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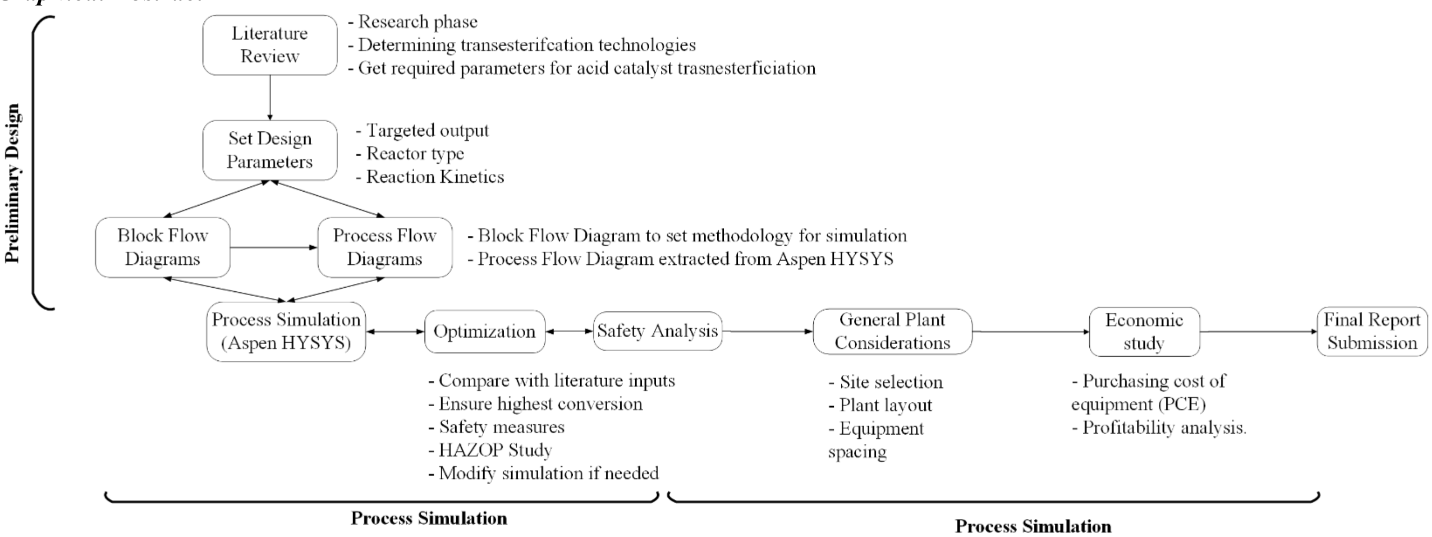
Process Simulation and Design for Biodiesel Production Plant from Waste Cooking Oil

Abstract: This paper evaluates the design of waste cooking oil (WCO) derived from biodiesel plant of industrial scale based on the technical and economic feasibility through a twofold method namely: process simulation and plant design. Aspen HYSYS V10 was used to simulate a steady state of transesterification process in the presence of a catalyst using sulfuric acid. The approach included schematic process flow diagram, thorough plant design phase which entailed Hazard and Operability (HAZOP) study, plant layout, site selection, etc., and the economic analysis. The simulation was managed to attain the high biodiesel yield of 97% conversion of fatty acid methyl esters (FAME) and the mass flow of 1006 kg/hr in the product line. This outcome is in agreement with what has been obtained in recent literature on other catalyzed transesterification reactions. The economic analysis validated that the project could be conducted within its financial stability, and the fixed capital investment within the entire project added as much as $8,448,760, and an expected net profit of $2,726,000 as a yearly profit. This gives a good Return on Investment (ROI) of 32.3% and a quick payback of 3 years due to operation and thus the final plant design presented is not only technically sound, safe but also economically viable. This study illustrates the existence of a solid and viable route towards valorization of WCOs, which helps to solve the issue of additional and renewable energy supplies and lends a hand to waste management and the sustainability of the environment.

Keywords: Acid Catalyst; Biodiesel; Plant Design; Transesterification; Waste Cooking Oil.

Graphical Abstract



I. Introduction

The decline in diesel fuel availability and its related pollution has established the necessity for the quest for new sources of energy, where the biodiesel has been found to be a top contender due to its similar combustion with diesel. Industrialization has, since over a century ago, depended heavily on fossil fuels like oil, coal, and natural gas, but these are now facing immense rapid depletion due to the unsustainable consumption rates [2]. Increasing worldwide energy demand has raised apprehensions regarding the finite nature of fossil fuels, creating an interest in cleaner, renewable sources of energy to reduce environmental damage and contribute towards combating climate change [3, 4]. The utilization of fresh edible vegetable oil for the generation of biodiesel is an acute economic and ethical problem, in addition to food competition. The second alternative, though less viable and sustainable, is the use of low-quality feedstocks, such as waste cooking oil (WCO), waste frying oil (WFO), and waste vegetable oil (WVO), otherwise used ineffectively [2]. Use of such waste oils as a renewable, biodegradable, and environmentally friendly source is a new means to address the increasing energy requirement [3]. WCO is also used in binary hybrid feedstocks blended with other oils like palm oil or jatropha oil to form biodiesel that may be blended with pure diesel fuel [5]. The conversion of waste cooking oil into biodiesel is typically done through a process of transesterification. Such low-grade feedstocks, though, are characterized by high free fatty acid and water contents, thus making the process of production complex. Catalytic approaches have evolved to offer sustainable solutions to such issues. Heterogeneous catalysis, for example, through the use of solid acid catalysts is capable of performing both esterification and transesterification in a one-step process even with high free fatty acid content [2]. Other type-specific catalysts are also under development, such as a nanocellulose-coated magnetite-strontium oxide catalyst [6] and bifunctional magnetic nanocatalysts with which

