

OPTIMISATION, DESIGN, AND AUTOMATION OF A SMALL-SCALE BIO- DIESEL PRODUCTION PLANT

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DOI: <https://doi.org/10.5281/zenodo.8216988>

Published Date: 05-August-2023

Abstract: The project examined the optimization, design, and automation of small-scale production of biodiesel from waste cooking oil (WCO). It covered optimization proceedings (feedstock pretreatment and conditioning) that were aimed at ensuring maximum biodiesel yield from the WCO with fewer non-desired by-products such as glycerin through the esterification reaction reactions using sulphuric acid.

It is noteworthy that the design generated can be used on different feedstocks. (With high Free Fatty Acids [FFA] and those without FFA). Pretreatment can be run concurrently with the Alkali catalyzed process or the processes independently of each other.

Being a small-scale production, some recovery units such as the catalyst recovery unit were not employed given the economic infeasibility.

The main transesterification reaction under implementation was the alkali-catalyzed process owing to its easily attainable reaction conditions and reaction time in contrast with the supercritical method and acid-catalyzed method whose major downfalls are extreme reaction conditions and longer reaction times respectively.

The use of simulation program DWSIM version 8.3.5 (Classic UI, 64-bits) was employed to develop the process plant's design. The simulation was carried out at different FFA levels using a similar model developed in all cases.

The data generated from the simulation was analyzed using MATLAB version R2022b and graphs describing relationships were generated.

Finally, the automation of the process with aid of valves, a heater and heat exchangers.

Keywords: optimization, design, automation, and simulation.

LIST OF ACRONYMS

C-1	Logic Controller Block
CL	Cooler
CS	Component Separator
CW	Cold Water
E	Energy Streams
FFA	Free Fatty Acids
GHG	Green House Gases

H ₂ SO ₄	Sulphuric Acid
HT	Heater
HW	Hot Water
HX	Heat Exchanger
LLE	Liquid-Liquid Equilibrium
ME	Methyl Ester
MeOH	Methanol
MIX	Stream Mixer
NaOH	Sodium Hydroxide
NRTL	Non-Random Two Liquid
R	Recycle Stream
RCNV	Conversion Reactor
SCOL	Shortcut Column
SPL	Stream Splitter
SRK	Soave Redlich-Kwong
TG	Tri-Glyceride
UNIFAC	UNIQUAC Functional-group Activity Coefficients
UNIQUAC	UNIversal QUasi-chemical Activity Coefficients
V1	The volume of Sodium Hydroxide used in Titration
V2	The volume of Sodium Hydroxide used in Blank Titration
VLE	Vapor-Liquid Equilibrium
WCO	Waste Cooking Oil

1. INTRODUCTION

1.1 Background

Recently, there has been an enormous increase in energy use, along with an annual increase in the use of diesel, leading to a continual increase in price. On the other hand, the globe faces the grave issue of running out of already finite fuel reserves. Utilizing alternative energy sources is necessary owing to the overwhelmingly serious issues brought on by the overuse of fossil fuels (Leduc et al., 2009).

Emissions of greenhouse gases (GHG) from human-caused activities such as burning fossil fuels for energy, are the primary reason for the temperature rise. By 2050, GHG emissions must be reduced by at least 40% to keep global warming at 1.5 °C on average (Lee & Eng, 2008).

Biodiesel has been considered one of the most adaptable alternatives to fossil-derived diesel with similar properties and numerous environmental benefits such as reducing toxic elements disposal into the atmosphere (*Correction IPCC Working Group II Contribution to the Sixth Assessment Report-Corrigenda to the Final Draft_Rev2*, n.d.). Biodiesel manufacturing attained extended attention and dramatic growth observed in the last decade. Unfortunately, that hasn't been the case for a larger part of Uganda.

Manufacturing of biodiesel is carried out as a base-catalyzed oil transesterification with low-valent alcohol ("Introduction to Biodiesel Production," 2011). For obtaining biodiesel the following raw materials are used; vegetable oil (WCO being of focus) as well as animal fats, low-valent alcohol and potassium hydroxide or sodium hydroxide as a catalyst (Rutz, n.d.).

Despite technological advancements and the commercialization of high-quality biodiesel as a drop-in biofuel that meets standard specifications (EN 14214:2012 or ASTM 6751-12), the production of biodiesel is still a complicated process that necessitates both empirical study and modelling efforts (Schumacher, 2007).

Although there are various approaches to biodiesel production, Process design, Quantitative evaluation, and Optimization are essential for unlocking the complexity of the production process, and enhancing performance (Pasha et al., 2021).

1.2 Problem Statement

The overwhelming worries caused by the over-exploitation of fossil resources and rising fuel prices demand the use of alternative energy sources. With bio-diesel being a viable alternative to petroleum diesel, its production in Uganda has

mainly remained low in recent years, partly due to the expense of manufacturing being higher than that of purchasing petroleum diesel and partly due to the complexities involved. (Narl-kawanda, 2010).

In the last years, research has been focusing on the design and implementation of production plants to produce biodiesel from waste cooking oils to achieve the double aim of making people independent in biofuel production and taking advantage of WCO destined for expensive disposals (de Paola et al., 2021).

The project is centered on designing an optimized small-scale bio-diesel production plant (from WCO) that requires fewer technicalities to obtain the highest possible amount of fuel from the process.

1.3 Objectives

1.3.1 Main Objective

To design, optimize and automate a small-scale biodiesel production plant.

1.3.2 Specific Objectives

- i. To develop a simulation model for WCO.
- ii. To simulate the optimized production process.
- iii. To automate production of the simulated production process.
- iv. To determine the economic feasibility of the production process.

1.4 Research Questions

- What are the optimum process conditions?
- How much bio-diesel can be produced for a given feed quantity?

1.5 Significance of the Study

This study developed a small-scale optimized and automated production plant suited for use by small-scale bio-diesel producers. The small-scale optimized and automated production plant enabled the achievement of the following:

- Reduction in production errors associated with human intervention.
- Reduction in the need for high technological knowledge on the production of biodiesel.
- Increased production of bio-diesel and its use.

1.6 Justification

The production of biodiesel is still a complicated process that necessitates empirical study and modelling efforts to attain maximum yield. The study was aimed at small-scale production where the empirical study and modelling effort cannot be realized. This nullified the need for extensive technicalities for the production thereby giving the process the attention it deserves in the country.

In the current situation, diesel is the most dominant fuel in the world including in the area of transport, agriculture, power generation, and some industrial applications among others. To make long-term energy security an alternative should be found. Vegetable oil can be the alternative to diesel and it could be the fuel in the diesel engine. With the current price of petroleum diesel being UGX 5,855 (*Uganda Diesel Prices, 28-Nov-2022 | GlobalPetrolPrices.Com, n.d.*), an alternative fuel source is in order.

Biodiesel is ecologically beneficial and sustainable and may be utilized in diesel engines without the need for modification. In actuality, the usage of biodiesel lowers particulate matter by 47%, reduces hydrocarbon emissions by up to 67%, and reduces smog.

It also reduces greenhouse gas emissions by up to 86% and is non-toxic and biodegradable.

Utilizing WCO as a feedstock nullifies the need for its “environmentally sound” disposal that would otherwise cause the pipes to clog, the production of odour and the cost of wastewater treatment rises.

1.7 Scope

The primary purpose of this study was to design, optimize and automate a small-scale biodiesel production plant. This was aimed at providing technology to the local population that enables them to safely produce the fuel.

1.8 Conceptual and Theoretical Frameworks

This study aims at the optimization, designing, and automation of small-scale biodiesel plants using the simulation program DWSIM. The conceptual framework of the study is presented in figure 1, the independent variables include; Feedstock composition, Reaction conditions, Reactants used which influence Pretreatment, Degree of conversion, post-treatment as the independent variables.

The Catalytic effect, Time of reaction, Control precision is the moderating variable.

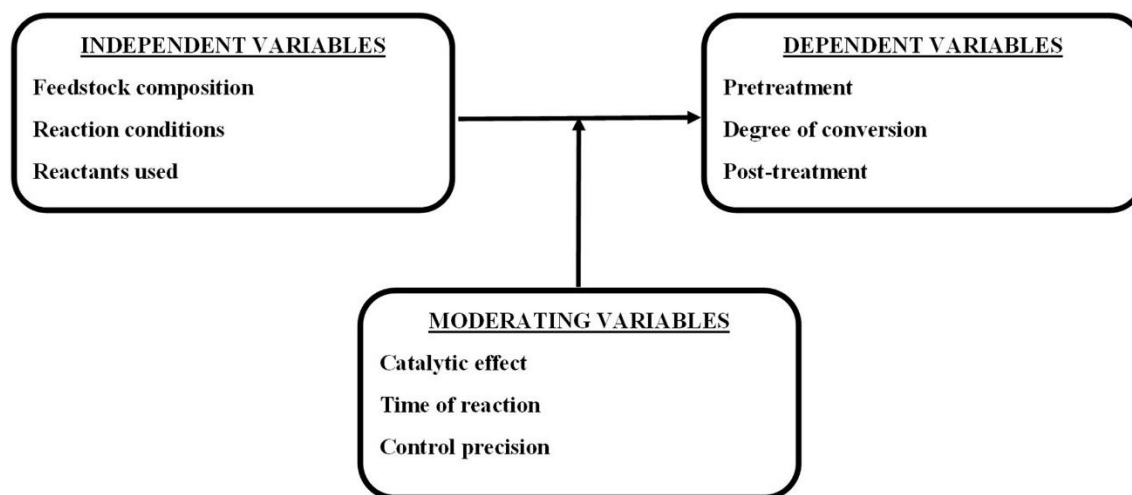


Figure 1. Conceptual Framework of Study

2. LITERATURE REVIEW

Biodiesel is made of alkyl esters that are either produced by trans-esterifying TGs or by esterifying FFAs with low molecular weight alcohols.

