

Maximizing Biodiesel Production and Combustion to Discover Optimal Pathways using Specific Hydrocarbons, Varying [KOH] and Alcohol-to-Oil Ratios

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Abstract— Biodiesel is a carbon-neutral alternative to address sustainability and rising CO₂ emission levels from fossil fuels. With the inevitable rise in global population, further research into biodiesel may lead to a fuel that can meet the world's growing food and energy demand. The objective of this study is to understand the relationships between hydrocarbon length and energy density; [KOH] and percent yield; and alcohol-to-oil ratios and percent yield to optimize biodiesel production and energy combustion. Canola oil, methanol, and varying [KOH] were used in the synthesis of various biodiesel batches. The resulting pure biodiesel underwent calorimetry. We hypothesized that longer hydrocarbon length results in greater energy density. Our results support our hypothesis, which found that precursor oils with longer hydrocarbon length resulted in significantly greater energy density. We further hypothesized that an increase in [KOH] would lead to a peak percent yield of fatty acid methyl esters at 1% [KOH] and decrease upon [KOH] >1%. Our results refuted our hypothesis, instead suggesting ≥2% [KOH] as the peak percent yield. Lastly, we hypothesized that a 3:1 alcohol-to-oil ratio would produce a greater percent yield than a 6:1 ratio; our results were inconclusive. Marginal variations in procedures among research teams in conjunction with extraneous variables resulted in slight inconsistencies. Our findings suggest a combination of canola oil, methanol, and 2% [KOH] to produce optimal biodiesel.

Index Terms— Alternative-Energy, Renewable Energy, Biodiesel, Hydrocarbons, [KOH], Alcohol-to-Oil Ratio, Emissions, Fuel

1 INTRODUCTION

SOCIETY, with an unprecedented amount of technological innovation in human history, can largely credit its advancement to energy. Energy has been a necessity for millennia, powering the world's everyday commodities: homes, factories, transportation, and other technologies. Currently, this energy comes from fossil fuels obtained beneath the Earth's surface. Examples of fossil fuels include: coal, oil, and natural gas. In 2017, BP (formerly British Petroleum) reports that nearly 85.5% of the world's energy consumption comes from fossil fuels [1]. Petroleum, commonly known as diesel, plays a significant role in powering much of the world's transportation. The National Academies of Sciences, Engineering, and Medicine reports that 92% of the energy used for transportation comes from fossil fuels, consisting primarily of gasoline and diesel fuels [2]. Fossil fuels are derived from the remains of deceased organisms that go through a process of fossilization which takes millions of years; thus, classifying it as a nonrenewable resource. With humans consuming fossil fuels at a faster rate than produced, there will be a global shortage of fossil fuels estimated by 2060 [3]. Additionally, the combustion and usage of fossil fuels release greenhouse gases (GHGs) that contribute to global climate change: primarily carbon in the form of CO₂. NASA discovered a 120 pm increase in fossil fuel CO₂ emission levels from 280 ppm in the last 150 years [4]. This pollutant gas acts as an atmospheric blanket over the Earth by trapping in heat from the sun [5]. Presently, the recycling of carbon is split between two different systems: a fast cycle and a slow cycle. The fast carbon cycle occurs in our day-to-day life when living things, namely plants and phytoplanktons, take in carbon dioxide from the atmosphere in combination with water to create sugar and oxygen. However, the slow carbon cycle, although similar, takes an unrealistically long duration (100-200 hundred million years) where organic substances are compressed

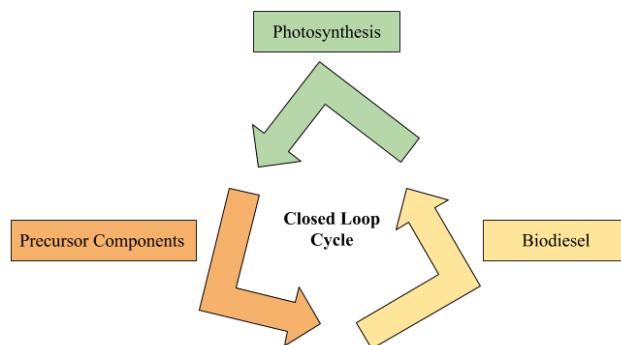
under ideal conditions, and allowed to settle over time [6]. As it stands, the slow carbon cycle does not occur at a fast enough rate to combat our current situation. The fast carbon cycle, responsible for CO₂ regulation, has been overwhelmed due to a greater level of CO₂ emission in comparison to intake as a result of human activity. Due to this, our planet is under a growing temperature crisis that can no longer be controlled. In fact, global warming has directly caused ocean acidification: the decrease in ocean water pH levels and increase in acidity, which negatively impacts ocean wildlife, ecosystems, and endangers the entire food web [7]. Carbon dioxide diffusion in water leads to a chemical reaction that forms carbonic acid shown through the equation: CO₂ (aq) + H₂O → H₂CO₃. The production of carbonic acid, a weak acid, leads to an increase in a H⁺ ions to cause an increased ocean acidification. At our current rate, CO₂ levels are expected to decrease ocean pH levels from 8.1 to 7.8 by 2090 [8]. The startling rate of fossil fuel consumption and growing environmental concerns have alarmed governments around the world to seek a long-term solution mitigating global warming. In conjunction with these factors, countries are in search of renewable, environmentally-friendly, and cost-friendly alternative sources of fuel.

Renewable energy consists of five major categories: biomass, hydropower, geothermal, wind, and solar [9]. Biodiesel is a sub-category of biomass and is widely considered as a replacement for petroleum diesel due to its biodegradable, renewable, environmentally-friendly, and nontoxic nature. Biodiesel is created through the usage of many replenishable sources: fats, greases, or natural oils in combination with an alcohol and the presence of a catalyst through a process called transesterification. According to the U.S Energy Information Administration (EIA), one gallon of biodiesel releases 17.9 lbs of CO₂ in comparison to

diesel fuel releasing 22.4lbs of CO₂ [10]. Biodiesel reduces GHGs by approximately 4.5 lbs of CO₂ in comparison to its counterpart, petroleum diesel. Additionally, biodiesels greater lubricity and lack of sulfur are expected to reduce engine water while also reducing engine pollution [11]. Biodiesel creates a closed cycle where any carbon released is recycled. At the beginning of the cycle, plants consume the carbon dioxide in the atmosphere. Then, those plants are harvested for their natural oils as part of the chemical process in creating biodiesel. The biodiesel is then burned for its energy; in turn, releasing carbon dioxide. Plants take in this carbon dioxide and the process begins again (Figure 1). Unlike biodiesel, fossil fuels have no means of recycling the carbon emitted into the atmosphere.

To maximize biodiesel yield, it is necessary to analyze the fatty acid compositions of various fats and oils. Hydrocarbons, the primary compound in fatty acids, are responsible for producing the majority of the energy found in biodiesel. Fatty acids are broken into three different types of fat: saturated, monounsaturated, and polyunsaturated. Saturated fats lack carbon double bonds, increase melting point and viscosity while also reducing lubricity. The more double bonds present, the greater the energy output (bond energy). The greater the viscosity, the more the engine will clog. Though this might be the case, it makes up for its weaknesses with decreased nitrogen oxide (NOx) emissions, greater oxidative stability, reduced deposition,

Figure 1: Closed Loop Cycle of Biodiesel



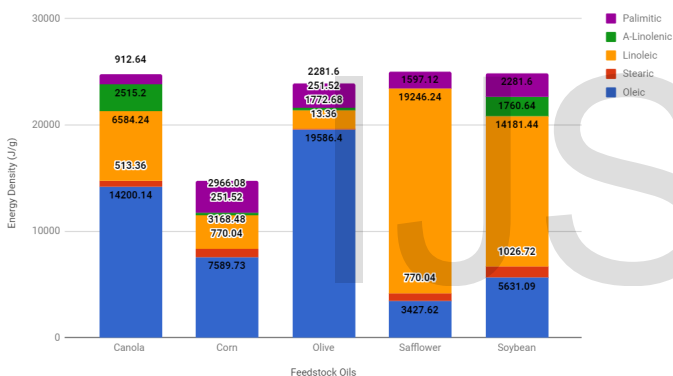
optimal cetane number and high calorific value [11, 12]. Conversely, unsaturated fats only contain a single double bond which leads to reduced oxidative stability, increased NOx emissions, increased deposition, and lower viscosity. However, unsaturated fats boast low gel points, high densities, and also reductions in HC, CO, and smoke emissions [13]. Similarly, polyunsaturated fats contain many of the same chemical properties as unsaturated fats with the only significant difference being that polyunsaturated fats contain one or more carbon double bonds. Taking all of these characteristics into careful consideration, canola oil stood out as the primary candidate with its high unsaturated content to low saturated content ratio in conjunction with its high energy content and liquidity at low temperatures.

Table 1: Oil Composition by Fat Type			
Oil	Saturated	Monounsaturated	Polyunsaturated
Canola oil	7%	62%	31%
Safflower oil	7%	14%	79%
Camelina oil	10%	33%	54%
Sunflower oil	10%	20%	66%
Corn oil	13%	24%	59%
Olive oil	14%	73%	11%
Soybean oil	16%	23%	58%
Peanut oil	17%	46%	32%
Chufa oil	20%	67%	12%
Cottonseed oil	26%	18%	52%
Lard	39%	45%	11%
Palm oil	49%	37%	9%

Butter	63%	26%	4%
Coconut oil	90%	6%	2%

To determine the theoretical rankings of notable precursor oils, it is necessary to calculate the energy density in constituent of each fatty acid by analyzing their molecular structure and determining their total bond energy. To demonstrate, canola contains 56% oleic acid, 26% linoleic acid, 10% alpha-linolenic acid, 4% palmitic acid, and 2% stearic acid [14]. The sum of these acids only composes 98% of canola oil with an unknown 2%. For this reason, the 2% was added to the constituent fatty acid with the greatest overall makeup (%) of the oil. For canola, instead of oleic acid composing of 56%, it now made up 58%. 14200.14 J/g, 513.36 J/g, 6584.24 J/g, 2515.2 J/g, and 912.64 J/g altogether results in a predicted energy density of 24725.58 J/g. The theoretical energy density contribution of each respective oil's constituent fatty acid is pictured in Figure 4 (from least to greatest): palm (23,847.68 J/g), olive (24,405.56 J/g), canola (24725.58 J/g), corn (24745.85 J/g), soybean (24881.49 J/g), and safflower (25041.02 J/g).