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one can perform a life cycle assessment [7]. Additionally, conventional catalysts like sodium hydroxide (NaOH) and potassium hydroxide (KOH) deactivate and are susceptible to sensitivity towards impurities, so catalysts like rare earth metal oxides are a better choice [8]. Pretreatment of the WCO is also an important step to enhance raw material quality, for example, by de-acidification using an adsorbent from industrial wastes [9]. Other novel catalysts include metal-oxides bifunctional catalysts prepared from waste eggshell [10] and Ni-Co-Cu ferrites [11]. Very high yields of biodiesel from WCO were obtained in various studies using these novel methods. Approximately 97% yield of biodiesel was achieved using a solid acid catalyst at 75°C conditions[2]. 95.00% biodiesel was revealed under ideal conditions by another study with a catalyst of nanocellulose-coated magnetite-strontium oxide [5]. Additionally, the use of a heterogeneous catalyst under a Response Surface Methodology Box Behnken Design at a temperature of 60°C effectively produced approximately 94.12% biodiesel [3, 10]. Use of heterogeneous catalysts has a number of environmental benefits in that they can easily be recovered and reused, eliminating the need for cumbersome purification procedures and reducing energy and water consumption [2]. From the analysis point of view, advanced learning techniques such as artificial neural networks (ANN) can be employed in a bid to model the density of WCO biodiesel-alcohol mixtures in a reliable manner [5]. Use of waste cooking oil (WCO) as a feedstock in biodiesel production can make the process cost-effective to a large degree due to the low cost. In contrast to edible oils, use of WCO does not stimulate the "food versus fuel" debate, is readily available, and solves environmental issues associated with its disposal. The manufacture of biodiesel from WCO may be an effective solution in the developing world by offering a low-cost and viable source of renewable energy. A study found that for the production of biodiesel from supernatant waste cooking oil (S-WCO), total costs were $1.342/L and incomes were $2.481/L, with net return amounting to $1.157/L and benefit-to-cost ratio of 1.876. Biodiesel also has a higher flash point compared to traditional fuels; thus it is safer and more energy-efficient for storage and transportation. Heterogeneous recyclable catalysts to drive the biodiesel yield to its maximum while minimizing conversion cost can be employed to make production economical. Furthermore, utilization of unused materials such as WCO and waste rubber to blend fuel presents a viable, sustainable alternative for traditional diesel, enabling valorization of waste-to-energy. Biodiesel is very promising as a fuel alternative to conventional fossil fuels due to renewability, biodegradability, and nontoxicity. Biodiesel may be used directly in existing diesel engines without mechanical modification in its pure form or in mixing with conventional diesel. This is due to its physical and chemical properties being nearly identical to those of petroleum diesel. Biodiesel's use in engines can result in improved performance, reduced carbon monoxide (CO) and particulate emissions, and even extend the operating life of an engine because of the lubricity associated with it. For example, ternary blend of biodiesel from WCO and rubber seed oil was indicated as a viable replacement fuel for unmodified diesel engines because it gave fewer unburnt hydrocarbons and CO emissions than diesel. Blending waste cooking oil biodiesel with waste rubber pyrolysis oil (50:50) resulted in a fuel of properties closely resembling the conventional diesel, and the engine torque was also increased with reduced emissions. Overall, biodiesel production from waste cooking oil has the benefit of being an alternative energy source for the production of liquid fuels from biomass and has advantages in terms of waste management, economics, and environmental sustainability [12]. This study differentiates itself from recent research by integrating process simulation, plant design, safety (HAZOP), and techno-economic analysis into a unified framework for WCO biodiesel. In contrast to previous studies that primarily focus on reaction kinetics or economic feasibility, our work bridges this gap by linking validated Aspen HYSYS simulation with industrial-scale design and risk assessment, thereby offering a more comprehensive evaluation. The potential and economic viability for applying the transition towards green energy transition is assessed in this study in the form of a two-stage analysis for the production of biodiesel, also known as fatty acid methyl ester (FAME) from waste cooking oil on the industrial scale, in which the two-stage analysis consists of process simulation and design of the production plant.

II. Methodology

The study has been divided into two main sections as shown in **Fig.1** The study's framework is adopted from a previously conducted plant design study, where this study is divided into two main stages: process simulation and plant design [13]. The process simulation section discusses the process of production of biodiesel from waste cooking oil via transesterification, utilizing an acid catalyst. While sulfuric acid was chosen for its well-documented efficacy in managing high free fatty acid (FFA) content, heterogeneous catalysts, such as Mg-Al hydrotalcites and bifunctional nanocatalysts, have shown comparable yields with the added benefits of reusability and ease of separation [10, 14]. Future research could integrate these catalysts into simulations to assess potential economic and environmental advantages.

The results are then analyzed in comparison to previous simulation results deduced from past literature. The second stage, which is the plant design phase, involves analyzing safety procedures to perform necessary measures that ensure sufficient safety protocols are followed, thus mitigating accidents and risk of damage to equipment and personnel. This is followed by general plant considerations such as plant layout and site selection, which is then followed by an economic study that consists of determining the purchasing costs of equipment as well as profitability analysis which has been conducted to deduce an estimate for the payback period for the plant.

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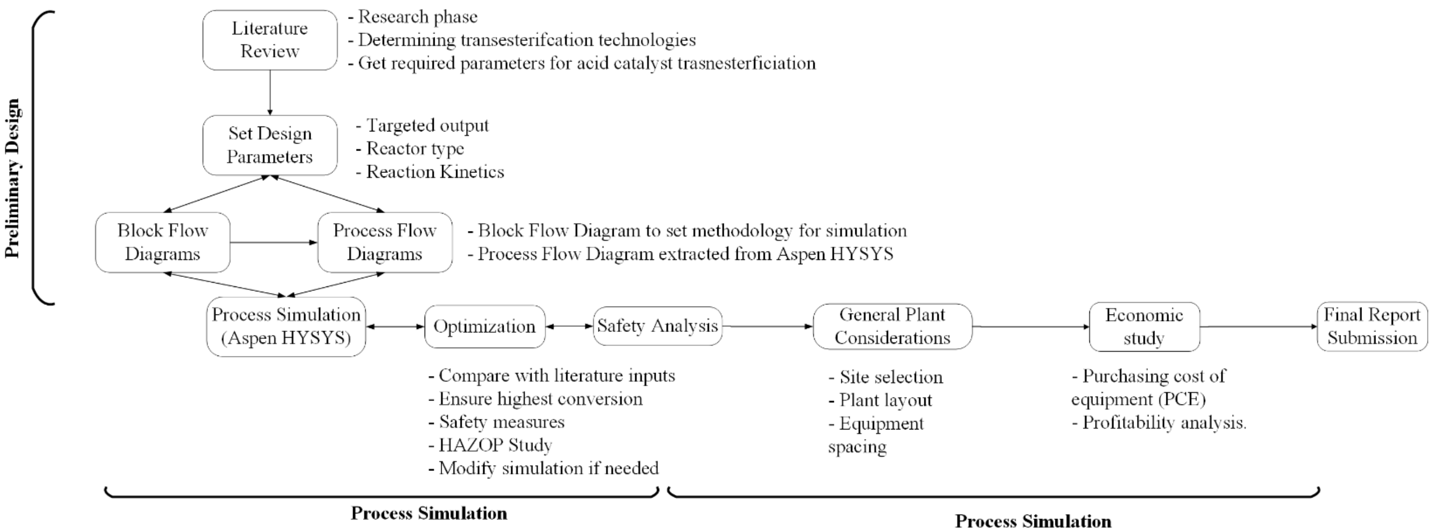

Figure 1: Study methodology flowchart.

