂ is reduced to NO over a catalyst. The NO is reacted with internally generated ozone (O₃) to form NO₂ in an electronically excited state. The excited molecule immediately reverts to the ground state emitting photons (red light), which is measured by a photodiode. The intensity of the chemiluminescence is directly proportional to the NO_x concentration. The determination of O₂ concentration is based on measurement of the magnetic susceptibility of the sample gas. O₂ is strongly paramagnetic, while other common gases are weakly diamagnetic.

3.2.2 DILUTION TUNNEL

Figure 3 shows the set up for the mini dilution tunnel to measure particulate matter in the exhaust. The sample of exhaust flows from the exhaust pipe through a heated line and to the dilution tunnel via a venturi on the dilution air inlet. The dilution air flowrate is measured with a turbine meter. This exhaust flowrate is measured using differential pressure across the venturi as it flows into the dilution air. The mixture is passed through a residence chamber to simulate particulate mixing with ambient air. The humidity and temperature is measured. Then a portion of the flow is pulled from the base of the residence chamber to the Teflon filters where particulate matter (PM) is collected. PM is collected in a filter downstream of the PM₁₀ cyclone, which eliminates particulates larger than 10 μm. Filters collect all particulate matter that passes through the cyclone. The filters are weighted before and after the test using a precision balance, accurate to 1

microgram. Labview software, made by National Instruments is used for the data acquisition system, which monitors exhaust sample mass flowrate, dilution air flowrate, dilution ratio, and system temperatures.

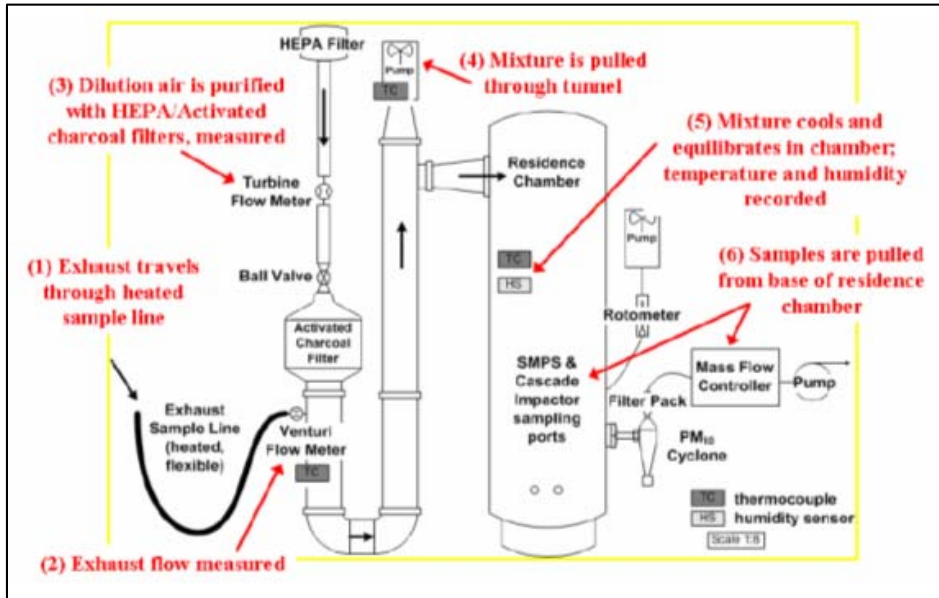


Figure 5 Dilution Tunnel Schematic Set Up



Figure 6: Actual Dilution Tunnel Set UP

3.3 ENGINE TEST PROCEDURE

The following testing sequence was followed.

1. The dilution tunnel dilution ratio was maintained between 5 and 10.
2. The specific test sequence using the SVOs were as follows:
 - a. The 50% torque (217 Nm) at 1700 rpm.
 - b. Take 5 minute data point on diesel with PM and 5-gas
 - c. Put in new PM filter

- d. Switch to SVO and take 5 minute data point with PM and 5-gas
 - e. Switch back to diesel and put in new PM filter
 - f. Repeat the above for all the SVOs.
3. Then the remaining SVOs were tested for repeatability and a sweep over 50%, 75% and 100% loads at 2200 rpm.

Notes:

- The quantities of Camelina 4 and Camelina 5 were too little to have a repeatability and sweep. Hence, the repeatability and sweep data for these oils could not be recorded.
- Post the repeatability test of the oils, the quantities of Camelina 2 and Camelina 3 were insufficient to perform a sweep test.
- Since the properties of these oils were similar, the remaining quantities were mixed together (ratio of 1:1) to perform a load sweep test. Key engine parameters are provided in Table 3.

Table 3: Engine Testing Parameters

Engine Parameters	Values
Engine Speed (Part Load)	1700 rpm
Engine Speed (Rated)	2200rpm
50% Torque	217 Nm
Fuel Inlet temperature	43.2 ^o C – Diesel 73.5 ^o C - SVO
Exhaust Temperature	386 ^o C
Jacket Water Temperature	86.21 ^o C
Lube Oil Pressure	3.55 bar

3.4 FUEL PROPERTY TESTING

These SVOs were also tested for physical properties like density and viscosity, calorific value, metal content, and cold flow properties like according to standards available. The following shows the test apparatus

- **Density Meter** – Anton Paar density meter (DSA 5000 M) was used to measure the density and the speed of sound in the fuel sample according to ASTM standard. It is equipped with a density and sound velocity cells. The fuel sample is introduced into the Anton Paar oscillating U Tube made of borosilicate glass which is then excited to vibrate electronically at its characteristic frequency. This frequency is a function of

the density of the fuel. The density is then deduced using mathematical co-relation.

Figure 6 shows the Anton Paar Density Meter.



Figure 7: Anton Paar Density Meter

- **Viscosity Meter:** - Anton Paar Viscosity Meter (SVM 3000) was used to measure the viscosity of the fuel sample. A tube is filled with the sample fuel rotates at a constant speed. This tube is suspended in a hollow measuring rotor made of Titanium. This measuring rotor is centered in the heavier liquid by buoyancy forces due to its low density. A permanent magnet is used to guide the rotor axially and deliver the speed using eddy currents. The difference in the torque due to the shear stress influences the rotor speed

which can then be used to calculate the viscosity of the sample. Figure 7 shows the Anton Paar viscosity meter.



Figure 8:- Anton Paar Viscosity Meter SVM 3000

- **Cloud and Cold Filter Plug Point:** - Lawler Corporation's Integrated Automated Analyzer with Direct Refrigeration Unit - DR4-14 was used to measure the cloud and cold filter plug points. Each of CP and CFPP test points have independent test tubes and a common chilling unit. Vacuum control is provided by a two jar system. When the test sample cools to the preselected temperature, the vacuum is applied and timer is activated to draw the sample into the pipette. This is repeated by cooling the sample temperature by 1°C. The vacuum is then released allowing the sample back into the test tube. The

test stops at the temperature at which the sample fails to fill the pipette in 60 sec and the CFPP result is displayed.

Cloud point testing comprises of cooling the sample to a preselected temperature and a pulse light being emitted and captured by probes and optical fibers. This light of a specific wavelength is used to determine the cloud point. Cloud point stops when this wavelength has been measured. The figure below shows the CP and CFPP testing equipment



Figure 9: Lawler DR4-14 CP and CFPP Tester

- **Metals:** - Spectro Metals ICP was used to analyze the metal concentration in the sample. The sample fuel is first diluted with a blank liquid and then vaporized on the spark stand by an induced spark arc. The atoms and ions in this vapor get excited and emit

radiation of varied wavelengths. The radiation intensity is proportional to the concentration of a particular metal element in the sample. Figure 9 shows the metals ICP.



Figure 10:- Spectro Metals Analyzer

- **Calorimeter**:-An IKA-200C was used to measure the heating value of the fuel sample. A known weight of the sample is taken in a crucible and is placed in a steel container. This container also called the bomb is filled with 99.95% oxygen at 30 bar. The sample is then ignited with a cotton thread of known heating value and allowed to burn. This burning of the sample heats up the known quantity of water surrounding the bomb at a known temperature. This temperature rise is measured and the heating value of the sample is measured. Figure 10 shows the IKA bomb calorimeter.



Figure 11: IKA-200C Bomb Calorimeter

- **Fatty Acid Profiling:** - The sample fuels were tested for their fatty acid profile by the Department of Soil and Crop Sciences, Colorado State University. This gave us the composition of the saturated/unsaturated components and the average chain lengths. The results are discussed in the next sections of this thesis.

4. RESULTS

4.1 STRAIGHT VEGETABLE OIL PROFILE

The fatty acid profile analysis was done by the Department of Soil and Crop Sciences, Colorado State University. Cargill, a company specializing in food, agriculture, financial and industrial products and services have one of their offices in Fort Collins, Colorado, where these oil samples were tested for their fatty acid profiling. Table 4 shows the fatty acid profile in detail. The table shows that higher chain length with unsaturated links was more common. C18 with one double bond, C18 with two double bonds, C18 with three double bonds, and C20 with one double bond were most common oil composition structures. The Total Saturates were between 11 and 6. Camelina had the most saturates, in the range of 10 to 11, while Juncea and Canola were very proximate to each other in the 6 to 7 range. The level of Polyunsaturation had a vast range, from about 10 to 56. Camelina had unsaturation in the range of 47 to 56, Juncea in the range of 33 to 36 while Canola was in the range of 10 to 21. The average chain length of these triglycerides in these species was very similar to each other and within the range of 18 to 19. The variation in the tail pipe emissions of these parameters are shown and discussed in section 4.6.

Table 4:Fatty Acid Profile

Samples	C14_0	C16_0	C16_1	C18_0	C18_1	C18_2	C18_3	C20_0	C20_1	C20_2	C22_0	C22_1	C24_0	C24_1	TOTSA T
Cam 10	0.069	6.02	0.172	2.99	25.8	16.3	29.9	1.49	13.5	0.795	0.356	1.97	0.193	0.447	11.1
Cam 10 & 214	0.069	5.95	0.178	2.94	25.1	16.1	30.1	1.57	13.6	0.801	0.369	2.24	0.307	0.638	11.2
Cam 117 & 227 & 148	0.068	5.90	0.172	2.71	19.9	19.8	32.9	1.45	12.5	1.28	0.387	2.22	0.227	0.513	10.7
Cam 202	0.048	6.09	0.155	2.76	20.2	23.2	30.3	1.46	11.8	1.31	0.327	1.86	0.147	0.350	10.8
Cam 202 & 44	0.074	5.85	0.159	2.67	21.1	19.9	30.6	1.61	13.2	1.22	0.380	2.53	0.221	0.534	10.8
Cam 214	0.075	5.74	0.184	2.88	24.1	16.1	31.5	1.59	13.1	0.974	0.549	2.27	0.376	0.653	11.2
Cam 244	0.071	6.11	0.167	2.82	18.3	18.3	35.8	1.56	12.4	1.32	0.401	2.13	0.207	0.469	11.2
Cam 25	0.068	5.80	0.193	2.64	21.7	18.3	32.1	1.56	13.2	1.03	0.381	2.41	0.195	0.439	10.7
Cam 44	0.064	5.79	0.192	2.58	22.8	17.2	32.1	1.48	13.5	1.05	0.357	2.31	0.188	0.479	10.5
JC011	0.053	2.95	0.229	1.67	25.2	21.1	12.2	0.917	11.3	0.815	0.717	21.3	0.415	1.194	6.72
Juncea blend	0.062	3.38	0.310	1.71	36.9	22.1	9.12	0.776	7.76	0.665	0.631	15.3	0.337	0.924	6.91
V1037	0.059	3.64	0.258	2.27	70.1	18.2	2.67	0.628	1.24	0.086	0.363	0.105	0.186	0.149	7.14
V2018	0.048	3.20	0.230	2.22	81.1	7.95	2.15	0.657	1.36	0.070	0.379	0.253	0.184	0.173	6.68

4.2 PHYSICAL AND COLD FLOW PROPERTIES:

Table 5 shows the Physical properties of fuels tested using ASTM techniques. These are then compared to diesel, which is the standardized fuel currently being used for most of the agricultural equipment. The Cold Filter Plug Point for the triglycerides were much higher than diesel. Diesel had a Cold Filter Plug Point of -19°C , while all of the triglycerides were in the positive temperatures, Canola and Juncea blends were as high as 25°C which results in a failed test even at room temperatures.

The Cloud Point of the triglycerides were generally higher than diesel. The CP of Juncea was at least 9 degrees higher than diesel while that for Camelina was close to that of diesel.

The density of the triglycerides were generally higher than diesel by about 10%. The viscosity was much higher, approximately 15 to 18 times as that of diesel. Running triglycerides in engines would require them to be at a viscosity closer to diesel so that the fuel flows smoothly and the engine does not starve for fuel at any point in its operation. Heating the triglycerides with auxiliary heaters in the fuel lines to reduce the viscosity and improve the flow, use of fuel additives like ValvTect™ and Penray® to improve the cold filter plug point and the cloud point could be some of the methods that might help off-set the drawbacks of triglycerides.

Table 5: Physical and Cold Flow Properties

Fuel	ASTM 6371	ASTM D2500		ASTM D7042	
	CFPP	CP	Density g/cm ³	Viscosity mm ² /s	Bulk Modulus N/m ²
	°C	°C	20°C	40°C	(x10 ⁹)
Off Road Diesel	-19	-18	0.838	2.570	1.574
Camelina 25	9	-10	0.919	30.122	1.991
Camelina 10+214	9	-10	0.915	30.397	1.986
Camelina 244	13	-17	0.920	30.492	1.999
Camelina 44+202	11	-10	0.920	31.051	1.995
Camelina 117+227+148	13	-11	0.920	30.728	1.999
Canola V2018	23	-13	0.908	36.857	1.950
Canola V1037	25	-12	0.914	36.078	1.966
Canola - Albertsons	19	-10	0.915	36.720	1.975
Juncea Blend	22	-10	0.911	33.813	1.957
Juncea 0011	25	-9	0.913	39.709	1.981
Corn Oil - Great Value	18	-13	0.912	33.057	1.971

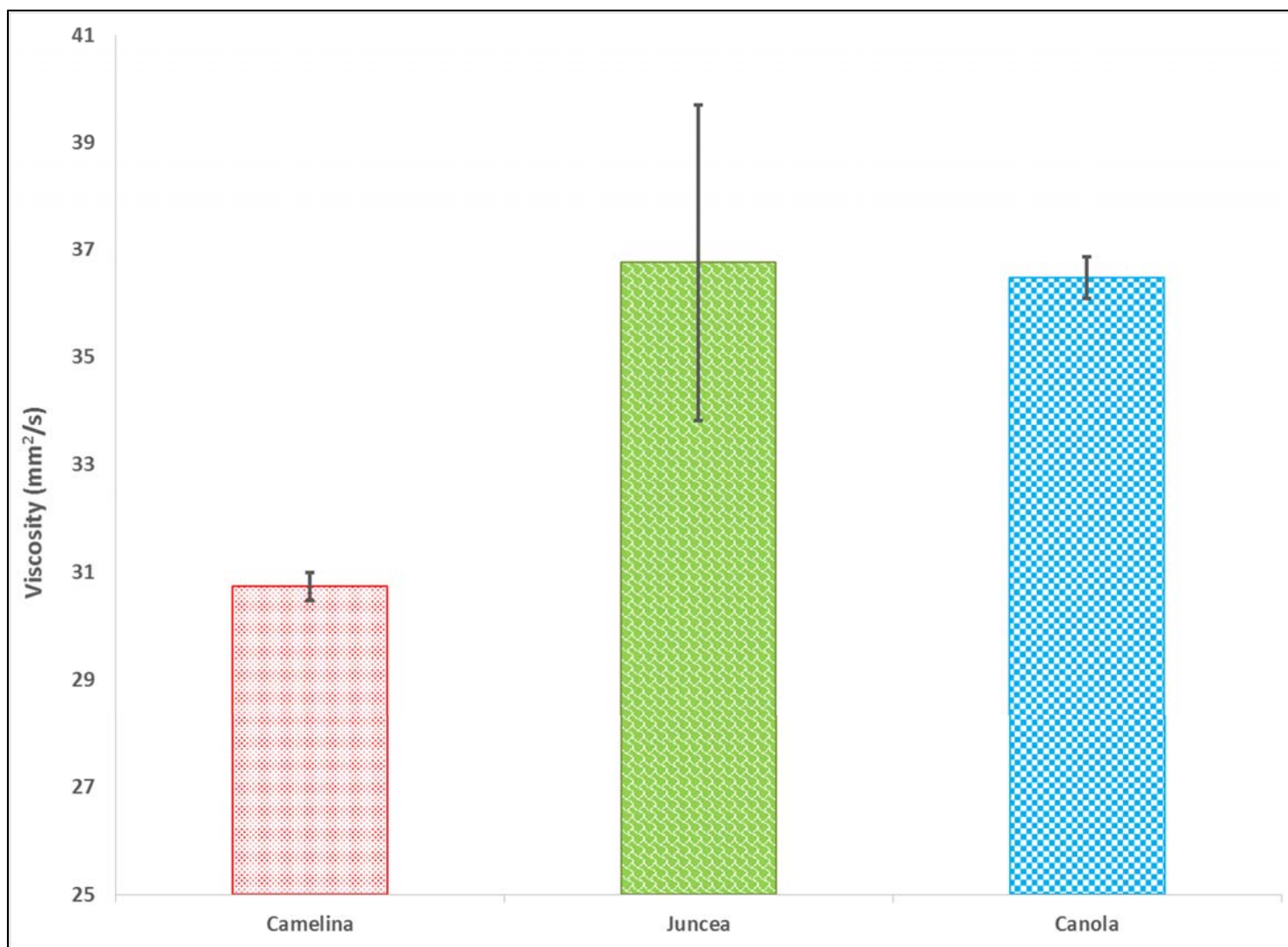


Figure 12: Viscosity (Similar oil family Grouped)

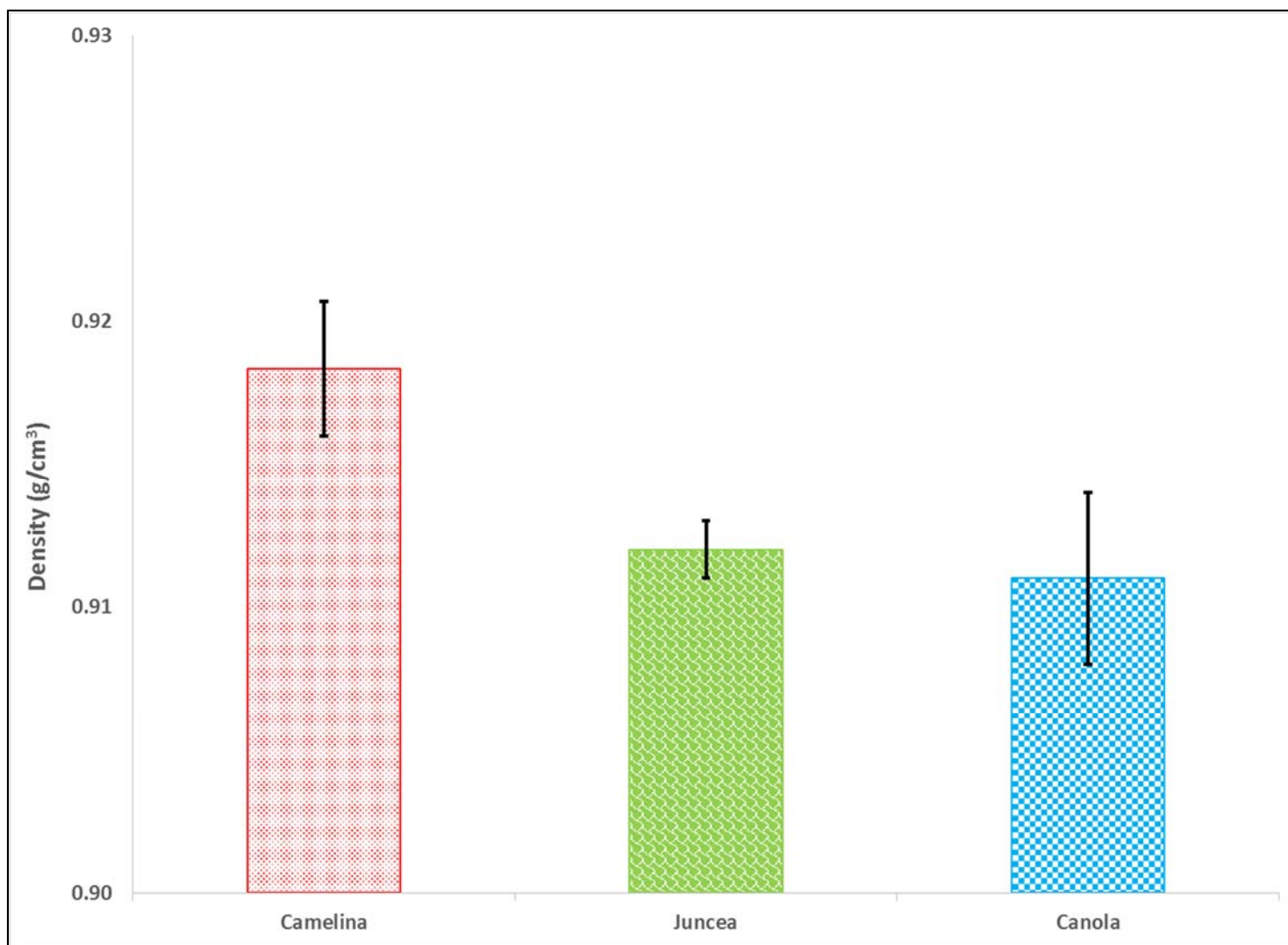


Figure 13: Density (Similar oil family Grouped)

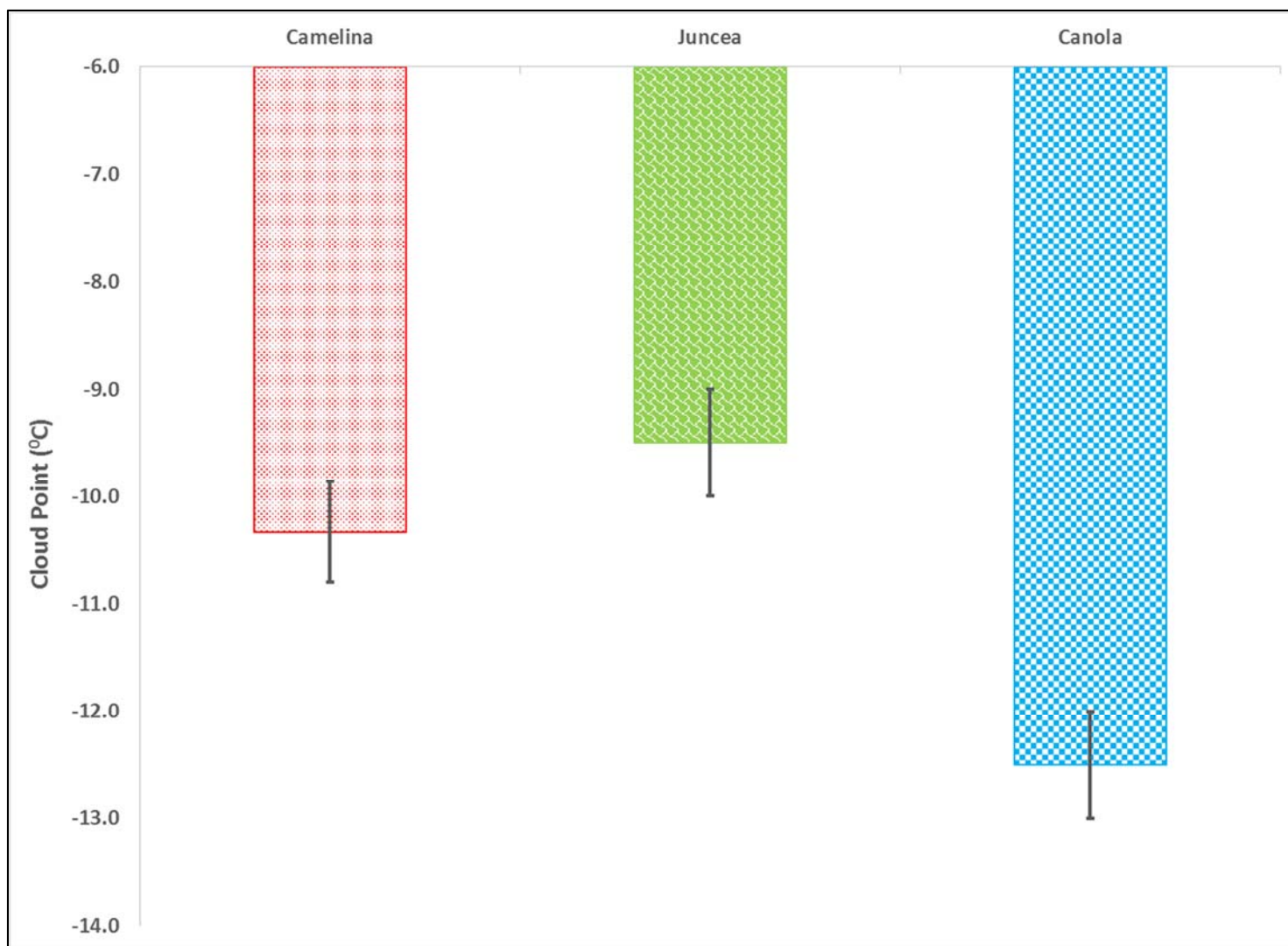


Figure 14 Cloud Point (Similar oil family Grouped)

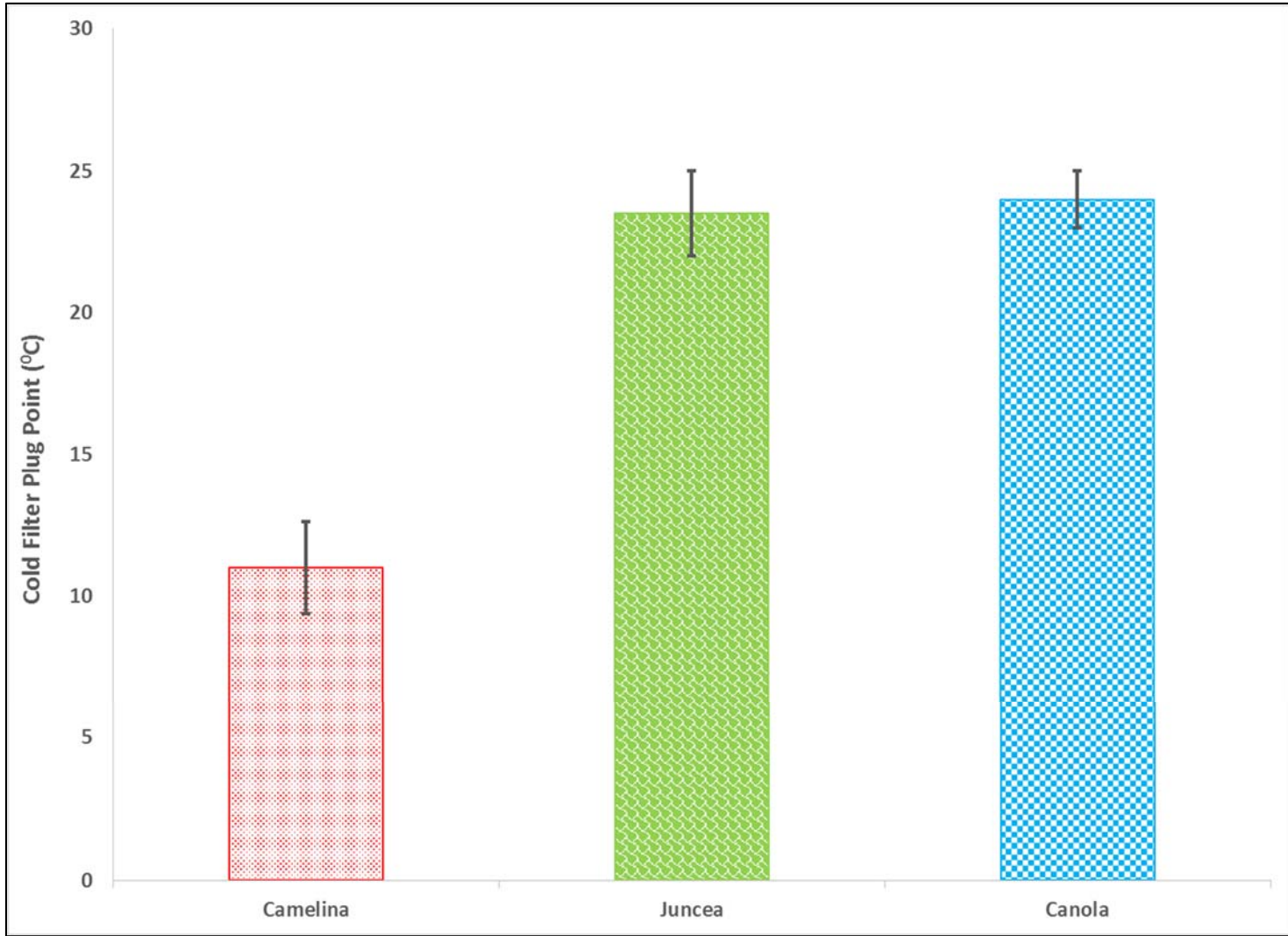


Figure 15 Cold Filter Plug Point (Similar oil family Grouped)

4.3 METALS/MINERALS

The metals and minerals present ($r^2 > 0.95$ to 0.97) in the triglycerides are shown in the Table 6 below. The coefficient of determination, r^2 being greater than 95% suggests that the results were within the +/- 5% error range. Spectro's ICP was used to determine following ASTM 6751 standards. The ASTM standard sets a limit of 10 ppm for Phosphorus. Diesel fuel contained about 1.1 ppm of Phosphorous. The Phosphorus content in the triglycerides is higher than diesel by 6 to 11 times on average. This is close to the ASTM set limit. Juncea Blend had about 34 times the phosphorous content as diesel. The store brought Canola and Corn oil that is suitable for human consumption had lower Phosphorus content. This can be attributed to the purification process of degumming and de-waxing that is done to the triglycerides to make them fit for human consumption.

