Manufacturing and testing of emulsified micro and nano biodiesel blends using water and other natural resources for enhancement of fossil fuels

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MANUFACTURING AND TESTING OF EMULSIFIED MICRO AND NANO BIODIESEL BLENDS USING WATER AND OTHER NATURAL RESOURCES FOR ENHANCEMENT OF FOSSIL FUELS

A Dissertation by

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Doctor of Philosophy

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The following faculty members have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirement for the degree of Doctor of Philosophy with a major in Industrial Engineering.

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DEDICATION

To my dear loving parents, Mahshid and Mohsen; to my dear sister, Arina, who have consistently provided me with unwavering support throughout my academic career.

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ABSTRACT

The pursuit of alternative energy and carbon footprint reduction has become the pinnacle of concern not only for nations all around the world but also for research scientists. Petroleum fuels such as diesel, gasoline, and bunker oil, for instance have powered the transportation, cargo, and energy production industries for over 100 years [20]. Some nations, more than others, have a vision of transferring all energy expectation from electricity in hopes of battling environmental concerns and realities. Not only will this idea harm the environment more but it will still require one form of fossil fuel or another to produce electricity. In the present study one of the most abundant natural resources, water, was utilized to be formulated with conventional diesel at different weight percentages (5 to 35 wt%). While completely deserting the utilization of fossil fuels is rather inefficient and impractical, making an alternative fuel that combines the two together will result in compelling outcomes that can aid in the issues that the world is facing. The combination of water with diesel fuel in this case has always been negatively viewed without further research and analysis until now. With the introduction of 20% water per given volume of diesel, engine performance improved over 5%, fuel economy improved about 20%, greenhouse gas emissions were reduced. In addition to water, alternative additives such as seed-oils and animal fats were also formulated for engine testing and analysis. Seed-oils in this study ranged from percentages of 5 to 50 wt% per given volume with compelling fuel economy improvement of over 20%. Ultimately B100 biodiesel was formulated in this research using various animal fats, such beef tallow for instance. Beef tallow proved extreme potential as biodiesel by replacing 100% of conventional diesel per volume and achieving a fuel economy improvement of nearly 25%. After achieving the above data from test results, further experiments are called for with higher percentages of natural resources as additives for the enhancement of fossil fuel.

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LIST OF ABBREVIATIONS

AFB	Animal Fat Biodiesel
ATJ	Alcohol-To-Jet
ATP	Adenosine Triphosphate
ASTM	American Society for Testing and Materials
B5	5% Biodiesel
B10	10% Biodiesel
B20	20% Biodiesel
B50	50% Biodiesel
B70	70% Biodiesel
B100	100% Biodiesel
BSEC	Brake Specific Energy Consumption
BTE	Brake Thermal Efficiency
BTU	British Thermal Unit
CaO	Calcium Oxide
CI	Compression Ignition
CO_2	Carbon Dioxide
CO	Carbon Monoxide
CSTR	Continuous Stirred Tank Reactors
$CuFe_2O_4$	Copper Iron Oxide
E10	10% Ethanol
E15	15% Ethanol
E85	85% Ethanol

LIST OF ABBRIVATIONS (continued)

EPA	Environmental Protection Agency
EU	European Union
FFA	Free Fatty Acids
FFET	Fossil Fuel Enhancement Technology
GHG	GreenhoV1use Gas Emissions
H_2O	Water
HACA	Hydrogen-Abstraction-C_2H_2-Addition
HC	Hydrocarbon
HDRD	Hydrogenation-Generated-Renewable-Diesel
HEFA	Hydro-processed Esters and Fatty Acids
HP	Horsepower
IBS	Intelligent Blending Station
KG	Kilogram
KJ	Kilojoule
KW	Kilowatt
LHV	Lower Heating Value
NO_2	Nitrogen Dioxide
NOx	Nitrogen Oxides
O_2	Oxygen
OEM	Original Equipment Manufacturer
PAH	Polycyclic Aromatic Hydrocarbon
PLN	Pump Line Nozzle

LIST OF ABBRIVATIONS (continued)

PM	Particulate Matter
PPM	Part Per Million
SAF	Sustainable Aviation Fuel
SCR	Selective Catalytic Reduction
SI	Spark Ignition
TAG	Triacylglycerol
TDC	Top Dead Center
TEM	Transmission Electron Microscopy
W20	20% Water
WID	Water in Diesel

CHAPTER 1: INTRODUCTION

1.1 Background

The production of biodiesel serves the primary purpose of providing an alternative to conventional fossil fuel that is not only renewable but also clean and biodegradable. This indicates that the transportation sector will make up most of its applications. More than 30% of the total energy used in the United States is attributed to the transportation sector, which is accountable for 24% of the planet's total energy consumption and more than 60% of the oil that is absorbed [46]. This indicates that the global automotive industry consumes more than one-third of the worldwide oil supply. As a result of its status as a renewable substitute for fossil fuel, biodiesel represents a significant step forward for the sector. Compression ignition (CI) engines are stronger and arguably more efficient than conventional ignition engines that utilize gasoline [22]. Vehicles that are powered by biodiesel and regular diesel are identical as affirmed in a recent study [46]. Even while light, moderate, and heavy-duty diesel cars are not strictly considered alternate energy vehicles, the majority of these vehicles can operate on biodiesel blends.

Findings show that the B20 blend, in which anything from 6% to 20% biodiesel is merged with petroleum diesel, is the most popular type of biodiesel blend [51]. Nevertheless, it is suggested that fleet cars also frequently make use of B5, which is a biodiesel blend that consists of 5% diesel and 95% biodiesel [11]. It is possible to utilize B20 and lower-level blends in several diesel engines without making any modifications to the engine. Both the cetane amount of the fuel and its ability to lubricate itself are improved when biodiesel is used. If the engine has a more significant cetane number, it will be easier to start and have a shorter ignition delay [51]. When it comes to preventing moving parts from wearing down too quickly, diesel engines rely on the fuel's lubricity. Increased lubrication lowers the amount of friction that occurs between the moving parts, which prevents excessive wear. At blend concentrations as low as 1%, biodiesel has been shown to increase the fuel's flowability, and that is one of its most significant benefits [51].

1.2 Motivation

Over the past decade, most efforts on reducing the carbon footprint and utilization of fossil fuels have concentrated on alternative forms of energy such as electricity, biofuels, and production of hydrogen as fuel. Such efforts have been entertained by many nations around the world, however, the reality of fossil fuel dependance is still overpowering in terms of demand and convenience. The Environmental Protection Agency (EPA) has made regulations stricter on fossil fuel emissions making it challenging for large corporations to operate without paying carbon tax [21]. The demand for alternative forms of fuel is quite evident and calls for further investigation, particularly considering energy dependent nations, current reserves of petroleum fuels, and the emissions emitted using conventional fossil fuels. Another challenge that is faced when using petroleum fuels is the cost to consumer at the pump. When nations around the world who are energy independent engage in conflict, one side effect is an increase in fuel cost, which ultimately impacts everyone.

- By developing new fuel formulations, the greenhouse gas emissions and the carbon footprint left behind by conventional diesel fuel will decrease by using newly formulated biodiesels.
- To further stretch the current reserves of petroleum fuels, the newly formulated biodiesel fuels will range anywhere from 5 to 100% renewable as a result of the new formulations.
- The current research focused on utilizing natural resources that are abundant around the world, making new formulations possible globally.

1.3 Research Gap

Although biodiesel has been produced for decades, the possibility to formulate water with diesel fuel at mass production scale was not a possibility until now. The abundance of water around the globe makes it a very resourceful component to be used in biodiesel. The utilization of other natural resources such as seed-oils has also been limited to very few in order to control cost and demand. Lastly unconsumable animal fats are currently not being utilized efficiently for biodiesel production.

1.4 Objectives

The high cost of petroleum fuels such as diesel is currently putting pressure not only on the economy but also the end consumer. The cost of fuel is among many aspects of utilizing fuels such as diesel. Diesel fuel can also emit harmful greenhouse gases, such as NOx, CO_2, HC, and CO [21]. Diesel fuel is used globally in the transportation, logistics, and energy industries. In many countries around the world diesel fuel is imported, which ultimately means there will be a specific amount of fuel reserve per import.

The increase of biodiesel production can aid in the challenges that industries are currently facing. To aid in a solution against the current challenges, the following objectives have been identified:

- To develop as many formulations of biodiesel as possible with the following as available resources:
  - Water (H_2O)
  - Seed-Oils
  - Animal Fats
- Require zero modifications to current diesel engine platforms.

- To test each biodiesel formula for the following:
    - Engine Performance (Dynamometer Testing)
    - Engine Emissions Testing (Greenhouse Gases)

This research aims to address the current challenges that have become the reality of using petroleum fuels such as diesel. With the development of new biodiesel using water, seed-oils, and animals fats the following will be achieved:

- Lowered fuel costs.
- Decrease in greenhouse gas emissions.
- Matched and improved engine performance.
- Stretch current fuel reserves per volume.
- Improved fuel economy.
- Extended engine life cycle.
- No required engine modifications.

CHAPTER 2: LITERATURE REVIEW

2.1 Different Types of Biodiesels and Renewable Diesel

It is possible to mix biodiesel with other fuels and utilize it in various proportions. It is suggested that the most popular types are B5, which contains up to 5% biodiesel, and B20, which contains between 6% and 20% biodiesel [64]. B100, often known as pure biodiesel, is seldom utilized as a transportation fuel because it is more commonly utilized as a blendstock in the production of lower blends [8]. Figure 2.1 shows the evolution of biodiesel from edible, non-edible, and algal biomasses [64].

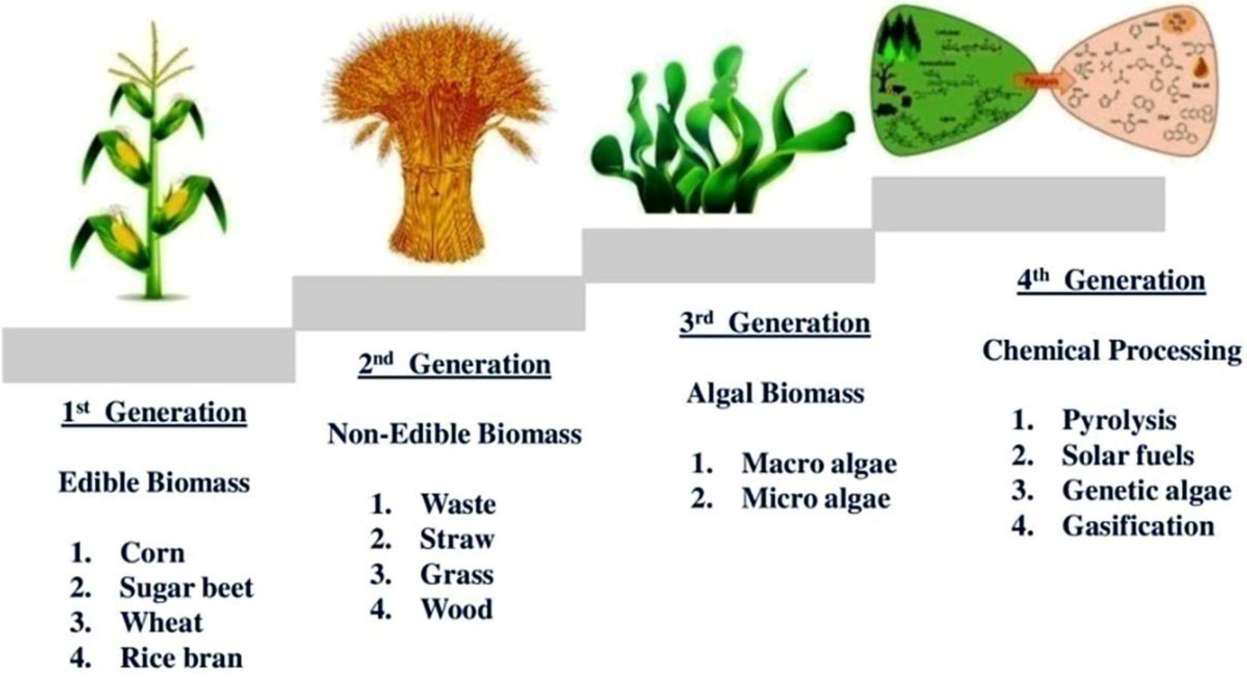


Figure 2-1. Evolution of Biodiesel [64].

2.1.1 Low-Level Blends

Conventional diesel fuel is one of the many items for which ASTM International is responsible for developing the specifications [6]. According to this criterion, biodiesel proportions of up to B5 can be referred to as diesel fuel, and different branding at the pump is not required. It has approved using low-level biodiesel blends, such as B5, in any compression-ignition machine initially intended to run on petroleum diesel [6]. This could include light-duty and heavy-duty diesel automobiles and trucks, as well as tractors, boats, and electricity generators.

2.1.2 B20 Biodiesel

B20 biodiesel is a common blend since it strikes an optimal balance in terms of price, emissions, efficiency in cold weather, compliance with materials, and the capacity to operate as a solvent [66]. Most biodiesel consumers acquire blends with a B20 percentage or lower than their standard gasoline suppliers or biodiesel dealers. According to the Energy Policy Act of 1992, authorized fleets that utilize biodiesel blends at least 20% more biodiesel than conventional diesel are eligible for biodiesel fuel consumption credits [66]. The quality requirements in ASTM D7467 must be satisfied before B20 can be considered acceptable.

In particular, B20 and lower-level blends are utilized in engines currently on the market without any necessary alterations [64]. Many of the original equipment manufacturers (OEMs) of diesel engines permit using B20. Before utilizing biodiesel, customers should always check the warranty information of their vehicles and engines. Machines that run on B20 possess a lower fuel usage, horsepower output, and torque output comparable to engines that run on petroleum. Although B20, with a 20% biodiesel composition, will possess 1% to 2% less power per gallon than petroleum, many consumers of B20 frequently confirm that there is no perceptible change in either efficiency or fuel affordability [25]. Additionally, biodiesel can reduce pollution, particularly in older vehicles constructed before 2010 [64]. When it comes to improving air quality, engines outfitted with selective catalytic reduction (SCR) systems get the same advantages regardless of whether they operate on biodiesel or petroleum diesel. Figure 2.2 shows the different types of feedstocks that are mainly used for biodiesel production in the European Union, the United State of America (USA), and the rest of the world [25].

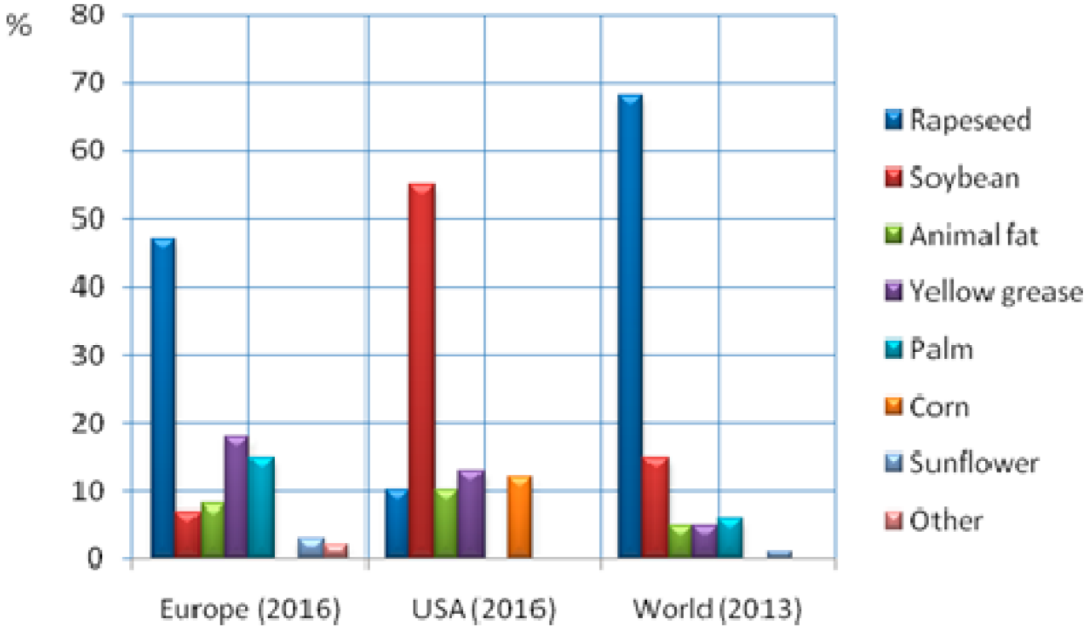


Figure 2-2. Feedstock inputs for Biodiesel Production in the European Union, USA, and the World [25].

2.1.3 B100 Biodiesel and High-Level Blends

Because of a deficiency of regulatory incentives and affordability, B100 and other high-level biodiesel blends are not utilized directly as a transportation fuel as frequently as B20 and lower blends [36]. B100 can be utilized in some engines manufactured after 1994 thanks to the development of biodiesel-compatible materials for use in specific sections, such as hoses and gaskets [36]. Because of its solvent properties, B100 can be used to clean the fuel system of a vehicle and remove deposits that have been generated as a result of using petroleum diesel. The discharge of these residuals may at first cause the filters to become clogged, necessitating regular replacement of the filters of high-level blends.

When working with high-level blends, a few considerations need to be made. On a proportional scale, diesel made from pure biodiesel has a lower energy content than diesel made from petroleum [66]. Because of this, the energy composition of a gallon of biodiesel fuel is lower when the amount of biodiesel is higher (over 20%). In addition, high biodiesel blend levels can void engine warranties, cause the fuel to gel when exposed to low temperatures, and possibly cause unusual storage complications. B100 could also lead to a rise in nitrogen oxide emissions, even though it significantly reduces emissions of other dangerous substances [8].

B100 requires careful management and may call for some adjustments to existing equipment. ASTM D6751 must be complied with for B100 to be acceptable for engine use. A No.1-B and a No.2-B category are included in the ASTM Specification D6751 [6]. The No.1-B grade is distinguished from the No.2-B grade by having restrictions on monoglycerides and filterability that are more stringent. The No.1-B grade of biodiesel is a special-purpose biodiesel class used in situations where the capacity to operate at low temperatures is required.

2.2 Renewable Diesel

The vast majority of renewable diesel is either hydrogenation-generated renewable diesel (HDRD) or hydro-processed esters and fatty acids (HEFA), both of which, are created through the hydroxylation of triglycerides in a manner analogous to that which is utilized for the desulfurization of petro-diesel [8]. Because of this, current oil refineries can easily be turned into facilities capable of producing renewable diesel with only a few minor modifications. The hydrotreatment of renewable sources, on the other hand, calls for a great deal more hydrogen than the desulfurization of diesel, and the origin of the hydrogen can affect whether or not the renewable diesel can satisfy state or federal regulations for biofuels [64]. Gasification and pyrolysis are two more techniques that can be utilized in manufacturing renewable fuel. Renewable diesel fuel and renewable heating oil are both products that meet the requirements of ASTM D396 for fuel oils.

The term "renewable jet fuel," also known as "sustainable aviation fuel" (SAF), may be used based on the circumstances or fuel specification in which it can be utilized. Renewable jet fuel complies with ASTM D7566, which permits a maximum blend ratio of 50-50 between components obtained from biomass and jet fuel made from petroleum [6]. In addition to fuel ethanol, other non-ethanol biofuels include recyclable naphtha, renewable gasoline, renewable propane (a byproduct of producing renewable diesel and SAF), and other upcoming biofuels. Alcohol-to-jet (ATJ) is yet another potential aircraft biofuel that is now undergoing testing (or ethanol-to-jet (ETJ).

Ethanol is a renewable fuel that may be produced from maize and other plant material. The usage of ethanol is widespread, and in the United States, more than 98% of gasoline comprises some level of ethanol. E10, which contains 10% ethanol and 90% gasoline, is the most popular type of ethanol blend [36]. Ethanol is also present in E85, often known as flex fuel, high-level ethanol blending that can contain anywhere from 51% to 83%, based on the region and the time of year [36]. Flexible fuel cars are designed to run on E85. E15, another type of blend, is becoming more prevalent on the market. It has been given the go-ahead for use in light-duty traditional gas vehicles manufactured after 2001.

The term "hydrogen fuel" describes the practice of transporting energy in the form of hydrogen gas (H2) [66]. Hydrogen can be generated from biomasses such as agricultural and forest wastes, consumer effluents, and other particular crops. This method of producing hydrogen fuel is known as the biomass-to-hydrogen method. The second method of producing renewable hydrogen fuel is known as the "water-to-hydrogen" method. Particularly, hydrogen fuel is formed by a process known as gasification, in which biomass is converted into a flammable gas and then burned, or through pyrolysis, a linked procedure that can result in hydrogen gas that is appropriate for use in fuel-cell applications [66]. These processes can be thought of as intermediate steps to producing hydrogen fuel. In both of these procedures, the generation of undesirable byproducts is a topic that has been and will always be the core of experiments.

Other contaminating gases frequently depend on the biomass feedstock's actual content, which can be challenging to handle [25]. This can make it challenging to determine whether or not the gases are present. Algae are an additional potential source for the biological synthesis of hydrogen fuel. It was developed in the late 1990s that if algae are denied sulfur, they will transition from oxygen generation, as they do in typical photosynthesis, to hydrogen generation [25]. Attempts are being made at pilot algae farms to render algae a viable energy source from an economic perspective. Several Physicochemical processes can produce hydrogen; most involve water electrolysis [25]. When this method derives its power from renewable energy sources, including wind turbines or solar cells, it needs minimal usage of resources that are not constantly being replenished. When hydrogen fuel is generated using sustainable forms of energy like wind or solar power, it is referred to as green hydrogen, a renewable fuel.

2.3 Biodiesel Usage in The United States and Globally

2.3.1 Producing Power and Electrical Current

Additionally, biodiesel can generate power in reserve generators in jurisdictions like schools, hospitals, and residential neighborhoods where pollutants are of the utmost importance. Because of this, biodiesel is an enhancement to the fuel cells that have an operation that generates power and is thus accessible for electricity. In addition to using batteries, customers can charge and power electronic devices such as laptops and cell phones by using biodiesel instead of batteries [48]. These cells are still in the research and development stage, but they promise to become a reliable power source. For instance, biodiesel made from soybeans has a life cycle energy efficiency ratio of 3.2 units of fuel energy produced for every 1 unit of fossil fuel energy used [48]. Since biodiesel production relies on the sun-driven photosynthetic activity carried out by the plant feedstock while it is in the growth stage, the term "liquid sunshine" is often used to refer to this fuel type. Figure 2.3 below demonstrates an estimate of the amount of ethanol consumption on transportation based on the combination of various statistics for ethanol consumers [48].

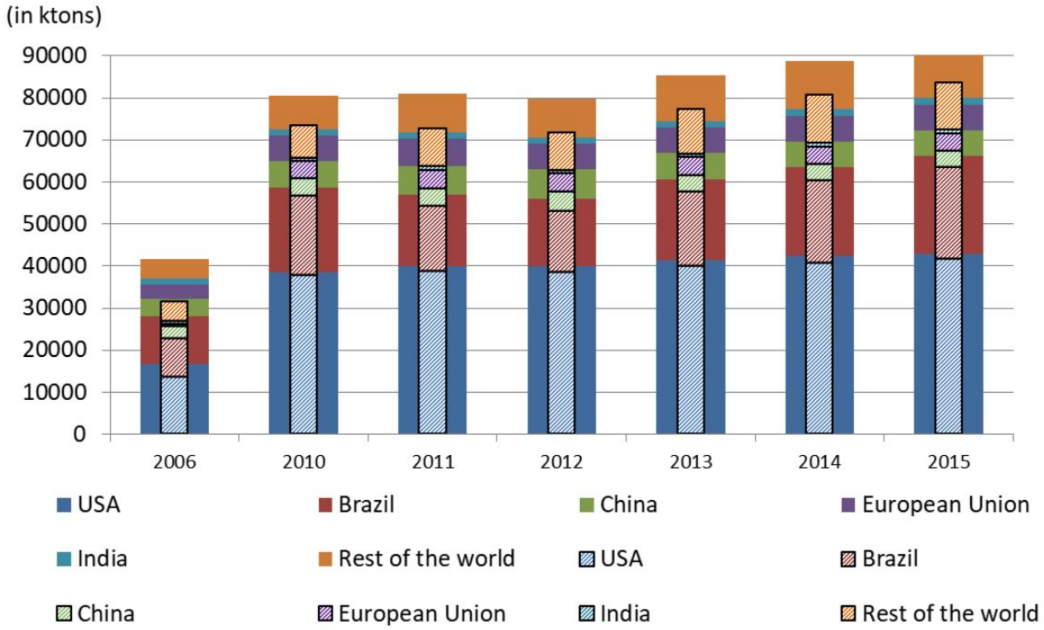


Figure 2-3. Consumption of Ethanol for Biofuels Use (narrow bars) and Total Ethanol Consumption (wide bars) for Brazil, for the EU, for USA [48].

Producing high-quality biodiesel fuel is a challenge that many farmers are not interested in taking on since they already have a lot on their plates. The energy included in biodiesel is lower than that of petroleum diesel. Biodiesel contains 8% fewer BTUs per gallon, which means that users of B100 typically experience either an 8% decrease in power or an 8% increase in fuel consumption [48]. These results are based on the volumetric comparison. Biodiesel is somewhat denser than petrodiesel. On the other hand, it has roughly 11% oxygen, in contrast to petrodiesel, which has zero 0% oxygen [48]. Even though oxygen does not add to the total energy, it does help the gasoline burn more effectively, resulting in fewer pollutants being released from the exhaust. The production of biodiesel results in a net gain of energy above the amount of energy used in the process.

2.3.2 Generating Heat through Biodiesel

Using biofuels to generate heat has become increasingly popular in the last few years. Using biodiesel as a heating source is essential to its operation. It takes the place of wood, traditionally the most useful heating source. When used for heating, a mixture of biodiesel and traditional diesel fuel can cut emissions of sulfur dioxide as well as nitrogen. This heat can also be utilized for cooking, eliminating the need for kerosene, often required for stoves and lanterns without wicks. A recent study shows that it is possible to mix biodiesel with petroleum heating oil to create a blend that may be used in any home heating set-up at a ratio of up to 20% without requiring any adjustments to be made to the system [11]. B3 is the name given to a mix that consists of 97% home heating oil and 3% biodiesel. The term "B20" refers to a mix that consists of 80% traditional home heating oil and 20% biodiesel [11].

Upon analysis, households will need more than 3 billion gallons of fuel for their home heating systems to stay warm [11]. Between October and March, the typical oil-heated home in the United States will go through approximately 500 gallons of heating oil. More jurisdictions are demanding biodiesel blends. Compared to traditional fuels, biodiesel has been positioned as the superior option due to its cleaner combustion. The vast majority of oil-burning heaters should have no trouble operating with a mixture of up to 20% biodiesel [11]. In most cases, cooking or soy oil is the foundation of the composition, which is subsequently augmented with conventional heating oil. Most of the oil comes from restaurants; however, it cannot be utilized immediately after being thrown out in the kitchen; instead, it must first be cleansed and purified before it can be used again. Restaurants are the principal cause of the oil.

2.3.3 Cleansing Oil Spills

Because biodiesel is safe for the environment, it can be utilized to clean up oil spills and grease. It has undergone testing to see whether or not it is effective as a potential cleaning solution for regions where crude oil pollutes the water. Results show that even if biodiesel is accidentally dropped or discharged into the surroundings, it induces much less damage than fossil diesel because it is less ignitable [46]. The findings have also shown that increasing the retrieval zones and allowing it to be extracted from the water is possible due to these findings. Because it is not hazardous to manage, store, or ship, it is an excellent choice for cleaning up oil spills. As a degreasing agent, it has been utilized for cleaning up crude oil that has fouled shorelines. Testing has demonstrated that it can boost the crude oil recovery rate from sand columns [46]. Because of this, it has the potential to be valid on beaches and in other coastal locations.

A discharge of biodiesel would result in significantly less harm than the same spill of petroleum fuel. In addition, the threshold for biodiesel is more significant than 130 degrees Celsius [46]. This contrasts with the threshold for petroleum diesel, which is approximately 52 degrees Celsius [46]. Because it contains methyl esters, biodiesel can help clean up oil spills. This ability is made possible by the presence of methyl esters in the material. These fatty acids contribute to a reduction in crude oil's fluidity, making it possible for biodiesel to act as a proper solvent. Even though this may occasionally result in traces of water being left behind in the biodiesel, they may be eliminated once the crude oil has dissolved due to the high stability of the oil. In addition, there will be no additional pollution increase because biodiesel's toxicity is lower than that of table salt.

2.3.4 Engine Lubrication

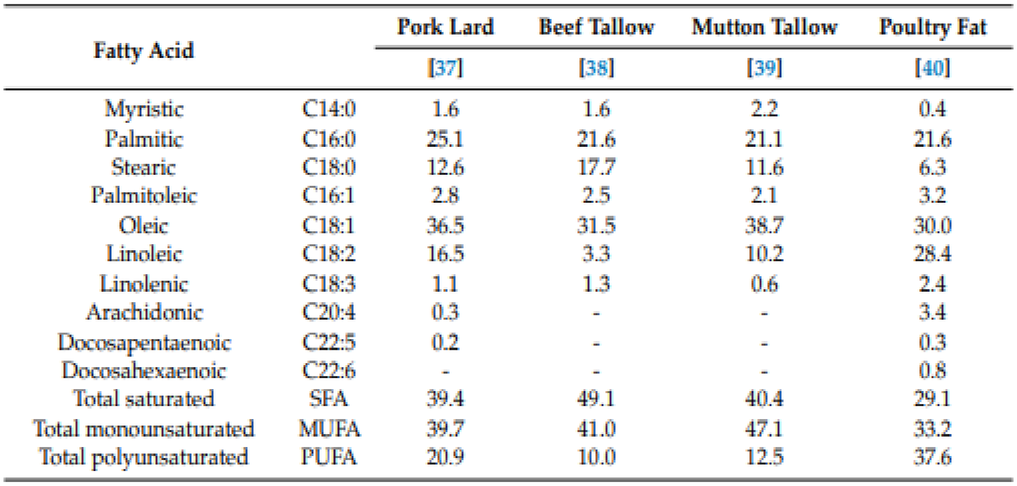
It is essential to have biodiesel in automobile engines because it lowers the proportion of sulfur, and sulfur is the component of gasoline that offers the highest lubricity. As a result, biodiesel maintains the engine's optimal performance and protects against the onset of early infection failure. It lowers the amount of friction and wearing that sliding surfaces experience, extending the engine's longevity. In a recent study, the parameters of wear and friction exhibited by palm oil biodiesel (B10, B20, B50, and B100) were subjected to a constant load and rotated at one of four distinct speeds (600, 900, 1200, and 1500 rpm) [51]. The amount of wear and friction reduced as the proportion of biodiesel grew, and the injection of biodiesel significantly reduced the degree of wear and friction experienced by the sliding surfaces. In most cases, a high bandwidth revolving friction and wear experimental set-up is utilized to assess biodiesel's lubricating qualities. Both B5, which is diesel blended with 5% rapeseed biodiesel, and B100, which is 100% rapeseed biodiesel, had a lesser friction coefficient than diesel [51].

Products explicitly intended for the removal of paint are frequently quite hazardous. This is because they require the paint to be whittled away. Biodiesel is an excellent substitute for applications that are not crucial and are conducted on a lower scale [11]. It is not suitable for the bespoke paint job you have done on your car; nonetheless, it is ideal for most household uses. It is also helpful in eliminating the adhesive residues left behind after removing things such as duct tape. Additionally, biodiesel is an excellent lubricant and degreaser for bicycle chains. If a bike chain begins to creak, a little B100 will have the most significant impact. Additionally, it is an efficient solvent for cleaning industrial metals [11].

2.4 Animal Fat-based Biodiesel Production

At industrial plants that produce biodiesel, transesterification with alkaline catalysis is still the common method when generating biodiesel from animal fat [59]. However, technological advances for procedure augmentation, such as sonography and microwave, have been invented to be used in transesterification and enhance biodiesel yield. These techniques have the potential to strengthen biodiesel fuel. Irradiation at lower frequencies with ultrasonic waves can be used in a huge application to emulsify incompatible liquids [59]. When subjected to microwave irradiation, reagents can be heated to the desired temperature effectively and expediently. Other process intensification methods, such as oscillatory tubular reactors, static blenders, capillary breeders, or microreactors, are also designed to boost the speed of the reaction and maximize biodiesel synthesis. Table 2.1 lists the different type of fatty acids composition in animal fats [53].

TABLE 2-1 FATTY ACIDS COMPOSITION IN ANIMAL FATS [53].



Fatty Acid		Pork Lard	Beef Tallow	Mutton Tallow	Poultry Fat
		[37]	[38]	[39]	[40]
Myristic	C14:0	1.6	1.6	2.2	0.4
Palmitic	C16:0	25.1	21.6	21.1	21.6
Stearic	C18:0	12.6	17.7	11.6	6.3
Palmitoleic	C16:1	2.8	2.5	2.1	3.2
Oleic	C18:1	36.5	31.5	38.7	30.0
Linoleic	C18:2	16.5	3.3	10.2	28.4
Linolenic	C18:3	1.1	1.3	0.6	2.4
Arachidonic	C20:4	0.3	-	-	3.4
Docosapentaenoic	C22:5	0.2	-	-	0.3
Docosahexaenoic	C22:6	-	-	-	0.8
Total saturated	SFA	39.4	49.1	40.4	29.1
Total monounsaturated	MUFA	39.7	41.0	47.1	33.2
Total polyunsaturated	PUFA	20.9	10.0	12.5	37.6

In a recent experiment the utilization of microwave combustion for animal fats comprising up to 20% free fatty acids (FFAs) enabled a reduction in the duration needed for FFA minimization, which led to a rise in the extraction yield [53]. The utilization of supercritical methanol at temperatures ranging from 300 to 400 degrees Celsius, pressures reaching up to 41.1 megapascals, alcohol-to-fat proportions of 3:1 and 6:1, and a limited period (between 2 and 6 minutes) resulted in a conversion efficiency of 88% for chicken fat. The amount of biodiesel that may be produced from distilled lard can also be produced from waste lard comprising fatty acids and water, and there is no necessity for any preparation for this. Even in the existence of free fatty acids and water linked with animal fats, supercritical procedures give quicker reaction rates without a catalyst. Additionally, these procedures eliminate the requirement for pre-treatment. Neste's renewable diesel production begins with triglyceride hydrolysis into the respective alkanes and propane, which is then accelerated by hydrogen. Results reinforce that five facilities generate up to three million tons annually, which is then combined with fossil diesel and used in various industries, including aircraft, turbines, generators, and ships [53].

In order to facilitate the manufacturing of biodiesel, new heterogeneous catalysts that are capable of being easily retrieved, rejuvenated, and repurposed have been designed. The manufacturing of biodiesel from chicken fat was developed and tested with a new nano-catalyst made up of CaO and $CuFe_2O_4$ [16]. This catalyst was used throughout the transesterification process. Tests were performed to determine whether a sodium silicate precursor that fails to integrate with FFAs throughout transesterification can be used to make biodiesel [16]. If successful, this catalyst would allow biodiesel to be mixed with diesel at up to 30% concentrations without compromising functionality. According to test result findings, the particular fuel for the brakes was 26% more expensive than diesel, and the thermal performance of the braking was 4% lower, but the amount of CO produced was decreased by 24.4%, and the number of hydrocarbons produced was lowered by 22.9% [16]. Despite this, there was no rise in emissions of 11%, even at higher loads. Figure 2.4 below illustrated the transesterification process from slaughterhouse to ultimately biodiesel as the main product and glycerin as a byproduct [52].

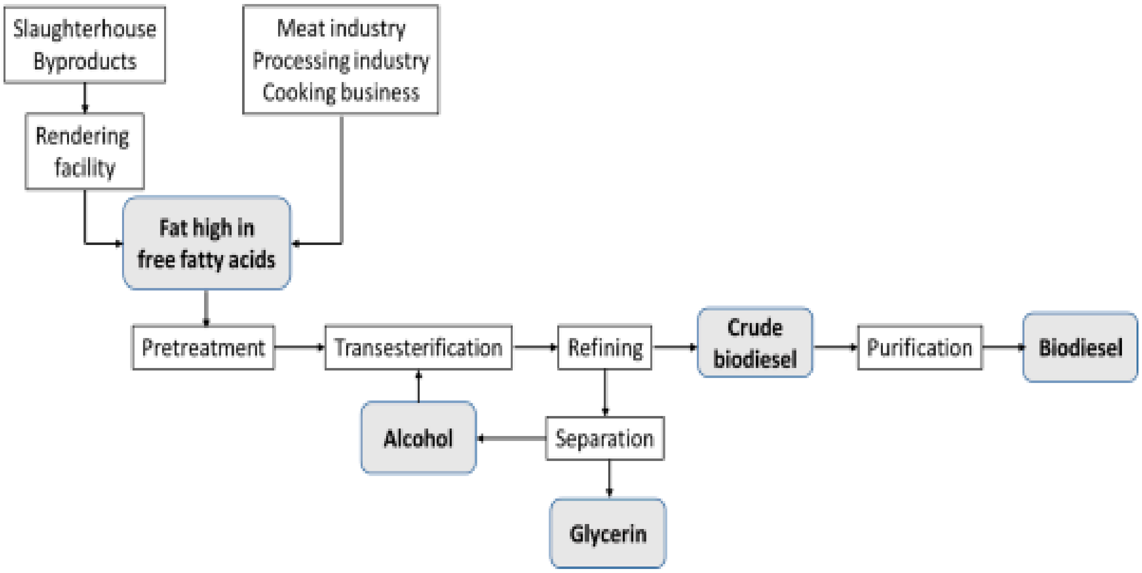


Figure 2-4. Transesterification Process Flowchart [52].

A calcined scallop shell is a potent catalyst for the transesterification of rapeseed oil [33]. For the pre-treatment of animal fats with a large concentration of FFAs that could be detoxified up to 99% with alcohol under optimal conditions, a previously approved catalyst for the pre-treatment of animal fats comprised of hydrated metal salts that are both inexpensive and risk-free has been suggested [33]. The methyl esters were found to have persisted in the oily phase and could be employed immediately with alkaline catalysts for the transesterification process. On the other side, a biorefining approach was developed to convert free fatty acids into triglycerides for animal fat waste. These triglycerides could then be combined with fossil fuel and employed in the combustion systems of engines.

Adsorbed lipases and lipases from different microbes, such as Candida antarctica and Candida rugosa, Pseudomonas cepacia, and Pseudomonas spp., have been described as being effective for the synthesis of biodiesel [52]. When lipases are used, a reduced amount of energy is required, and there is no need to use soaps. Another benefit of using lipases is that they are specific and selective, which reduces the likelihood of unintended reactions. However, the price of the enzyme is prohibitively high. It is susceptible to denaturation when exposed to alcohol and has only one use. Immobilization of the enzyme improves its stability and makes it possible to reuse it, even though alcohol may cause some dissociation. The transesterification process using immobilized lipase in supercritical carbon dioxide decreases the interface between methanol and the enzyme, as well as its toxic effects, and results in the fast removal of CO_2 from the product [52].

Adsorbents such as magnesium aluminum hydroxycarbonate and 3,5-desert-butyl-4-hydroxybenzene benzene have recently been presented as a means to improve the oxidative steadiness of biodiesel and its derivatives and, as a result, to delay the breakdown of these fuels [59]. A reduction of up to 9% in the acid value is possible. Adsorbents can eliminate the antecedents of biodiesel deterioration by preserving the produced free radicals and blocking them from beginning new oxidation chains. This allows the adsorbents to eliminate the progenitors of biodiesel deterioration. In biodiesel made from vegetable oils, precipitates of steryl glucosides are sometimes present. These precipitates have the potential to clog filters. A recent study confirms that adsorption with 3% silica at 112 degrees Celsius for 72 minutes is how their elimination is accomplished [59].

Enzymatically catalyzed transesterification is more desirable when there is a large quantity of water and free fatty acids, such as in animal fats [31]. In the vicinity of an acyl acceptor, the enzyme lipase can convert free fatty acids and triglycerides into biodiesel. The key benefits are gentle reactivity circumstances, good selectivity, the precision of transesterification, a more comprehensive range of substrates, the absence of soap production, a lower alcohol-to-oil ratio, fewer purification procedures, and better productivity [31]. However, the majority of the expense is attributable to the enzyme itself and its poor stabilization, which results in a prolonged reaction speed, and a reduced conversion rate, which is related to the diffusion induced by the enzyme's byproduct. These problems can be alleviated by immobilizing the enzymes on an inert support, which boosts the enzymes' persistence, eliminates the requirement for enzyme dissociation, and enhances the procedure's efficiency [31].

Pre-treatments are required prior to the process of transesterification in order to eliminate the surplus of FFAs, water and suspended particles that are present in animal fats as showcased in a recent study [31]. Drying with heat and treating with silica gel, calcium chloride, or anhydrous sodium sulfate are some examples of pre-treatment methods that can help reduce moisture levels. Neutralization and segregation can eliminate the surplus of free fatty acids. In addition, the dispersed debris can be eliminated by filtration through cellulose filters or a vacuum [31]. However, the pre-treatment stages lead to higher expenditures, even though they improve both the quality and production of biodiesel. An alternate solution would involve a dual step transesterification reaction, with the first phase consisting of an acid-catalyzed pre-treatment to esterify the free fatty acids and, as a result, reduce the amount of these acids present, and the second stage involving the transesterification of triacylglycerols using an alkaline catalyst. These catalysts have a higher resilience for high amounts of water and free fatty acids and can also be recycled [31].

When large proportions of alcohol to fat are present, the enzyme loses its ability to function correctly, which results in additional expenditures. Therefore, using methanol in a sequential addition to replace methanol with an acyl acceptor such as methyl or ethyl acetate or to use a solvent such as t-butanol in order to increase the absorption of methanol [16]. These are the three approaches that have been presented. Lipases from a broad range of microbes, including Candida antarctica, Candida rugosa, Pseudomonas cepacian, Pseudomonas spp., and Rhizomucor miehei, as well as immobilized lipases [16]. At industrial facilities that produce biodiesel, transesterification via alkaline catalysis is still favored as the method of choice. This fact needs to be brought to your attention. Despite the significant amount of research that has been conducted on diverse enzyme stimulants, biodiesel manufacturers have not yet used these technologies.

2.5 Seed-Oil Biodiesel Production

Glycerin is extracted from vegetable oils to produce biodiesel by transesterification. The procedure yields methyl esters and glycerin as byproducts [41]. The chemical name for biodiesel is methyl esters, and glycerin is utilized in various goods, like soap. Oils generated from plant seeds and microalgae mainly consist of triacylglycerols (TAG) units with exceptionally high energy density, rendering them an attractive source for biofuels [15]. Most biodiesel is created by combining soybean oil or leftover cooking oils with methanol in major producing nations such as the United States. For alkali-catalyzed transesterification, biodiesel generation from feedstocks with low quantities of free fatty acids (FFA) involves multiple procedures. These consist of soybean oil, canola (rapeseed) oil, and waste restaurant oils of top grade. Alcohol, catalyst, and oil are blended in a activator and stirred at 60°C for approximately one hour [41]. Most larger facilities use progressive flow procedures with continuous stirred-tank reactors (CSTR) or plug flow processors instead of batch breeders. Figure 2.5 below shows the process that is required to extract biodiesel from seed-oils [56].

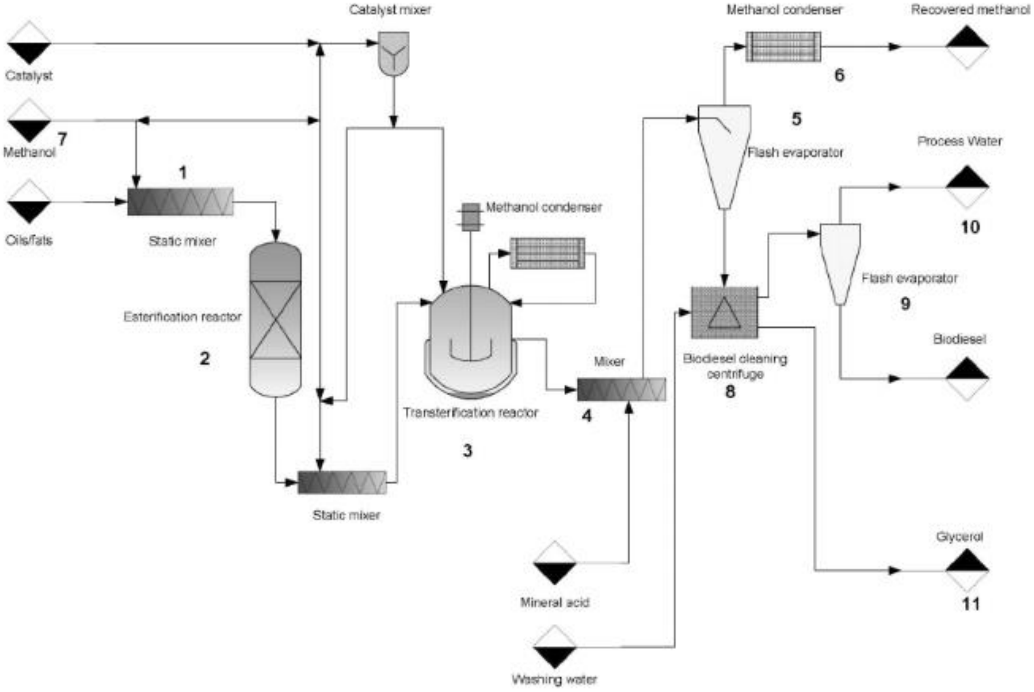


Figure 2-5. Extraction of Biodiesel from Plant Seed-Oil [56].

In a first-stage CSTR, 80% of the alcohol and catalyst are infused into the oil [56]. Occasionally, the reaction is performed in two stages. Before joining a second CSTR, the product channel from this activator undergoes a glycerol deduction process. In this second reactor, the residual 20% of the alcohol and catalyst is introduced [56]. This approach can potentially use less alcohol than single-step frameworks because it offers an extensive reaction. The glycerol is extracted from the methyl esters following the synthesis. Due to the minimal solubility of glycerol in the esters, this dissociation often occurs rapidly and can be accelerated. A settling chamber or a centrifuge may be used to achieve the task. The extra methanol behaves as a solubilizer and may impede the separation process [56]. Due to the risk of reverting the transesterification process, this excessive methanol is often not withdrawn from the activation channel until after the glycerol and methyl esters have been segregated. After the transesterification, water can be induced to the reaction mixture to facilitate the isolation of glycerol.

After being removed from the glycerol, the methyl esters undergo a nitrification process before being put through a methanol extractor and washed in water. The methanol extractor is often a vacuum flash procedure or a descending film impeller [38]. Acid is injected into the biodiesel product to divide any soap that may have accumulated during the process and to negate any remaining catalyst that may have been present in the product. During the process in which the water is washed, the salts will be extracted, but the FFA will be retained in the biodiesel. During the phase of water washing, the biodiesel is supposed to be cleaned of any residual catalyst, soap, salts, methanol, or free glycerol that may have been present [38]. Before washing, neutralization brings about a decrease in the quantity of water needed and a reduction in the possibility of the formation of emulsions once the wash water has been introduced to the biodiesel. After the wash process, the biodiesel goes through a vacuum flash procedure to extract any remaining water from it.

The glycerol stream discharged from the separator contains less than 50% of the target substance [38]. It carries the majority of the catalyst, the soap, and the majority of the extra methanol. In its current state, glycerol offers minimal benefit and may be difficult to dispose of. Due to the presence of methanol, the glycerol must be handled as if it were hazardous waste. When purifying glycerol, the first step that is typically done is to add acid in order to separate the soaps into FFA and salts [38]. Because the FFA are insoluble in glycerol, they will float to the surface, where they may be skimmed off, collected, and reused. The method for esterifying these FFA and then bringing them back into the transesterification reaction channel was cited in the previous sentence [38]. Salts do not separate from glycerol; however, some salts may precipitate out based on the other chemical components. Potassium phosphate, a salt that could be utilized as fertilizer, can be produced as a byproduct of the reaction if potassium hydroxide is employed as the reaction catalyst and phosphoric acid is utilized to neutralize it [38].