A. Process Overview

The transesterification process was carried out using Aspen HYSYS V10, with Peng-Robinson as the properties package assigned in defining stream components. Initially, a block flow diagram (BFD) has been sketched as shown in **Fig.2** for the overview plan for the simulation process. After an intensive analysis of the current available conversion technologies, the main reaction being carried out with the highest potential would be transesterification of waste cooking oil using sulfuric acid as a homogenous acid catalyst [15, 16]. As seen visual in the figure, the BFD presents five main stages that occur during the process, which include mixing, conversion, separation, neutralization, followed by a final separation stage. The mixing unit consists of mixers and centrifugal pumps which aim to prepare the methanol to oil ratio as per recommendation, which is then modified iteratively to achieve the highest conversion rate. The mixture of the methanol, oil and catalyst is then at suitable conditions to initiate the transesterification process. The transesterification reactor takes place in the conversion reactor, where methanol reacts with the free fatty acids present in waste cooking oil stream forming triglyceride or commonly known as glycerol and FAME, or in other words, biodiesel [17, 18]. The conversion is then followed by neutralization, this is vital as the acid catalyst needs to be neutralized using a neutralizing agent in order to avoid soap formation, while optimizing biodiesel yield alongside catalyst recycling [14].

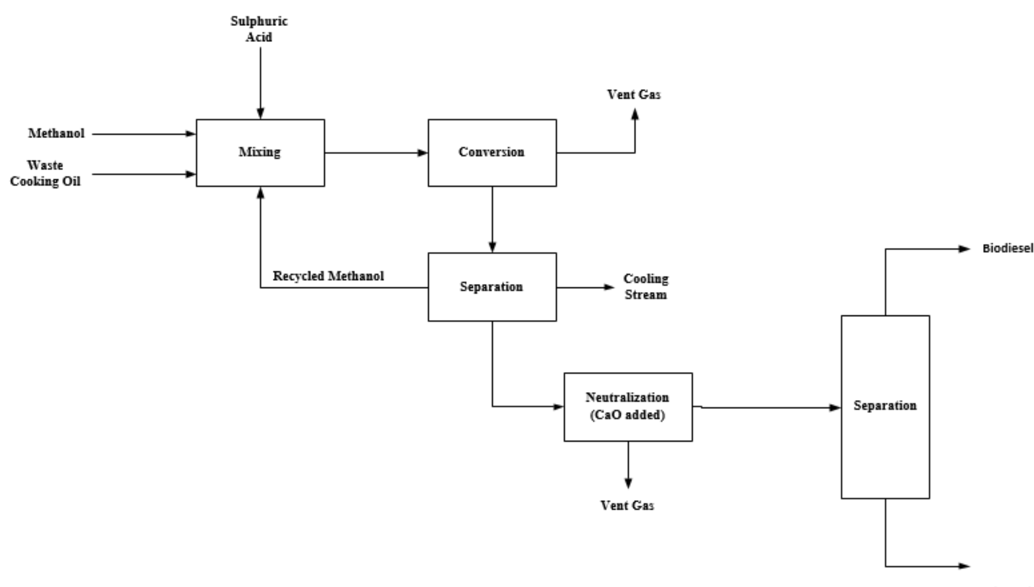

Figure 2: Block Flow Diagram for waste cooking oil transesterification process

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B. Plant Design Steps

The methodology of this research will be multi-directional, beginning in a highly elaborate safety assessment and concluding with the complete economic assessment. A Hazard and Operability (HAZOP) study will be carried out as the first risk identification method, which will be subject to a careful assessment of the process to determine areas of potential deviation from design intent and their consequences [19]. This systematic approach, a chemical industry's best practice since the 1970s, is central to the prevention of accidents such as explosions, fires, and toxic releases [20, 21]. The findings of the HAZOP study will be integrated in the production plant layout and site selection phase, informing decision making to eliminate or reduce the hazards that have been found and ensure maximum overall safety for the facility [22]. The plant layout will be designed for optimal material flow and at minimum cost, equipment spacing being optimized to achieve maximum productivity and reduce the risk of accidents [23, 24]. Finally, economic feasibility will be determined by detailed capital and operating cost analysis. This will encompass determination of cost of equipment purchase and profitability analysis by the use of key financial measures such as return on investment (ROI) and payback period (PBP) [25, 26]. The combined methodology will ensure that not only will the project be technically viable and safe but also financially viable.

III. Process Simulation Results

The flowchart displayed in **Fig.3** illustrates a steady-state process from the two primary feed streams of waste cooking oil and methanol, indicated as Methanol and H_2SO_4, respectively. The streams are pumped (P-100) and are then fed into a heat exchanger (E-100) to the ideal reaction temperature prior to their entry into a continuous stirred-tank reactor (CRV-100). The reactor is where the process meets its core in which the transesterification reaction occurs, where the WCO triglycerides are reacted to produce fatty acid methyl esters (FAME). The product is then sent for reaction through a separator to differentiate the product into crude glycerol stream and a stream of high FAME content.