Table 6: Metals

Metals - ASTM 6751					
Fuels	P	S	Na	K	
	(10 ppm)	(15 ppm)	Na + K < 10 ppm		
Off Road Diesel	1.152	14.379	< 0.098	0.858	0.858
Camelina 25	9.679	46.127	1.189	5.051	6.24
Camelina 10+214	6.558	37.782	0.683	3.266	3.949
Camelina 244	10.67	46.362	2.694	4.465	7.159
Camelina 44+202	9.54	43.407	1.527	4.511	6.038
Camelina 117+227+148	8.537	42.624	0.748	3.457	4.205
Canola V2018	7.037	15.498	1.238	3.042	4.28
Canola V1037	7.921	16.604	1.968	3.468	5.436
Canola - Albertsons	1.089	9.814	< 0.019	1.805	1.805
Juncea Blend	34.33	67.823	2.121	10.689	12.81
Juncea 0011	11.429	82.139	2.135	4.2	6.335
Corn Oil - Great Value	1.161	14.288	< 0.156	1.899	1.899

ASTM standard for Sulfur is set at 15ppm. Diesel fuel can be classified as “regular” (<15ppm) “low sulphur” (<5ppm) and “ultra-low sulphur” (<1ppm). The off road diesel that was used for testing had a sulfur content of 14.3 ppm which is just under the set limit. The unrefined triglycerides had high sulphur content, about 3 times on average ~ 45 ppm than the set limit. Canola was the lowest amongst the triglycerides having about 16.6 ppm while Juncea blends had the highest level of 67.8 and 82.1 ppm. The refined oil for human consumption had lower sulphur content than other triglycerides as expected, with Canola and Corn oils having 9.8 ppm and 14.3 ppm respectively.

When fuel combusts, sulphur is emitted to the atmosphere as SO_2 . Sulphur that is not converted to SO_2 , forms various metal sulphates and gets converted to sulphuric acid. These then react with precious metals in the exhaust catalyst to form SO_3 . These poison the catalyst resulting in poor efficiency of the catalyst which in turn results in its failure to reduce emissions at the tail pipe. Phosphorous is also a known catalyst poison. Elevation of sulfur and phosphorous in unrefined triglycerides will be problematic for newer engines with catalytic converters. This will result in faster catalyst degradation leading to shortened catalyst life.

ASTM standard for Sodium and Potassium is set at 10 ppm cumulative. Diesel fuel contained about 0.85 ppm of sodium and potassium. All the triglycerides were higher than diesel by about 4 to 10 times but within the set limit. As expected, the refined oils had lower sodium and potassium content, about 1.9 ppm. Camelina had the lowest content amongst the unrefined triglycerides ~ 4 ppm while Juncea had the highest ~ 12.8 ppm.

4.4 FUEL PROPERTY CORELATIONS:

A possible co-relation between the various fuel physical properties like Density, Viscosity, Cold Filter Plug Point, Cloud Point and minerals like Phosphorus, Sulphur, Sodium and Potassium was analyzed.

However with the number of samples analyzed and the diversity within them made it difficult to arrive at any strong co-relation. Figure 16 shows the co-relation between Viscosity and CFPP. The R^2 value was approximately 83% which is not very strong but certainly worth taking note of. Figure 17 shows the co-relation between Density and CFPP. The R^2 value was approximately 50%. Figure 18 shows the co-relation between Viscosity and Density. The R^2 value was approximately 45%. With more samples sequentially chosen with respect to their oil profiles and other standard physical properties would help us better understand the co-relations between various physical properties.

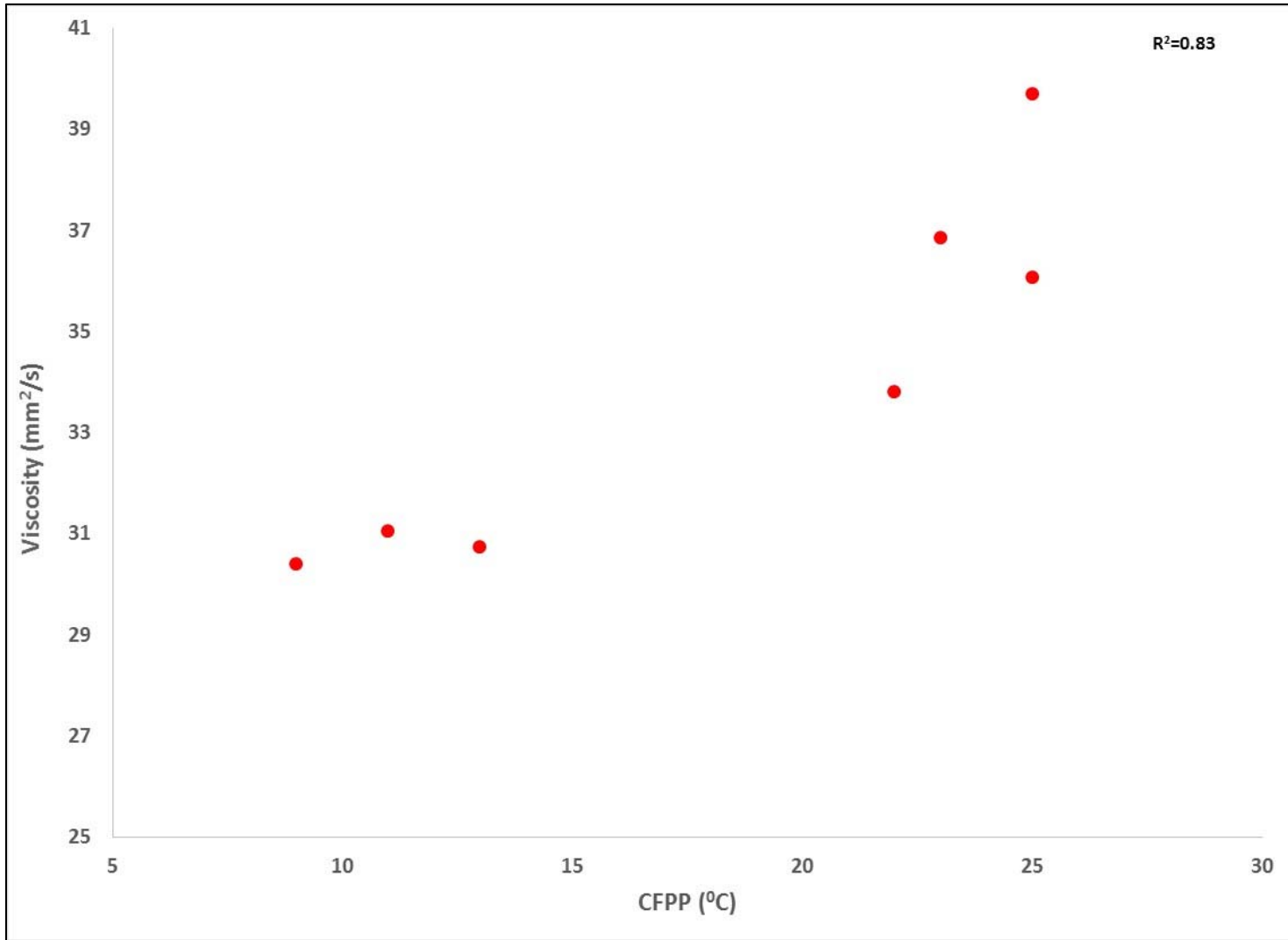


Figure 16: Viscosity vs CFPP

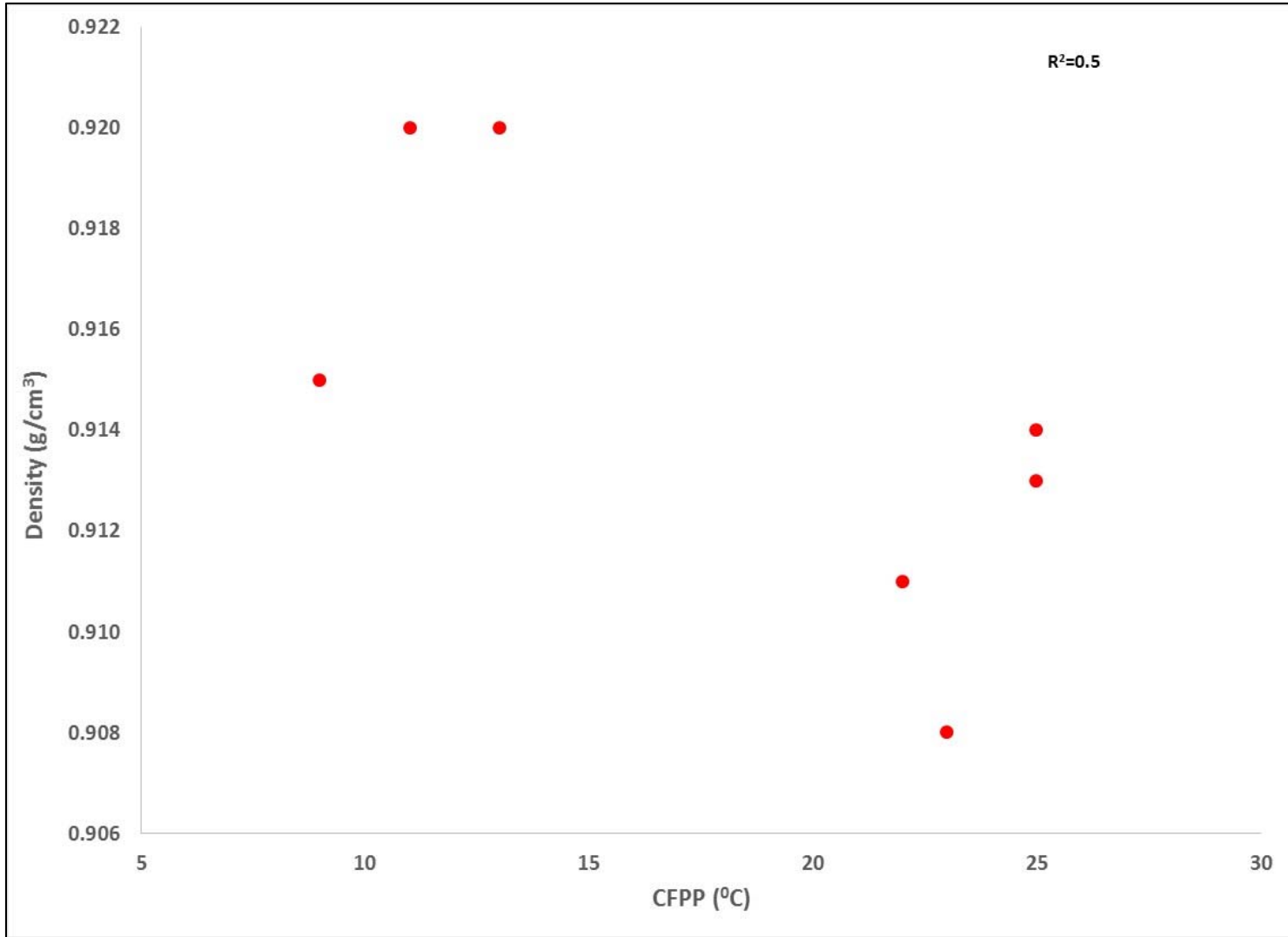


Figure 17: Density vs CFPP

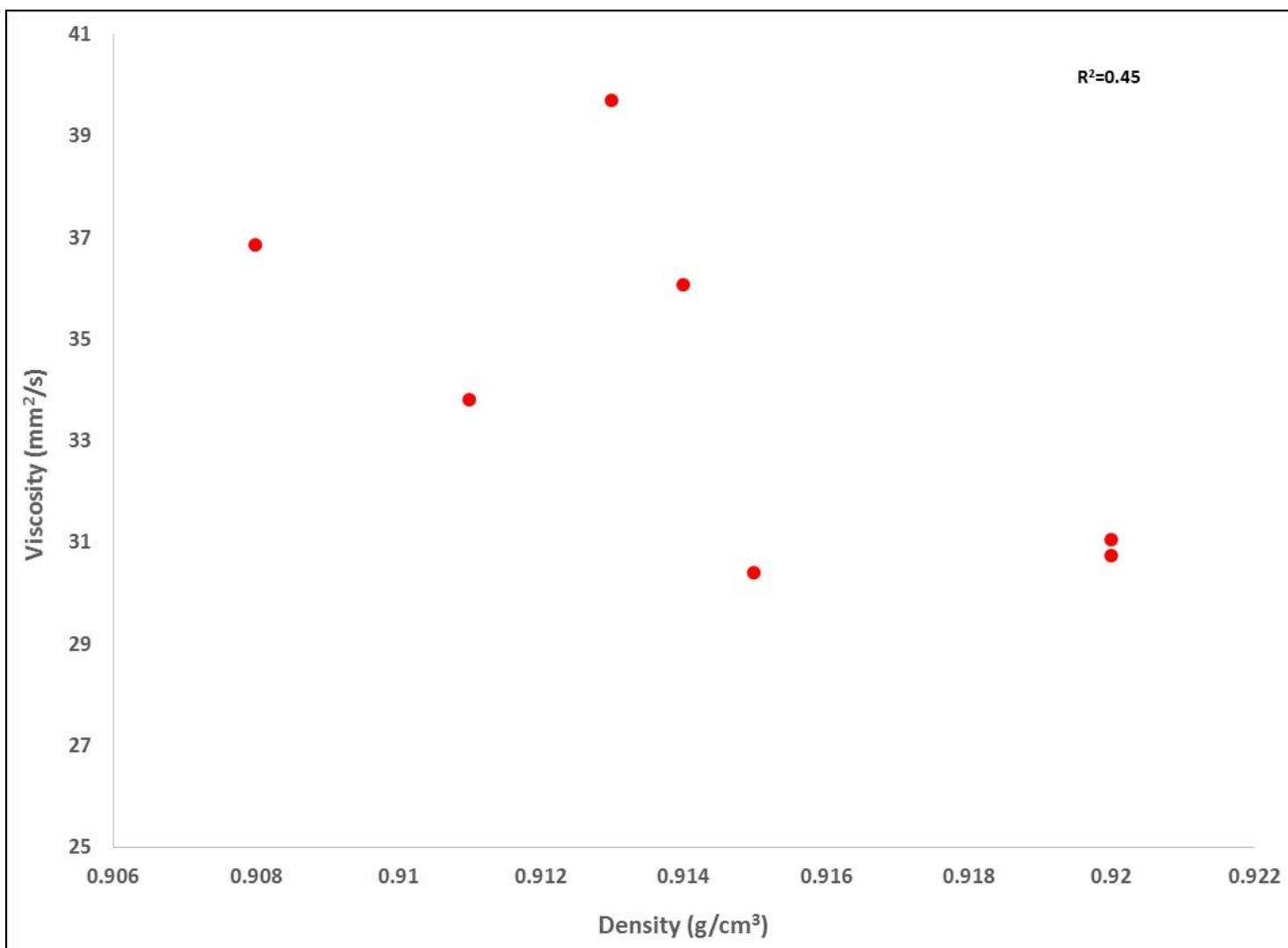


Figure 18: Viscosity vs Density

4.5 CALORIFIC VALUE:

The calorific value of the triglycerides was measured with a bomb calorimeter. Table 7 shows the calorific value of the triglycerides. The calorific value of the triglycerides were lower than that of diesel by about 15% on average. This would suggest that the fuel consumption would be higher than diesel by about 15%.

It is interesting to note that the refined oils, canola and corn, had calorific values in the vicinity of the untreated ones, which would suggest that the purification process does not affect the heating value.

Table 7: Calorific Values

Calorific Value		
	Fuel Sample	LHV MJ/Kg
1	Off Road Diesel	42.8
3	Camelina 25	36.6
4	Camelina 10+214	36.5
5	Camelina 244	34.0
6	Camelina 44+202	36.6
7	Camelina 117+227+148	36.5
8	Canola V2018	36.7
9	Canola V1037	36.9
10	Canola - Albertsons	37.0
11	Juncea Blend	36.8
12	Juncea 0011	36.7
13	Corn Oil - Great Value	36.4
16	Camelina 214	36.3
17	Camelina 10	36.3
18	Camelina 44	36.4

4.6 ENGINE PERFORMANCE:

Two sets of testing were performed on the Tier-II JD4045 engine. Exhaust emissions measurement was carried out using the 5 gas emissions analyzer for THC, CO, NOx, O₂, and CO₂ and the dilution tunnel for particulate matter. The two sets of testing were:

- i. Part Load - 50% Load and 1700 rpm.
- ii. Sweeps – 50, 75, 100% Load at 2200 rpm. Weighted average emissions were calculated based on a 3 point mode per ISO 8178.

NO_x, Particulates, fuel consumption, thermal efficiency, total hydrocarbons and carbon monoxide as percentage of diesel and brake specific emission are shown in the next section. The load and rpm was chosen assuming that farm equipment, such as tractors and combines, using this engine will be running at 50% load 1700 rpm on an average during the day. The absolute 3-mode weighted emissions for NO_x, PM, THC and CO of the various fuels are calculated and graphs are plotted. The thermal efficiencies at 50%, 75% and 100% load at 2200 rpm were also calculated and plotted. Additionally, the emissions were compared to the fuel oil profiles to understand how the fuel structure might impact the emissions, which will be discussed in the next section.

4.6.1 PART LOAD RESULTS

NO_x

Figures 11 and 12 show the NO_x emissions for the Tier-II engine at 50% Load, 1700 rpm. Figure 11 shows the NO_x emissions compared to diesel. The percentages were scattered, but within the +/- 10% range. The Canola V2018 triglycerides was 10% lower than diesel while that of V1037 other was 2.5 % higher than diesel. The Juncea JC0011 was lower than diesel by 3% while the JC002 was 4% higher than diesel. Camelina showed similar trends, where 202+44 and 117+227+148 were lower by 6% and 8% respectively. Camelina 202+44+227+117+148 and 10+214 were higher than diesel by 3% and 8% respectively. The refined oils, Corn, Canola and Coconut, were about 8% lower, equal and 1% higher than diesel respectively. The peak pressure of combustion of vegetable oils tends to be higher than diesel. This translates into higher combustion temperature which favors NO_x formation [57, 58]. It is interesting to note that some

measurements concluded that NO_x formations throughout the engine operation range is not uniform.

Figure 12 shows the brake specific NO_x emissions. The brake specific NO_x emission for diesel was approximately 5 g/kWh. The other triglycerides were within +/- 0.5 g/kWh of diesel. Canola V2018 was lower than diesel while Camelina 10+214 had the highest NO_x emissions at 5.4 g/kwh.