When used as fuel, the carbon will be neutral given the emission is equal to the animal or plant absorbed its whole life (ji, 2016). It is produced by transesterification with a monohydric alcohol, in this case, ethanol, with vegetable oil and possesses many important technical advantages over petroleum diesel, such as inherent lubricity, low toxicity, derivation from a renewable and domestic feedstock, biodegradability, negligible sulphur content, and lower exhaust emissions, superior flash point (423 K) that makes it less volatile and safer during transportation and handling (Moser, 2011).

2.1 Feed stocks

To a large extent, the end cost of biodiesel depends on the price of its feedstock. The predominant feedstocks currently are food-grade vegetable oils which mostly consist of triglycerides in the range of C12–C22 (Morais et al., n.d.).

However, the high costs and scarcity of biodiesel feedstocks are key challenges in this market. Vegetable oils can account for up to 75% of overall manufacturing expenses, making biodiesel manufacture around 1.5 times more expensive than diesel (Moser, 2011). For this reason, waste vegetable oils can effectively reduce production costs since they are 2-3 times cheaper than virgin vegetable oils (Phan & Phan, 2008). In addition, it helps solve environmental problems associated with the disposal of waste vegetable oils.

WCOs are generated daily in large quantities during food preparation by frying in fast-food franchises and local restaurants among others. This is an environmentally sound and economical way to produce biodiesel. WCOs food industries have a large variety of qualities due to the many variables involved in the frying process, such as temperature, heating time, and the kind of food subjected during frying which is the main downfall in its use as a raw material in the production of biodiesel.

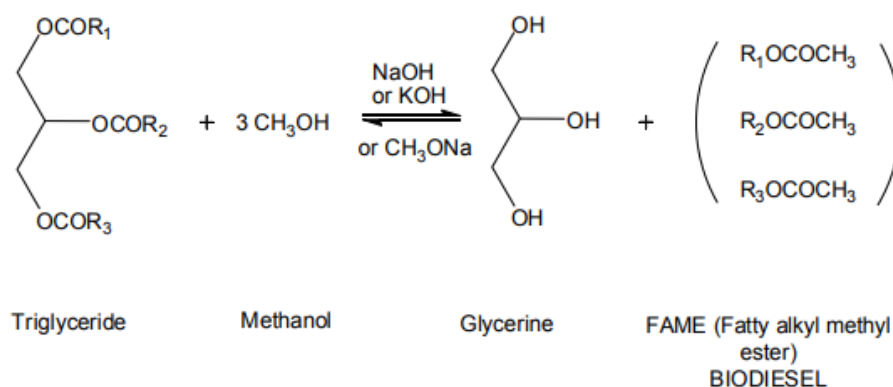
Such a raw material's key drawback is the requirement for standardization, particularly regarding acidity reduction. To address this issue, several solutions have been put up. In addition to the cited alkali refining method, it is noteworthy to highlight the addition of excess catalyst, solvent extraction, distillation refining process, and pre-esterification procedure. This final strategy appears to be the most alluring and has recently attracted a lot of interest. The physical and chemical properties of the oil change during frying. Vegetable oil goes through various chemical reactions among them polymerization, oxidation and hydrolysis thereby increasing FFAs and moisture contents owing to the hydrolysis of triglycerides in the presence of food moisture and oxidation (Canakci, 2007).

In a report by (Kalogianni et al., 2011), the FFA level of fresh soybean oil changed from 0.04% to 1.51% after 70 hrs of frying at 190°C in conjunction with an increase in viscosity owing to polymerization, which resulted in the formation of compounds with higher molecular weight. Therefore, using waste oils, with their variance in properties, as feedstock for biodiesel production is expected to present technical challenges.

2.2 Formation Reaction

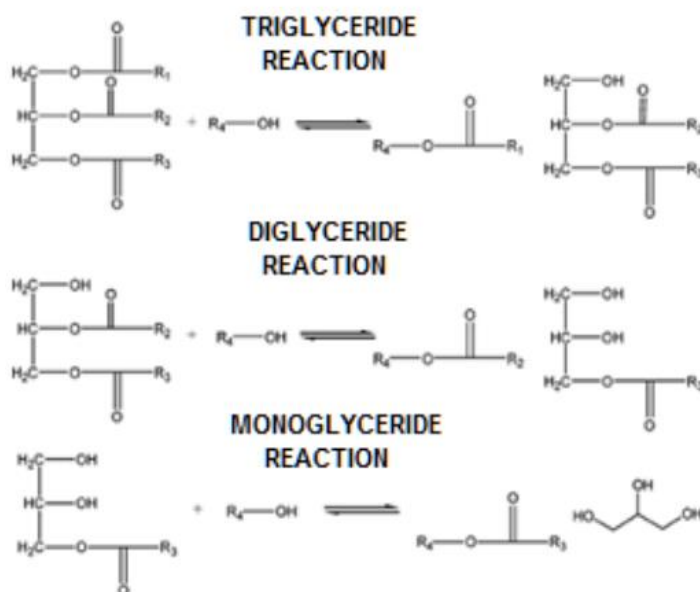
Stoichiometrically, a 3:1 ratio of methanol to oil is required to convert one glyceride molecule into a methyl ester molecule but in practice, the ratio is higher than that to provide a maximum ester yield of about 6:1.

Equation 1. Transesterification reaction.



The trans esterification reaction consists of a sequence of three reversible reactions; conversion of triglyceride into diglyceride; conversion of diglyceride to monoglyceride; and finally, monoglyceride into glycerol. The three fatty acids bound to the glycerol bond of triglyceride are combined to glycerol CH₃-group yielding three fatty acid methyl esters.

Equation 2. Three reversible transesterification reactions.



2.3 Catalysis

To improve the reaction rate and yield, a catalyst is used. The nature of the catalyst is fundamental given it determines the composition limits feedstock must conform to. The type of catalyst and feedstock used significantly affects the unit operation involved and closely relates to economic profitability. Conventional unit operations include; methanol recovery, water washing, neutralization and settler, and fuel and glycerol purification.

2.3.1 Supercritical Method

As proposed by (Saka & Kusdiana, 2001), the supercritical method is aimed at overcoming problems associated with catalysis processes. This process involves high temperatures and pressures. Under these conditions, a single homogenous oil and catalyst mixture phase is formed usually existing as a heterogenous phase owing to the immiscibility of the non-polar and polar components. They further reported that transesterification of the oil at 625.15 K and 45 MPa gave ester yields greater than 95% in about four minutes with methanol to oil ratios of 42:1. Owing to the high yield and catalyst absence, other process units such as separation, washing and drying were eliminated.

Despite the high conversion and purity, this method is not exactly economically feasible, especially for small-scale production given the extreme operation conditions thereby posing safety issues. (Srivastava & Prasad, 2000) reported that the homogenous reaction was approximately 4000 times slower and achieves a lower yield than the homogenous alkali-catalyzed reaction.

2.3.2 Acid Catalysis

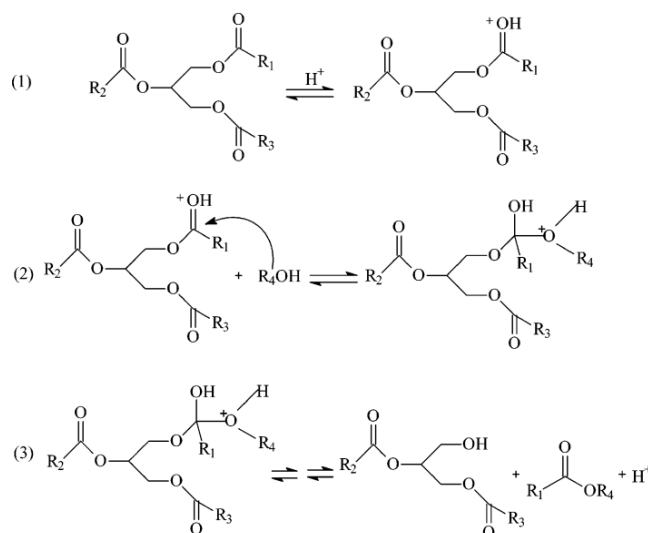
Base-catalyzed reactions need precise feedstock requirements, which has prompted researchers to look for processing and catalytic options that could ease this challenge and reduce production costs. Methodologies based on acid-catalyzed reactions may be able to accomplish this because acid catalysts don't exhibit any discernible FFA susceptibility.

Esterification and transesterification can both be catalyzed by acids. Consequently, a major benefit of acid catalysts is their ability to directly create biodiesel from inexpensive lipid feedstocks, which are typically associated with high FFA concentrations.

Recently, it has been demonstrated that base-catalyzed procedures using virgin oils cannot economically compete with acid-catalyzed processes for the generation of biodiesel, especially when the former uses inexpensive feedstocks.

The protonation of the carbonyl oxygen is a crucial step in the catalyst-substrate interaction shown in Equation 3 for an acid-catalyzed process. In turn, this raises the neighboring carbon atom's electrophilicity, making it more vulnerable to nucleophilic assault. Contrarily, base catalysis adopts a more direct method by first producing an alkoxide ion, which acts immediately as a potent nucleophile, resulting in a distinct chemical pathway for the reaction. The creation of a more electrophilic species by acid catalysis as opposed to a stronger nucleophile in base catalysis is a significant distinction that eventually accounts for the observed disparities in activity.