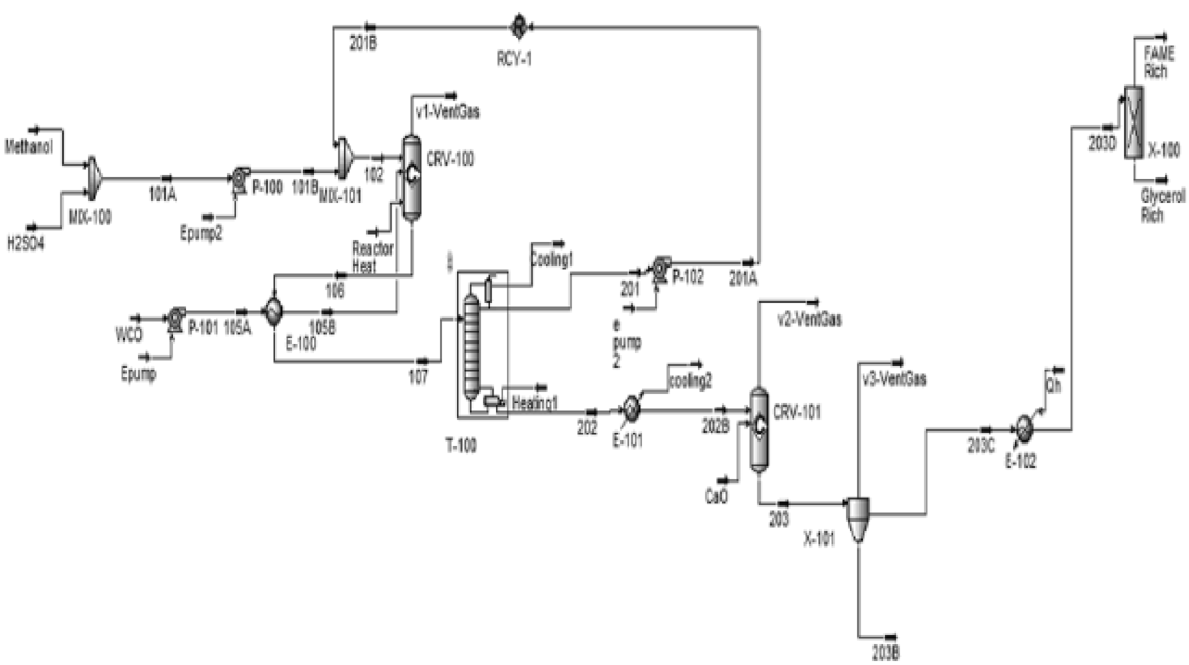

Figure 3: Process Flow Diagram from Aspen HYSYS software.

Operational parameters were chosen judiciously as shown in ***table 1*** in simulation such that it would be able to replicate conditions that have been found effective in WCO transesterification. The temperature in R-100 is kept at 60°C and pressure at 101.3 kPa, and 1 kg/hr of sulfuric acid is added as a catalyst. The conditions are in accordance with the latest scientific studies. For instance, studies on two-stage transesterification of WCO have been reported to employ reaction temperature in the range of 60-65°C and achieve high yield of biodiesel at low levels of the catalyst. The 142.3 kg/hr methanol and 1000 kg/hr WCO ratio of methanol to oil is also optimal in comparison with literature values for similar processes. This tedious selection of parameters considers the process design and assures the result of the simulation to be technologically sound and in accordance with actual applications.

Table 1: Overall streams summary table.

Stream No.	**Temperature (°C)**	**Pressure (kPa)**	**Molar Flow rate (kgmole/hr)**	**Mass Flow rate (kg/hr)**
WCO	25.0	101.3	1.2	1030.0

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Methanol	25.0	101.3	3.8	121.2
H2SO4	25.0	101.3	1.5	150.1
101A	25.0	101.3	5.3	271.3
101B	25.2	400.0	5.3	271.3
102	40.6	200.0	8.8	383.6
105A	25.2	400.0	1.2	1030.0
105B	30.0	400.0	1.2	1030.0
106	80.0	200.0	10.0	1414.0
107	76.7	200.0	10.0	1414.0
201	64.5	101.3	3.5	112.3
201A	64.5	200.0	3.5	112.3
201B	64.5	200.0	3.5	112.3
202	161.3	111.0	6.5	1301.0
202B	70.0	111.0	6.5	1301.0
v2-VentGas	-156.6	101.3	0.0	0.0
203	-156.6	101.3	10.0	1501.0
203B	-156.6	101.3	3.6	322.5
203C	-156.6	101.3	6.5	1179.0
v3-VentGas	-156.6	101.3	0.0	0.0
203D	120.0	200.0	6.5	1179.0
FAME Rich	120.0	100.0	3.4	1006.0
Glycerol Rich	101.8	100.0	3.1	172.6

The validation of the feed streams mass composition displayed in ***table 2*** ensures the optimality of the process simulation. The biodiesel product obtained boasts a mass flow rate of 1006 kg/hr and conversion rate of 97%. This level of such high yield is truly extraordinary and lies well within the standard levels of previously reported yields in recent literature, which often gives yields in the range of 93% to 97% for acid-catalyzed transesterification of waste cooking oil [27, 28, 29]. The simulation properly separated the target FAME from crude glycerol and other by-products, confirming the appropriateness of the chosen unit operations and their operating conditions. That kind of purity is necessary in the effort to meet the quality standards for application as a straight replacement or as a blend with regular diesel fuel. To further do validation, the simulation results were compared against experimental and pilot-scale results that were available. Other researchers have reported acid driven processes which disclose 93%-97% conversions of WCO under similar conditions [27, 29]. At 97%, the simulated conversion rate is thus essentially at the high boundary of these experimental findings, and thus proves to its credit. However, it is important to acknowledge potential deviations from idealized simulation conditions in practical operations, such as heat losses and mixing inefficiencies. Additionally, scale-up factors should be considered in future research endeavors.

Table 2 : Stream compositions summary table.

Stream No.	***Methanol***	***Glycerol***	***H_2SO_4***	***NaOH***	***H_2O***	***Triolein***	***Oleic Acid***	***M-Oleate***	***Calcium Sulfate***	***Calcium Oxide***
WCO	0.0000	0.0000	0.0000	0.0000	0.0000	1.1440	0.0602	0.0000	0.0000	0.0000
Methanol	3.7025	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2SO4	0.0000	0.0000	1.5300	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
101A	3.7825	0.0000	1.5300	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
101B	3.7825	0.0000	1.5300	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
102	7.2871	0.0000	1.5300	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
105A	0.0000	0.0000	0.0000	0.0000	0.0000	1.1440	0.0602	0.0000	0.0000	0.0000
105B	0.0000	0.0000	0.0000	0.0000	0.0000	1.1440	0.0602	0.0000	0.0000	0.0000
106	3.8977	1.1097	1.5300	0.0000	0.0000	0.0343	0.0000	3.3930	0.0000	0.0000

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107	3.8977	1.1097	1.5300	0.0000	0.0000	0.0343	0.0000	3.3930	0.0000	0.0000
201	3.5036	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
201A	3.5036	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
201B	3.5046	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
202	0.3941	1.1097	1.5300	0.0000	0.0000	0.0343	0.0000	3.3930	0.0000	0.0000
202B	0.3941	1.1097	1.5300	0.0000	0.0000	0.0343	0.0000	3.3930	0.0000	0.0000
v2-VentGas	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
203	0.3941	1.1097	0.0000	0.0000	1.5300	0.0343	0.0000	3.3930	1.5300	2.0366
203B	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.5300	2.0366
203C	0.3941	1.1097	0.0000	0.0000	1.5300	0.0343	0.0000	3.3930	0.0000	0.0000
v3-VentGas	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
203D	0.3941	1.1097	0.0000	0.0000	1.5300	0.0343	0.0000	3.3930	0.0000	0.0000
FAME Rich	0.0042	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	3.3930	0.0000	0.0000
Glycerol Rich	0.3899	1.1097	0.0000	0.0000	1.5300	0.0343	0.0000	0.0000	0.0000	0.0000