Figure 2: Feedstock Oils vs. Energy Density Contributed by Constituent Fatty Acids



The next component in the formulation of biodiesel is an alcohol. Examples of alcohols include methanol, ethanol, and butanol. To maximize data robustness, this study will be restricted to methanol and ethanol. In transesterification, an alcohol is combined with a catalyst to create a suitable environment for deprotonation which turns the alcohol into an oxide, a negatively-charged basic solution [15]. Methanol, also known as methyl alcohol, contains a single carbon atom while also being highly toxic — it can cause blindness in small doses if consumed [16]. Moreover, methanol can be produced from natural gases, coal, and renewable sources such as municipal waste, biomass and recycled CO₂ [17]. Conversely, ethanol has two carbon atoms and contains nearly two-thirds the energy content of gasoline while also being less toxic than its counterpart [16, 18]. Furthermore, the Biofuels Association of Australia describes how ethanol is created through fermentation, a process where yeast transforms glucose into ethanol [19]. Methanol contains approximately 22.7MJ/kg specific energy whereas ethanol contains 29.7MJ/kg — a 30.84% increase in energy per unit mass [20]. Logically, it would be wise to utilize ethanol due to its additional carbon atom,

low toxicity, and high energy content in combination with its easily renewable manufacturing process. However, a study regarding the impacts of alcohol type, ratio and stirring time on biodiesel production disproves the assumption of ethanols superiority in biodiesel yield (A. B. M. S. Hossain 2010). From his data, he concluded that methanol produced the highest biodiesel yield (49.5%) followed by ethanol (23.5%), and butanol (19.5%)(Figure 3)[21]. Furthermore, a study examining the thermal energy generated by methanol-based biodiesel and ethanol-based biodiesel by Briana Young supports Hossain's results. Young's findings indicate that methanol-based biodiesel generated a greater amount of thermal energy with a total run time more than double that of ethanol [22]. Longer run time means more thermal energy, and more thermal energy means greater energy output. The experimental results in comparison to theoretical results conclude methanol-based biodiesel as superior to that of ethanol by exhibiting greater energy output and overall greater biodiesel yield by more than 210%. Given these points, it is in our best interest to utilize methanol.

The catalyst is crucial in expediting the conversion of triglycerides into fatty acid methyl esters (FAMES) and fatty acid ethyl esters (FAEs). The most common alkaline catalysts used to produce biodiesel are NaOH, KOH, CH₃ONa, and CH₃OK [23]. To maximize data robustness, this study will be restricted to NaOH and KOH. NaOH can be created and purchased with a purity up to 99% (100% is impossible due to the catalysts hygroscopic behavior) and at a lower price than its counterpart. As a result of high purity, significantly lower amounts of NaOH are needed to fully catalyze a reaction.. The drawbacks of NaOH, however, are that it produces thick glycerin and solid soap. Conversely, KOH dissolves faster than NaOH and produces liquid soap, but due to the purity being limited to 90%, a greater amount of KOH (121g) is needed to dissolve 100mL of water [24]. In 2006, a study on optimized biodiesel production using alkaline catalysts found KOH (82.81%) to produce 7.5% more biodiesel than NaOH(75.31%) (A. Singh 2010). Furthermore, a second study came to the same conclusion that the percent yield for KOH (93.10%) would be greater in comparison to NaOH (87.70%) [26]. The former having 5.4% greater biodiesel yield in comparison to the latter. These findings confirm A. Singh's earlier works. Given these points, it is in our best interest to utilize KOH.

To investigate the hydrocarbon length to energy density relationship, we ask what effect does a longer hydrocarbon length have on the energy density of the resulting biodiesel? Our hypothesis states that the longer a hydrocarbons length, the greater the product biodiesels energy density. The value for energy density originates from the formation of CO₂ and H₂O upon combustion

which releases energy in the form of heat. These values predict the energy density of our end product (after synthesis) while also taking into account its hydrocarbon length. The greater the energy density of an oil, the longer its hydrocarbon length is due to the requirement of new, stronger bonds to combust and break to release more energy when the highly stable H_2O and CO_2 molecules form. An 18:1 carbon atom to double bond ratio, found commonly in canola oil, is an ideal ratio because having one double bond in a hydrocarbon is the ideal amount of unsaturation to avoid drying out and solidifying at high temperatures [27]. In our alternative hypothesis, we believe that an increase in hydrocarbons length would cause a decrease in energy density. Hydrocarbons consist of many hydrogen-to-carbon bonds with a lot of potential energy. When the double bonds form within the hydrocarbon they replace 2 C-H bonds which minimizes the potential energy found in a hydrocarbon [27]. Contrastly, in our null hypothesis, we believe that an increase or decrease in hydrocarbon length would prove inconclusive and have no effect on energy density.

To investigate the catalyst to triglyceride ratio, we ask what effect does an increase in KOH have on percent yield? Our hypothesis states an increase in our catalyst, KOH, would maximize the percent yield of fatty acid methyl esters at 1% [KOH] and steadily decrease upon [KOH] greater than 1%. Studies reported that a concentration of 1% KOH produced the highest percent yield in comparison to 0.5%, and 2% [KOH] [28]. This study is further supported by another article which found that fatty ester yield increased with catalyst concentration up to 1.0%. Excessive amounts of

catalyst resulted in saponification with triglycerides and the production of soap and water which reduces biodiesel yield. Insufficient catalyst concentrations resulted in a lack of necessary activation energy for the reaction to proceed [29]. In our alternative hypothesis, we believe that an increase in [KOH] $\geq 1\%$ would lead to a higher percent yield. Conversely, in our null hypothesis, we believe that an increase in [KOH] $\geq 1.0\%$ would prove inconclusive and have no effect on percent yield.

To investigate the alcohol-to-oil molar ratio, we ask what is the ideal alcohol-to-oil ratio to maximize biodiesel percent yield? Our hypothesis states that the ideal alcohol-to-oil ratio is 3:1. 3 moles of alcohol react with 1 mole of a triglyceride during transesterification to produce 3 moles of fatty acid esters and 1 mole of glycerol. The fatty esters are what make up biodiesel, so having a 3:1 ratio of alcohol-to-oil would produce an efficient amount of biodiesel and lead to the highest percent yield [30]. In our alternative hypothesis, we believe that since a 3:1 alcohol-to-oil ratio is the minimum ratio needed to break up triglycerides and produce fatty esters, the reaction will be limited and higher alcohol-to-oil ratios are required to increase percent yield. Le Chatelier's principle states that changing a variable that describes a system will result in a shift of the position of equilibrium that counteracts the effect of this change [31]. By using a ratio that is greater than the stoichiometric ratio, specifically a 6:1 alcohol-to-oil ratio, it is possible to double the amount of fatty esters produced which means a greater percent yield. Conversely, in our null hypothesis, we believe having an alcohol-to-oil ratio of 3:1 would have no effect on the percent yield

2 METHODS

2.1 Materials

The production of a 20g batch of biodiesel for Hypothesis 1 and Hypothesis 2 required 2.925 grams of methanol, 0.10g for 0.5% KOH, 0.15g for 0.75% KOH, 0.20g for 1% KOH, 0.4g for 2% KOH, and 0.17g of anhydrous magnesium sulfate. The production of a 20g batch of biodiesel for Hypothesis 3 required 2.21 grams of methanol, 0.07g of KOH for a 3:1 alcohol ratio, and 4.42g of methanol and 0.14g of KOH for a 6:1 alcohol-to-oil ratio. If the batches failed to separate, 0.66 of salt was used. 6.6g of water was needed to wash the biodiesel. The tools used for this procedure were 1 Labquest Mini, 1 thermometer probe to maintain temperature stability during synthesis, 1 mortar and pestle, 1 hot plate, 4 50mL glass beakers, 2 20mL amber vial, 1 10mL plastic pipette, 1 digital scale, 2 plastic weigh boats, 1 ring stand secured with a clamp, 1 50 mL separatory funnel and a glass stir rod. To perform calorimetry, the materials needed were 1 12 fl. oz. soda can, 1 3.81cm candle holder, 1 2cm wick, 1 aluminum heat shield, 1 12in ruler, and 1 alcohol thermometer capable of measuring up to 60°C. The tools must be clean and dried to avoid outside factors from affecting the results of our experiment. Additionally, every individual should have: 1 lab coat, 1 pair of safety goggles, and 1 pair of safety gloves to ensure safety when handling caustic substances.

2.2 Transesterification

Potassium hydroxide is used to catalyze the exothermic reaction between methanol and the triglyceride. It significantly decreases the activation energy required to be surpassed before turning into the products, fatty acid methyl esters (FAMES) and glycerol. Using a catalyst such as potassium hydroxide increases the probability of saponification due to the hygroscopic attributes of this catalyst. Potassium hydroxide is extremely prone to absorbing water, more water creates more soap and more soap creates less product. Thus, lowering percent yield. The transesterification process should be done with urgency to avoid outside factors like these from affecting the production of biodiesel.

In order to catalyze the reaction, add desired [KOH] of crushed potassium hydroxide (KOH) pellets into a 50mL glass beaker. Crush the pellets with the mortar and pestle so the catalyst dissolves faster into the mixture due to a larger surface area. Then, add desired grams of methanol into the glass beaker and mix the alcohol with a glass stir rod for 5-15 minutes until the catalyst is fully dissolved. This deprotonates methanol into methoxide. Next, add desired grams of anhydrous magnesium sulfate and gently stir. Magnesium sulfate is necessary in extracting the remaining water particles from the biodiesel to avoid reduced percent yield. Pour 20 grams of canola oil into the glass beaker and place the glass beaker onto a hot plate preheated to 50-60°C

for 6-15 minutes. Heating gives the required amount of energy needed for the reaction to occur by increasing collision frequency, thus increasing pressure and the rate of reaction. Continue to stir. By adding heat, we are adding the necessary amount of energy needed to break the preformed bonds and allowing them to create new bonds. In our case, the alcohol will break apart the carbon atom between the fatty acid and the glycerol forming fatty acid methyl esters (FAMES). The remaining glycerol molecules form a dense black layer with the other charged molecules in the solution, this is also known as our impurities. Pour the crude biodiesel into a 20mL amber vial and allow it to sit for 24 hours at room temperature. This allows the glycerol to settle to the bottom.

If separation fails, heat the mixture to 50°C and pour 0.66g of salt into the vial. The salt attracts the glycerol molecules to form the desired glycerol layer. Allow the mixture to settle for 4 hours before continuing to the next step.

Additionally, by using the Arrhenius equation, $k = Ae^{-\frac{E_a}{RT}}$, we can prove that the reaction rate increases. The initial temperature rose from 311 K (18°C) to a final temperature of 343K (50°C); as temperature increases, the average kinetic energy of molecules increases — proving that the rate constant 'k' increases as temperature 'T' increases. This demonstrates the exponential relationship between temperature and reaction rate.

2.3 Separation

Glycerol is a byproduct of the chemical reaction between the triglycerides, and the alcohol used to separate the carbon atoms. These carbon atoms are responsible for holding the fatty acids and glycerol together. Consequently, glycerol is harmful and unnecessary because it polymerizes at high temperatures clogging internal combustion engines and partially oxidizes into toxic acrolein.

To begin the separation process, gently decant the mixture into a 50 mL separatory funnel held up by a ring stand secured with a clamp. Wait until all of the crude biodiesel has been separated from the remaining glycerol molecules. Draining time will vary based on the amount of crude biodiesel, observe when the dark yellow glycerol layer fully separates from the yellow, crude biodiesel. Remove the remaining crude biodiesel into a 50 mL glass beaker.