Equation 3. *The protonation of the carbonyl oxygen in the catalyst-substrate interaction*



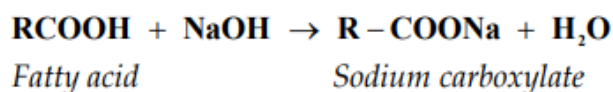
2.3.3 Alkali Catalysis

In comparison to using acid catalysts, the alkali-catalyzed reaction has several advantages; faster reaction rate, lower catalyst amount, lower reaction temperature and less corrosive final product. The process typically produces methyl esters with a high yield of 333K and atmospheric pressure (1 atm) in about an hour.

NaOH and KOH are preferred in the industrial setting due to their widespread availability and low price. But from a molecular perspective, the Methoxide ions are the active species with both kinds of catalysts. In one scenario, methoxide salts dissociate, whereas, in the other, methanol combines with hydroxyl ions from further alkaline hydroxides to produce methoxide ions. The carbonyl moiety in glyceride molecules is attacked by the methoxide ions, which are powerful nucleophiles once produced, to make the alkyl esters.

However, alkali catalysts are sensitive to feedstocks with high amounts of FFA and water (> 0.5% and > 0.06% respectively). These conditions result in saponification partially limiting the recovery of catalyst and fuel yield in addition to complications in the separation and purification steps as shown in Equation 4.

Equation 4. Saponification of FFAs in presence of alkali catalyst.



Given that WCOs have a lot of FFAs, their use as feedstock is not ideal for the conventional alkali-catalyzed biodiesel production method. This call for acid pretreatment to reduce the FFAs in the feedstock before it proceeds to the conventional alkali-catalyzed reactions.

Canaki & Yan Girven (1999) examined the conversion rate of methyl esters of soybean oil at different levels of FFAs using a 3 wt% acid catalyst and achieved 90 wt% conversions and (Saka & Kusdiana, 2001) compared the effects of water content on methyl esters formation from rapeseed oil via acid and alkali-catalyzed reactions. The results indicated that the moisture content of the feedstock affects the choice of catalyst to be used as approximately 70% conversion was achieved in alkali-catalyzed reactions whereas only 6% conversion for acid-catalyzed reactions.

The necessity for standardization, particularly regarding acidity reduction, is the main disadvantage of such raw materials. Several ways have been offered to deal with this problem. It is notable to draw attention to the addition of excess catalyst, solvent extraction, distillation refining process, and pre-esterification procedure in addition to the specified alkali refining method. This last tactic seems to be the most enticing and has recently generated a lot of interest.

2.3.4 Acid Pretreatment

In a study by Chai et al. (2014), at a 40:1 methanol-to-FFA molar ratio, FFA conversions at 45, 55, and 65 °C met the 2 mg KOH/g target, but not at 35 °C (2.2 mg KOH/g). This required 2.25 g of methanol and 0.05 g of sulfuric acid for every gram. Only at 55 and 65 °C, was the goal FFA value achieved at a methanol-to-FFA molar ratio of 30:1. At any temperature, even after further lowering the methanol-to-FFA molar ratio to the NREL-recommended value of 20:1, the goal acid value could not be reached (*Acid Value and Free Fatty Acids in Edible Oils*, n.d.).

For every gram of FFA in the oil, 2.25 g of methanol and 0.05 g of sulfuric acid are utilized, resulting in a 19.8:1 molar ratio of methanol to FFA and a 5% acid-to-FFA weight percentage. Based on pre-treatment time industrial practices, a response time of 2 hours was used. Although it can be used to correct a batch, extending the reaction time is typically not preferred due to the associated cost increase. The ideal temperature range for the reaction was 55–65 °C (Lotero et al., 2005).

The methanol to FFA molar ratio also affects FFA reduction. For all test temperatures, the 2-hour acid values fall to less than 2 mg KOH/g when using a 50:1 methanol to FFA molar ratio and 10% acid.

2.4 Process Design and Simulation

The classic process design consists of a hierarchy of activities that can be represented by the Onion Diagram's sequential layers, as seen in Figure 2. The chemical Reactor is where the development starts, and the system of Separations is where it continues. The Heat Exchange and Utility layers are then addressed in the design. Since a complete separation of the

aforementioned activities is not achievable, the ideal solution to the design problem should be comprehensive (Dimian et al., 2014). For instance, the design of the reactor and the separation system are closely related. Similar to how the reaction and separation systems are designed, the heat exchanger network and utility system are also connected.

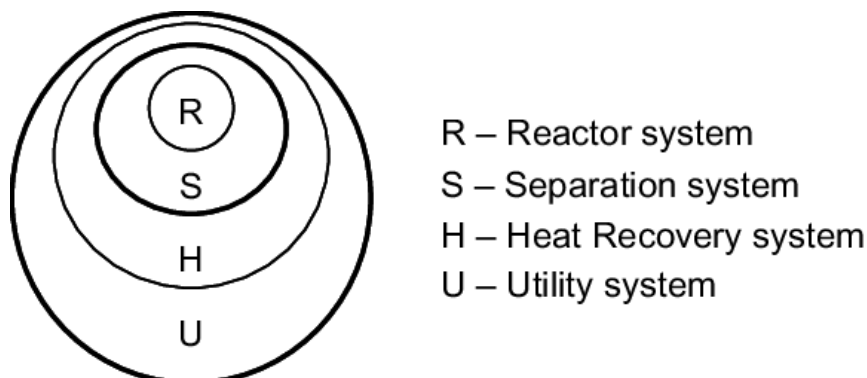


Figure 2. The onion model of process design.

Correct structure determination and optimization of the parameters in the design of reactor/separators systems constitute the most important tasks in process design. Selection of a better design is only possible after all possible designs with complete outer layers including utilities have been analyzed.

Process simulation is the modelling-based depiction of technical processes and unit operations in software, encompassing chemical, physical, biological, and other processes. The three primary engineering activities of research and development, design, and operation all center on simulation as in figure 3. The common factor is the generic nature of computational techniques and the scientific information ingrained in universal models. Thermodynamics, chemical kinetics, transport phenomena, and other "first-principle" models can all be used to explain these seemingly unrelated activities.

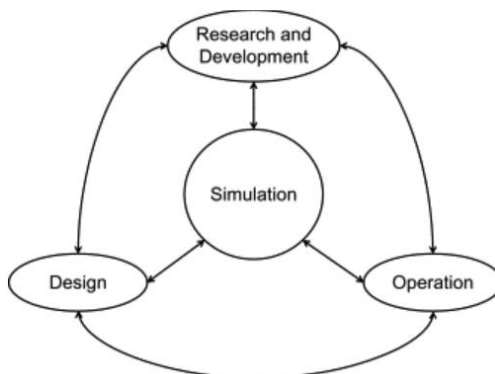


Figure 3. The three primary engineering activities.

2.4.1 Model Development

Researchers are faced with several challenges in modelling platforms first being defining and selecting appropriate chemical species to take part in the whole process. The use of realistic feed composition and sensitivity to change of composition is highly important to provide a more realistic assessment of the production plant as proven by (Lee & Eng, 2008) who simulated the biodiesel production process from waste oil using three different fatty acids; oleic acid, stearic acid, and palmitic acid; and one glyceride; triolein; as model components. (Abdurakhman et al., 2017) also carried out a more comprehensive representation of biodiesel using different fatty acids; linoleic acid, oleic acid, palmitic acid, stearic acid, linolenic acid; and triglycerides; tripalmitin, tristearin, triolein, tri-linolenic. To simulate the biodiesel production process from waste oil, Yun et al added three different fatty acids; oleic acid, stearic acid, and palmitic acid; and one glyceride; triolein; as model components.

(Lee & Eng, 2008) further reports that much as there are varying fatty acid chains in the simulator programs, their physical property data is not well-managed.

2.4.2 Fluid Package Selection

Identification of available chemical and physical properties in the database is another challenge. Biodiesel production systems in simulations employ NRTL, Wilson, SRK or UNIQUAC thermodynamic models owing to polar compounds and the non-polar ideal nature of transesterification reaction.

The Chemical consistent fragment approach applied by (Lou et al., 2008) for the esterification to determine the thermo-physical property of triglycerides was extended to individual mono and diglycerides employing the UNIFAC method resulting in reliable production of missing NRTL coefficients of triolein-methanol and triolein glycerol binary systems.

2.4.3 Data Collection

A great deal of important data needs to be collected before the process flow sheet design and simulation that is to say production capacity, operation mode, reactor type and catalyst among others. The applied approach in simulation usually starts from reactor selection and proceeds outward by adding separation and recycling systems. The reaction procedure and catalyst employed in the transesterification reaction are crucial and will determine the purity of products as well as the intensity of downstream purification steps. Many publications on process design and simulation for bio-diesel production are presented in table 1.

Different types of acids and alcohol can be used but the focus is on the alkali-catalyzed process mostly because it occurs at low temperatures and atmospheric pressure giving a high conversion in minimum time. Much as large-scale producers employ recycling of excess alcohol, small-scale producers find it economically and technically unfeasible. Batch stirred reactor is the simplest configuration for small plants.

Critical variables which significantly influence the final products include temperature and time, catalyst amount, and the molar ratio of alcohol to oil.