After the glycerol has been acidulated and the FFA has been separated, a vacuum flash method or another kind of evaporator is used to eliminate the methanol present in the glycerol. At this stage, the glycerol should have a pureness of at least 85%, at which point it is usually sold to a glycerol distiller [2]. Using either vacuum filtration or ion exchange techniques, the purity of the glycerol can be increased during the purification process until it reaches 99.5–99.7% [2]. When methanol is extracted from the methyl ester and glycerol stream, it tends to gather any water that may have been introduced into the reaction during that step. This water needs to be extracted from the row of distillation that comes before reintroducing the methanol into the procedure. This phase is made more complicated by alcohol, which creates an azeotrope when combined with water [2]. Examples of such alcohols include ethanol and isopropanol. After that, the water is extracted using a molecular sieve.

Through the use of mechanical pressers, a yield of croton oil that was 38.42% (v/w) was achieved [56]. However, the solvent dissociation provides greater yields of up to 41%, and its efficiency is constant, as observed by Adewuyi et al. on the oil generation using jatropha seeds [2]. In broad sense, it has been noted that the process of trans-esterification of triglycerides to alkyl esters (biodiesel) produces a mixture that estimate the characteristics and functionality of petroleum-based diesel. This enables it to be utilized explicitly as an alternate fuel without any adjustments or as melding substances for diesel fuel. These vegetable oils have seen a significant price hike as a direct consequence of the increased demand for them as feedstock, which is in direct competition with the need for food. This has a significant impact on the industry's capacity to make a profit from these substrates, which are used to make biodiesel. Consequently, they were undoubtedly proven impossible to implement and unsustainable, which led to the contemplation of oil-rich plant biomass that was both less costly and less competitive, as well as indigestible.

2.5.1 Acid-Catalyzed Pre-treatment

The oil must go through a unique processing step if it includes substantial FFA concentrations. FFA can range anywhere from 2–7% in used cooking oils. Some feedstocks with very minimal value, such as trap grease, can come close to having an FFA content of 100%. Feedstocks react with an alkaline catalyst to produce soap and water [68]. The synthesis can still be accelerated with an alkali catalyst up to about 5% FFA, but an extra catalyst must be introduced to compensate for the catalyst lost to soap during the process. Either the soap produced during the reaction is eliminated with the glycerol or rinsed away with the water during the subsequent step. When the FFA level is greater than 5%, the soap prevents the glycerol and methyl esters from being separated and leads to the creation of an emulsion during the water phase of the process [68]. In situations like these, an acid catalyst like sulfuric acid can be utilized to accomplish the esterification of FFA into methyl esters.

This procedure can be utilized as a pre-treatment to transform the FFA to methyl esters, ultimately resulting in a lower FFA level in the final product. After that, the low-FFA pre-treatment oil can be transesterified using an alkali stimulant to transform the triglycerides into methyl esters. Water is produced, and if it collects, it can halt the reaction well before it is finished as noted by [68]. After the reaction, it is suggested that the alcohol be allowed to get separated from the prepared oil or fat in some way. The extraction of this alcohol also results in the removal of the water produced as a byproduct of the esterification process, making it possible for another stage of esterification to occur. Conversely, one may continue immediately to alkali-catalyzed transesterification [68].

The mixture of methanol and water will also include some oil and FFA that has been absorbed in it and should be salvaged and put through further processing. Pre-treatment with an acidic ion-transmission polymer is also included. The low-grade residues of the oil refining sector, such as soapstock, can be utilized in the acid-catalyzed esterification process to make biodiesel [2]. After being desiccated, saponified, and esterified with methanol or another elementary alcohol utilizing an inorganic acid as a catalyst, soapstock, which is a blending of water, soaps, and oil, is ready for use in the production of soap. The technique depends on a substantial quantity of new alcohol, and the price of reclaiming this alcohol will determine whether or not it is economically viable.

2.5.2 Trends in Industrial Production

Because of the various products that are typically acquired during the procedure, such as seed cakes and oil cakes, hydraulic and solvent extraction techniques are frequently utilized for commercial oil production. This is due to the fact that these processes are typically more efficient. For the mechanical extraction procedure, one can select to employ either a hand-operated ram crusher or an engine-driven screw crusher. Because of its greater reactivity and lower cost, methanol is typically the alcohol of choice for transesterification rather than other types of alcohol. Ethanol is an alternative fuel because it has a greater cetane quantity, a greater heat capacity of fuel, and a lower hazardous load; nevertheless, the production of ethanol requires a significant amount of power and has problems with the dissociation of ester [41].

Through the use of mechanical pressers, a yield of croton oil that was 38.42% (v/w) was achieved [56]. However, the solvent dissociation provides greater yields of up to 41%, and its efficiency is constant, as observed in Adewuyi's study on the oil generation using jatropha seeds [2]. In broad sense, it has been noted that the process of trans-esterification of triglycerides to alkyl esters (biodiesel) produces a mixture that estimate the characteristics and functionality of petroleum-based diesel. This enables it to be utilized explicitly as an alternate fuel without any adjustments or as melding substances for diesel fuel. These vegetable oils have seen a significant price hike as a direct consequence of the increased demand for them as feedstock, which is in direct competition with the need for foods [38]. This has a significant impact on the industry's capacity to make a profit from these substrates, which are used to make biodiesel. Consequently, they were undoubtedly proven impossible to implement and unsustainable, which led to the contemplation of oil-rich plant biomass that was both less costly and less competitive, as well as indigestible.

2.6 Logistics and Supply Chain

From where it is produced, biodiesel is transported by trucks, trains, or ships to the fuel depots and wholesalers that sell it. Pipelines are utilized on occasion for the transport of B5, and the majority of biodiesel suppliers will send either B20 or B100 to merchants based on what type of biodiesel the latter prefers [40]. As part of a federal initiative to encourage the utilization of renewable energy sources, biodiesel fuel as an alternative to diesel fuel has been the subject of extensive advocacy and promotion. The use of biodiesel is accomplished by increasing the proportion of biodiesel to diesel fuel blended in line with the objectives established. Included on the list of nations that adhere to the requirement to make use of biodiesel are Argentina (B10), Colombia (B10), Australia (B2), India (B5), Indonesia (B20), and Malaysia (B10), amongst others [30]. As a result, there is a growing emphasis on doing research concerning the advancement of biodiesel technology as well as the efficiency of biodiesel supply chains. Figure 2.6 illustrates the biodiesel supply chain from the production leading to utilization [69].

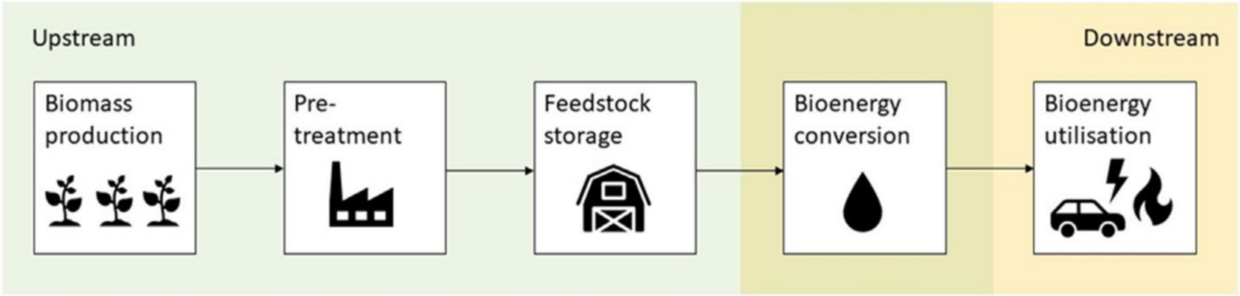


Figure 2-6. Biodiesel Supply Chain [69].

The movement of biomass from its source on the land to its ultimate application in biodiesel manufacturing is referred to as the biodiesel supply chain. The supply chains for biomass comprise various activities, including harvesting, manufacturing, mixing biodiesel with petroleum fuel, shipping, storage, and delivering to consumers [58]. These activities are carried out in various locations. The three entities engaged in this supply chain are the biodiesel sector, the fuel oil supplier who delivers to users, and cultivators of raw biodiesel resources [58]. In the event of an intervention by the government, there will be a total of four parties involved, including the authorities.

Due to the versatility of biomasses that can be utilized to make biofuels, biodiesel factories are more widely disseminated spatially than factories that generate corn-grain ethanol [29]. Most biodiesel factories process waste oil as a raw material rather than farm produce, which is one reason why biodiesel factories are more broadly disseminated [55]. Biodiesel is now the segment of biofuels that produces the most volume, second only to ethanol. In addition, biodiesel is often transported by vehicle, ship, or train [55]. Even if distributing the product via pipeline could be the most cost-effective method, further research needs to be done on the topic. Since biodiesel has poor cold-flow qualities, it may be challenging to transport in regions with colder weather. If the fuel is going to be used in states located in the northern tier, it must be kept liquid by being housed in warmed tanks specifically designed for the purpose.

Cold-flow qualities are the only ones that must be disclosed to the client [40]. However, the existing standards for biodiesels do not impose any limits on those characteristics. The absence of limitations makes the process of planning and operating a refinery more challenging. The quantity of diesel generated from various standard petroleum crude oils is restricted because of their poor cold-flow qualities. The operation of a refinery that can handle biodiesels with varying cold-flow characteristics would be complex and costly. In order to prepare for the worst possible case, which would involve poor cold-flow qualities, the base petroleum flows would need to be generated [40]. As a result of the fact that cold-flow qualities do not always blend consistently, refineries are required to generate conservative mixtures. The re-blending or reprocessing of a product that does not meet the specifications for cold-flow qualities can be an expensive endeavor for a refinery.

Biodiesel utilization in the US has been steadily growing ever since the Energy Policy Act of 2005 was signed into law [40]. The Renewable Transport Fuel Obligation law requires fuel suppliers in the United Kingdom to incorporate at least 5% of renewable fuel into all of the fuel they sell by the year 2010 [40]. This translates to approximately 5% biodiesel content for road diesel (B5). The United States, the world's largest biodiesel producer, has consequently constructed more intricate distribution networks. Direct supplies to clients are being made available by biodiesel producers such as Sirona in Oakland. This eliminates the need for a traditional intermediary and enables users to purchase fuel at a lower cost than is available at conventional gas stations. In the instance of Sirona, they provide biodiesel at the usual station at a price that is 25 cents a gallon less expensive than diesel [40]. They shipped a thousand gallons among all new buyers in just the first ten days after they began selling directly to consumers rather than simply to retail stores. This was after they had previously only sold to retail shops. Used cooking oil contributes to the company's production of around 50,000 gallons per month [40].

In the control of biodiesel supply chains, three primary decision-making procedures were identified: strategic decisions, tactical decisions, and operational decisions [30]. The decisions that will have the most impact over the coming years and decades are considered strategic. After a strategic choice has been reached, it is incredibly improbable that it will be changed shortly. In the biodiesel supply chain, some of the strategic choices that are frequently made involve, but are not restricted to, the following: (I) the choice of energy production innovations; ii) the set-up of the system; iii) the supply and demand agreements; iv) the guarantee of sustainable practices; and v) the position of the refinery. Figure 2.7 below shows the 3 stages of decision-making for biodiesel supply chain, categories, strategic, tactical, and operational [63].

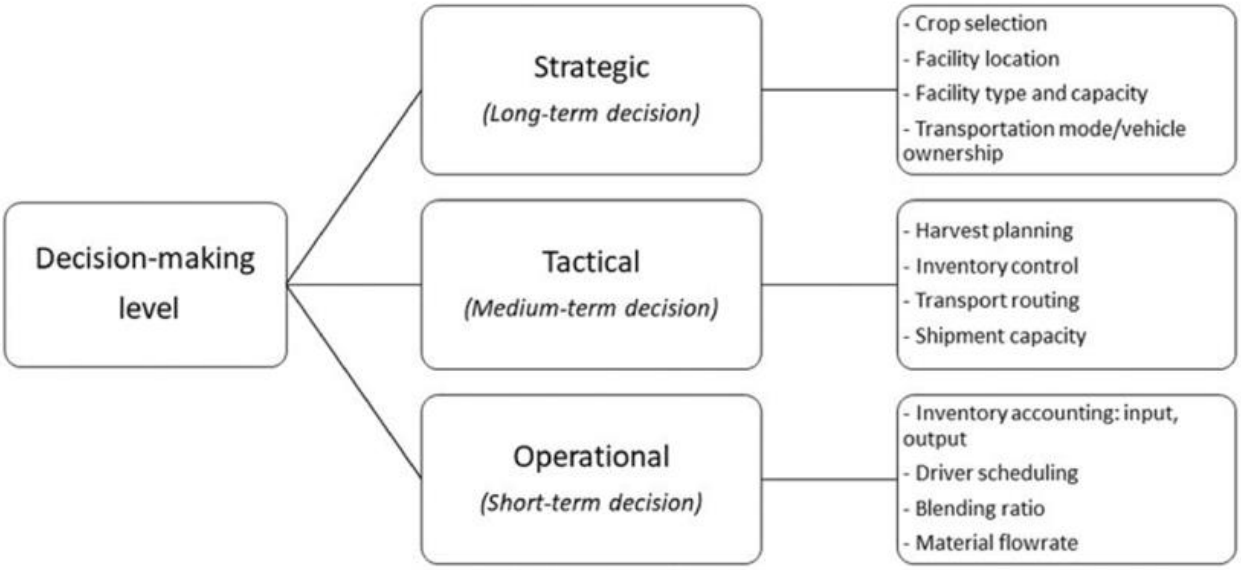


Figure 2-7. Decision-making Stages of Biodiesel Supply Chain [63].

Tactical decisions are made with a medium-term horizon and include sourcing decisions, production decisions, timing, shipping, logistical agreements, and the defining of the planning phase [30]. The decisions pertaining to inventory, such as its location, reliability, and amount, are also considered. The decisions made at the tactical level are designed to attain and carry out the strategic level objectives. Decisions about the procurement of bioenergy are crucial in the biodiesel supply chain for various reasons, including reducing the amount of geographic proximity that must be traveled and increasing the ease with which raw material resources may be accessed. This guarantees that the relatively isolated geographical distribution of considerable biodiesel can elevate researchers' enthusiasm for determining the accessible biomass amounts over a region and then progressing with choosing the best biomasses. Additionally, this guarantees that the scientists can determine the available biomass volumes.

Short-term judgments termed operational decisions are made to guarantee that the factories and other operations in the supply chain continue to function normally [30]. These decisions are taken daily, weekly, or even more frequently, depending on the circumstances, to ensure that biodiesels are manufactured, transported, and delivered in a timely manner while minimizing associated costs. The decisions made at the operational level include the comprehensive planning of manufacturing, the daily monitoring of fleets, and the daily or weekly evaluation of inventories [21]. The accomplishment of the strategy or framework that was decided upon by the tactical supply chain choices is the primary focus at this juncture [30]. Fulfilling the monthly objectives requires daily actions and preparation in the biodiesel supply chain, such as sales forecasting, evaluation, and budgeting for distribution. This decision threshold is typically responsible for reviewing the production planning of the plants as well as the total production and materials requirements schedule.

2.7 Water in Oil Emulsions

As described, emulsions as colloidal systems made up of two liquid stages, typically water and oil, with one of the stages diffusing into the other [67]. Emulsions known as water-in-oil (W/O) are made up of an aqueous phase that is disseminated, in the manner of minute droplets, within a continuous oil phase. The addition of water to biodiesel contributes to a decrease in both nitrogen oxides and particulate matter at the same time [67]. There are three ways that water could be launched: by intravenous infusion into the burning cabin, by releasing water into the uptake plenum, or by gearing up water in fuel emulsification. Intake manifold remediation is the term used to describe injecting water into the intake plenum. All intake manifold fumigation methodologies require a specialized stipulation for the water supply. During the compression stage, the infused water goes into the cylinder at the same time as the intake air, and both the water and the air evaporate due to the heating that occurs during the concussion [67].

A recent study shows that since the water droplets are nearer to the flame while the combustion is taking place, the amount of NOX that can be reduced by infusing water straightaway into the burning cabin utilizing a different injector is higher than the amount that can be reduced by fumigating the intake plenum [67]. On the other hand, in addition to producing more HC and CO, these techniques require the engine to undergo essential modifications. An emulsion is defined as a mixture of two or more liquids incompatible with one another, with one of the liquids existing as droplets scattered across the liquid's progressive phase. While the other liquid is in its exterior phase, the scattered droplet falls underneath the internal phase. According to the size of the individual droplets that were distributed, a mixture is called an emulsion if it has a particle size of between 1 and 10 micrometers. If the particle size is less than 0.2 micrometers, it is a microemulsion. A nanoemulsion has a particle size of fewer than 300 nanometers [14].

Emulsions of water in oil can be a potential solution because they do not require any adjustments to be made to the engine, yet they help minimize NOX and PM while improving the capacity with which combustion occurs [58]. Both diesel and biodiesel fall under the oil category that was previously mentioned. Water injection into gasoline because the boiling temperature of gasoline is quite close to that of water (about 100 degrees Celsius) [10]. In contrast, the gap between the boiling points of biodiesel and water is typically quite large (around 180 to 340 degrees Celsius).

2.7.1 Water in Oil Emulsion-Characteristics

Microemulsions are thermodynamically stable, whereas emulsions are volatile [32]. Generally, water-in-diesel emulsified fuel is steady for three months; however, this depends on several variables, including the form and proportion of the emulsifier, temperature, flowability, unit weight, and moisture content. Emulsions will transform into two distinct phases over time [32]. Water in diesel emulsion gradually dodges its consistency through gelation, agglomeration, creaming, and recrystallization [62]. Creaming is the first stage of instability in which the density difference between two liquids takes effect. After creaming, aggregation occurs, in which the droplets are enticed to one another. Therefore, these droplets condense into larger droplets, resembling a cluster of grapes divided by a dielectric layer in a procedure called flocculation. Because of Vander-Waals forces, the thickness of the layer dividing the clustered droplets gradually decreases, resulting in its rupture and the creation of a giant globule, representing the coalescence process. Predicated on the concentrations of the internal and external stages, these drizzles either accumulate to the bottom or float to the surface sedimentation process [32]. All these operations continue and ultimately result in the detachment of both stages.

2.7.2 Impact of Surfactant Concentration on Resilience of Oil-in-Water Emulsions

Surfactant functions as emulsifying stimulator by increasing the contact regions between two immiscible fluids, assisting in forming a steady solution. As the surfactant is incorporated into the water-oil combination, its polar molecules adjust to the water, and its non-polar units spin to the oil, thereby decreasing the interfacial friction between the two liquids. Without adding a surfactant, three minutes of churning and a mixing pace of 15,000 rpm divided the mixture into less than five minutes [10]. This demonstrates the significance of surfactants. Typically, 0.1 to 2% of the surfactant is introduced to the sample of two immiscible fluids. After examining the stabilization characteristic of water in diesel blends and determined that equalization of fluid in diesel blends with a greater water concentration (>20%) required a larger surfactant dosage [10]. Figure 2.8 below shows the stability of emulsion fuel in hours based on different percentages of water present in the mixture [10].

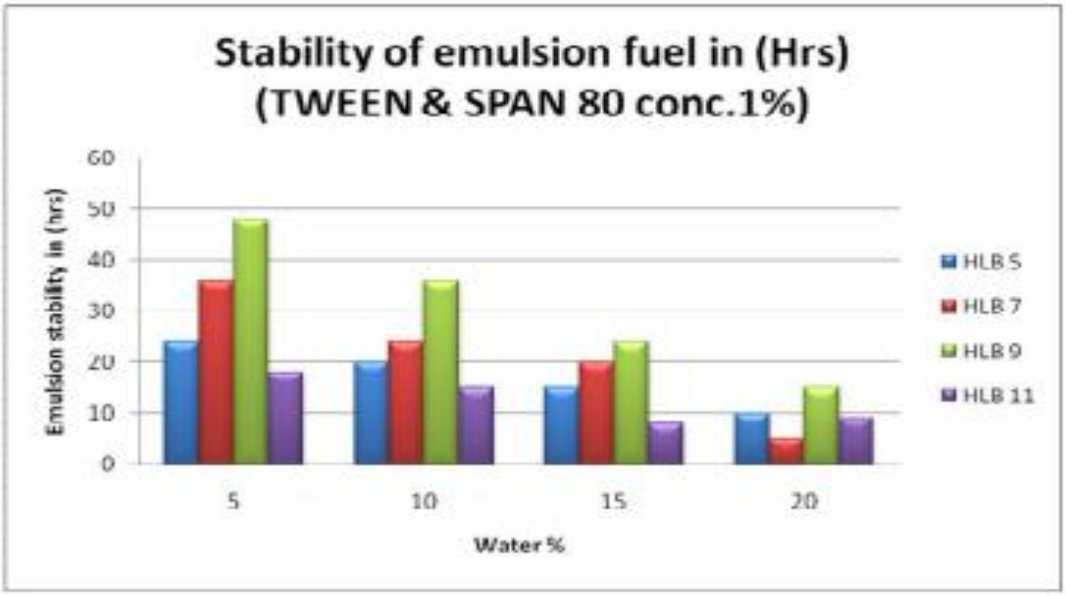


Figure 2-8. Stability of Emulsion Fuel in Hours [10].

To improve the steadiness of a W/D emulsion containing 30% water, surfactants in quantities ranging from 0.2% to 1.75 % were administered for a frequency of 20,000 revolutions per minute and a blending duration of 30 minutes [17]. They have noticed that the inclusion of surfactant at various concentrations has a significant effect on the increase of emulsion stability. The volume of water isolated from the blend reduced drastically as the quantity of surfactant increased. The emulsion containing 1.75% surfactant, 30% water, and 68.25% diesel emulsion was stable for nearly one week [17]. The stability of a second sample containing 2% surfactant in a 30% W/D emulsion was barely maintained for four hours. As the surfactant concentration exceeds its optimum output of 2%, the resilience of the emulsion will diminish. Due to the quick convergence that happens when a higher dose of surfactant is introduced, this is the case. They have concluded that the overall solution is 0.5% by volume [17]. Similar tendencies can be detected even when water is present in biodiesel blends. Investigations have demonstrated that elevating the aggregation of surfactant would improve the steadiness of W/B emulsions.

2.7.3 The Influence of Mixing Velocity on the Stability of Water-in-Oil Emulsions

An emulsion can be made of two liquids incompatible in several different ways [70]. In most cases, the injection of mechanical energy is what is necessary to accomplish emulsification. The huge droplets are meant to be broken up into smaller droplets as part of the mixing process, which ultimately results in a more stable combination. When the emulsion is generated at 30000 rpm and with 0.2% surfactant, it has been discovered that it has a stability of 4 weeks for 10% W/D emulsion [70]. It is necessary to significantly boost the blending speed to obtain a greater concentration of the whole amount of water. An increased level of stirring intensity produces a more stable emulsion. For the researched emulsion system, 2500 revolutions per minute was the ideal mixing speed [70]. However, a speed greater than the optimal value will cause the emulsifier to detach from the oil-water contact.

2.7.4 Influence of Water Content on Water Stability in Oil Emulsions

Several W/D emulsions with 0.2% surfactant, 15,000 rpm mixing velocity, and 2-minute mixing period were created [32]. The 10% W/D emulsion stayed steady for nearly 4 weeks, whereas the 20% W/D emulsion stayed constant for 10 days. The 30%, 40%, and 50% water emulsions barely budged for only five hours before the water precipitated out. Eventually, the particles dissociated from the blending. The conclusion is that, given the similar surfactant assemblage, agitation speed, and mixing period, the solution with the highest moisture content will be the least stable. Additionally, as water concentration rises, the proportion of water that is partitioned rises. Increasing the surfactant content would render the emulsion more steady, but it would be too expensive to create. After finding that the emulsion steadiness rose with a reduced diesel-to-water ratio, it was proposed that the optimal water ratio to diesel is 1:1 [32].

2.7.5 Viscosity and Heating Value of the Emulsion Fuel

The substance's viscosity is an essential quality that plays a role in determining its atomization properties. If the viscidity of the fuel is too strong, it will result in poor fluid parameters, whereas if the viscosity of the fuel is too low, it will end in abrasive wear. The amount of water that is present in diesel results in an increase in the viscosity of the diesel. It has also been discovered that the kinematic viscosity of W/B blending is greater than that of diesel refined without water [9]. The heating value of a fuel denotes the amount of energy it contains and, as a result, the amount of fuel it consumes. It has been discovered that diesel has a reduced heating value with an increase in the amount of water included. When the water concentration was not factored into the heating value calculation, the heating value of the W/B emulsion was 7.6-8.7% higher than that of pure biodiesel [9].

2.8 Engine Performance of Biodiesel

Engine testing results that compared blends of diesel fuel with biodiesel to pure biodiesel derived from microalgae were presented [7]. The studies were carried out on a diesel vehicle equipped with four cylinders and four strokes. To make up for the decreased cetane quantity of the microalgae biodiesel that was evaluated, the authors investigated blends with percentages of biodiesel ranging from 5% to 95% by volume. These blends included B5, B10, B20, and B50 [7]. In comparison to diesel fuel, the researchers discovered that the engine's power production was reduced by up to 6% when using 100% pure biodiesel (B100). The low cetane quantity of the microalgae biodiesel is to blame for this drop in performance, as it led to inefficient fuel burning [7]. On the other hand, this appears highly improbable, particularly because the authors also observed a decrease in CO emissions. Figure 2.9 illustrates the diesel engine set up used in collecting the data for the different biodiesel blends [7].

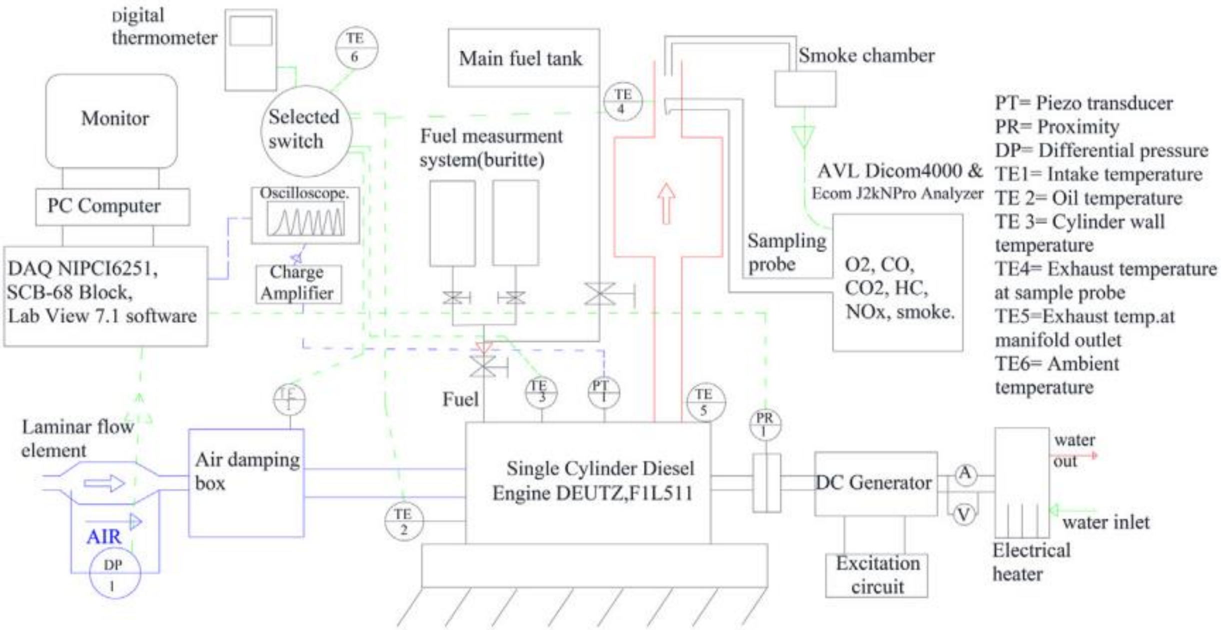


Figure 2-9. Diesel Engine Setup [7].

Details regarding the fuel injection apparatus were not provided [50]. It is most likely a pump-line-nozzle (PLN) system utilized by the engine. If the greatest amount of fuel that could be injected was restricted, the difference in heating value between both fuels might have been the primary contributor to the decreased production. It is also possible that this is linked to variations in the phasing of the combustion process, which is caused by variances in ignition delay periods. When assessing diesel fuel and B100 in terms of their heating values, the researchers found that the most significant difference was approximately five kJ/kg [50]. The torque output was decreased as the proportion of microalgae biodiesel in the blends increased (a reduction of 5% for biodiesel that was not blended). In terms of the emissions, it was indicated earlier that switching from diesel fuel to biodiesel resulted in a lower level of CO. This was because biodiesel has a higher level of oxygen levels when compared to diesel fuel. Compared to the burning of diesel fuel, this characteristic of biodiesel, regardless of its source or feedstock, is well established.

During the burning of microalgae biodiesel, there was a decrease in the amount of air that was pulled into the cylinder, which the authors attribute to the decrease in the amount of NOx that was produced [47]. Furthermore, this is incredibly uncommon; these distinctions must be affiliated with other variables since there is no rationale for why so little air would have been passing through the engine when fuels are shifted, and it would necessitate a glaring discrepancy before NOx discharge would be impacted. This phenomenon may be linked to changes in ignition slow down between the fuels and potential alterations in the actual commencement of infusion. Per the cetane number, which is significantly lesser than diesel fuel, a prolonged ignition timing should be anticipated, which would lead to greater in-cylinder temperatures and, as a result, higher NOx levels; however, the contrary was seen [47].

In addition, engine evaluations for three different blends to analyze the impact of adding butanol to mixed microalgae biodiesel and diesel [43]. These mixtures included varying proportions of diesel fuel and butanol, but the quantity of microalgae biodiesel remained constant at 20% of the total. The studies were carried out using the same diesel engine with four cylinders and four strokes. Under full load conditions, tests were carried out at speeds ranging from 1200 to 2800 revolutions per minute. The net biodiesel concentration was 886 kg/m3, and its viscosity was 4.47 mm2/s [43]. The biodiesel's cetane number was 48.3. When butanol was injected into mixes of biodiesel and diesel fuel, the horsepower and torque generation of the engine were marginally lowered. This may again be connected with the lower heating value (LHV) and the set injection length.

The results of an experimental inquiry into biodiesel production from microalgae were published [28]. There was no report of the strain of the microalgae. The evaluations were performed on a diesel engine with a single cylinder, four strokes, and air cooling. At 1500 revolutions per minute, it generates a braking power of 7.4 kW. The experiments were carried out in a stable position with various weights at a speed of 1500 revolutions per minute, which was the engine's high torque speed. After initial testing with diesel fuel to establish a baseline, the engine was refueled with algal biodiesel and put through its paces again. According to the findings of the tests conducted on algal biodiesel, the thermal performance of braking with diesel fuel is superior to that of algae biodiesel. However, the amount of power generated by algae biodiesel is inferior to that of diesel fuel. This could be attributable to algae biodiesel having a lesser calorific value alongside its high density and kinematic viscosity [28]. Compared to diesel fuel, biodiesel fuel has a lower calorific value, which may explain why it has a higher consumption rate.

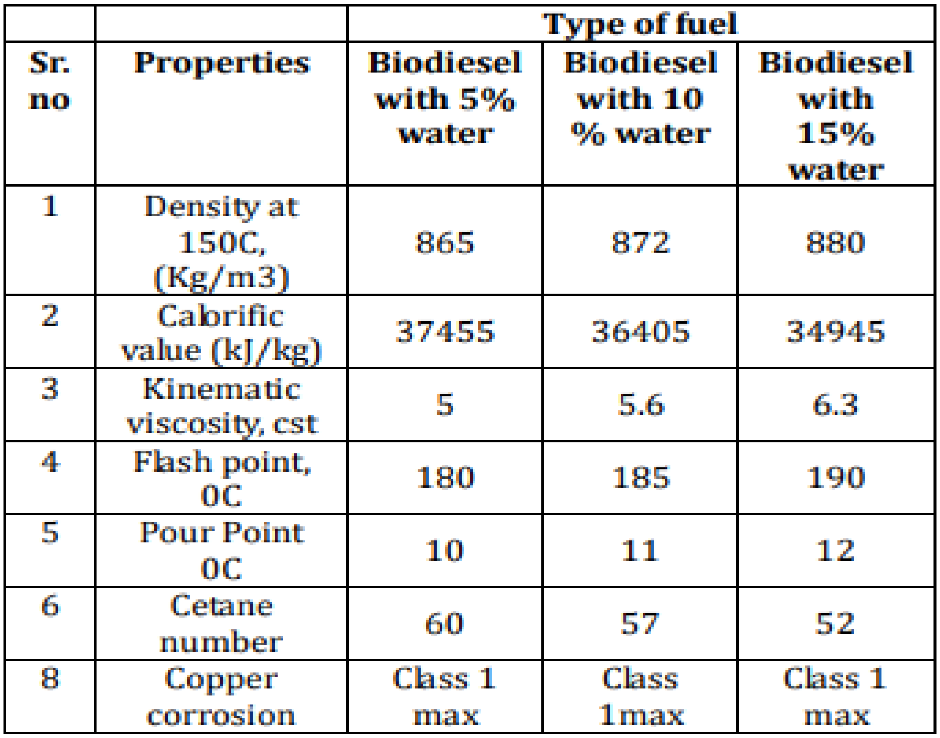
Regarding exhaust fumes emissions, utilizing biodiesel resulted in lower CO levels, but the difference was only 0.2% [28]. This is conceivable due to the greater oxygen content of biodiesel than diesel fuel; hence, much of the carbon monoxide is transformed into carbon dioxide, resulting in full combustion. In contrast to, replacing diesel fuel with biodiesel made from algae reduced HC emissions by approximately half [50]. In any applied load, the emissions of nitrogen oxides (NOx) produced by algae biodiesel are significantly higher than those produced by diesel fuel. As observed in prior articles, a lower level of smoke was produced by the use of algal biodiesel in contrast to diesel fuel under all load circumstances. Due to the presence of this component, the quality of combustion produced by algal biodiesel is superior to that produced by diesel fuel.

The blends and revealed that they had a more significant cetane quantity than diesel fuel was analyzed [50]. The density of the biodiesel made from algae was measured at 0.83g/cm3, and its kinematic viscosity was 5.76 mm2/s. The results indicated that B15 had a larger peak compression than diesel fuel at any capacity. With an increment in compression ratio in the region of 6–12 bar, the mixes performed better under any load situation that was being applied. It was attributed to the rise in cetane amount contrasted to plain diesel fuel, which affects the ignition setback and increases blended burning [50]. According to the findings, the temperature of combustion lessens as blends are used, but the cetane quantity gradually rises, which shortens the ignition setback time and raises the in-cylinder tension and heat flux ratio to some extent.

B5 had a specific energy consumption of 0.285 kg/kWh when operating at 3 KW of brake power, which was superior to diesel fuel [18]. Because more oxygen is present in the fuel when the blending proportion rises, the fuel usage rises moderately greater than diesel fuel used alone. Because B15 has a higher oxygen concentration in its composition, its brake specific energy consumption (BSEC) is lower under all test conditions contrasted to that of diesel fuel. The BTE of the blends, particularly B15, was also more significant than that of diesel fuel. It is possible that an early launch of oxygen is to blame for the modest change in BTE that was found at B5 and B10, where it was measured. Reducing the emissions of HC, CO, smoke, and particulate matter from the exhaust accompanies the drop in NOx emissions. The reduction in the density of mixtures, which leads to finer atomization and improved combustion, is responsible for the rise in NOx [18].

The output of braking power of biodiesel blends was marginally superior to that of diesel fuel [43]. The improved combustion efficiency of biodiesel was the primary contributor to the rise in the brake power of the biodiesel blend. At a speed of 1600 revolutions per minute, the diesel fuel and B10 both produced a maximum brake power of 10.3 kW, while the B10 produced 11.2 KW [43]. Due to the high oxygen quantity in biodiesel, the CO emission in the blend was reduced when the amount of biodiesel used in the blend was raised. Compared with diesel fuel, B10 decreased NOx during optimal emission levels of 40.4% while the engine operated at a similar speed. It was concluded that the presence of B5 had no impact on the engine's functioning [43]. The mixtures that contained a smaller amount of biodiesel as a proportion of total fuel produced the best outcomes. Table 2.2 below lists the properties of the different types of biodiesels based on the percentage of water present in the blend ranging from 5-15% [43].

TABLE 2-2. PROPERTIES OF EXAMINED FUEL BLEND [43].



		Type of fuel		
Sr. no	**Properties**	**Biodiesel with 5% water**	**Biodiesel with 10 % water**	**Biodiesel with 15% water**
1	Density at 150C, (Kg/m3)	865	872	880
2	Calorific value (kJ/kg)	37455	36405	34945
3	Kinematic viscosity, cst	5	5.6	6.3
4	Flash point, 0C	180	185	190
5	Pour Point 0C	10	11	12
6	Cetane number	60	57	52
8	Copper corrosion	Class 1 max	Class 1max	Class 1 max

The experiment conducted discovered three characteristics of biodiesel [50]. These characteristics are fuel efficiency, engine wear, and clogging. Because biodiesel has a reduced energy capacity than conventional diesel, it typically results in a marginal decrease in the vehicle's overall fuel economy. In most cases, the decrease in performance occurs within the same spectrum as the decrease in maximum engine speed (3-5%). It has been determined that the use of biodiesel results in far less rapid engine wear than does the use of petroleum diesel. When utilizing biodiesel, it is anticipated that engines will incur less wear over the course of their lifetimes. However, long-term testing has not been reported. It has been frequently cited that biodiesel can cause sediments and clogs, although the root cause of these issues is typically found to be biodiesel that is any one of poor quality or has gotten oxidized. Coatings in the motor should not generally be a concern in the event that the quality of the gasoline is excellent [44].

In recent research study, the pollution caused by engine exhaust as well as the cold-weather functionality of biodiesel-driven engines [28]. Because it has more oxygen and does not contain "aromatic chemicals" or sulfur, biodiesel contributes far less to the pollution of the atmosphere. The only thing that breaks this rule is the generation of nitrogen oxide (NOx), which has a tendency to be significantly larger when biodiesel is used. Nevertheless, this issue can be mitigated to some degree by ensuring that the engine is tuned properly. In a manner analogous to that of petroleum diesel, engines put through their paces in chilly conditions generally exhibit substantial difficulties in functioning. These difficulties are primarily brought on by the blockage of the filters and/or the fouling of the nozzles. It has been demonstrated that the addition of flow-improving compounds and the creation of "winter mixtures" of biodiesel and petroleum can effectively broaden the temperature ranges at which biodiesel fuel can be used. In general, undiluted biodiesel may function effectively at temperatures as low as roughly 5 degrees Celsius depending on the type of oil used. Additives often result in a reduction of that range by anywhere between 5 and 8 degrees, although winter mixes have been shown to be beneficial at temperatures as frigid as -20 degrees Celsius and lower.

2.9 Diesel Engine Emissions

When contrasted with gasoline, biodiesel, ethanol, propane, and natural gas, diesel emissions are argued to be either the least or most harmful, depending on various researchers. Even while the amount of carbon monoxide produced by diesel fuel is still a cause for worry, the amount produced by gasoline-powered engines is noticeably higher than that produced by diesel-powered engines [1]. Carbon monoxide is a carcinogenic gas that deleteriously affects practically every living thing within the biosphere [19]. The effects of carbon monoxide on people might range from problems with their nervous systems to issues with their hearts. Inhaling carbon monoxide can lead to symptoms such as nausea, vomiting, dizziness, and headaches [1]. There is a correlation between access to moderate and large amounts of CO over extended periods and an increased likelihood of developing heart disease. Those lucky enough to survive severe CO poisoning may have chronic health issues.

Diesel engines emit a significantly greater quantity of nitrogen oxides when compared to gasoline engines in terms of the total amount of each emission that both kinds of engines are responsible for [61]. Nitric oxide (NO), nitrogen dioxide (NO2), and nitrous oxide are the three forms of nitrogen oxides that are typically present in diesel emissions. Nitric oxide and nitrous oxide are not harmful to people, but they can have a disastrous impact on the ecosystem if released into the atmosphere. Nitrogen oxides are compounds that have both nitrogen and oxygen atoms. As a result of the chemical bond that forms between nitrogen and oxygen, which together make up a significant part of the air that is utilized to oxidize the hydrocarbons located in fossil fuels, engines generate nitrogen oxides during combustion, even though neither nitrogen nor oxygen is located in abundant amounts in fossil fuels. During the combustion process, diesel engines that use compression ignition emit a far more significant amount of nitrogen oxides than gasoline engines that use spark ignition emit [61].

The fuel economy of modern diesel engines is better than it has ever been. This indicates that they make more efficient use of diesel fuel. The higher the efficiency with which a fossil fuel fires, the higher the temperatures reached during combustion. Nitrogen oxide emissions from diesel engines are significantly higher than in the past because of improvements in the efficiency of the combustion process. Changes in the system parameters of the engine that raise the maximum cycle temperature or oxygen levels in the burnt gases cause a rise in the nitric oxide concentration in the output. The amounts of nitric oxide that were measured were closer to the equilibrium concentration that corresponded to the maximum cycle temperature and pressure as compared to the optimum concentration obtained under exhaust parameters [45].

Hydrocarbon emissions are yet another type of pollution that diesel burning can cause. Even though they create a far smaller amount of hydrocarbon emissions than gasoline vehicles, diesel engines can still do so. Hydrocarbon emissions are produced when an engine does not entirely burn the fuel it consumes [37]. Consequently, the hydrocarbons in a fuel (the critical component of fossil fuels that burn) exit the exhaust partly consumed or incomplete combustion and reach the atmosphere. Aldehydes, alkyl nitrates, benzene, and benzene molecules are the key elements of hydrocarbon emissions that cause the most worry among scientists. Burning hydrocarbons, such as motor fuel or plywood, produces aldehydes, hazardous chemicals. Aldehydes can also be found in nature. It has been demonstrated that they hinder the process of photosynthesis in plants, irritate the eyes and lungs, and may potentially cause cancer [37].

Particulate matter, also known as soot, is the primary contributor to the black smoke formation and is considered the most problematic of all diesel emissions [42]. Particulate matter, including sulfur oxides and nitrogen oxides, can negatively impact human health and the health of flora, fauna, and plant life. However, its contribution to global warming is negligible. The mixture of sulfur and nitrogen oxides that make up particulate matter can be seen visually. The particulate matter produced by a diesel engine can range from 2.5 to 10 micrometers in size. The tinier the particulate matter, the higher the chance that it will be capable of causing health issues in both people and animals [42]. This is since smaller particles are more likely to be able to gain entry to the lungs and travel through the bloodstream. It has been shown that particles' size is directly correlated with their ability to cause adverse health effects.

Every one of the EPA's regulations on emissions includes the procedures for conducting an emission test, whether on a vehicle or an engine. The findings of the tests are what the EPA utilizes to assess whether or not a facility complies with the applicable emission limits. The number of tests and the kinds of tests conducted differs depending on the industry being controlled. Certification testing is a type of validation needed as a requirement of certification and is typically carried out before issuing a certificate. Certification testing falls under the umbrella term "compliance testing." After the vehicles or engines have been approved, they go through a process called "in-use testing," which is often performed on privately owned vehicles or engines. The purpose of production line testing, also known as assembly line screening, is to ensure that a manufacturer is manufacturing compliant cars by inspecting the emissions standards of vehicles or engines that are currently in production but have not yet been serviced.

According to the Clean Air Act, Section 202(a)(1) necessitates the Environmental Protection Agency (EPA) to establish emission standards for air contaminants, such as oxides of nitrogen (NO X), that are produced by diesel motor vehicles or new motor vehicle engines [26]. The entity has determined that these pollutants contribute to air pollution, posing a risk to public health or wellness. The NOx emission guidelines for heavy-duty vehicles and engines, as well as specific other emissions regulations, are required to "reflect the highest extent of reducing emissions attainable through the utilization of technology which the Administrator specifies will be accessible for the prototype year to which such standards pertain, offering proper consideration to charge, power, and safety level linked to the use of such innovation [26]. This provision also covers other emission standards. It is required by Section 202(a)(3)(C) that standards be in effect for a minimum of three model years and cannot take effect until at least four years after they have been promulgated.

When the EPA establishes emission requirements for a specific engine or vehicle category, the manufacturers must provide engines that comply with those rules within the period specified by the agreed schedule for those criteria. The Clean Air Act (CAA) stipulates that all engines and motor vehicles that are a part of the commercial supply chain in the United States must conform to a specific set of emission criteria to remain in business [26]. Anyone who wants to sell an engine or vehicle inside the United States is expected to showcase conformity with the Clean Air Act and all applicable requirements set forth by the Environmental Protection Agency. EPA may provide a Certificate of Compliance, which grants authority for manufacturing and selling within the United States, upon receipt of a satisfactory statement of conformity from the manufacturer and perhaps a confirmatory assessment performed by the EPA.

When a manufacturer files a proposal for certification to the EPA for a collection of vehicles or engines that share the exact construction, and emission parameters, the procedure of becoming certified officially gets underway. In order to obtain a license of compliance from the EPA, producers are required to demonstrate that they have satisfied all of the prerequisite conditions by supplying the agency with extensive documentation to back up their claims [26]. The certification proposal provides details on the automobiles or engines that the certificate of conformance will particularly address. The certificate, permission to manufacture and sell the car, is limited to only certain automobiles or engines expressly mentioned in the application.

As a direct result of these emissions, numerous stakeholders are currently implementing particular countermeasures. It is now conceivable, owing to alterations made to internal engines, to reduce particulate matter pollution and nitrogen oxide while experiencing almost no loss in horsepower. The recirculating of chilled exhaust gas is one of these improvements; others include enhanced injection devices, modified charging units, and modified ignition sources with significant agitation. Pollutant emissions have markedly declined as a result of the implementation and minimization of engine exhaust aftertreatment structures, such as the catalytic converter and the diesel particulate bait, as well as NOx-minimizing structures [45]. Because of the usage of low-sulfur fuel in Europe, the issue of sulfur causing toxicity of diesel oxidation accelerators is no longer regarded to be a contemporary issue. In the present, there will be a greater emphasis placed on the utilization of biofuels, which, in average, have an ameliorative effect on the particulate pollutants and do not contribute to a rise in the particle mass discharges.

2.9.1 Diesel Fuel Soot Shell Formation During Combustion

The breakdown or burning of hydrocarbons at high temperatures produces soot, which is composed primarily of carbon [13]. Trace quantities of other components, such as hydrogen and oxygen, are typically found in soot. The production of soot, also known as the transformation of a hydrocarbon fuel molecule that only has a small number of carbon atoms into a carbonaceous agglomeration with millions of carbon molecules, is undeniably a phenomenon fraught with a great deal of difficulty. It is a form of transition from the gaseous state to a solid-state phase, although the solid phase does not display its distinct chemical and physical composition [13]. Therefore, the structure of soot is comprised of a variety of chemically and physically distinct procedures. Some examples of these procedures include the creation and development of substantial aromatic hydrocarbons and their transformation into particles, the clotting of primary particles into larger clusters, and the development of solid particles by picking up expansion elements from the gas phase.

2.9.2 Molecular Events That Lead to Formation of Soot

The first aromatic ring is formed by adding vinyl to acetylene [49]. At high temperatures, it produces vinylacetylene accompanied by acetylene coupling ton-C4H3 radicals generated by H-abstraction from vinylacetylene. The introduction of acetylene to vinyl at a small temperature yields n-C4H5, which generates benzene following the addition of acetylene. The H-abstraction mechanism and its inverse transform benzene and phenyl into one another [49]. More extensive aromatic elements develop primarily through the HACA (H-Abstraction-C2H2-Addition) process.