2.4 Purification

Crude biodiesel contains several impurities: free fatty acids, unreacted precursor oil molecules, potassium hydroxide, methanol, and liquid soap. The presence of free fatty acids and water causes soap formation which consumes and reduces catalyst effectiveness which reduces percent yield [32].

To remove these impurities, begin by gently adding 6-6.9 grams of water heated to 15-35°C into the separatory funnel. Then, gently stir to avoid disrupting and mixing the impurities with the biodiesel for 2-3 minutes till the remaining impurities are dissolved. Drain the biodiesel into a dry 50 mL beaker. Lastly, stir the mixture for approximately 1-2 minutes and remove the leftover, purified biodiesel into a clean 20 mL amber vial.

If emulsion occurs, add 2-4 grams of liquid glycerol to remove the excess water from the biodiesel layer, mix gently, and allow the emulsions to settle.

To determine the percent yield, weigh the biodiesel and compare the initial mass of 20g with its final mass using the equation below. After doing so, record the % yield.

$$\text{Percent Yield} = \frac{\text{Actual Yield}}{20\text{g Precursor Oil}} \times 100\%$$

2.5 Calorimetry

50g of room temperature water was poured into a clean 12 fl. oz. soda can and secured onto a ring stand's arm. Biodiesel was poured into a 3.81 cm candle holder until it was full and a 2 cm wick was placed in the center of it. The soda can was lowered until it was 2 cm above the wick. The mass of the candle holder with the purified biodiesel was recorded. The candle holder and biodiesel were surrounded by an aluminum heat shield to reduce heat loss and increase safety from the combustion gases. The wick was lit on fire and temperature of the water was monitored every 1 minute until 5 minutes passed. The height of the soda can was adjusted during the experiment to keep it 2 cm above the wick and ensure heat loss during calorimetry was at a minimum. The fire was snuffed out after 5 minutes and the mass of the candle holder with biodiesel after the experiment was recorded.

The energy of the biodiesel in Joules was calculated using the equation $Q = mC\Delta T$. m was the mass of water that was heated during the combustion reaction. It should be noted that since the experiment was not a closed system, some of the energy produced by the biodiesel escaped into the surroundings. Thus, the calorimetry constant of 2.2 was calculated and used to correct for the heat lost to the calorimeter.

Energy density (J/g) was calculated using Q from above. The heat produced by the combustion reaction was divided by the mass of the biodiesel burned. The mass of the burned biodiesel was found by subtracting the initial mass of the candle holder and biodiesel with its final mass. This data was used to understand the energy density of the studied biodiesel.

3 RESULTS

The analysis of our experimental data in comparison to the theoretical data (Figure 2) compares precursor oils to energy density (J/g). Figure 3 illustrates the energy density (J/g) of all the canola-based biodiesel batches (n=134), corn-based biodiesel batches (n=7), olive-based biodiesel batches (n=41), safflower-based biodiesel batches (n=8), and soybean-based biodiesel batches (n=27) from the performed experiments with standard error values. The average energy density of our experimental data on canola oil biodiesels was 26732.4 J/g; this is a 2006.82 J/g increase from our theoretical calculations on canola oils contributions to the biodiesels composite energy density. The average for corn oil biodiesels was 27709.83 J/g, a 2963.98 J/g increase from our theoretical value. The average for olive oil biodiesels was 22986.97 J/g, a 1418.59 J/g decrease from our theoretical value. The average for safflower oil biodiesels was 29103.79 J/g, a 4062.77 J/g increase from our theoretical value. The average for soybean oil biodiesels was 20047.85 J/g, a 4833.64 J/g decrease from our theoretical value. The highest average energy density came from safflower oil biodiesels, and the lowest came from soybean oil biodiesels. The standard error value for each oil (from least to greatest): canola, olive, soybean, corn, and safflower (Table 1). Figure 4 illustrates the hydrocarbon length of each selected precursor oil ordered from shortest to longest length. The hydrocarbon lengths were 17.74, 17.8, 17.8, 17.86, and 17.92 for corn, olive, soybean, safflower, and canola respectively. Figure 5 illustrates a cubic polynomial trendline correlating hydrocarbon length with energy density. The r-squared value of 0.922 demonstrates a high statistical correlation between hydrocarbon length and the cubic polynomial regression line.

Figure 3: Experimental vs. Theoretical Data On Hydrocarbon Length

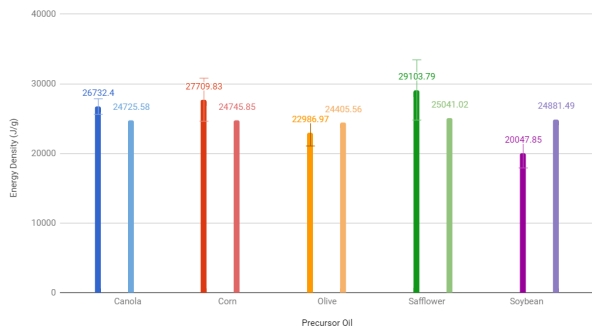


Figure 4: Hydrocarbon Length of Precursor Oils vs. Energy Density (J/g)

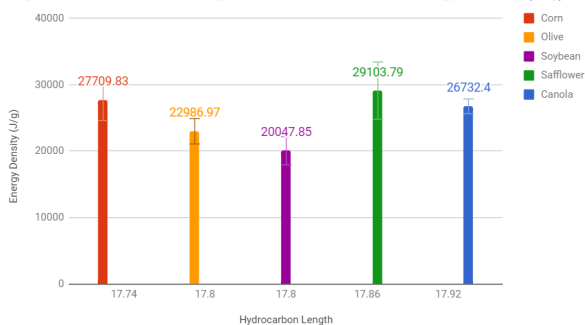


Figure 5: Hydrocarbon Length in Various Precursor Oils vs. Energy Density (J/g)

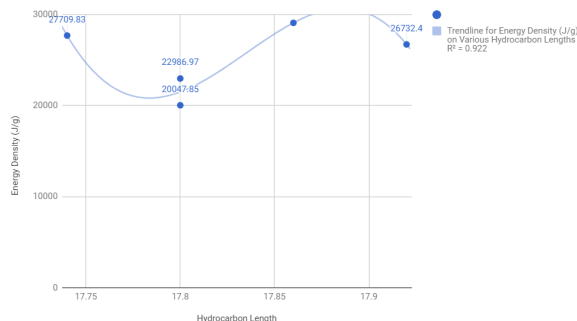


Table 2 displays the statistical data on energy density for precursor oils. The lowest energy density came from olive oil biodiesels and the highest energy density came from canola oil biodiesels. The range for canola was 74050.92 J/g, for corn oil biodiesels was 20443.06 J/g, for olive oil biodiesels was 50699.27 J/g, for safflower oil biodiesels was 37042.55 J/g, and for soybean oil biodiesels was 40449.24 J/g. The smallest range was from corn oil biodiesels and the largest came from canola oil biodiesels. The median for canola oil biodiesels was 25840.11 J/g, for corn oil biodiesels was 26668.40 J/g, for olive oil biodiesels was 22149.31 J/g, for safflower oil biodiesels was 30616.89 J/g, and for soybean oil biodiesels was 16,108.40 J/g. The lowest median was from soybean oil biodiesels and the highest median came from safflower oil biodiesels. The largest mean came was from safflower oil biodiesels and the smallest mean came from olive oil biodiesels. The standard error for canola oil biodiesels was 1115.39 J/g, for corn oil biodiesels was 3086.83 J/g, for olive oil biodiesels was 1919.52 J/g, for safflower oil biodiesels was 4320.24 J/g, and for soybean oil biodiesels was 2131.25 J/g. The lowest standard error (1115.39 J/g) was from canola oil biodiesels and the highest standard error (4320.34 J/g) came from safflower oil biodiesel.

Table 2: Range and Standard Error Values on Energy Density for Precursor Oil Data

Oil	Lowest Value (J/g)	Highest Value (J/g)	Data Range (J/g)	Standard Error (J/g)
Canola	3446.28	77497.20	74050.92	±1115.39
Corn	18235.58	38678.64	20443.06	±3086.83
Olive	3069.88	53769.15	50699.27	±1919.52
Safflower	1111.05	48153.60	37042.55	±4320.34
Soybean	3231.76	43681.00	40449.24	±2131.25

The analysis of our data on 0.5%, 0.75%, 1%, and 2% [KOH] compares varying catalyst concentrations to percent yield. Figure 16 illustrates the average percent yield of all batches made with 0.5% [KOH] (n=61), 0.75% [KOH] (n=35), 1.0% [KOH] (n=5), and 2.0% [KOH] (n=6). The average percent yield for 0.50% [KOH] was 51.01% percent yield, 0.75% [KOH] was 48.64%, 1% [KOH] was 57.39%, and 2% [KOH] was 59.52%.

Figure 16: KOH Concentration (%) vs. Average Percent Yield (%)

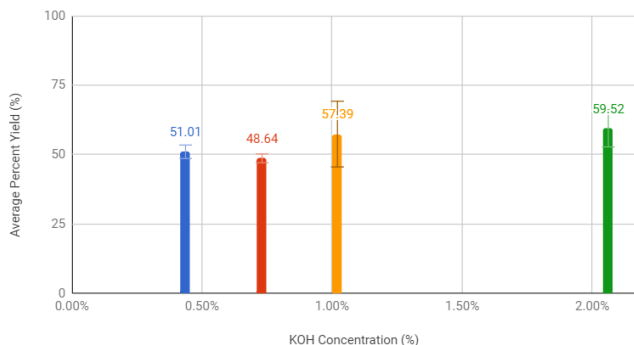


Table 3 displays the statistical data on percent yield for [KOH]. The lowest percent yield was from 0.75% [KOH] biodiesel and the highest percent yield came from 1% [KOH] biodiesel. The data range for 0.5% [KOH] biodiesels was 54.80%, for 0.75% it was 79.87%, for 1% it was 68%, and for 2% it was 46.05%. The smallest range was from 2% [KOH] biodiesels, and the largest came from 0.5% concentration KOH biodiesels. The median for 0.5% concentration KOH biodiesels was 54.8%, for 0.75% [KOH] biodiesels it was 48.50%, for 1% [KOH] biodiesels it was 48% and for 2% [KOH] biodiesels it was 56.35%. The smallest median came from 1% [KOH] biodiesels and the largest median came from 2% [KOH] biodiesels. The largest mean came from 2% [KOH] biodiesels and the smallest mean came from 0.75% [KOH] biodiesels. The standard error for 0.5% [KOH] biodiesels was ±2.44%, for 0.75% [KOH] biodiesels it was ±3.27%, for 1% [KOH] biodiesels it was ±11.84%, and for 2% [KOH] biodiesels it was ±6.76%. The lowest standard error was from 0.5% [KOH] biodiesels and the highest standard error came from 1% [KOH] biodiesels.