Table 1. Key features of reported simulation studies in biodiesel production (Ramadhas et al., 2006)

MODEL		THERMO- PHYSICAL PROPERTIES ESTIMATION AND THERMODYNAMI C MODEL	REACTOR		SIMULATIO N TOOL
FEED COMPOSITION	PROCESS OF PRODUCTIO N		REACTION MODE	REACTIO N MODULE	
Triolein	Homogenous and heterogeneous alkali-catalysed		Batch	Batch	Super-Pro Designer
Pure triolein acid + oleic	Alkali and acid- catalysed processes	NRTL and UNIQUAC-LLE	Yield	Continuous	Aspen HYSYS
Pure triolein acid + oleic	Alkali, acid, heterogeneous acid-catalysed and supercritical processes	NRTL, UNIFAC-LLE and UNIFAC-VLE	Yield	Continuous	Aspen HYSYS
Triolein and trilinolein	Supercritical process	NRTL and UNIFAC with Redlich– Kwong equation of state	Yield	Continuous	Aspen PLUS
Triolein, tripalmitin and trilinolein	Supercritical with power cogeneration process	UNIFAC and –Soave –Redlich– Kwong equations of state		Continuous	CHEMCAD
Triolein	Enzyme- catalysed process	UNIFAC and –Soave –Redlich– Kwong equations of state	Balanced equation	Continuous	Aspen PLUS
Triolein, mono- olein, stearic acid, palmitic acid, oleic acid	Enzyme- catalysed process	NRTL and UNIFAC- DMD	Balanced equation	Continuous	Aspen PLUS

2.5 Automation

In recent years, automation's significance in the process industries has grown significantly. Process automation helps to improve product quality, control the full spectrum of goods, increase process safety and plant availability, effectively use resources, and reduce emissions in highly industrialized nations.

Process automation is mostly used in rapidly growing nations for mass production. The pharmaceutical business has the fastest-growing need for process automation hardware, standard software, and services. The chemical, power generation, and petrochemical industries have the highest need for process automation.

The traditional barriers between information, communication and automation technology are, in the operational context, gradually disappearing.

In recent years, automation's significance in the process industry has grown significantly. The whole chemical, oil, gas, and biotechnology industries are now affected by it. Complex processes are now controlled by innovative instrumentation systems, which also ensure process safety and dependability and serve as the foundation for cutting-edge maintenance tactics. There is no other choice but to increase productivity in the chemical and bio industries due to ongoing cost pressures.

Process control guarantees that plant assets run predictably and constantly within the most profitable range, resulting in a higher output of consistent products, reliability, yield, and quality while using less energy (Benson, 1997). This technology will aid in boosting output, enhancing quality, and quickening retrofitting and system modifications intended to promote adaptability.

Over 90% of industrial multivariable control systems currently use model predictive control, which has established itself as a mainstream solution in the continuous process industry. Its capability to manage multivariable systems with input and output limits is one factor in its success.

2.6 Waste Management and Environmental Considerations

The main by-product is glycerol, it may be produced in a small amount given it's a small-scale production and the pretreatment future checks on its production but it builds up with continued production hence the need for its proper disposal or being put to use. Other wastes include biodiesel washing waters and solid wastes.

After being produced, biodiesel is frequently "washed" with water to remove impurities including soap, glycerin, leftover methanol, and catalyst. To break the soap, an acid might be added to the biodiesel to limit the amount of wastewater.

Before being converted into biodiesel, WCO must be filtered to remove particulates like breadings or pieces of meat and bone. Animal feed can be purchased from the solids that are separated from the spent oil.

Small biodiesel producers cannot purify the glycerin to the required level of 80 per cent purity for sale to glycerin refiners, who will then refine it to the required level of 99.5 per cent purity for the majority of commercial markets.

3. METHODOLOGY

The core of this study was the simulation stage. This made it imperative for the collection of data to attain valid and realistic simulation results. Given that the quality of a simulation greatly depends on the quality of data fed in, feedstock characterization (WCO) was of great importance to developing a more realistic feedstock model.

First, different amount of FFA content was used given the inconsistency from one feedstock to another owing to different conditions it was subjected to before it was considered WCO. These FFA are the ones responsible for the soap formation hence determine the extent of pretreatment.

Using the available components in the DWSIM databases, the model was developed. To optimize production, the pretreatment section was designed first (aiming at reducing soap formation on account of the fuel). This was followed by feeding the desired results of the pretreatment process to the main transesterification process and treatment of the waste products before their disposal, and finally the automation.

3.1 WCO Characterization.

The acid value and the free fatty acid content are important parameters used for the characterization and the quality assessment of WCO. Furthermore, the content of free fatty acids was used for purity testing allowing in certain cases conclusions about the pre-treatment processes and occurring decomposition reactions. The higher the acid value and free

fatty acid content, the lower the quality of WCO (May 1998, Vol75, No5, P563-568, n.d.). Given that WCO never had consistent FFA contents, i.e., FFA content varied in different feedstocks depending on the time of usage (before it was regarded as WCO), different values of FFA content were considered to come with various model compounds that called for different pretreatment reaction times. It was also of importance to note that there might be solid particles in the WCO that calls for filtering as added pretreatment stage.

In order to ensure realistic simulation, about 10 liters of WCO was obtained from IGAR restaurants located at Jinja. The oil was left to settle and then filtered three times using sieves of different diameters (0.2, 0.1, and 0.05 mm) in the order of largest to smallest and its density established.

3.1.1 FFA Determination by Titration

Titration is a common method used to determine the percentage of free fatty acids in waste cooking oil. The process involved neutralizing the free fatty acids in the oil with a standardized sodium hydroxide (NaOH) solution. The amount of NaOH solution required to neutralize the free fatty acids in the sample was used to calculate the percentage of free fatty acids.

Here are the steps involved in determining the percentage of free fatty acids in waste cooking oil by titration:

3.1.1.1 Materials required

- Waste cooking oil sample
- NaOH solution (0.1 N)
- Phenolphthalein indicator
- Erlenmeyer flask
- Burette
- Pipette
- Distilled water
- Retort stand

3.1.1.2 Procedure

- 5 grams of the waste cooking oil sample were weighed into an Erlenmeyer flask.
- 50 ml of isopropyl alcohol were added to the flask and swirled to dissolve the oil.
- 3 drops of phenolphthalein indicator were added to the flask.
- The oil solution was titrated with the NaOH solution until a permanent pink colour is obtained.
- The volume of NaOH solution used in the titration was recorded V1.
- A blank titration with 50 mL of isopropyl alcohol was performed to account for any neutralization that may have occurred due to the alcohol itself. the volume of sodium hydroxide used was recorded as V2.
- The titration was repeated twice to ensure accuracy.

The percentage of free fatty acids was calculated using the following formula:

$$\text{Net volume of NaOH} = (V1 - V2)$$
$$\%FFA = \left[\frac{(\text{Net volume of NaOH used}) \times (\text{Normality of NaOH}) \times F \times (28.2)}{\text{weight of oil sample}} \right]$$

Note:

- F = 0.995 is the Isopropyl alcohol factor
- Equivalent weight of NaOH for oleic acid, which is commonly used as a standard for calculating free fatty acids.

The percentage of free fatty acids in the waste cooking oil sample was used to determine its quality and degree of pretreatment required. A higher percentage of free fatty acids indicated that the oil had undergone more degradation and required more pretreatment.

3.2 Pretreatment Procedure

1. Calculated amount of ethanol and sulphuric acid are premixed.
2. Oil is passed through filter to trap any suspended impurities which is then filled in the reactor.
3. Reactor is heated to desired temperature and once there, methanol and sulphuric acid mixture is added slowly.
4. Mixture is agitated for about an hour at constant temperature.

Key notes;

- Dosing requires 2.25 gm methanol and 0.05 gm sulphuric acid for each gram of FFA present in oil (usually 15-35%)
- Methanol quality is crucial and reaction temperature is about 55-60°C.

3.3 Process Design and Simulation

3.3.1 Model Development

With data chosen in section 3.1, and information in the DWSIM database, a representative model for the WCO (containing the glyceride and FFAs), biodiesel (methyl esters) and soap (sodium carboxylate) was developed. The model was then used in the selection of the fluid packages for the simulation. Compounds from the database were chosen to represent the glyceride (triolein) and two more chosen to represent the variable FFAs (stearic acid, and palmitic acid).

3.3.2 Simulation

This section entailed the detailed use of the DWSIM simulation program to arrange process units and simulate the chemical reactions and separations that a necessary to affect the desired results i.e., 40 L biodiesel production with the best recovery/yield possible. Expected process units include; filtration, drying, esterification, and decantation.

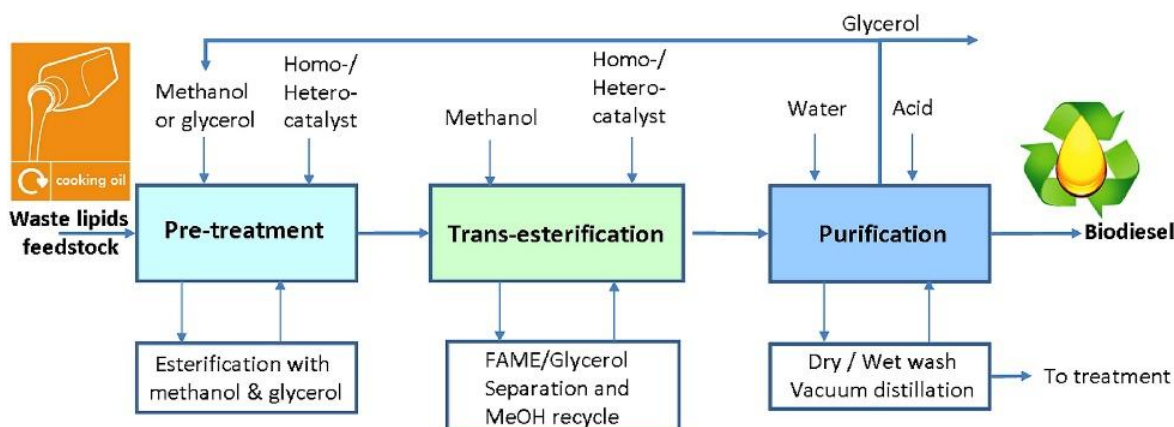


Figure 4. Anticipated Schematic for the production process

It also comprised two of the three major sections of the production process, that is to say, esterification pretreatment and alkali-catalyzed transesterification.