IV. Safety Analysis

The provided Hazard and Operability (HAZOP) study in ***table 3*** is the systematic exploration of potential risks in the key steps of the biodiesel production process, from feed preparation to the handling of the final product. The analysis of feed preparation, where mixing and pumping of waste cooking oil (WCO) occurs, identifies crucial flow deviations such as "No Flow" from a pump blockage, which would halt the entire process. The recommended remedial measure is to install flow alarms to alert operators to such issues. Conversely, an "Overfeed" situation ("More" flow) would lead to overfilling and spills, a risk prevented by the use of flow control valves. For the heat exchanger and preheating section, the analysis considers temperature and pressure excursions. A "More" temperature excursion, which can be caused by control failure, presents a fire risk, one that can be managed through the use of temperature alarms. A "Less" temperature deviation, due to heater failure, would lead to incomplete conversion and necessitate heater repair and a backup heater. Within the core Transesterification Reactor, the HAZOP table takes into account several important parameters. A "Low" temperature due to control or heating system failure can lead to incomplete reaction and poor conversion. The responses to alleviate this are to supply low-temperature alarms and audit heating capacity. A "High" pressure deviation, caused by vapor generation or a blocked outlet, is a critical safety hazard with possible vessel rupture and requires pressure sensors and relief systems. In the separators, the focus of the analysis is separation efficiency and flow issues. For the Solid Separator, "Less" separation due to mechanical failure or high feed rate would cause downstream equipment fouling, which is corrected by introducing a robust monitoring system. For the Phase Separator, "Less" separation due to emulsion formation or incorrect temperature causes off-spec products, which is corrected by introducing interface level controls. The methanol handling and recovery section also deals with such fundamental issues as corrosion in piping, which can lead to leaks with the risk of fire and exposure, resolved by implementing gas detectors. The thoroughness of this HAZOP table demonstrates a diligent approach to safety and operational integrity for the entire plant. To supplement HAZOP analysis, semi-quantitative ranking matrix was adopted in regard to risk. Each identified deviation had likelihood (rating out of 1-5) and severity (rating out of 1-5) so that the Risk Priority Number (RPN) could be obtained. An example would be a deviation of high-pressure in the reactor with a score of 4 (likelihood) 5 (severity) = 20 which would signal that there is high risk that requires priority of precautions to be taken but a deviation on the speed of the agitator scored 2 x 2 = 4 signaling that it would be in the low-risk area. This measurement will enable a more systematic prioritization of safety interventions.

Table 3: HAZOP study for all equipment.

Deviation	Guide word	Causes	Consequence	Action
Feed preparation (WCO mixing and pumping)				
Flow	No	Pump Blockage	Process stops	Install glow alarms
	More	Overfeed	Overfilling spills	Flow control valves
Mixing	Less	Low agitator speed	Low reaction efficiency	RPM monitoring
Heat exchanger and preheating				
Temperature	More	Control failure	Fire risk	Temperature alarms

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	Less	Heat failure	Incomplete conversion	Heater maintenance, backup heater
Pressure	More	Blockage	Safety hazard	Pressure relief valves
Transesterification Reactor (R-100)				
Temperature	Low	Heating system failure, Control system malfunction	Incomplete reaction, Poor conversion, Product quality issues	Add low temperature alarms, Review heating capacity
Pressure	High	Vapor generation, Blocked outlet, Relief valve failure	Mechanical stress, Vessel rupture risk, Safety hazard	Pressure indicators, Relief systems
Flow	No	Pump Failure	Reaction stoppage, Process shutdown	Flow indicators, Pump status indications
Composition	Other than	Feed control difficulties	Incomplete reaction	Flow ratio controls
Mixing	Less	Low agitator speed	Poor conversion	Add agitator performance monitoring
Solid Separator				
Separation	Less	Feed rate too high, Mechanical failure, Fouling	Downstream equipment fouling	Install strong monitoring system.
Flow	No	Inlet/outlet blockage, Pump failure	Process shutdown, Pressure buildup upstream	Add flow monitoring alerts
Pressure	High	Excessive fouling, Partial blockage	Mechanical stress	Pressure differential indicators
Phase Separator				
Separation	Less	Emulsion formation, Incorrect temperature	Off-spec products (FAME and Glycerol streams)	Add interface level control.
Temperature	High	Heating system malfunction	Vapor generation, Pressure increase	Add temperature control interlocks
Pressure	Low	Leaks, Control valve issues	Two-phase flow issues	Pressure indicators
Flow	Reverse	Pressure fluctuations	Product contamination	Install additional backflow prevention
Methanol handling and recovery				
Flow (Pipe tank leak)	Also	Corrosion	Fire, Exposure	Gas detectors

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Pressure (Over pressure)	High	Blocked vent	Rupture, vapor release	Pressure relief

V. General Plant Considerations

When considering plant design, three main factors are to be considered during this stage. Site selection is important to select the most suitable area to construct and operate in. When the site location is set, the layout of the plant is to be addressed in order to understand the overall structure of the plant. Equipment spacing is also necessary to ensure the safe distance between equipment, avoiding cramming, and risk of chain consequences during accidents and disasters.

A. Site Selection

Location of a plant is an important, two-stage management choice consisting of selection of a general location and then a specific site. The choice represents a long-term strategic judgment subject to technological, marketing, and financial considerations. The aim is to identify an "ideal location" minimizing cost of production, maximizing market share, minimizing risk, and yielding maximum social return. An ideal site represents one yielding the lowest unit cost of production and distribution. The location of plants is significant as it has an effect on plant design, capital expenditures, and cost of operations. The universal principle remains to reduce the aggregate cost of industrialization and distribution. Numerous factors come into play, and the most important aim remains to reduce cost of production and distribution as the first consideration and also take into consideration future growth as well as safety of both the plant and the surrounding neighborhood. The factors include availability of raw materials, market proximity, and sufficiency of land. The location should be flat, well-drained, and possess firm load characteristics to reduce construction expenses. Transportation remains another significant factor and accessibility via at least two modes of transit like rail and road would be ideal. Access to both skilled and unskilled workers remain another imperative for construction of plants as well as for operations of plants. In addition, accessibility to amenities like water supply, fuel supply, and electricity supply remains imperative for operations of the manufacturing process as well as various pieces of equipment. The ability to dump effluent and minimize environmental degradation remains further significant requirements. The location also remains important due to consideration of the local community, climate, and strategic and political considerations like taxes and statutory limitations. The article also provides the "Weight Rating Method" of site selection, where the location with the highest weighted value is selected. A six-step procedure is defined, from establishing the consideration factor list up to finding the best recommendation by maximum points achieved. For our particular case of the biodiesel plant, the Weight Rating Method was applied, and as displayed in ***table 4***, Borg El Arab resulted as the best location with 90% ratings.