Table 3: Range and Standard Error Values on Percent Yield (%) for [KOH] Data				
[KOH] (%)	Lowest Value (%)	Highest Value (%)	Data Range (%)	Standard Error (%)
0.5%	10.80	95.65	84.85	±2.44
0.75%	9.25	89.12	79.87	±3.27
1%	28.00	96.00	68.00	±11.84
2%	39.00	85.05	46.05	±6.76

and 14:1 compares varying alcohol-to-oil ratios to percent yield. Figure 29 illustrates the average percent yield of all batches made with 1:1 (n=3), 3:1 (n=8), 4:1 (n=), 5:1 (n=54), 6:1 (n=36), 7:1 (n=3), 8:1 (n=4), 9:1 (n=6), and 14:1 (n=2). The average percent yield for 1:1 was 22.17%, 3:1 was 59.12%, 4:1 was 62.72%, 5:1 was 47.47%, 6:1 was 53.68%, 7:1 was 39.65%, 8:1 was 53.10%, 9:1 was 57.88%, and 14:1 was 69.28%.

Figure 29: Average Percent Yield vs. Methanol Alcohol:Oil Ratios

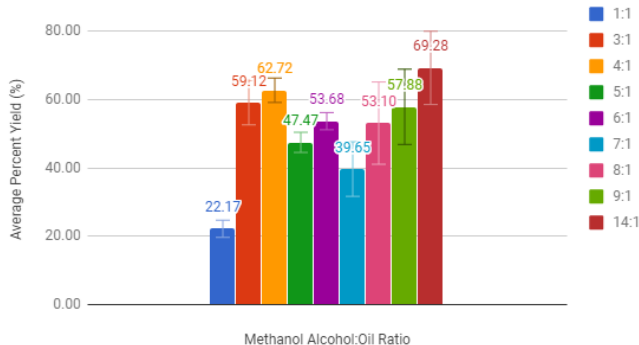


Table 4 displays the statistical data on percent yield for alcohol-to-oil ratio data. The lowest average percent yield was from the 1:1 alcohol-to-oil ratio and the highest percent yield came from the 3:1 alcohol-to-oil ratio. The data range for the 1:1 ratio was 8.50%, for the 3:1 ratio it was 60.45%, for the 5:1 ratio it was 87.45%, for the 6:1 ratio it was 67.05%, and for the 7:1 ratio it was 25.50%. The smallest range was from the 1:1 ratio, and the largest came from the 5:1 ratio. The median for the 1:1 ratio was 21.00%, for the 3:1 ratio it was 57.50%, for the 5:1 ratio it was 50.35%, for the 6:1 ratio it was 56.75%, and for the 7:1 ratio it was 33.45%. The smallest median came from the 1:1 ratio and the largest median came from the 3:1 ratio. The largest standard error came from the 1:1 ratio and the smallest standard error came from the 3:1 ratio. The standard error for the 1:1 ratio was ±2.52%, for the 3:1 ratio it was ±6.53%, for the 5:1 ratio it was ±2.95%, for the 6:1 ratio it was ±2.52%, and for the 7:1 ratio it was ±7.99%. The lowest standard error was from the 1:1 ratio and the highest standard error came from 5:1 ratio.

Table 4: Range and Standard Error Values on Percent Yield (%) for Alcohol-to-Oil Ratio Data				
Ratio	Lowest Value (%)	Highest Value (%)	Data Range (%)	Standard Error (%)
1:1	18.50	27.00	8.50	±2.52
3:1	29.00	89.45	60.45	±6.53
5:1	8.55	96.00	87.45	±2.95
6:1	21.10	88.15	67.05	±2.52
7:1	30.00	55.50	25.50	±7.99

The analysis of our data on 1:1, 3:1, 4:1, 5:1, 6:1, 7:1, 8:1, 9:1,

4 DISCUSSION

The analysis on hydrocarbon length supports Hypothesis 1 which states that longer hydrocarbon lengths results in greater energy density. When comparing canola-based biodiesels to olive-based biodiesels, canola has a longer hydrocarbon length according to our theoretical calculations which is further supported by the experimental data; the experimental data found canola-based biodiesels to have a greater average energy density than olive-based biodiesels. The correlation between hydrocarbon length and energy density is further evident when comparing canola-based biodiesels to soybean-based biodiesels. The theoretical calculations determined canola as having a greater hydrocarbon length than soybean; the experimental data found that canola-based biodiesels had a greater average energy density than soybean-based biodiesels. Additionally, the comparison of safflower-based biodiesels to soybean-based biodiesels demonstrates another significant correlation between hydrocarbon length and energy density.

Figure 3: Experimental vs. Theoretical Data On Hydrocarbon Length

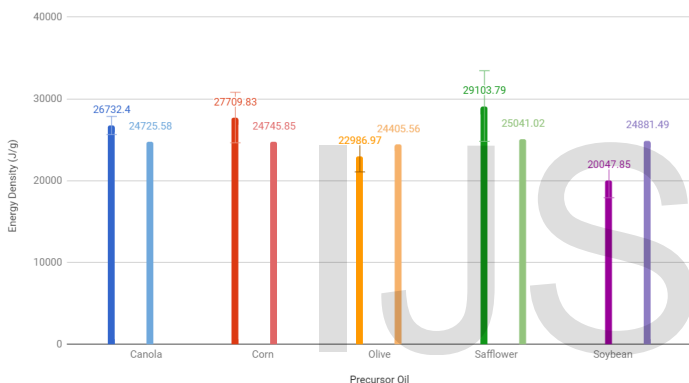
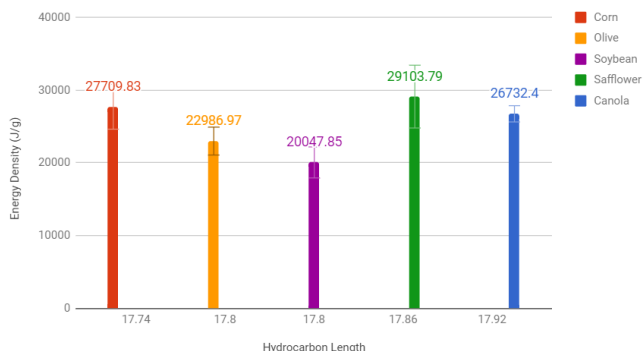


Figure 4: Hydrocarbon Length of Precursor Oils vs. Energy Density (J/g)



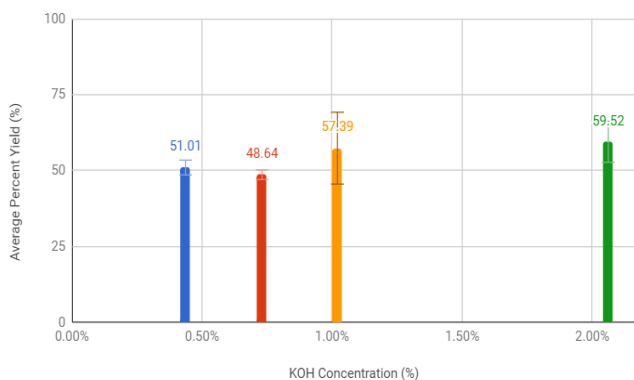
When comparing safflower-based biodiesels to soybean-based biodiesels, safflower has a longer hydrocarbon length according to our theoretical calculations; the experimental data found safflower-based biodiesels to have a greater average energy density than olive-based biodiesels. However, the comparison between corn-based biodiesels to soybean-based biodiesels demonstrates an inverse relationship; our theoretical calculations determined soybean biodiesels as having a longer hydrocarbon length than corn but the experimental data discovered corn-based biodiesels as having a greater average energy density than soybean-based biodiesels. This comparison is an outlier due to the lack of a substantial sample size of biodiesels produced with corn oil. From this comparison, it is possible to verify our alternative hypothesis which states that longer hydrocarbon length corresponds to lower energy density. Nonetheless, the experimental data supports Hypothesis 1 with three positive correlations in comparison to an outlier inverse correlation. However, more data is needed to create a stronger conclusion.

Table 2: Range, Mean, Median and Standard Error Values on Energy Density for Precursor Oil Data

Oil	Lowest Value (J/g)	Highest Value (J/g)	Data Range (J/g)	Mean (J/g)	Median (J/g)	Standard Error (J/g)
Canola	3446.28	77497.20	74050.92	26732.4	25840.11	±1115.39
Corn	18235.58	38678.64	20443.06	27709.83	26668.40	±3086.83
Olive	3069.88	53769.15	50699.27	22986.97	22149.31	±1919.52
Safflower	11111.05	48153.60	37042.55	29103.79	30616.89	±4320.34
Soybean	3231.76	43681.00	40449.24	20047.85	16108.40	±2131.25

The analysis on [KOH] refutes Hypothesis 2 which states that an increase in our catalyst, KOH, would lead to a peak percent yield of fatty acid methyl esters at 1% [KOH] and decrease upon [KOH] greater than 1%. When comparing 1% [KOH] biodiesels (n=5) to 0.5% (n=61), 0.75% (n=35), and 2% (n=6), we concluded that Hypothesis 2 was refuted, with 1% [KOH] biodiesels failing to produce the greatest average percent yield. Instead, 2% [KOH] biodiesels produced the greatest average percent yield. The standard error for 1% [KOH] biodiesel was 11.84%, the largest value, while the standard error in comparison to other concentrations ranged from a decrease of 0.83% to 9.4%.

Figure 16: KOH Concentration (%) vs. Average Percent Yield (%)



The averages of each respective [KOH] is heavily skewed upon initial examination; the high ranges indicate that the endpoints of the data are greatly spread out. These respective outliers can greatly skew the average to be significantly greater or lower than what the majority of the data would otherwise suggest. The error bars on 1% [KOH] creates an average range between a minimum of 45.55% and a maximum of 69.23%. The largest difference between 1% [KOH] biodiesels and 0.5% [KOH] biodiesels was 20.66% (1% max to 0.5% min), 23.86% for 0.75% [KOH] biodiesels (1% max to 0.75% min), and 2% [KOH] biodiesels was 16.47% (1% max to 2% min). The overlapping standard error bars indicate the possibility of varying [KOH]'s effect on percent yield; this is further evident when examining the largest possible difference between the averages of each respective [KOH], the impact on percent yield being at least 16% (Figure 16, Table 3). For instance, the percent yield of a 1% [KOH] biodiesels could increase to the maximum value of the standard error bar while the other concentrations decreased to their minimum values. In this case, it would be accurate to claim 1% [KOH] as having the greatest percent yield. However, the comparison between 0.75% [KOH] biodiesels and 2% [KOH] biodiesels illustrates 2% [KOH] biodiesel as having a greater average percent yield. From this comparison, it is possible to verify our alternative hypothesis which states that greater amounts of [KOH] results in greater percent yield. Nonetheless, the majority of the data supports our null hypothesis due to a lack of correlation between each respective [KOH]. Though, more data is needed to create a stronger conclusion.