The HACA technique implies a continuous two-step procedure for generating aromatic rings: H-abstraction, which stimulates aromatic units, is accompanied by acetylene addition, which promotes ongoing molecular development and cyclization of polycyclic aromatic hydrocarbon (PAH) molecules [49]. When beginning combustion with an aromatic fuel, "straight integration" of the whole aromatic rings gets vital. The original benzene molecules break down to generate acetylene as the process continues. Immediately after the beginning of the reaction period, when the quantity of acetylene equals that of benzene, the HACA mechanism takes over for PAH development. Figure 2.10 below illustrates the HACA technique for PAH growth [49].

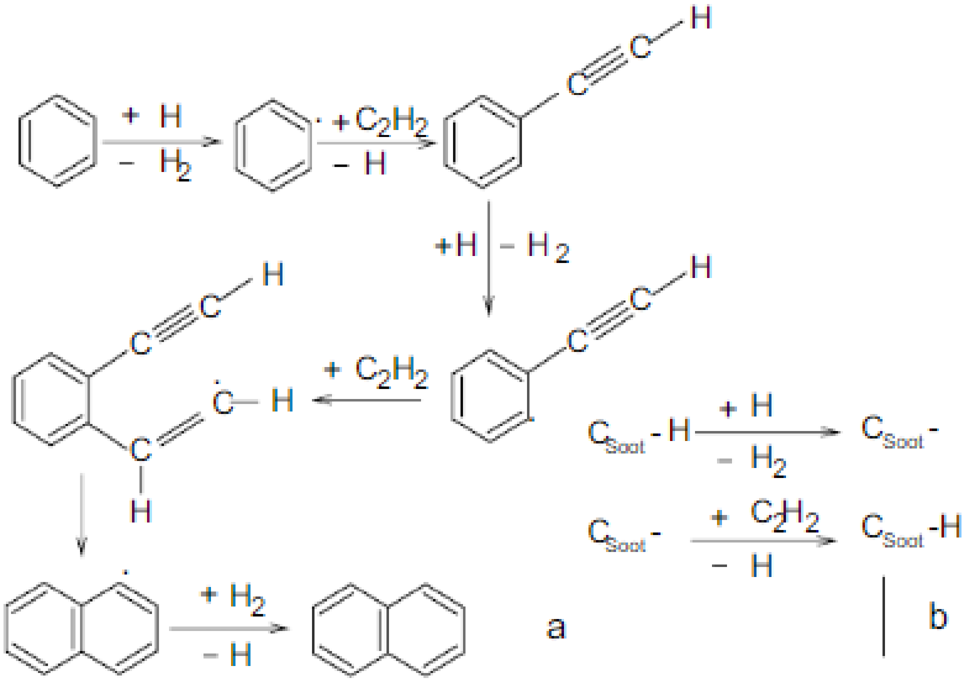


Figure 2-10. HACA Technique for PAH Growth [49].

Several acetylene additions processes in the HACA series create exceptionally stable aromatic compounds. These molecules include pyrene, coronene, and others. Because of the substantial shift in Gibbs free energy that occurs during these processes, it is nearly impossible for them to be reversed. This, in turn, has the impact of "pushing" the reaction chain ahead toward creating massive PAH particles. Other stages in the accumulation of acetylene are highly reversible, and in these cases, the rate of progress in one route is virtually identical to the rate of progress in the opposite direction. These stages, which include reaction velocities that are carefully managed, produce a thermodynamic barrier that prevents PAH development. In contrast to the open-shell carbon clusters that can rise to fullerenes, the emergence of generally stable, confined aromatic rings can be attributed to this thermodynamic barrier.

2.9.3 Particles Nucleate or Originate from Hefty PAH Molecules Through Inception

In this phase, mass is changed from molecular to particulate structures. Heavy PAH molecules create nascent soot particles with a molar size of around 2000 amu, but it is usually assumed to begin at 300–700 amu, and width of roughly 1.5 nm [65]. Utilizing gas chromatography, the recognition of structures produced at different phases of the developmental process is restricted to molecular masses below 300 amu. In contrast, high-definition electron microscopy's analysis and tallying of soot particles are restricted to particle sizes greater than 1.5 nm [65]. According to the polyyne concept, every radical susceptible to producing polyyne compounds becomes a polymerization hotspot. Polyyne complexes are formed when a polyyne molecule and a polyyne radical or two polyyne molecules interact. The carbon of acetylene and polyyne molecules remains in the gaseous phase as the most thermodynamically stable configurations of tiny carbon bunches at high temperatures when C-H bonds are relatively flexible. Recent laboratory research and theoretical investigations have discovered that the configurations of carbon groups up to C20 that are the most resilient are chains and monocycles. This discovery lends credence to the polyyne framework, which was recently suggested based on the spontaneous chemical aggregation hypothesis.

2.9.4 Mass Increase of Particles Due to Gas Phase Molecule Insertion

After the fledgling soot pieces have been formed, their mass is enhanced by the presence of gas phase species such as acetylene and PAH, especially PAH radicals [39]. In the event of stabilized reagents like acetylene and steady PAH, it is thought that these reactions involve radical spots on the soot particles. However, this is not necessarily the scenario of PAH radicals. During the surface growth phase, a considerable proportion of soot stacking is obtained, particularly when compared to the mass of the soot particles created during the nucleation stage. Surface development can occur at lower temperatures, even beneath the lower threshold necessary for the homogenous nucleation of soot particles. Naturally, this activity will not change the total quantity of soot particles [39].

The fundamental mechanism contributing to the soot surface formation is not yet wholly grasped. A mechanistic understanding of surface growth processes was developed, which treats surface growth interactions equivalent to the planar development of polycyclic aromatic hydrocarbons [57]. This observation also adds to the argument for the polyyne concept. The HACA process is being transferred to the heterogeneous surface development of soot particles; this is the fundamental idea behind this technique. To put it another way, the assumption is that the face of soot particles is similar to the edge of a big PAH molecule in that it is coated with C-H bonds. It is hypothesized that the removal of these H atoms activates the sites, resulting in the formation of surface radicals [57]. These surface radicals then interact with entering gaseous hydrocarbon molecules, which causes the surface development process to continue.

2.9.5 Coagulation Through the Collision of Reactive Particles with One Another

During the phase of mass expansion, clashes between particles result in a significant rise in the concentration and a reduction in particle number, but these changes do not affect the total mass of soot available (Chen & Jiang, 2020). Because of the agglomeration of the particles, the collisions between the particles result in the creation of larger particles. Studies have shown that particle coagulation, which results in a reduction in the number of particles, takes place almost instantly after the creation of soot particles or when soot particles are relatively young or tiny (Chen & Jiang, 2020). In electron microscopy pictures of soot particles, the character of principal particulate components is partially obscured because the substantial molecular introduction of gas phase elements continues after the early establishment of composite particles through sticking particle-particle collisions.

The free-molecular phase, the continuum system, or the transition paradigm are the three possible settings in which particle coagulation may occur. In their investigation of high-pressure lami-nar premixed flames, the extensive Smoluchowski framework, which is suitable for all three domains, was implemented [63]. Nevertheless, according to their findings, the crystallization of diesel soot elements is not delicate to the theoretical system (unrestricted molecule versus spectrum), as the coagulation periods approximated for the continuum system and the free molecular system are similar and can therefore be outlined in terms of the free molecular hypothesis. Figure 2.11 below shows the different stages that take place in soot shell modelling [13].

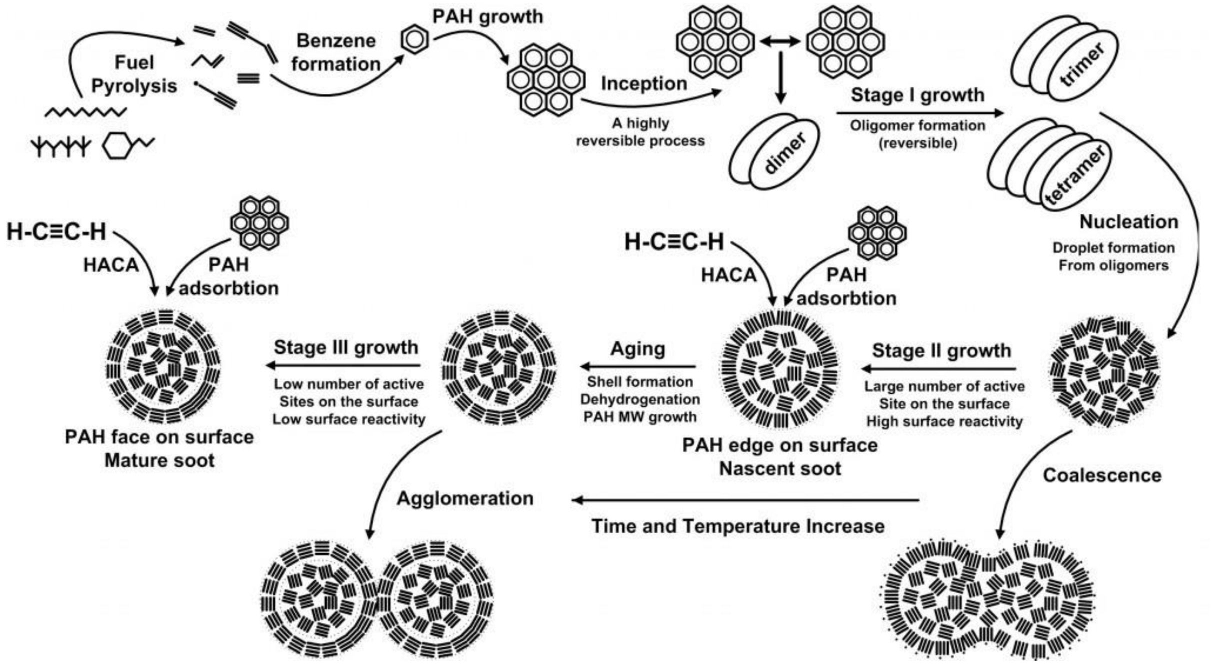


Figure 2-11. Soot Shell Modelling [13].

2.9.6 Particulate Material Carbonization

When soot particles have reached their mature state and soot generation has progressed to its latter stages, the soot particles commence to carbonize and adhere to one another [65]. The polyaromatic substance that makes up the produced particles goes through substituent eradication, cyclization, ring consolidation, and ring blending. This is followed by dehydrogenation and the development and orientation of polyaromatic layers. During this phase, the soot material, originally crystalline, is transformed into a carbon substance that is gradually more graphitic. There is also a reduction in particle mass, but there is no alteration in the total number of particles. As a result of the decrease in the number of binding sites on the soot particles for surface expansion, the carbonization procedure does not induce merging but instead results in the creation of chain-like, open-structured granules that encompass between 30 and 1800 primary particles [65]. Recent research into this mechanism has been inspired by the discovery of soot with curved or fullerenic layers.

The true soot shell is found in an area that is not reactive. In this region, soot is solely distributed due to thermophoresis. Temperatures in this zone are too low for any meaningful reaction, apart from aggregation. A concentration of larger particles is noticed when edging closer to the soot shell, at which point the thermophoretic transit shifts the clusters apart from the reactive zone and into the steady ideal level. It was recently indicated in a study that even though particle dispersion is equivalent to what is typically noticed in embers in the vicinity of the flame flanks, a concentration of larger particles is witnessed when sticking close to the soot shell [63]. The aerosol stage is modeled using a bounded number of different segments, which precludes additional expansion of magnitude greater than 200 nm and then fosters their buildup [63]. As a result, the multitude of particles with diameters greater than 200 nm has increased, which corresponds to an increase in the number of droplets with the biggest diameters in interaction with the soot shell.

2.10 Biodiesel/Renewable vs. Diesel Cost

In the same way that propane has a lower price per gallon on aggregate than gasoline, biodiesel has a lesser price per gallon than diesel. The national average for the price of B20 gasoline at retail stations in the United States reached 4.8 dollars for each gasoline gallon equivalent in July 2022 [54]. This is comparable to the price of ordinary diesel fuel, which is 5.02 dollars in the United States. The B20 diesel blend fuel contains 20% biodiesel in its total volume. In the retailing industry, the fuel price will be higher depending on the percentage of biodiesel it contains. In July 2022, the average retail price for B100 was 5.48 United States dollars, nearly 70 cents more expensive than the cost of B20 diesel [54]. Surprisingly, since October 2017, alternative B20 has been the most cost-effective choice for most consumers [54].

In the majority of markets, the cost of biodiesel blends equivalent to B-20 can be found at levels that are comparable to or even lower than diesel fuel prices. According to recent findings, the generation of biodiesel and renewable diesel in the United States continuously reduces the cost of distillate fuels by contributing to an increase in supply [19]. The manufacturing and accessibility of safer and greener fuels have improved over the past decade, which resulted in the price impact increasing to a profit of 4% in 2020 and 2021 [19]. Even though the economy has been in a state of emergency over the past few years, the biodiesel and renewable diesel industries have boosted manufacture and distribution to the point where they can meet more than 6% of the country's demand for diesel fuel. Although it may not seem like much savings, 3.91 million Class 8 trucks traveled an aggregate of 62,571 miles [19]. If they had utilized renewable diesel, each vehicle would have conserved an aggregate of $1,317.77 per year; therefore, if all Class 8 trucks had been running on renewable diesel, this would have culminated in a savings amount of $5.15 billion per year [19].

The savings amount to around 22 cents per gallon based on the national standard value of diesel fuel as it is now [27]. The effect of these lower prices is felt all across the economy. Diesel fuel ensures that basic things such as food and utilities, as well as other retail items, can be transported around the country. Because there is now a scarcity of diesel fuel and prices are high, any rise in expenses related to the decline in biodiesel and renewable diesel production will be transferred to customers in the form of higher prices for a variety of necessities. Annually, the biodiesel and renewable diesel business in the United States is responsible for maintaining over 65,000 employment and more than $17 billion in economic output. It is estimated that 3,200 jobs and $780 million in economic mobility are supported for every 100 million gallons of supply [27]. The manufacture of biodiesel contributes around 13% to the price of each bushel of soybeans produced in the United States [27].

However, the case is different in other regions as the price of biodiesel seems expensive. According to the findings of a recent investigation into the actual costs of biofuels, the price of biodiesel on the wholesale market is currently between 70 and 130 % higher than the price of gasoline and diesel [4]. An organization known as Transport & Environment has urged the European Union to stop the required merging of crop biofuel from helping alleviate the pressure that is being placed on both food and gasoline costs. Compared to fossil fuels, the cost of biofuels in Europe has steadily increased throughout the past few years. The price gap between biofuels and fossil fuels is widening due to recent increases in the cost of many of the biomasses used to produce biofuels. For instance, the cost of bioethanol produced in the EU is roughly equivalent to gasoline. The annual fuel cost in Europe has risen by €17 billion due to the increased use of biofuels [4].

Diesel is more popular and cost-effective in Asia than biodiesel, making the region comparable to Europe. According to a recent study, the additional cost of combusting through fuel rapidly is not very noticeable because diesel in countries such as Indonesia is already so inexpensive compared to biodiesel [71]. The additional expense of burning through fuel quicker is estimated to be approximately $8 per year for a regular car, provided that the exact biodiesel blend threshold is around 11%. In 2016, drivers in Indonesia collectively paid additional fuel expenditures of nearly $100 million. Asians perceive biodiesel to have 8-9% less power per liter than petroleum diesel [71]. Because of this, vehicles that operate on biodiesel mixes traverse fewer miles per liter. As a result, these vehicles need to have their fuel tanks refilled more frequently to travel the same mileage as a vehicle that operates on diesel made entirely from petroleum. Therefore, biodiesel seems more expensive due to its immediate consumption in Indonesia [23].

2.11 Diesel Fuel Testing

2.11.1 Ash Testing

EPA authorized in 2007 that diesel fuel could no longer possess a sulfur content of more than 15 parts per million (ppm) (ASTM, 2022). As a direct result, testing procedures for diesel fueling have been strengthened. The ash test is one example of such a strategy, and it involves sacrificing a small portion of the fuel so it can be burned. The quantity of ash that can be discovered in the sample is determined by leaving the residue behind after all the moisture has evaporated and then weighing it. If there is a smaller amount of ash left over, the gasoline burned is rendered clean. A fuel with a more excellent ratio of ash can pose a risk to a vehicle's fuel injection system and may result in wear on engine parts such as piston rings.

2.11.2 Aromaticity and Carbon Residue

To determine the fuel sample's aromaticity, an equation is used that takes into account both its density and its viscosity [35]. The result of this equation is the aromaticity measurement. When there is a higher concentration of aromatic compounds, there is a more potent suppression of microbial growth. On the other hand, hazardous emissions and an excessive amount of ash can be produced by fuel that contains an excessive number of aromatics. In order to test for the presence of carbon residue, a tiny quantity of fuel is diluted until 90% of the sample is collected [35]. After that, the residue is brought to a temperature of 1022 degrees Fahrenheit. Afterward, most of the sample is lost to evaporation [35]. After the sample has been cooled, the remainder is weighed, and the results are used to determine the carbon intensity. A high rate of carbon residue suggests that the fuel could cause accumulations in the combustion chamber.

2.11.3 Cetane Index and ATP Testing for Microbes

To determine the combustion quality of diesel fuel, cetane index testing is performed. Diesel fuel must have the appropriate cetane score in order for any diesel engine to function correctly when operating in cold weather [24]. Insufficient amounts of cetane have substantial harmful consequences on the engine, such as causing it to operate roughly and noisily and increasing the likelihood that it may smoke when it first starts up. Additionally, diesel engines have a more challenging time starting when exposed to high cetane concentrations. If the fuel has a low cetane rating, the driver can add a cetane improver to it. The number of prevalent microbes in diesel fuel can be determined through Adenosine Triphosphate testing (ATP) [24]. If there is microbial development, a biocide should be added, and the fuel should be manually circulated to ensure that all organisms are killed. If there is sludge in the tank, the driver should use a sludge emulsifier and follow that up with a fuel buffing regimen to thoroughly clean it out.

2.11.4 Cloud Point and Color

In the cloud point test, a sample of fuel that has been thoroughly cleaned is analyzed at regular intervals over some time while the temperature is lowered [3]. This test determines the temperature under which a haze can be seen for the first time. The outcomes of this test provide individuals with information regarding the heat flux at which wax crystals will begin to form on the surface of the fuel. If one utilizes the fuel in their machinery, a poor cloud point assessment can exhibit a more significant occurrence of clogged fuel filters or even a potential engine shutoff. In color testing, a portion of the fuel is evaluated in the presence of a consistent light source. After that, different hued glass plates are contrasted with the fuel sample to allocate a numerical value to the fuel's color. These figures range anywhere from 0.5, which represents (the lightest) to 8.0 (the darkest) [3]. The presence of dark gasoline may indicate the presence of fuel destabilization.

2.11.5 Lubricity and Distillation

While the fuel sample is being tested for lubricity, a steel ball is loaded down and moved over a steel plate for seventy-five minutes [24]. The lubricity of the gasoline can be evaluated based on the size of the worn surface that is left on the steel ball after 75 minutes. It is possible to forecast that the gasoline will not be able to keep the fuel injectors and pumps from wearing down prematurely if the lubricity is poor. The distillation test evaluates the combustibility of the fuel and assures that it will burn correctly in the engine by measuring its combustion parameters. If the fuel's distillation trajectory is off, the engine will operate coarsely, emit black smoke, and there is a possibility that it will not function at all [24]. In the event that an individual receives an inaccurate reading from the distillation process, the only idea is to change the fuel.

2.11.6 Oxidations and Thermal Stability

A fuel sample is heated to 203 degrees Fahrenheit for 16 hours while oxygen is fizzed through the sample to determine its oxidation stability [34]. After the testing period has concluded, the sample is cooled and sifted to obtain the insoluble impurities that have formed. Trisolvent is utilized to remove the devout insoluble material. After evaporating the trisolvent, the quantity of clinging insoluble is obtained. This evaluates the fuel's resistance to silt forming when subjected to oxygen radicals. After filtering, samples are packed in tubes and exposed to air at 302 degrees Fahrenheit for 90 and 180 minutes to determine thermal stability [34]. The samples are cooled and purified, followed by the collection and measurement of the inert material. This measurement demonstrates a fuel's resistance to the creation of sediment after prolonged exposure to extreme temperatures.

CHAPTER 3: METHODOLOGY

3.1 Formulation and Process

The biodiesels that are researched in this proposal can be divided under three main categories as follows:

- AquaCharged Diesel (Water in diesel)
- Seed-Oil Biodiesel
- Animal Fat Biodiesel (AFB)

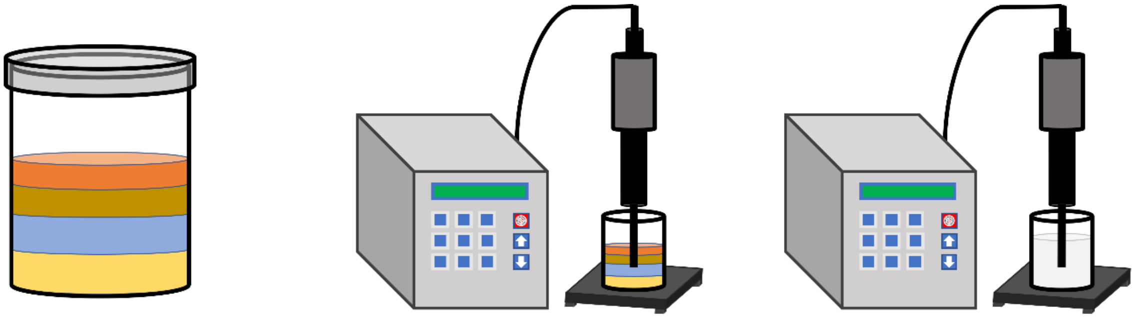
During the research and development of the categories above, priority was given to utilizing main ingredients that are easily accessible and abundant. This consideration was made to manage production costs and fulfill demand. The fuel categories mentioned above contain a blend of additives and emulsifiers such as Triton X-100, Span 80, Tween 80, Isopropyl Alcohol, Ethylene Glycol, Octanol, and Hexadecane. The specific proportions and ratios of these additives differ for each biodiesel formulation.

As stated in the trademarked name, AquaCharged simply means that the conventional diesel fuel has been charged or mixed with water or aqua in Latin. The type of water used in the formulation for testing is distilled water. Aside for water and conventional diesel, two other ingredients are mixed into the formula during mixing to allow for a fully atomized and homogenous mixture without separation. While it is important for the final fuel to be stable without separation, it is also incumbent for the fuel to have a similar viscosity property at different temperatures as conventional diesel fuel.

The current market is certainly no stranger when it comes to plant seed-based biodiesel. The goal of achieving an improved and advantageous seed-oil biodiesel product requires experimental analysis with the highest biodiesel percentage possible per volume. The initial seed-oils that are intended for research in this study are as follows:

- Red Palm Oil
- Soybean Oil
- Cottonseed Oil
- Canola Oil
- Peanut Oil
- Safflower Oil

The targeted animal fats used in this experiment focused on byproducts that are the highest in production. Tallow and lard are among the highest animal fats produced as byproducts of beef and pork. Figure 3.12 below shows the unique steps and process necessary for the formulation of biodiesels using water, seed-oils, and animals fats as explained in the patent application [5].



Put all ingredient in a jar with a lid
- Diesel
- Additives
- Emulsifiers
- Oils/Water/Fat

Sonicate the ingredients for 10 min at 20% power capacity to ensure a Homogenous mixture.

Result: Clear and stable nano-emulsion product.

Step 1

Step 2

Step 3

Figure 3-1. Individual Steps in Biodiesel Formulation using Sonication.

3.2 Testing Environment

The experimental testing environment of the biodiesel formulations plays a crucial part in ensuring that the outcome of the data is accurate and repeatable. Figure 3.2 below shows the different components of the testing environment that was established to carryout testing on the subjected biodiesel.

Figure 3-2. Biodiesel Engine and Emissions Testing Components.

A naturally aspirated single cylinder engine diesel engine is used throughout the entirety of the research study. The specified diesel engine is a Carrol Stream CS186 without a catalytic converter installed. Unlike gasoline engines which are spark ignited (SI), diesel engines utilize compression ignition (CI) to ignite the air and fuel mixture in the engine [20]. Figure 3.3 below shows the four engine cycles of a compression ignition engine [20].

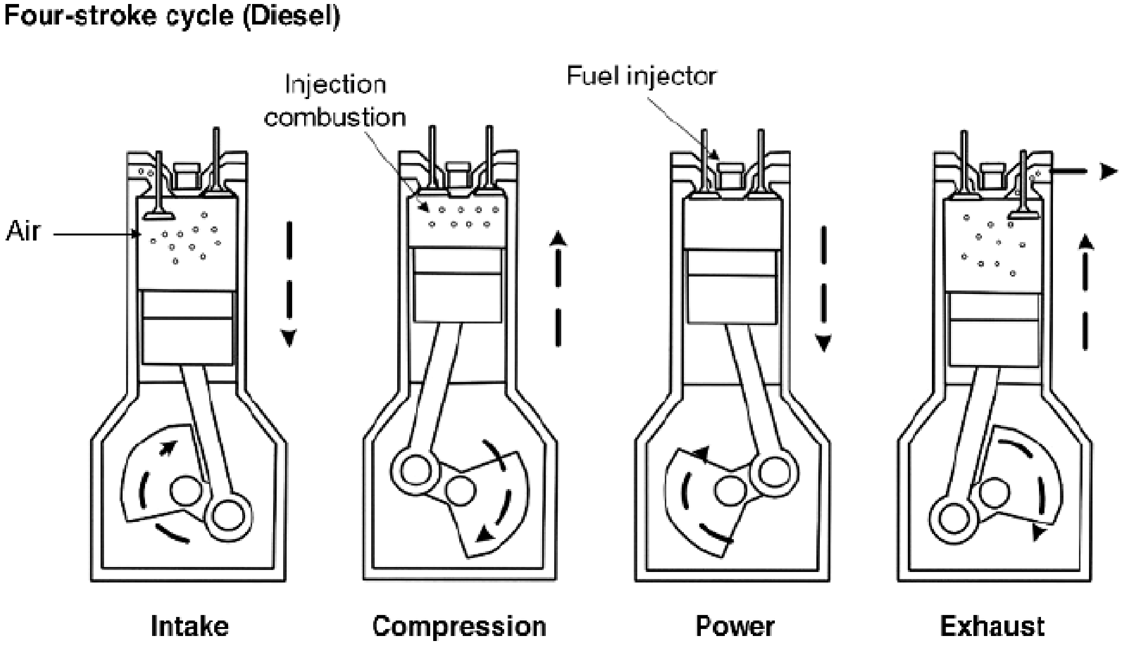


Figure 3-3. Compression Ignition (CI) Engine Cycles.

To measure the horsepower and torque outputs of the newly formulated biodiesel formulations in comparison to conventional diesel, a dynamometer is used. Figure 3.4 shows all the components of the water brake dynamometer used to run all engine tests.

Figure 3-4. 7” Water Brake Dynamometer Set Up.

While running the diesel engine with the newly formulated biodiesel, the greenhouse gases that are emitted are measured using a 5-gas exhaust analyzer, which is attached to the exhaust port. The gas analyzer will measure the following 5 gases produced during engine operation:

- Carbon Dioxide – CO_2
- Carbon Monoxide – CO
- Hydrocarbon – HC
- Nitrogen Oxides – NOx
- Oxygen – O_2

Figure 3.5 below shows the gas analyzer and exhaust pipe probe that is used in measuring the GHG emitted during engine operation.

Figure 3-5. Enerac 700 5-Gas Analyzer.

During engine operation the Enerac 700 shows the gases being measured in real time via the provided ENERCOM software. Shortly after testing is completed, a receipt is printed directly from the gas analyzer with the test results.

3.3 Testing Procedure

Additionally, a test plan that utilizes the previously mentioned equipment is crucial in producing compelling data that has a high repeatability rate. When it comes to engine testing, all testing conditions are expected to be similar. Each biodiesel formulation is tested under the same engine dynamometer conditions in comparison to conventional diesel fuel. Conventional diesel is tested first during separate testing sessions to have a standard variable to compare biodiesel test results to.

3.3.1 Dynamometer Testing

Each fuel is tested 10 times back-to-back to ensure repeatability and establish a standard deviation in the generated results. Conventional diesel fuel was tested at the beginning of any given testing session. This was done to have a standard variable for comparison and analysis of test results from the new biodiesel formulations. The same amount of load was put on the engine for each fuel. Equation 1.1 shows the conversion from mechanical horsepower measured by the dynamometer to kilowatts.

$$1\ hp(I) = 745.699872\ W = 0.745699872\ kW$$
$$P_{(kW)} = 0.745699872 \bullet P_{(hp)} \tag{1.1}$$

3.3.2 Emissions Testing

To measure the emissions for each fuel test accurately, the engine will run for a period of 5 minutes. During the 5 minutes, the single cylinder engine will reach operating temperatures and the exhaust gases are measured accordingly. Similar to the engine dynamometer testing, conventional diesel fuel is tested for emission for each testing session in order to establish a standard variable for comparison and analysis purposes.

3.3.3 Fuel Consumption Testing

Furthermore, during the 5-minute period another very important variable is measured, fuel consumption. Prior to starting the engine for emissions testing, 500ml of fuel is measured each time and poured into the fuel tank of the diesel engine. The fuel is then measured at the end of the period in efforts to determine fuel consumption. Since each fuel formulation is produced in amount of 500ml, the remainder of the fuel from the consumption test is utilized in the engine for dynamometer testing. Equation 1.2 below shows how the fuel consumption is derived.

$$V_s(Volume\ Start) - V_C(Volume\ Consumed) = V_R(Volume\ Remaining)$$

$$\frac{V_C}{T} = Consumption\ Rate\ (C_R) \tag{1.2}$$

CHAPTER 4: RESULRS AND DISCUSSION

4.1 Experimental Analysis Results

The biodiesel formulations described in Chapter 3 were tested for engine performance, greenhouse gases emissions and fuel economy. Each fuel was formulated and measured in the amount 500ml before being poured into the fuel tank of the CS186, single cylinder diesel engine. Conventional diesel was measured for 500ml and was tested first during each testing session. Each was utilized in the engine for a period of 5 minutes to measure fuel consumption and the greenhouse gases emitted from the exhaust.

After the fuel consumption was measured and calculated the remainder of the fuel was poured back into the fuel tank to perform engine dynamometer testing. For each fuel tested in the diesel engine, 10 dynamometer tests were performed continuously. Each fuel test results were compared to the test results of conventional diesel.

4.2 AquaCharged Diesel™ (W20) Microsized Emulsion

The W20 AquaCharged diesel formulation was produced containing 20% water as a renewable source. The main and obvious characteristic of the AquaCharged diesel is the white or milky appearance that it displays. The white appearance represents a micro-sized emulsion of diesel and water. This characteristic does not affect the performance of the fuel in any way. The engine performance of the AquaCharged diesel matched the performance of conventional diesel considering that 20% of regular diesel was substituted with water per volume. Figure 4.1 shows the final formulation in a 500ml glass measuring beaker (Davani, 2022).

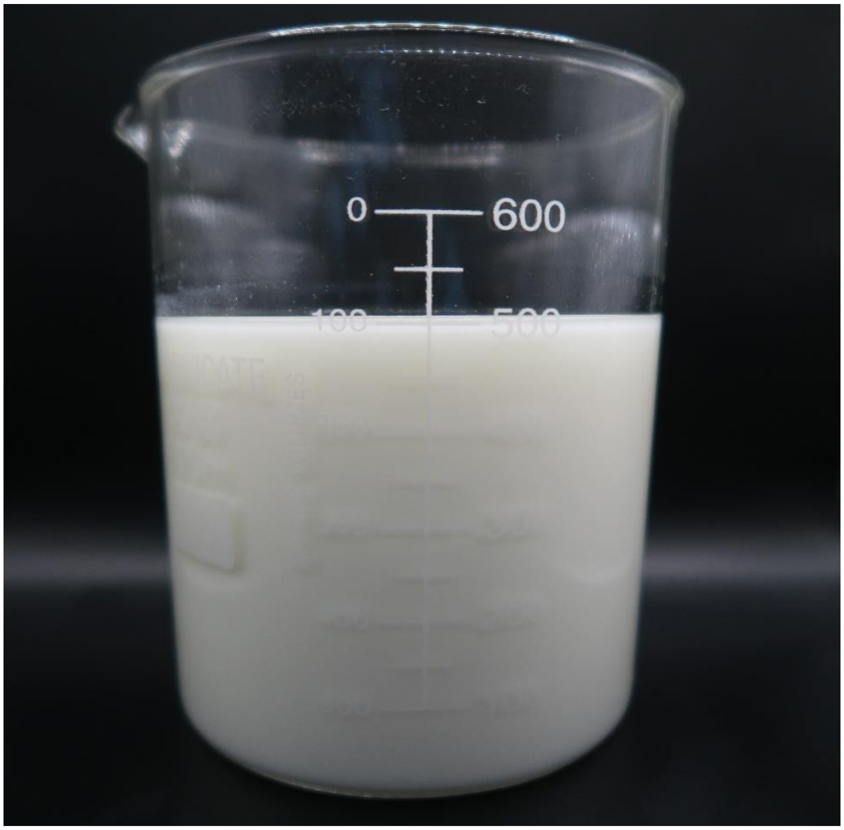
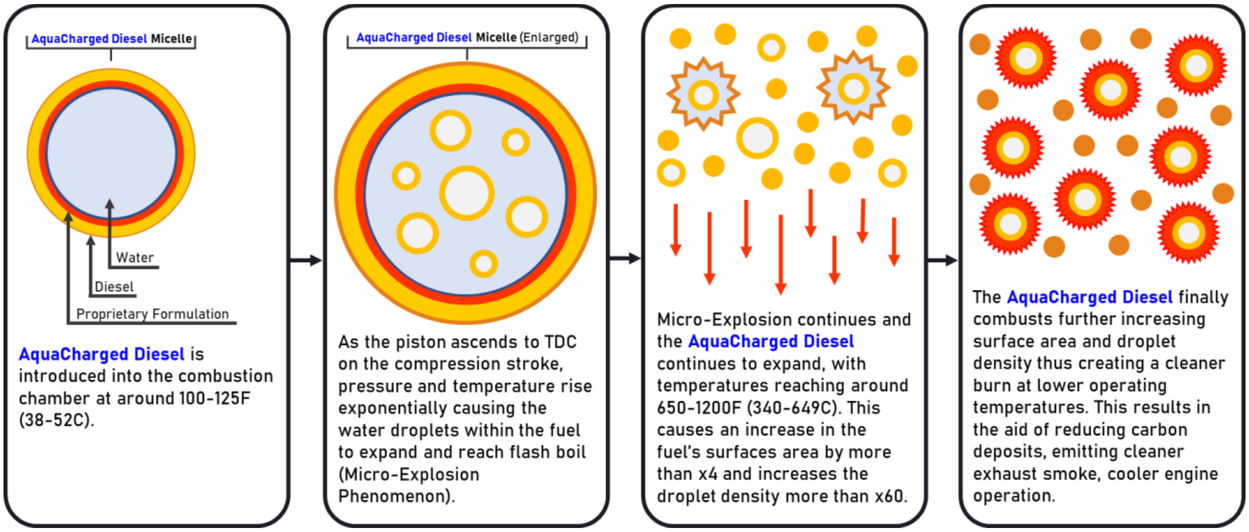


Figure 4-1. AquaCharged Diesel™ containing 20% water.

4.2.1 Micro-Explosion Phenomenon

Once the AquaCharged Diesel fuel is formulated, a fully atomized mixture is introduced in the combustion chamber of the diesel engine during primary atomization with temperatures between 100-125°F or 38-52°C on the intake stroke. During the compression stroke, the piston ascends to top dead center (TDC) resulting in secondary atomization of the fuel droplets, pressure and temperature in the combustion chamber rise exponentially causing the water in the fuel droplet to reach flash boil, thus resulting in the micro-explosion phenomenon.

The micro-explosion continues to take place allowing the atomized AquaCharged Diesel to expand reaching operating temperatures between 600-1200°F. The fuel's surface area increases by about 4 times and the droplet density more than 50 times. Figure 4.2 illustrates the progressive stages of micro-explosion.



AquaCharged Diesel is introduced into the combustion chamber at around 100-125F (38-52C).

As the piston ascends to TDC on the compression stroke, pressure and temperature rise exponentially causing the water droplets within the fuel to expand and reach flash boil (Micro-Explosion Phenomenon).

Micro-Explosion continues and the **AquaCharged Diesel** continues to expand, with temperatures reaching around 650-1200F (340-649C). This causes an increase in the fuel's surfaces area by more than x4 and increases the droplet density more than x60.

The **AquaCharged Diesel** finally combusts further increasing surface area and droplet density thus creating a cleaner burn at lower operating temperatures. This results in the aid of reducing carbon deposits, emitting cleaner exhaust smoke, cooler engine operation.

Figure 4-2. Stages of the Micro-Explosion Phenomenon Explained.

4.2.2 Soot Shell Conversion

One of the main byproducts concerning diesel engines is the soot that is physically emitted from the exhaust pipes into the atmosphere. Simply put, soot is the byproduct of an incomplete fuel burn during combustion. Since diesel fuel is not ignited like gasoline, not all the fuel within the cylinder is burned simultaneously during combustion. During the exhaust stroke, the unburned portion of the diesel fuel then travels through the extremely hot exhaust system, causing it to burn and result in the formation of soot. Figure 4.3 shows a TEM image of conventional diesel fuel.

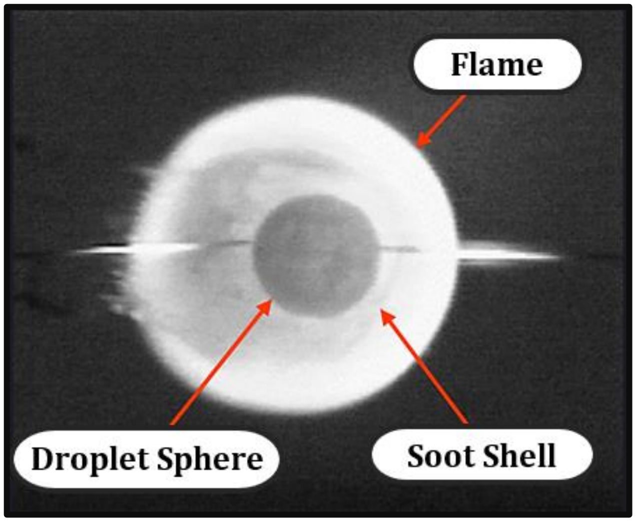


Figure 4-3. Transmission Electron Microscopy (TEM) Image of a Diesel Fuel Droplet Following Detonation.

Internal combustion engines typically create more power when more fuel is burned during combustion. When soot is formed during the combustion phase, it restricts complete burn of the diesel fuel resulting in limited engine performance. To achieve complete burn of the diesel fuel that is introduced into the cylinder during the intake stroke, the formation of the soot shell needs elimination.

As previously stated in section 4.2.1, the pressure and temperature within the cylinder rise exponentially as the piston rises to TDC. This causes the water in the fuel droplet to reach flash boil much quicker than diesel fuel. Figure 4.4 illustrates the transformation of the soot shell via water vapor/steam as a result of reaching flash boil.

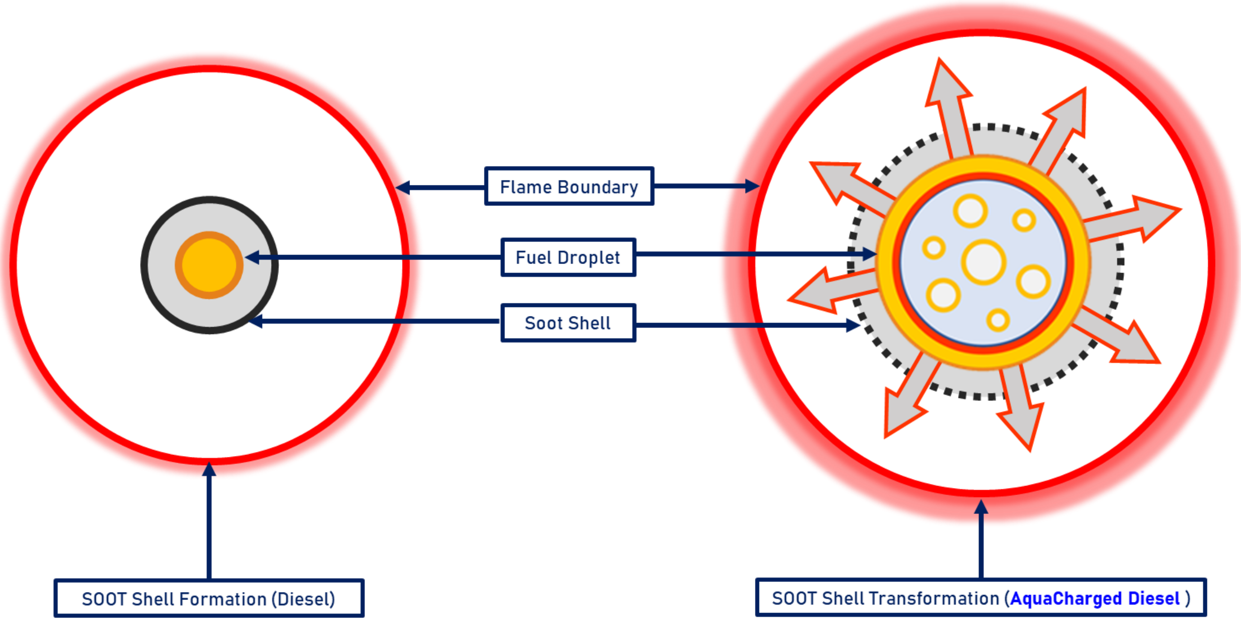


Figure 4-4. Soot Shell Transformation via Water Flash Boil.

As shown in the figure above, the fuel droplet on the left side of the diagram is that of conventional diesel fuel, while the fuel droplet on the right side is that of the AquaCharged Diesel. As results of the water vapor/steam generated during the flash boil, the soot shell has broken apart as illustrated with the dotted circle and the flame boundary achieves a larger diameter.

It is now possible for the initially unburned fuel to break free from the soot shell and burn in the combustion chamber producing increased engine performance and reducing soot emitted from the exhaust system. Figure 4.5 below illustrates the multi-stage combustion that results in reduced greenhouse gas emission (Davani, 2022).

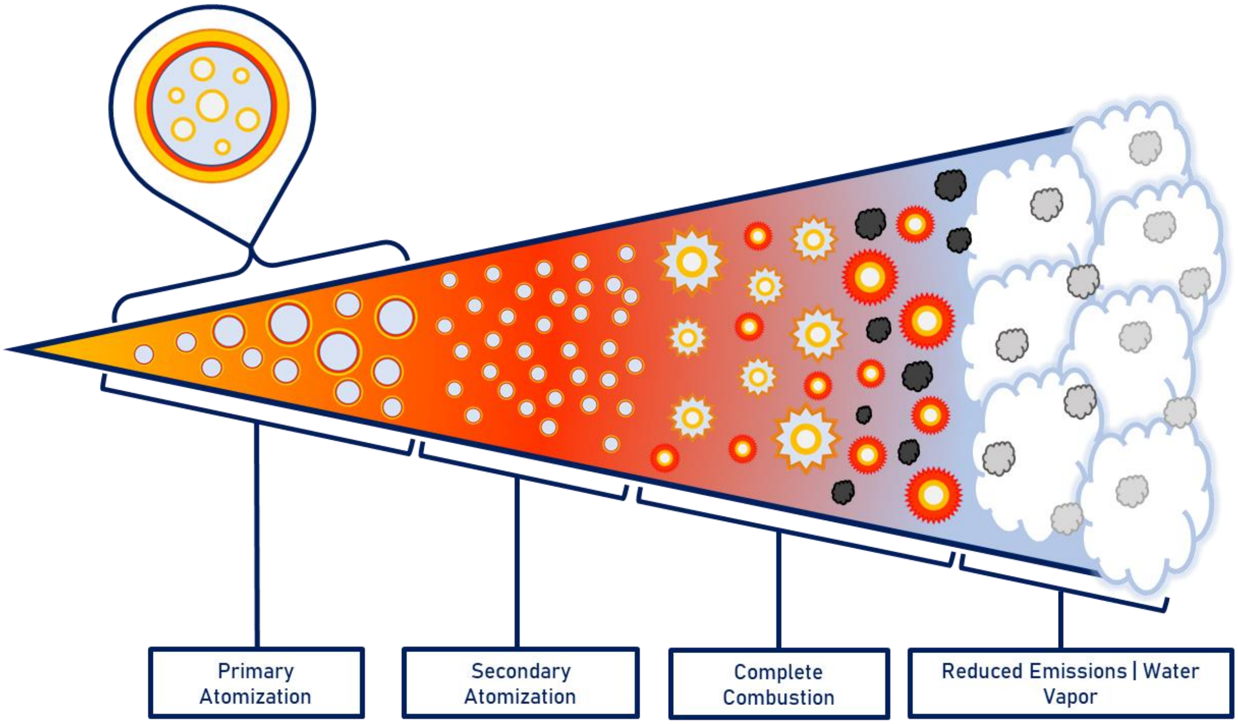
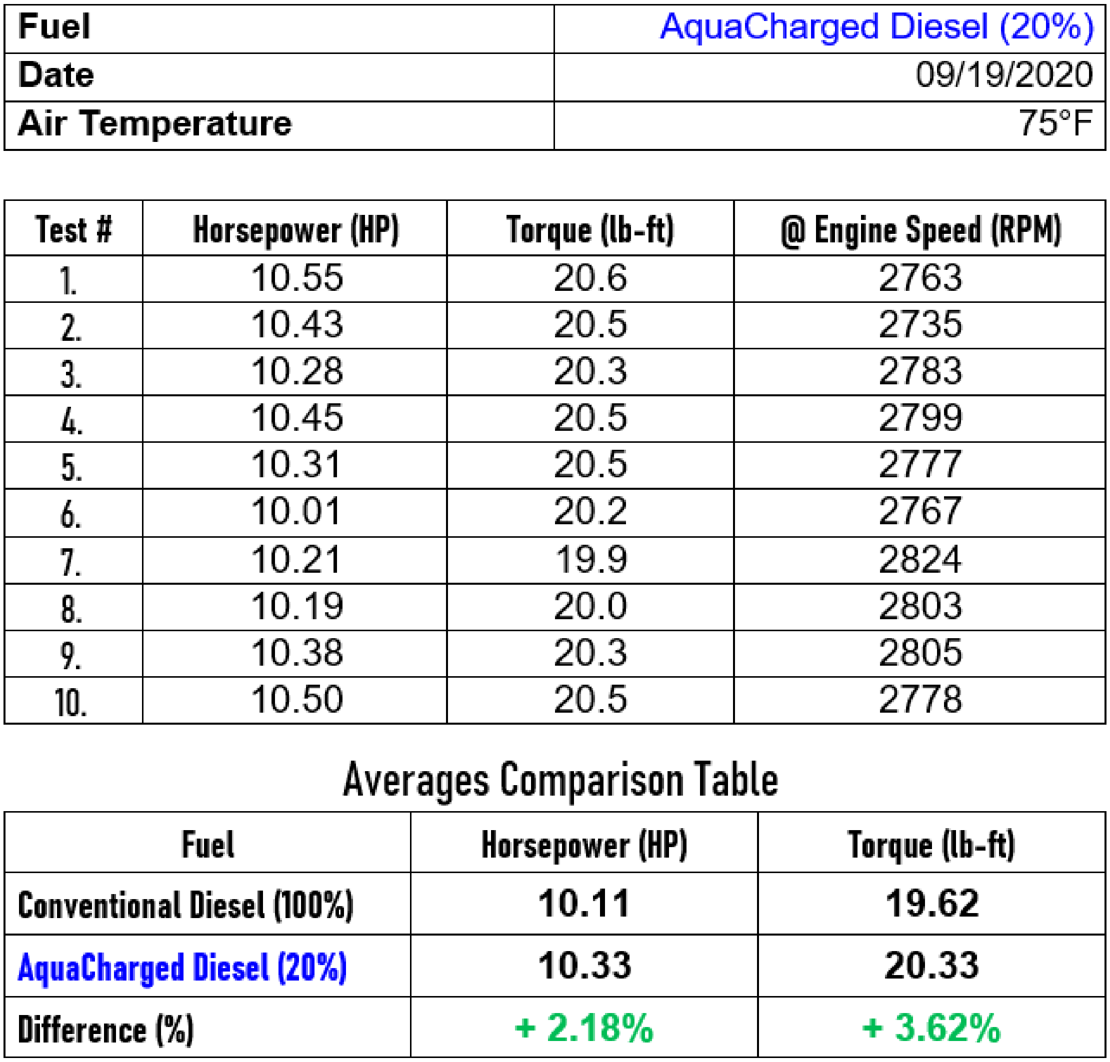


Figure 4-5. Soot Shell Transformation via Water Flash Boil.