Table 4 :Site selection using weighted score method.

	Loc 1 Borg El Arab City	**Loc 2 6th of October City**	**Loc 3 Sadat City**	**Loc 4 10th Of Ramadan City**	**Loc 5 New Valley Governorate**	**Notes**
Raw materials supply: Availability Use of substitute materials Distance	10	8	7	7	5	There is a steady supply of waste cooking oil and palm oils in Borg El Arab
Markets: Demand vs. distance Growth of decline Inventory storage requirements Competition– present and future	10	7	6	7	4	Borg El Arab, Alexandria, presents strong market potential due to local demand, export opportunities, and government policies promoting renewable energy.
Transportation, availability & rates: Rail Highway Water Pipeline Air	10	8	6	8	4	**6th of October-** It is close to both Cairo and Alexandria, where the main market is present.

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Labor: Availability skills Labor relations Stability of rates	7	7	7	7	6	Labor availability in Locations 1,2,3,4 is highly present among all of them as they are all industrial areas that already have existing factories and plants which require already-existing labour workers and technical expertise.
Power and fuel supply: Availability of electricity several types of fuel Future reserves Costs	8	8	8	8	3	Locations 1,2,3,4 are adequately supplied with an effective power supply that is capable of bearing the large loads of running
Water supply: Quantity Dependability Costs	7	7	8	9	3	Recycled wastewater treatment
Availability of land: Plant procurement and construction	8	6	7	6	9	Major government land programs; vast availability with minimal restrictions.
Environmental Impact Waste disposal Regulation laws Stream carry-off possibilities Air-pollution possibilities	7	7	7	7	5	In such industrial areas, the waste of the biodiesel plant can be used by other surrounding factories for further processing; Also waste disposal and air pollution are guided by systems that route such aspects to environmental treatment in order to adhere to environmental laws.
Local Community Considerations: Local population wellbeing ; Adequate facilities for plant personnel.	8	8	8	8	9	Supportive but small communities; limited resistance but limited benefit too.

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Climate: Investment required for construction Humidity and temperature conditions Hurricanes, and earthquakes	6	8	8	8	6	The 6th of October City, El Sadat City and the 10th of Ramdan are known to be subjected to consistent climatic conditions throughout the year with moderate mean temperature. Only several cooling systems and dust & sand maintenance should be placed to counteract in peak summer months and maintain equipment parts from dust.
Regulatory laws: Building codes Zoning ordinances Highway restrictions Waste-disposal codes	9	9	9	9	9	All of the regulatory laws are applied in all the governorates in Egypt, especially within the context of industrial areas or newly developing areas for procurement and construction in order to maintain a common mechanism through which all plants and factories must adhere to.
TOTAL POINT SCORE	90	83	81	84	63	**Site Location: Borg El Arab**

B. Plant Layout

It is crucial to integrate the wind direction in Borg El Arab-Alexandria, as the chosen site location for the construction of the biodiesel plant, is a crucial reference upon which the site layout is planned out; therefore, the prevailing wind direction in Borg El Arab comes from the north/ north-west directions [30]. As shown in **Fig.4**, the wind rose is an important figure to determine the wind distribution of the location.

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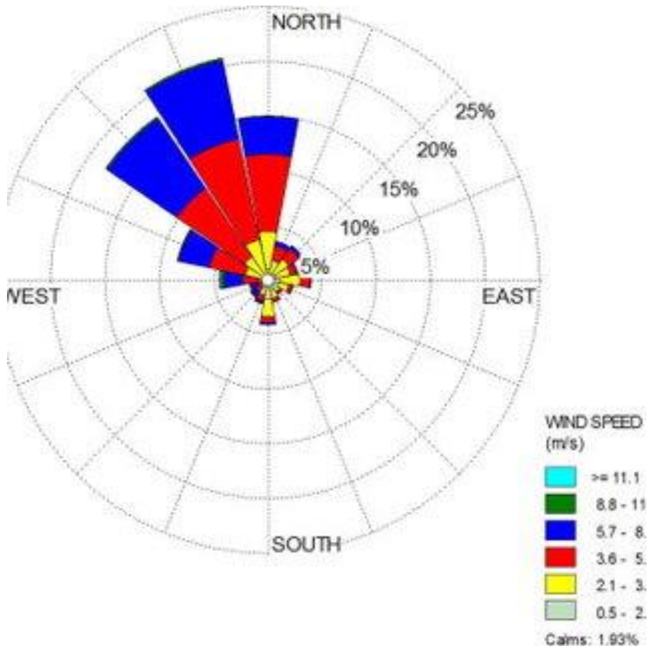

Figure 4 :Wind rose for Borg El Arab -Alexandria [30]**.**

The plant layout can be defined as a method of finding the best location of work, services, and machines at an establishment to produce maximum products and quality at least cost and time. The ideal good plant layout goals are operating at maximum capacity and at least time and cost, increasing proper work environment for workers for improving quality of products, and enhancing work productivity and work safety. A location carefully planned with amenities one could only think of should enhance work safety and productivity and utilize available spaces to the maximum and reduce points of temporary construction to the least. Good siting of the site planning included siting of processing units and ancillary buildings strategically, keeping hazardous operations at safe distances from others for safety reasons. The design also has to allow for future expansion of the site. Simple manufacturing flow and economy of floor space utilization are distinguishing features of an ideal factory layout' because they allow workers and materials free access to all machines at all times and prevent wastage, respectively. The design also ought to allow free movement of people, materials, and machinery by providing adequate width of broad paths to avoid accident and damages, respectively. Location of machinery at positions minimizing movement of goods from one process to another could minimize wastage of raw materials and working hours. Good layout also enhances working conditions with ventilation, water supply, and toilets and flexibility to allow change of management policy or change of machinery. In addition, it also ought to allow storage area at strategic points to allow easy supply of materials, to allow easy supervision and coordination, and protection and safety of workers through clear instructions and warnings. There are some points to be considered while designing an industrial plant layout, and they include construction and operating cost, process requirements, standard of maintenance, workers' safety and health, and future growth. The construction cost could be regulated by an economical construction plan of minimizing the length of connectable piping work and steel work utilization at construction. The siting of equipment has to be comfortable and easily accessible with proper gaps and heights for easy servicing and change over. Special consideration has to be given for frequent servicing or cleaning of equipment like heat exchangers, and they could be installed at easily accessible positions, ideally outside the central building. Safety first, and insulation walls around danger equipment are needed to restrict explosion. All factors have been included when designing the plant layout as shown in **Fig. 5.**