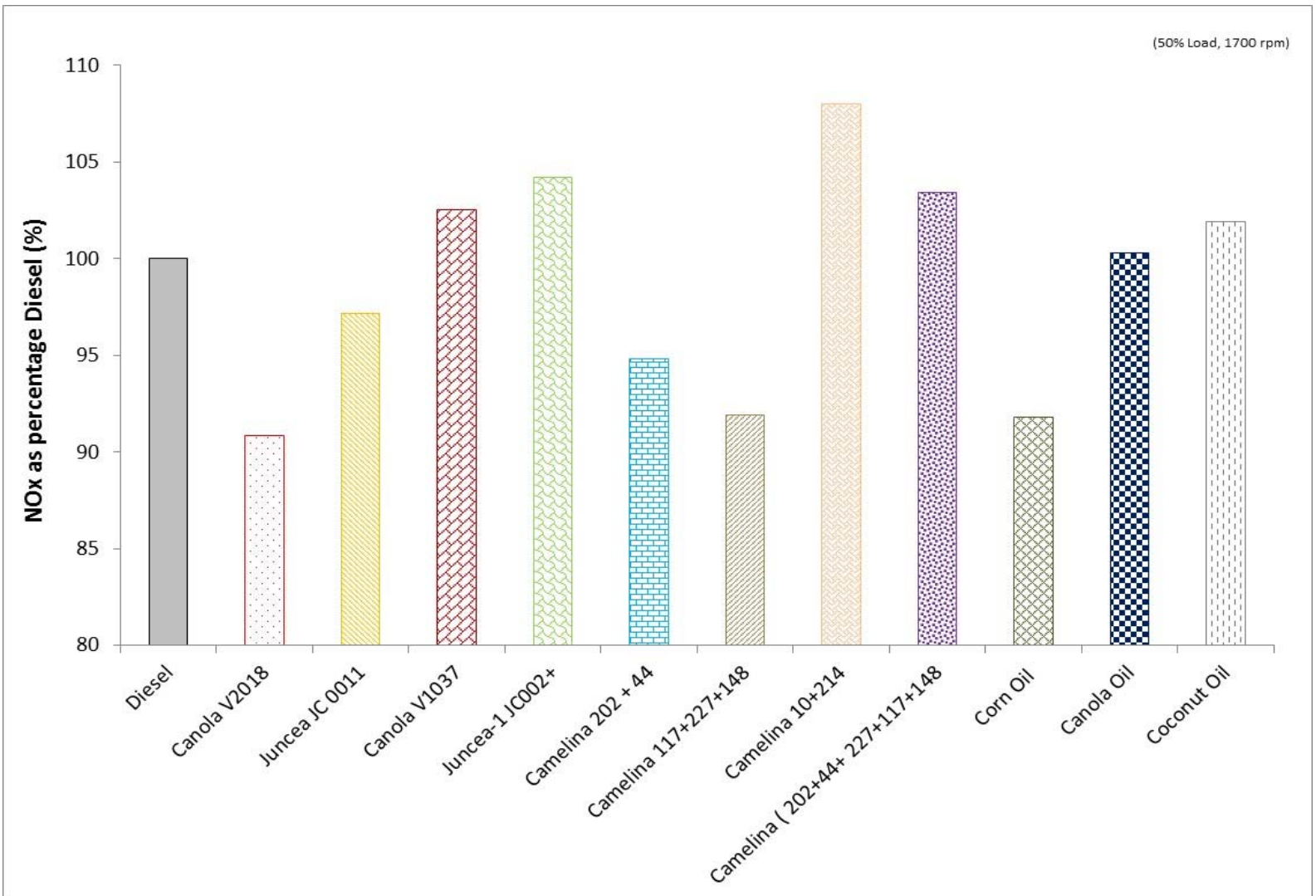


Figure 19: NOx as percentage of Diesel

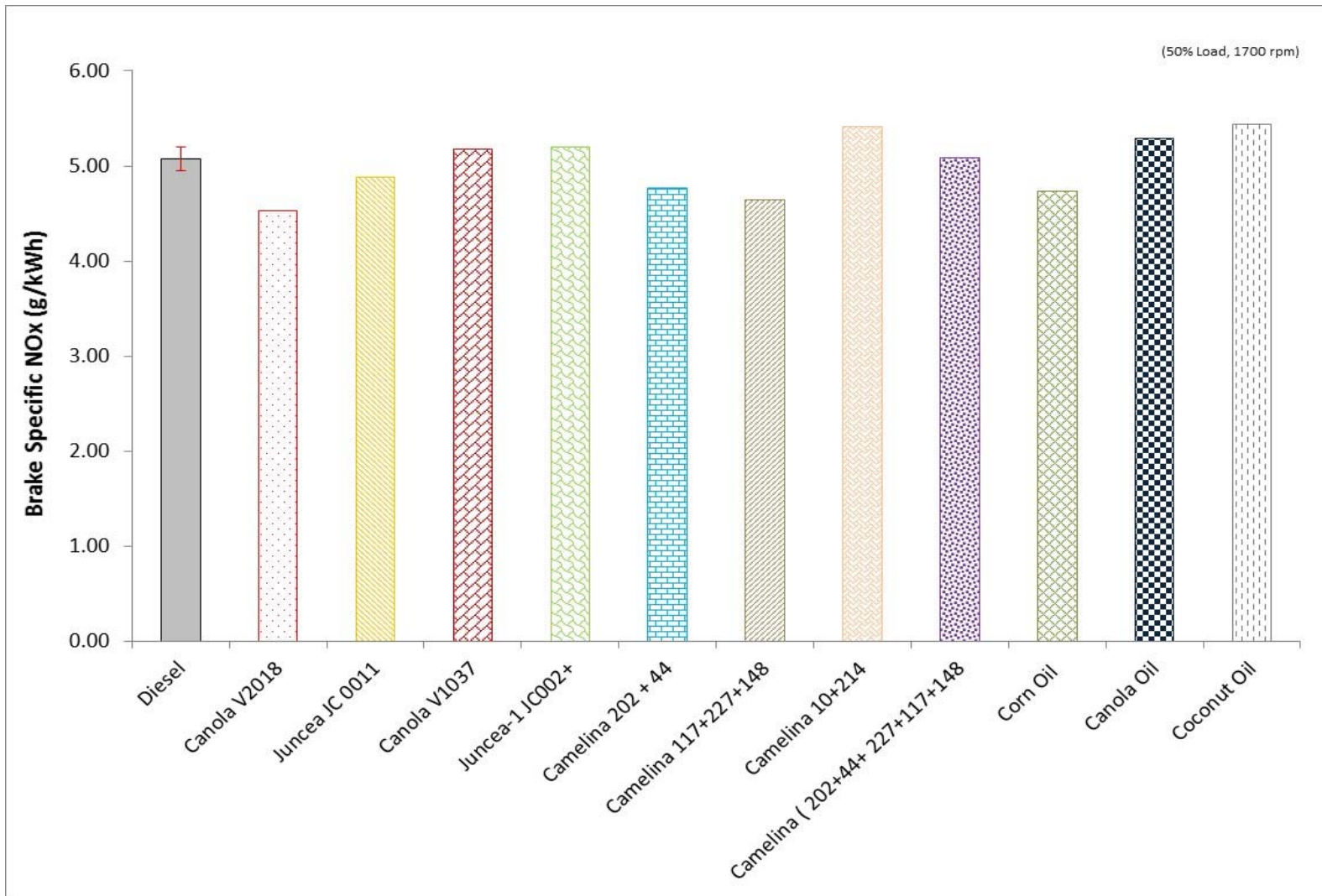


Figure 20: Brake Specific NOx at 50% Load, 1700 rpm

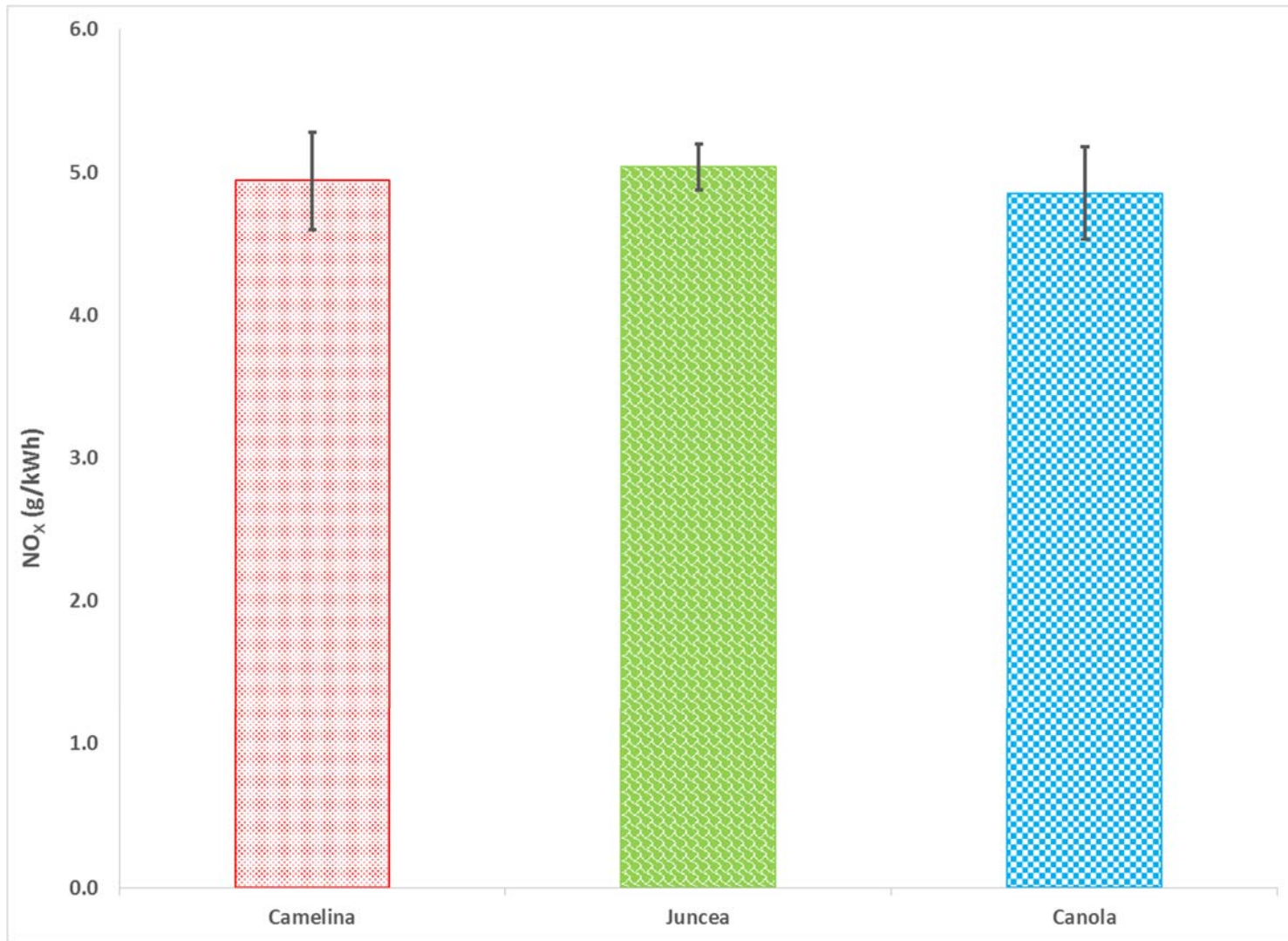


Figure 21: NOx (Similar Oil family grouped)

PARTICULATE MATTER:

Figures 13 and 14 show the PM emissions for the Tier-II engine at 50% Load, 1700 rpm. Figure 13 shows the percentage PM emissions compared to diesel. The percentages were scattered, but overall lower than diesel for most triglycerides. The refined corn was higher than diesel by ~ 30% while Camelina 117+227+148 was lower than diesel by ~ 69%. Canola triglycerides V2018 and V1037 were 37% and 19% lower than diesel respectively. Juncea blends JC0011 and JC002 were ~ 8% and ~ 60% lower than diesel respectively. The refined canola was ~40% lower than diesel while the refined coconut was ~ 8% higher than diesel.

Figure 14 shows the brake specific PM emissions. The brake specific PM emission for diesel was ~ 0.27 g/kWh. The triglycerides were within the set limit of 0.30 g/kWh. Juncea JC002 had the lowest PM emissions ~0.12 g/kWh while Camelina 202+44+227+117+148 blend had the highest of 0.24 g/kWh. Amongst the refined triglycerides, Canola had the lowest of ~0.11 g/kWh while Corn had the highest of 0.31 g/kWh.

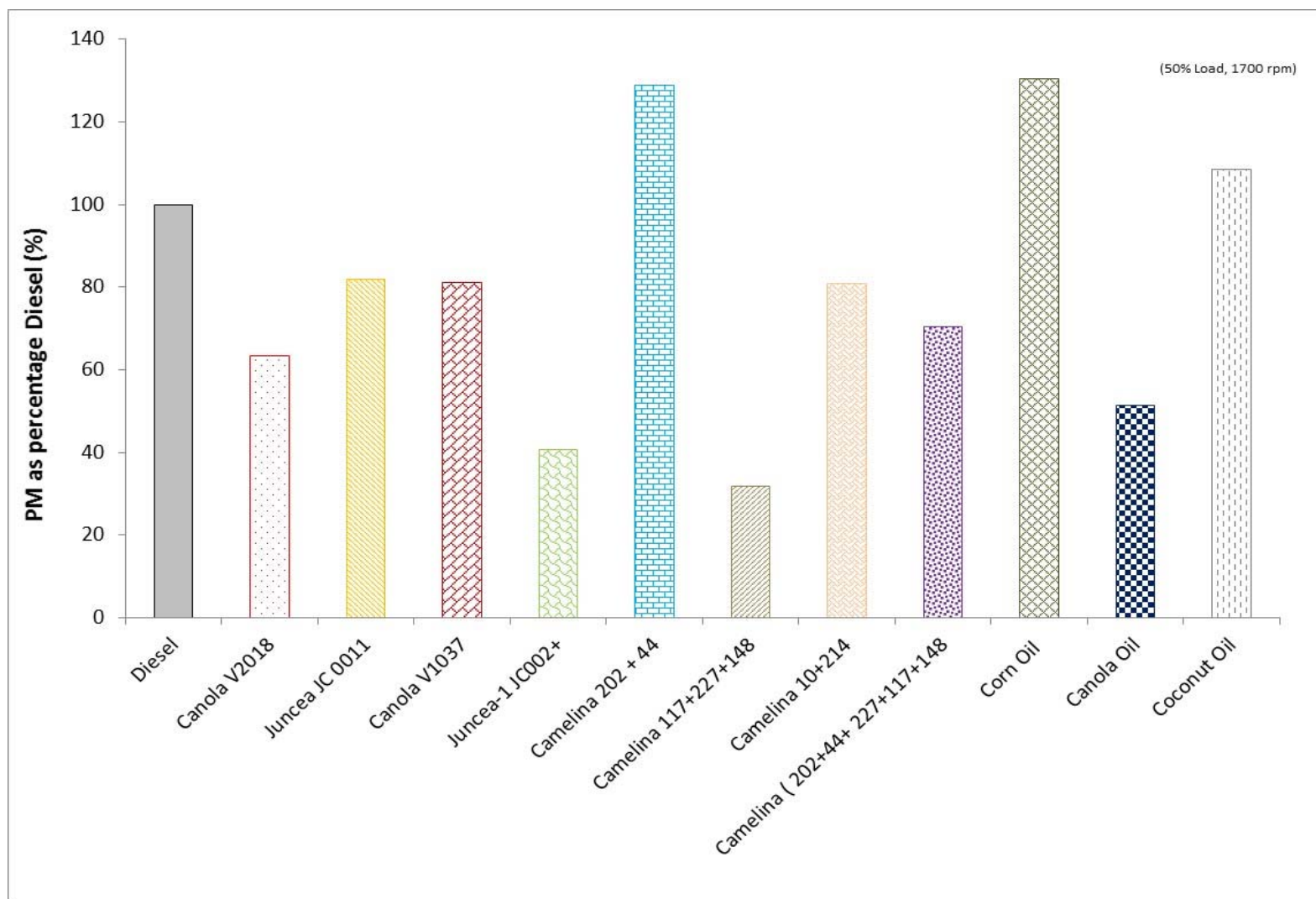


Figure 22: PM as percentage of Diesel

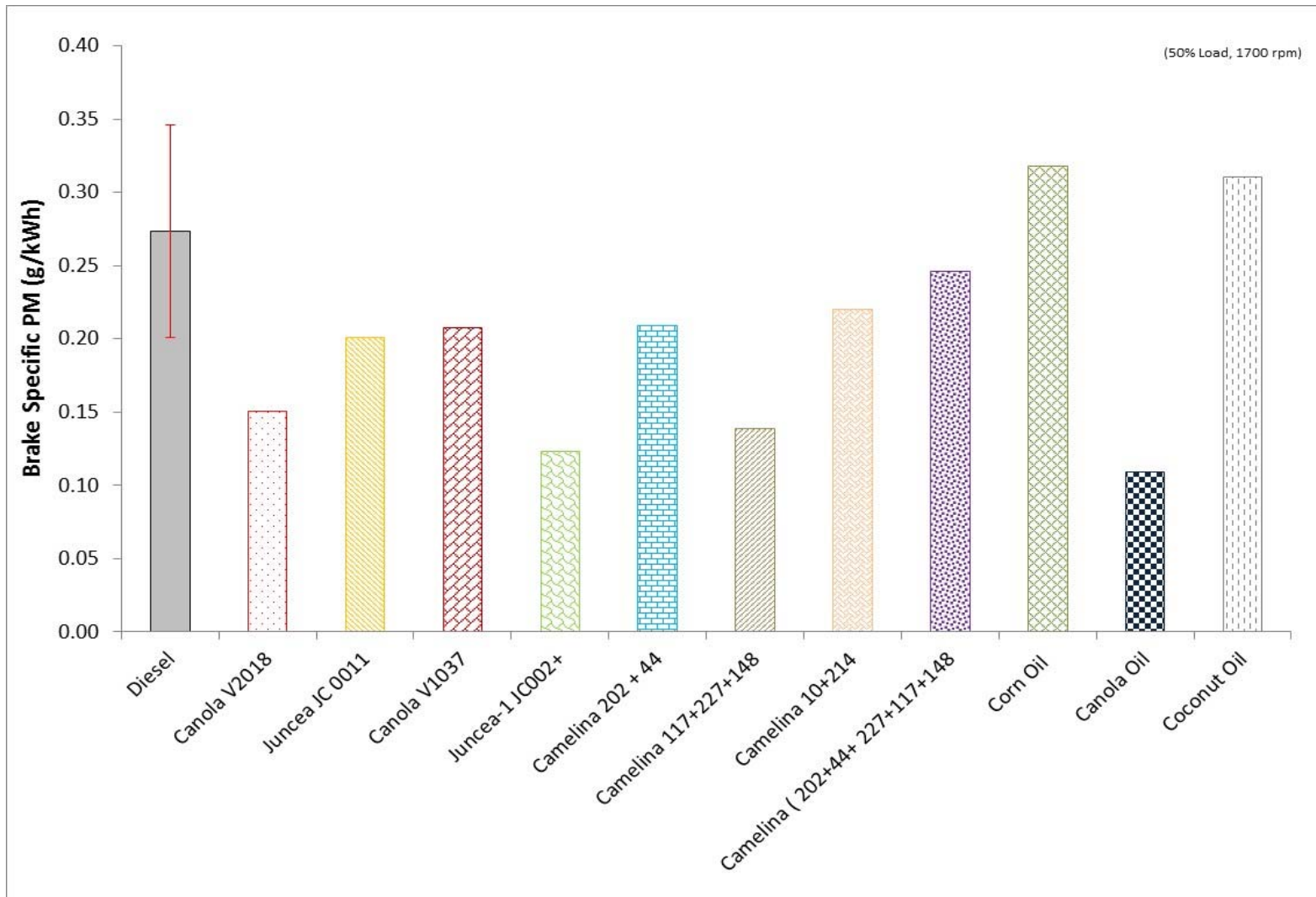


Figure 23: Brake Specific PM Emission at 50% Load, 1700 rpm

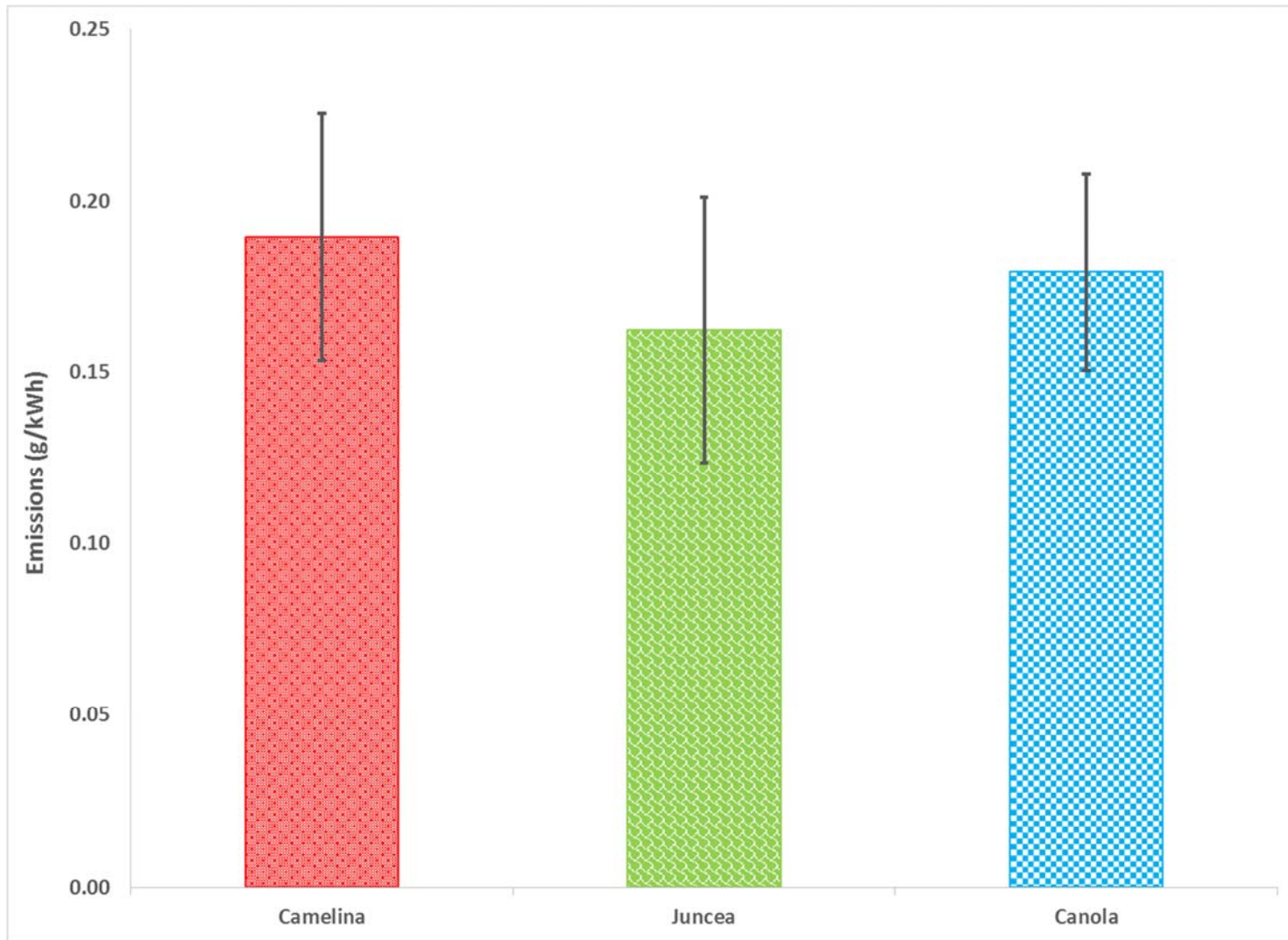


Figure 24: PM (Similar oil family Groupe)

FUEL CONSUMPTION

Figures 15 and 16 show the fuel consumption for the Tier-II engine at 50% Load, 1700 rpm. Figure 15 shows the percentage fuel consumption compared to diesel. The triglyceride percentages were higher than diesel. The fuel consumption showed a correlation to the calorific value. Triglyceride lower heating values are approximately 15% lower than diesel. The data shows triglyceride fuel consumption was higher than diesel by approximately 12 to 15%, which is consistent with the difference in lower heating value. The Camelina 117+227+148 blend had approximately 1% lower fuel consumption than diesel. The refined oils, Corn, Canola and Coconut, were about 1%, 12% and 17%, respectively, higher than diesel. Figure 16 shows the brake specific fuel consumption. Diesel has a fuel consumption of ~ 228 g/kWh (2.83 gallons/hr). The other triglycerides had higher fuel consumption. Canola V1037 and Juncea JC002 had fuel consumption of ~ 260 g/kWh (2.96 gallons/hr) and ~ 264 g/kWh (3.00 gallons/hr) respectively. Amongst the refined oils, Corn had the lowest fuel consumption of ~ 230 g/kWh (2.84 gallons/hr) followed by Canola and Coconut with ~ 256 g/kWh (2.91 gallons/hr) and 267 g/kWh (3.03 gallons/hr), respectively.

Based on the volume, Canola V1037 was higher than diesel by 4.6% and Juncea JC002 by 6%. The store brought Corn was higher by 0.35%, Canola by 2.8% and Coconut by 7%. Thus there is no significant change in the fuel consumption due to purification – degumming and de-waxing.