Table 3: Range and Standard Error Values on Percent Yield (%) for [KOH] Data				
[KOH] (%)	Lowest Value (%)	Highest Value (%)	Data Range (%)	Standard Error (%)
0.5%	10.80	95.65	84.85	±2.44
0.75%	9.25	89.12	79.87	±3.27
1%	28.00	96.00	68.00	±11.84
2%	39.00	85.05	46.05	±6.76

The analysis on alcohol-to-oil ratio refutes Hypothesis 3 which states that a 3:1 alcohol-to-oil ratio would produce the highest percent yield in comparison to other ratios. When comparing a 3:1(n=8) alcohol-to-oil ratio to 1:1(n=3), 5:1(n=54), 6:1(n=36), 7:1(n=3) alcohol-to-oil ratio, we concluded that Hypothesis 3 was refuted with 3:1 alcohol-to-oil ratio failing to produce the greatest percent yield. Instead, suggesting a null relationship between the alcohol-to-oil ratio and biodiesel percent yield.

Figure 29: Average Percent Yield vs. Methanol Alcohol:Oil Ratios

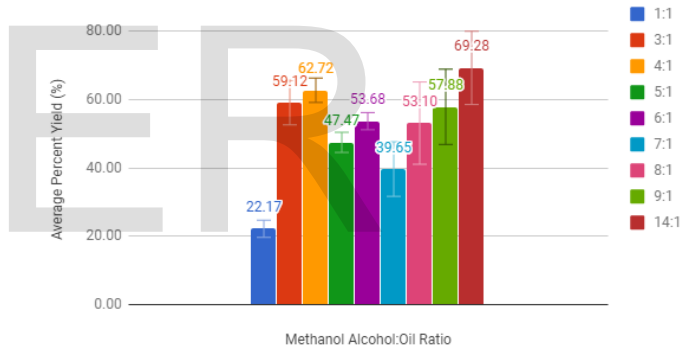


Table 4: Range and Standard Error Values on Percent Yield (%) for Alcohol-to-Oil Ratio Data				
Ratio	Lowest Value (%)	Highest Value (%)	Data Range (%)	Standard Error (%)
1:1	18.50	27.00	8.50	±2.52
3:1	29.00	89.45	60.45	±6.53
5:1	8.55	96.00	87.45	±2.95
6:1	21.10	88.15	67.05	±2.52
7:1	30.00	55.50	25.50	±7.99

4.1 Errors in Experimental Design

Due to the high standard error from our experiments, most notably 1% and 2% [KOH] biodiesels, we identified potential errors in our experimental design. The varying environmental temperature during experimentation resulted in inconsistencies with biodiesel synthesis, biodiesel yield, and glycerol separation. Additionally, varying humidity levels resulted in greater possibilities of saponification due to the lye's hygroscopic nature. The formation of soaps and glycerin increases as the water content in the mixture increases. With a relative humidity between 50%-55%, the probability of biodiesel with high water content increased significantly thus reducing biodiesel percent yield and creating unwanted outliers. For the calorimetry procedures, variations in candle wick length and in the height of the calorimeter above the flame led to an influx in energy density (J/g) calculations. In addition, maintaining the calorimeter above the flame as the wick burned down was not accounted for, and variations in combustion duration resulted in possibilities of data inaccuracy. The database used to compile information from our experiments was modified after the collection of data used in our analysis, which could heavily affect our results and conclusion. This was partially due to the lack of cohesiveness among research teams; for example, other research teams followed different processes and procedures. Additionally, the reliability of data collected from other research teams poses a significant concern. This variation in methodology heavily restricted data robustness due to the inconsistencies with stir time, heating duration, and temperature.

4.2 Future Work

We must ensure that all of these possible issues are clearly addressed before hand to ensure unwanted variables do not resurface. To further research the effects of hydrocarbon length on energy density (J/g), it is necessary to establish consistency and reliability with controllable variables: experimentation temperature, humidity levels, and procedure consistency. To address experimentation temperature, we advise tracking the transesterification temperature for 10 intervals and analyzing the relationship between average temperature and percent yield/energy density. To address varying humidity levels, we advise to perform experiments in an environment where humidity can be kept stable and consistent. To address procedure consistency among all research teams, we advise a cohesive process and procedure followed among all groups with the addition of bi-diurnal meetings to ensure each and every research groups objectives are consistent with one another. Additionally, we advise utilizing machinery to perform transesterification and calorimetry to a stricter degree: precise measurement of biodiesel components and greater consistency with stir time and temperature. Due to the inconclusive results from Hypothesis 2, we feel as if our study is incomplete and that further research into [KOH] on percent yield is necessary to better understand the corresponding relationship. For example, an experiment manipulating [KOH] from 2% to 5% with 0.5% intervals. We propose that we repeat this specific portion of the experiment while implementing the aforementioned procedure modifications to control extraneous variables.

The world's current rate of fossil fuel consumption and technology is steadily increasing while fossil fuels finite reserves are continually depleting. With the current global population projected to reach 9.7 billion by 2050, a sustainable energy source is expected to keep pace with demands for necessities such as food, water, housing, and electricity [33]. Biodiesel is a temporary alternative to address this energy crisis, which presents an inquiry: how can we maximize our already strained resources? The importance of high biodiesel yield and energy density will become increasingly apparent as time progresses.

5 Acknowledgements

The process of understanding and creating biodiesel was not a simple task. Many obstacles arose along the way; however, these obstacles were overcome with the help of many people: Brandon Htet, Soren Spada, and Justin Aranda. Most notably, our research mentor, Mr. Davey, who provided all of the lab equipment and supplies required for our experiments. Additionally, he provided us with essential insight and feedback to help us better understand the components, and the process involved in creating biodiesel. His dedication to this study was paramount in the conclusion and success of this research study. Lastly, we would like to recognize and appreciate our 11th and 12th grade class for giving us the opportunity to analyze their data — information we could not have collected ourselves.

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7 Appendices

Appendix A

Figure 6 displays the energy density of all the canola batches (n=134), the shape of the data is illustrated in Figure 7 and Figure 7a. The distribution is positively skewed to the right with a long tail on the right side. The mean, (26732 J/g) is greater than the median (25840.11 J/g) and is closer to the first quartile (18446.4 J/g) than it is to the third (34539.12 J/g). The majority of the data is clustered between 22216 J/g to 29620 J/g, and 29621 J/g to 37025 J/g; the mode is: 22216-29620 J/g and 29621-37025 J/g.

Figure 6: Energy Density (J/g) vs. Canola Sample #

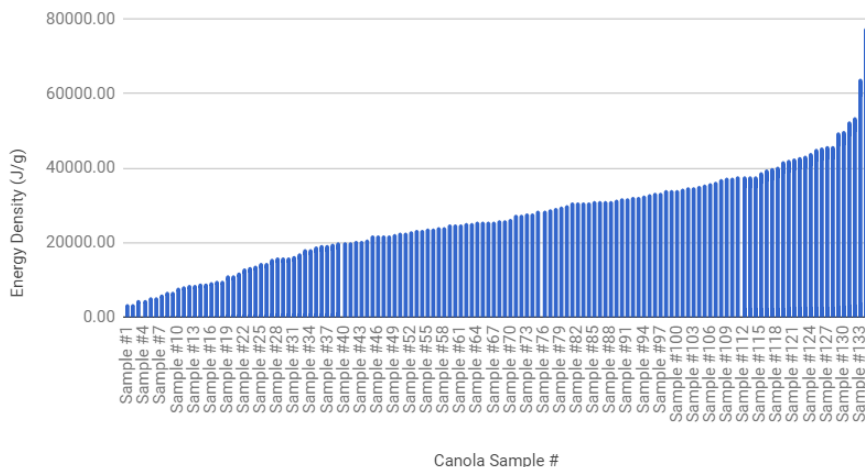


Figure 7: Canola Oil Energy Density (J/g) Distribution

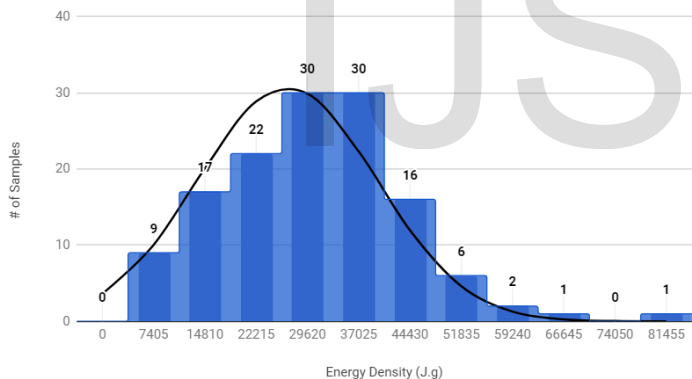
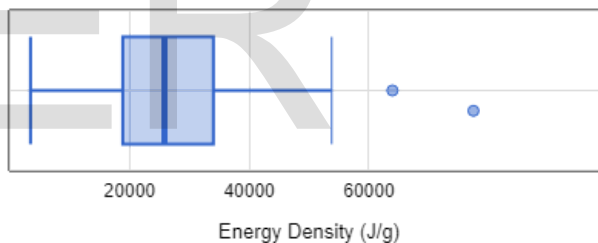


Figure 7a: Canola Oil Energy Density (J/g) Distribution



Appendix B

Figure 8 displays the energy density of all the corn batch (n=7), the shape of the data is illustrated in Figure 9 and Figure 9a. The distribution is negatively skewed to the left with a long tail on the left side. The mean (27709.83 J/g) is greater than the median (26668.40 J/g) and is closer to the third quartile (34129.65 J/g) than it is to the first (21063.44 J/g). The majority of the data is clustered from 13629 J/g to 40884 J/g; the mode is 13629-20442 J/g, 20443-27256 J/g and 34071-40884 J/g.