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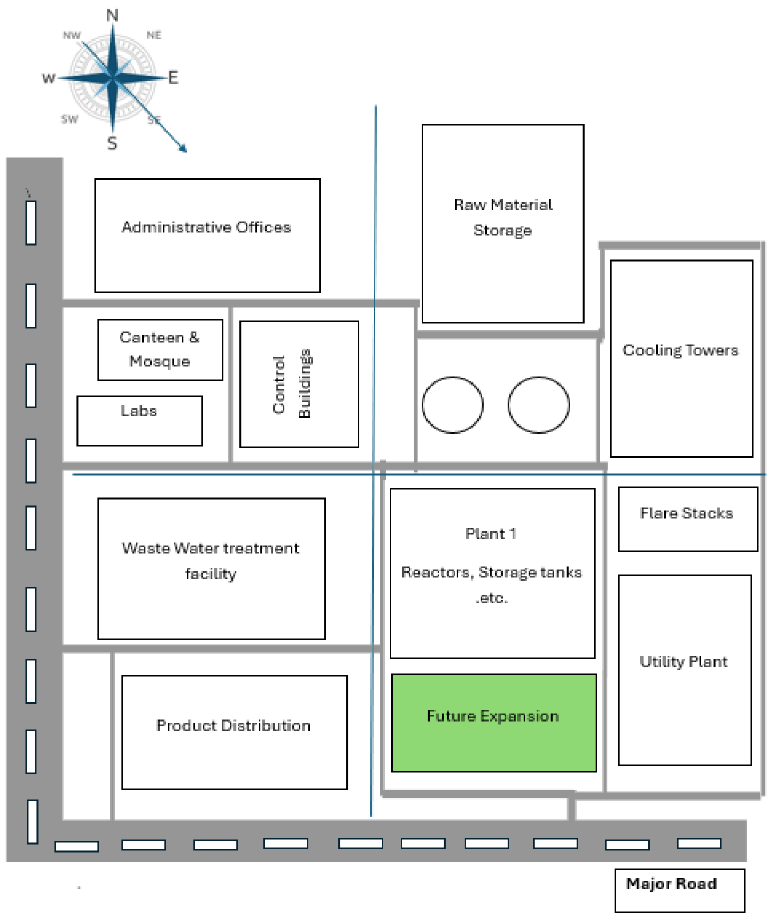

Figure 5 :Plant Layout.

C. Equipment Spacing

Spacing of equipment is a very important element in plant design as it is a major factor in influencing safety and efficiency of the plant operation by providing an appropriate and safe space in which operations can be performed. Proper spacing is also significant to a good layout of the factory structure as it does not only keep workers, materials and machines safely but also allows that there is enough space and broad roads of path which prevent some forms of damage and accidents. The layout must also be such that dangerous operations are located at a safe distance and well away in order to avoid risk. In addition to this, the document points out that equipment that needs regular care or repair should be assigned suitable and comfortable accommodation to facilitate access and changeover. The plant design should also take into consideration where the control rooms and laboratories would be placed so that they are safe distances from hazardous activities should there be an incident then the personnel can be saved. The road, pipeline and drainage planning can also be strategic based on where the equipment will be placed since this connectivity is crucial in the operation and maintenance of the plant. **Fig.6** also represents these philosophies by demonstrating a plant layout with special spacing that makes sure it is safe. The sketch depicts the schematic of major equipment, a furnace, different pumps, a heat exchanger, and a control facility. There is a clear distinction between hazardous areas and non-hazardous areas, and the control room is in a non-hazardous area, and this serves to demonstrate that the purpose is to reduce the exposure of personnel to high-risk activities. It is meant to reduce the risk of injury/death by having this varying equipment spacing even though there exists the possibility of efficient flow of the production process.

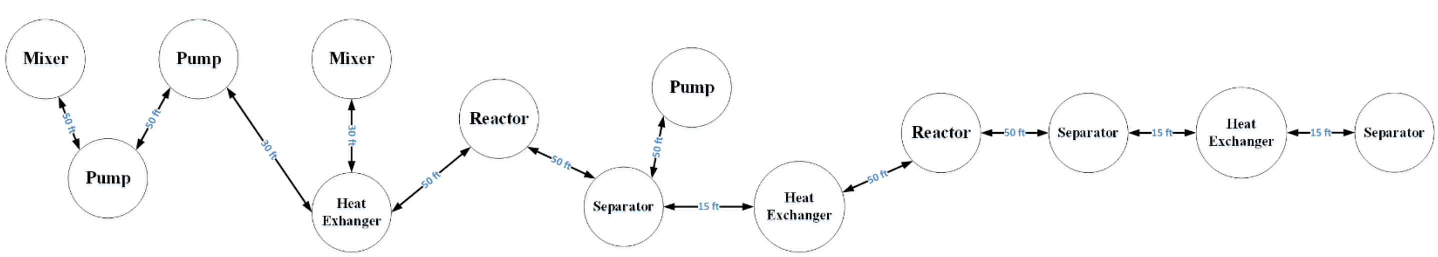

Figure 6 :Equipment spacing for all equipment displayed previously in PFD.

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VI. Economic Study

A. Purchasing Cost of Equipment

The CapCost table that is provided in ***table 5*** gives a very detailed specification of the costs of purchasing the main equipment that will be needed within the plant, as well as a specification of the total capital investment and an overview of one of the greatest indicators towards determining profits. The table includes the prices of separate pieces of equipment, and as can be seen, the reactor is by far the most expensive piece, with the price of purchase of one piece being $320,000, and two storage tanks with the price of $250,000 each. The other costs which are also substantial are the evaporator $120,000, the heater $100,000 and the separator $80,000. The cheapest of these items are the mixers and pumps and their prices are between $14,000 and $40,000 . These amounts further determine the cost of the total capital investment of the project being as indicated as $1,713,744.

Table 5: Purchasing Cost of Equipment using CapCost.