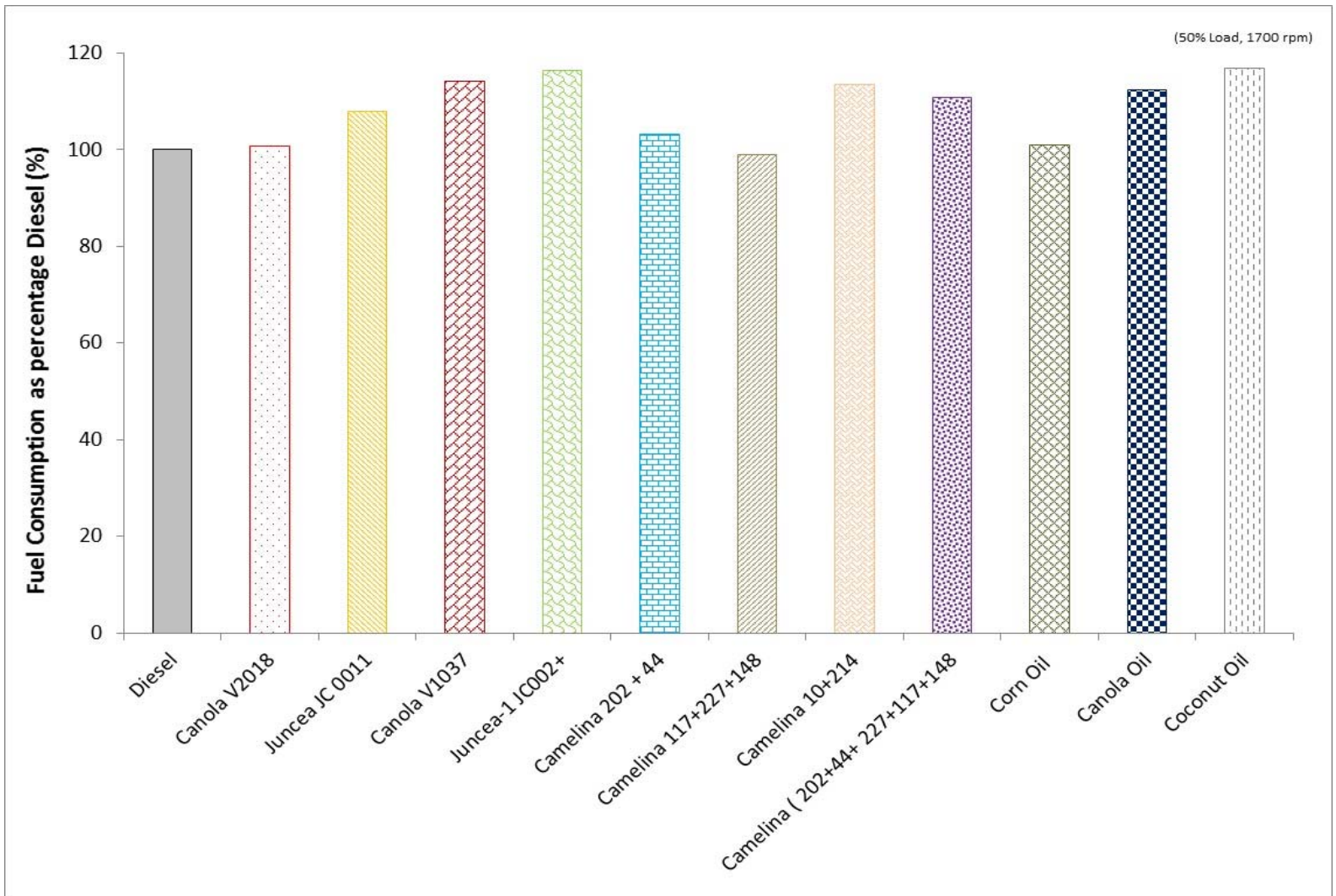


Figure 25: Fuel Consumption as percentage of Diesel

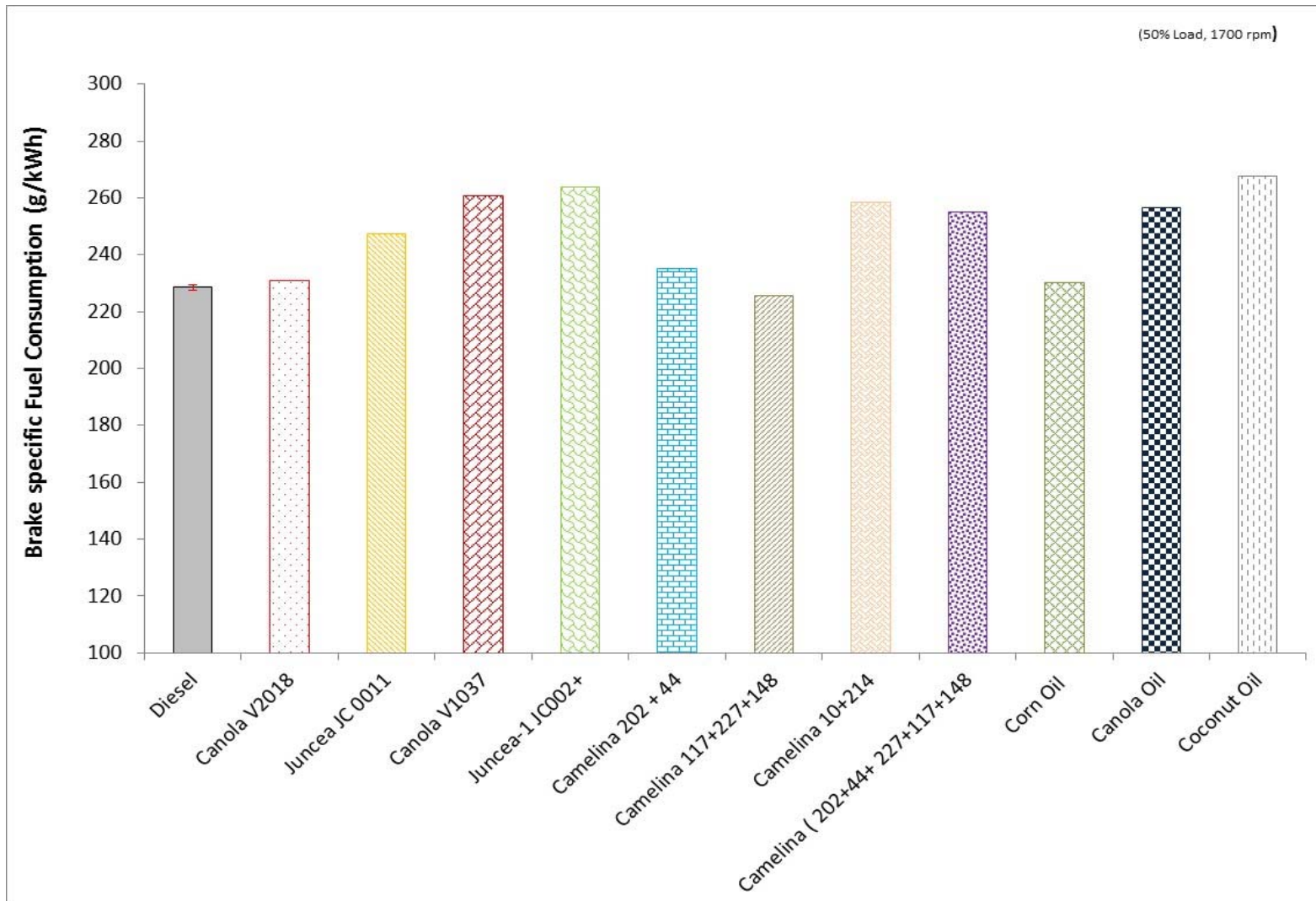


Figure 26: Brake specific fuel consumption at 50% Load, 1700 rpm

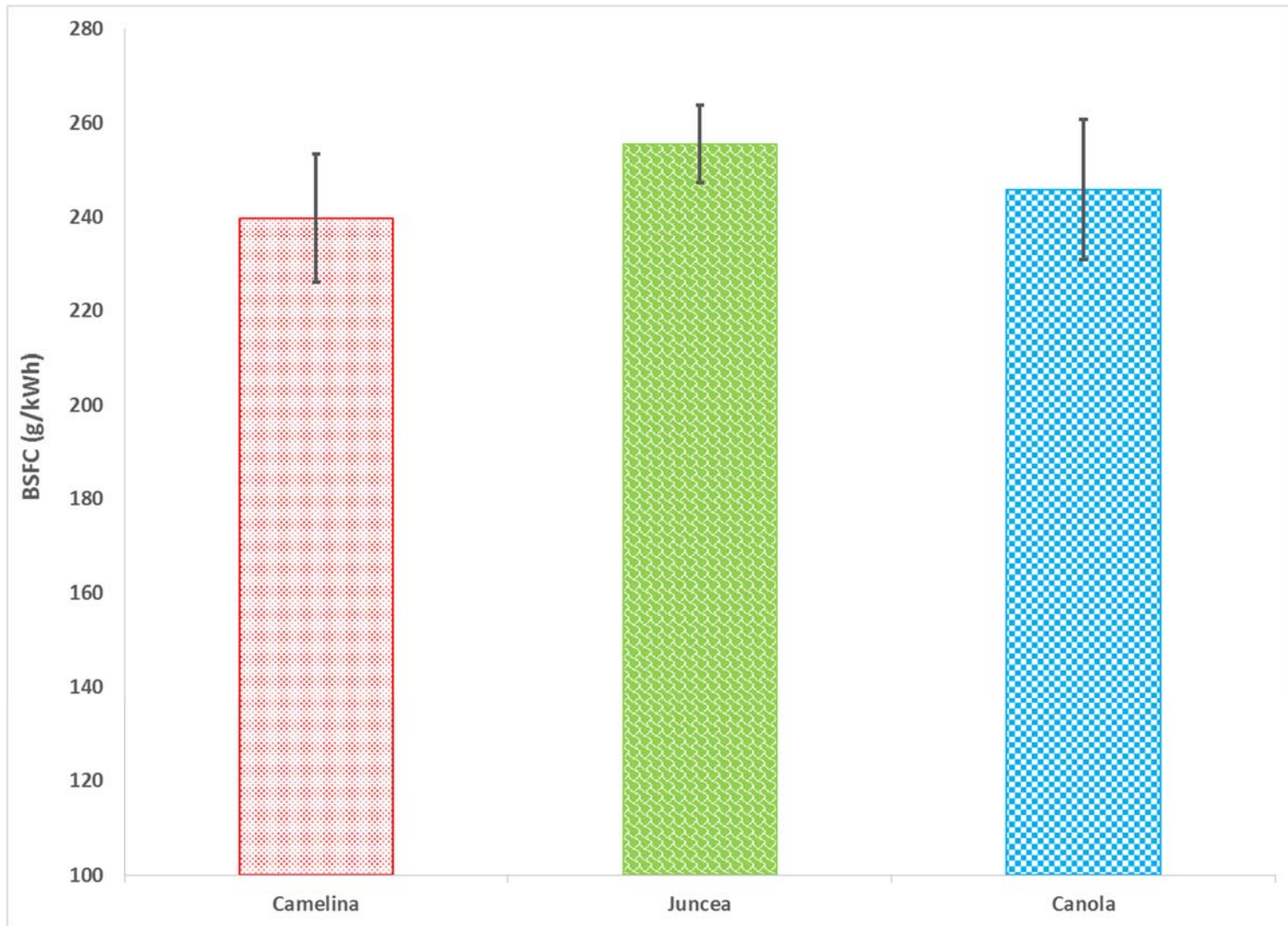


Figure 27: BSFC (Similar oil family Grouped)

BRAKE THERMAL EFFICIENCY

Figures 17 and 18 show the brake thermal efficiency for the Tier-II engine at 50% Load, 1700 rpm. Figure 17 shows the percentage brake thermal efficiency as compared to diesel. The percentages were scattered, but overall higher than diesel by about 3% to 18%. Canola and Camelina were the highest by about 15% and 18% respectively. The other blends were about 2% to 8 % higher than diesel. The refined oils, Corn, Canola and Coconut efficiencies were about 16%, 3% and 0.3% higher than diesel, respectively. Figure 18 shows the absolute brake thermal efficiency. The brake thermal efficiency for diesel was ~ 37%. The triglycerides had a higher efficiencies than that of diesel. Canola V2018 and Camelina 117+227+148 had efficiencies of 42.5% and 43.5%, respectively. Juncea-1 JC002+ had an efficiency of 37.05 and Canola V1037 has an efficiency of 37.46% which is close to that of diesel. The refined oils – Corn, Canola and Coconut's had efficiencies of 43% 38%, 38% respectively.

The higher efficiency of the triglycerides can be attributed to various factors. There are studies that conclude the brake thermal efficiency to be slightly lower than diesel while some of them mention them to be as high as 18% more than diesel. The concept of Air utilization factor plays a role. The oxygen content in the triglycerides help in increasing the air utilization which in turn helps the engine run at a higher efficiency[59]. This could be due to the improved lubricity, reduced friction and the chemical composition of the fuel as compared to diesel. Some researchers have found that the presence of fatty acids in the fuel improves ignition quality, fuel flow properties and fuel stability [60]. Due to the high bulk modulus of vegetable oils, the initiation of the fuel into the combustion chamber

is earlier than as compared to diesel due to the shock waves after the fuel pump causing an early lift of the needle. This initiates an earlier combustion of the fuel and a longer combustion of the fuel which helps in efficient burning of the fuel [61]. Mathematically lower value of the product of calorific value and fuel consumption as compared to diesel for the same power output[62].

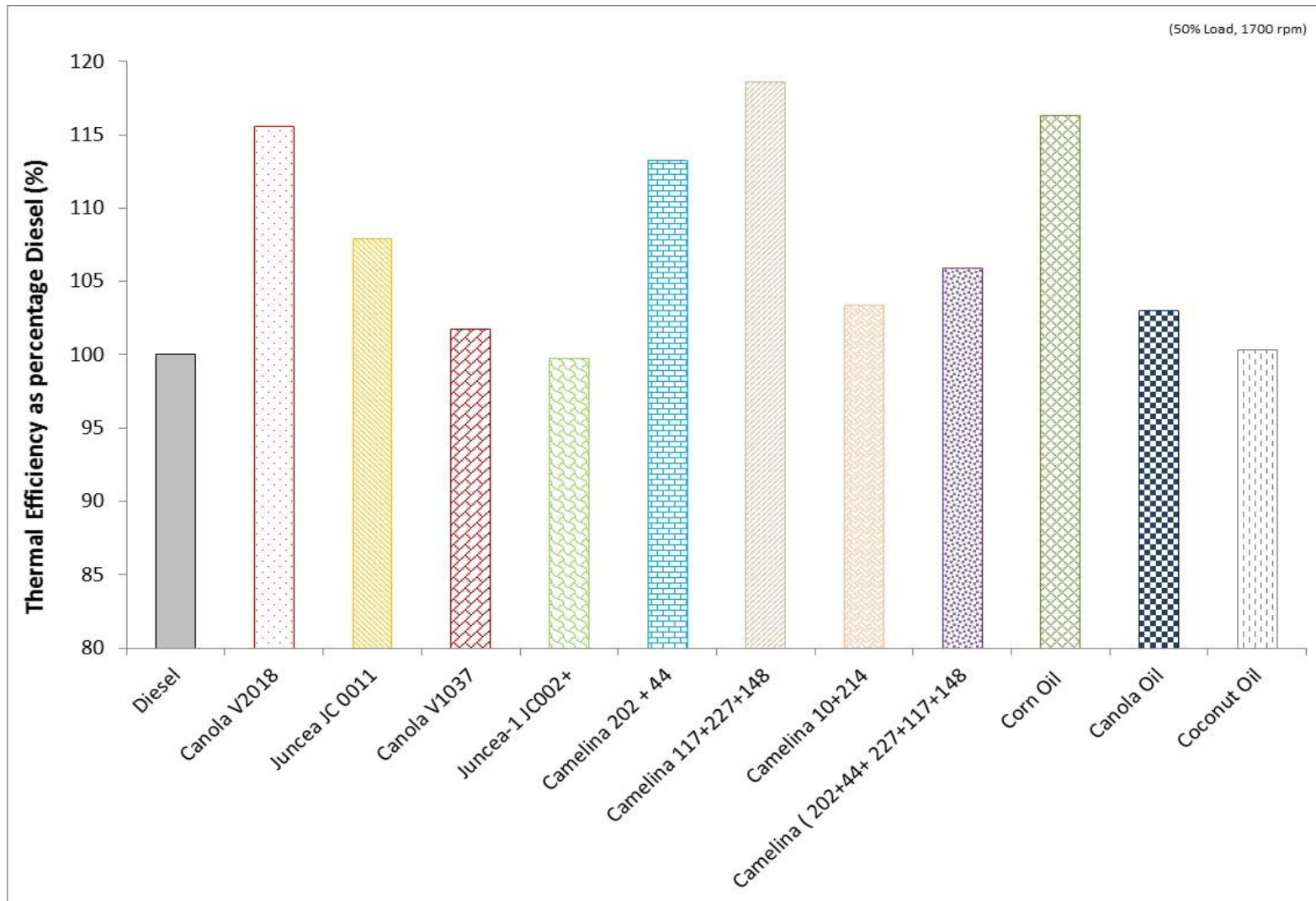


Figure 28: Thermal Efficiency as percentage of Diesel

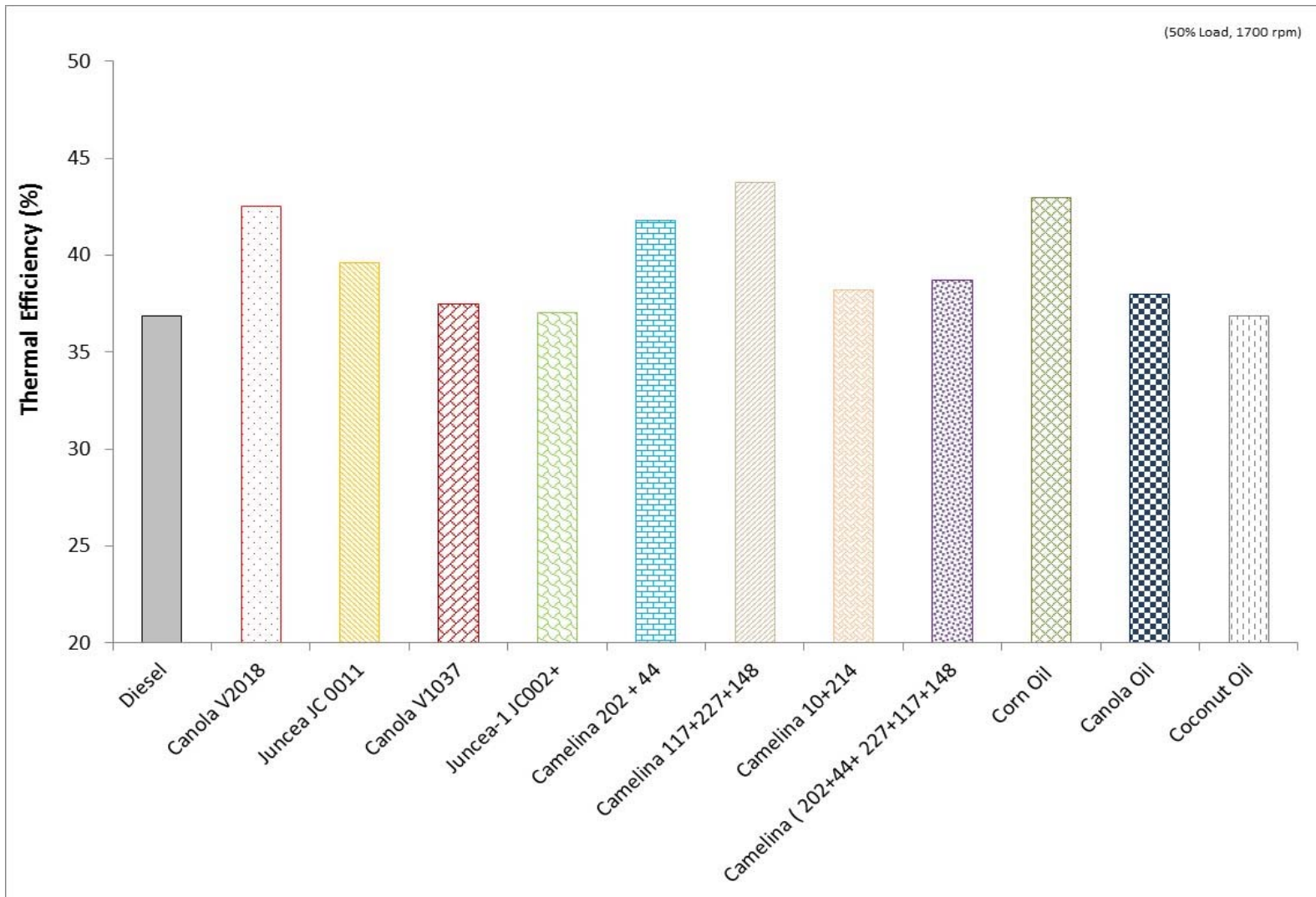


Figure 29: Brake Specific Thermal Efficiency, 50% Load, 1700 rpm

TOTAL HYDROCARBON:

Figures 19 and 20 show the THC emissions for the Tier-II engine at 50% Load, 1700 rpm. Figure 19 shows the percentage THC emissions compared to diesel. The percentages are scattered, but within the +/- 5% range on an average. Camelina 10+214 triglyceride was 10% higher than diesel while the Camelina 117+227+148 was approximately 5.5 % lower than diesel. The Juncea-1 JC002 was higher than diesel by ~ 14% while Juncea JC0011 was higher than diesel by approximately 3.5%. Canola showed similar trends, where V2018 was lower by ~ 4% and V1037 was higher by ~ 6%. The refined oils – Corn and Canola were higher than diesel by ~4.5% and 12% respectively, while coconut was lower by ~ 3.3%.

Figure 20 shows the brake specific THC emissions. The brake specific THC emission for diesel was ~ 0.29 g/kWh. The emissions from triglycerides were higher on an average ranging from 0.3 g/kWh to 0.42 g/kWh. Canola V2018 was lower than diesel at ~ 0.25 g/kWh while Camelina 202+44+227+117+148 had the highest THC emission at 0.42 g/kWh.

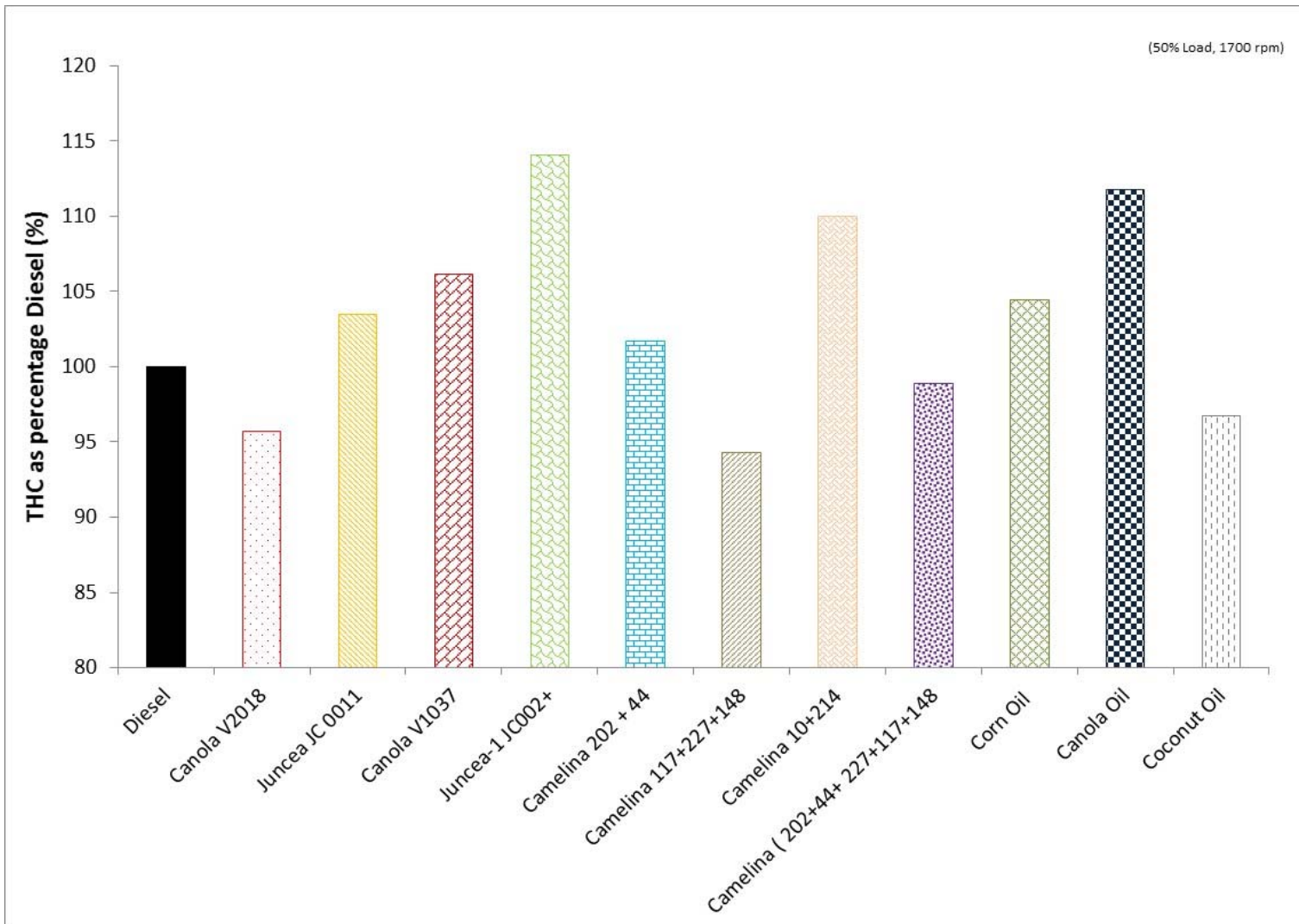


Figure 30: THC as percentage of diesel

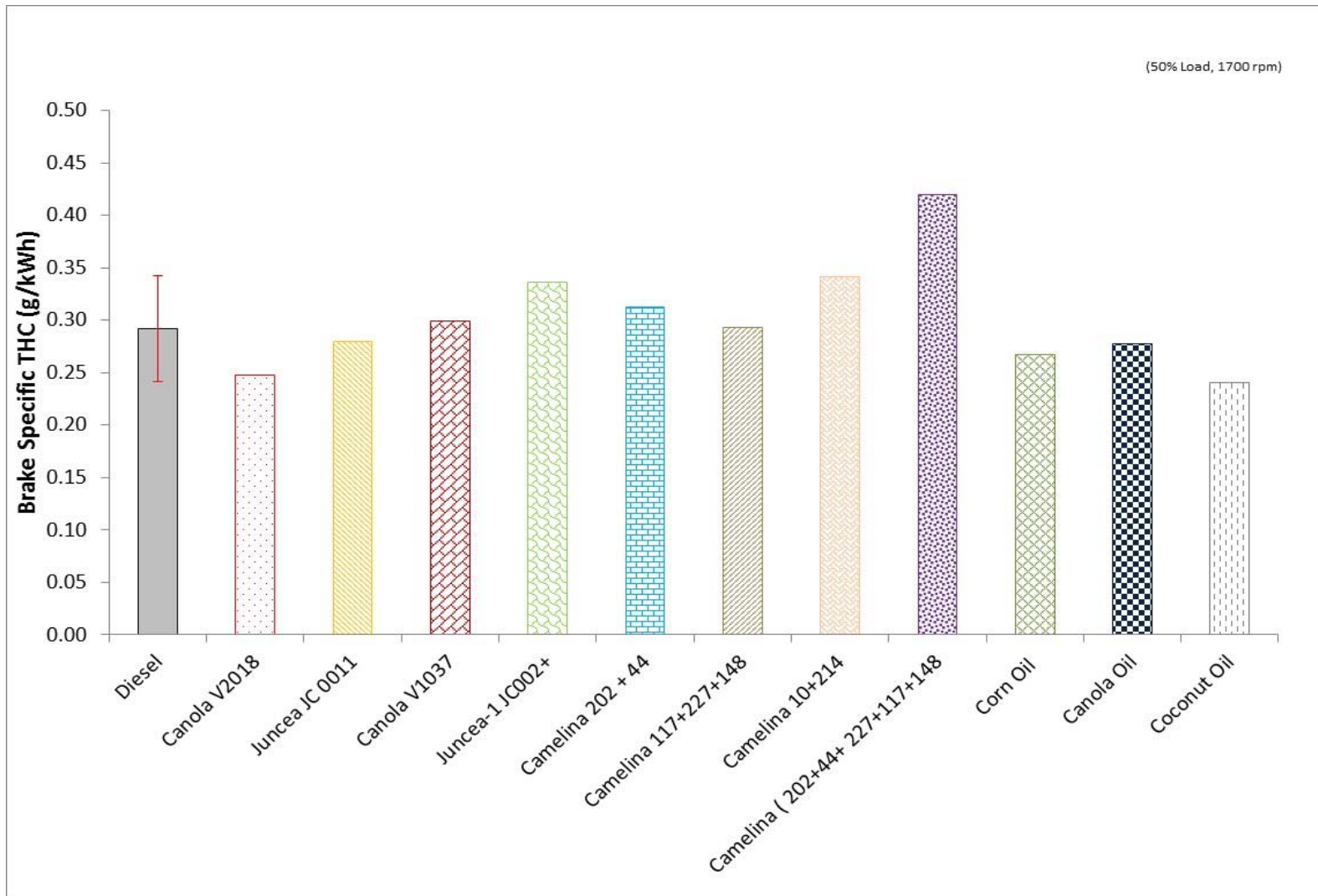


Figure 31: Brake Specific THC 50% Load, 1700 rpm

CARBON MONOXIDE:

Figures 21 and 22 show the CO emissions for the Tier-II engine at 50% Load, 1700 rpm. Figure 21 shows the percentage CO emissions compared to diesel. The percentages are scattered, but lower than diesel by approximately 7.5% to 28%. Canola V2018 and V1037 blends were lower by approximately 22% and 10% respectively. Juncea JC 0011 and JC002 blends were lower by approximately 14% and 8% respectively. CO emissions from Camelina triglycerides was lower by ~ 18% to ~ 7.5%. The refined oils – Corn, Canola and Coconut were lower than diesel by ~ 18%, 10% and 25% respectively. This is in agreement with various literature available. The vegetable oils undergo chemical reactions under high temperature (cracking) and pressure resulting in polymerization at the spray core. This heavy, low volatile spray base has difficulty in atomization and hence the air-fuel mixture is affected resulting in locally rich mixtures producing more CO due to lack of oxygen [57, 58].

Figure 22 shows the brake specific CO emissions. The brake specific CO emission for diesel was approximately 1.7 g/kWh. The emissions from triglycerides were lower on an average ranging from 1.3 g/kWh to 1.6 g/kWh. The refined oils – Corn, Canola and Coconut had CO emissions of ~ 1.34 g/kWh, ~1.47 g/kWh and ~ 1.25 g/kWh, respectively.