Figure 8: Energy Density vs. Corn Sample #

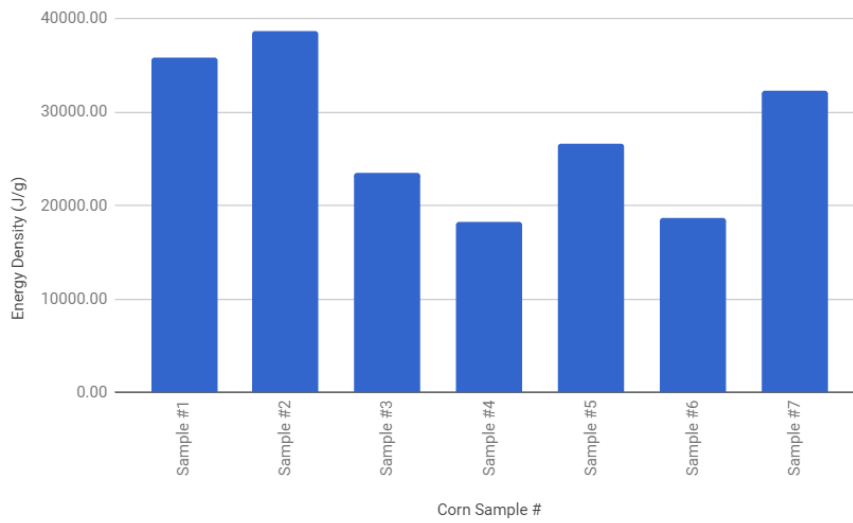


Figure 9: Corn Oil Energy Density (J/g) Distribution

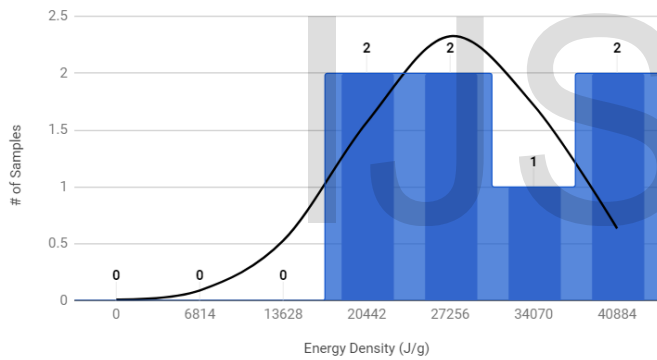
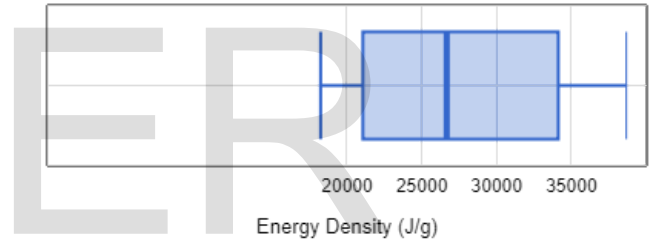


Figure 9a: Corn Oil Energy Density (J/g) Distribution



Appendix C

Figure 10 displays the energy density of all the olive batch (n=41), the shape of the data is illustrated in Figure 11 and Figure 11a. The distribution is positively skewed to the right with a long tail on the right side. The mean (22986.97 J/g) is greater than the median (22149.31 J/g) and is closer to the first quartile (13807.2 J/g) than it is to the third (32232.2 J/g). In addition, the majority of the data is clustered from 8451 J/g to 33800 J/g; the mode is 8451-16900 J/g.

Figure 10: Energy Density (J/g) vs. Olive Sample #

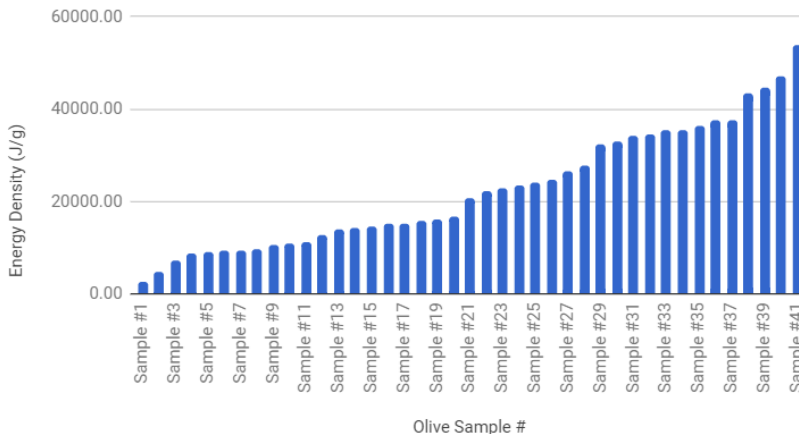


Figure 11: Olive Oil Energy Density (J/g) Distribution

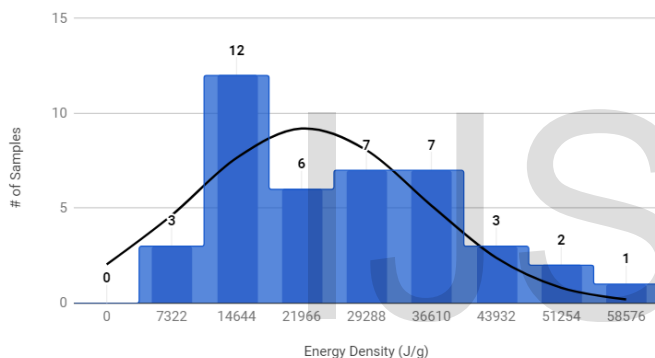
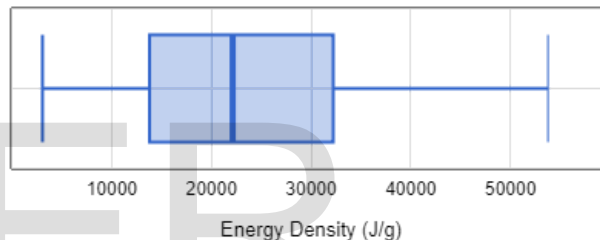


Figure 11a: Olive Oil Energy Density (J/g) Distribution



Appendix D

Figure 12 displays the energy density of every safflower batch (n=8), the shape of the data is illustrated in Figure 13 and Figure 13a. The distribution is positively skewed to the right with a long tail on the right side. The mean (29103.79 J/g) is less than the median (30616.89 J/g) and is closer to the first quartile (20891.75 J/g) than it is to the third (37011.44 J/g). In addition, the majority of the data is clustered from 18521 J/g to 27780 J/g and 27781 to 37040 J/g; the mode 18521-22780J/g.

Figure 12: Energy Density (J/g) vs. Safflower Sample #

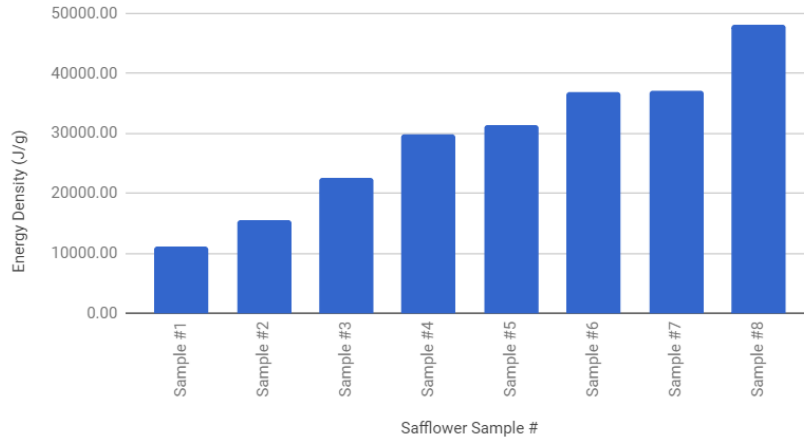


Figure 13: Safflower Oil Energy Density (J/g) Distribution

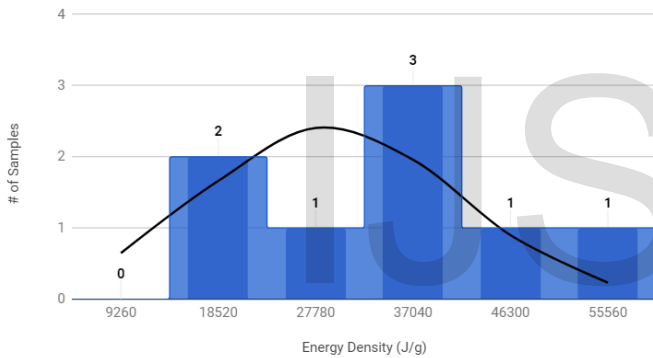
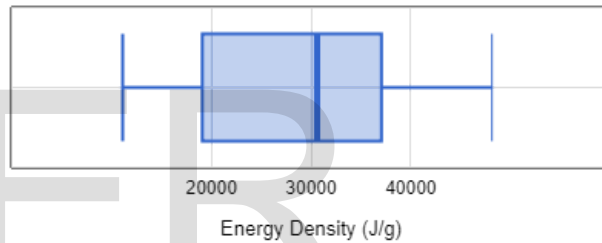


Figure 13a: Safflower Oil Energy Density (J/g) Distribution



Appendix E

Figure 14 displays the energy density of every soybean batch (n=27), the shape of the data is illustrated in Figure 15 and Figure 15a. The distribution is positively skewed to the right with a long tail on the right side. The mean (20047.85 J/g) is less than the median (16108.40 J/g) and is closer to the first quartile (12064.86 J/g) than it is to the third (29975.06 J/g). In addition, the majority of the data is clustered from 4495 J/g to 17976 J/g; the mode is 13482-17976 J/g.

Figure 14: Energy Density (J/g) vs. Soybean Sample #

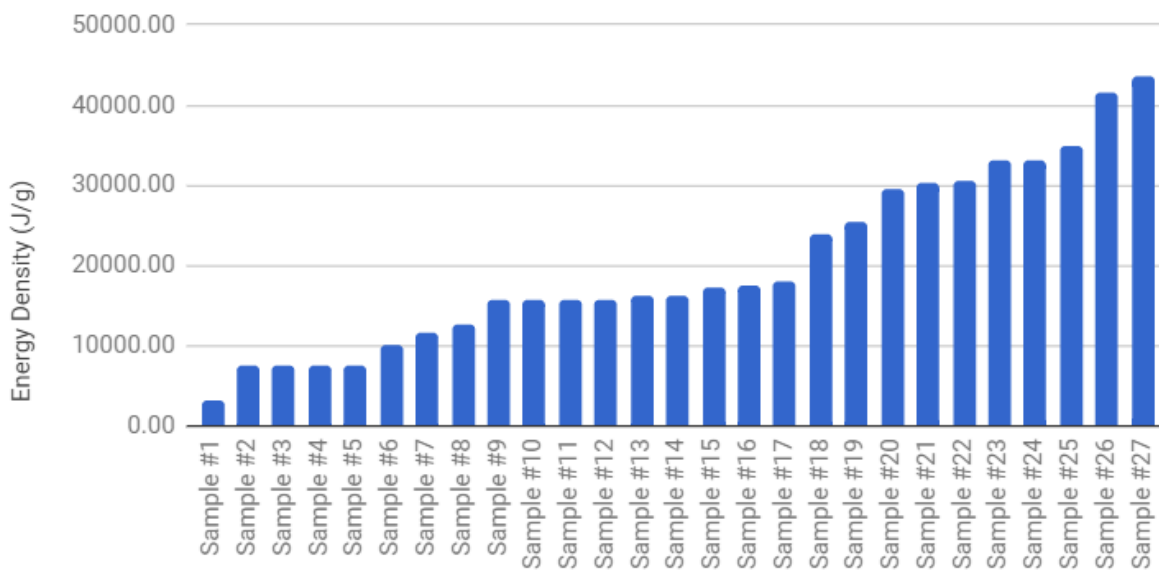
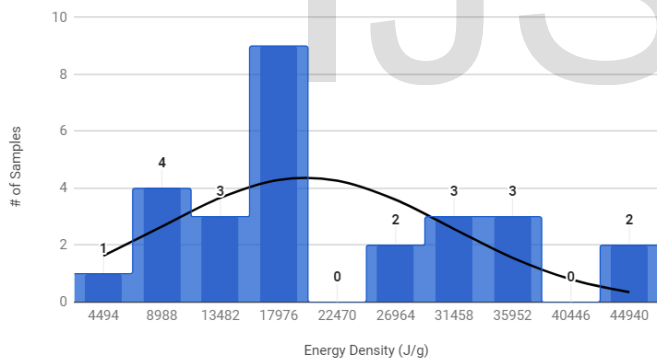
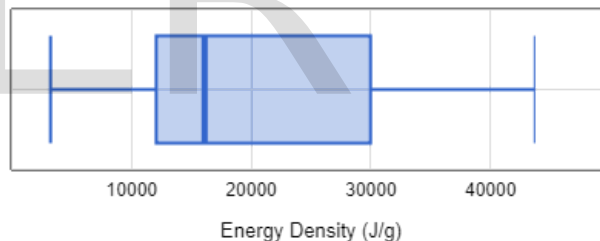