4.2.3 Engine Dynamometer Testing

The engine was dyno tested 10 times while running on the AquaCharged Diesel fuel. After running the dynamometer 10 times the horsepower (HP) and torque data were averaged to determine the standard deviation in comparison to conventional diesel fuel. Table 4.1 provides the data collected from the dynamometer tests. It is evident in the averages table that an increase of over 2% for HP and over 3.5% for torque was achieved while running on the AquaCharged Diesel fuel.

TABLE 4-1 AQUACHARGED DIESEL DYNAMOMEMTER TEST RUNS AND AVERAGES COMPARED TO CONVNENTIONAL DIESEL.



Fuel	AquaCharged Diesel (20%)
Date	09/19/2020
Air Temperature	75°F

Test #	Horsepower (HP)	Torque (lb-ft)	@ Engine Speed (RPM)
1.	10.55	20.6	2763
2.	10.43	20.5	2735
3.	10.28	20.3	2783
4.	10.45	20.5	2799
5.	10.31	20.5	2777
6.	10.01	20.2	2767
7.	10.21	19.9	2824
8.	10.19	20.0	2803
9.	10.38	20.3	2805
10.	10.50	20.5	2778

Averages Comparison Table

Fuel	Horsepower (HP)	Torque (lb-ft)
Conventional Diesel (100%)	**10.11**	**19.62**
AquaCharged Diesel (20%)	**10.33**	**20.33**
Difference (%)	**+ 2.18%**	**+ 3.62%**

4.2.4 Emissions and Fuel Consumption Testing

A total amount of 500ml of AquaCharged Diesel is formulated for emissions and fuel consumption testing. The engine operated at a constant speed for a duration of 5 minutes. While the engine was running the exhaust gases were monitored and measured using the Enerac700 5-gas analyzer. After 5 minutes the fuel that remains in the fuel tank is measured to determine total fuel consumption. Table 4.2 gives the emissions and fuel consumption data for the W20 Diesel.

TABLE 4-2 AQUACHARGED DIESEL EMISSIONS AND FUEL CONSUMPTION DATA

Fuel Consumption

Fuel	Run Time	Starting Volume	Ending Volume	Consumed (ml)	Consumed (%)
Conventional Diesel	5 min	500 ml	411 ml	89 ml	17.8 %
AquaCharged Diesel	5 min	500 ml	409 ml	91 ml	18.2 %
Assessment					**- 2.25 %**

Emissions Data

Fuel	Oxygen (O2) - %	Carbon Monoxide (CO) - PPM	Carbon Dioxide (CO2) - %	Hydrocarbons (HC) - PPM	Nitric Oxides (NOx) - PPM
Conventional Diesel	16.8%	0 PPM	2.8%	36 PPM	100.4 PPM
AquaCharged Diesel	16.9%	0 PPM	2.5%	39 PPM	30.08 PPM
Difference	+ 0.1%	0 PPM	- 0.3%	+3 PPM	-70.32 PPM

Emissions Data Assessment (%)

Oxygen (%)	Carbon Monoxide (%)	Carbon Dioxide (%)	Hydrocarbons (%)	Nitric Oxides (%)
+ 0.6 %	**0 %**	**- 10.71 %**	**+ 8.33%**	**- 70.04%**

The graphs presented compare the test results of conventional diesel vs. AquaCharged Diesel. Figure 4.6 shows the test results from the fuel consumption test for conventional diesel fuel and AquaCharged Diesel. The red bar (conventional diesel) represents a total fuel consumption of 17.8% consumed from the starting fuel volume of 500ml. On the right side of the graph, the blue bar (AquaCharged Diesel) represents a total fuel consumption of 18.2% consumed from the starting volume of 500ml. In comparison, the AquaCharged Diesel fuel increased fuel economy by only 2.25%.

Figure 4.7 analyzes the exhaust emissions in percentage produced for conventional diesel and AquaCharged Diesel. The oxygen produced from the exhaust gases when operating the AquaCharged Diesel fuel was 0.6% higher than conventional diesel. On the right-hand side of the graph the CO2 that was produced from the exhaust gases are compared. It is evident that conventional diesel produced 12% more CO2 than the AquaCharged Diesel during engine operation.

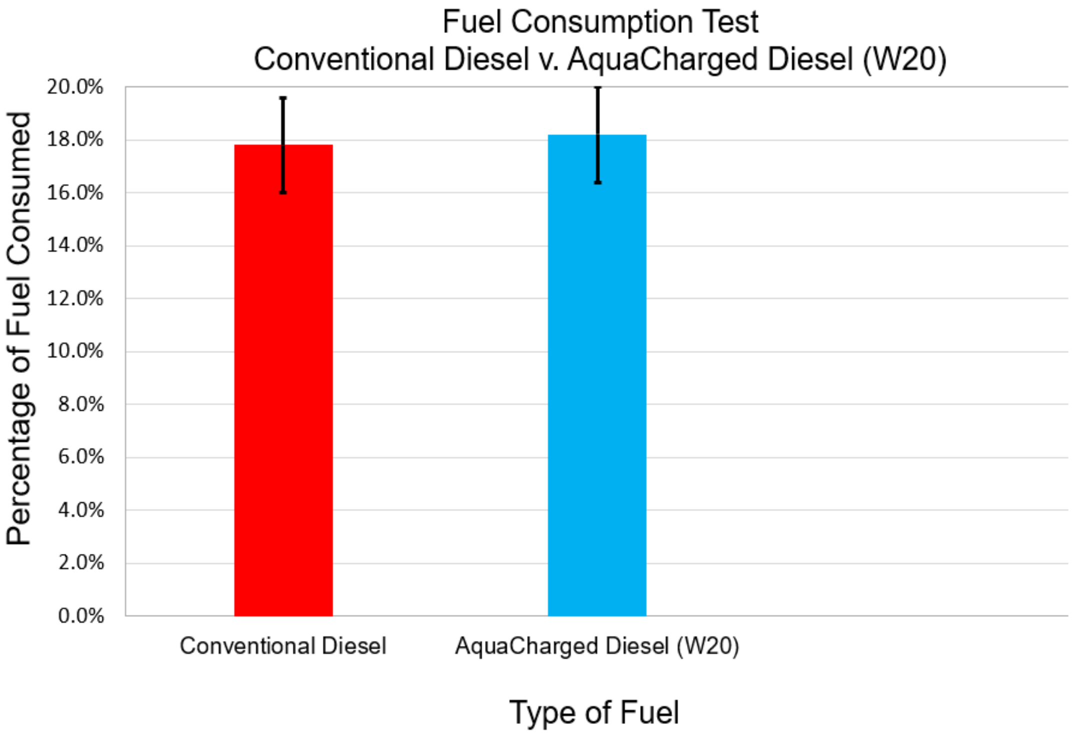


Figure 4-6. Fuel Consumption Test – Conventional Diesel vs. AquaCharged Diesel.

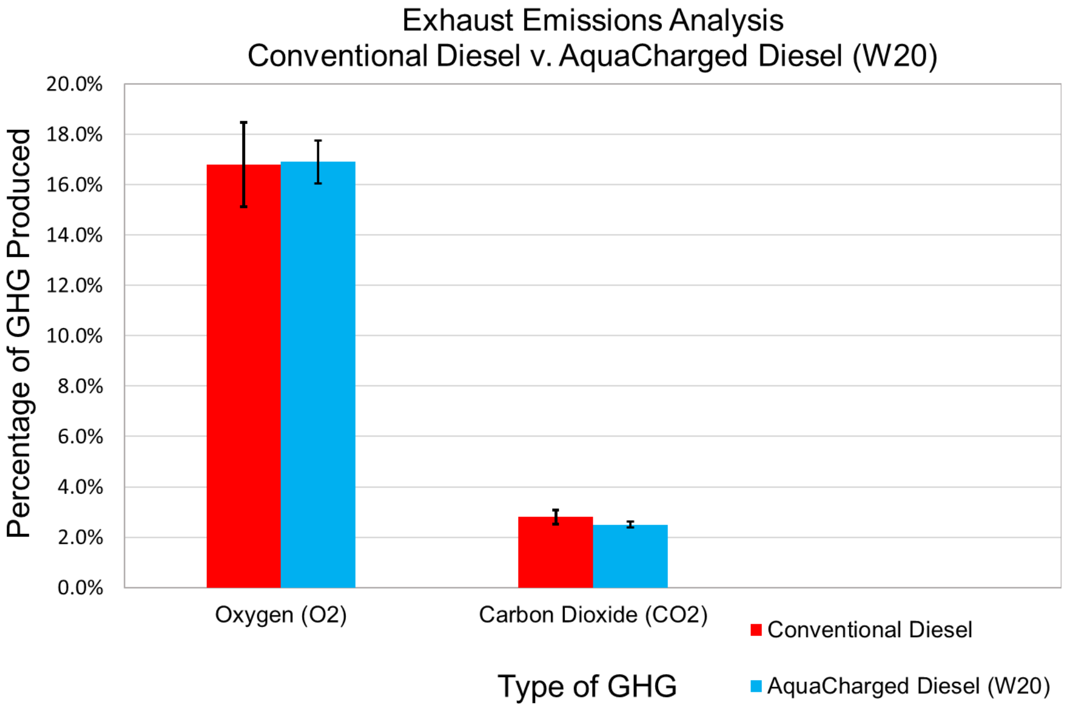


Figure 4-7. Exhaust Emissions Analysis in % (O2 & CO2) – Conventional Diesel vs. AquaCharged Diesel.

The last graph below in Figure 4.8, compares the exhaust emissions data for the remaining gases measured in parts per million (PPM). The far-left side of the graph represents the amount of HC produced from the tested fuels. The HC that was produced from the AquaCharged Diesel was 39 PPM which is an increase of 3 PPM from conventional diesel. Due to the reduced combustion temperatures with the utilization of AquaCharged Diesel a substantial drop in NOx emission is presented. The NOx emission produced from AquaCharged Diesel was 30.08 PPM which is 70.32 PPM or 70.04% lower than that of conventional diesel. The right side of the graph shows the production of CO emissions which of course is zero. Carbon monoxide is produced when incomplete combustion reactions take place, usually due to the lack of oxygen [20].

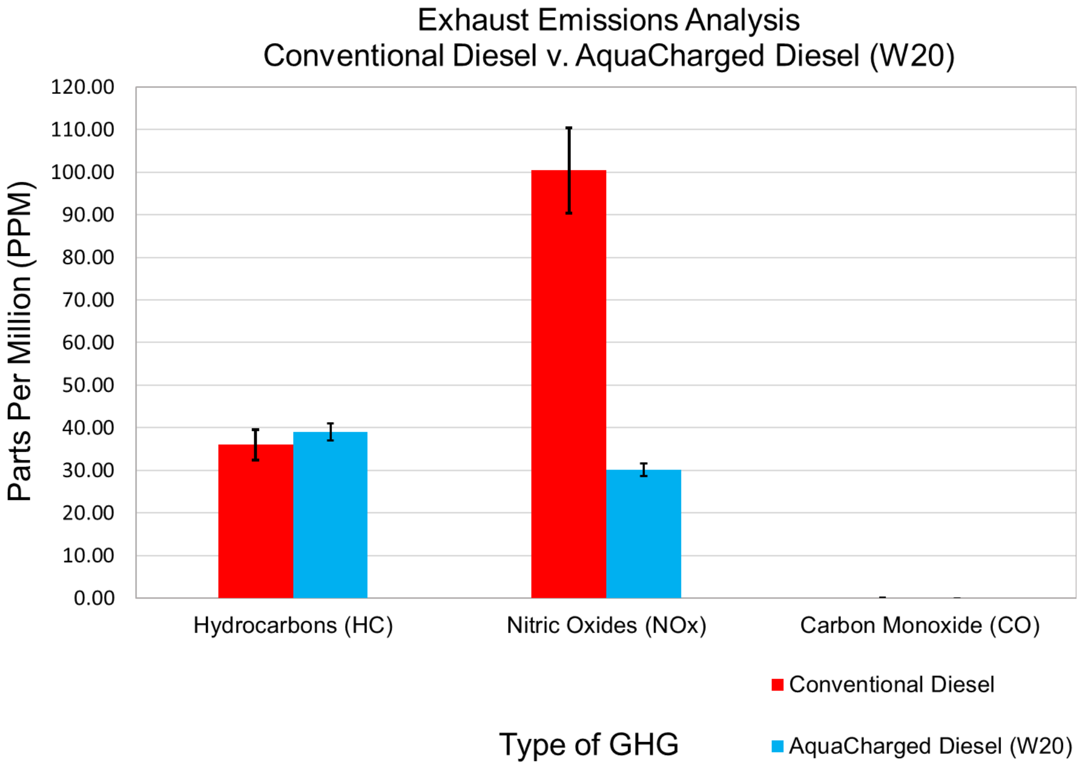


Figure 4-8. Exhaust Emissions Analysis in PPM (HC, NOx, CO) Conventional Diesel vs. AquaCharged Diesel.

4.3 AquaCharged Diesel™ [+] (W20) Nanosized Emulsion

The AquaCharged Diesel (+) formulation is a nanosized biofuel blend containing 20% water as a renewable source. Unlike the micro-sized emulsion of AquaCharged Diesel, this blend is transparent, due to a few extra steps in the fuel formulation process. While the engine performance of AquaCharged Diesel (+) falls slightly short of conventional diesel, it delivers a noticeable improvement in fuel economy. Figure 4.9 shows the final formulation of the transparent fuel in a 500ml glass measuring beaker (Davani, 2022). The AquaCharged Diesel (+) resembles conventional diesel in terms of appearance and flowability.

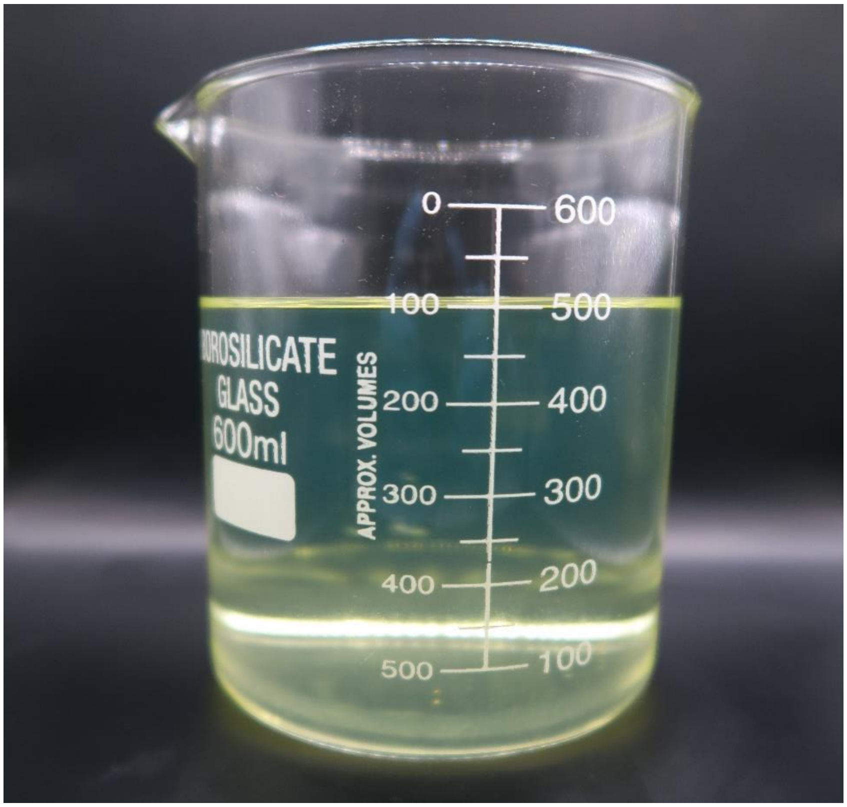
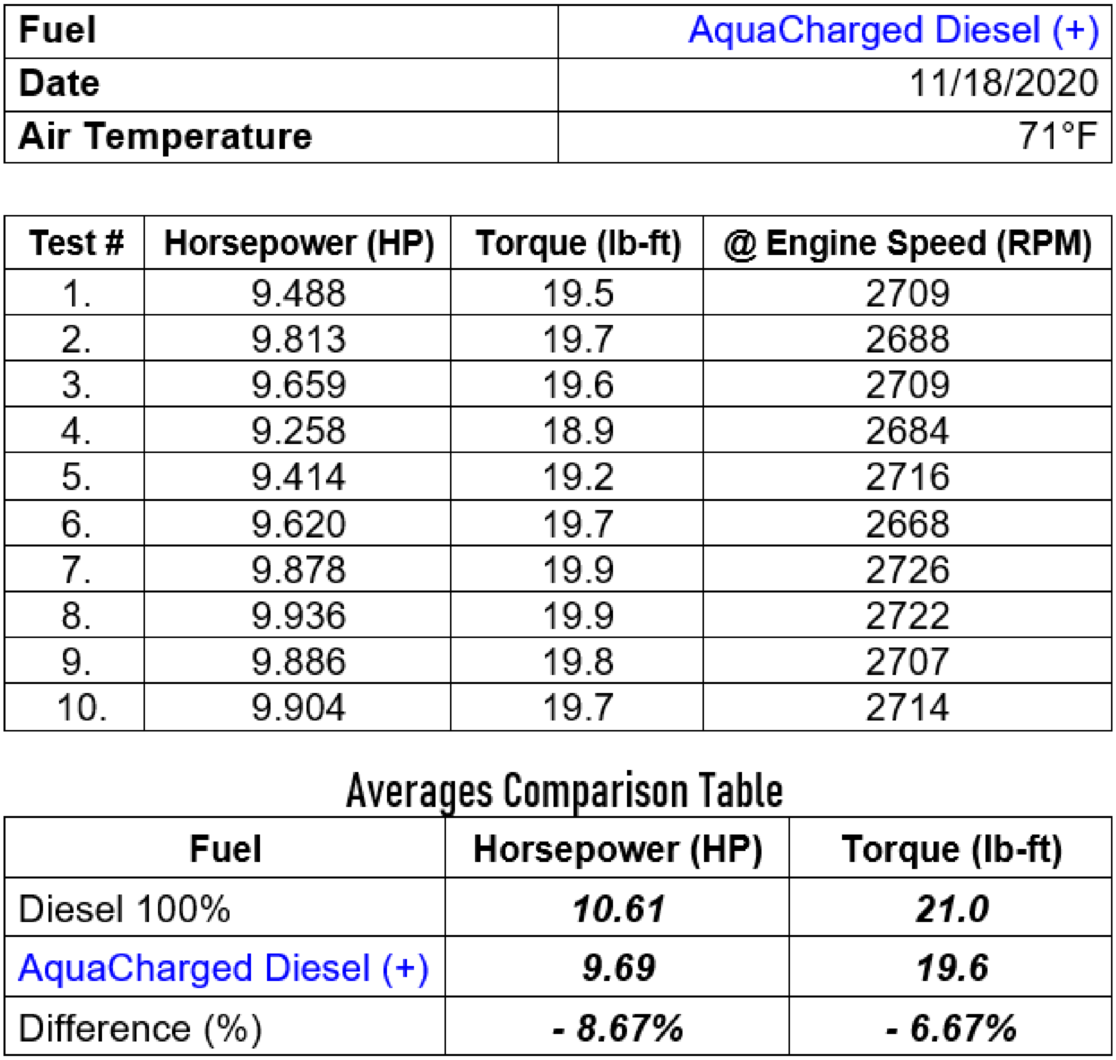


Figure 4-9. AquaCharged Diesel™ (+) containing 20% Water.

4.3.1 Engine Dynamometer Testing

The engine was dyno tested 10 times while running on the AquaCharged Diesel (+) fuel. After running the dynamometer 10 times the horsepower (HP) and torque data were averaged to determine the standard deviation in comparison to conventional diesel fuel. Table 4.3 provides the data collected from the dynamometer tests. It is evident in the averages table that a decrease of over 8% for HP and over 6% for torque was recorded while running on the AquaCharged Diesel (+) fuel.

Table 4-3. AQUACHARGED DIESEL (+) DYNAMOMEMTER TEST RUNS AND AVERAGES COMPARED TO CONVNENTIONAL DIESEL.



Fuel	AquaCharged Diesel (+)
Date	11/18/2020
Air Temperature	71°F

Test #	Horsepower (HP)	Torque (lb-ft)	@ Engine Speed (RPM)
1.	9.488	19.5	2709
2.	9.813	19.7	2688
3.	9.659	19.6	2709
4.	9.258	18.9	2684
5.	9.414	19.2	2716
6.	9.620	19.7	2668
7.	9.878	19.9	2726
8.	9.936	19.9	2722
9.	9.886	19.8	2707
10.	9.904	19.7	2714

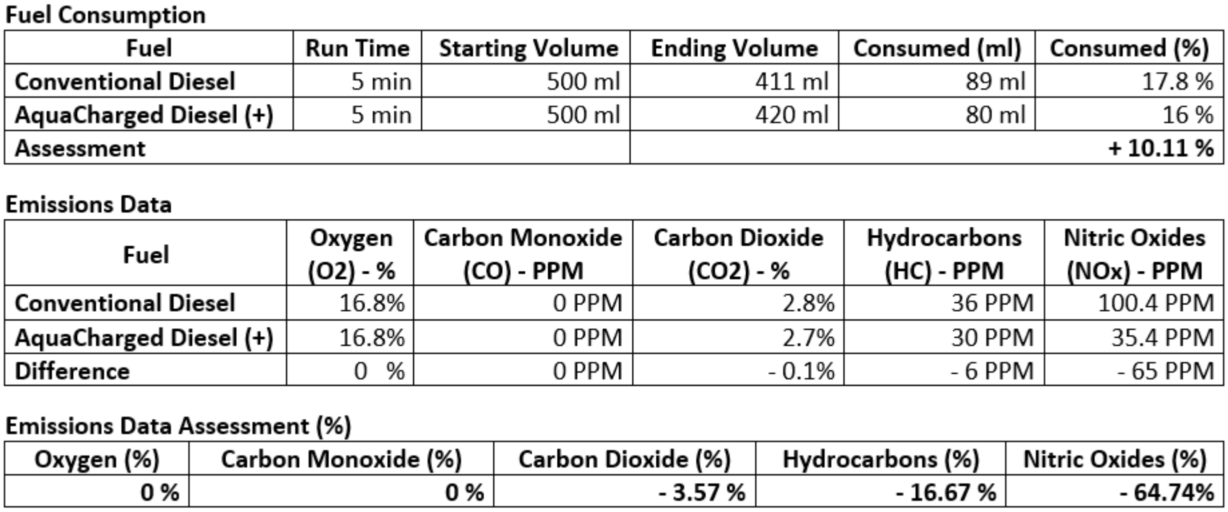
Averages Comparison Table

Fuel	Horsepower (HP)	Torque (lb-ft)
Diesel 100%	***10.61***	***21.0***
AquaCharged Diesel (+)	***9.69***	***19.6***
Difference (%)	***- 8.67%***	***- 6.67%***

4.3.2 Emissions and Fuel Consumption Testing

A total amount of 500ml of AquaCharged Diesel (+) is formulated for emissions and fuel consumption testing. The engine operated at a constant speed for a duration of 5 minutes. While the engine is running the exhaust gases are monitored and measured using the Enerac700 5-gas analyzer. After 5 minutes the fuel that remains in the fuel tank is measured to determine total fuel consumption. Table 4.4 gives the emissions and fuel consumption data for W20 (+) Diesel.

Table 4-4. AQUACHARGED DIESEL (+) EMISSIONS AND FUEL CONSUMPTION DATA



Fuel Consumption

Fuel	Run Time	Starting Volume	Ending Volume	Consumed (ml)	Consumed (%)
Conventional Diesel	5 min	500 ml	411 ml	89 ml	17.8 %
AquaCharged Diesel (+)	5 min	500 ml	420 ml	80 ml	16 %
Assessment			**+ 10.11 %**		

Emissions Data

Fuel	Oxygen (O2) - %	Carbon Monoxide (CO) - PPM	Carbon Dioxide (CO2) - %	Hydrocarbons (HC) - PPM	Nitric Oxides (NOx) - PPM
Conventional Diesel	16.8%	0 PPM	2.8%	36 PPM	100.4 PPM
AquaCharged Diesel (+)	16.8%	0 PPM	2.7%	30 PPM	35.4 PPM
Difference	0 %	0 PPM	- 0.1%	- 6 PPM	- 65 PPM

Emissions Data Assessment (%)

Oxygen (%)	Carbon Monoxide (%)	Carbon Dioxide (%)	Hydrocarbons (%)	Nitric Oxides (%)
0 %	**0 %**	**- 3.57 %**	**- 16.67 %**	**- 64.74%**

The presented graphs depict a comparison of the test outcomes of conventional diesel fuel and AquaCharged Diesel (+). In Figure 4.10, the fuel consumption test results for both fuels are shown. The red bar (conventional diesel) indicates that 18% of the starting fuel volume of 500ml was consumed. On the other hand, the blue bar (AquaCharged Diesel (+)) shows a total fuel consumption of 17.8% from the same starting volume of 500ml. Consequently, AquaCharged Diesel (+) exhibited an improvement in fuel economy by 10.11%.

Figure 4.11 analyzes the exhaust emissions in percentage produced for conventional diesel and AquaCharged Diesel (+). The oxygen produced from the exhaust gases when operating the AquaCharged Diesel (+) fuel consistent with conventional diesel. On the right-hand side of the graph the CO2 that was produced from the exhaust gases are compared. It is evident that conventional diesel produced 3.7% more CO2 than the AquaCharged Diesel (+) during engine operation.

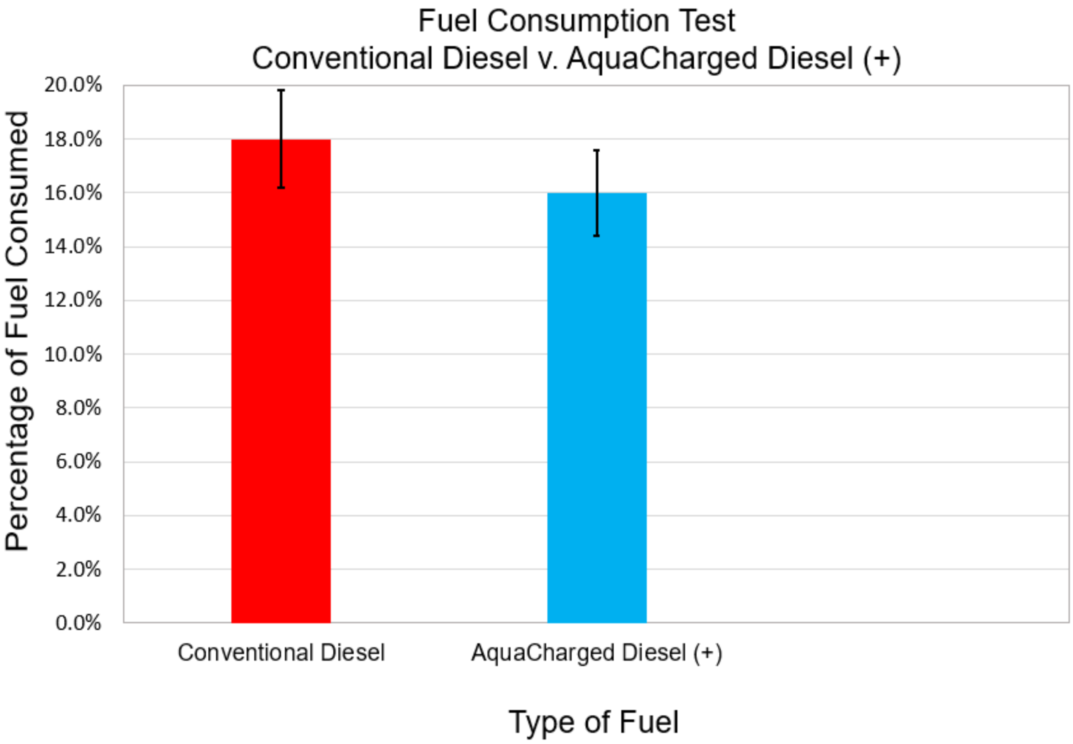


Figure 4-10. Fuel Consumption Test – Conventional Diesel vs. AquaCharged Diesel (+).

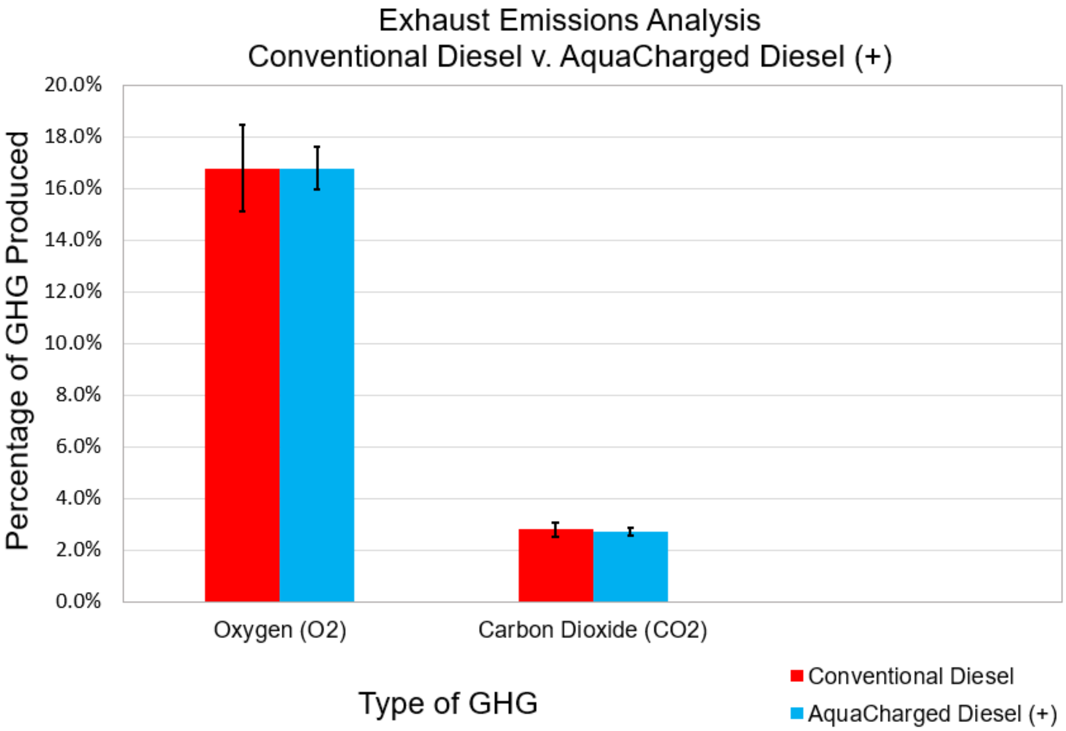


Figure 4-11. Exhaust Emissions Analysis in % (O2 & CO2) – Conventional Diesel vs. AquaCharged Diesel (+).

The last graph below in Figure 4.12, compares the exhaust emissions data for the remaining gases measured in parts per million (PPM). The far-left side of the graph represents the amount of HC produced from the tested fuels. The HC that was produced from the AquaCharged Diesel (+) was 30 PPM which is a decrease of 6 PPM from conventional diesel. Due to the reduced combustion temperatures with the utilization of AquaCharged Diesel (+) a substantial drop in NOx emission is presented. The NOx emission produced from AquaCharged Diesel (+) was 35.4 PPM which is 65 PPM or 64.74% lower than that of conventional diesel. The right side of the graph shows the production of CO emissions which of course is zero. Carbon monoxide is produced when incomplete combustion reactions take place, usually due to the lack of oxygen [20].

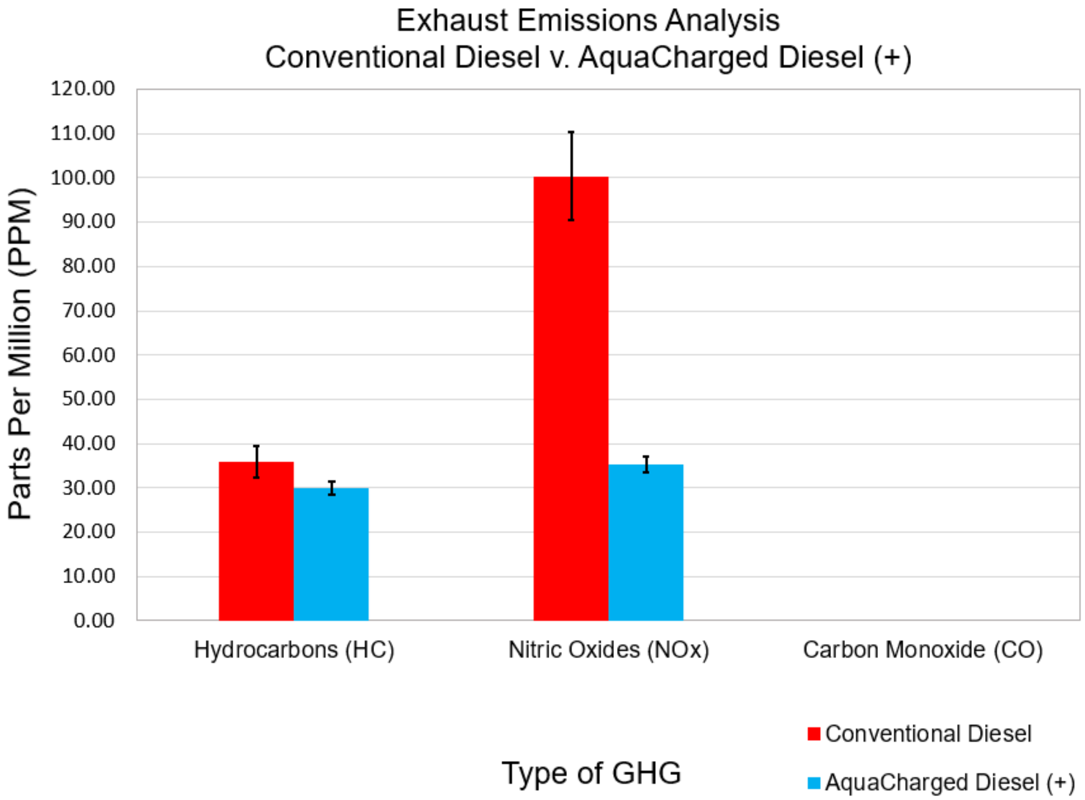


Figure 4-12. Exhaust Emissions Analysis in PPM (HC, NOx, CO) Conventional Diesel vs. AquaCharged Diesel (+).

4.4 TEST #27 - Soybean Oil Biodiesel (B50)

The composition of Test #27 (code name) biodiesel is 50% Soybean Oil as a renewable source and the remainder is conventional diesel fuel and the proprietary additives. Figure 4.13 shows Test #27 in a glass beaker quickly after the formulation process and right before being poured in the engine fuel tank for dynamometer testing.

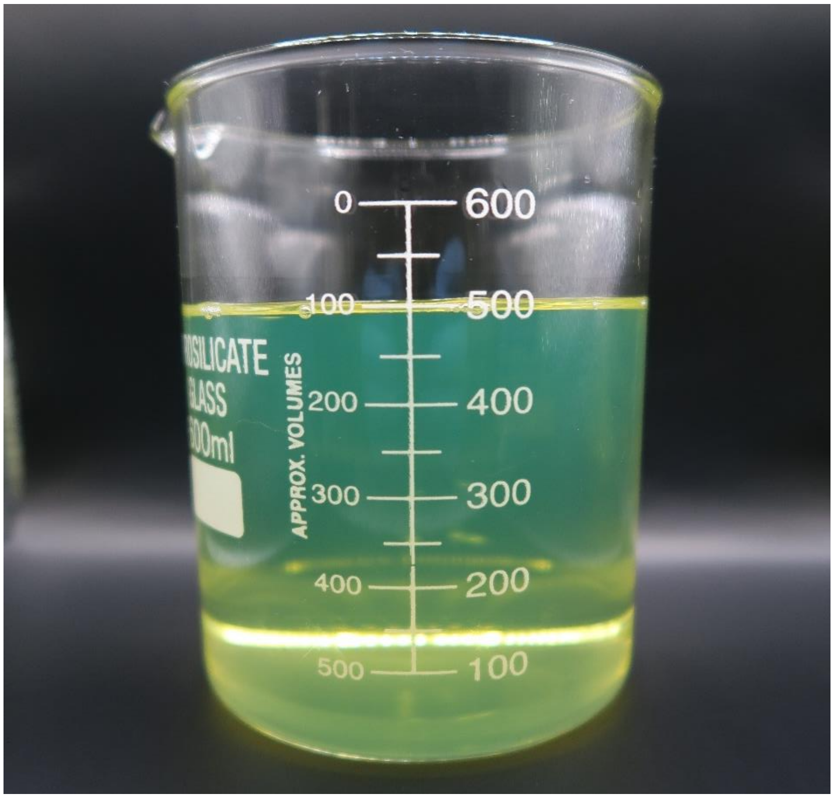
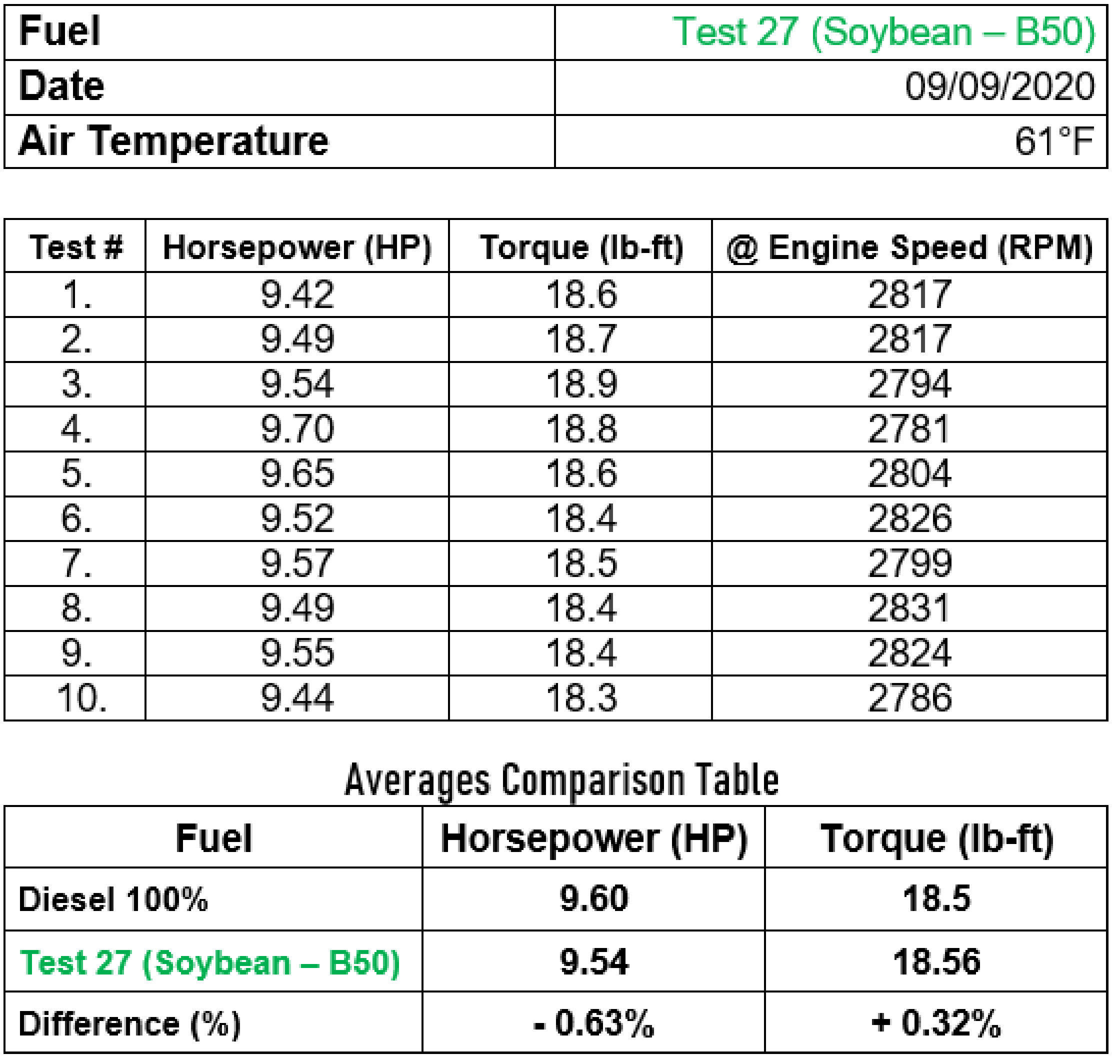


Figure 4-13. Biodiesel Test #27 containing 50% Soybean Oil.

4.4.1 Engine Dynamometer Testing

The engine was dyno tested 10 times while running on Test #27 biodiesel fuel. Furthermore, after running the dynamometer 10 times the horsepower (HP) and torque data were averaged to determine the standard deviation in comparison to conventional diesel fuel. Table 4.5 gives the data collected from the dynamometer tests. The averages table shows a slight decrease of .63% for HP and an increase of .32% for torque outputs.

Table 4-5. TEST #27 BIODIESEL DYNAMOMEMTER TEST RUNS AND AVERAGES COMPARED TO CONVNENTIONAL DIESEL



Fuel	Test 27 (Soybean – B50)
Date	09/09/2020
Air Temperature	61°F

Test #	Horsepower (HP)	Torque (lb-ft)	@ Engine Speed (RPM)
1.	9.42	18.6	2817
2.	9.49	18.7	2817
3.	9.54	18.9	2794
4.	9.70	18.8	2781
5.	9.65	18.6	2804
6.	9.52	18.4	2826
7.	9.57	18.5	2799
8.	9.49	18.4	2831
9.	9.55	18.4	2824
10.	9.44	18.3	2786

Averages Comparison Table

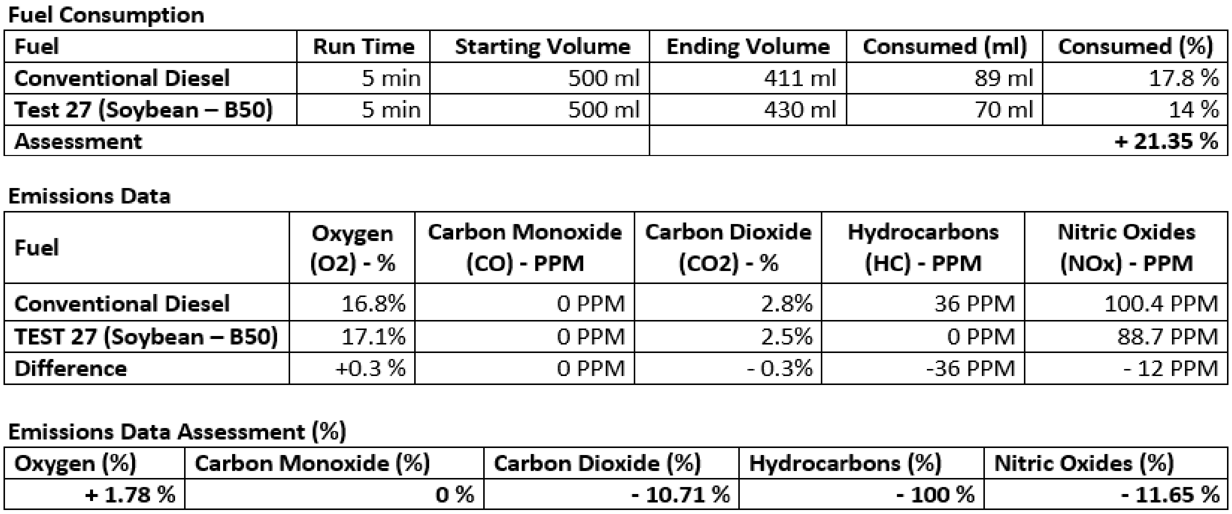
Fuel	Horsepower (HP)	Torque (lb-ft)
Diesel 100%	**9.60**	**18.5**
Test 27 (Soybean – B50)	**9.54**	**18.56**
Difference (%)	**- 0.63%**	**+ 0.32%**

4.4.2 Emissions and Fuel Consumption Testing

A total amount of 500ml of Test #27 biodiesel is formulated for emissions and fuel consumption testing. The engine ran at a constant speed for a total of 5 minutes. While the engine was running the exhaust gases are again monitored and measured using the Enerac700 5-gas analyzer. After 5 minutes of engine operation the fuel the remainder of the fuel in the tank is measured to determine total fuel consumption. Table 4.6 shows the emissions and fuel consumption data relative to conventional diesel fuel. With 50% of conventional diesel

eliminated per volume, Test #27 displayed compelling data with significant reduction in CO_2, HC, and NOx emissions, while improving fuel economy by over 21%.

Table 4-6. TEST #27 BIODIESEL (B50) EMISSIONS AND FUEL CONSUMPTION DATA



Fuel Consumption

Fuel	Run Time	Starting Volume	Ending Volume	Consumed (ml)	Consumed (%)
Conventional Diesel	5 min	500 ml	411 ml	89 ml	17.8 %
Test 27 (Soybean – B50)	5 min	500 ml	430 ml	70 ml	14 %
Assessment			**+ 21.35 %**		

Emissions Data

Fuel	Oxygen (O2) - %	Carbon Monoxide (CO) - PPM	Carbon Dioxide (CO2) - %	Hydrocarbons (HC) - PPM	Nitric Oxides (NOx) - PPM
Conventional Diesel	16.8%	0 PPM	2.8%	36 PPM	100.4 PPM
TEST 27 (Soybean – B50)	17.1%	0 PPM	2.5%	0 PPM	88.7 PPM
Difference	+0.3 %	0 PPM	- 0.3%	-36 PPM	- 12 PPM

Emissions Data Assessment (%)

Oxygen (%)	Carbon Monoxide (%)	Carbon Dioxide (%)	Hydrocarbons (%)	Nitric Oxides (%)
+ 1.78 %	**0 %**	**- 10.71 %**	**- 100 %**	**- 11.65 %**

The following graphs present an evaluation of test results comparing conventional diesel fuel to Test #27 biodiesel. Figure 4.14 illustrates the outcomes of a fuel consumption test for both fuels. The red bar (representing conventional diesel) indicates that 17.8% of the starting fuel volume (500ml) was consumed. On the right side, the green bar (representing Test #27 biodiesel) shows a total fuel consumption of 14% from the initial 500ml volume. Notably, Test #27 biodiesel exhibited a 21.35% improvement in fuel economy compared to conventional diesel.

Figure 4.15 examines the exhaust emissions in percentage produced by both fuels. When operating on Test #27 biodiesel, the exhaust gases produced 1.78% more oxygen compared to conventional diesel. On the right side of the graph, a comparison of CO2 emissions reveals that conventional diesel generated 12% more CO2 than Test #27 biodiesel during the testing period, indicating the potential environmental benefits of using biodiesel.