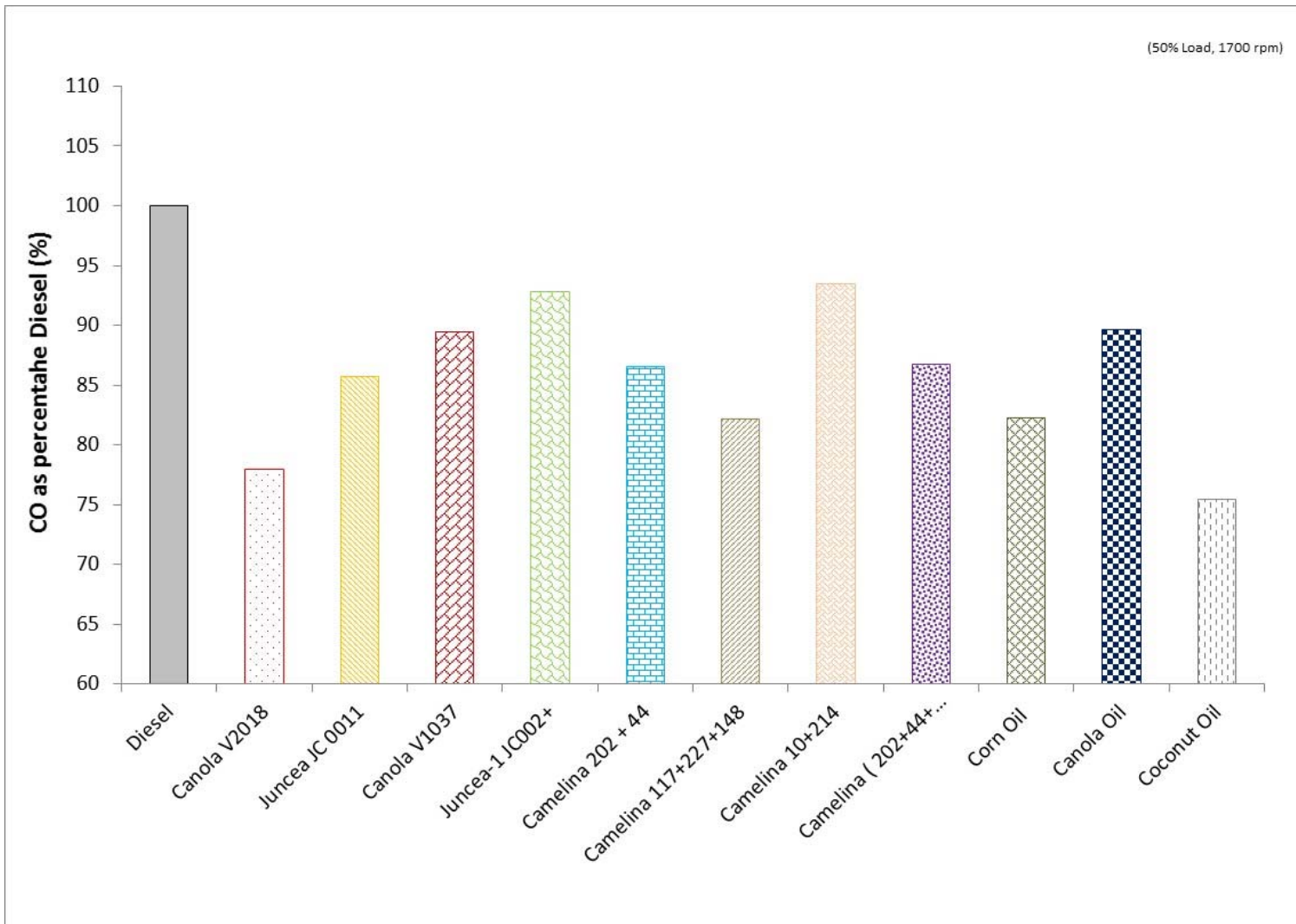


Figure 32: CO as percentage diesel

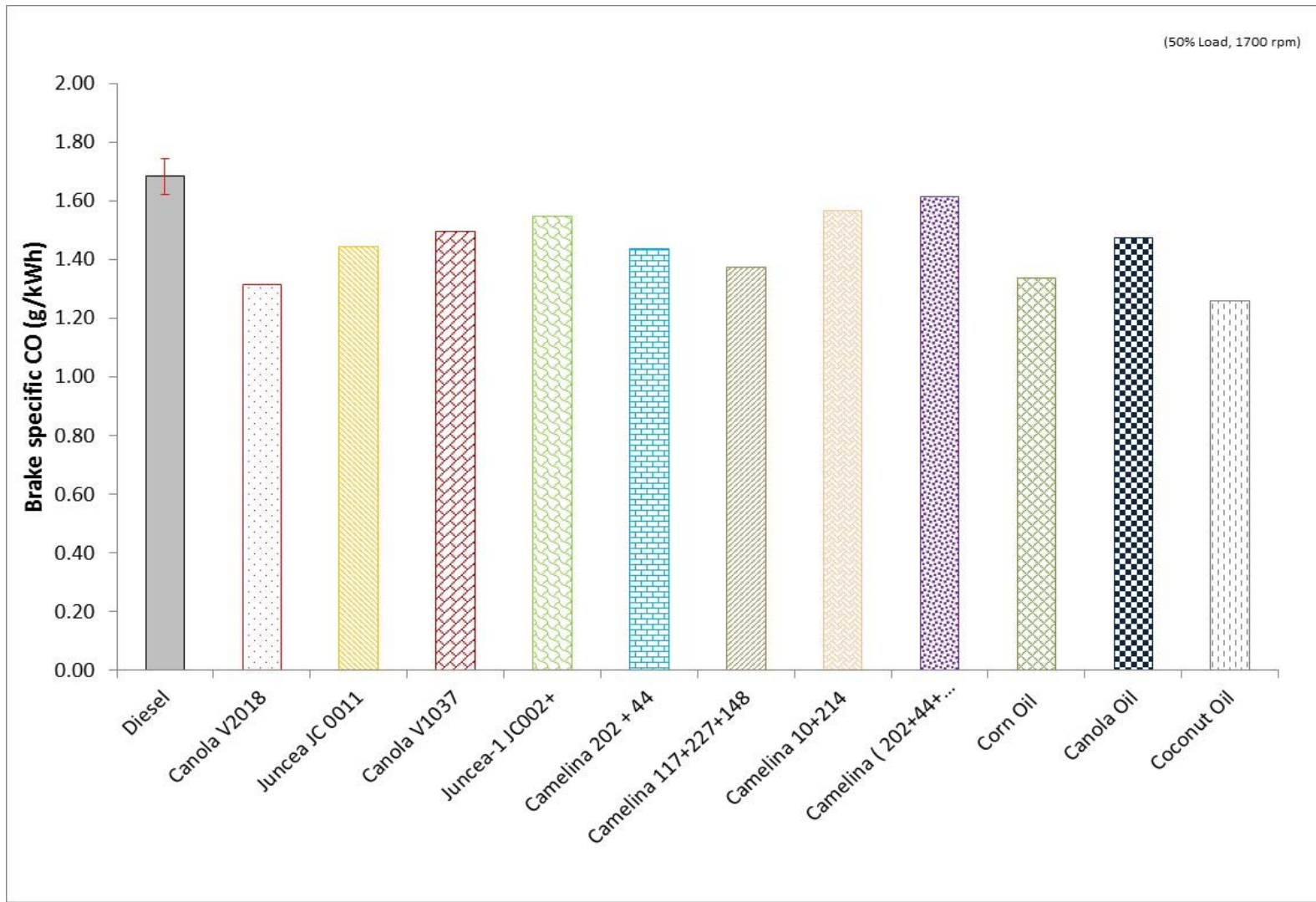


Figure 33: Brake Specific CO 50% Load, 1700 rpm

4.6.2 ISO 8178 WEIGHTED AVERAGES:

Figures 23, 24, 25 and 26 show the weighted average brake specific emissions of NO_x, PM, THC and CO using ISO 8178 Test Cycle D1, which contains 3 modes. The three modes are 100% Load-Rated speed, 75% Load-Rated speed and 50% Load-Rated speed.

NO_x

Figure 23 shows the weighted average brake specific NO_x. The weighted average brake specific NO_x of diesel was 4.92 g/kWh. The triglycerides were generally slightly higher than diesel, with the exception of Camelina 2+3 which was slightly lower than diesel at 4.76 g/kWh. Canola V2018 had the highest NO_x emission at 5.67 g/kWh while Canola V1037 had an NO_x emission of approximately 5 g/kWh. The refined oils were also higher than diesel in the range 5.25 g/kWh for Coconut oil to 5.5 g/kWh for Corn oil.

The Tier-II emission regulation specifies the sum of NO_x + (NMHC) as 6 g/kWh. Since diesel fuel was used, the presence of methane in the fuel is practically zero. Hence the sum of NO_x and THC is assumed to be the same as NO_x and NMHC. By adding the THC to NO_x, we can conclude that all these fuels meet the NO_x + NMHC limit of 6 g/kWh, except Canola V2018.. Table 8 shows the NO_x and THC data for all fuels tested.

PM

Figure 24 shows the weighted brake specific PM. The brake specific PM of diesel was 0.27 g/kWh. The triglycerides were generally scattered around diesel. Amongst the unrefined triglycerides, Juncea JC0011 had the lowest PM emission at 0.15 g/kWh while Canola V1037 was higher than diesel at 0.51 g/kWh. Camelina 2+3 has a PM emission of 0.19 g/kWh. Amongst the refined oils, Canola had the lowest PM emission with 0.16 g/kWh followed by Coconut with 0.29 g/kWh while Corn had the highest with 0.27 g/kWh. The Tier-II regulation limit for PM is 0.3 g/kWh. All the fuels with the exception of the unrefined Canola, were well within the limit.

THC

Figure 25 shows the weighted brake specific THC. The brake specific THC for diesel was ~ 0.32 g/kWh. The triglycerides were generally scattered around diesel. Amongst the unrefined triglycerides, Camelina 2+3 had the lowest THC emission at ~ 0.28 g/kWh while Canola V2018 was higher than diesel at 0.40 g/kWh. Juncea JC0011 had a THC emission of 0.34 g/kWh. Amongst the refined oils, Canola had the lowest THC emission with 0.19 g/kWh followed by Corn with 0.25 g/kWh while Coconut had the highest with 0.28 g/kWh. As discussed in the NO_x section, the following table shows the sum of NO_x and THC and compares it to the Tier-II emission standards:

Table 8:NO_x+THC Tier-II Emission

	NO_x	THC	NO_x + THC
Diesel	4.92	0.32	5.24
Camelina 2+3	4.76	0.28	5.04
Juncea JC0011	5.00	0.34	5.34
Canola V2018	5.63	0.40	6.03
Canola V1037	5.05	0.35	5.4
Corn Oil	5.46	0.25	5.71
Canola Oil	5.24	0.19	5.43
Coconut Oil	5.25	0.28	5.53

CO

Figure 26 shows the weighted average brake specific CO. The weighted brake specific CO of diesel was 1.40 g/kWh. The triglycerides were generally lower than diesel. This is consistent with the low 50% load, 1700 rpm data. Amongst the unrefined triglycerides, Camelina 2+3 had the lowest CO emission at approximately 1.08 g/kWh, followed by Juncea JC0011 with 1.28 g/kWh while Canola V1037 was highest at 1.37 g/kWh. Amongst the refined oils, Coconut had the lowest CO emission with 0.96 g/kWh followed by Canola with 1.09 g/kWh while Corn had the highest with 1.13 g/kWh.

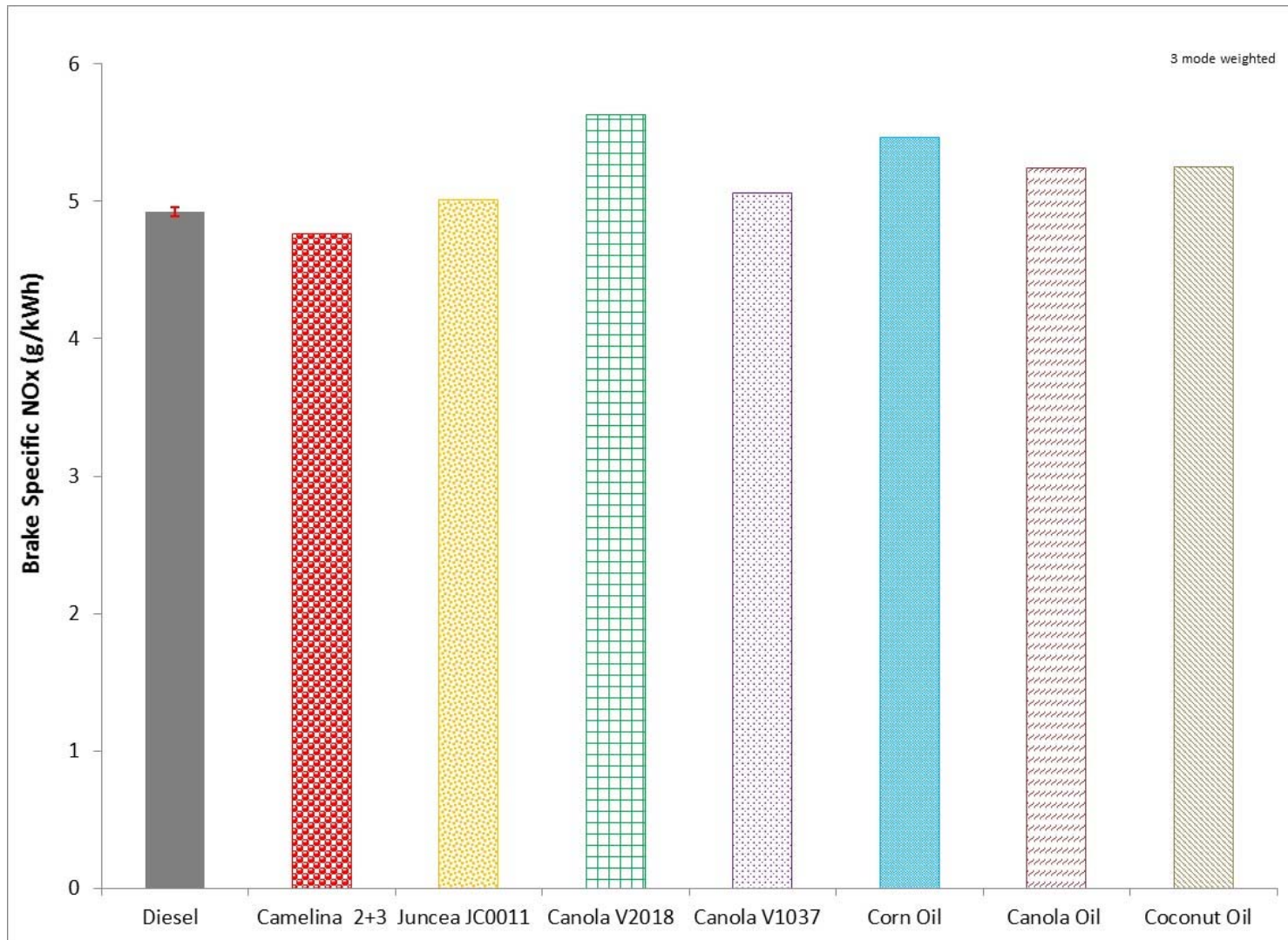


Figure 34: Brake Sp. NOx Weighted (Tier-II)

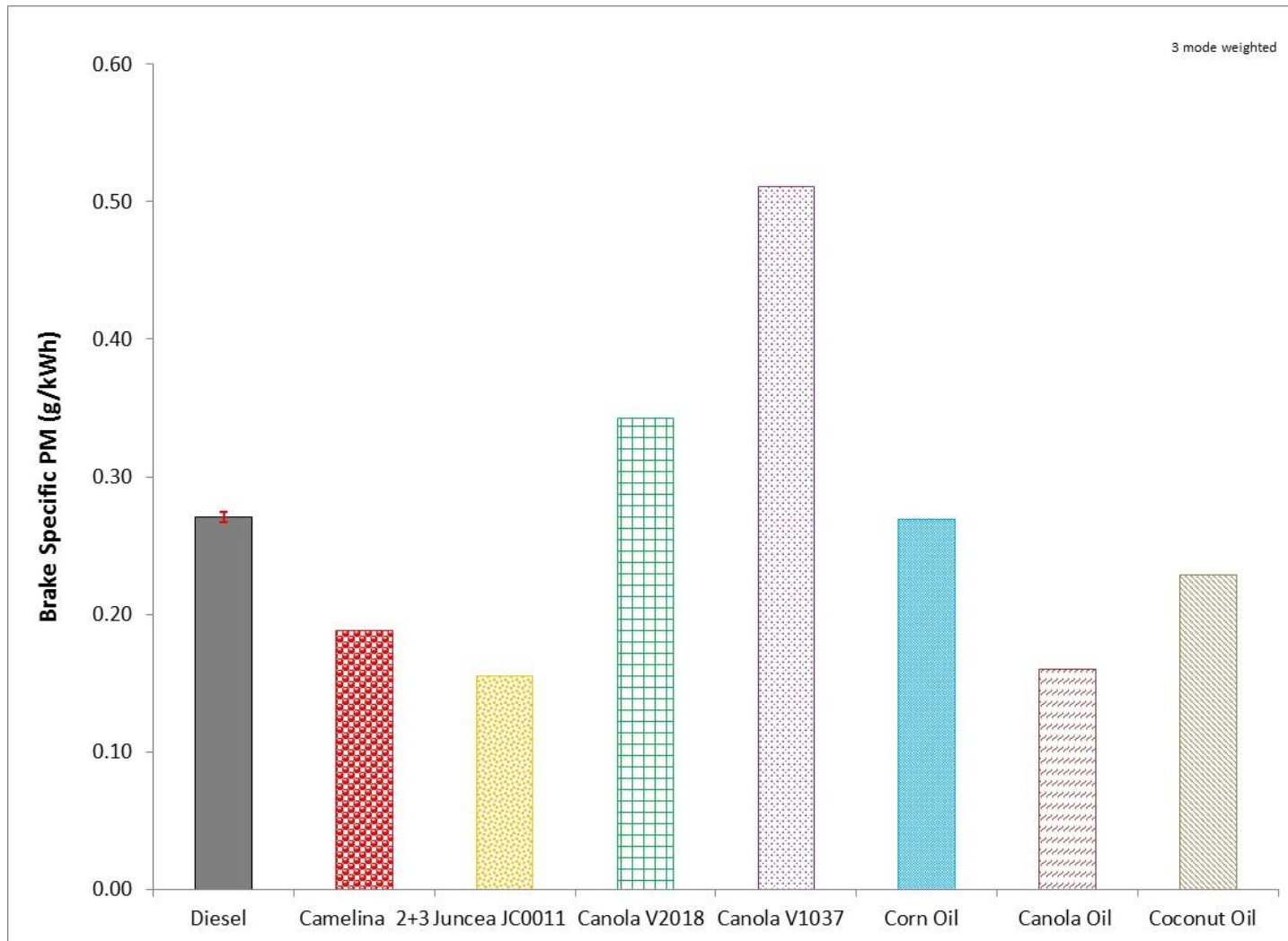


Figure 35: Brake Specific PM Weighted (Tier-II)

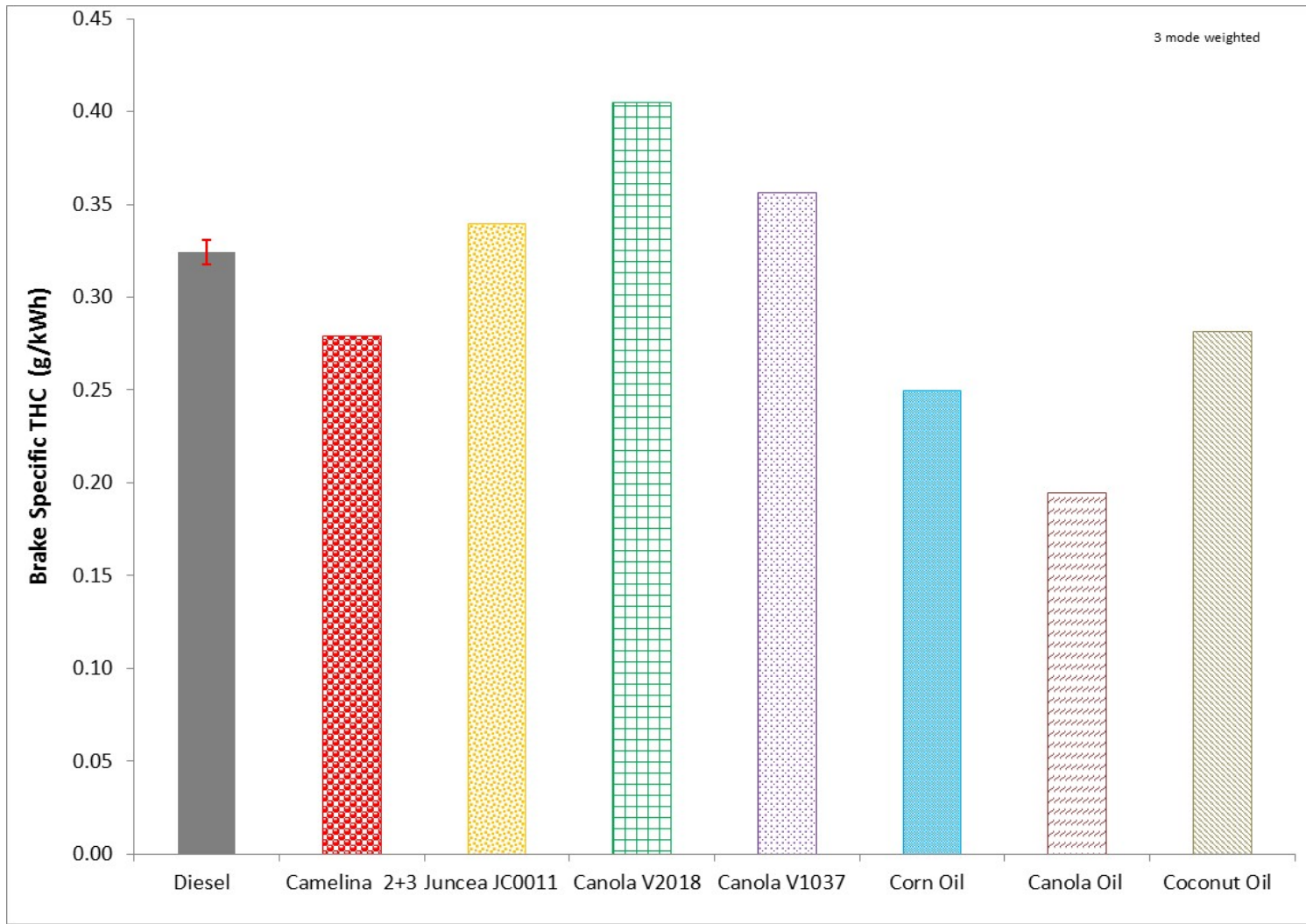


Figure 36: Brake Specific THC Weighted (Tier-II)

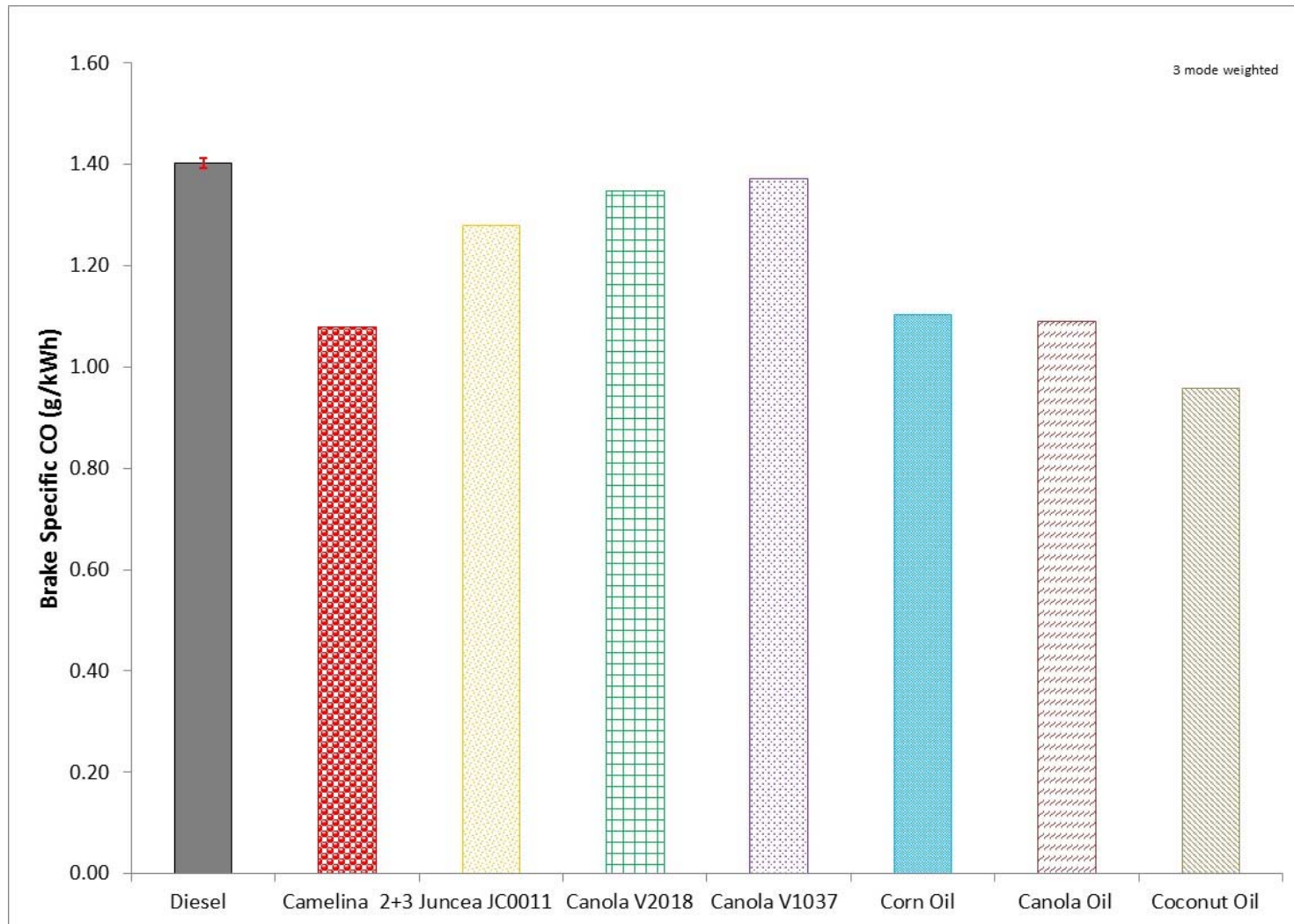


Figure 37: Brake Specific CO Weighted (Tier-II)

4.6.3 THERMAL EFFICIENCY:

Figures 27, 28 and 29 show the brake thermal efficiency of the fuels the three ISO 8178 Test Cycle D1 modes. The three modes for this test cycle are 50% Load, 75% Load and 100% Load at rated speed of 2200 rpm. At 50% Load, 2200 rpm, the diesel thermal efficiency was ~ 35.5%. The triglycerides was generally a little higher than diesel by ~ 0.3% to ~ 1.3%. The refined corn was the highest with 37.3%. The unrefined Canola V2018 was the lowest with 23.9% followed by the unrefined Camelina 2+3 at 27.90%. At 75% Load, 2200 rpm, the diesel thermal efficiency was ~ 37.3%. The triglycerides were generally a little higher than diesel by ~ 0.3%, with the exception of Camelina 2+3 which was higher at 46.01%. At 100% Load, 2200 rpm, the diesel thermal efficiency was 38.1%. The triglycerides was generally a little higher than diesel by ~ 1.0%, with the exception of Camelina 2+3 which was higher at 48.4%. Juncea JC0011 came close second at 43.0%. Amongst the refined oils, Corn was the highest 39.9% followed by Canola with 39.7% and Coconut with 38.2%.

The overall trend is that the thermal efficiency tends to increase as the load increases. The increases for the triglycerides are much significant compared to diesel.