Figure 15: Soybean Oil Energy Density (J/g) Distribution



Soybean Sample #

Figure 15a: Soybean Oil Energy Density (J/g) Distribution



Appendix F

Figure 17 displays the percent yield (%) of every 0.5% [KOH] batch (n=61), the shape of the data is illustrated in Figure 18 and 18a. The distribution is negatively skewed to the left with a long tail on the left side. The mean (51.01%) is less than the median (54.80%) and is closer to the third quartile (60.15%) than it is to the third (36%). In addition, the majority of the data is clustered from 40% to 70%, the mode is 50-60%.

Figure 17: Percent Yield (%) vs. 0.5% [KOH] Sample #

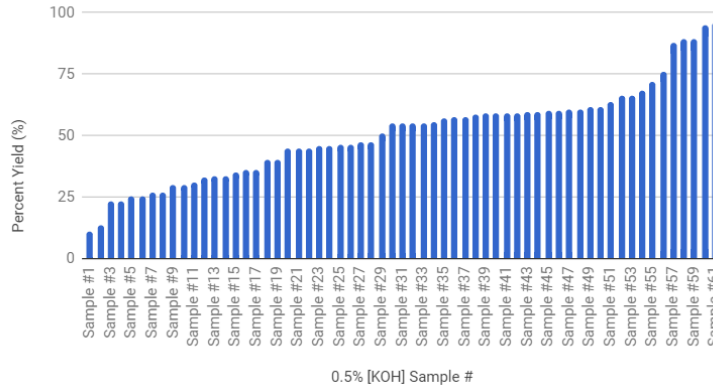


Figure 18: 0.5% [KOH] Percent Yield (%) Distribution

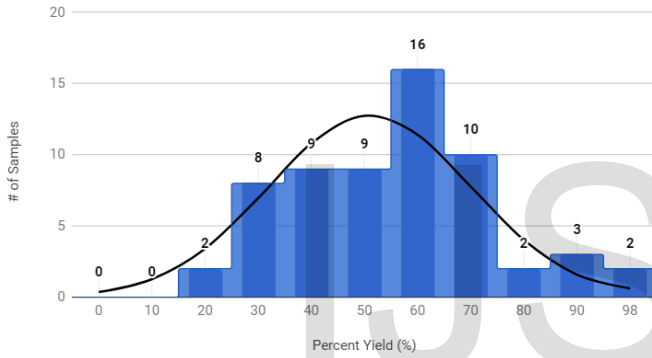
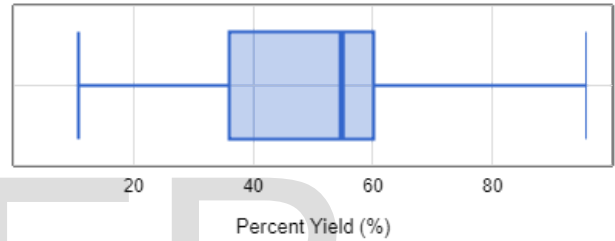


Figure 18a: 0.5% [KOH] Percent Yield (%) Distribution



Appendix G

Figure 19 displays the percent yield (%) of every 0.75% [KOH] batch (n=35), the shape of the data is illustrated in Figure 20 and 20a. The distribution is positively skewed to the right with a long tail on the right side. The mean (48.64%) is greater than the median (48.50%) and is closer to the first quartile (37%) than it is to the third (65.97%). In addition, the majority of the data is clustered from 30% to 60%; the mode is 40-50%.

Figure 19: Percent Yield (%) vs. 0.75% [KOH] Sample #

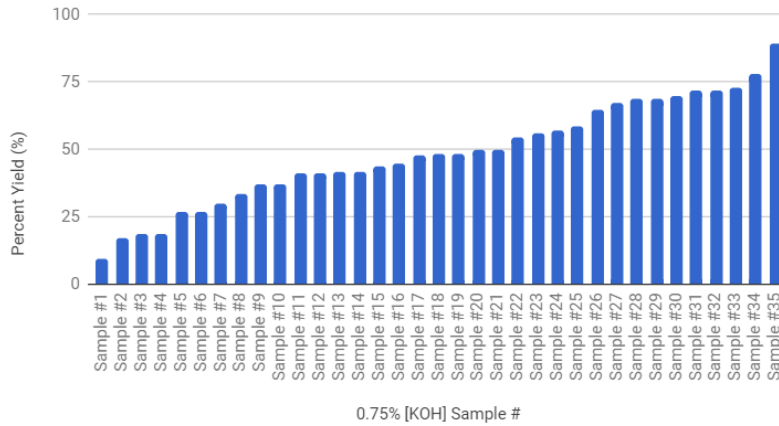


Figure 20: 0.75% [KOH] Percent Yield (%) Distribution

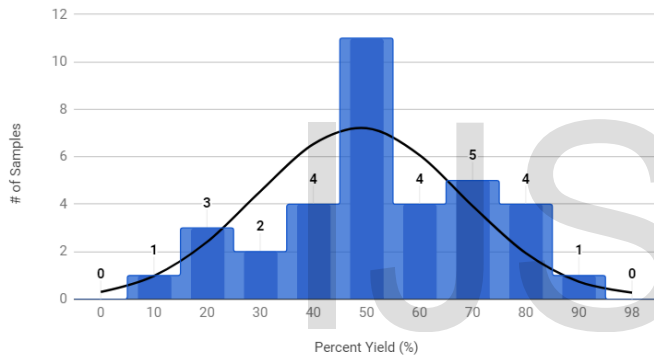
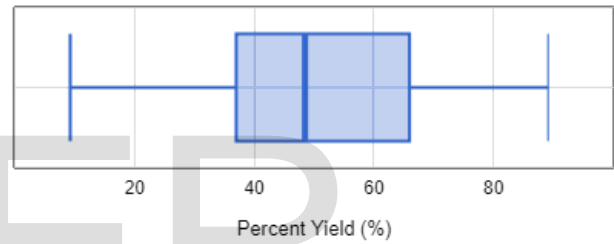


Figure 20a: 0.75% [KOH] Percent Yield (%) Distribution



Appendix H

Figure 21 displays the percent yield (%) of every 1% [KOH] batch (n=5), the shape of the data is illustrated in Figure 22 and 22a. The distribution is positively skewed to the right with a long tail on the right side. The mean (57.39%) is greater than the median (48.00%) and is closer to the first quartile (44.05%) than it is to the third (70.90%). In addition, the majority of the data is clustered from 40% to 50%; the mode is 40-50%.

Figure 21: Percent Yield (%) vs. 1% [KOH] Sample #

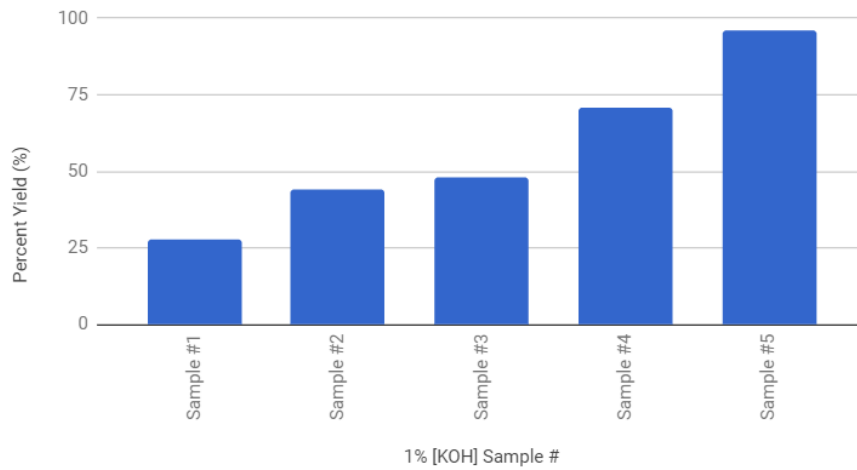


Figure 22: 1% [KOH] Percent Yield (%) Distribution

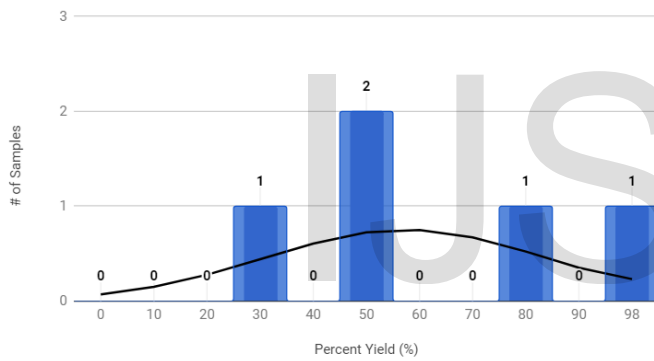
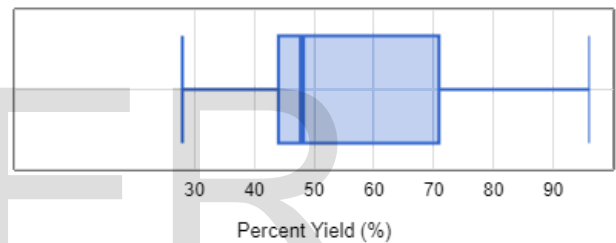


Figure 22a: 1% [KOH] Percent Yield (%) Distribution



Appendix I

Figure 23 displays the percent yield (%) of every 2% [KOH] batch (n=6), the shape of the data is illustrated in Figure 24 and 24a. The distribution is positively skewed to the right with a long tail on the right side. The mean (59.52%) is greater than the median (56.35%) and is closer to the first quartile (50.125%) than it is to the third (68.3125%). In addition, the majority of the data is clustered from 50% to 70%; the mode is 50-60%.