Fluid packages (thermodynamic models) that were employed include Steam Tables (IAPWS-IF97), Wilson, SRK, and UNIQUAC owing to polar compounds and the non-polar ideal nature of the transesterification reaction. The main aim of the simulation was to predict the behaviour of the plant if it was constructed in real-time.

3.3.2.1 Alkali Catalyzed Process Dosage.

	Stoichiometry	Typical
WCO	100kg	100 kg
MeOH	10kg	16-20 kg
Catalyst NaOH 1% w/w WCO	1 kg	1 kg

3.4 Process Automation In order to control reaction temperatures, a heat supply system consisting of the heater, heat exchangers and valves was implemented. The parameters to be controlled include;

- Reaction temperatures.
- Mixing.
- Total reaction time.

3.5 Waste Management and Environmental Considerations

The third major step in production was waste management either by putting the waste (by-products) to use or treating them before their disposal. Typically, the biodiesel process produces glycerin with a purity of 50%. This might be a disposal issue. The glycerin cannot be safely released into the environment because it includes methanol. The only real choices for proper disposal are anaerobic digestion or transportation to a larger biodiesel factory that can do the required refining

3.6 Economic Analysis

The conduct of an economic analysis of the plant was necessary to estimate the costs and potential revenues associated with each of these factors. It involved researching market prices for feedstocks and by-products, obtaining quotes from equipment suppliers, and identifying potential customers for the biodiesel fuel. The economic analysis involved the evaluation of costs and potential revenues associated with producing biodiesel fuel from renewable feedstocks. The following are some of the key factors that were considered when analysing the economics of plant plant:

- Feedstock costs:

The cost of the feedstock used to produce biodiesel was a critical factor in determining the economic viability of the plant. Feedstocks typically used in biodiesel production included soybean oil, canola oil, and waste cooking oil. The price of these feedstocks was affected by factors such as weather conditions, demand, and supply chain disruptions.

- **Capital costs:** The capital costs associated with building and operating a small-scale biodiesel plant included the costs of purchasing and installing equipment, and constructing the plant. These costs can vary depending on the size of the plant, location, and the technology used.
- **Operating costs:** Operating costs included ongoing expenses such as labor, energy, and maintenance costs. These also varied depending on the size of the plant and the type of technology used.
- **Revenue streams:** The revenue generated from biodiesel production came from the sale of the biodiesel itself, as well as by-products such as glycerin, which was composted.

Once these estimates were made, a financial model was created to determine the potential profitability of the biodiesel plant. This model typically included a cash flow analysis, which took into account the initial capital investment, ongoing operating costs, and expected revenues over a period of time. The analysis helped identify potential risks and opportunities associated with the biodiesel plant and informed decisions about whether or not to proceed with the project.

4. RESULTS AND DISCUSSION

4.1 Model Development

Following the procedure in section 3.1.1, the values obtained were manipulated as follows to determine the percentage FFA in the WCO.

- Weight of oil sample = 5.0 grams
- $V_2 = 0.5$ ml
- Net Volume of NaOH solution used in trial 1 = $(V_1 - V_2) = (71.3 - 0.5) = 70.8$ ml
- Net Volume of NaOH solution used in trial 2 = $(V_1 - V_2) = (71.5 - 0.5) = 71.0$ ml
- Net Volume of NaOH solution used in trial 3 = $(V_1 - V_2) = (71.4 - 0.5) = 70.9$ ml
- Normality of NaOH solution = 0.1 N
- $F = 0.995$

To calculate the percentage of free fatty acids, the formula below was used.

$$\%FFA = \left[\frac{(volume\ of\ NaOH\ used) \times (Normality\ of\ NaOH) \times Fx(28.2)}{weight\ of\ oil\ sample} \right]$$

For each trial:

$$\%FFA\ (trial\ 1) = \left[\frac{(70.8) \times (0.1) \times (0.995) \times (28.2)}{5.0} \right] = 39.73\%$$

$$\%FFA\ (trial\ 2) = \left[\frac{(71.0) \times (0.1) \times (0.995) \times (28.2)}{5.0} \right] = 39.84\%$$

$$\%FFA\ (trial\ 3) = \left[\frac{(70.9) \times (0.1) \times (0.995) \times (28.2)}{5.0} \right] = 39.79\%$$

To obtain the average percentage of free fatty acids, the values obtained from all trials were added and divided by the number of trials (3):

$$\%FFA\ (average) = \left[\frac{39.73 + 39.84 + 39.79}{3.0} \right] = 39.79\%$$

Therefore, the average percentage of free fatty acids in the waste cooking oil sample was noted as approximately 40%.

4.2 Process Simulation

4.2.1 Data collection

Given the FFA levels vary in different feed stock, the simulation was carried out at different FFA levels i.e., 15%, 25%, 30%, 45%, and 55% for the non-pretreated alkali catalyzed process.

Filtration was the first step which is thereby followed by the pretreatment (acid catalyzed esterification) after which the alkali transesterification process.

To ensure consistence with reality, an oil sample of about 300 ml of about 40% FFA was pretreated for about an hour at 55°C and methyl esters formed separated from the rest of the solution using a separating funnel. About 110 ml of methyl ester was collected a conversion of about 92% FFA. This information was used in the pretreatment scheme conversion reactor.

Using a rotary evaporator, the filtration residue was freed of the alcohol and partly the acid. The remaining high boiling point oils were then subjected to the alkali catalyzed reaction batch wise. Here methyl esters were formed in conjunction with soap with made settling and room temperature separations difficult. Hence the mode of separation involves sedimentation of solids at bottom and the draining off the methyl esters which come just above the solids.

171 ml of methyl esters was collected surmounting to a conversion of about 95%.

With a non-pretreated WCO sample, the alkali catalyzed process was also tried out in order to determine the conversion value for the saponification process. The conversion value was determined to be in the neighborhood of 98% since 110.4 ml of soap were formed for a 40% FFA WCO. The isolation of the soap was a tedious process that involved evaporation, press filtering and liquification of solids.

4.2.2 Model Development

A representative model was generated for the WCO. WCO is a composition of Triglycerides, Diglycerides (usually small amounts), Monoglycerides (main FFA constituent), mild amounts of water, and solid particle. The FFAs present include oleic acid, palmitic acid, and stearic acid among others.

4.2.3 Reactions

The reactions that happened in the process are as follows;

- Mild hydrolysis of Triolein to form glycerol and oleic acid.
- Reaction between Methanol and FFA (Palmitic acid and Stearic acid) to form Methyl Palmitate and Methyl Stearate.

- Formation of water and sodium salts with respective FFAs and Sodium hydroxide.
- Conversion reaction between Triolein and Methanol to Methyl Oleate and glycerol.

The first two reactions mainly happened in the Pretreatment section as the last to in the in the Alkali catalyzed reactions section. Hence two reaction sets were set up RXN-1 and RXN-2 one for the pretreatment as the other for the alkali catalyzed process.

The conversion values used in these reactions are those that were determined practically in the laboratory so as to attain realistic simulation results.

As for the hydrolysis reaction, the conversion was assumed to be 5%.

The dialog box is titled 'Add New Conversion Reaction'. It contains the following fields and tables:

- Identification:** Name: Triolein Hydrolysis; Description: Mild hydrolysis of Triolein to form glycerol and oleic acid.
- Components/Stoichiometry Table:**

Name	Molar Weight	ΔHf (kJ/kg)	Include	BC	Stoich. Coeff.
Triolein	885.432	-2061.45	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	-1
Water	18.0153	-13422.7	<input checked="" type="checkbox"/>	<input type="checkbox"/>	-3
Stearic acid	284.477	-2685.63	<input type="checkbox"/>	<input type="checkbox"/>	0
Glycerol	92.0938	-6328.33	<input checked="" type="checkbox"/>	<input type="checkbox"/>	1
Oleic acid	282.461	-2300.14	<input checked="" type="checkbox"/>	<input type="checkbox"/>	3
- Stoichiometry:** OK, Balance, Heat of Reaction (kJ/kmol_BC) (25 °C): 18812
- Equation:** C57H104O6 + 3HOH --> HOCH2CH(OH)CH2OH + 3CH3(CH2)7CHCH(CH2)7COOH
- Conversion Reaction Parameters:** Base Comp: Triolein, Phase: Liquid, Conversion [%, f(T)] = 5, T in K.

Figure 5. Set-up of the Mild Hydrolysis reaction.

The dialog box is titled 'Add New Conversion Reaction'. It contains the following fields and tables:

- Identification:** Name: Methyl Palmitate Formation; Description: Reaction between Methanol and Palmitic acid to form Methyl Palmitate
- Components/Stoichiometry Table:**

Name	Molar Weight	ΔHf (kJ/kg)	Include	BC	Stoich. Coeff.
Water	18.0153	-13422.7	<input checked="" type="checkbox"/>	<input type="checkbox"/>	1
Stearic acid	284.477	-2685.63	<input type="checkbox"/>	<input type="checkbox"/>	0
Glycerol	92.0938	-6328.33	<input type="checkbox"/>	<input type="checkbox"/>	0
Oleic acid	282.461	-2300.14	<input type="checkbox"/>	<input type="checkbox"/>	0
Methyl palmitate	270.451	-2590.86	<input checked="" type="checkbox"/>	<input type="checkbox"/>	1
- Stoichiometry:** OK, Balance, Heat of Reaction (kJ/kmol_BC) (25 °C): -18574
- Equation:** CH3(CH2)14COOH + CH3OH --> HOH + CH3(CH2)14COOCH3
- Conversion Reaction Parameters:** Base Comp: Palmitic acid, Phase: Liquid, Conversion [%, f(T)] = 92, T in K.