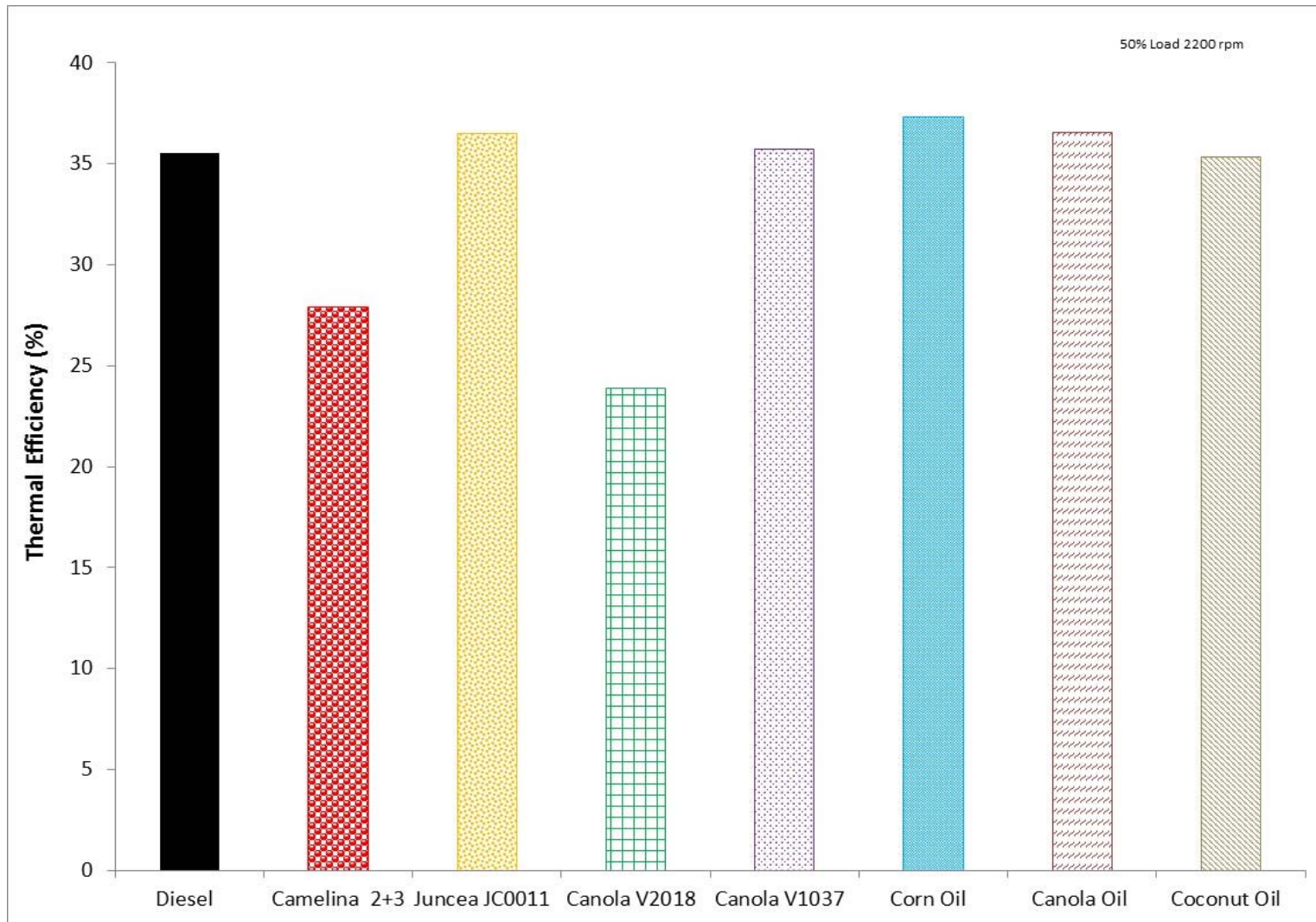


Figure 38: Brake Thermal Efficiency, 50% Load, 2200 rpm

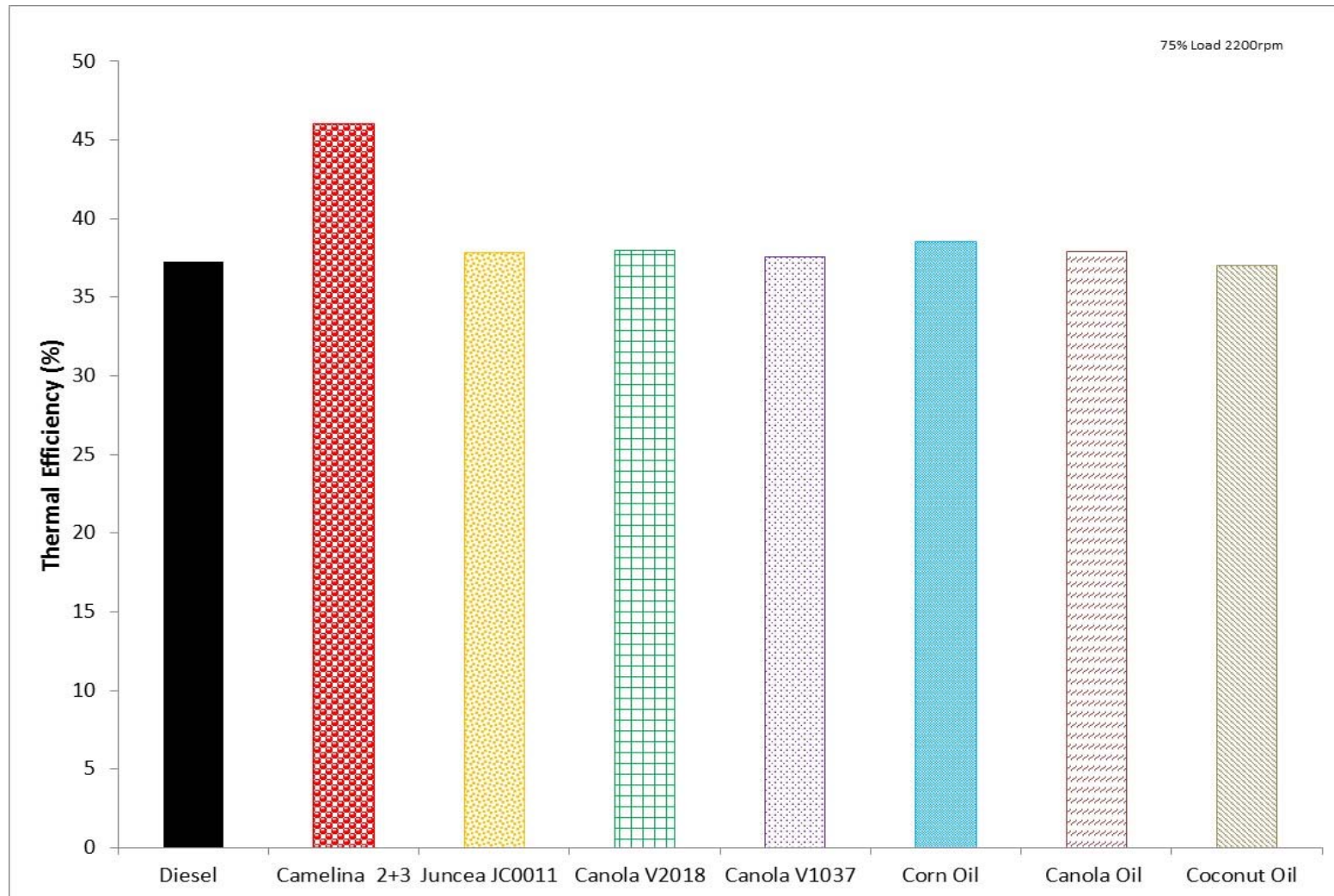


Figure 39: Brake thermal Efficiency, 75% Load, 2200 rpm

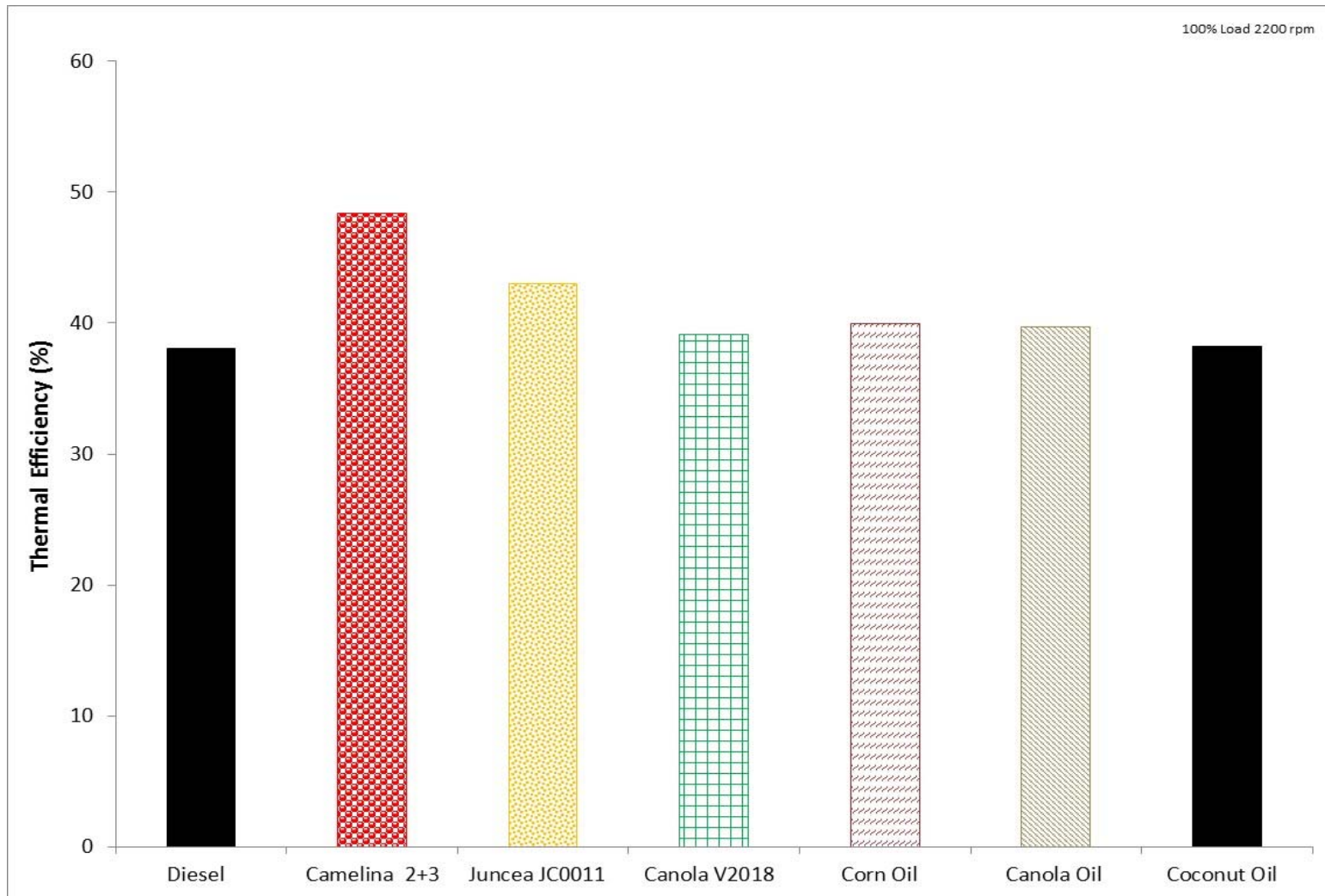


Figure 40: Brake Specific Efficiency, 100% Load, 2200 rpm

4.7 ENGINE PERFORMANCE VS OIL PROFILE

The brake specific emissions, NO_x, THC, CO and PM at 50% load, 1700 were plotted with respect to the average chain length in Figure 30 and with respect to the degree of unsaturation in Figure 3. The trends were similar for all brake specific emissions. Starting with average chain length of 18.0 and 18.02, the numbers gradually increased as the chain length increased to 18.32. After this point, the brake specific numbers saw a decrease as the chain length increased to 19.01. Similar trends are observed in Figure 31 with respect to the degree of unsaturation from 10.29 to 55.14.

However, it is difficult to draw strong conclusions with these trends since the brake specific emissions do not vary substantially. The variation of +/- 5% with one another might not be accepted as a conclusive evidence. A detailed study with a large population and sample size ranging over a large spectrum of chain lengths and the degree of unsaturation will be helpful in understanding the emission trends.

A cumulative average chain length was calculated by grouping the triglycerides in their crop category (e.g. Canola). Figure 32 shows the trends of the brake specific emissions. It shows a slight increase in the emissions with an increase in chain length. It is also interesting to note that that increase in the emissions is proportional to the increase in the chain length.

Similar approach was carried out using the cumulative average degree of unsaturation to analyze the trends in the brake specific emissions. Figure 33 shows the emission trends plotted as a function of the degree of unsaturation that increases slightly as the degree of unsaturation increases. However, the increase is not in proportion to the increase in the degree of unsaturation. This calls for an expressive analysis of the degree of unsaturation

on exhaust emissions[63]. Higher degree of unsaturation increases the ignition delay, adiabatic flame temperature and the injection, this resulting in higher tailpipe emissions. However, for a more conclusive result, studying the degree of unsaturation with the varying percentage of oxygen content in the fuel needs to be studied in detail [64] [65]. Fuel properties like Cetane number is known to increase as the chain length increases or as the branching decreases. Higher cetane number for biofuels is also suitable and it produces lower emissions. Cetane number decreases as the number of double bond or the degree of unsaturation increases. Since biofuels are a mixture of various fatty acid esters, the co-relation to chain length over a small range weakens the comparative study [50, 66, 67].

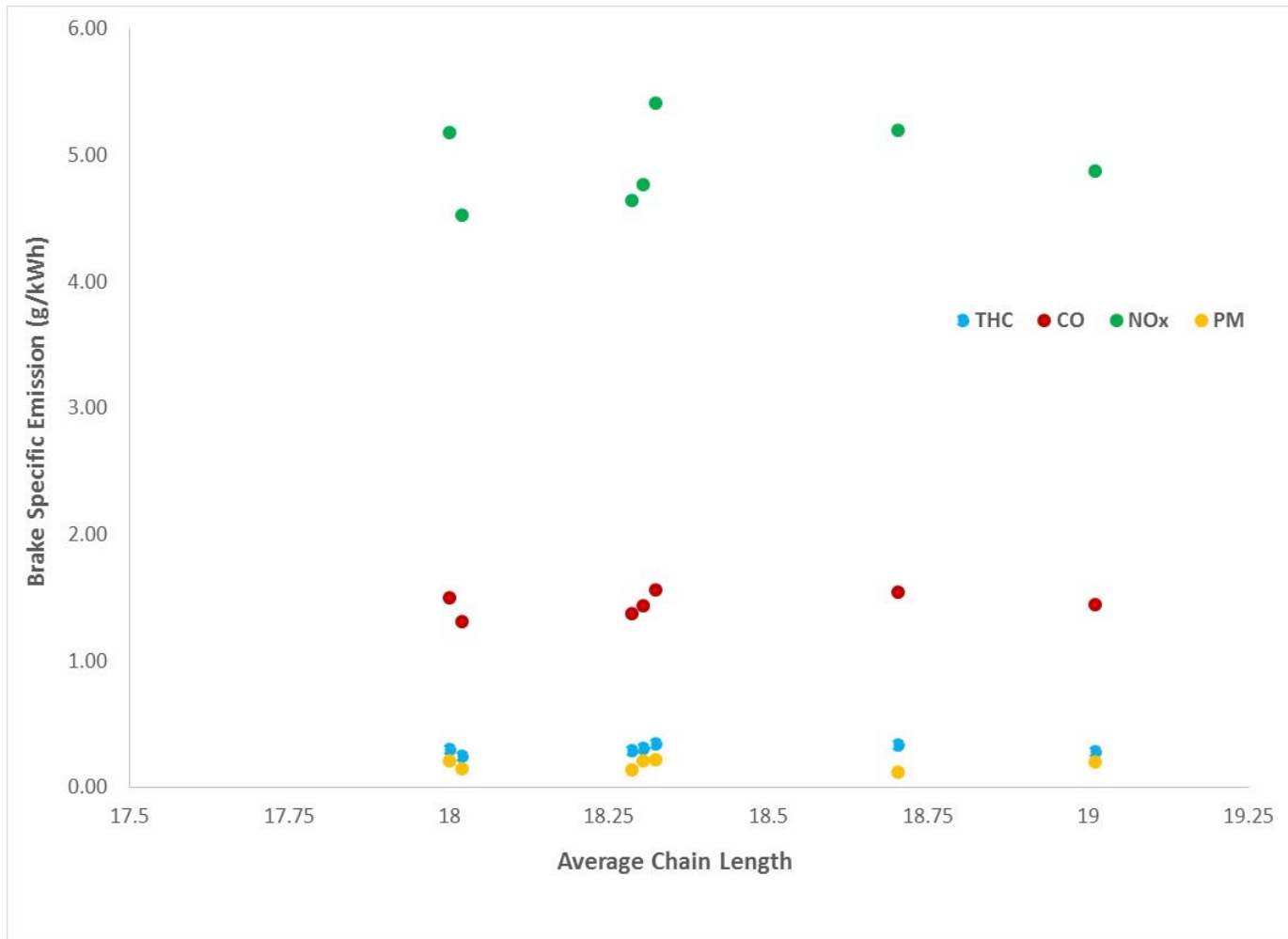


Figure 41: Emissions trends Vs. Chain Length

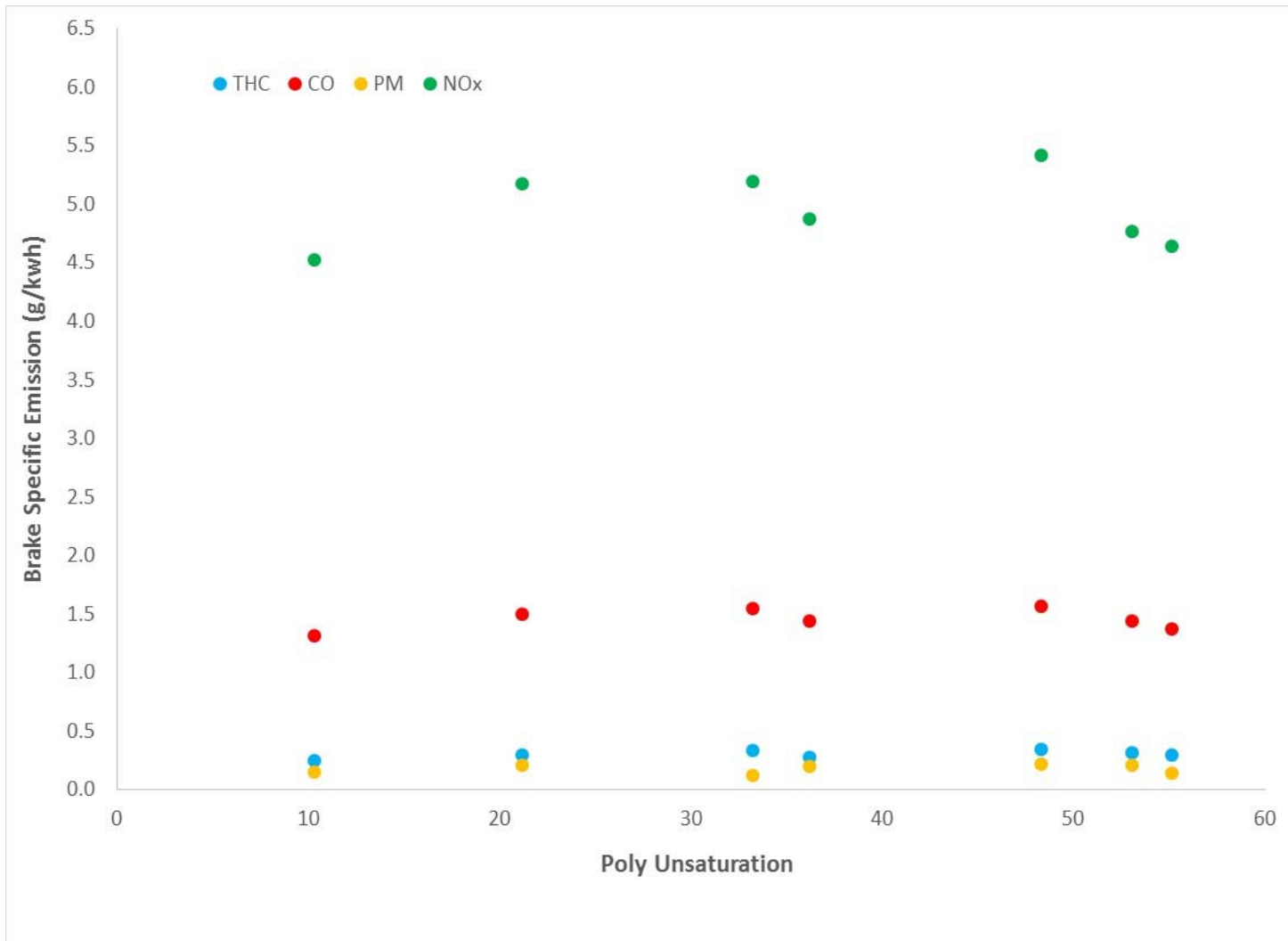


Figure 42: Emission Trends vs Polyunsaturation

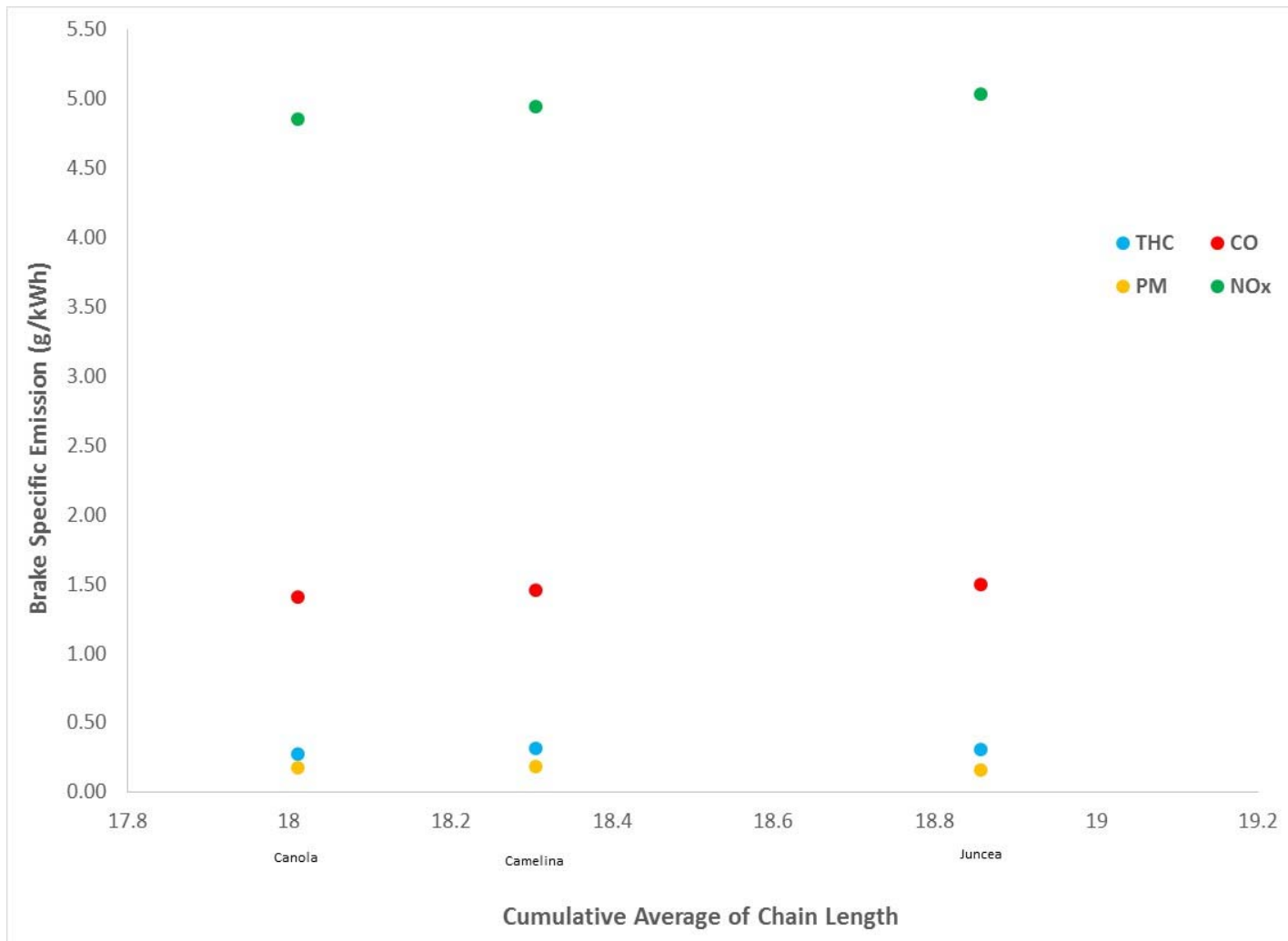


Figure 43: Emission Trends vs Cumulative Chain Length

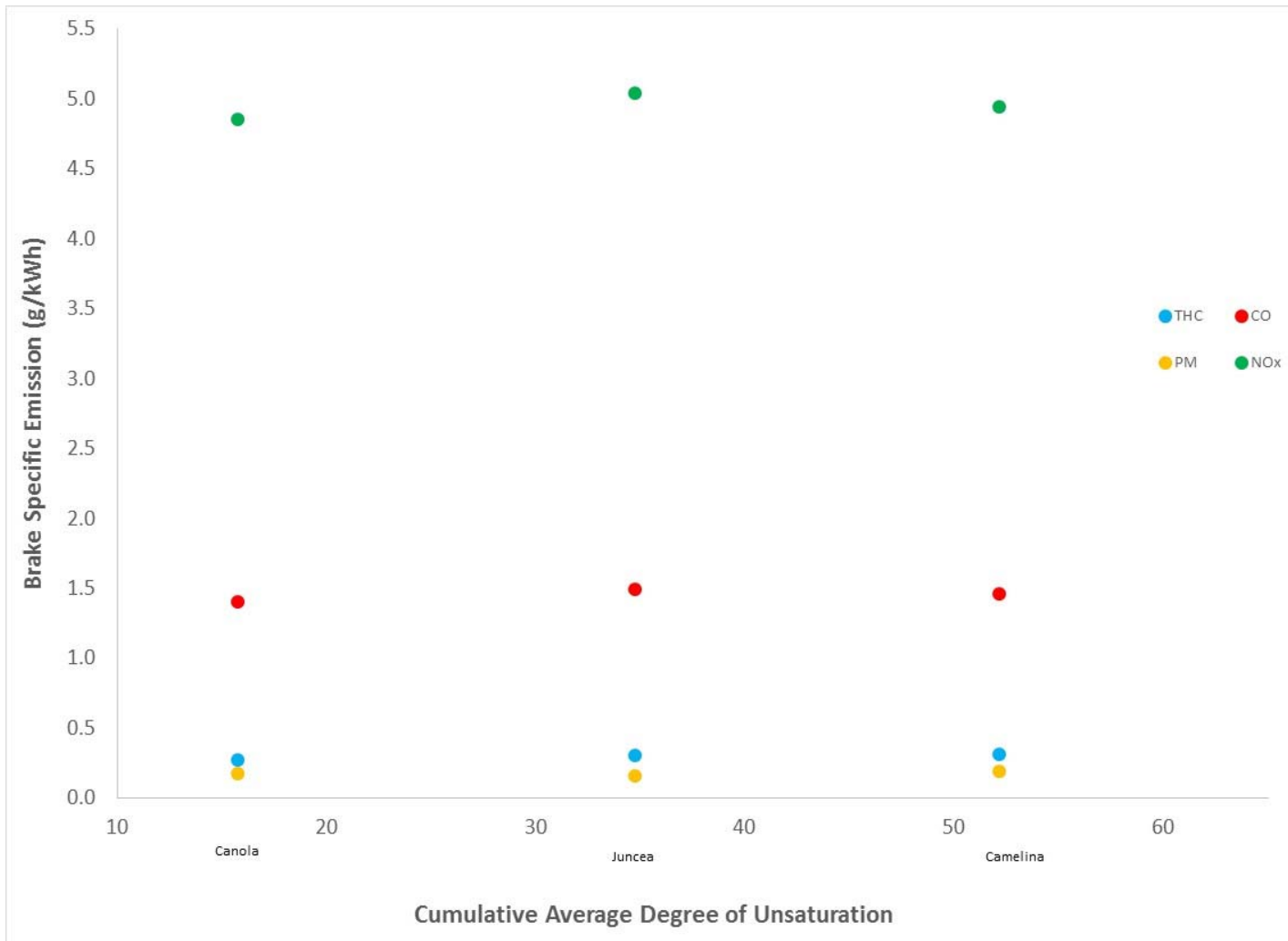


Figure 44: Emission Trends vs Cumulative Degree of Unsaturation

5. CONCLUSIONS

There is a growing interest in bio-energy and biofuel crop development due to the rising fuel prices, rising energy demand and concerns about energy security. Development of bio-energy has the potential to give renewed impetus to the agricultural and rural sector.