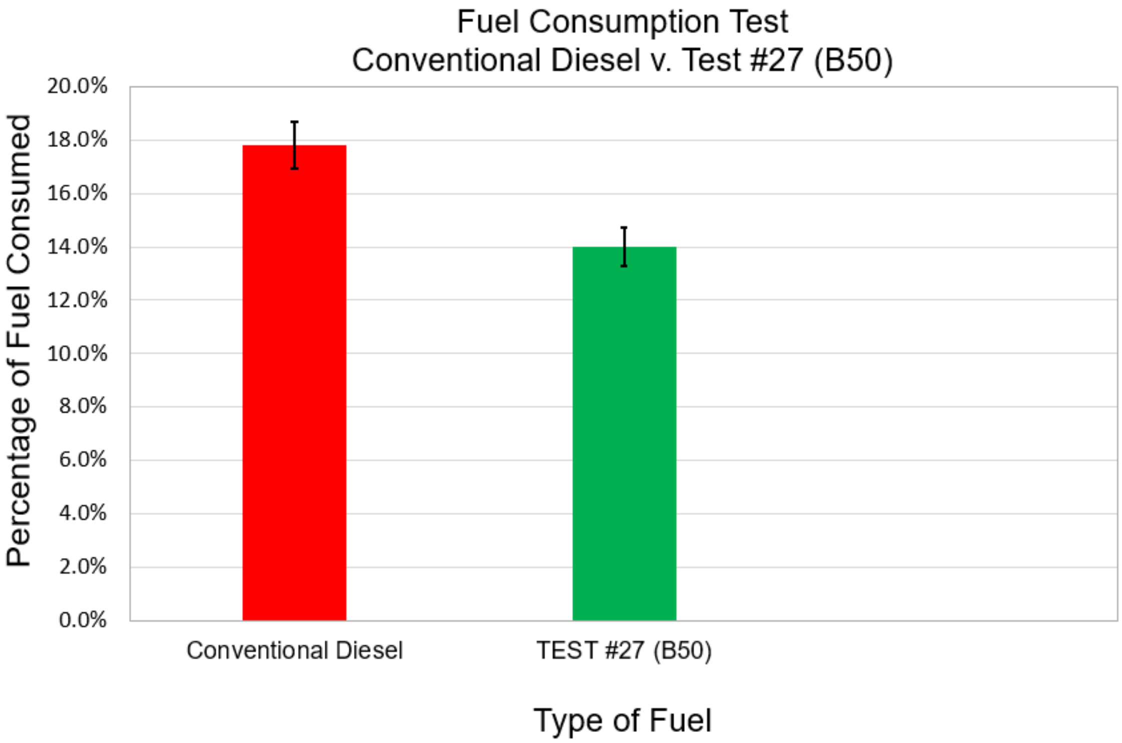


Figure 4-14. Fuel Consumption Test – Conventional Diesel v. Test #27 Biodiesel.

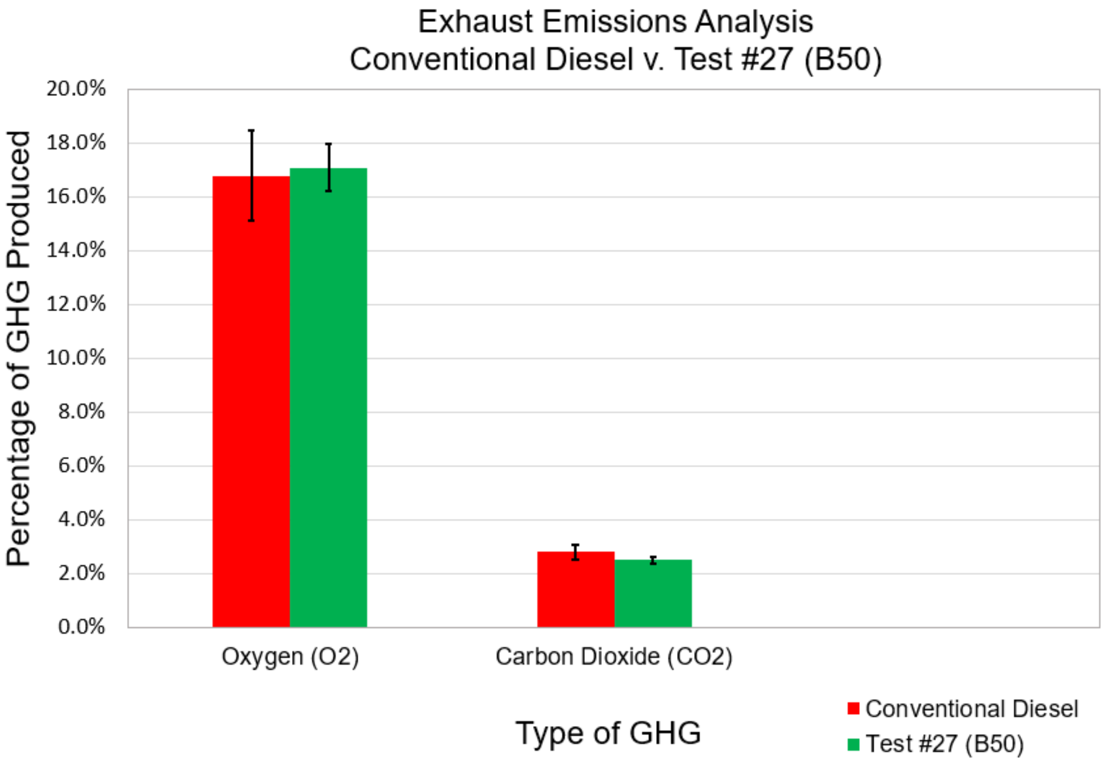


Figure 4-15. Exhaust Emissions Analysis in % (O_2 & CO_2) – Conventional Diesel v. Test #27 Biodiesel.

The last graph below in Figure 4.16, compares the exhaust emissions data for the remaining gases measured in parts per million (PPM). The far-left side of the graph represents the amount of HC produced from the tested fuels. The HC that was produced from the Test #27 biodiesel was 0 PPM which is a reduction of 36 PPM or 100% from conventional diesel. Due to reduced combustion temperatures while utilizing Test #27 biodiesel a drop in NOx emission was recorded. The NOx emission produced from Test #27 biodiesel was 88.7 PPM which is 12 PPM or 11.65% lower than that produced from conventional diesel. The right side of the graph shows the production of CO emissions which is zero as a result of complete combustion reactions and sufficient amount of oxygen.

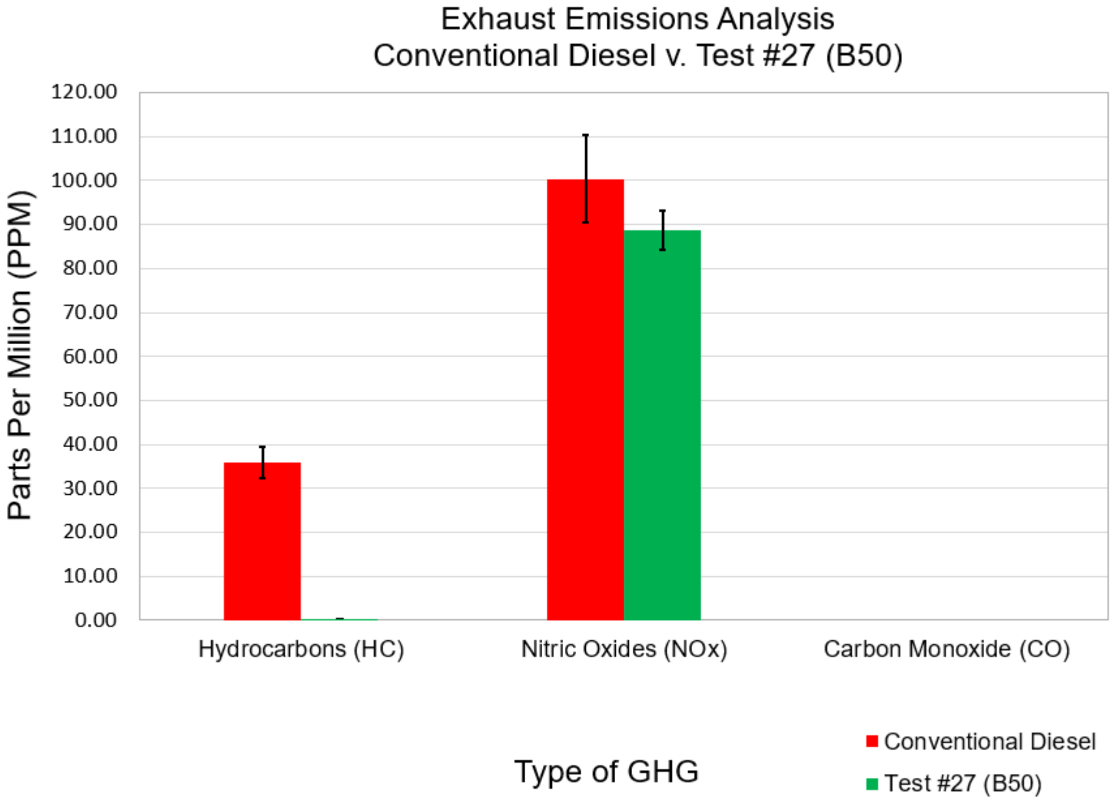


Figure 4-16. Exhaust Emissions Analysis in PPM (HC, NOx, CO) Conventional Diesel v. Test #27 Biodiesel.

4.5 TEST #30 - Red Palm Oil Biodiesel (B50)

The composition of Test #30 (code name) biodiesel is 50% red palm oil as a renewable source and the remainder is conventional diesel fuel and the proprietary additives. Figure 4.17 shows Test #30 in a glass beaker quickly after the formulation process and right before being poured in the engine fuel tank for dynamometer testing.

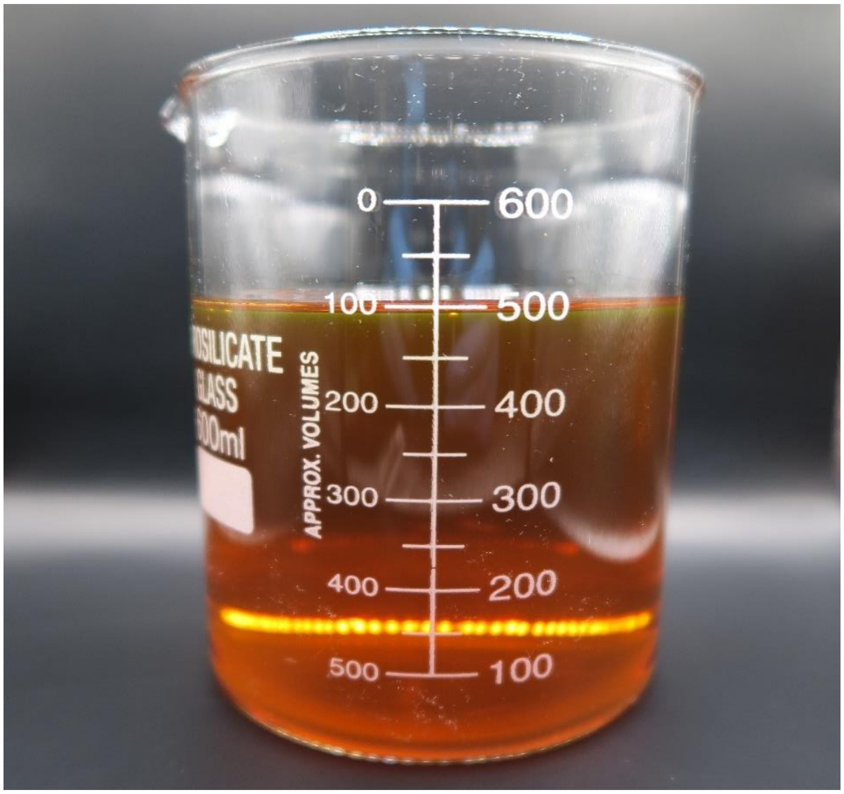
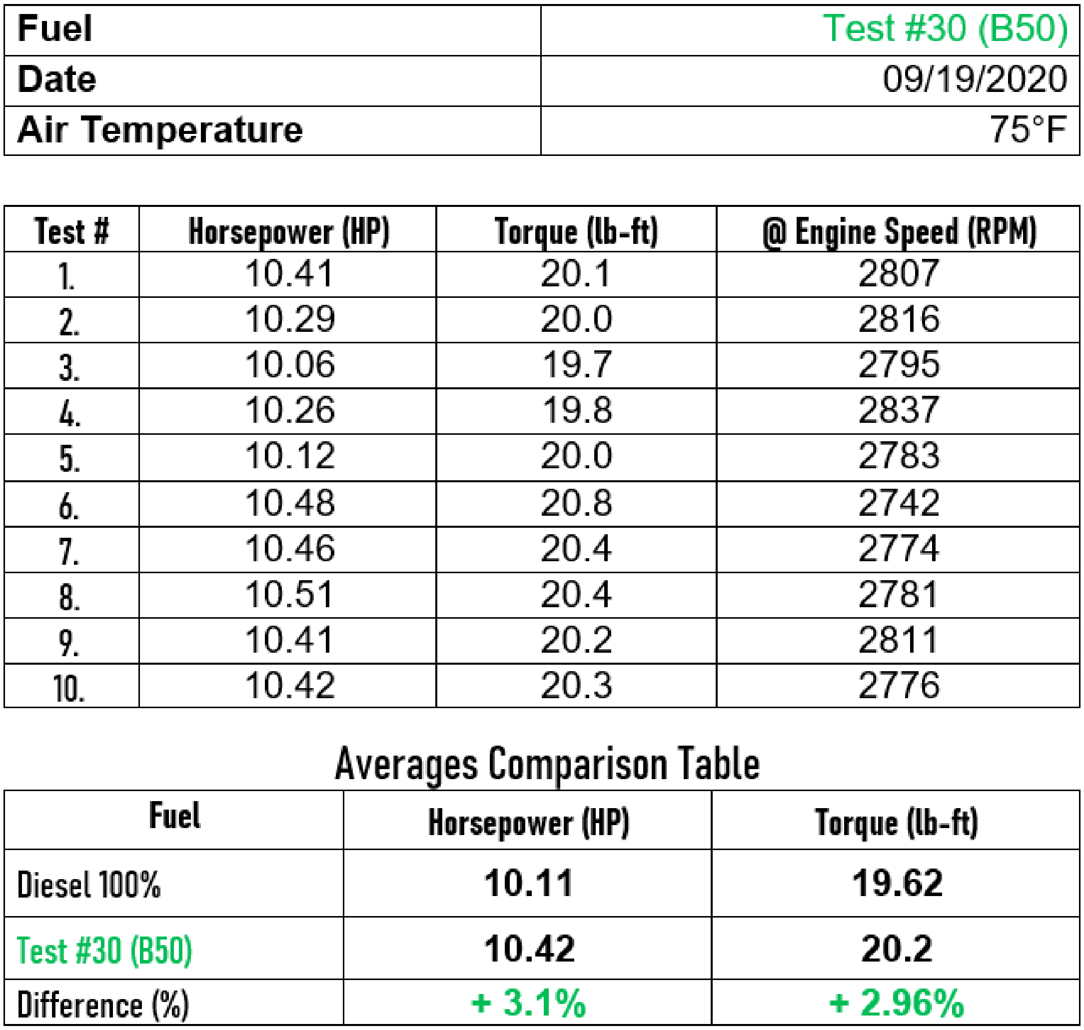


Figure 4-17. Biodiesel Test #30 containing 50% Red Palm Oil.

4.5.1 Engine Dynamometer Testing

The engine was dyno tested 10 times while running on Test #30 biodiesel fuel. Furthermore, after running the dynamometer 10 times the horsepower (HP) and torque data were averaged to determine the standard deviation in comparison to conventional diesel fuel. Table 4.7 gives the data collected from the dynamometer tests. The averages table shows an increase of over 3% for HP and about 3% for torque outputs.

Table 4-7. TEST #30 BIODIESEL DYNAMOMEMTER TEST RUNS AND AVERAGES COMPARED TO CONV NENTIONAL DIESEL.



Fuel	Test #30 (B50)
Date	09/19/2020
Air Temperature	75°F

Test #	Horsepower (HP)	Torque (lb-ft)	@ Engine Speed (RPM)
1.	10.41	20.1	2807
2.	10.29	20.0	2816
3.	10.06	19.7	2795
4.	10.26	19.8	2837
5.	10.12	20.0	2783
6.	10.48	20.8	2742
7.	10.46	20.4	2774
8.	10.51	20.4	2781
9.	10.41	20.2	2811
10.	10.42	20.3	2776

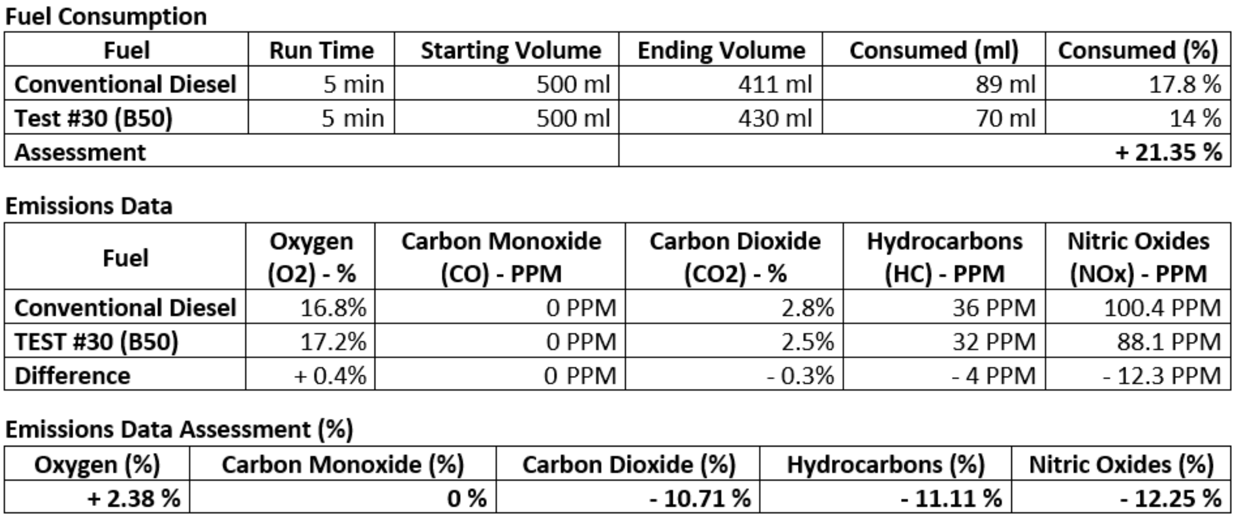
Averages Comparison Table

Fuel	Horsepower (HP)	Torque (lb-ft)
Diesel 100%	**10.11**	**19.62**
Test #30 (B50)	**10.42**	**20.2**
Difference (%)	**+ 3.1%**	**+ 2.96%**

4.5.2 Emissions and Fuel Consumption Testing

For emissions and fuel consumption testing, a 500ml batch of Test #30 biodiesel was prepared. The engine operated at a constant speed for 5 minutes, during which the exhaust gases were continuously monitored and measured using the Enerac700 5-gas analyzer. After the 5-minute engine run, the remaining fuel in the tank was measured to calculate the total fuel consumption. The results presented in Table 4.8 indicate that Test #30 biodiesel exhibited impressive performance compared to conventional diesel fuel. With 50% less conventional diesel used per volume, Test #30 demonstrated significant reductions in CO2, HC, and NOx emissions, while also achieving a nearly 10% improvement in fuel economy.

Table 4-8. TEST #30 BIODIESEL (B50) EMISSIONS AND FUEL CONSUMPTION DATA



Fuel Consumption

Fuel	Run Time	Starting Volume	Ending Volume	Consumed (ml)	Consumed (%)
Conventional Diesel	5 min	500 ml	411 ml	89 ml	17.8 %
Test #30 (B50)	5 min	500 ml	430 ml	70 ml	14 %
Assessment					**+ 21.35 %**

Emissions Data

Fuel	Oxygen (O2) - %	Carbon Monoxide (CO) - PPM	Carbon Dioxide (CO2) - %	Hydrocarbons (HC) - PPM	Nitric Oxides (NOx) - PPM
Conventional Diesel	16.8%	0 PPM	2.8%	36 PPM	100.4 PPM
TEST #30 (B50)	17.2%	0 PPM	2.5%	32 PPM	88.1 PPM
Difference	+ 0.4%	0 PPM	- 0.3%	- 4 PPM	- 12.3 PPM

Emissions Data Assessment (%)

Oxygen (%)	Carbon Monoxide (%)	Carbon Dioxide (%)	Hydrocarbons (%)	Nitric Oxides (%)
+ 2.38 %	**0 %**	**- 10.71 %**	**- 11.11 %**	**- 12.25 %**

The graphs shown below evaluate the test results of conventional diesel v. Test #30 biodiesel. Figure 4.18 shows the test results from the fuel consumption test for conventional diesel fuel and Test #30 biodiesel. The red bar (conventional diesel) represents a total fuel consumption of 17.8% consumed from the starting fuel volume of 500ml. On the right side of the graph, the green bar (Test #30 biodiesel) represents a total fuel consumption of 14% consumed from the starting volume of 500ml. In comparison, the Test #30 biodiesel improved fuel economy by 21.35%.

Figure 4.19 analyzes the exhaust emissions in percentage produced for conventional diesel and Test #30 biodiesel. The oxygen produced from the exhaust gases when operating the Test #30 biodiesel fuel was 2.38% higher than conventional diesel. On the right-hand side of the graph the CO_2 that was produced from the exhaust gases are compared. It is evident that conventional diesel produced 12% more CO_2 than Test #30 biodiesel during testing.

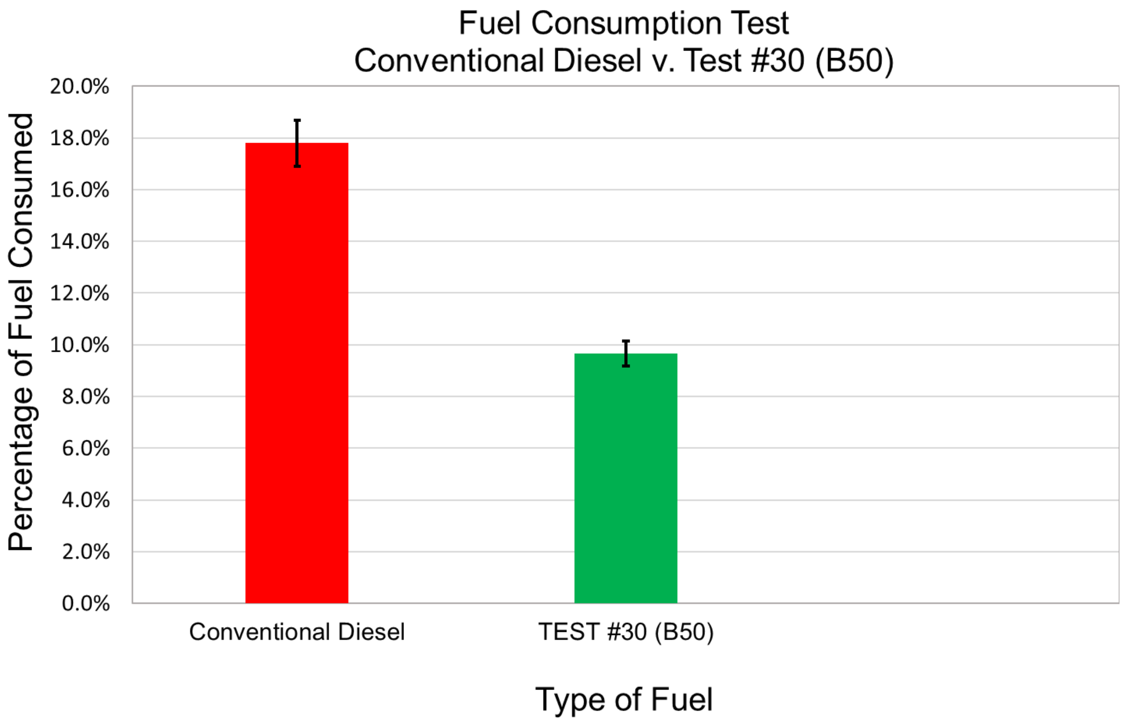


Figure 4-18. Fuel Consumption Test – Conventional Diesel v. Test #30 Biodiesel.

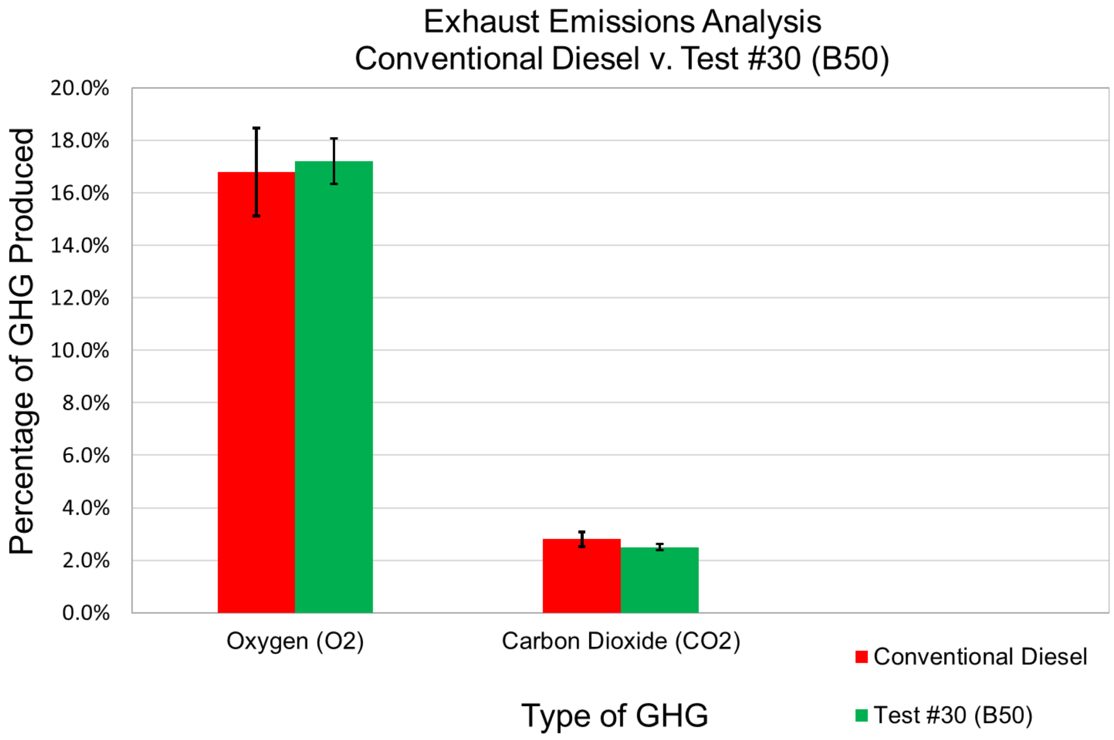


Figure 4-19. Exhaust Emissions Analysis in % (O_2 & CO_2) – Conventional Diesel v. Test #30 Biodiesel.

The last graph below in Figure 4.20, compares the exhaust emissions data for the remaining gases measured in parts per million (PPM). The far-left side of the graph represents the amount of HC produced from the tested fuels. The HC that was produced from the Test #30 biodiesel was 32 PPM which is a reduction of 4 PPM or 11.11% from conventional diesel. Due to reduced combustion temperatures while utilizing Test #30 biodiesel a drop in NOx emission was recorded. The NOx emission produced from Test #30 biodiesel was 88.1 PPM which is 12.3 PPM or 12.25% lower than that produced from conventional diesel. The right side of the graph shows the production of CO emissions which is zero as a result of complete combustion reactions and no lack of oxygen.

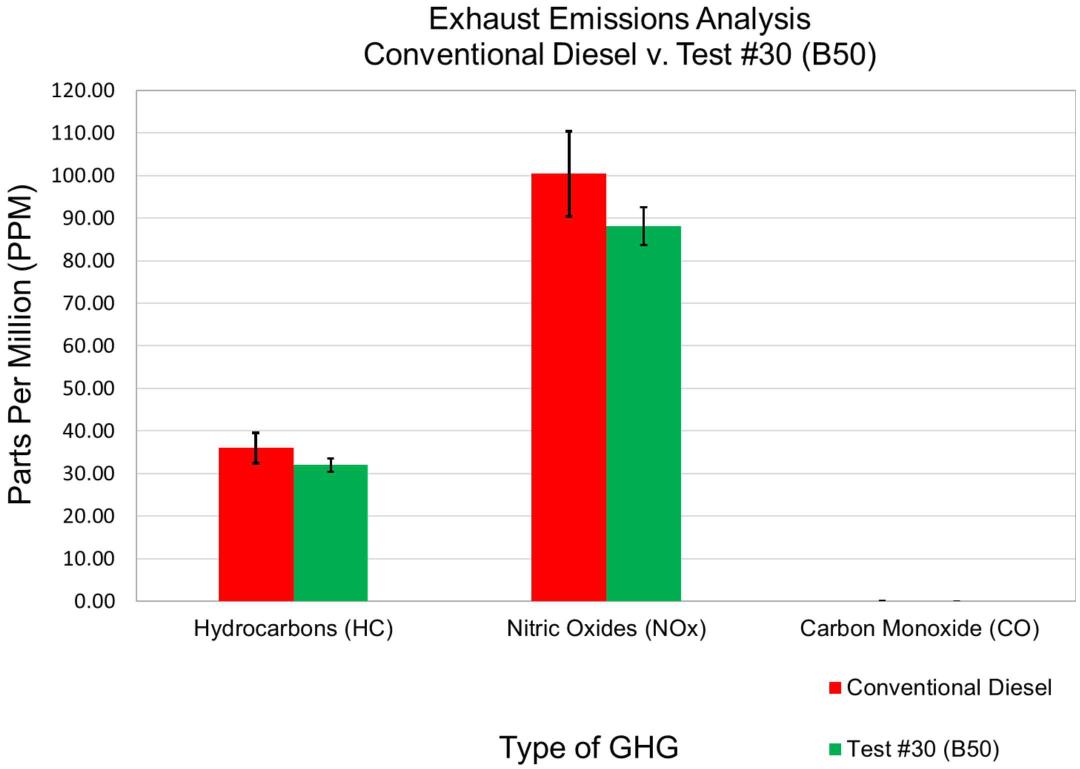


Figure 4-20. Exhaust Emissions Analysis in PPM (HC, NOx, CO) Conventional Diesel v. Test #30 Biodiesel.

4.6 TEST #65 - Cottonseed Oil Biodiesel (B50)

The composition of Test #65 (code name) biodiesel is 50% cottonseed oil as a renewable source and the remainder is conventional diesel fuel and the proprietary additives. Figure 4.21 shows Test #65 in a glass beaker quickly after the formulation process and right before being poured in the engine fuel tank for dynamometer testing.

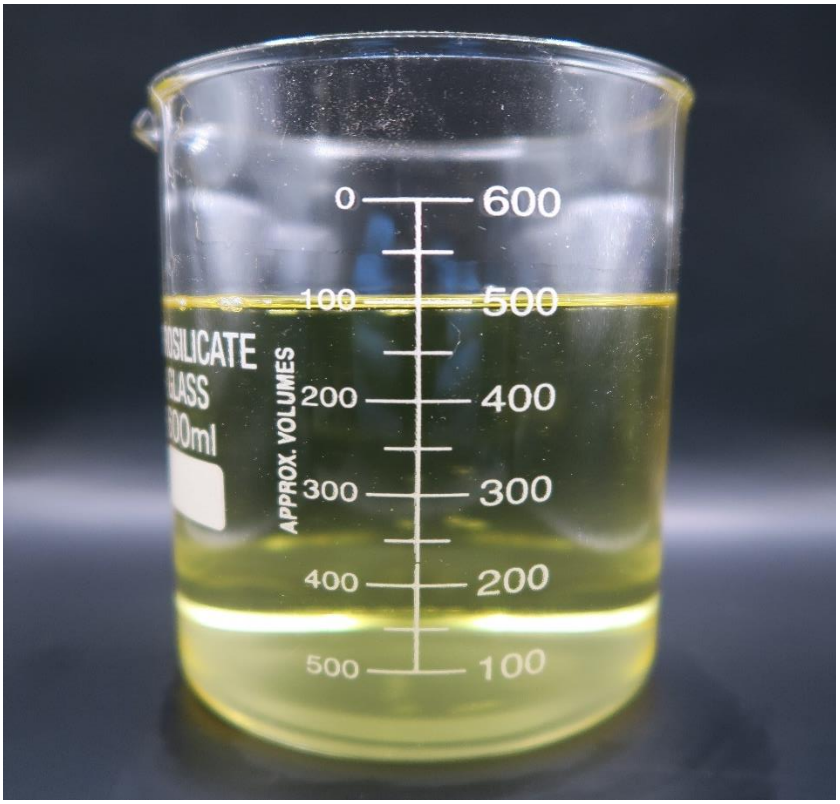
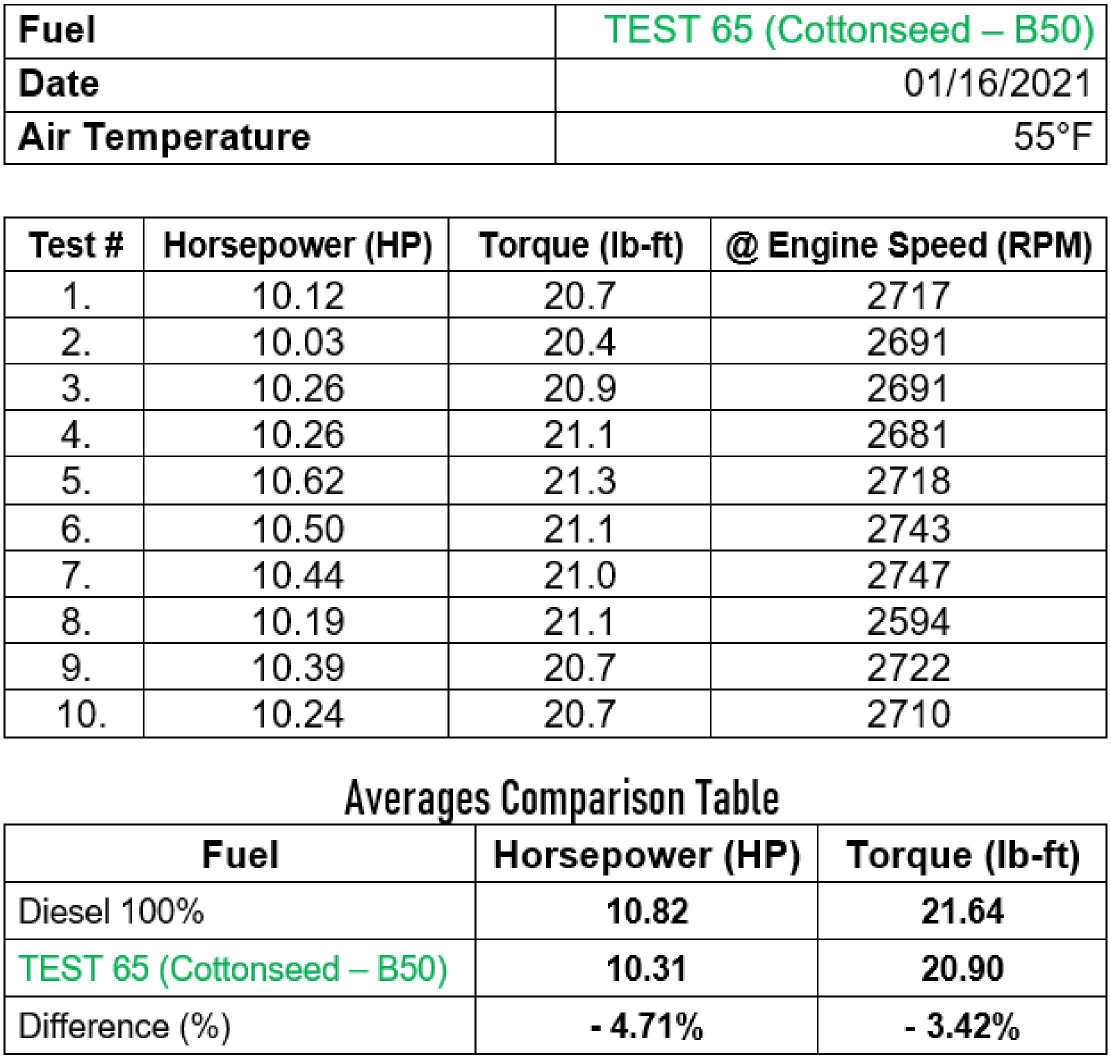


Figure 4-21. Biodiesel Test #65 containing 50% Cottonseed Oil.

4.6.1 Engine Dynamometer Testing

The engine was dyno tested 10 times while running on Test #65 biodiesel fuel. Furthermore, after running the dynamometer 10 times the horsepower (HP) and torque data were averaged to determine the standard deviation in comparison to conventional diesel fuel. Table 4.9 gives the data collected from the dynamometer tests. The averages table shows a slight decrease of 4.71% for HP and about 3.42% for torque outputs.

Table 4-9. TEST #65 BIODIESEL DYNAMOMEMTER TEST RUNS AND AVERAGES COMPARED TO CONV NENTIONAL DIESEL.



Fuel	TEST 65 (Cottonseed – B50)
Date	01/16/2021
Air Temperature	55°F

Test #	Horsepower (HP)	Torque (lb-ft)	@ Engine Speed (RPM)
1.	10.12	20.7	2717
2.	10.03	20.4	2691
3.	10.26	20.9	2691
4.	10.26	21.1	2681
5.	10.62	21.3	2718
6.	10.50	21.1	2743
7.	10.44	21.0	2747
8.	10.19	21.1	2594
9.	10.39	20.7	2722
10.	10.24	20.7	2710

Averages Comparison Table

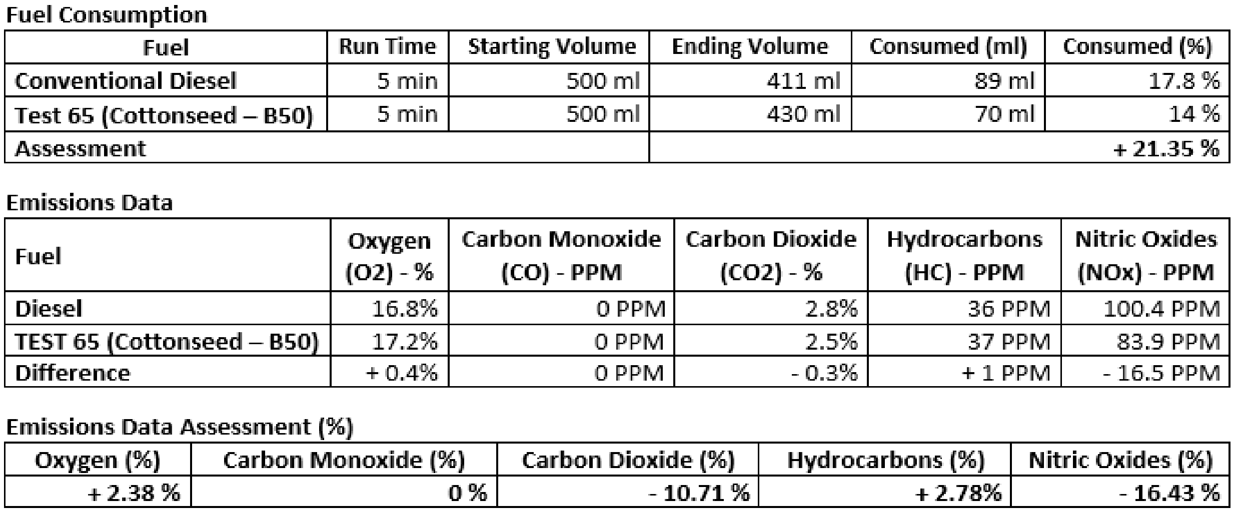
Fuel	Horsepower (HP)	Torque (lb-ft)
Diesel 100%	**10.82**	**21.64**
TEST 65 (Cottonseed – B50)	**10.31**	**20.90**
Difference (%)	**- 4.71%**	**- 3.42%**

4.6.2 Emissions and Fuel Consumption Testing

A total amount of 500ml of Test #65 biodiesel is formulated for emissions and fuel consumption testing. The engine ran at a constant speed for a total of 5 minutes. While the engine was running the exhaust gases are again monitored and measured using the Enerac700 5-gas analyzer. After 5 minutes of engine operation the fuel the remainder of the fuel in the tank is measured to determine total fuel consumption. Table 4.10 shows the emissions and fuel consumption data relative to conventional diesel fuel. With 50% of conventional diesel

eliminated per volume, Test #65 displayed compelling data with significant reduction in CO_2, HC, and NOx emissions, while improving fuel economy by over 21%.

Table 4-10. TEST #65 BIODIESEL (B50) EMISSIONS AND FUEL CONSUMPTION DATA



Fuel Consumption

Fuel	Run Time	Starting Volume	Ending Volume	Consumed (ml)	Consumed (%)
Conventional Diesel	5 min	500 ml	411 ml	89 ml	17.8 %
Test 65 (Cottonseed – B50)	5 min	500 ml	430 ml	70 ml	14 %
Assessment			+ 21.35 %		

Emissions Data

Fuel	Oxygen (O2) - %	Carbon Monoxide (CO) - PPM	Carbon Dioxide (CO2) - %	Hydrocarbons (HC) - PPM	Nitric Oxides (NOx) - PPM
Diesel	16.8%	0 PPM	2.8%	36 PPM	100.4 PPM
TEST 65 (Cottonseed – B50)	17.2%	0 PPM	2.5%	37 PPM	83.9 PPM
Difference	+ 0.4%	0 PPM	- 0.3%	+ 1 PPM	- 16.5 PPM

Emissions Data Assessment (%)

Oxygen (%)	Carbon Monoxide (%)	Carbon Dioxide (%)	Hydrocarbons (%)	Nitric Oxides (%)
+ 2.38 %	0 %	- 10.71 %	+ 2.78%	- 16.43 %

The graphs shown below evaluate the test results of conventional diesel v. Test #65 biodiesel. Figure 4.22 shows the test results from the fuel consumption test for conventional diesel fuel and Test #65 biodiesel. The red bar (conventional diesel) represents a total fuel consumption of 17.8% consumed from the starting fuel volume of 500ml. On the right side of the graph, the green bar (Test #65 biodiesel) represents a total fuel consumption of 14% consumed from the starting volume of 500ml. In comparison, the Test #65 biodiesel improved fuel economy by 21.35%.

Figure 4.23 analyzes the exhaust emissions in percentage produced for conventional diesel and Test #65 biodiesel. The oxygen produced from the exhaust gases when operating the Test #65 biodiesel fuel was 2.38% higher than conventional diesel. On the right-hand side of the graph the CO_2 that was produced from the exhaust gases are compared. It is evident that conventional diesel produced 12% more CO_2 than Test #65 biodiesel during testing.

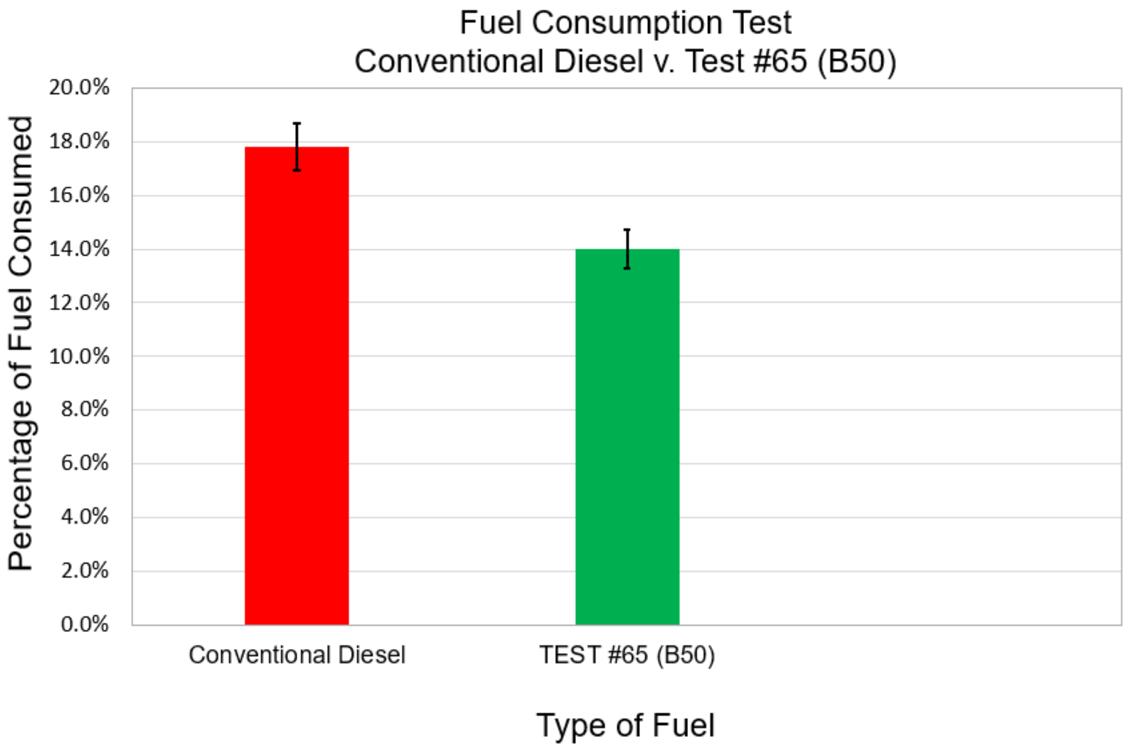


Figure 4-22. Fuel Consumption Test – Conventional Diesel v. Test #65 Biodiesel.

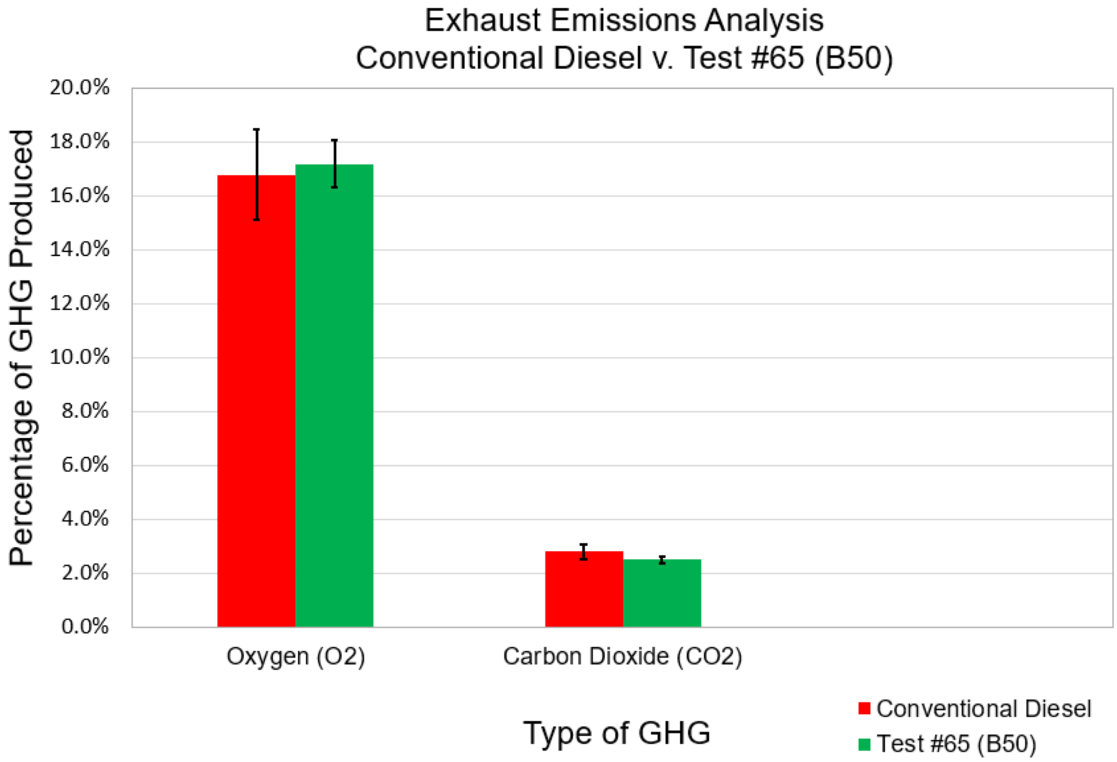


Figure 4-23. Exhaust Emissions Analysis in % (O_2 & CO_2) – Conventional Diesel v. Test #65 Biodiesel.