Figure 6. Set-up for Saponification reaction

Add New Conversion Reaction

Identification
 Name: Methyl Oleate Formation.
 Description: The conversion of Triolein to Methyl Oleate.

Components/Stoichiometry

Name	Molar Weight	ΔHf (kJ/kg)	Include	BC	Stoich. Coeff.
Methanol	32.0419	-6271.17	<input checked="" type="checkbox"/>	<input type="checkbox"/>	-3
Sulfuric acid	98.08	-8168.23	<input type="checkbox"/>	<input type="checkbox"/>	0
Sodium Hydroxide	39.997	-10675.8	<input type="checkbox"/>	<input type="checkbox"/>	0
Sodium Palmitate	278.406	-1826.11	<input type="checkbox"/>	<input type="checkbox"/>	0
Methyl oleate	296.488	-2121.5	<input checked="" type="checkbox"/>	<input type="checkbox"/>	3

Stoichiometry: OK Balance Heat of Reaction (kJ/kmol_BC) (25 °C): -41710

Equation: $C57H104O6 + 3CH3OH \rightarrow HOCH2CH(OH)CH2OH + 3CH3(CH2)7CHCH(CH2)7COOCH3$

Conversion Reaction Parameters
 Base Comp: Triolein Phase: Liquid
 Conversion [%, f(T)] = 95 T in K

Use '.' as the decimal separator on the conversion expression.

Cancel OK

Figure 7. Set-up of Methyl Oleate Formation Reaction

DWSIM - Reaction Set Editor

Identification
 Name: RXN-1
 Description: Reaction set for pretreatment reactions.

Reactions

Reaction	Type	Equation	Active	Seq.
Triolein Hydrolysis	Conversion	$C57H104O6 + 3HOH \rightarrow HOCH...$	<input checked="" type="checkbox"/>	0
Methyl Palmitate Formation.	Conversion	$CH3(CH2)14COOH + CH3OH \rightarrow ...$	<input checked="" type="checkbox"/>	0
Methyl Stearate Formation	Conversion	$CH3(CH2)16COOH + CH3OH \rightarrow ...$	<input checked="" type="checkbox"/>	0

Cancel OK

Figure 8. Components of Pretreatment Reaction Set.

DWSIM - Reaction Set Editor

Identification
 Name: RXN-2
 Description: Alkali Catalyzed Reactions Process

Reactions

Reaction	Type	Equation	Active	Seq.
Saponification reaction	Conversion	$CH3(CH2)14COOH + NaOH \rightarrow ...$	<input checked="" type="checkbox"/>	0
Methyl Oleate Formation.	Conversion	$C57H104O6 + 3CH3OH \rightarrow HO...$	<input checked="" type="checkbox"/>	0

Cancel OK

Figure 9. Components of Alkali Catalyzed Reaction Set.

Name	Description	Name	Type	Equation
Default Set	Default Reaction Set	Triolein Hydrolysis	Conversion	$C57H104O6 + 3HOH \rightarrow HOCH2C...$
RXN-1	Reaction set for pretreat...	Methyl Palmitate Formation.	Conversion	$CH3(CH2)14COOH + CH3OH \rightarrow ...$
RXN-2	Alkali Catalyzed Reaction...	Methyl Stearate Formation	Conversion	$CH3(CH2)16COOH + CH3OH \rightarrow ...$
		Saponification reaction	Conversion	$CH3(CH2)14COOH + NaOH \rightarrow H...$
		Methyl Oleate Formation.	Conversion	$C57H104O6 + 3CH3OH \rightarrow HOCH...$

Figure 10. Reactions and their corresponding reaction set.

4.2.4 Simulation

With this information, three simulation was executed starting with non-pretreated feed stock, pretreatment and the combined pretreatment and alkali catalyzed processes. The data generated from the simulations particularly the methyl ester streams was used to compare the properties of those streams with the methyl esters produced in lab. These had a great similarity.

4.2.4.1 Non-pretreated Alkali Process

The PFD below has values attached to it corresponding to the 40% FFA content Waste Cooking Oil (WCO). A table detailing the results of this simulation can be referred to in appendix B table B 1.

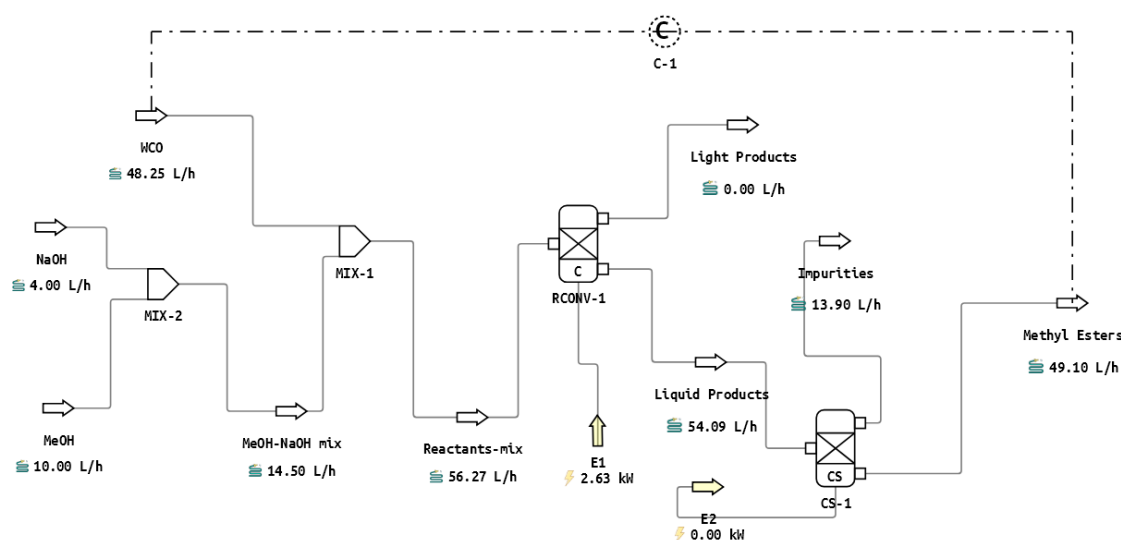


Figure 11. Non-pretreated Alkali Catalyzed Reaction Experimental Set-up.

The simulation aims at determining the amount of WCO required to produce 43.5228L methyl esters stream [40L of methyl oleate (Biodiesel)] without.

FFAs are represented by palmitic acid and the triglycerides are represented by Triolein in the WCO. Methyl Oleate represents the Biodiesel.

Following the procedure in section 3.3.2.1, Reaction was carried out as per the schematic in figure 18. Reaction set RXN-2 was used in the conversion reactor RCONV-1 after which they are sent to the component separator CS-1.

The logic controller C-1 was used in predicting the required amount of feed stock at different FFA levels required to attain the same amount of MEs.

The simulation is repeated with different values of FFA% and results tabulated below,

Target y = 40L/h methyl oleate.

Table 2. Shows the Dependency of amount of WCO required to produce similar amounts of methyl esters at different FFA levels.

FFA%	Amount of WCO used x (L/h)	Formation % [(y/x) *100%]
15	45.33	88.30
25	47.76	83.75
30	48.19	82.99
35	48.70	82.14
40	49.22	81.27
45	53.46	74.82
55	61.69	64.82
60	63.66	62.83

As seen from the table and graph above, the increase in FFA% calls for use of more WCO to attain the same amounts of methyl esters.

Graph Showing variation of Amount of WCO used and Percentage Formation with Percentage FFA present in feed.

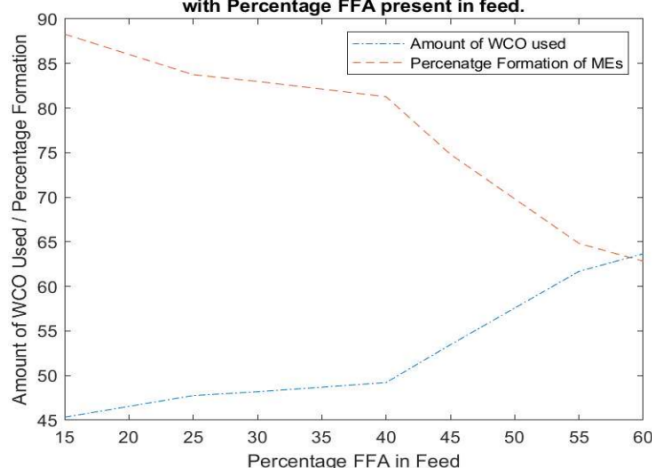


Figure 12. Graph Showing variation of Amount of WCO used and Percentage Formation

Table 3. Master Property table at 40% FFA.

PROPERTY TABLE									
Object	WCO	Reactants-mix	NaOH	Methyl Esters	MeOH-NaOH mix	MeOH	Liquid Products	Light Products	Impurities
Temperature	25	25.0494	25	55	26.5595	25	55	55	55 C
Pressure	1.01325	1.01325	1.01325	1.01325	1.01325	1.01325	1.01325	1.01325	1.01325 bar
Mass Flow	43.6946	59.2322	7.64961	42.0653	15.5377	7.88805	59.2322	0	17.1669 kg/h
Volumetric Flow	40.2491	56.2706	4	49.1018	14.4964	10	54.0875	0	13.8998 L/h
Density (Mixture)	905.604	1052.63	1912.4	856.697	1071.03	788.805	1095.12	--	1235.05 kg/m3
Volumetric Fraction (Overall Liquid)	1	1	1	1	1	1	1	NaN	1
Molar Fraction (Overall Liquid) / Methyl oleate	0	0	0	0.968426	0	0	0.286182	NaN	0

This implied that the higher the FFA, the more WCO was required to attain the same amount of MEs a clear wastage in soap formation. This required optimization such that these FFA be converted to MEs in place of Soap (Sodium Palmitate).