Oil seeds of Juncea, Camelina, Canola varieties were grown Colorado State University in different climatic, genetic and agricultural conditions. These seeds were then harvested, crushed and filtered to obtain the Straight Vegetable Oils. In addition to these SVOs, de-gummed and de-waxed canola, corn and coconut oils were procured from the store. These oils were then used as fuels in a Tier 2 John Deere 4.5 liter 4 cylinder engine at the Engines and Energy Conversion Laboratory (EECL). The engine was loaded with an eddy-current. Exhaust emissions were analyzed and compared to diesel emissions.

There does not appear to be a large advantage or disadvantage of triglycerides for pollutant emissions. Overall the use of triglycerides results in higher brake thermal efficiencies, but slightly higher fuel consumption. Emissions and fuel consumption trends with triglyceride composition are present, but very small. These results are specific to a turbocharged, high pressure common rail fuel injection compression ignition engine. Though the emissions and fuel consumption results for triglycerides are favorable, engine durability is not addressed with the testing. To run triglycerides directly in a compression ignition engine, hardware modification with a SVO kit is required. This is an added expense that must be considered.

The following conclusions can be derived from the data analysis:

1. The Phosphorus content in the triglycerides is higher than diesel by 6 to 11 times on an average. The Cold Filter Plug Point for the triglycerides was much higher than diesel; all were in positive temperatures.
2. The Cloud Point (CP) of the triglycerides was generally higher than diesel. The CP of Juncea, on an average was at least 9 degrees higher than diesel while that for Camelina 244 was close to that of diesel.
3. The density of the triglycerides were generally higher than diesel by about 10% across the board. The triglyceride viscosity was much higher, approximately 15 to 18 times as that of diesel.
4. The calorific value of the triglycerides was lower than that of diesel by about 15% on an average. This would suggest that the fuel consumption would be higher than diesel by about 15%. The industrial refining process, degumming and de-waxing, does not affect the calorific value.
5. The fuel consumption of SVO is generally higher than diesel due to the approximately 13-15% lower energy content. However, the brake thermal efficiency for many SVOs is significantly higher than diesel.
6. Engine operation on SVO produced lower CO emissions than diesel in all cases. THC and NOx emissions are generally scattered around diesel and within the +/-10% range. All SVOs produced weighted average NOx + NMHC emissions lower than the tier 2 regulation limit of 6 g/kW-h. PM emissions were similarly scattered. Canola triglycerides generally exceeded the Tier -II PM limit (0.3 g/kWh).

7. The overall trend of thermal efficiency tends to increase as the load increases. The increases for the triglycerides are much significant as compared to diesel at part loads. At rated speed, on an average, the triglycerides had about 5% higher efficiency.
8. The Total Saturates was in between 11 and 6. Camelina had the most saturates in the range of 10 to 11 while Juncea and Canola were very proximate to each other in the 6 to 7 range.
9. The Poly Unsaturation had a vast range: from about 10 to 56. Camelina had unsaturation in the range of 47 to 56, Juncea in the range of 33 to 36 while Canola was in the range of 10 to 21.
10. The average chain length of these triglycerides was very similar to each other and within the range of 18 to 19.
11. The trends with respect to the average chain length and the degree of unsaturation were the same all throughout the brake specific emissions. Emissions increase slightly as the average chain length and degree of poly unsaturation increases.

6. RECOMMENDATIONS FOR FUTURE WORK

The use of triglycerides as an alternative fuel in diesel engines looks bright, there still is a lot of areas that need testing and improvements.

One of the major drawbacks to these triglycerides are its cold flow and physical properties. Use of additives which will may or may not alter the chemical composition and the straight chain arrangement, but would improve the properties would be a good area to explore.

By blending aromatic fuels like gasoline, diesel or reference fuels heptane and butanol, one could look at the cetane number and how they can affect the physical and chemical properties.

Combustion studies could lead us into understanding the combustion process like the peak pressure and the burnt mass fractions. This might help us in adjusting the ignition timings and other engine parameters to help us give better combustion, lower emissions and higher efficiency.

Finally a durability test to understand the wear and tear, build up in the combustion chamber, injector spray pattern and the chemical analysis of the burnt ash would be a good data set to evaluate the fuels and the cost that might be associated with it.

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8. APPENDIX

The oils of same family like Camelina, canola and Juncea were added together and the average chain length was calculated as shown in Table 9.

Table 9: Consolidated Oil types and Emissions as function of Chain Length

Ascending order of Chain Length						
	AVG L	THC	CO	NOx	PM	BSFC
Canola	18.011	0.2737	1.4075	4.8531	0.1792	245.758
Camelina	18.305	0.3158	1.4608	4.9423	0.1895	239.703
Juncea	18.856	0.308	1.4976	5.0382	0.1623	255.620

The oils of same family like Camelina, canola and Juncea were added together and the average degree of unsaturation was calculated as shown in Table 10.

Table 10: Consolidated Oil types and Emissions as function of degree of unsaturation

	Poly. Un	THC	CO	NOx	PM	BSFC
Canola	15.742	0.274	1.408	4.853	0.179	245.758
Juncea	34.726	0.308	1.498	5.038	0.162	255.620
Camelina	52.168	0.316	1.461	4.942	0.189	239.703

The oils of same family like Camelina, canola and Juncea were added together and the average degree of saturation was calculated as shown in Table 11.

Table 11: Consolidated Oil types and Emissions as function of degree of saturation

	TOTSATS	THC	CO	NOx	PM	BSFC
Juncea	6.812	0.308	1.498	5.038	0.162	255.620
Canola	6.911	0.274	1.408	4.853	0.179	245.758
Camelina	10.917	0.316	1.461	4.942	0.189	239.703

X-Y scatter plots of various physical properties and emissions were plotted to analyze co-relations if any. However, no strong co-relations were observed ($R^2 < 0.45$). Figures 47 to 60 show the scattered plots.