Figure 23: Percent Yield (%) vs. 2% [KOH] Sample #

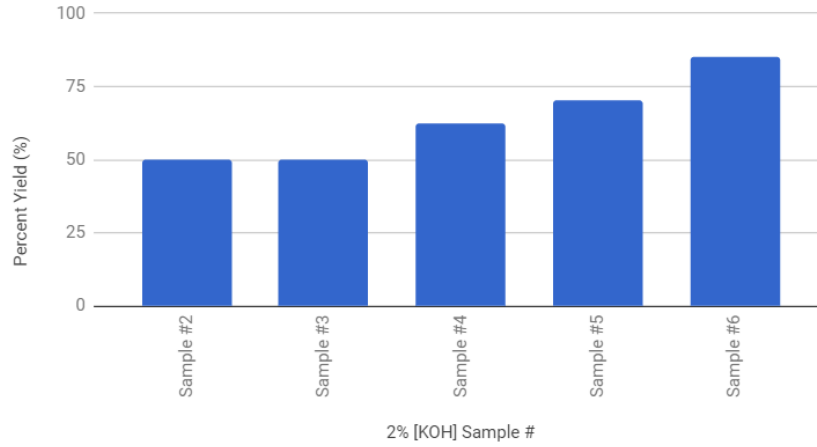


Figure 24: 2.0% [KOH] Percent Yield (%) Distribution

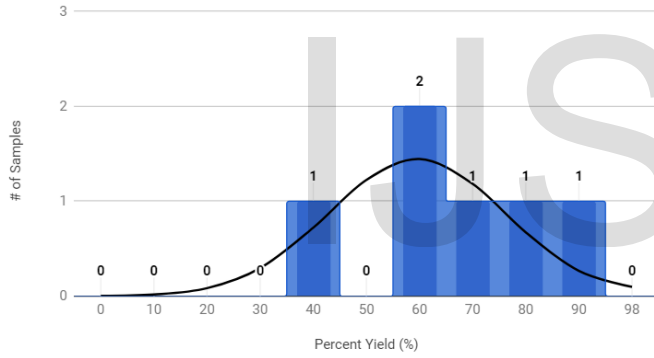
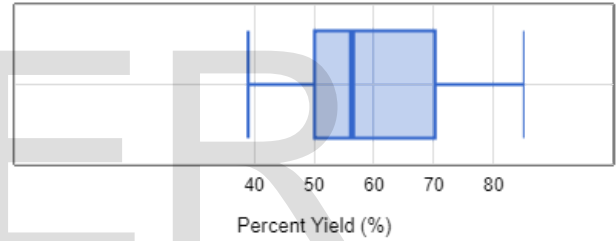


Figure 24a: 2% [KOH] Percent Yield (%) Distribution



Appendix J

Figure 25 displays the percent yield of every methanol 3:1 batch (n=8), the shape of the data is illustrated in Figure 26 and Figure 26a. The distribution is positively skewed to the right with a long tail on the right side. The mean (59.12%) is greater than the median (57.5%) and is closer to the first quartile (50.575%) than it is to the third (65.175%). In addition, the majority of the data is clustered from 50% to 90%; the mode is 50-60%.

Figure 25: Percent Yield (%) vs. Methanol 3:1 Sample #

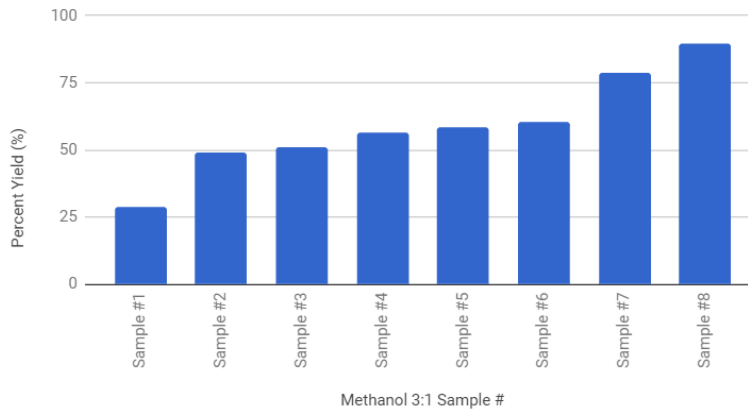


Figure 26: Methanol 3:1 Percent Yield (%) Distribution

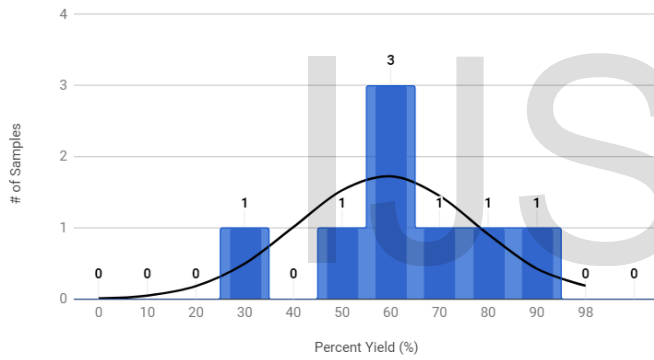
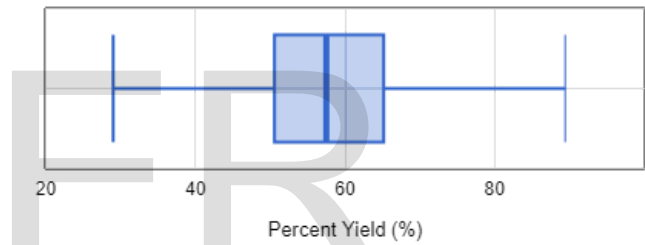


Figure 26a: Methanol 3:1 Percent Yield (%) Distribution



Appendix K

Figure 27 displays the percent yield of every methanol 6:1 batch (n=36), the shape of the data is illustrated in Figure 28 and Figure 28a. The distribution is negatively skewed to the left with a long tail on the left side. The mean (53.68%) is less than the median (56.75%) and is closer to the third quartile (60.5%) than it is to the first (42.025%). In addition, the majority of the data is clustered from 50% to 80%; the mode is 50-60%.

Figure 27: Percent Yield (%) vs. Methanol 6:1 Sample #

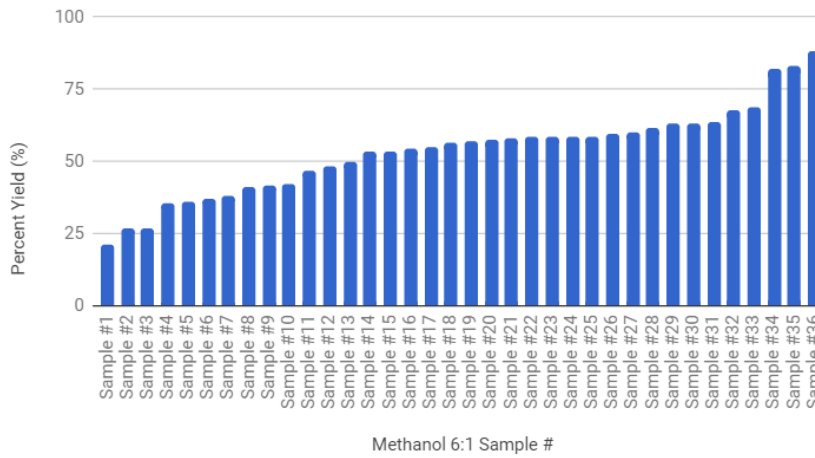


Figure 28: Methanol 6:1 Percent Yield (%) Distribution

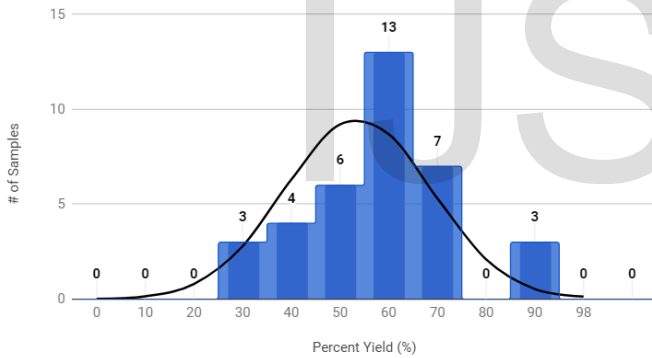
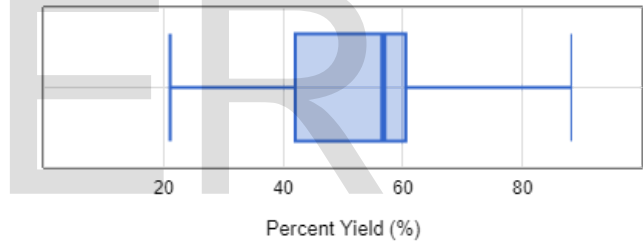


Figure 28a: Methanol 6:1 Percent Yield (%) Distribution



Appendix L

Figure 18a: 0.5% [KOH] Percent Yield (%) Distribution

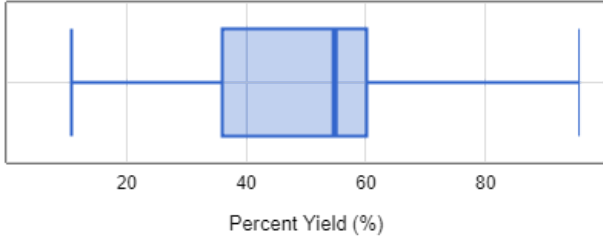


Figure 20a: 0.75% [KOH] Percent Yield (%) Distribution

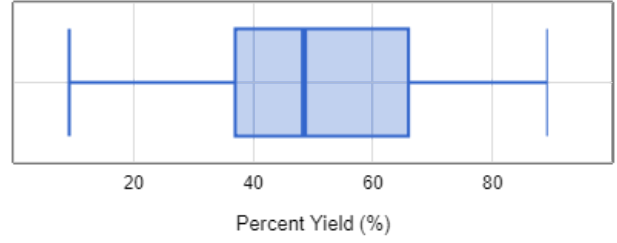


Figure 22a: 1% [KOH] Percent Yield (%) Distribution

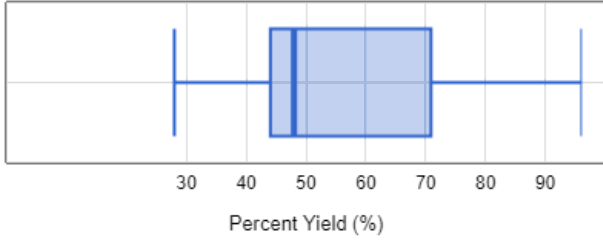
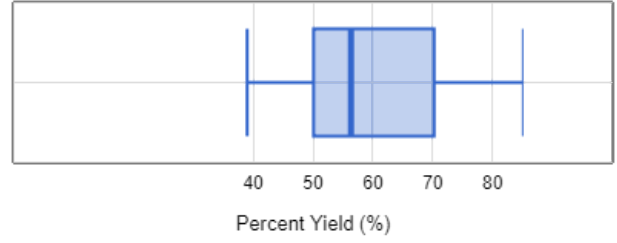


Figure 24a: 2% [KOH] Percent Yield (%) Distribution



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