This called for pretreatment in the next simulation (section 4.2.4.2).

4.2.4.2 Pretreatment Scheme

Following the pretreatment procedure in section 3.2, the PFD in figure 20 was generated. Acid catalyst was mixed with methanol and resultant solution added to the filtered WCO in the conversion reactor RCONV-1. The dosage as I section 3.2 was utilized.

In practice, the component separator CS-1 involves a settling/sedimentation tank where methyl esters formed settle at bottom owing to their high density as the other components take up the upper layers as depicted in the experimental figures in the appendix A of pictures.

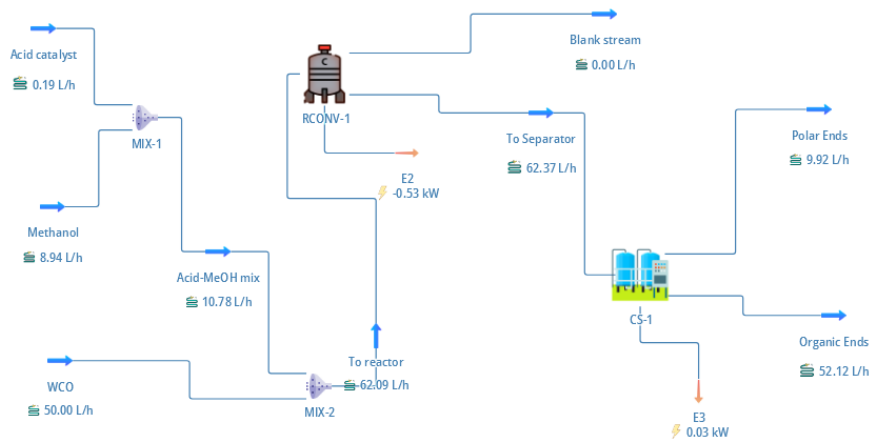


Figure 13. First Pretreatment PFD

As seen in figure 21, the Polar Ends streams is mainly methanol, this necessitated the need of methanol recovery as depicted in the figure 23. A considerable amount of methanol can be recovered the can be recycled. A shortcut column was used and the simulation results for is shown in figure 24. in practice this could be controlled heating/vaporization in a given temperature range in cases where a column is costly to implement.

The organic ends stream contained methyl esters i.e., methyl oleate and methyl palmitate (0.06802 and 0.39586-mole fraction respectively). Also 0.03914 and 0.20781 mass fractions respectively a sum of 0.24695.

The total mass of this stream being 45.6617 kg/h means that 11.2762 kg/h of methyl esters are formed which would otherwise have been saponified. Given the stream, density is 876.165 kg/m³ from the master property table, then the volume of methyl esters formed is 12.8699 L/h. Table B 2 in appendix B shows the detailed results of the simulation more so for the material streams.

It should be noted that methyl palmitate was chosen to represent the FFAs. The methyl oleate was formed as a result of the esterification of oleic acid formed due to the mild hydrolysis of Triolein. The WCO used in this experimental simulation was considered to have 45% FFA.

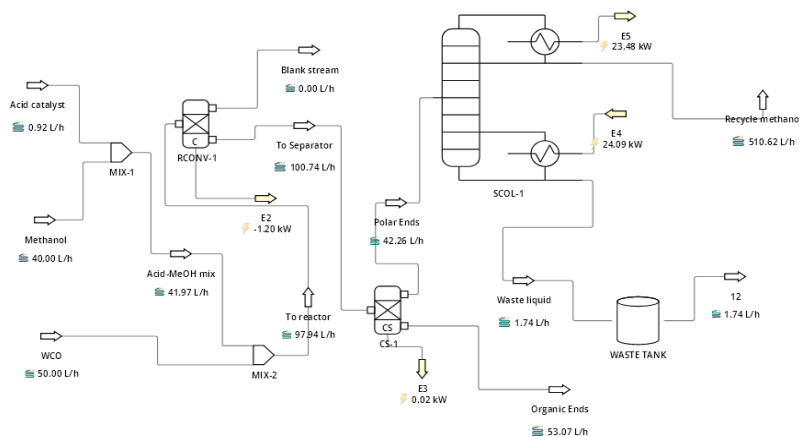


Figure 14. Final Pretreatment PFD with Alcohol Recovery Column.

Table 4. Master Property Column for Final Pretreatment PFD.

MASTER PROPERTY TABLE												
Object	Waste liquid	WCO	To reactor	To Separator	Recycle methanol	Polar Ends	Organic Ends	Methanol	Acid-MeOH mix	Acid catalyst	12	
Temperature	119.763	25	25.0137	55	64.7477	55	55	25	24.999	25	119.763	C
Pressure	1.01325	1.01325	1.01325	1.01325	1.01325	1.01325	1.01325	1.01325	1.01325	1.01325	1.01325	bar
Volumetric Flow	1.73789	50	97.9419	100.736	510.625	42.2621	53.0671	40	41.9718	0.919877	1.73789	L/h
Density (Mixture)	1569.93	914.715	812.451	789.916	59.4595	782.964	875.932	788.805	806.189	2484.03	1569.93	kg/m ³
Volumetric Fraction (Overall Liquid)	0.937965	1	1	1	0.0776684	1	1	1	1	1	0.937965	

Results		
Property	Value	Units
Minimum Reflux Ratio	0.222989	
Minimum Number of Stages	9.59731	
Actual Number of Stages	12.898	
Optimal Feed Stage	10.9906	
Stripping Liquid	2.42704	kmol/h
Rectify Liquid	1.42758	kmol/h
Stripping Vapor	2.3793	kmol/h
Rectify Vapor	2.3793	kmol/h
Condenser Duty	23.4831	kW
Reboiler Duty	24.0929	kW

Figure 15. Simulation Results of Distillation Column for Alcohol Recovery

4.2.4.3 Combined Pretreatment and Alkali Catalyzed Process

Thereafter, the simulation was taken another step combining the pretreatment with the alkali catalyzed process one after the other respectively

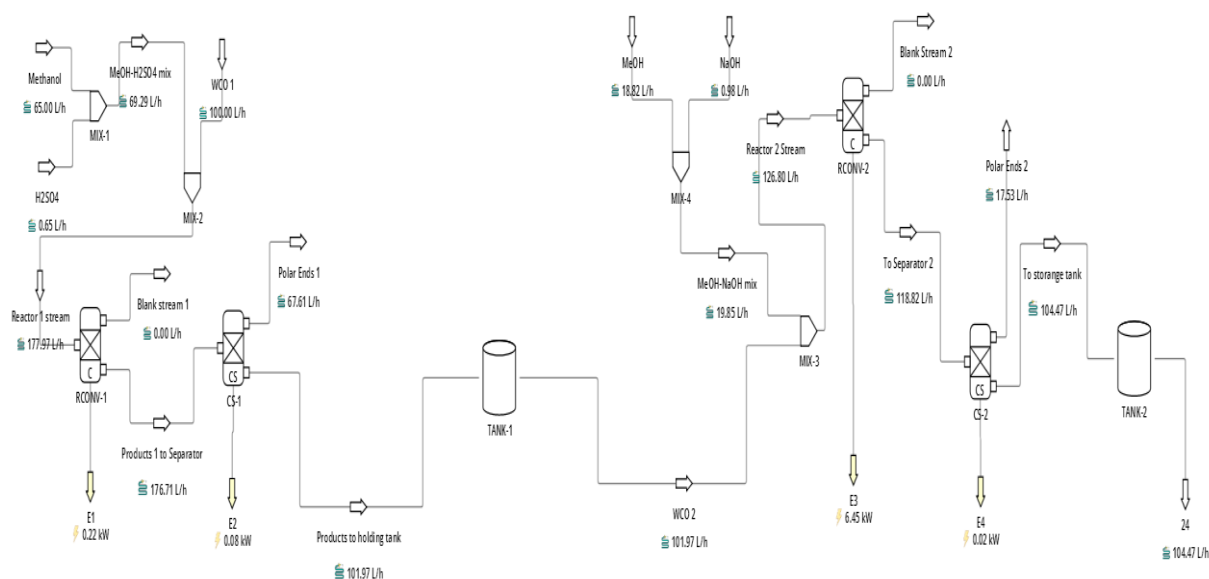


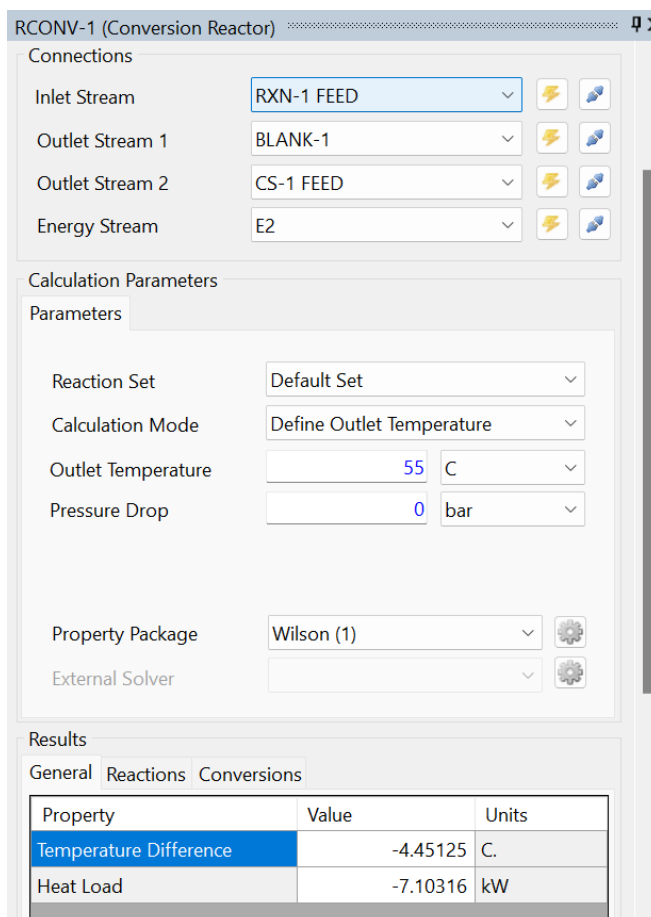
Figure 16. PFD for Combined Simulation without Methanol Recovery.