The last graph below in Figure 4.24, compares the exhaust emissions data for the remaining gases measured in parts per million (PPM). The far-left side of the graph represents the amount of HC produced from the tested fuels. The HC that was produced from the Test #65 biodiesel was 37 PPM which is a reduction of 1 PPM or 2.78% from conventional diesel. Due to reduced combustion temperatures while utilizing Test #65 biodiesel a drop in NOx emission was recorded. The NOx emission produced from Test #65 biodiesel was 83.9 PPM which is 16.5 PPM or 16.43% lower than that produced from conventional diesel. The right side of the graph shows the production of CO emissions which is zero because of complete combustion reactions and sufficient amount of oxygen.

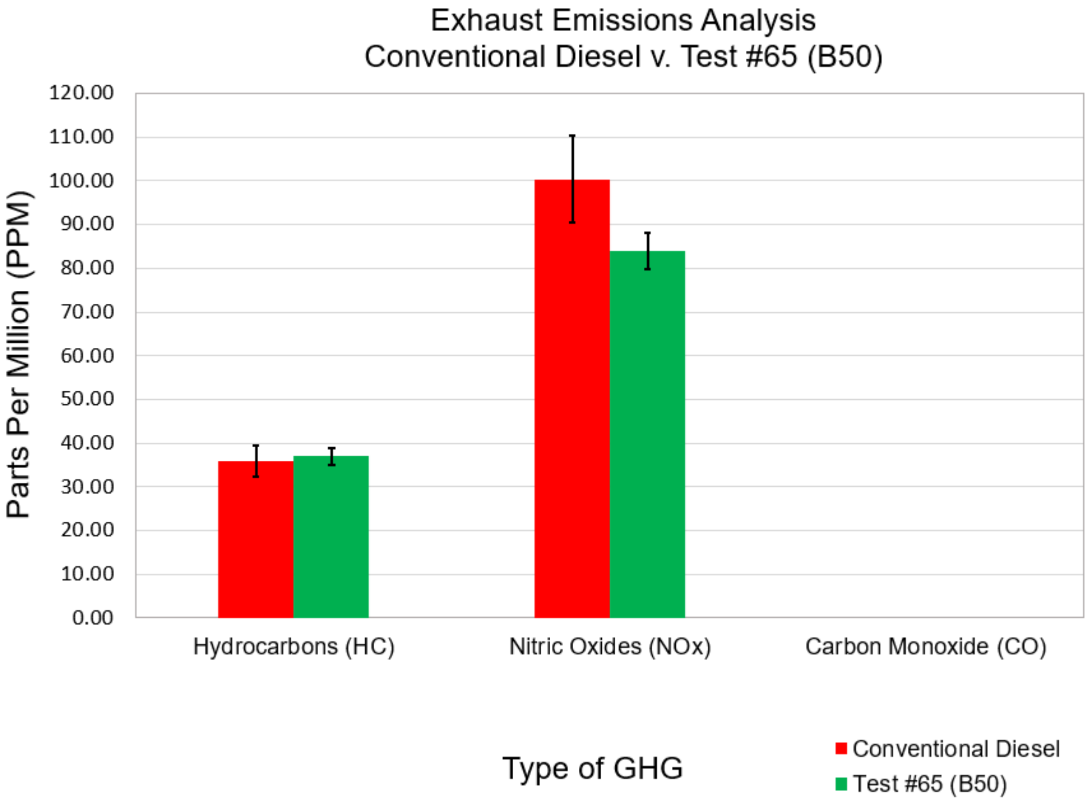


Figure 4-24. Exhaust Emissions Analysis in PPM (HC, NOx, CO) Conventional Diesel v. Test #65 Biodiesel.

4.7 TEST #68 – Canola Oil Biodiesel (B50)

The composition of Test #68 (code name) biodiesel is 50% canola oil as a renewable source and the remainder is conventional diesel fuel and the proprietary additives. Figure 4.25 shows Test #68 in a glass beaker quickly after the formulation process and right before being poured in the engine fuel tank for dynamometer testing.

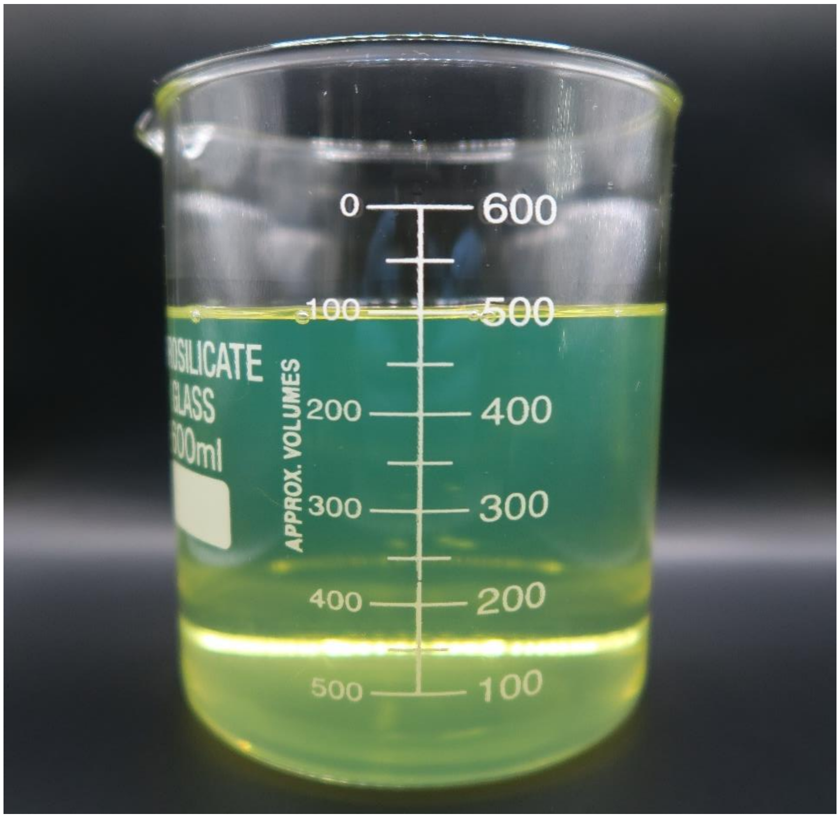
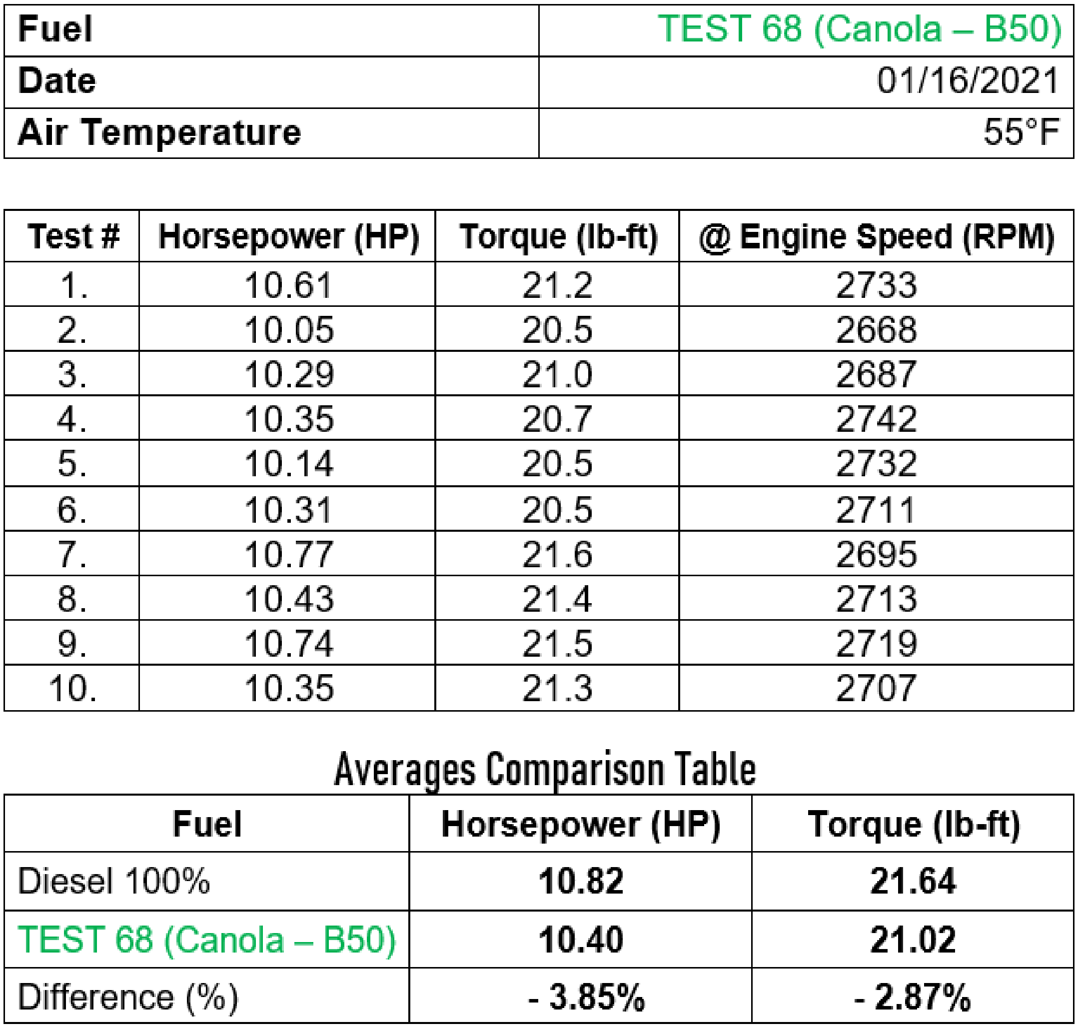


Figure 4-25. Biodiesel Test #68 containing 50% Canola Oil.

4.7.1 Engine Dynamometer Testing

The engine was dyno tested 10 times while running on Test #68 biodiesel fuel. Furthermore, after running the dynamometer 10 times the horsepower (HP) and torque data were averaged to determine the standard deviation in comparison to conventional diesel fuel. Table 4.11 gives the data collected from the dynamometer tests. The averages table shows a decrease of 3.85% for HP and about 2.87% for torque outputs.

Table 4-11. TEST #68 BIODIESEL DYNAMOMEMTER TEST RUNS AND AVERAGES COMPARED TO CONVNENTIONAL DIESEL.



Fuel	TEST 68 (Canola – B50)
Date	01/16/2021
Air Temperature	55°F

Test #	Horsepower (HP)	Torque (lb-ft)	@ Engine Speed (RPM)
1.	10.61	21.2	2733
2.	10.05	20.5	2668
3.	10.29	21.0	2687
4.	10.35	20.7	2742
5.	10.14	20.5	2732
6.	10.31	20.5	2711
7.	10.77	21.6	2695
8.	10.43	21.4	2713
9.	10.74	21.5	2719
10.	10.35	21.3	2707

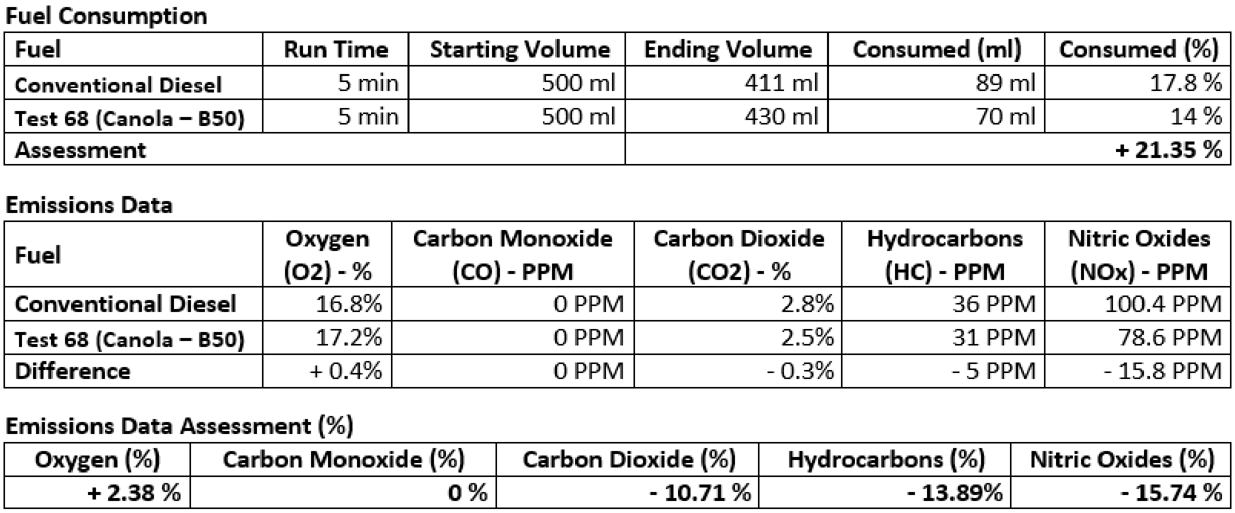
Averages Comparison Table

Fuel	Horsepower (HP)	Torque (lb-ft)
Diesel 100%	**10.82**	**21.64**
TEST 68 (Canola – B50)	**10.40**	**21.02**
Difference (%)	**- 3.85%**	**- 2.87%**

4.7.2 Emissions and Fuel Consumption Testing

A total amount of 500ml of Test #68 biodiesel is formulated for emissions and fuel consumption testing. The engine ran at a constant speed for a total of 5 minutes. While the engine was running the exhaust gases are again monitored and measured using the Enerac700 5-gas analyzer. After 5 minutes of engine operation the fuel the remainder of the fuel in the tank is measured to determine total fuel consumption. Table 4.12 shows the emissions and fuel consumption data relative to conventional diesel fuel. With 50% of conventional diesel eliminated per volume, Test #68 displayed compelling data with significant reduction in CO_2, HC, and NOx emissions, while improving fuel economy by over 21%.

Table 4-12. TEST #68 BIODIESEL (B50) EMISSIONS AND FUEL CONSUMPTION DATA



Fuel Consumption

Fuel	Run Time	Starting Volume	Ending Volume	Consumed (ml)	Consumed (%)
Conventional Diesel	5 min	500 ml	411 ml	89 ml	17.8 %
Test 68 (Canola – B50)	5 min	500 ml	430 ml	70 ml	14 %
Assessment			**+ 21.35 %**		

Emissions Data

Fuel	Oxygen (O2) - %	Carbon Monoxide (CO) - PPM	Carbon Dioxide (CO2) - %	Hydrocarbons (HC) - PPM	Nitric Oxides (NOx) - PPM
Conventional Diesel	16.8%	0 PPM	2.8%	36 PPM	100.4 PPM
Test 68 (Canola – B50)	17.2%	0 PPM	2.5%	31 PPM	78.6 PPM
Difference	+ 0.4%	0 PPM	- 0.3%	- 5 PPM	- 15.8 PPM

Emissions Data Assessment (%)

Oxygen (%)	Carbon Monoxide (%)	Carbon Dioxide (%)	Hydrocarbons (%)	Nitric Oxides (%)
+ 2.38 %	**0 %**	**- 10.71 %**	**- 13.89%**	**- 15.74 %**

The graphs shown below evaluate the test results of conventional diesel v. Test #68 biodiesel. Figure 4.26 shows the test results from the fuel consumption test for conventional diesel fuel and Test #68 biodiesel. The red bar (conventional diesel) represents a total fuel consumption of 17.8% consumed from the starting fuel volume of 500ml. On the right side of the graph, the green bar (Test #68 biodiesel) represents a total fuel consumption of 14% consumed from the starting volume of 500ml. In comparison, the Test #68 biodiesel improved fuel economy by 21.35%.

Figure 4.27 analyzes the exhaust emissions in percentage produced for conventional diesel and Test #68 biodiesel. The oxygen produced from the exhaust gases when operating the Test #68 biodiesel fuel was 2.38% higher than conventional diesel. On the right-hand side of the graph the CO_2 that was produced from the exhaust gases are compared. It is evident that conventional diesel produced 12% more CO_2 than Test #68 biodiesel during testing.

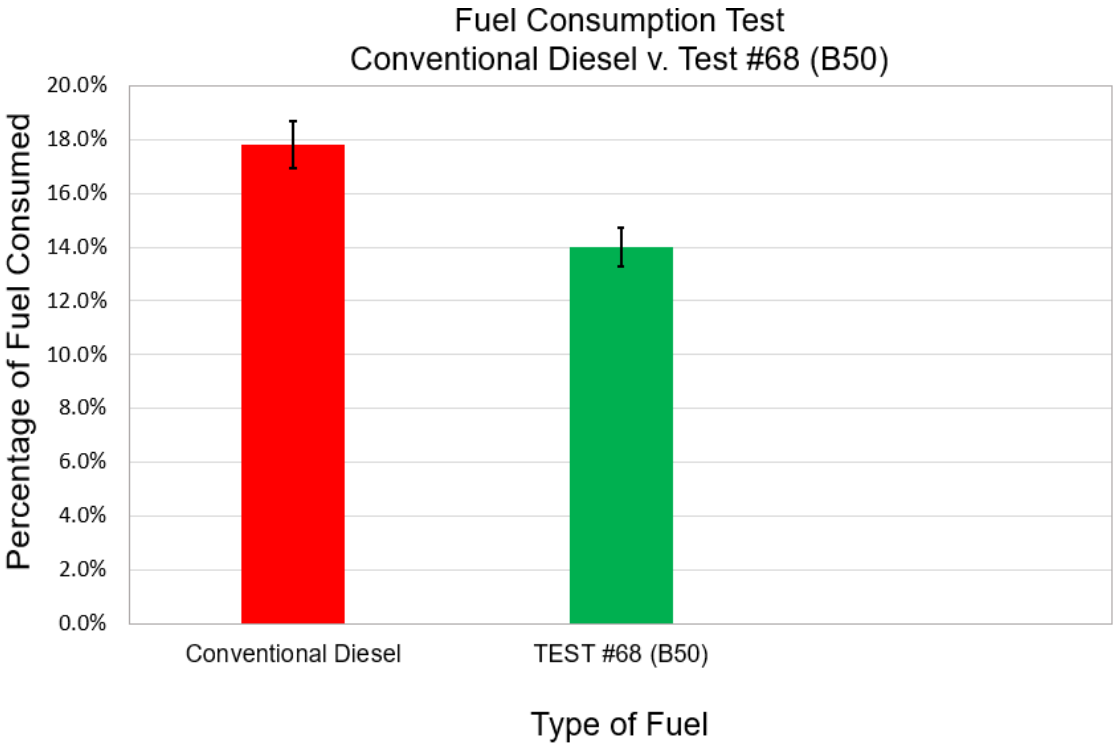


Figure 4-26. Fuel Consumption Test – Conventional Diesel v. Test #68 Biodiesel.

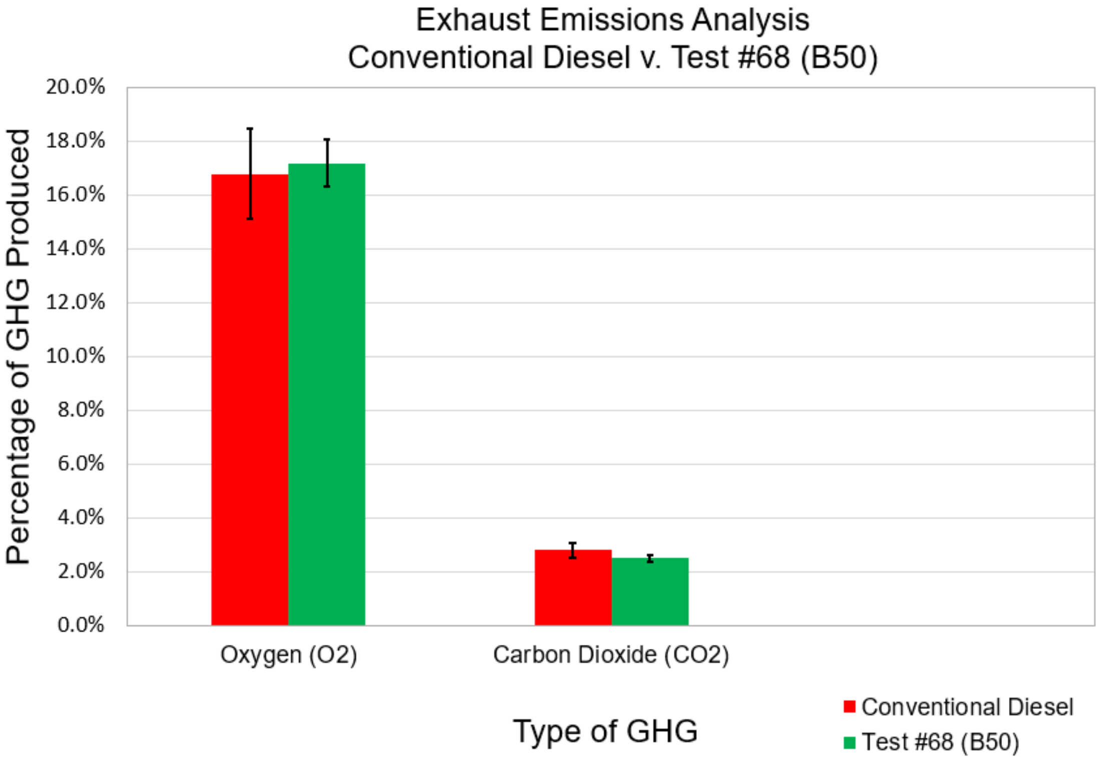


Figure 4-27. Exhaust Emissions Analysis in % (O_2 & CO_2) – Conventional Diesel v. Test #68 Biodiesel.

The last graph below in Figure 4.28, compares the exhaust emissions data for the remaining gases measured in parts per million (PPM). The far-left side of the graph represents the amount of HC produced from the tested fuels. The HC that was produced from Test #68 biodiesel was 31 PPM which is a reduction of 5 PPM or 13.89% from conventional diesel. Due to reduced combustion temperatures while utilizing Test #68 biodiesel a drop in NOx emission was recorded. The NOx emission produced from Test #68 biodiesel was 78.6 PPM which is 15.8 PPM or 15.74% lower than that produced from conventional diesel. The right side of the graph shows the production of CO emissions which is zero as a result of complete combustion reactions and sufficient amount of oxygen.

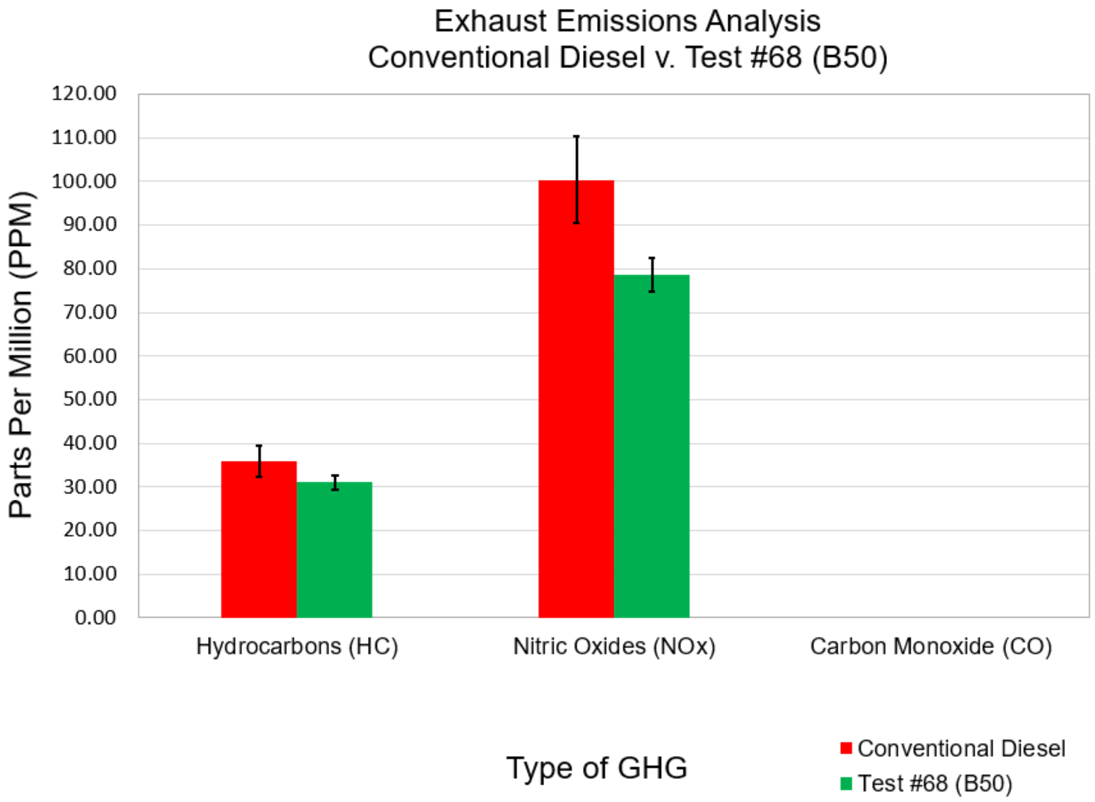


Figure 4-28. Exhaust Emissions Analysis in PPM (HC, NOx, CO) Conventional Diesel v. Test #68 Biodiesel.

4.8 TEST #69 - Peanut Oil Biodiesel (B50)

The composition of Test #69 (code name) biodiesel is 50% peanut oil as a renewable source and the remainder is conventional diesel fuel and the proprietary additives. Figure 4.29 shows Test #69 in a glass beaker quickly after the formulation process and right before being poured in the engine fuel tank for dynamometer testing.

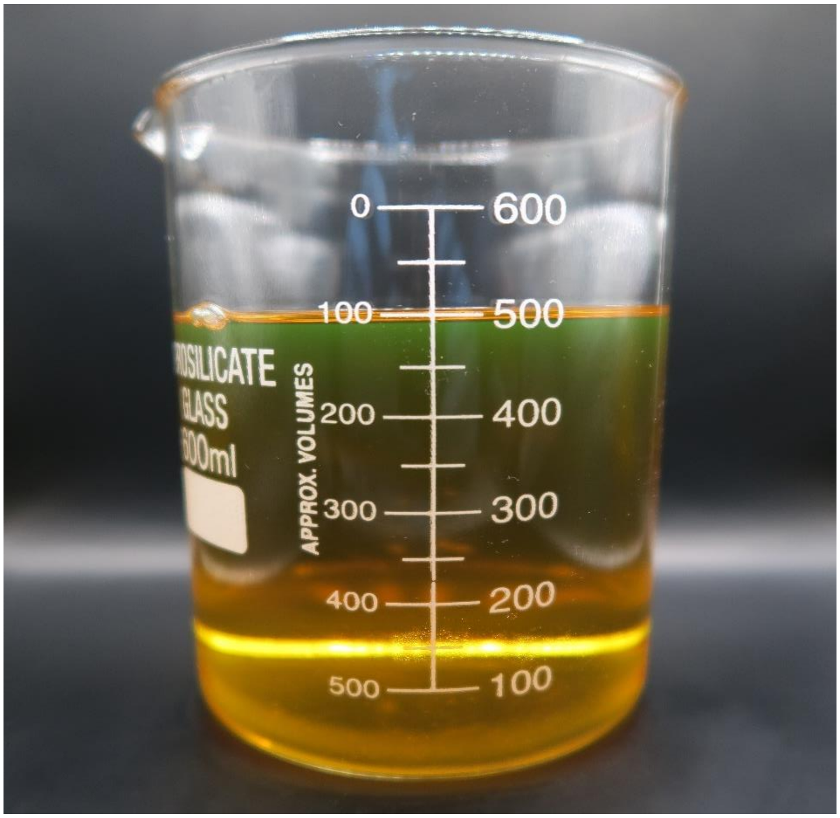
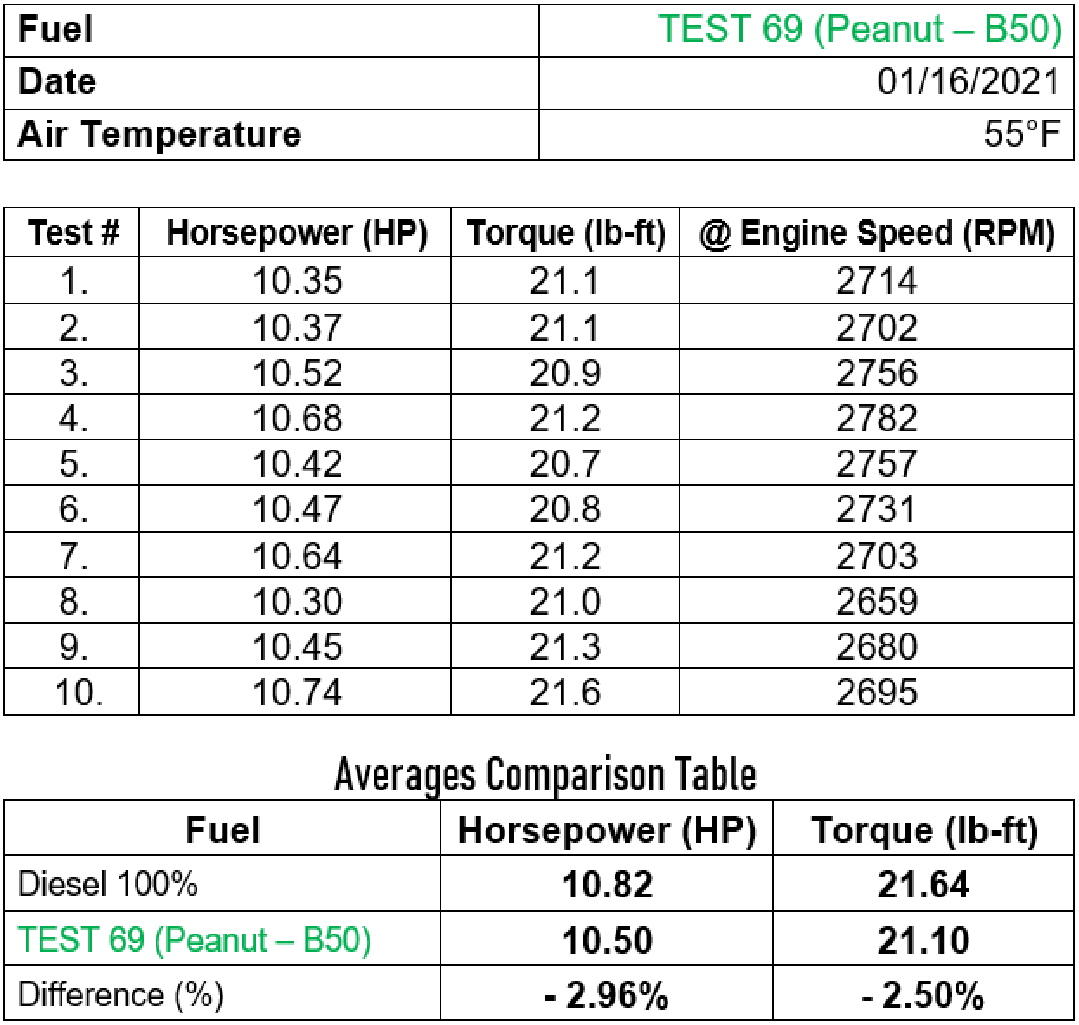


Figure 4-29. Biodiesel Test #69 containing 50% Peanut Oil.

4.8.1 Engine Dynamometer Testing

The engine was dyno tested 10 times while running on Test #69 biodiesel fuel. Furthermore, after running the dynamometer 10 times the horsepower (HP) and torque data were averaged to determine the standard deviation in comparison to conventional diesel fuel. Table 4.13 gives the data collected from the dynamometer tests. The averages table shows a decrease of nearly 3% for HP and 2.5% for torque outputs.

Table 4-13. TEST #69 BIODIESEL DYNAMOMEMTER TEST RUNS AND AVERAGES COMPARED TO CONV NENTIONAL DIESEL.



Fuel	TEST 69 (Peanut – B50)
Date	01/16/2021
Air Temperature	55°F

Test #	Horsepower (HP)	Torque (lb-ft)	@ Engine Speed (RPM)
1.	10.35	21.1	2714
2.	10.37	21.1	2702
3.	10.52	20.9	2756
4.	10.68	21.2	2782
5.	10.42	20.7	2757
6.	10.47	20.8	2731
7.	10.64	21.2	2703
8.	10.30	21.0	2659
9.	10.45	21.3	2680
10.	10.74	21.6	2695

Averages Comparison Table

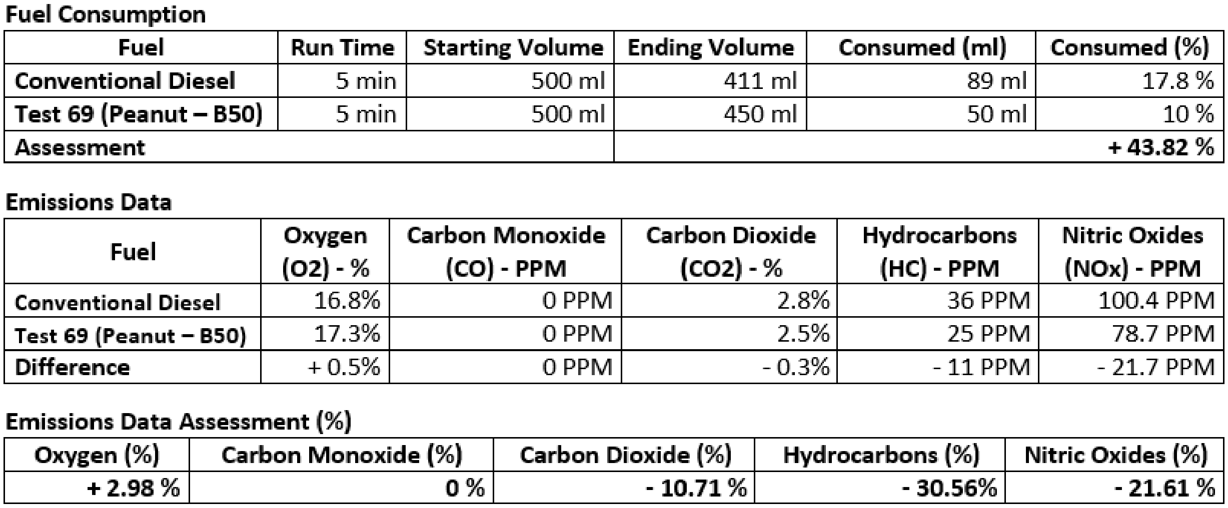
Fuel	Horsepower (HP)	Torque (lb-ft)
Diesel 100%	**10.82**	**21.64**
TEST 69 (Peanut – B50)	**10.50**	**21.10**
Difference (%)	**- 2.96%**	**- 2.50%**

4.8.2 Emissions and Fuel Consumption Testing

A total amount of 500ml of Test #69 biodiesel is formulated for emissions and fuel consumption testing. The engine ran at a constant speed for a total of 5 minutes. While the engine was running the exhaust gases are again monitored and measured using the Enerac700 5-gas analyzer. After 5 minutes of engine operation the fuel the remainder of the fuel in the tank is measured to determine total fuel consumption. Table 4.14 shows the emissions and fuel consumption data relative to conventional diesel fuel. With 50% of conventional diesel

eliminated per volume, Test #69 displayed compelling data with significant reduction in CO_2, HC, and NOx emissions, while improving fuel economy by nearly 49%.

Table 4-14. TEST #69 BIODIESEL (B50) EMISSIONS AND FUEL CONSUMPTION DATA



Fuel Consumption

Fuel	Run Time	Starting Volume	Ending Volume	Consumed (ml)	Consumed (%)
Conventional Diesel	5 min	500 ml	411 ml	89 ml	17.8 %
Test 69 (Peanut – B50)	5 min	500 ml	450 ml	50 ml	10 %
Assessment			**+ 43.82 %**		

Emissions Data

Fuel	Oxygen (O2) - %	Carbon Monoxide (CO) - PPM	Carbon Dioxide (CO2) - %	Hydrocarbons (HC) - PPM	Nitric Oxides (NOx) - PPM
Conventional Diesel	16.8%	0 PPM	2.8%	36 PPM	100.4 PPM
Test 69 (Peanut – B50)	17.3%	0 PPM	2.5%	25 PPM	78.7 PPM
Difference	+ 0.5%	0 PPM	- 0.3%	- 11 PPM	- 21.7 PPM

Emissions Data Assessment (%)

Oxygen (%)	Carbon Monoxide (%)	Carbon Dioxide (%)	Hydrocarbons (%)	Nitric Oxides (%)
+ 2.98 %	**0 %**	**- 10.71 %**	**- 30.56%**	**- 21.61 %**

The graphs shown below evaluate the test results of conventional diesel v. Test #69 biodiesel. Figure 4.30 shows the test results from the fuel consumption test for conventional diesel fuel and Test #69 biodiesel. The red bar (conventional diesel) represents a total fuel consumption of 17.8% consumed from the starting fuel volume of 500ml. On the right side of the graph, the green bar (Test #69 biodiesel) represents a total fuel consumption of 10% consumed from the starting volume of 500ml. In comparison, Test #69 biodiesel improved fuel economy by 43.82%.

Figure 4.31 analyzes the exhaust emissions in percentage produced for conventional diesel and Test #69 biodiesel. The oxygen produced from the exhaust gases when operating the Test #69 biodiesel fuel was 2.98% higher than conventional diesel. On the right-hand side of the graph the CO_2 that was produced from the exhaust gases are compared. It is evident that conventional diesel produced 12% more CO_2 than Test #69 biodiesel during testing.

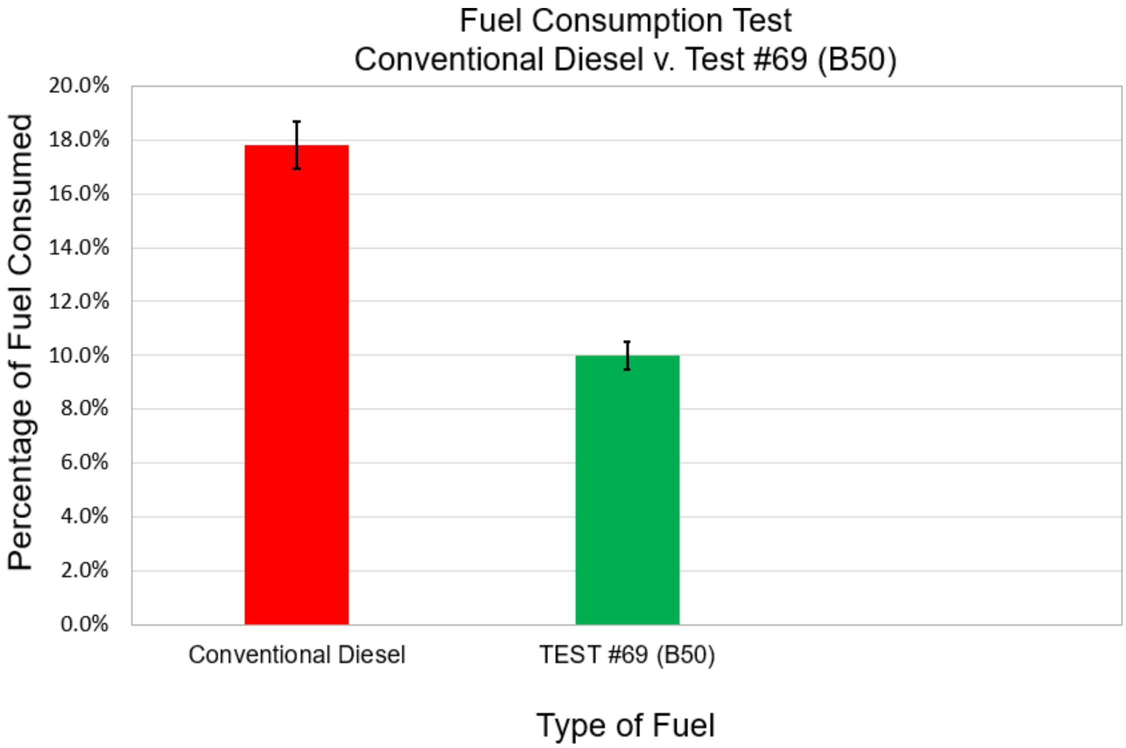


Figure 4-30. Fuel Consumption Test – Conventional Diesel v. Test #69 Biodiesel.

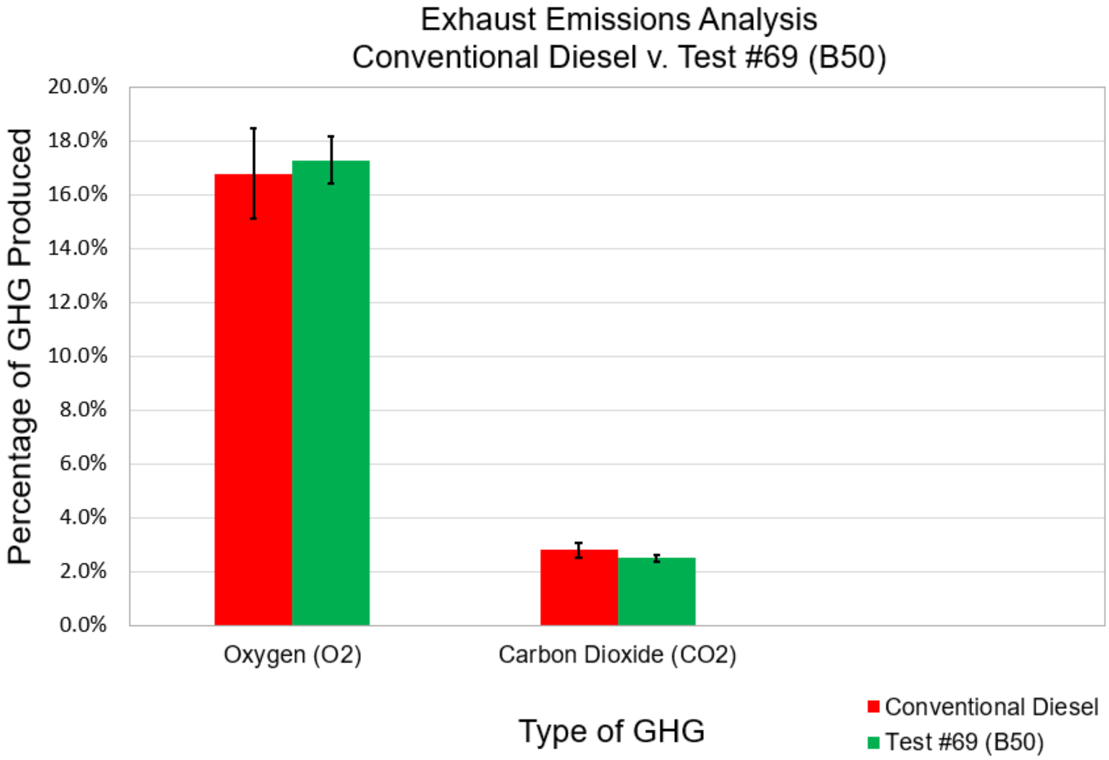


Figure 4-31. Exhaust Emissions Analysis in % (O_2 & CO_2) – Conventional Diesel v. Test #69 Biodiesel.

The last graph below in Figure 4.32, compares the exhaust emissions data for the remaining gases measured in parts per million (PPM). The far-left side of the graph represents the amount of HC produced from the tested fuels. The HC that was produced from the Test #30 biodiesel was 25 PPM which is a reduction of 11 PPM or 30.56% from conventional diesel. Due to reduced combustion temperatures while utilizing Test #69 biodiesel a drop in NOx emission was recorded. The NOx emission produced from Test #69 biodiesel was 78.7 PPM which is 21.7 PPM or 21.61% lower than that produced from conventional diesel. The right side of the graph shows the production of CO emissions which is zero as a result of complete combustion reactions and sufficient amount of oxygen.

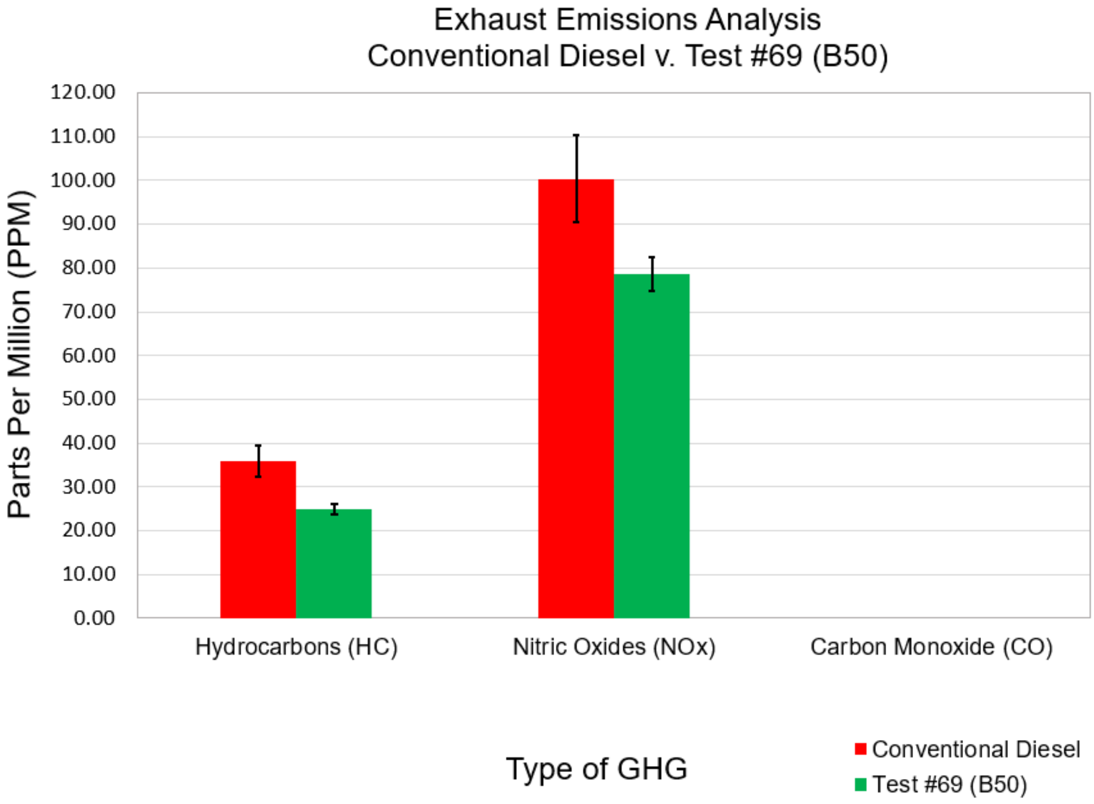


Figure 4-32. Exhaust Emissions Analysis in PPM (HC, NOx, CO) Conventional Diesel v. Test #69 Biodiesel.

4.9 TEST #70 - Safflower Oil Biodiesel (B50)

The composition of Test #70 (code name) biodiesel is 50% safflower oil as a renewable source and the remainder is conventional diesel fuel and the proprietary additives. Figure 4.33 shows Test #70 in a glass beaker quickly after the formulation process and right before being poured in the engine fuel tank for dynamometer testing.