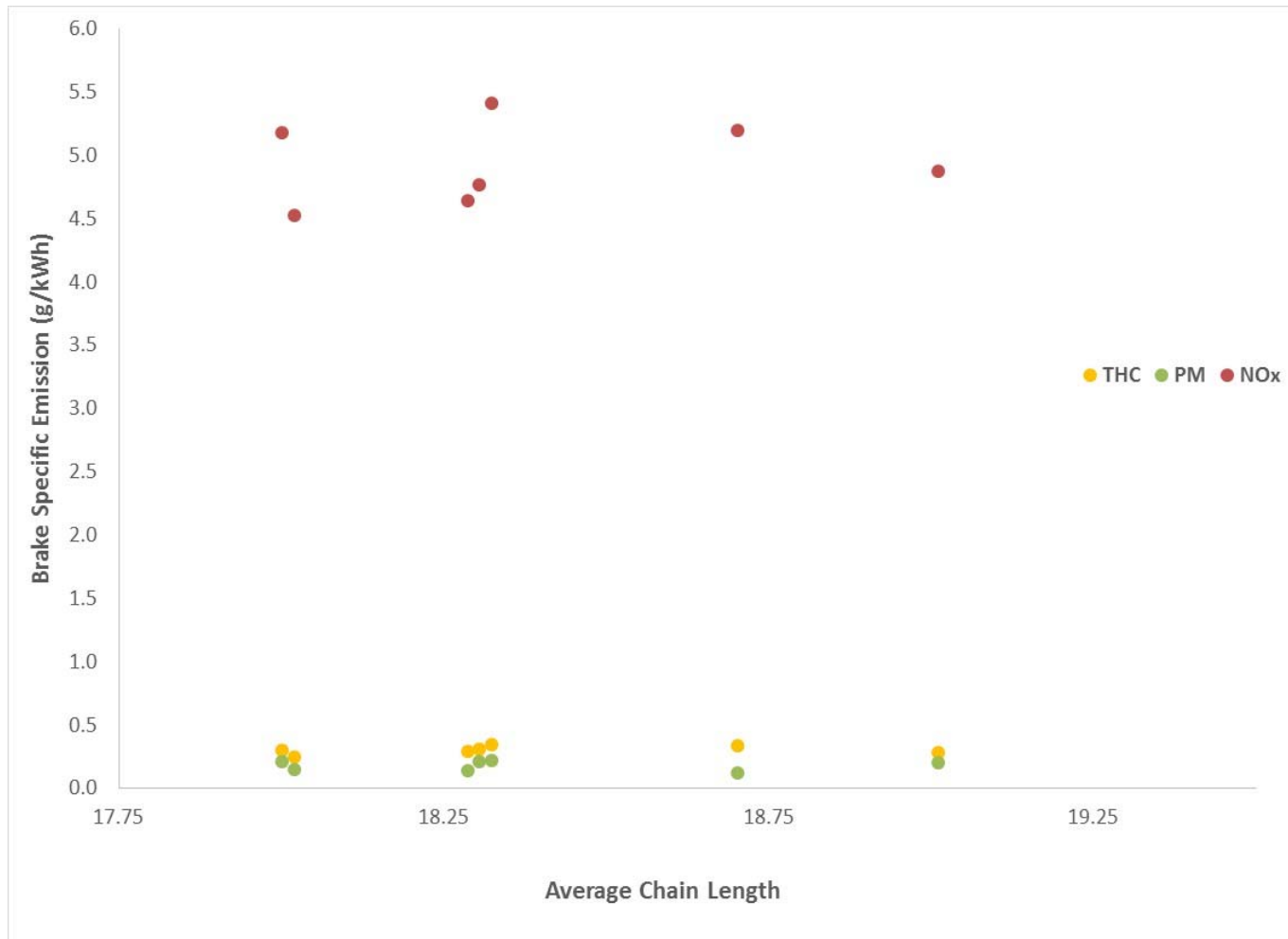


Figure 45 Brake specific Emission as a function of chain length

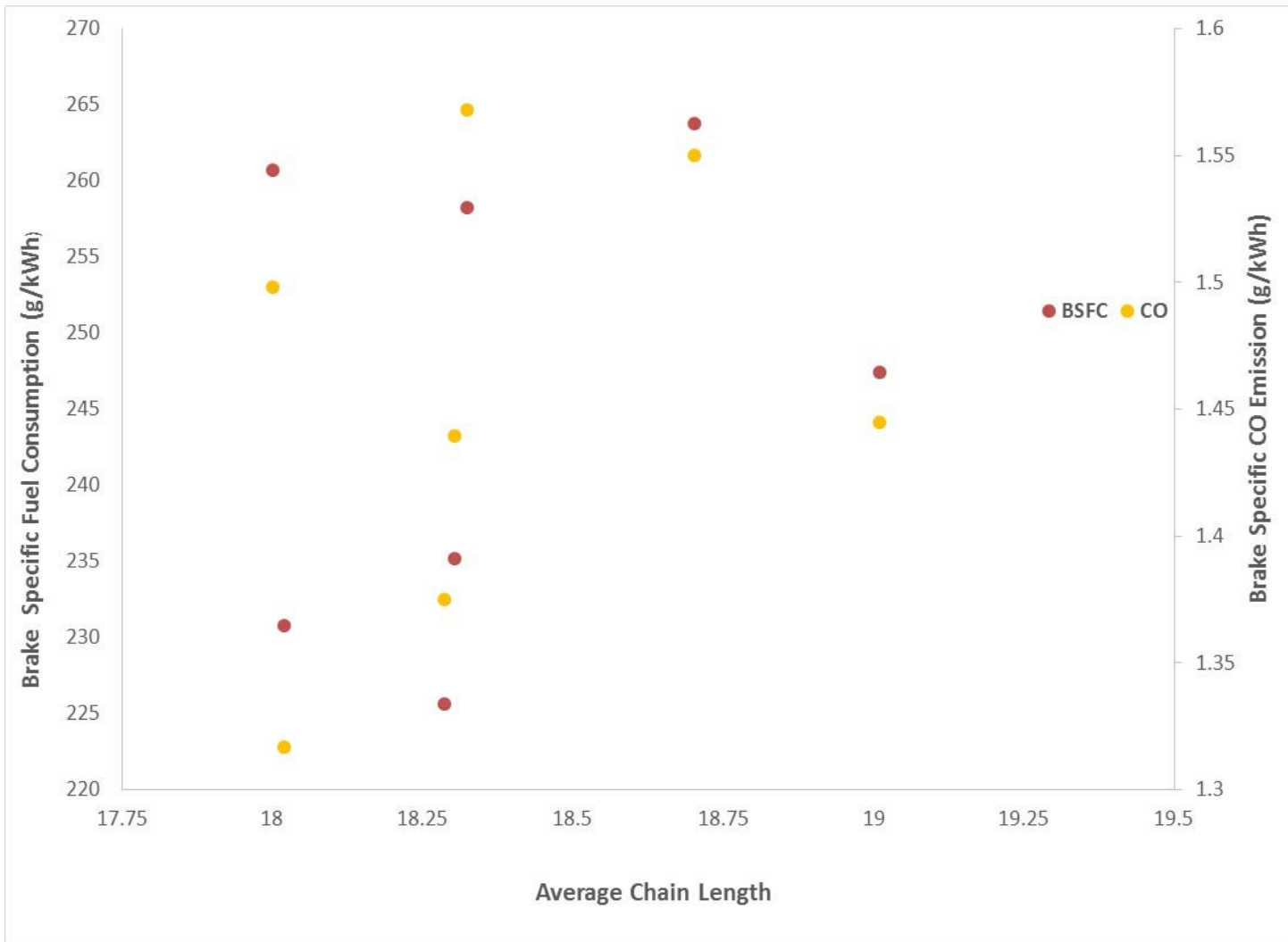


Figure 46 Brake Specific measurements as a function of Average Chain length

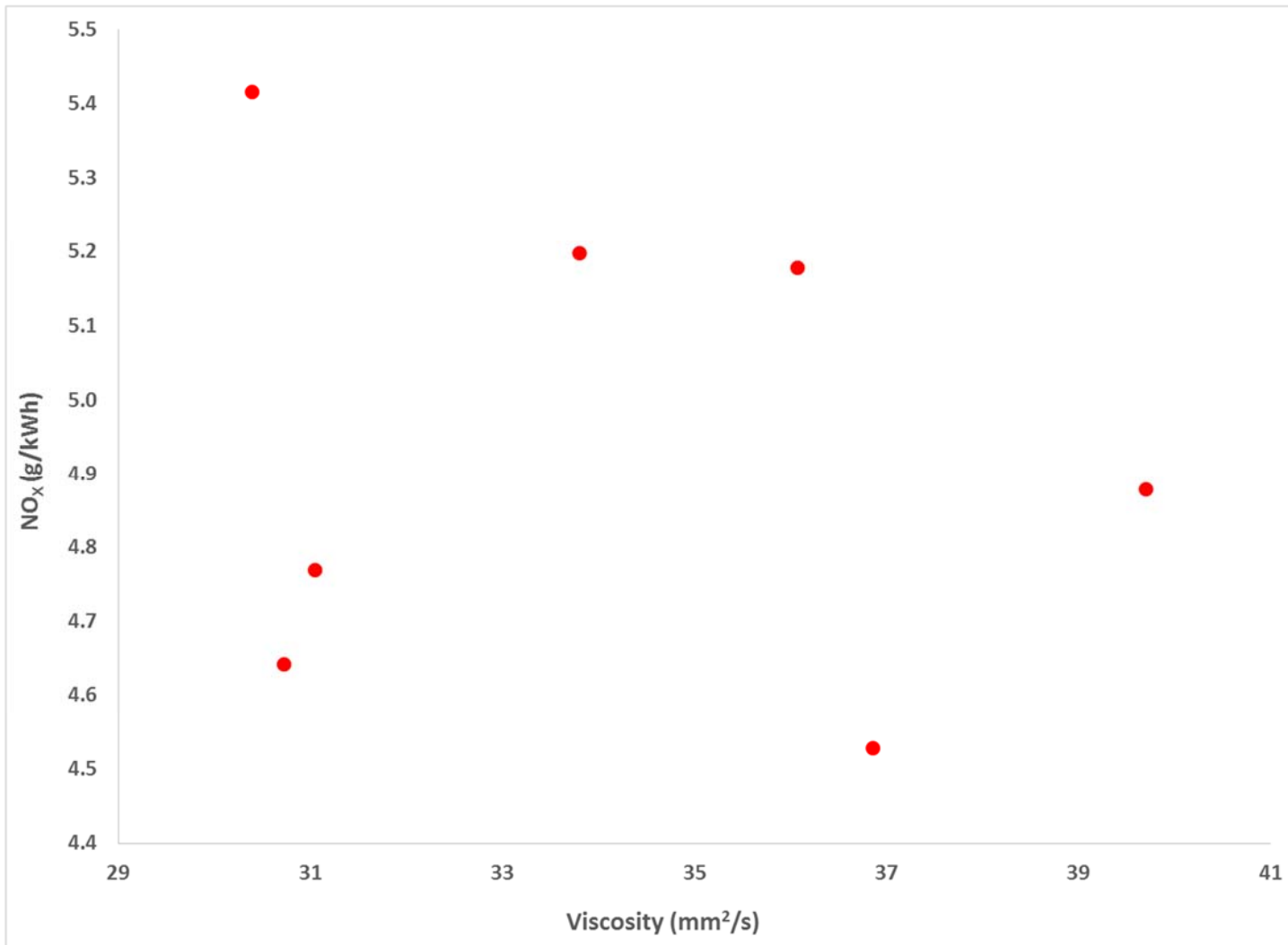


Figure 47: NO_x vs Viscosity

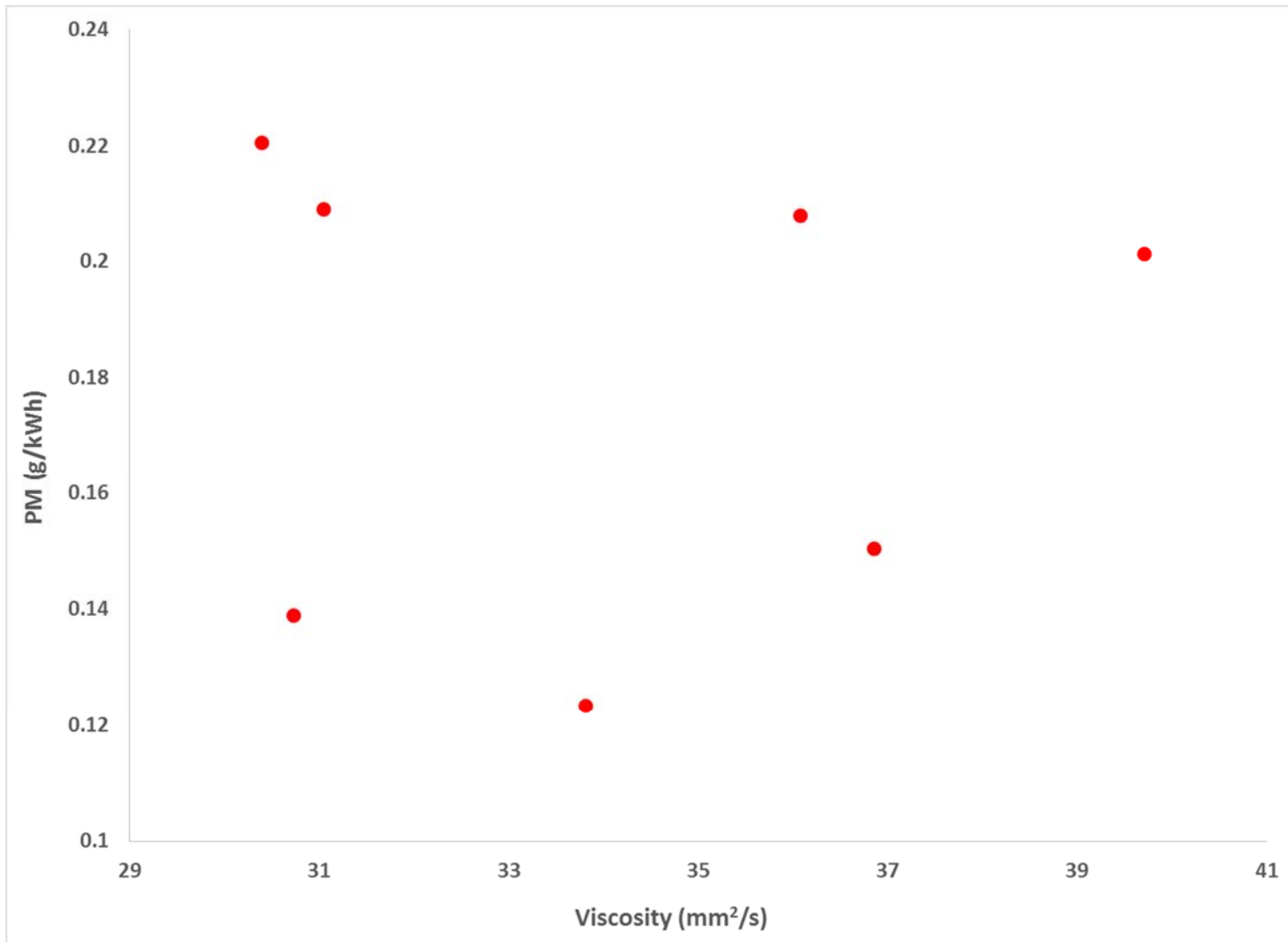


Figure 48: PM vs Viscosity

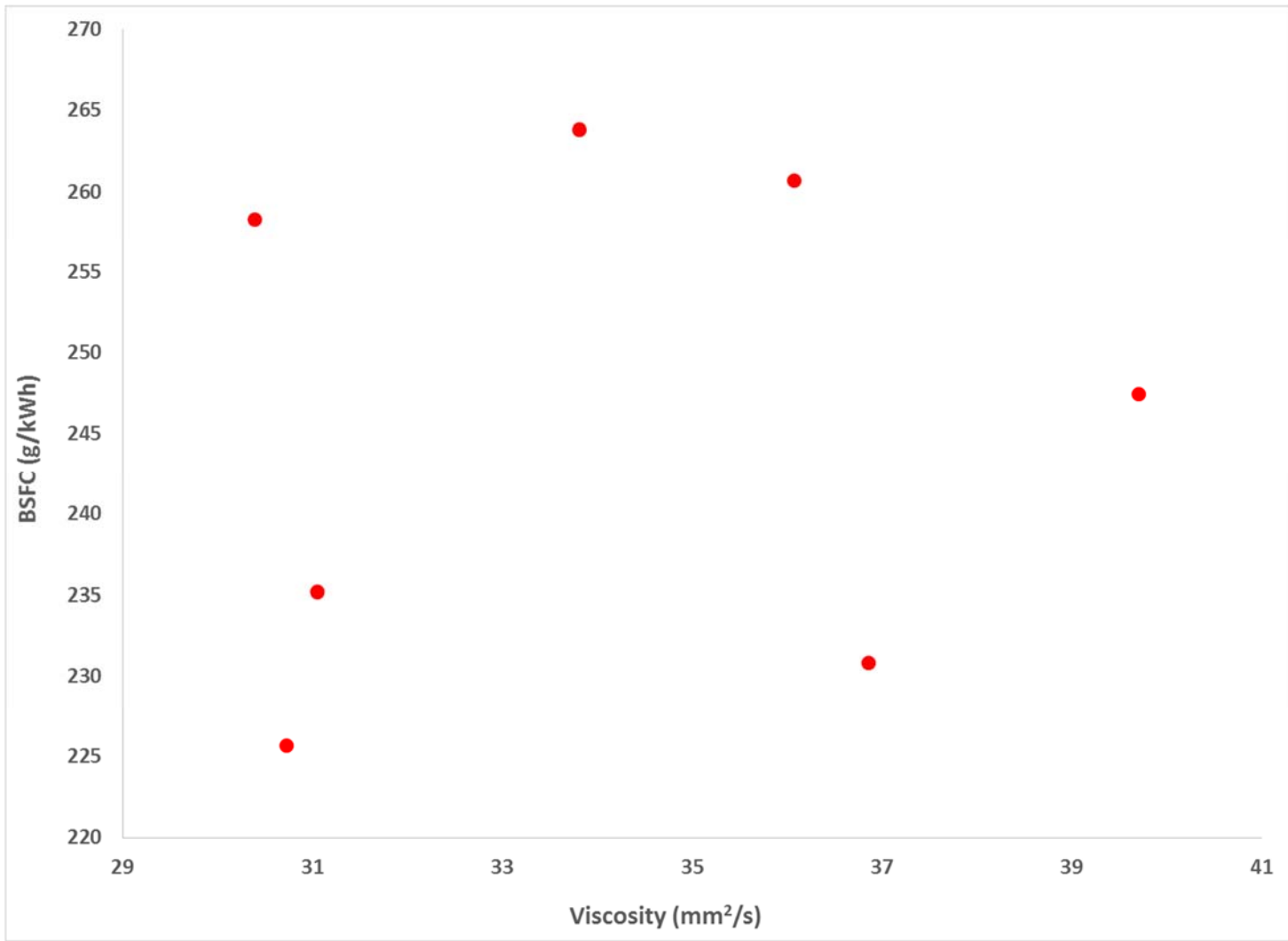


Figure 49: BSFC vs Viscosity

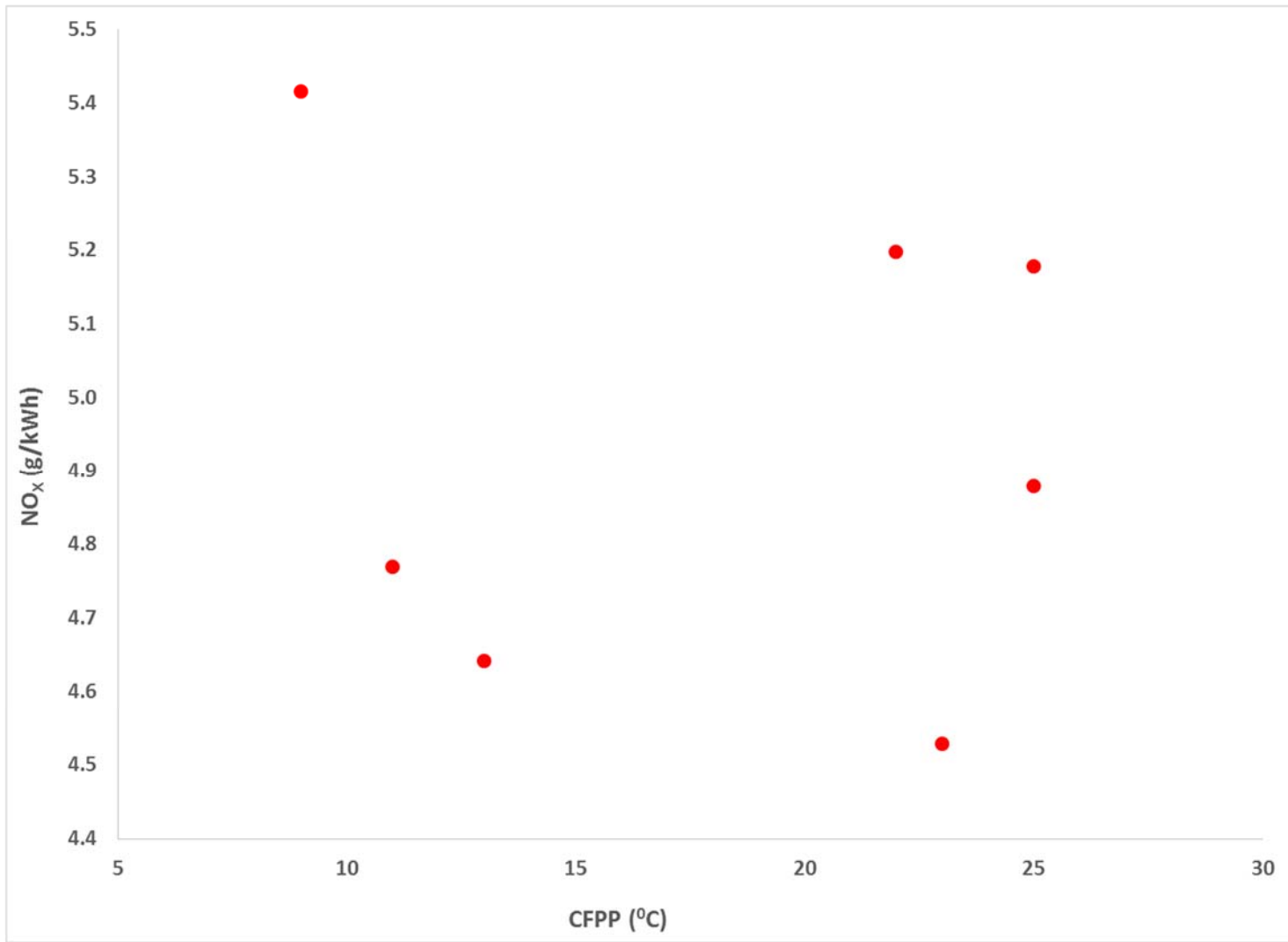


Figure 50: NO_x vs CFPP

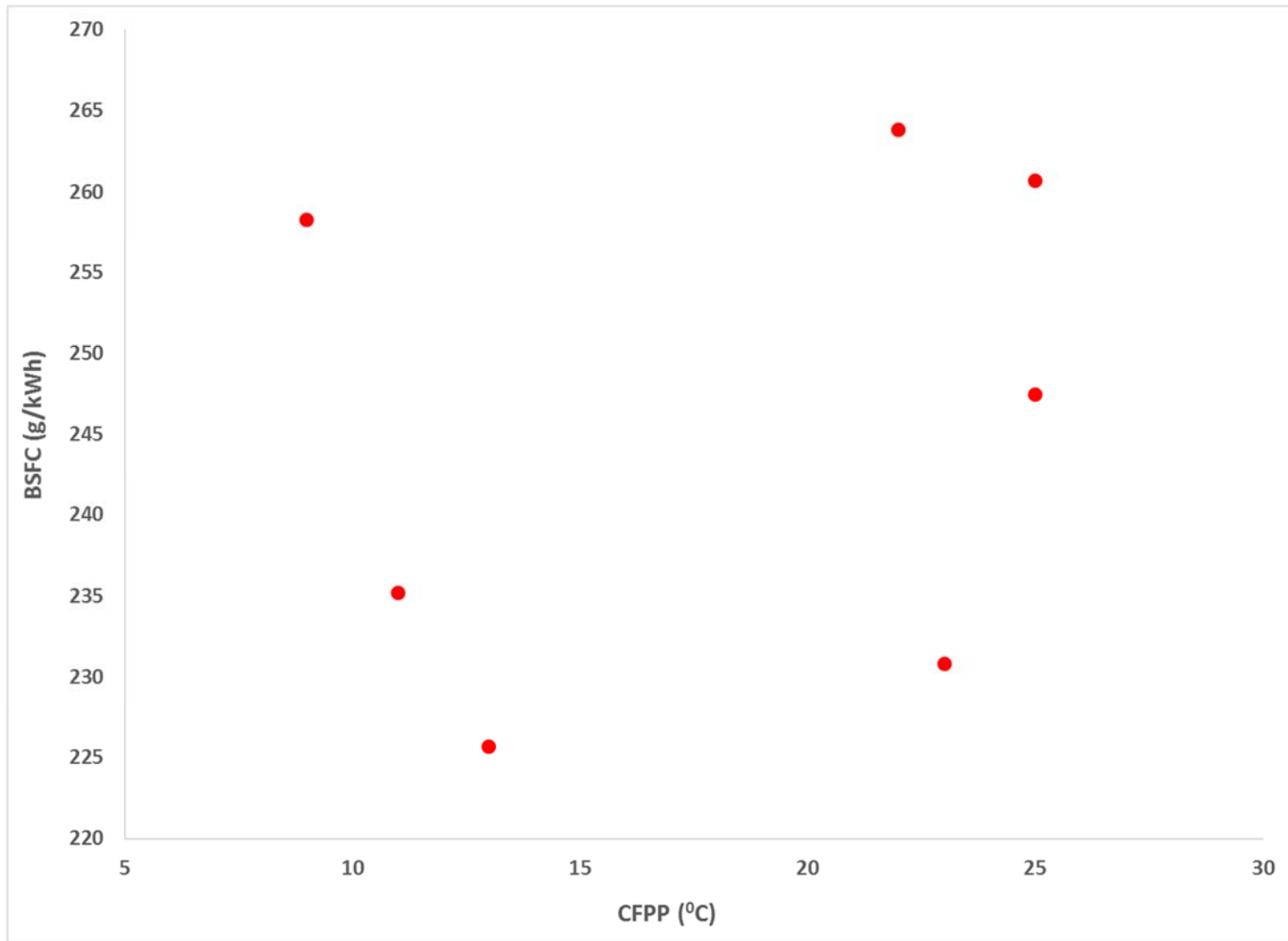


Figure 51: BSFC vs CFPP

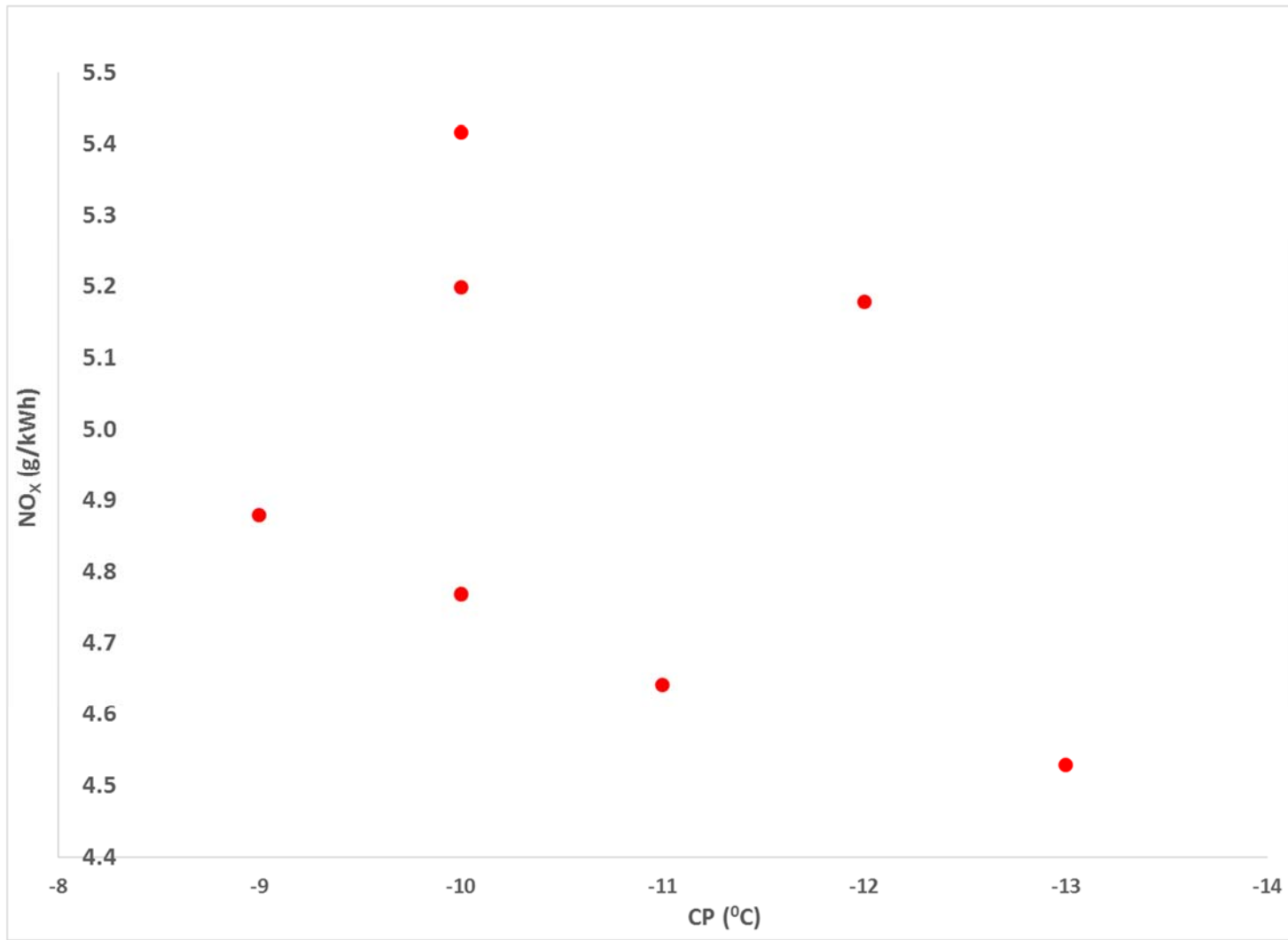


Figure 52: NO_x vs CP

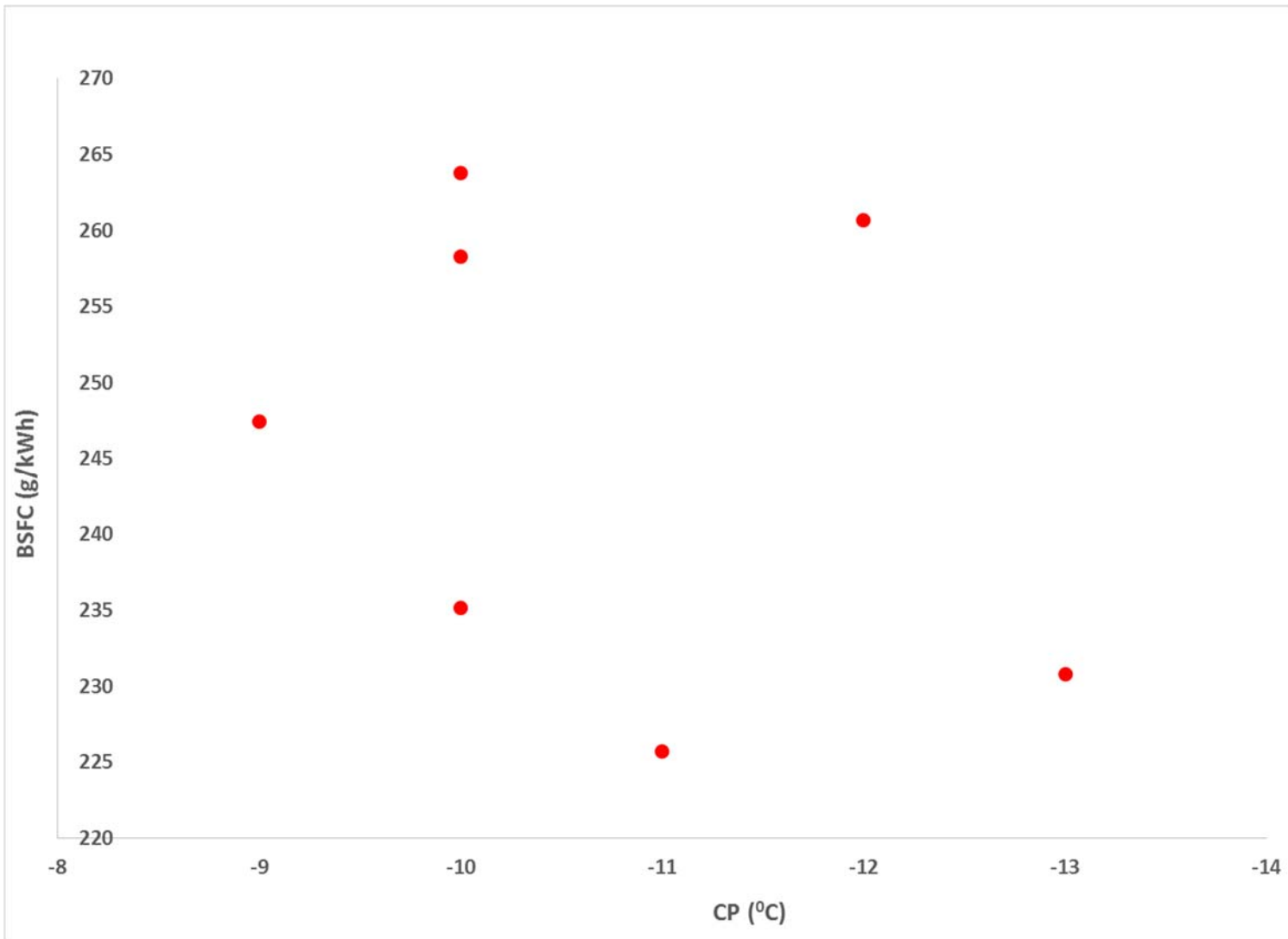


Figure 53: BSFC vs CP

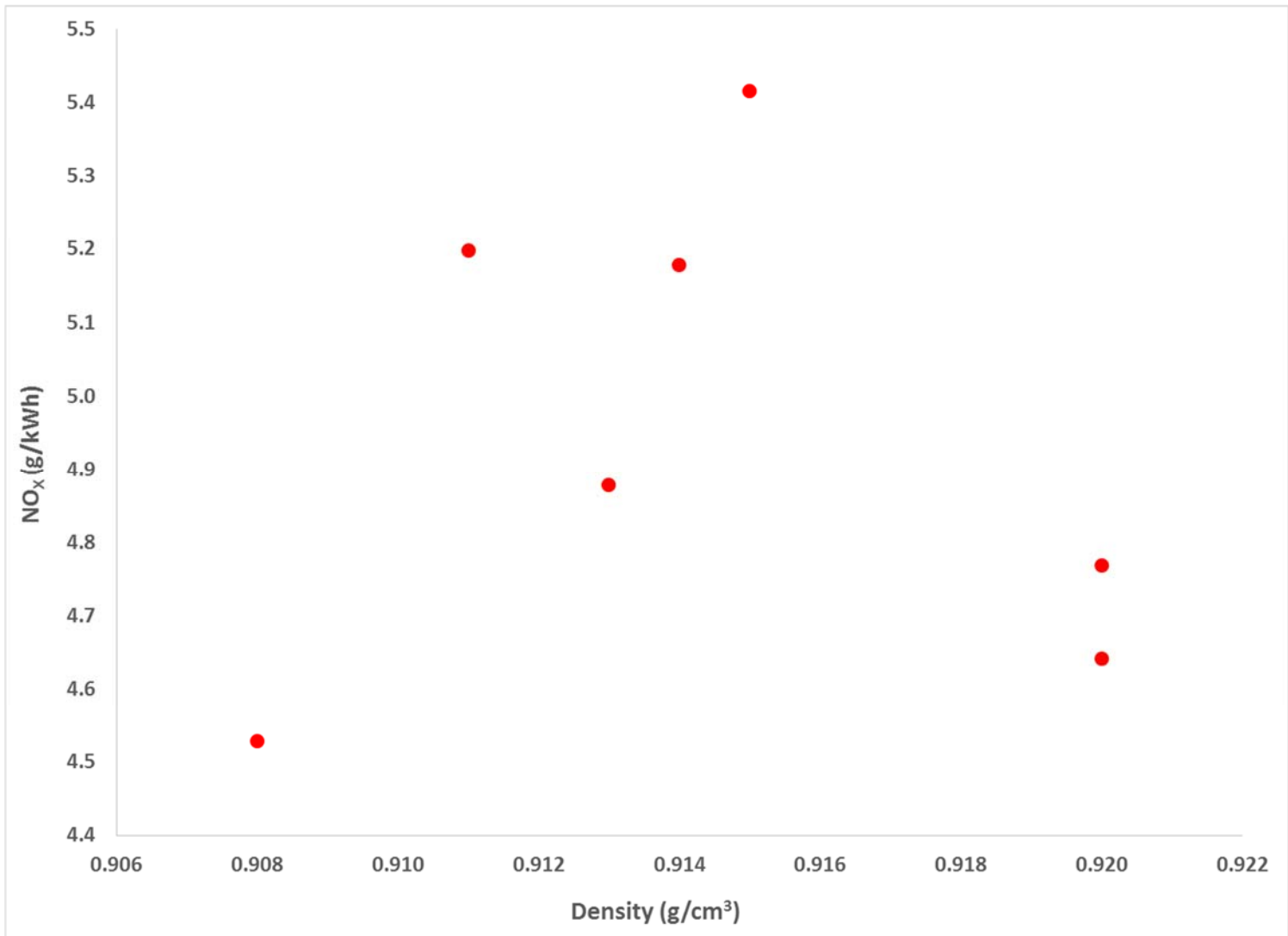


Figure 54: NO_x vs Density

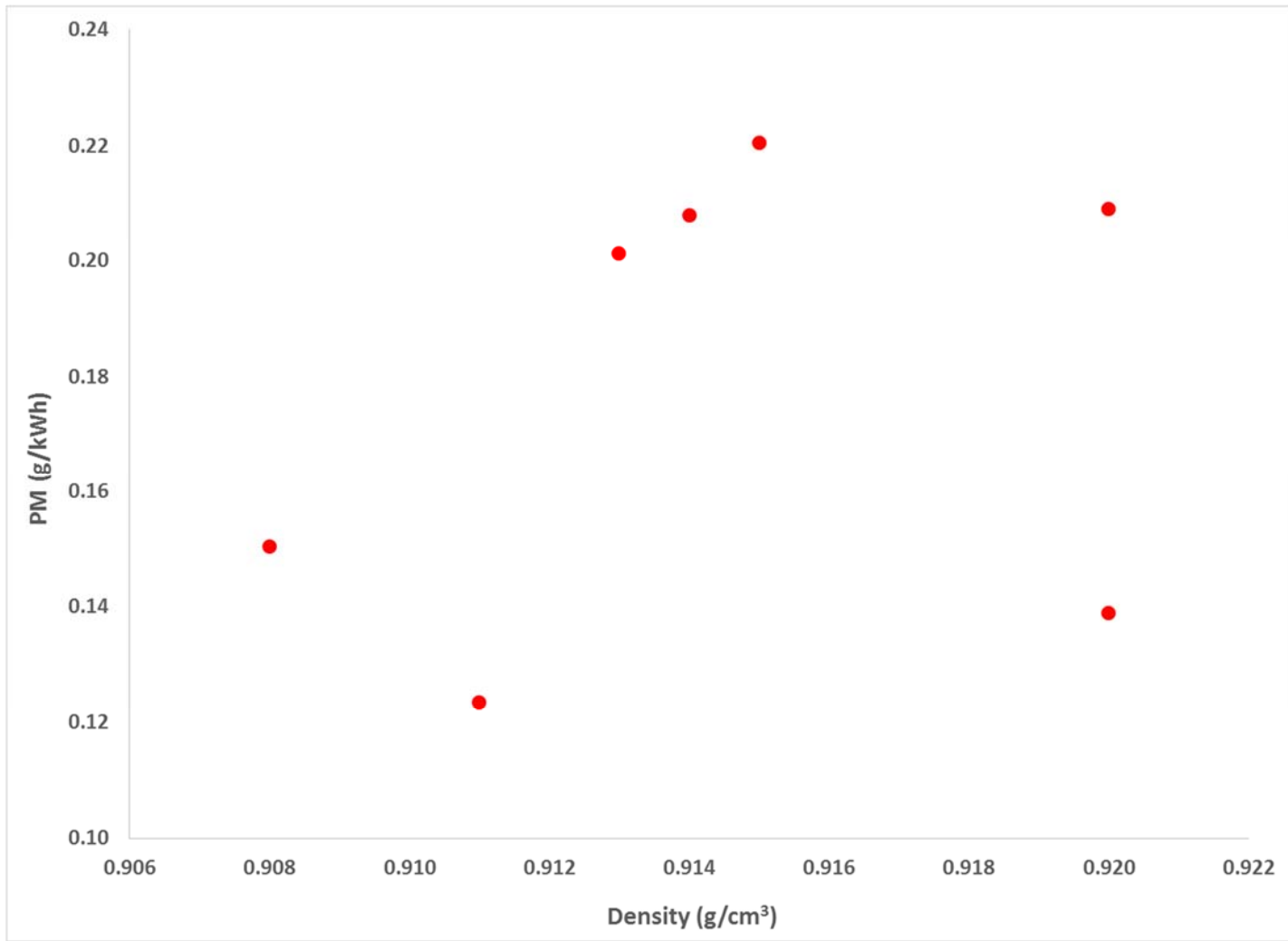


Figure 55: PM vs Density

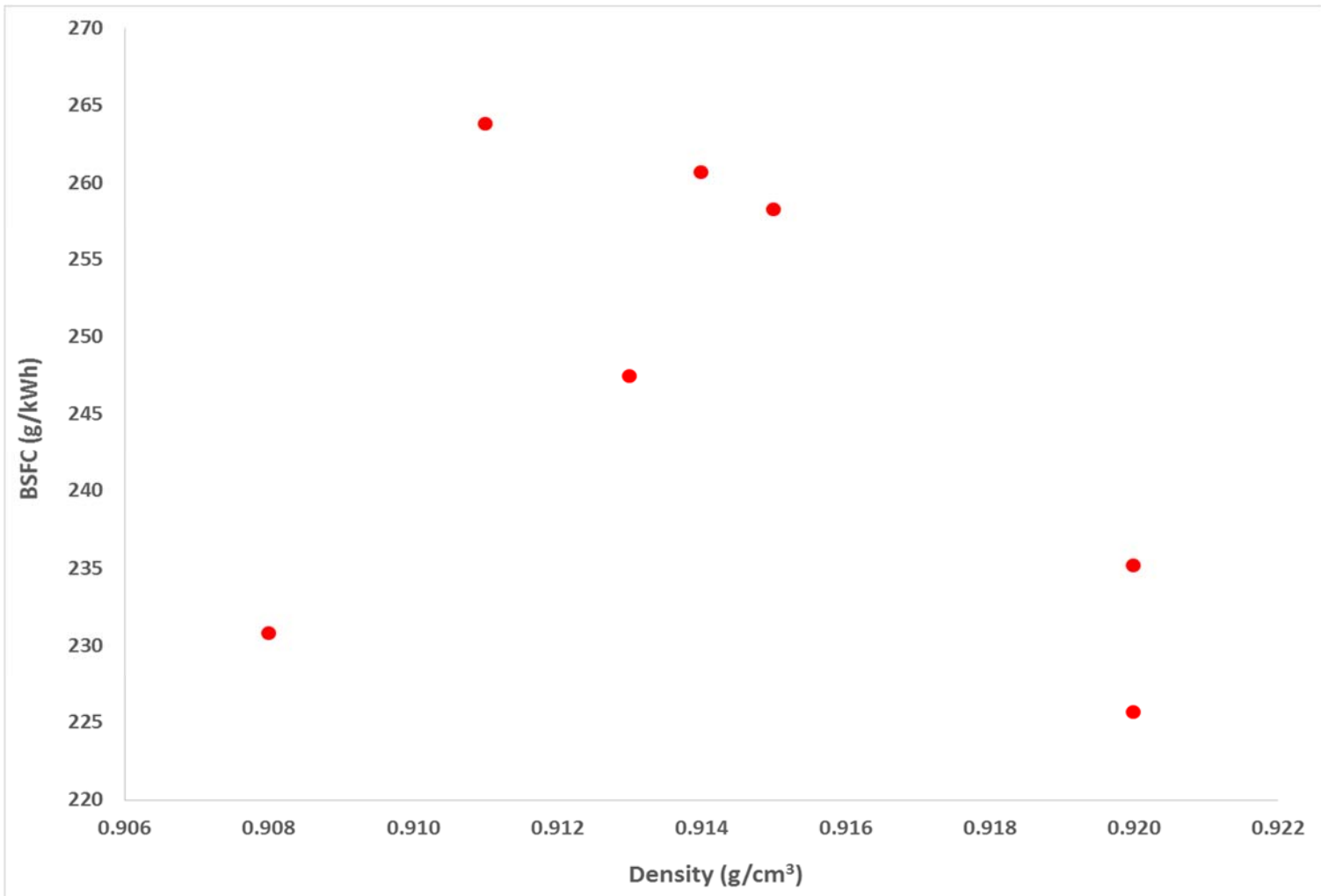


Figure 56: BSFC vs Density