It should be noted that the higher the production amounts in a given run, the more necessity to implement Methanol recovery a case in point as seen in the Master Property Table, the volumetric flow of Polar Ends stream is quite high given that about 90% and 58% of these streams is Methanol.

Table 5. Master Property Table for Combined Simulation without Methanol Recovery.

MASTER PROPERTY TABLE									
Object	WCO 2	WCO 1	To storage tank	Products to holding tank	Polar Ends 2	Polar Ends 1	Methanol	MeOH	
Temperature	25	25	25	25	25	25	25	25	C
Pressure	1.01325	1.01325	1.01325	1.01325	1.01325	1.01325	1.01325	1.01325	bar
Mass Flow	90.7343	89.8642	90.9112	90.7343	16.3231	55.6167	51.4868	15	kg/h
Volumetric Flow	101.97	100	104.47	101.97	17.5307	67.6106	65	18.8181	L/h
Density (Mixture)	889.81	898.642	870.216	889.81	991.115	822.603	792.104	797.106	kg/m ³
Mass Flow (Overall Liquid) / Methyl palmitate	19.1733	0	19.4913	19.1733	0	0	0	0	kg/h
Mass Flow (Overall Liquid) / Methyl oleate	0	0	69.8294	0	0	0	0	0	kg/h

On the other hand, the pretreatment products [Products to holding tank stream] recovered a great deal of methyl esters from the FFAs about 19.1733 kg/h which supplemented that produced from the Alkali catalyzed reaction i.e., 69.8294 kg/h, a total of about 89.3207 kg/h. The additional 0.318 kg/h is derived from the esterification side reactions in the second phase of the process. Given the input mass flow rate was 89.8642 kg/h [WCO 1 stream], the mass conversion can be said to be 99.395% a clear improvement from the previous process. Figure 27 presents a flow sheet with a short cut distillation column aiming at determining whether Methanol recovery can be justified in the long run of production. As seen in the PFD in figure 27, a considerable amount of Methanol can be recovered from the Polar Ends stream 1.



4.3 Plant Automation

This section involved integration of heating system and valves as shown in figure 29. A heater, a heat exchanger, and valves were introduced in the flow sheet. The purpose of the heater was to generate hot water that was to be used in the conditioning of the feed stocks for the two reactors given the reaction temperature is best at around 55-60°C.

4.4 Waste Management

Waste management is an essential aspect of any biodiesel production plant, regardless of the scale of the operation. Here are the proceedings implemented for managing waste in a small-scale biodiesel production plant:

- Segregation:

The waste generated was separated into different categories such as hazardous waste, non-hazardous waste, and recyclable waste.

- Hazardous waste disposal:

Hazardous waste generated in the plant, such as chemicals, should be disposed of as per local regulations. Contact the relevant authorities to learn more about hazardous waste disposal options. In this case, the wastes for pretreatment and alkali catalyzed process were neutralized using NaOH solution when acidic and in some cases sulphuric acid when alkaline such as the wash waters for MEs-1 and MEs-2 respectively.

- Composting:

The organic waste generated from the production process, such as glycerol, could be composted (anaerobic digestion) to produce fertilizer. This can reduce waste and provide a useful product for the local community.

- Recycling and Reuse:

This option was explored mainly in the pretreatment step where methanol was recycled so as to mitigate the wastes produced, about 61.0L.

- Monitor and optimize:

Regular monitoring of the waste generated from the plant and implementing ways to optimize the production process to reduce waste

4.5 Economic Analysis

Here is a sample economic analysis of a small-scale biodiesel production plant:

Considerations:

- Feedstock: Waste cooking oil, priced at UGX 20,000 per 20L.
- Plant capacity: 5,000 L per month.
- Diesel Price: UGX 4,800.
- Estimated Capital cost: UGX 65,000,000.
- Operating costs: UGX 15,000,000 per month.
- Revenue streams:

Biodiesel fuel sold at UGX 4,800 per litre, and glycerin by-product composted sold at UGX 150 per kilogram.

Cash flow analysis for the first year:

- Estimated Capital cost: UGX 65,000,000.
- Operating costs: UGX 17,000,000 per month.

Revenue per month from biodiesel sales: UGX 48,000,000 (5,000 liters x UGX 4,800 per liter)

Revenue per month from glycerin sales: UGX 150,000 (5,000 L x 0.2 kg of glycerin per liter x UGX 150 per kilogram)

Total revenue per month: UGX 24,150,000.

Annual revenue: UGX 289,800,000.

Annual operating costs: UGX 204,000,000.

Net cash flow for the first year: UGX 20,800 (-UGX 65,000,000 capital investment – UGX 204,000,000 operating costs + UGX 289,800,000 revenue + UGX 0 tax credit). Based on this analysis, the biodiesel plant would have an almost negative cash flow in the first year, primarily due to the capital investment required to build the plant. Over time, the plant could become profitable if it is able to increase its production volume and reduce its operating costs. The analysis could be refined by incorporating more detailed cost and revenue data, as well as sensitivity analyses to explore the impact of different market conditions on the plant's profitability.

5. LIMITATIONS, CONCLUSION, AND RECOMMENDATIONS

5.1 Limitations

While designing and optimizing a small-scale biodiesel production plant is a feasible project, there are some limitations and challenges to consider as follows;

- **Feedstock availability and cost:** The availability and cost of the chosen feedstock can have a significant impact on the economics of the biodiesel production plant. The cost of feedstock can fluctuate based on various factors such as crop yield, weather, and demand. Limited availability of feedstock can also affect the production capacity of the plant.
- **Production process complexity:** The production process for biodiesel can be complex and requires specialized knowledge and skills to operate. The use of certain chemicals and catalysts such as methanol and sulphuric acid can also pose safety hazards and require special precautions.
- **Capital and operating cost:** The capital and operating costs associated with building and operating a biodiesel production plant can be significant. This includes costs associated with land, equipment, labor, utilities, and maintenance.
- **Environmental impacts:** Biodiesel production can have both positive and negative environmental impacts. For example, while biodiesel can reduce greenhouse gas emissions, the production process may generate wastewater and other waste products that require proper disposal.

In summary, designing and optimizing a small-scale biodiesel production plant requires careful consideration of various factors, including feedstock availability and cost, production process complexity, capital and operating costs, environmental impacts, market demand and competition, and regulatory requirements. It is important to conduct thorough research and seek expert advice before embarking on such a project

5.2 Conclusion

In conclusion, designing and optimizing a small-scale biodiesel production plant requires careful planning, attention to detail, and a thorough understanding of the production process.

The selection of appropriate equipment, development of a detailed processing protocol, and optimization of the process are all critical components in achieving efficient and cost-effective production.

Incorporating automation technology into the plant design can help streamline the production process and reduce the need for manual labor.

5.3 Recommendations

Here are some recommendations to consider for the biodiesel production project:

- Conduct a feasibility study:

Before starting the project, it is recommended to conduct a feasibility study to assess the potential of the project. This study should consider factors such as the availability and cost of feedstock, the market demand for biodiesel, the regulatory environment, and capital and operating costs.

- Selection of an appropriate location:

The location of the biodiesel production plant is important, as it can impact the availability and cost of feedstock, transportation costs, and access to the market. Factors such as proximity to feedstock suppliers, transportation infrastructure, and local regulations should be put into consideration.

- Choosing an appropriate production process:

There are different production processes for biodiesel, and each has its advantages and disadvantages. A process that is suitable for the feedstock available and the scale of the project.

- Optimization of the production process:

To maximize efficiency and reduce costs, it is recommended to continuously optimize the production process. This may involve experimenting with different production parameters, implementing automation, and exploring new technologies.

- Implement quality control measures: Quality control measures are important to ensure that the biodiesel meets the required standards. Implementation of regular testing of the feedstock and the final product for impurities and monitoring of the production process to maintain consistency..

By following these recommendations, the biodiesel production project can be designed and optimized to be efficient, sustainable, and profitable.

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APPENDICES

APPENDIX A





Figure 25. Heating Bath for Feed Conditioning.



Figure 26. Conditioned WCO



Figure 27. Setup of Experimentation Table.



Figure 28. Vaporization of Excess MeOH in Oven



Figure 29. Clear Filtered WCO.



Figure 30. Separation of MEs using Filtering Funnel.



Figure 31. Filtered WCO in Water Bath for Conditioning.



Figure 32. An Individual Recording Experimental Results



Figure 33. MEs collected in conical flask



Figure 34. Separated Methyl Ester Layer as from Pretreatment Stage