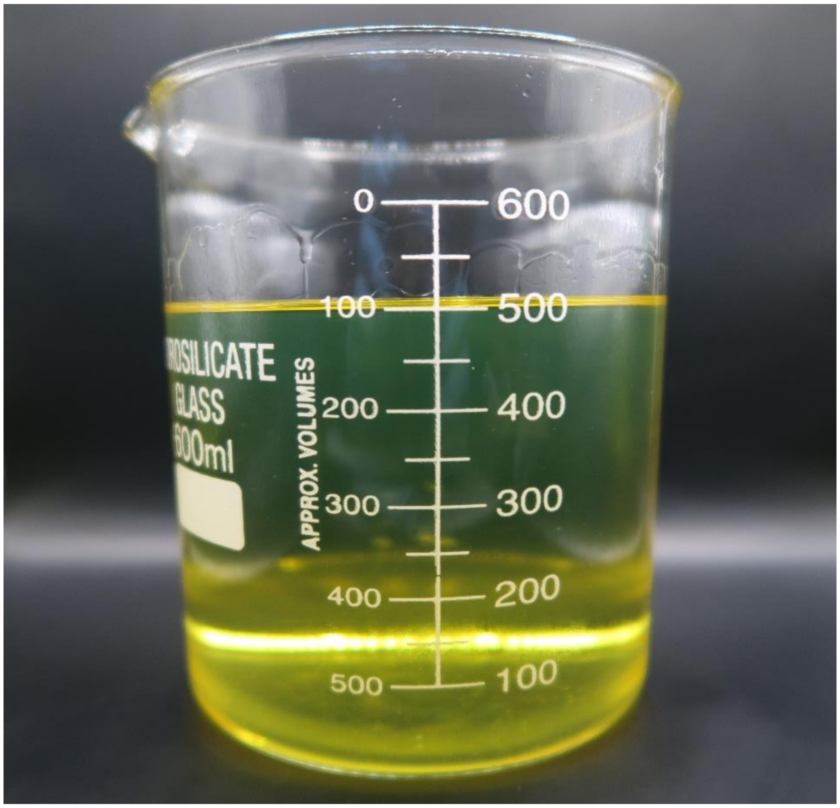
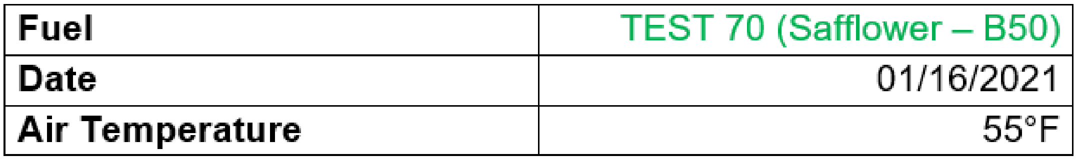


Figure 4-33. Biodiesel Test #70 containing 50% Safflower Oil.

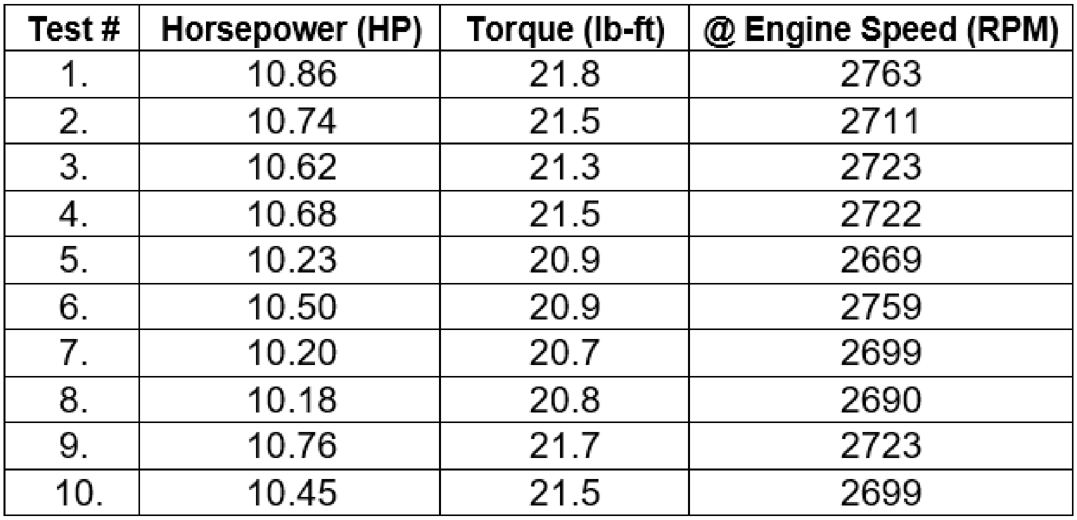
4.9.1 Engine Dynamometer Testing

The engine was dyno tested 10 times while running on Test #70 biodiesel fuel. Furthermore, after running the dynamometer 10 times the horsepower (HP) and torque data were averaged to determine the standard deviation in comparison to conventional diesel fuel. Table 4.15 gives the data collected from the dynamometer tests. The averages table shows a decrease of 2.77% for HP and 1.76% for torque outputs.

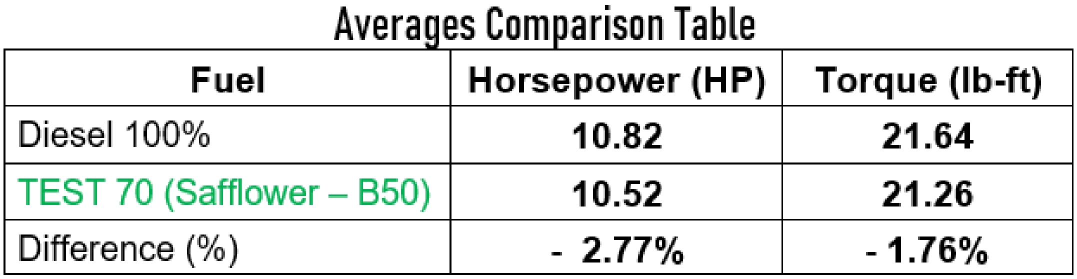
Table 4-15. TEST #70 BIODIESEL DYNAMOMEMTER TEST RUNS AND AVERAGES COMPARED TO CONV NENTIONAL DIESEL.



Fuel	TEST 70 (Safflower – B50)
Date	01/16/2021
Air Temperature	55°F



Test #	Horsepower (HP)	Torque (lb-ft)	@ Engine Speed (RPM)
1.	10.86	21.8	2763
2.	10.74	21.5	2711
3.	10.62	21.3	2723
4.	10.68	21.5	2722
5.	10.23	20.9	2669
6.	10.50	20.9	2759
7.	10.20	20.7	2699
8.	10.18	20.8	2690
9.	10.76	21.7	2723
10.	10.45	21.5	2699



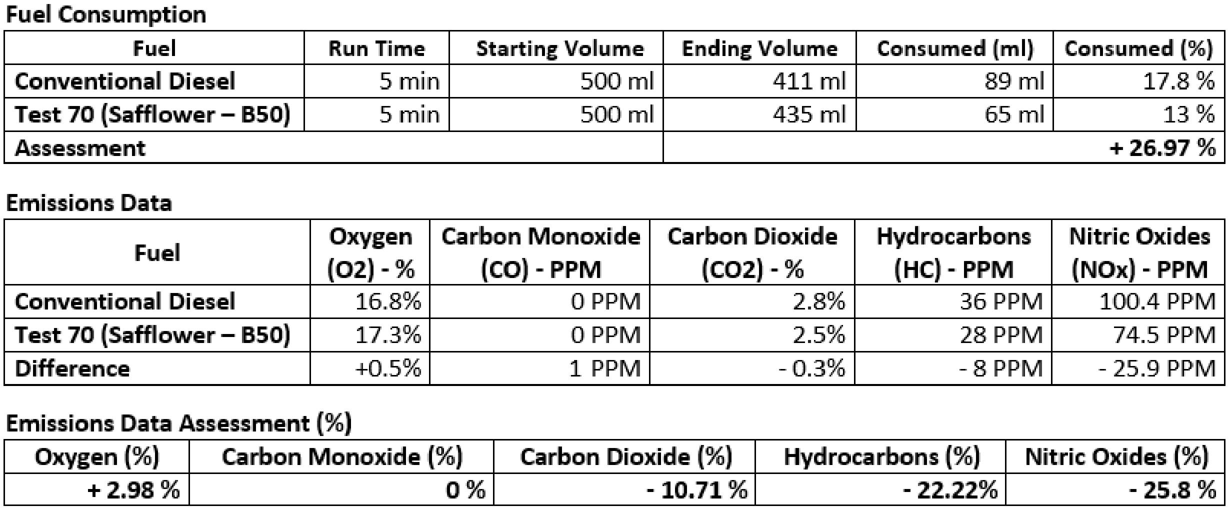
Averages Comparison Table

Fuel	Horsepower (HP)	Torque (lb-ft)
Diesel 100%	**10.82**	**21.64**
TEST 70 (Safflower – B50)	**10.52**	**21.26**
Difference (%)	**- 2.77%**	**- 1.76%**

4.9.2 Emissions and Fuel Consumption Testing

A total amount of 500ml of Test #70 biodiesel is formulated for emissions and fuel consumption testing. The engine ran at a constant speed for a total of 5 minutes. While the engine was running the exhaust gases are again monitored and measured using the Enerac700 5-gas analyzer. After 5 minutes of engine operation the fuel the remainder of the fuel in the tank is measured to determine total fuel consumption. Table 4.16 shows the emissions and fuel consumption data relative to conventional diesel fuel. With 50% of conventional diesel eliminated per volume, Test #70 displayed compelling data with significant reduction in CO_2, HC, and NOx emissions, while improving fuel economy by nearly 27%.

Table 4-16. TEST #70 BIODIESEL (B50) EMISSIONS AND FUEL CONSUMPTION DATA



Fuel Consumption

Fuel	Run Time	Starting Volume	Ending Volume	Consumed (ml)	Consumed (%)
Conventional Diesel	5 min	500 ml	411 ml	89 ml	17.8 %
Test 70 (Safflower – B50)	5 min	500 ml	435 ml	65 ml	13 %
Assessment			**+ 26.97 %**		

Emissions Data

Fuel	Oxygen (O2) - %	Carbon Monoxide (CO) - PPM	Carbon Dioxide (CO2) - %	Hydrocarbons (HC) - PPM	Nitric Oxides (NOx) - PPM
Conventional Diesel	16.8%	0 PPM	2.8%	36 PPM	100.4 PPM
Test 70 (Safflower – B50)	17.3%	0 PPM	2.5%	28 PPM	74.5 PPM
Difference	+0.5%	1 PPM	- 0.3%	- 8 PPM	- 25.9 PPM

Emissions Data Assessment (%)

Oxygen (%)	Carbon Monoxide (%)	Carbon Dioxide (%)	Hydrocarbons (%)	Nitric Oxides (%)
+ 2.98 %	**0 %**	**- 10.71 %**	**- 22.22%**	**- 25.8 %**

The graphs shown below evaluate the test results of conventional diesel v. Test #70 biodiesel. Figure 4.34 shows the test results from the fuel consumption test for conventional diesel fuel and Test #70 biodiesel. The red bar (conventional diesel) represents a total fuel consumption of 17.8% consumed from the starting fuel volume of 500ml. On the right side of the graph, the green bar (Test #70 biodiesel) represents a total fuel consumption of 13% consumed from the starting volume of 500ml. In comparison, Test #70 biodiesel improved fuel economy by 26.97%.

Figure 4.35 analyzes the exhaust emissions in percentage produced for conventional diesel and Test #70 biodiesel. The oxygen produced from the exhaust gases when operating the Test #70 biodiesel fuel was 2.98% higher than conventional diesel. On the right-hand side of the graph the CO_2 that was produced from the exhaust gases are compared. It is evident that conventional diesel produced 12% more CO_2 than Test #70 biodiesel during testing.

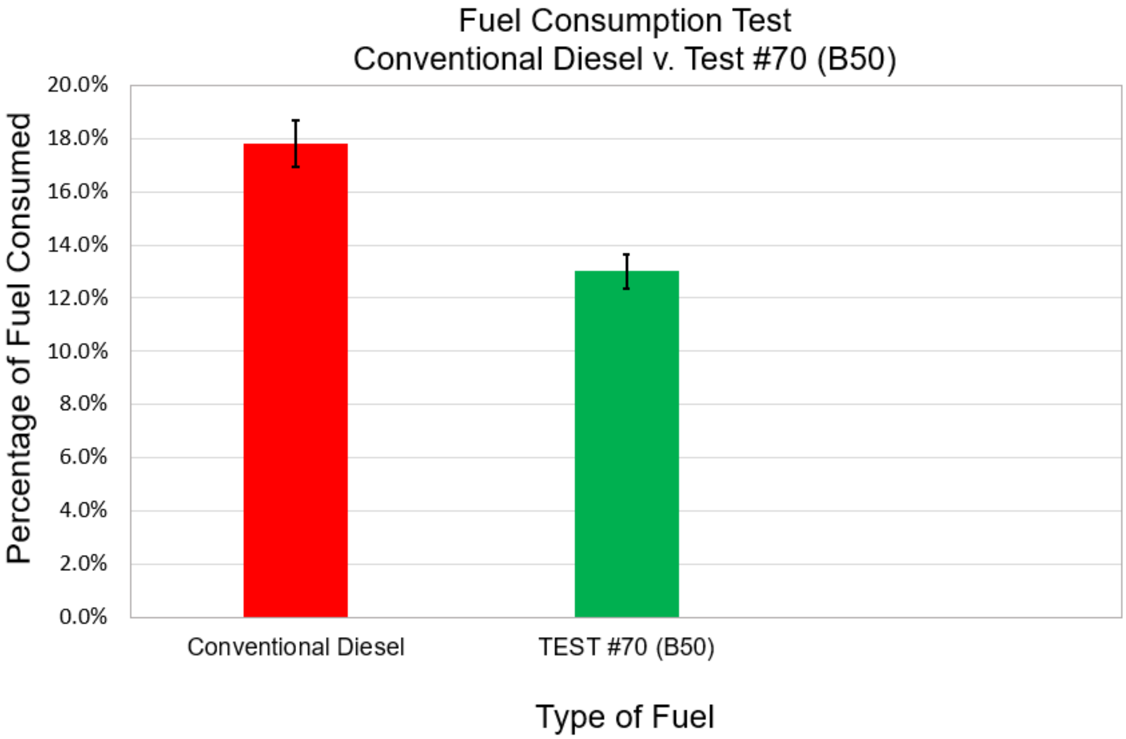


Figure 4-34. Fuel Consumption Test – Conventional Diesel v. Test #70 Biodiesel.

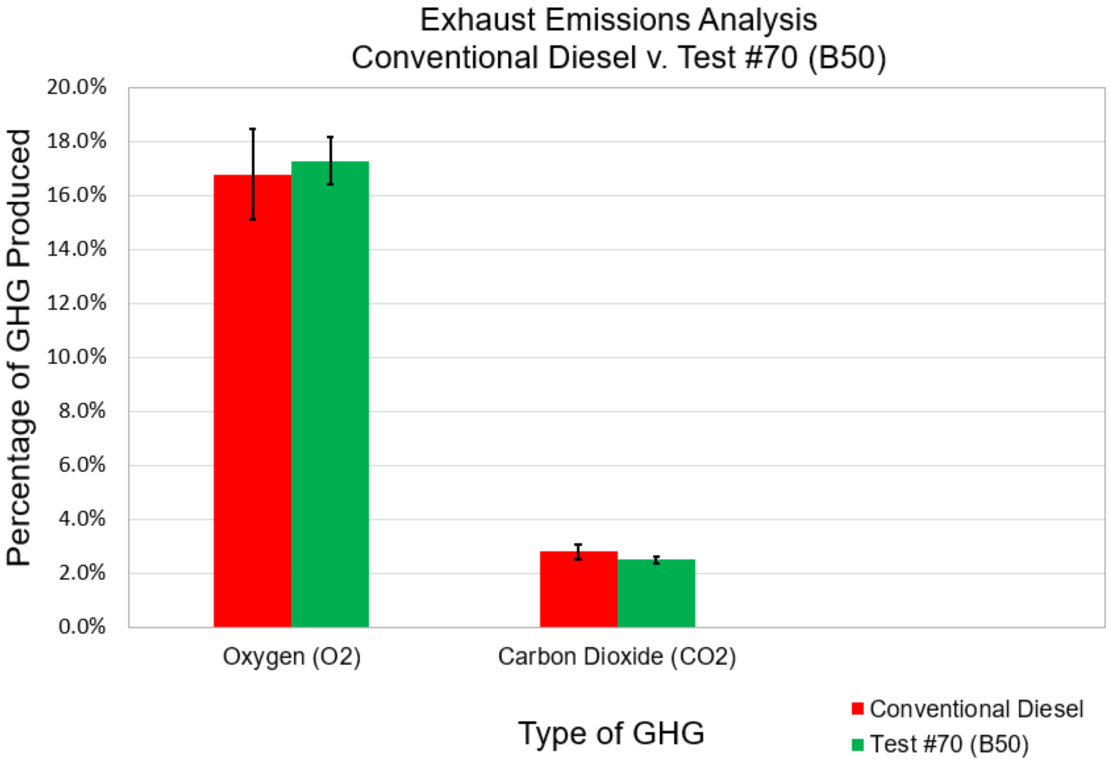


Figure 4-35. Exhaust Emissions Analysis in % (O_2 & CO_2) – Conventional Diesel v. Test #70 Biodiesel.

The last graph below in Figure 4.36, compares the exhaust emissions data for the remaining gases measured in parts per million (PPM). The far-left side of the graph represents the amount of HC produced from the tested fuels. The HC that was produced from the Test #70 biodiesel was 28 PPM which is a reduction of 8 PPM or 22.22% from conventional diesel. Due to reduced combustion temperatures while utilizing Test #70 biodiesel a drop in NOx emission was recorded. The NOx emission produced from Test #70 biodiesel was 74.5 PPM which is 25.9 PPM or 25.8% lower than that produced from conventional diesel. The right side of the graph shows the production of CO emissions which is zero as a result of complete combustion reactions and a sufficient amount of oxygen.

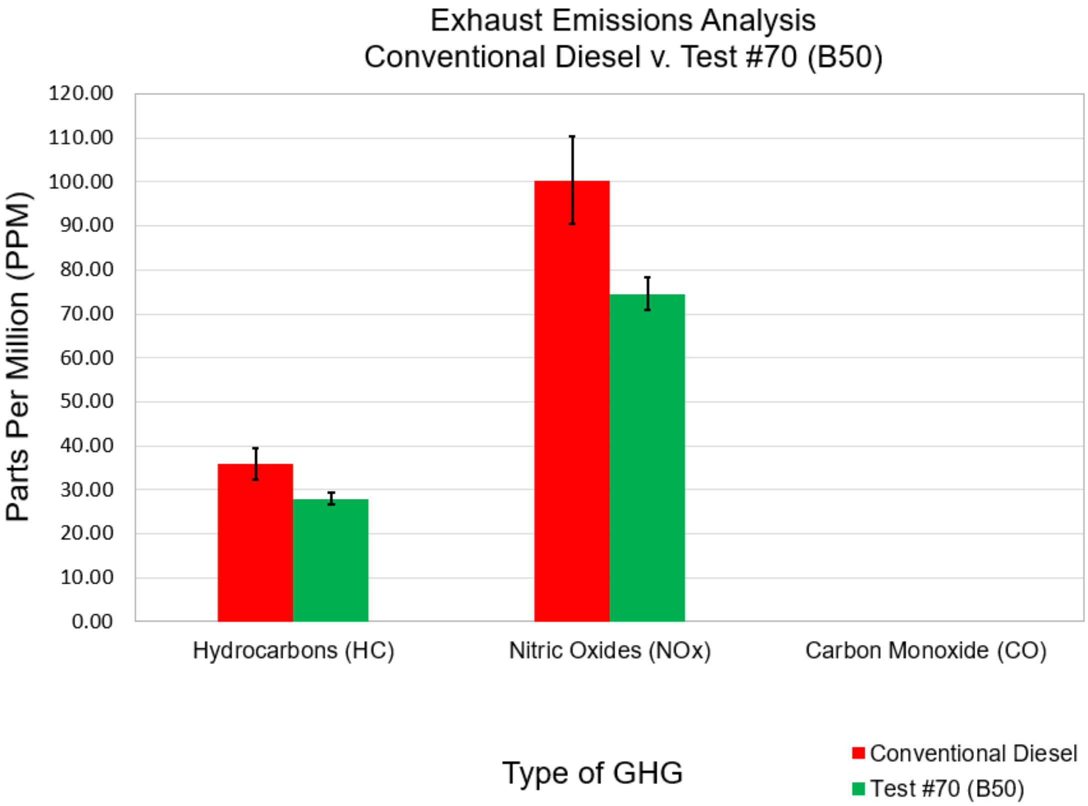


Figure 4-36. Exhaust Emissions Analysis in PPM (HC, NOx, CO) Conventional Diesel v. Test #70 Biodiesel.

4.10 Test AFB #30 – Beef Tallow Biodiesel (B100)

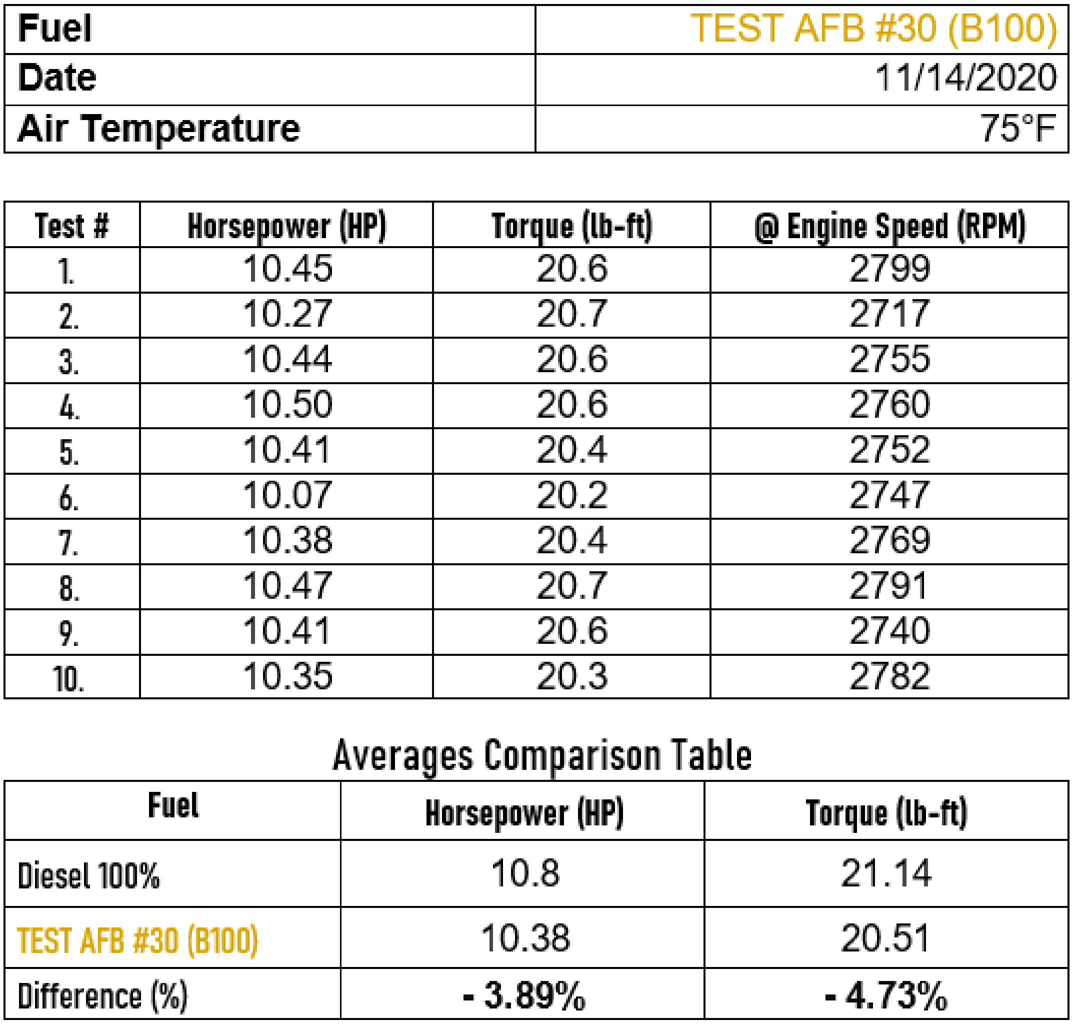
The composition of Test AFB #30 biodiesel is 100% diesel free. Figure 4.37 shows Test AFB #30 in a glass beaker shortly after the formulation process (Davani, 2022). The appearance of Test AFB #30 is very clear and translucent. Test AFB #30 can be used in any diesel engine without any modification necessary.

Figure 4-37. Biodiesel Test AFB #30 (B100).

4.10.1 Engine Dynamometer Testing

The engine was dyno tested 10 times while running on the Test AFB #30 biodiesel fuel with promising performance. After operating the engine dynamometer 10 times the HP and torque recording were averaged to determine the engine performance in comparison to conventional diesel fuel. Table 4.17 shows the data collected from the dynamometer tests. The average comparison in Table 7 shows a slight decrease in HP and torque outputs under 5%. When taken into consideration, Test AFB #30 contains no fossil fuel yet demonstrates engine performance very similar to conventional diesel fuel.

Table 4-17. TEST AFB #30 BIODIESEL DYNAMOMEMTER TEST RUNS AND AVERAGES COMPARED TO CONV NENTIONAL DIESEL.



Fuel	TEST AFB #30 (B100)
Date	11/14/2020
Air Temperature	75°F

Test #	Horsepower (HP)	Torque (lb-ft)	@ Engine Speed (RPM)
1.	10.45	20.6	2799
2.	10.27	20.7	2717
3.	10.44	20.6	2755
4.	10.50	20.6	2760
5.	10.41	20.4	2752
6.	10.07	20.2	2747
7.	10.38	20.4	2769
8.	10.47	20.7	2791
9.	10.41	20.6	2740
10.	10.35	20.3	2782

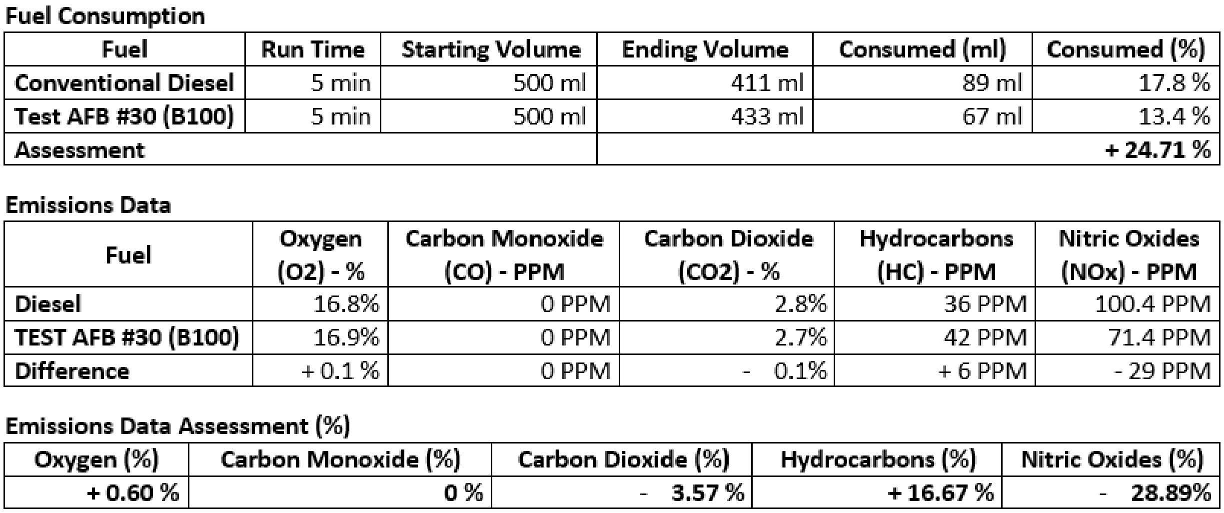
Averages Comparison Table

Fuel	Horsepower (HP)	Torque (lb-ft)
Diesel 100%	10.8	21.14
TEST AFB #30 (B100)	10.38	20.51
Difference (%)	**- 3.89%**	**- 4.73%**

4.10.2 Emissions and Fuel Consumption Testing

Similar to tests done in section 4.2.4 and 4.3.2 a total amount of 500ml of Test AFB #30 is formulated for emissions and fuel consumption testing. The engine was operated at a constant speed for a duration of 5 minutes. While the engine is running the exhaust gases are monitored and measured using the Enerac700 5-gas analyzer. After 5 minutes the fuel that remained in the fuel tank was measured to determine total fuel consumption. Table 4.18 gives the emissions and fuel consumption data for Test AFB #30 containing no diesel.

Table 4-18. TEST AFB #30 BIODIESEL (B100) EMISSIONS AND FUEL CONSUMPTION DATA



Fuel Consumption

Fuel	Run Time	Starting Volume	Ending Volume	Consumed (ml)	Consumed (%)
Conventional Diesel	5 min	500 ml	411 ml	89 ml	17.8 %
Test AFB #30 (B100)	5 min	500 ml	433 ml	67 ml	13.4 %
Assessment			**+ 24.71 %**		

Emissions Data

Fuel	Oxygen (O2) - %	Carbon Monoxide (CO) - PPM	Carbon Dioxide (CO2) - %	Hydrocarbons (HC) - PPM	Nitric Oxides (NOx) - PPM
Diesel	16.8%	0 PPM	2.8%	36 PPM	100.4 PPM
TEST AFB #30 (B100)	16.9%	0 PPM	2.7%	42 PPM	71.4 PPM
Difference	+ 0.1 %	0 PPM	- 0.1%	+ 6 PPM	- 29 PPM

Emissions Data Assessment (%)

Oxygen (%)	Carbon Monoxide (%)	Carbon Dioxide (%)	Hydrocarbons (%)	Nitric Oxides (%)
+ 0.60 %	**0 %**	- **3.57 %**	**+ 16.67 %**	- **28.89%**

The following graphs displayed evaluate the test results of conventional diesel vs. Test AFB #30 biodiesel. Figure 4.38 shows the test results from the fuel consumption test for conventional diesel fuel and Test AFB #30 biodiesel. The red bar (conventional diesel) represents a total fuel consumption of 17.8% consumed from the starting fuel volume of 500ml. On the right side of the graph, the green bar (Test AFB #30 biodiesel) represents a total fuel consumption of 13.4% consumed from the starting volume of 500ml. In comparison, the Test AFB #30 biodiesel improved fuel economy by 24.71%.

Figure 4.39 analyzes the exhaust emissions in percentages produced from conventional diesel and Test AFB #30 biodiesel. The oxygen produced from the exhaust gases when operating on Test AFB #30 biodiesel fuel was 0.60% higher than conventional diesel. On the right-hand side of the graph the CO_2 that was produced from the exhaust gases are compared. It is evident that conventional diesel produced 3.7% more CO_2 than Test AFB #30 biodiesel during engine operation.

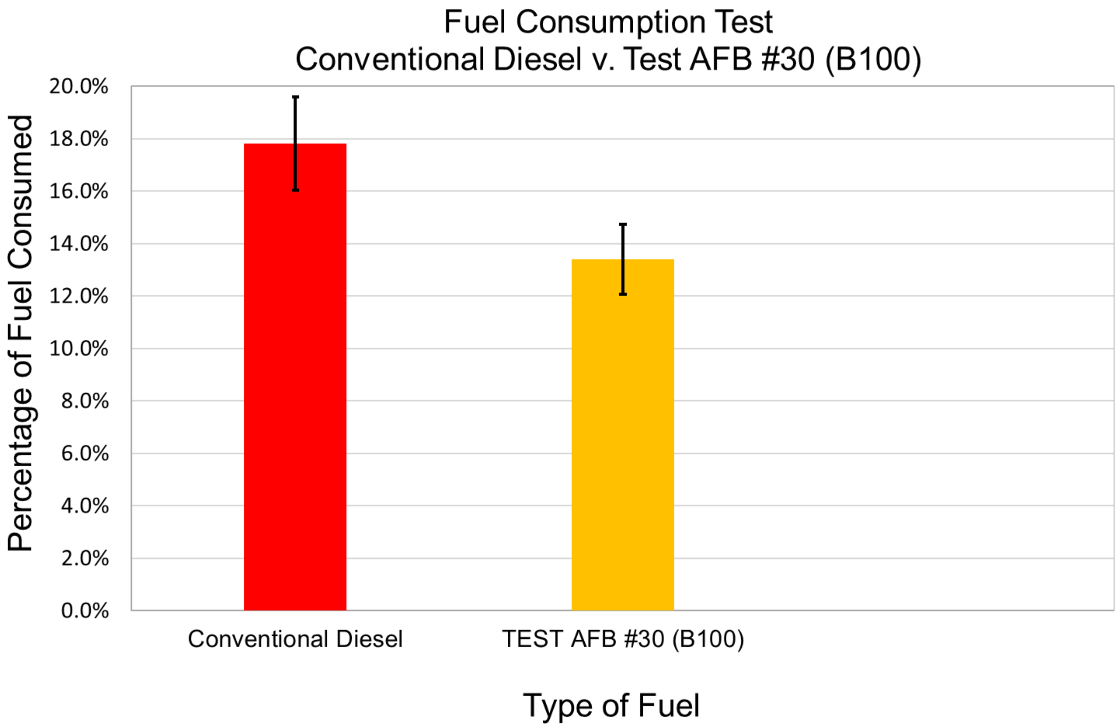


Figure 4-38. Fuel Consumption Test – Conventional Diesel v. Test AFB #30 Biodiesel.

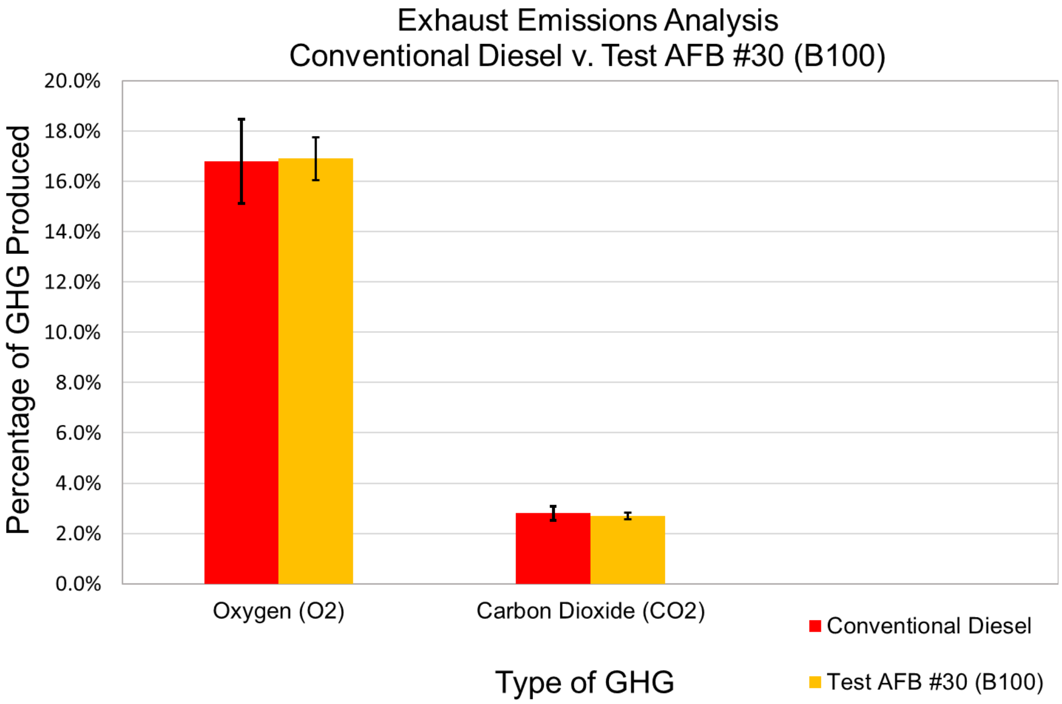


Figure 4-39. Exhaust Emissions Analysis in % (O_2 & CO_2) – Conventional Diesel v. Test AFB #30 Biodiesel.

The final graph in Figure 4.40 compares the exhaust emissions data for the remaining gases measured in parts per million (PPM). The far-left side of the graph represents the amount of HC produced from the tested fuels. The HC that was produced from the Test AFB #30 biodiesel was 42 PPM which is an increase of 6 PPM or 16.67% from conventional diesel, however, the CS186 diesel engine was not equipped with a catalytic converter. A catalytic converter reduces over 90% of hydrocarbons through utilizing a chamber referred to as a catalyst, which converts the harmful emissions into safe gases, like steam [60].

Due to lowered combustion temperatures while utilizing Test AFB #30 biodiesel a drop in NOx emission was achieved. The NOx emission produced from Test AFB #30 biodiesel was 71.4 PPM which is 29 PPM or 28.89% lower than that produced from conventional diesel. The right side of the graph shows the production of CO emissions being zero, because a complete combustion reaction was achieved for both fuels during engine operation.

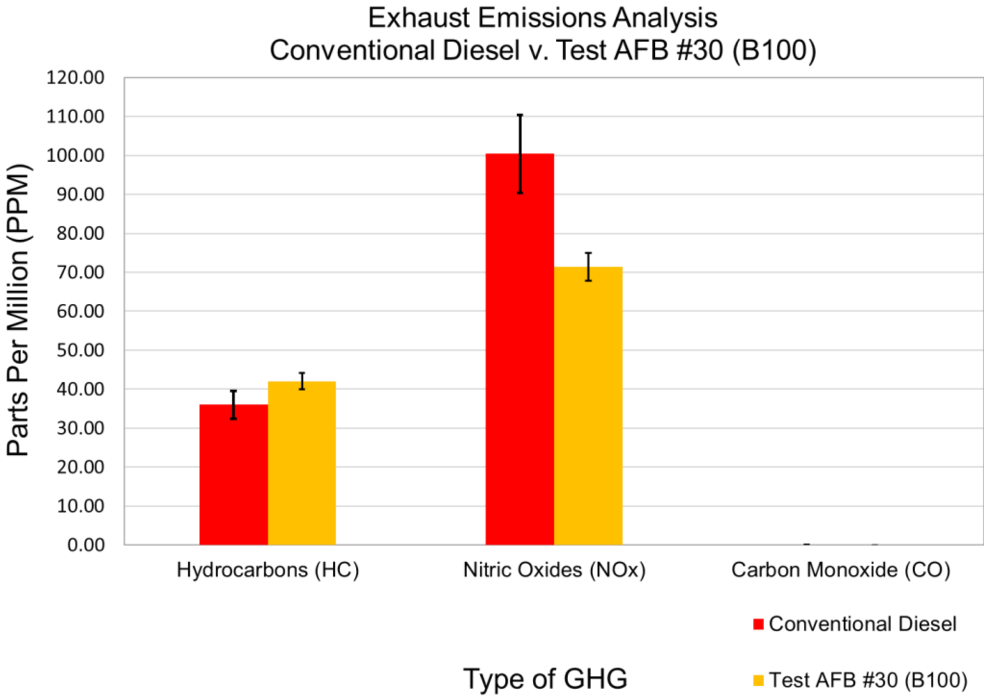


Figure 4-40. Exhaust Emissions Analysis in PPM (HC, NOx, CO) Conventional Diesel v. Test AFB #30 Biodiesel.

4.11 Test AFB #33 – Beef Tallow Biodiesel (B50)

The composition of Test AFB #33 biodiesel is 50% conventional diesel and 50% of Test AFB 30. Figure 4.41 shows Test AFB #33 in a glass beaker shortly after the formulation process (Davani, 2022). The appearance of Test AFB #33 is very clear and translucent. Test AFB #33 can be used in any diesel engine without any modification necessary.

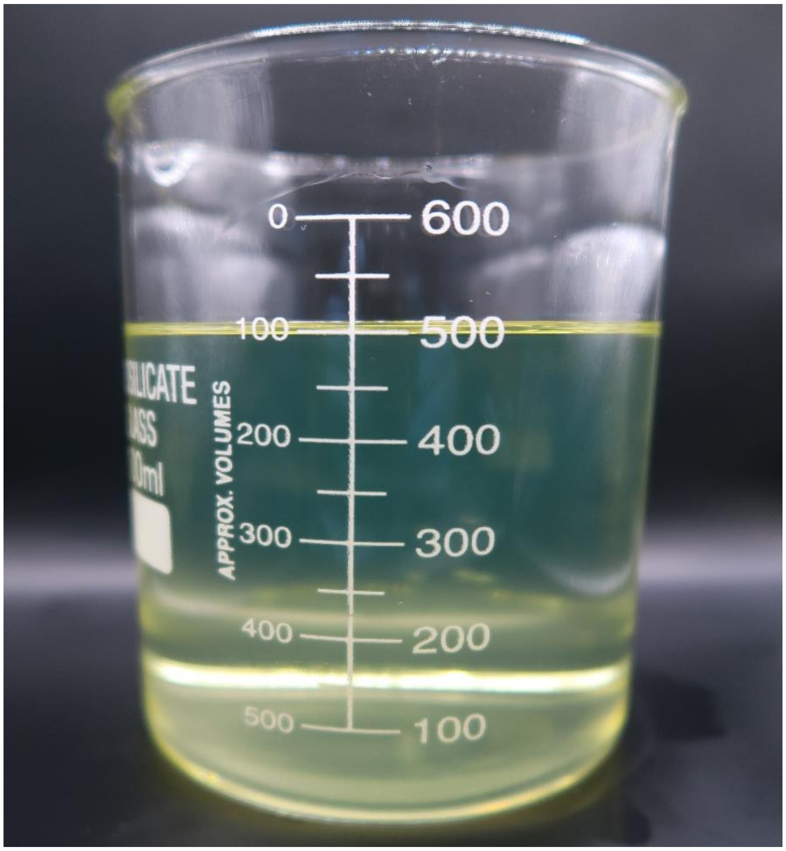
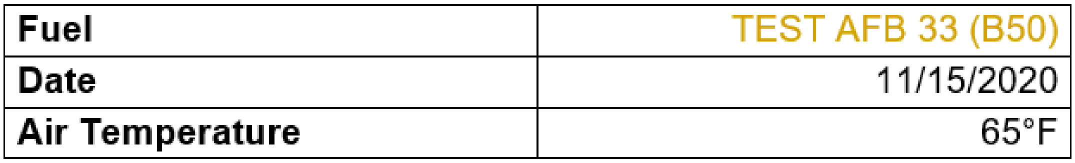


Figure 4-41. Biodiesel Test AFB #33 (B50).

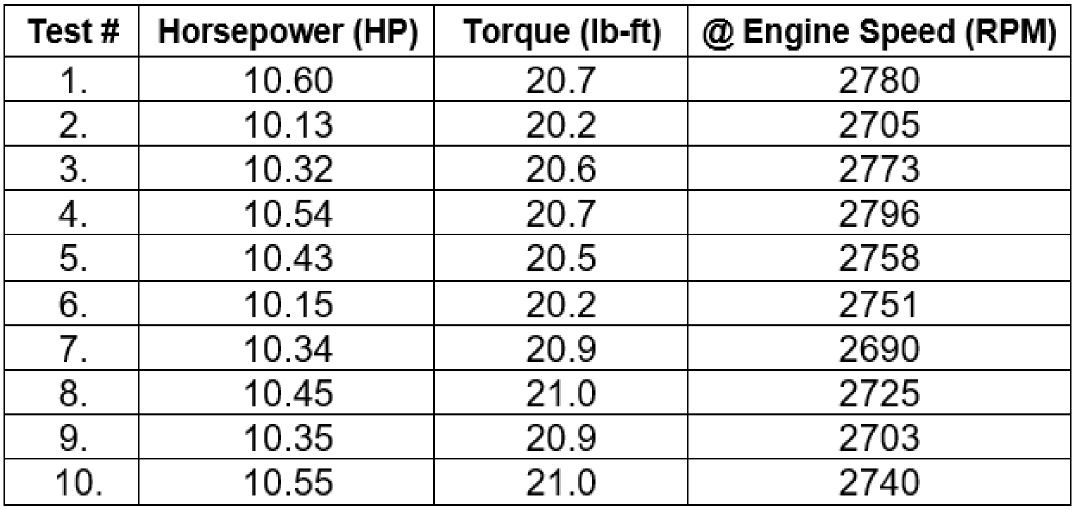
4.11.1 Engine Dynamometer Testing

The engine was dyno tested 10 times while running on the Test AFB #33 biodiesel fuel with promising performance. After operating the engine dynamometer 10 times the HP and torque recording were averaged to determine the engine performance in comparison to conventional diesel fuel. Table 4.19 shows the data collected from the dynamometer tests. The average comparison in Table 4.19 shows a slight increase in HP and torque outputs of under 1%. When taken into consideration, Test AFB #33 contains only 50% fossil fuel yet demonstrates engine performance very similar to 100% conventional diesel fuel.

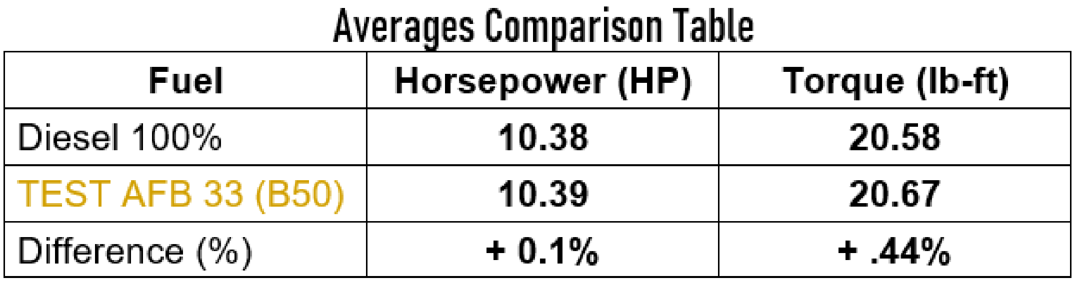
Table 4-19. TEST AFB #33 BIODIESEL DYNAMOMEMTER TEST RUNS AND AVERAGES COMPARED TO CONV NENTIONAL DIESEL.



Fuel	TEST AFB 33 (B50)
Date	11/15/2020
Air Temperature	65°F



Test #	Horsepower (HP)	Torque (lb-ft)	@ Engine Speed (RPM)
1.	10.60	20.7	2780
2.	10.13	20.2	2705
3.	10.32	20.6	2773
4.	10.54	20.7	2796
5.	10.43	20.5	2758
6.	10.15	20.2	2751
7.	10.34	20.9	2690
8.	10.45	21.0	2725
9.	10.35	20.9	2703
10.	10.55	21.0	2740



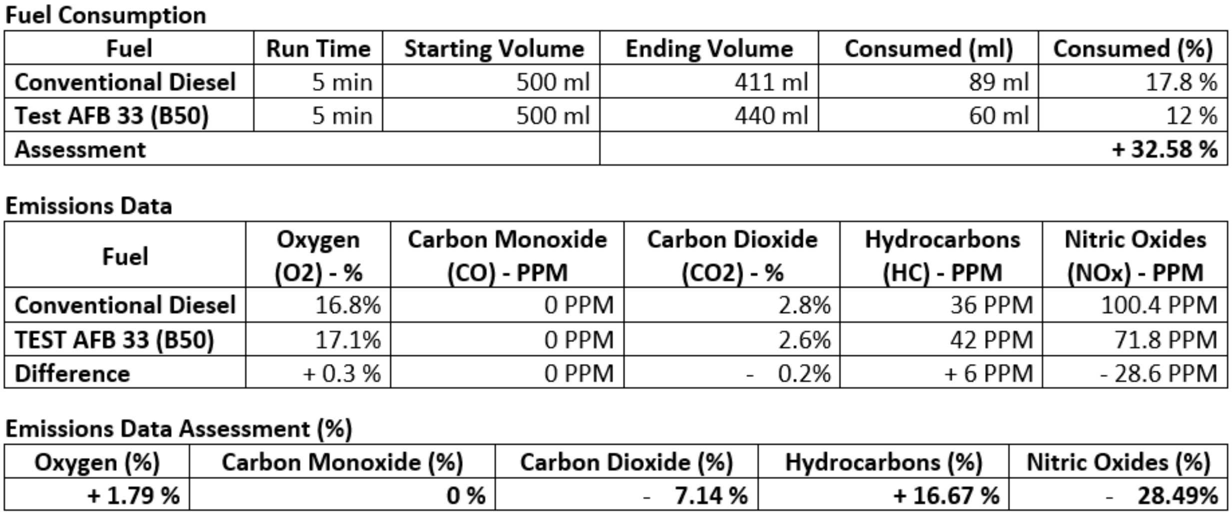
Averages Comparison Table

Fuel	Horsepower (HP)	Torque (lb-ft)
Diesel 100%	**10.38**	**20.58**
TEST AFB 33 (B50)	**10.39**	**20.67**
Difference (%)	**+ 0.1%**	**+ .44%**

4.11.2 Emissions and Fuel Consumption Testing

Similar to tests done in section 4.2.4 and 4.3.2 a total amount of 500ml of Test AFB #33 is formulated for emissions and fuel consumption testing. The engine was operated at a constant speed for a duration of 5 minutes. While the engine is running the exhaust gases are monitored and measured using the Enerac700 5-gas analyzer. After 5 minutes the fuel that remained in the fuel tank was measured to determine total fuel consumption. Table 4.20 gives the emissions and fuel consumption data for Test AFB #33 containing only 50% conventional diesel.

Table 4-20. TEST AFB #33 BIODIESEL (B100) EMISSIONS AND FUEL CONSUMPTION DATA



Fuel Consumption

Fuel	Run Time	Starting Volume	Ending Volume	Consumed (ml)	Consumed (%)
Conventional Diesel	5 min	500 ml	411 ml	89 ml	17.8 %
Test AFB 33 (B50)	5 min	500 ml	440 ml	60 ml	12 %
Assessment					**+ 32.58 %**

Emissions Data

Fuel	Oxygen (O2) - %	Carbon Monoxide (CO) - PPM	Carbon Dioxide (CO2) - %	Hydrocarbons (HC) - PPM	Nitric Oxides (NOx) - PPM
Conventional Diesel	16.8%	0 PPM	2.8%	36 PPM	100.4 PPM
TEST AFB 33 (B50)	17.1%	0 PPM	2.6%	42 PPM	71.8 PPM
Difference	+ 0.3 %	0 PPM	- 0.2%	+ 6 PPM	- 28.6 PPM

Emissions Data Assessment (%)

Oxygen (%)	Carbon Monoxide (%)	Carbon Dioxide (%)	Hydrocarbons (%)	Nitric Oxides (%)
+ 1.79 %	**0 %**	- **7.14 %**	**+ 16.67 %**	- **28.49%**

The following graphs displayed evaluate the test results of conventional diesel vs. Test AFB #33 biodiesel. Figure 4.42 shows the test results from the fuel consumption test for conventional diesel fuel and Test AFB #33 biodiesel. The red bar (conventional diesel) represents a total fuel consumption of 17.8% consumed from the starting fuel volume of 500ml. On the right side of the graph, the green bar (Test AFB #33 biodiesel) represents a total fuel consumption of 12% consumed from the starting volume of 500ml. In comparison, the Test AFB #33 biodiesel improved fuel economy by 32.58%.

Figure 4.43 analyzes the exhaust emissions in percentages produced from conventional diesel and Test AFB #33 biodiesel. The oxygen produced from the exhaust gases when operating on Test AFB #33 biodiesel fuel was 1.79% higher than conventional diesel. On the right-hand side of the graph the CO_2 that was produced from the exhaust gases are compared. It is evident that conventional diesel produced 7.69% more CO_2 than Test AFB #33 biodiesel during engine operation.

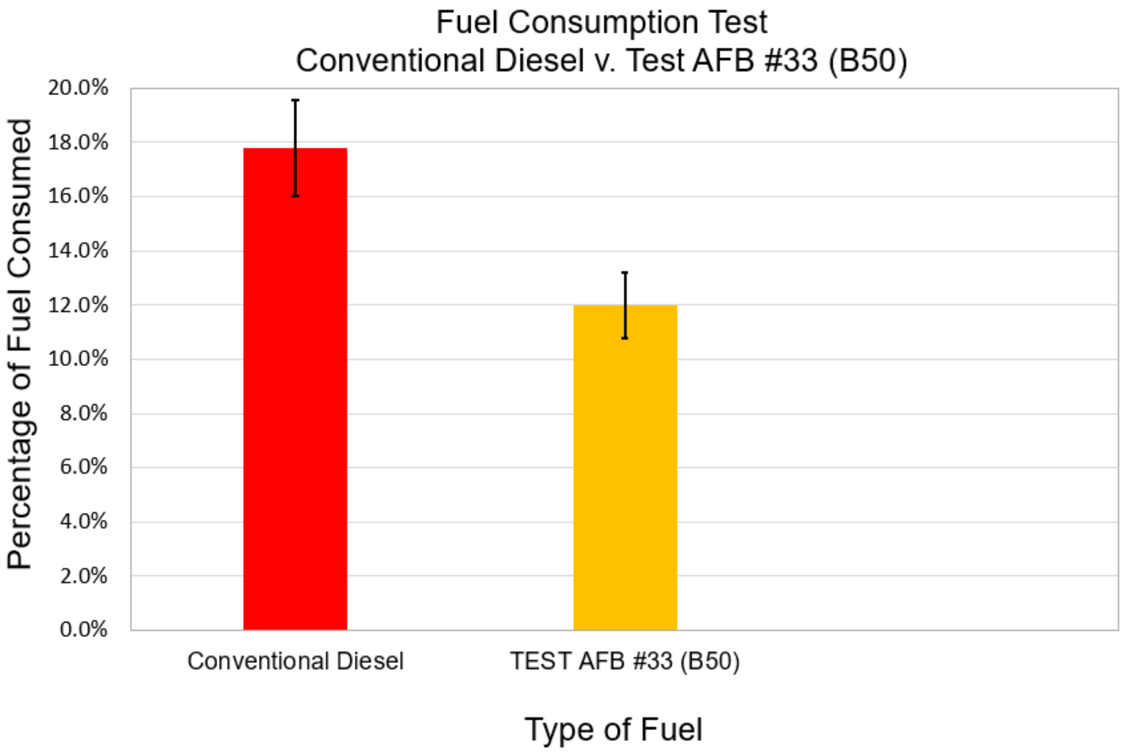


Figure 4-42. Fuel Consumption Test – Conventional Diesel v. Test AFB #33 Biodiesel.

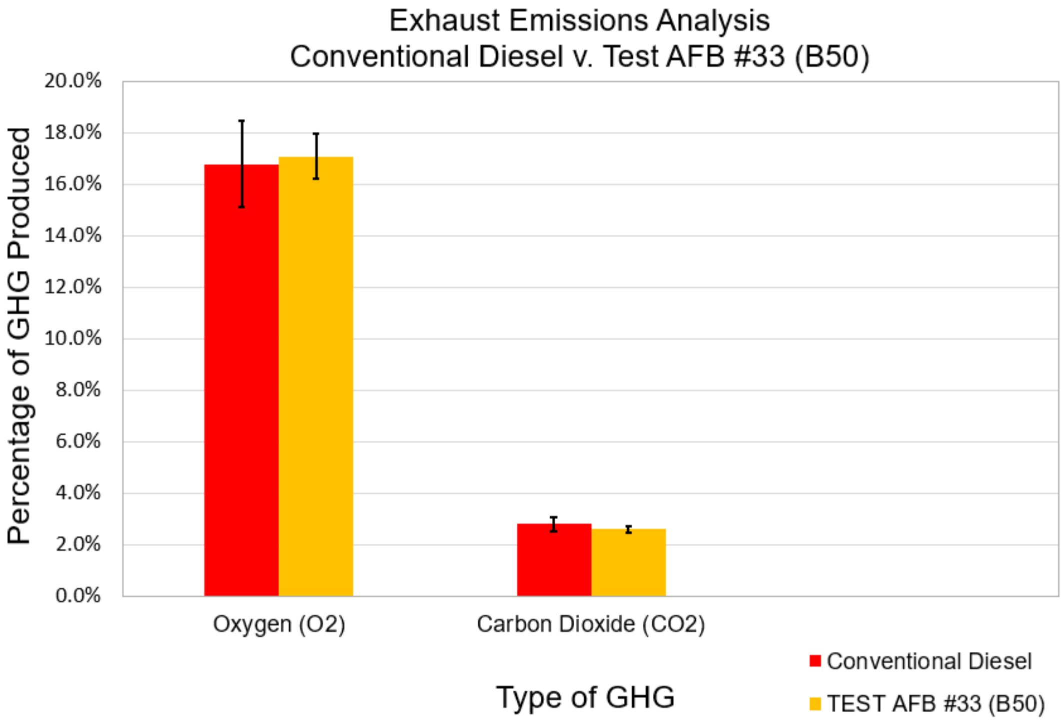


Figure 4-43. Exhaust Emissions Analysis in % (O_2 & CO_2) – Conventional Diesel v. Test AFB #33 Biodiesel.

The final graph in Figure 4.44 compares the exhaust emissions data for the remaining gases measured in parts per million (PPM). The far-left side of the graph represents the amount of HC produced from the tested fuels. The HC that was produced from the Test AFB #33 biodiesel was 42 PPM which is an increase of 6 PPM or 16.67% from conventional diesel, however, the CS186 diesel engine was not equipped with a catalytic converter. A catalytic converter reduces over 90% of hydrocarbons through utilizing a chamber referred to as a catalyst, which converts the harmful emissions into safe gases, like steam [60].

Due to lowered combustion temperatures while utilizing Test AFB #33 biodiesel a drop in NOx emission was achieved. The NOx emission produced from Test AFB #33 biodiesel was 71.8 PPM which is 28.6 PPM or 28.49% lower than that produced from conventional diesel. The right side of the graph shows the production of CO emissions being zero, because a complete combustion reaction was achieved for both fuels during engine operation.

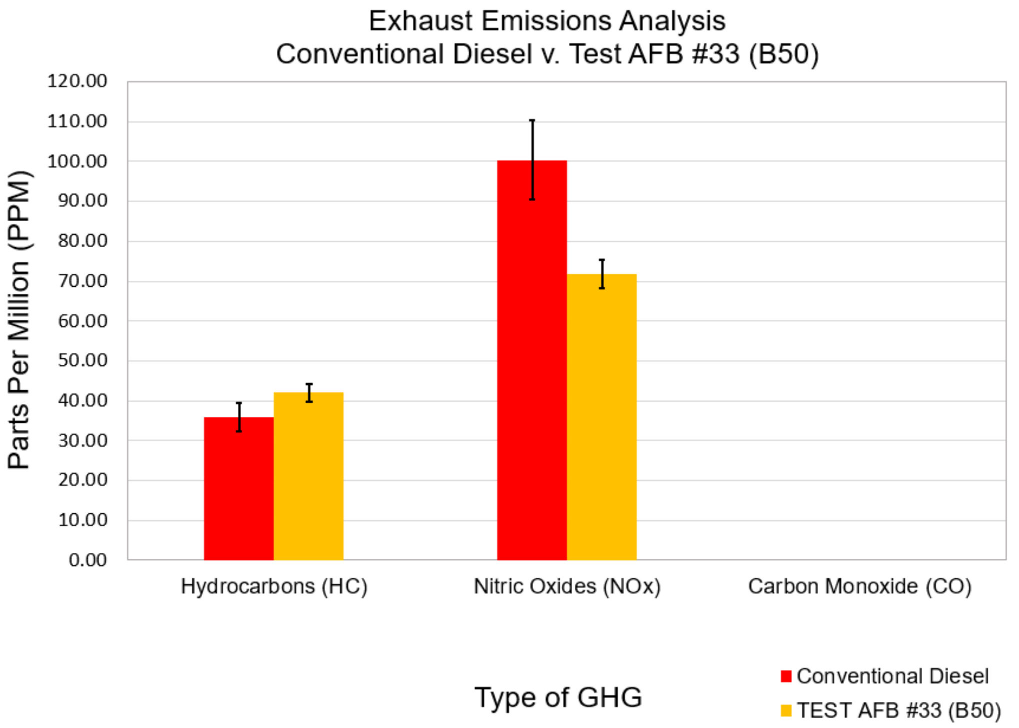


Figure 4-44. Exhaust Emissions Analysis in PPM (HC, NOx, CO) Conventional Diesel v. Test AFB #33 Biodiesel.

4.12 Test AFB #35 – Beef Tallow + Cottonseed Oil Biodiesel (B70)

The composition of Test AFB #35 biodiesel consists of 30% conventional diesel, 35% beef tallow (Test AFB 30), and 35% cottonseed oil. Figure 4.45 shows Test AFB #35 in a glass beaker shortly after the formulation process (Davani, 2022). The appearance of Test AFB #35 is very clear and translucent. Test AFB #35 can be used in any diesel engine without any modification necessary.

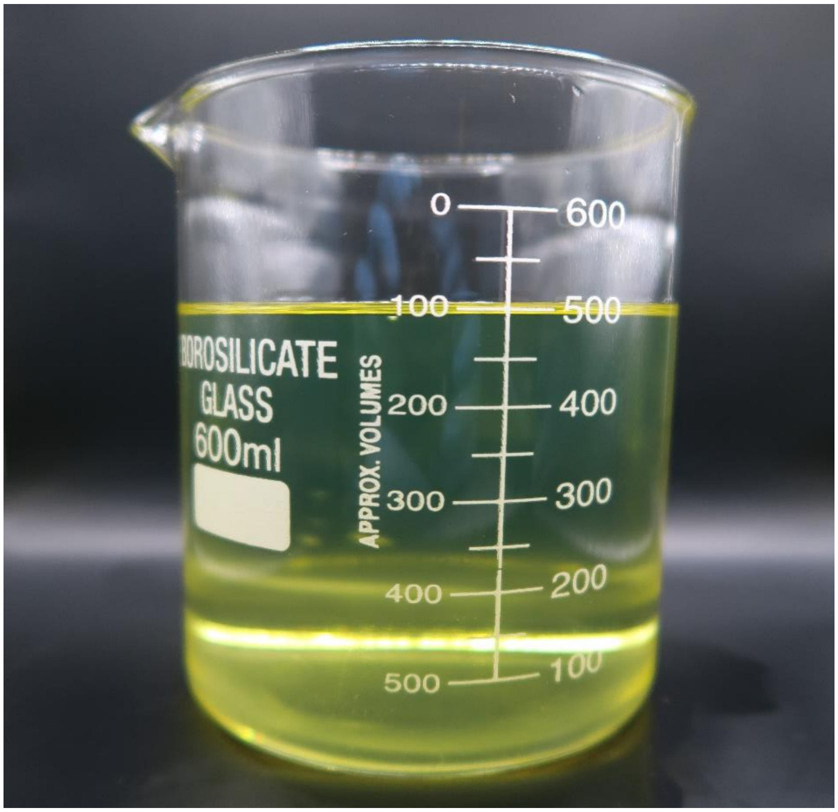


Figure 4-45. Biodiesel Test AFB #35 (B70).

4.12.1 Engine Dynamometer Testing

The engine was dyno tested 10 times while running on Test AFB #35 biodiesel fuel with promising performance. After operating the engine dynamometer 10 times the HP and torque recording were averaged to determine the engine performance in comparison to conventional diesel fuel. Table 4.21 shows the data collected from the dynamometer tests. The average comparison in Table 4.21 shows a slight increase in HP and torque outputs under 1%. When taken into consideration, Test AFB #35 contains only 30% fossil fuel yet demonstrates engine performance exceeding conventional diesel fuel.

Table 4-21. TEST AFB #35 BIODIESEL DYNAMOMEMTER TEST RUNS AND AVERAGES COMPARED TO CONV NENTIONAL DIESEL.

Fuel	TEST AFB 35 (B70)
Date	11/16/2020
Air Temperature	67°F

Test #	Horsepower (HP)	Torque (lb-ft)	@ Engine Speed (RPM)
1.	10.68	21.0	2766
2.	10.38	20.8	2754
3.	10.37	20.7	2730
4.	10.58	20.7	2789
5.	10.24	20.4	2758
6.	10.20	20.4	2762
7.	10.36	20.2	2760
8.	10.08	20.2	2718
9.	10.31	20.2	2782
10.	10.29	20.2	2761

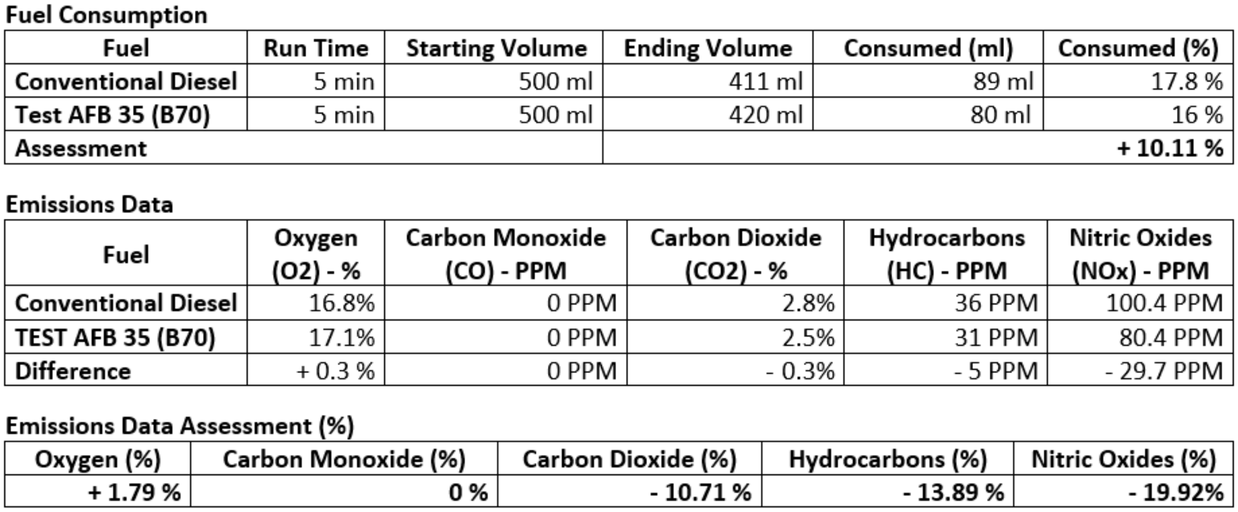
Averages Comparison Table

Fuel	Horsepower (HP)	Torque (lb-ft)
Diesel 100%	**10.30**	**20.41**
TEST AFB 35 (B70)	**10.35**	**20.48**
Difference (%)	**+ 0.49%**	**+ .34%**

4.12.2 Emissions and Fuel Consumption Testing

Similar to tests done in section 4.2.4 and 4.3.2 a total amount of 500ml of Test AFB #35 is formulated for emissions and fuel consumption testing. The engine was operated at a constant speed for a duration of 5 minutes. While the engine is running the exhaust gases are monitored and measured using the Enerac700 5-gas analyzer. After 5 minutes the fuel that remained in the fuel tank was measured to determine total fuel consumption. Table 4.22 gives the emissions and fuel consumption data for Test AFB #35 containing no diesel.

Table 4-22. TEST AFB #35 BIODIESEL (B70) EMISSIONS AND FUEL CONSUMPTION DATA



Fuel Consumption

Fuel	Run Time	Starting Volume	Ending Volume	Consumed (ml)	Consumed (%)
Conventional Diesel	5 min	500 ml	411 ml	89 ml	17.8 %
Test AFB 35 (B70)	5 min	500 ml	420 ml	80 ml	16 %
Assessment			**+ 10.11 %**		

Emissions Data

Fuel	Oxygen (O2) - %	Carbon Monoxide (CO) - PPM	Carbon Dioxide (CO2) - %	Hydrocarbons (HC) - PPM	Nitric Oxides (NOx) - PPM
Conventional Diesel	16.8%	0 PPM	2.8%	36 PPM	100.4 PPM
TEST AFB 35 (B70)	17.1%	0 PPM	2.5%	31 PPM	80.4 PPM
Difference	+ 0.3 %	0 PPM	- 0.3%	- 5 PPM	- 29.7 PPM

Emissions Data Assessment (%)

Oxygen (%)	Carbon Monoxide (%)	Carbon Dioxide (%)	Hydrocarbons (%)	Nitric Oxides (%)
+ 1.79 %	**0 %**	**- 10.71 %**	**- 13.89 %**	**- 19.92%**

The following graphs displayed evaluate the test results of conventional diesel vs. Test AFB #35 biodiesel. Figure 4.46 shows the test results from the fuel consumption test for conventional diesel fuel and Test AFB #35 biodiesel. The red bar (conventional diesel) represents a total fuel consumption of 17.8% consumed from the starting fuel volume of 500ml. On the right side of the graph, the green bar (Test AFB #35 biodiesel) represents a total fuel consumption of 16% consumed from the starting volume of 500ml. In comparison, the Test AFB #35 biodiesel improved fuel economy by 10.11%.

Figure 4.47 analyzes the exhaust emissions in percentages produced from conventional diesel and Test AFB #35 biodiesel. The oxygen produced from the exhaust gases when operating on Test AFB #35 biodiesel fuel was 1.79% higher than conventional diesel. On the right-hand side of the graph the CO_2 that was produced from the exhaust gases are compared. It is evident that conventional diesel produced 12% more CO_2 than Test AFB #35 biodiesel during engine operation.

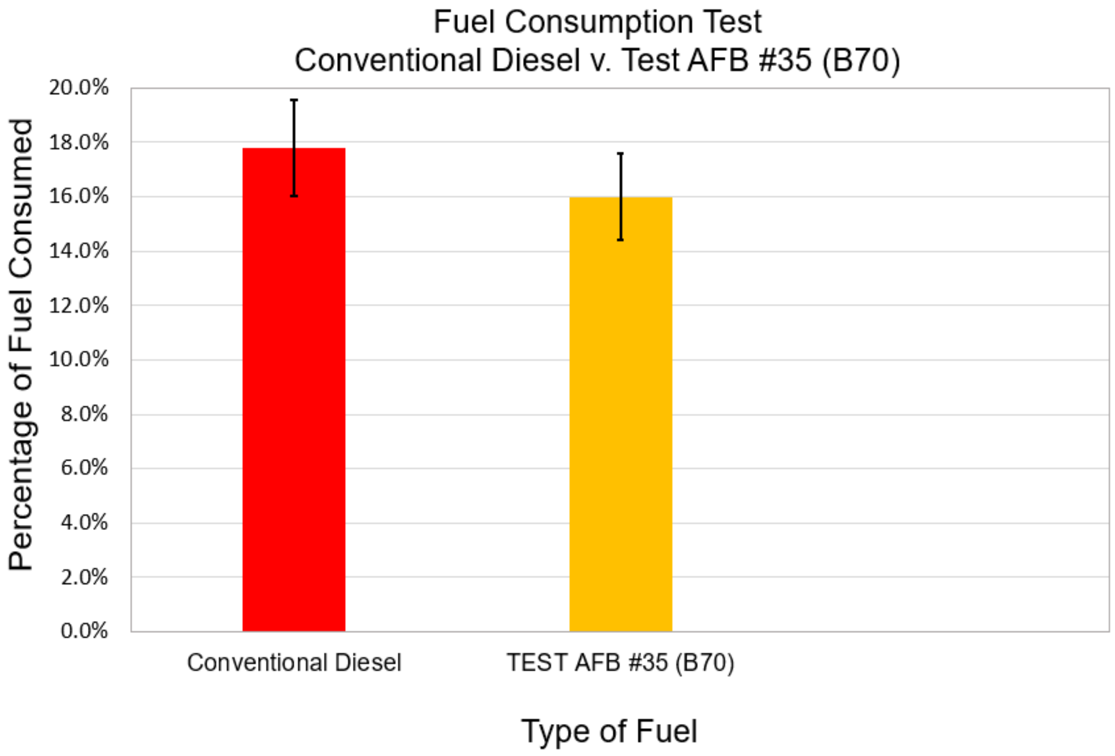


Figure 4-46. Fuel Consumption Test – Conventional Diesel v. Test AFB #35 Biodiesel.

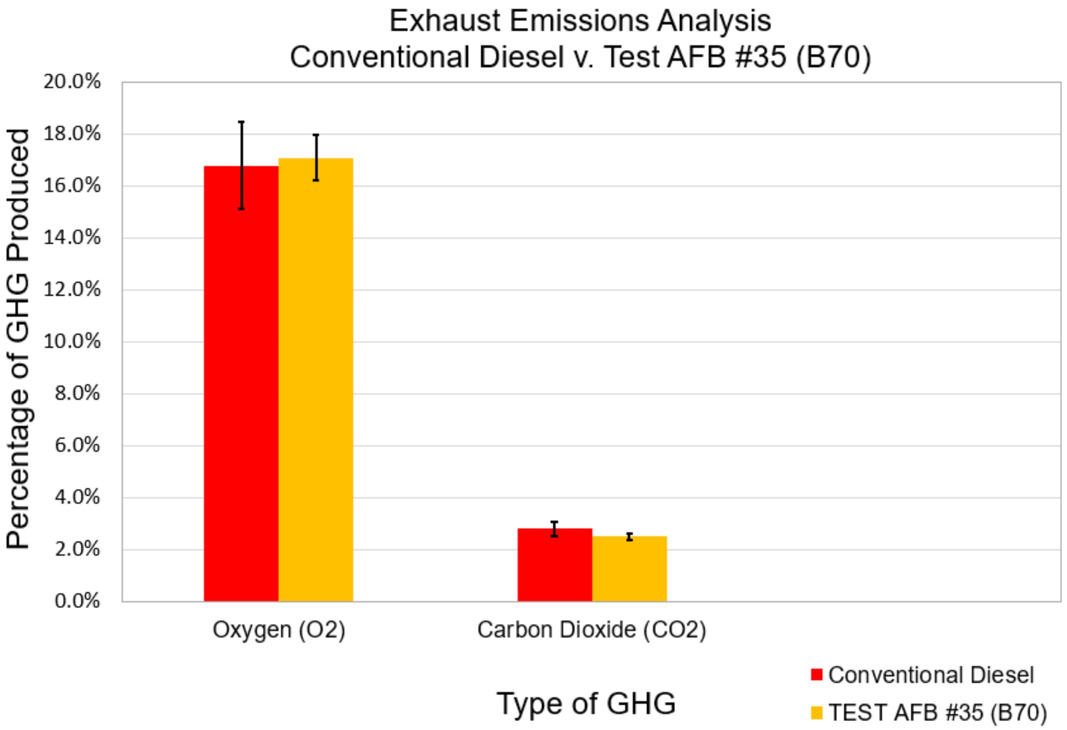


Figure 4-47. Exhaust Emissions Analysis in % (O_2 & CO_2) – Conventional Diesel v. Test AFB #35 Biodiesel.

The final graph in Figure 4.48 compares the exhaust emissions data for the remaining gases measured in parts per million (PPM). The far-left side of the graph represents the amount of HC produced from the tested fuels. The HC that was produced from the Test AFB #35 biodiesel was 31 PPM which is a decrease of 5 PPM or 13.89% from conventional diesel, however, the CS186 diesel engine was not equipped with a catalytic converter. A catalytic converter reduces over 90% of hydrocarbons through utilizing a chamber referred to as a catalyst, which converts the harmful emissions into safe gases, like steam [60].

Due to lowered combustion temperatures while utilizing Test AFB #35 biodiesel a drop in NOx emission was achieved. The NOx emission produced from Test AFB #35 biodiesel was 80.4 PPM which is 29.7 PPM or 19.92% lower than that produced from conventional diesel. The right side of the graph shows the production of CO emissions being zero, because a complete combustion reaction was achieved for both fuels during engine operation.

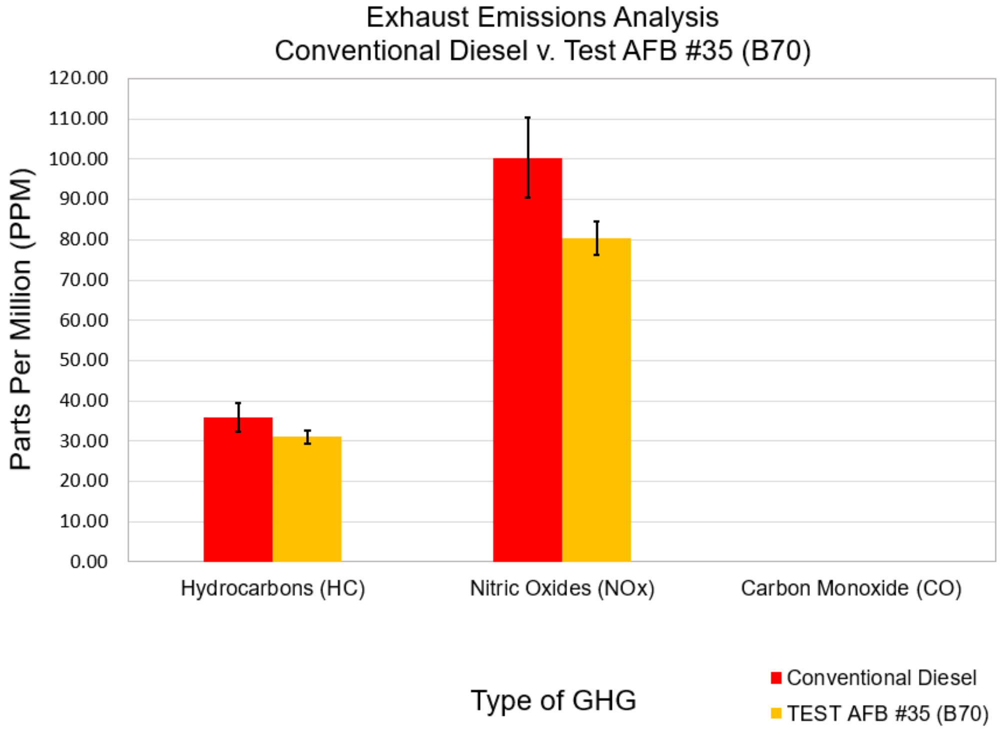


Figure 4-48. Exhaust Emissions Analysis in PPM (HC, NOx, CO) Conventional Diesel v. Test AFB #35 Biodiesel.

As illustrated in Figure 4.49 below, the current demand for utilization of fossil fuel is continuing to increase conservatively until 2040 [12]. Therefore, continued efforts in internal combustion engine and alternative fuel research must remain as top priority in global economic agendas. Biodiesel production aids in continued utilization of fossil fuels, such as conventional diesel, while improving the performance, fuel economy, and more importantly provides a reduction in greenhouse gas emissions.

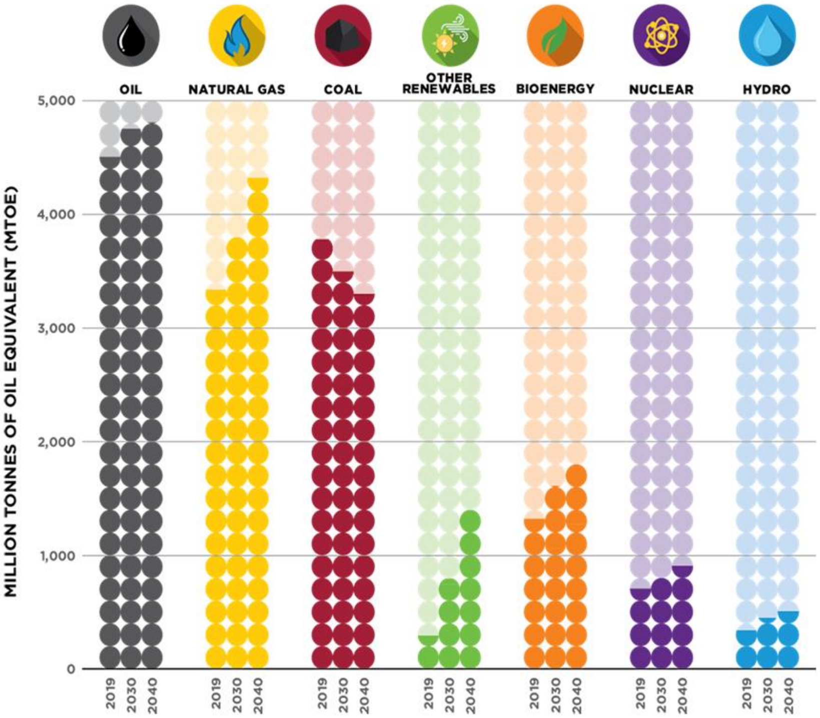


Figure 4-49. Global Energy Demand 2019-2040 [12].

Despite global efforts to transition to renewable energy sources, the demand for fossil fuels continues to rise. This is driven by factors such as population growth, industrialization, and the lack of affordable and scalable alternatives. As a result, there is a need for innovative solutions to address this growing demand while minimizing the negative impact such as greenhouse gas emissions on the environment.

CHAPTER 5: CONCLUSION

In this proposal research study, 3 main categories of biodiesel were formed under the following:

- AquaCharged Diesel (W20)
- Seed-Oil Biodiesel (B50)
- Animal Fat Biodiesel (B50, B70, B100)

The AquaCharged Diesel formulation contained 20% water as a renewable in the fuel composition. After extensive dynamometer testing the AquaCharged Diesel surpassed conventional diesel in engine performance. A significant reduction in carbon dioxide and nitic oxides were observed during the emissions testing. Since water is abundant around the globe, commercialization of the AquaCharged Diesel is very likely and feasible to the industry.

The initial seed-oil biodiesel that was formulated for this experiment contained a composition of 50% red palm oil and displayed compelling data after numerous dynamometer and emissions testing. Test #30 achieved over 10% reduction in greenhouse gas emission all around including CO2, HC, and NOx. After comparing fuel consumption to conventional diesel, Test #30 improved fuel economy by nearly 22%.

The final category, Animal Fat Biodiesel, Test AFB #30 eliminated 100% diesel from the fuel composition, classifying the biodiesel as a B100. Although a slight reduction in engine performance was observed, the significant reduction in emissions and improvement in fuel economy makes Test AFB #30 far from dismissible. An improved fuel economy of nearly 25% was achieved during fuel consumption testing of the animal fat biodiesel.

From an alternative perspective, fuel efficiency in this case can be categorized as Fossil Fuel Enhancement Technology (FFET). Although all 3 fuel that were formulated and tested displayed major improvement in fuel economy, it must not be forgotten that the amount of conventional diesel fuel that was replaced with the renewable source or biodiesel can now be formulated into additional fuel. This method allows for extended usage of the volume of conventional diesel.

In conclusion, the experimentation with AquaCharged Diesel, Seed-Oil Biodiesel, and Animal Fat Biodiesel demonstrated promising results in engine performance and emissions reduction. The utilization of water as a renewable in the AquaCharged Diesel composition was proven to be effective, surpassing conventional diesel in engine performance and exhibiting a significant reduction in carbon dioxide and nitric oxides during emissions testing. The commercialization of AquaCharged Diesel is feasible and likely due to the abundance of water globally. The Seed-Oil Biodiesel and Animal Fat Biodiesel also showed impressive improvements in fuel economy and emissions reduction, despite some reduction in engine performance. These alternative fuels have great potential to contribute to the industry's transition towards sustainability and reduce reliance on fossil fuels.

CHAPTER 6: FUTURE WORK

The major mission for future work would involve global commercialization of the subjected biodiesel formulations, particularly AquaCharged Diesel. Several nations around the globe are not energy independent and import their petroleum fuel, such as diesel. Diesel fuel is utilized in numerous industries such as transportation, cargo shipping, and energy production. FFET can aid in extending the current reserves of diesel fuel to allow for fuel cost reduction and lean towards energy independence.

The biodiesel formulation can be produced at the refinery and distributed through currently established pipelines. However, since the pipelines are not accessible everywhere, alternative measures must take place for access to fuel in general. At gas stations that already have logistics in place for daily or weekly fuel refills, alternative machines can aid in biodiesel production and distribution on demand. As a pilot project to biodiesel production, Intelligent Blending Station or IBS machine are in the works to allow for easy access to AquaCharged Diesel and other biodiesels regardless of location. Figure 27 below illustrates the preliminary layout of an Intelligent Blending Station (Davani, 2022).

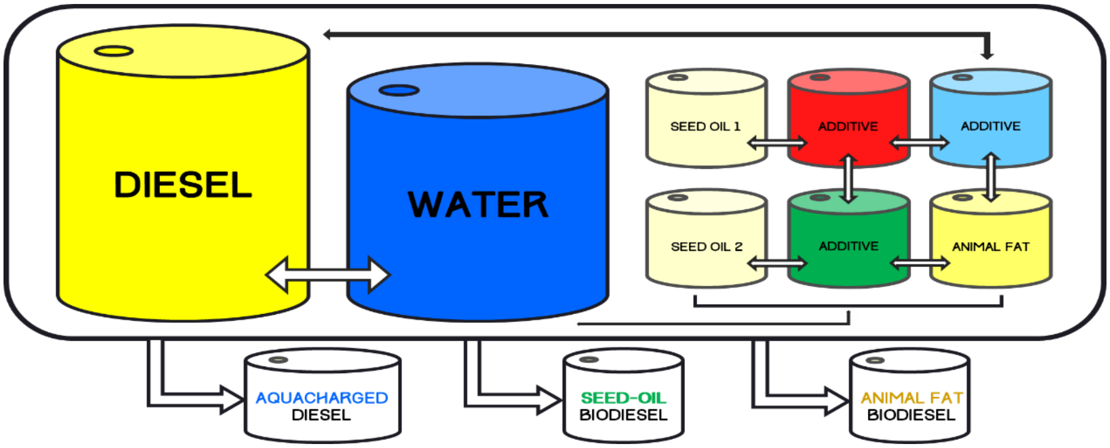


Figure 6-1. Intelligent Blending Station (IBS).

The IBS machines can also be utilized at independent construction sites where heavy machinery and equipment are in steady use, and even at farms where farming equipment needs frequent diesel replenishment. Lastly, it is possible to also adapt the patented FFET to the following petroleum fuels also:

- Gasoline
- Bunker Oil/Fuel
- Jet Fuel (SAF)
- Heating Oils

The focus of future work is to globally commercialize the formulated biodiesel, particularly the AquaCharged Diesel, to aid nations that are not energy independent and rely on imported petroleum diesel. The use of FFET can help to extend the current reserves of diesel fuel, leading to fuel cost reduction and increased energy independence. The biodiesel formulations can be produced at refineries and be distributed through established pipelines, but alternative measures must be taken for areas without pipeline access.

The Intelligent Blending Station (IBS) machine illustrated in Figure 6.1 is being developed as a pilot project for easy access to biodiesel at gas stations, construction sites, farms, and other locations. This innovative system will enable on-site blending of biodiesel with traditional diesel, providing a convenient and sustainable fuel option. The IBS can play a crucial role in regions where pipeline infrastructure is limited, ensuring that communities and industries can readily access and benefit from the advantages of biodiesel.

Moreover, the patented FFET technology's adaptability to gasoline, bunker oil/fuel, jet fuel, and heating oils opens up new possibilities for reducing greenhouse gas emissions and fossil fuel dependence across various sectors. By implementing FFET in these fuel types, significant progress can be made towards achieving more environmentally friendly and energy-efficient transportation, shipping, aviation, and heating solutions worldwide.

In summary, the global commercialization of these biodiesel formulations, combined with the application of FFET in diverse fuel segments, holds the potential to create a substantial positive impact. It can not only address energy security concerns for nations relying heavily on imported petroleum diesel but also contribute to global efforts in combatting climate change and transitioning towards a greener, sustainable energy future.

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APPENDIX

APPENDIX

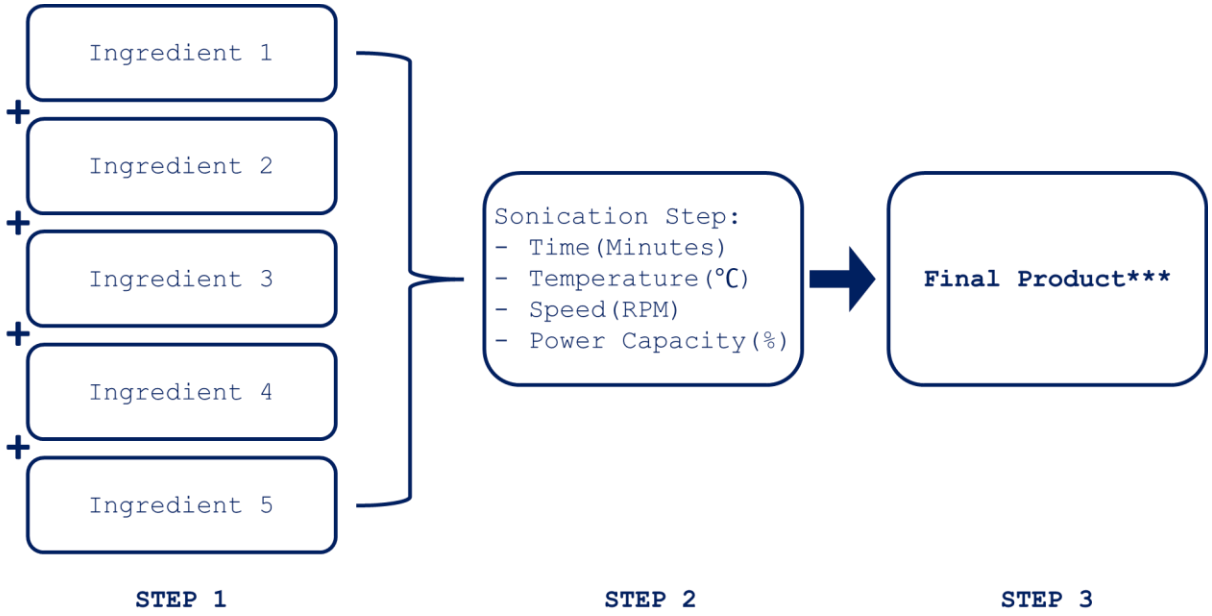

Figure A 1. Biodiesel Formulation Method and Process

Figure A 2. AquaCharged Diesel Being Poured in a 2021 RAM 2500 Turbo-Diesel Truck

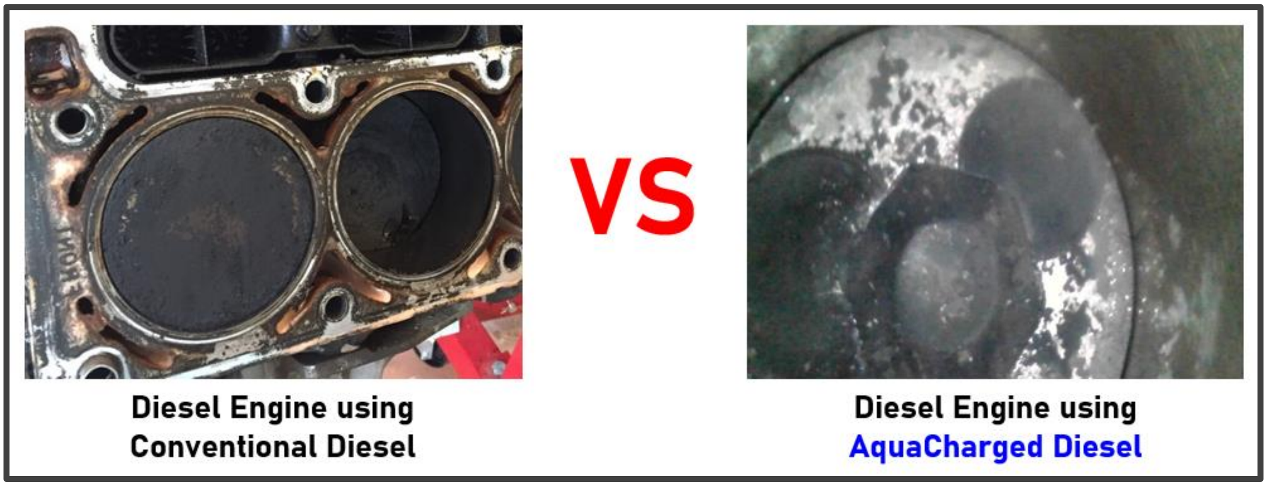

Figure A 3. Soot Formation Comparison Between Conventional Diesel and AquaCharged Diesel Utilization in a Diesel Engine.

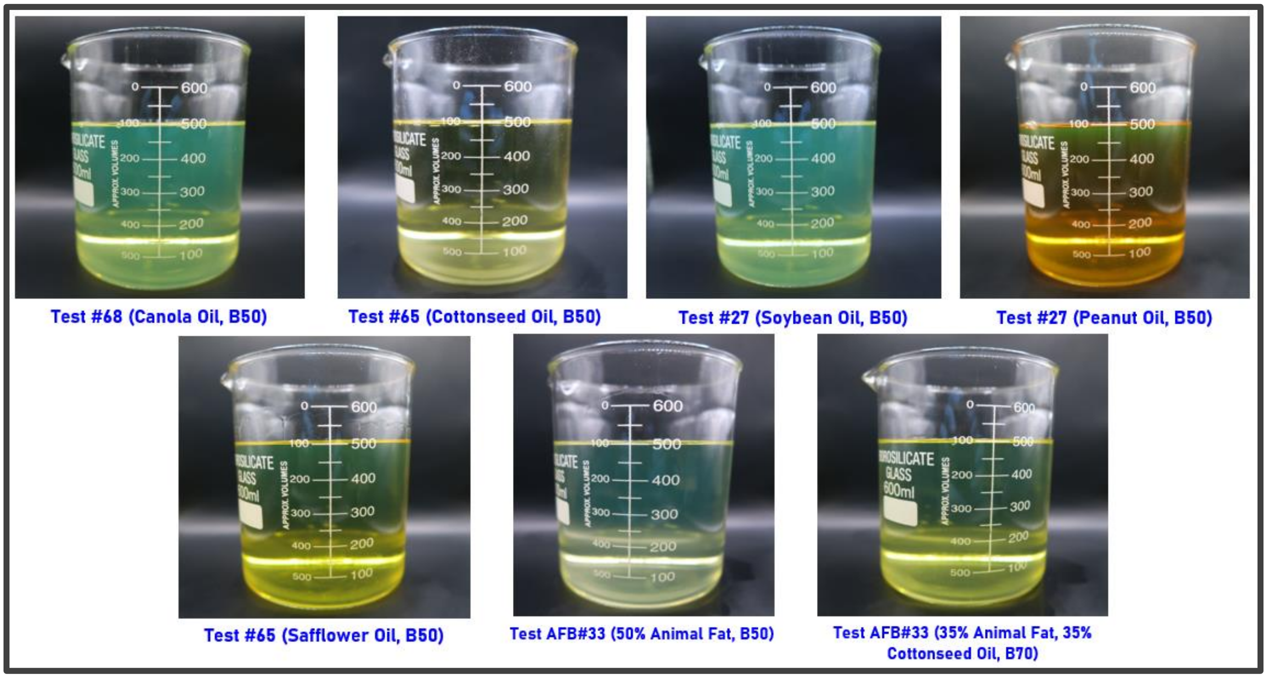
Test #68 (Canola Oil, B50)
Test #65 (Cottonseed Oil, B50)
Test #27 (Soybean Oil, B50)
Test #27 (Peanut Oil, B50)
Test #65 (Safflower Oil, B50)
Test AFB#33 (50% Animal Fat, B50)
Test AFB#33 (35% Animal Fat, 35% Cottonseed Oil, B70)

Figure A 4. Side by Side Comparison of Seed-Oil and Animal Fat Biodiesel Formulations Manufactured in this Study.