Power (kw)	#Spares				Purchased Equipment Cost	Bare Module Cost	Base Equipment Cost	Base Bare Module Cost
0.25	0				$9,965	$13,374	$9,695	$13,374
0.25	0				$9,695	$13,374	$9,965	$13,374
Power (kw)	#Spares	MOC	Discharge Pressure (barg)		Purchased Equipment Cost	Bare Module Cost	Base Equipment Cost	Base Bare Module Cost
0.02586	0	Stainless Steel	4		$1,417	$3,080	$620	$2,010
0.125	0	Stainless Steel	4		$5,230	$10,740	$1,960	$6,320
0.00552	0	Stainless Steel	2		$541	$1,176	$240	$767
Height (m)	Diameter (m)	Tower MOC		Pressure (barg)	Purchased Equipment Cost	Bare Module Cost	Base Equipment Cost	Base Bare Module Cost
2	1	Stainless Steel		2	$75,400	$118,000	$21,000	$48,000
Length/Heigh (m)	Diameter (m)	MOC		Pressure (barg)	Purchased Equipment Cost	Bare Module Cost	Base Equipment Cost	Base Bare Module Cost
2	1	Stainless Steel		2	$27,400	$69,700	$8,810	$35,800
2	1	Stainless Steel		1.11	$27,400	$69,700	$8,810	$35,800
2	1	Stainless Steel		1.01	$27,400	$69,700	$8,810	$35,800
1.9	1	Stainless Steel		2	$26,700	$67,900	$8,590	$35,000
			Total		**$774,878**	**$1,713,744**	**$283,830**	**$908,245**

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Total Equipment Cost	**$774,878**

B. Profitability Analysis

The profitability analysis was concucted to assess three main factors; payback period (PBP), Return on Investment (ROI), and initial investment costs.The initial investment consists of the fixed costs, varied cost and other contributing expenses such as sales, taxes and other miscellaneous expenses. The value calculated is then divided by the net cash flow, resulting the payback period in years. ROI can also be calculated using the initial investment, where the net profit is divided by that value to give the ROI as a percentage.There is a full examination of profitability presented in ***table 6***, including the list of the fixed and the variable costs he or she refers to the biodiesel production plant and the breakdown of major financial performance indicators. It starts with the capital costs including a total Purchased Equipment Cost (PCE) of $1,713, 745 and a Plant Purchased Cost (PPC) of $5,827,730. The result is a Fixed Capital Investment of $8,448,760 and Total Investment of $10,138,512 for the project's erection. The table later divides the variable and fixed cost of operating costs. Raw materials and utilities are dependent on the level of production worth $1/kg and $1.16/kWh respectively, and the cost of some miscellaneous materials is $84,490. The fixed costs which remain the same regardless of the level of production are also not negligible and they include the maintenance ($844,876), operating labor ($800,000), laboratory costs ($176,000) and a substantial figure representing the local taxes ($2,112,190). Activity-based overall cost of production that accommodates a component "Sub Section C" to take account of sales and general overheads amounts to $1,176,735 per year. According to the profitability ratios, considering that the total annual capacity of the plant is 8,260,560 liters, the annual net profit that will be recorded will be $2,726,000. This will come up with a production cost per liter of $0.71 and an acceptable profit margin of $0.33 per liter. The financial feasibility and attractiveness of the biodiesel plant is confirmed with a good return on investment (ROI) of 32.3% and a payback period (PBP) that is lucrative at 3 years following operation. A sensitivity analysis was carried out to evaluate how sturdy the economic results worked out. Changes of the feedstock prices between 0.7-1.3 per kilogram shifted ROI by 25% to 38% and utility price changes of +/-20% shifted payback between 2.8-3.5 years. These findings show that the most important factors in determining economic viability is the supply of feedstock and energy prices. The analysis thus brings about visibility and supports the economic premises raised.

Table 6 :Profitability analysis for biodiesel production plant.

Fixed and Variable Cost	
PCE	$1,713,745
PPC	$5,827,730
Fixed Capital Investment	$8,448,760
Total Investment	**$10,138,512**
Variable Cost	
Raw materials	$1/kg
Miscellaneous material	$84,490
Utilities	$1.16/kWh
Shipping and Packaging	Not applicable
Sub Section A	**$84,500**
Fixed Cost	
Maintenance	$844,876
Operating Labor	$800,000
Laboratory costs	$176,000
Supervision costs	$160,000
Plant Overheads	$400,000
Capital Charges	$844,876
Insurance	$84,490
Local taxes	$2,112,190
Royalties	Not applicable
Sub section B	**$4,622,432**
Direct cost (A+B)	**$4,706,940**
Sub Section C	
Sales expenses	$1,176,735
General overheads	Not applicable
Research & Development	Not applicable

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Sub Section C	**$1,176,735**
Profitability	
Annual Production Costs (A+B+C)	**$1,176,735**
Production cost per liter	**$0.71/L**
Profit per liter	**$0.33/L**
Total annual production	**8260560 L**
Annual Net Profit	**$2,726,000**
ROI	**32.3%**
PBP	**3 years after operation**

VII. Environmental Impact Assessment

A complete environmental impact analysis of the intended biodiesel plant should include the aspects other than the basic sustainability benefits biodiesel proffers due to waste valorization. To that end, is adopted a life-cycle assessment (LCA) framework that evaluates the environmental footprint viewpoint under cradle-to-gate, which spans feedstock collection processes, transportation/ transport, and processing processes. The major degree of environmental advantage is achieved to the level of the feedstock acquisition. The use of waste cooking oil (WCO) as the raw material means that the process avoids the time and labor-consuming land-use change, deforestation, and agricultural inputs involved in biodiesel production introduced with virgin oil crops (the prevailing emitters of biodiesel as the biofuels of the first generation) altogether [31]. This strategic choice matches the plant with the principles of the circular-economy which transform a waste-management liability into a sustainable resource. The core processing operations, with their respective environmental impact, are controlled so that their overall impact is minimal. At a very significant portion of the direct air emissions (including greenhouse gases) and of nitrogen oxides (NOx), is energy consumption, mostly in the form of natural-gas-fired heaters. Nevertheless, in the LCA framework, the WCO-based biodiesel will always bring about more than 80 percent of a cut in the GHGs emission compared to the traditional petroleum diesel, following the biogenic process of the oil to undergo combustion and the energy-intensive separation of crude oil to refining, respectively [32]. In addition, the possibility of emitting volatile organic compounds (VOC) gases, specifically methanol emitted during handling and recovery processes is avoided by utilizing closed-system systems and vapor-recovery units. One of the notable environmental issues in the environment of the facility is wastewater that comes about in the process of neutralization and purification. The denser feature of this effluent stream is the high chemical oxygen demand (COD) that can be explained by the presence of remnants of methanol and glycerol, which require a specific treatment on-site before being discharged to avoid aquatic toxicity and keep to the best practice in treating industrial effluents [33]. The valorisation of the crude glycerol by-product also optimizes the environmental performance. We should not dispose of it as waste, but its extraction and recovery later as chemical or pharmaceutical material alleviates environmental costs related to the production of biodiesel and avoids the requirements of virgin glycerol production which is again supported by the concept of the life-cycle philosophy [33]. Overall, despite the fact that the activities of the plant are characterized by controllable consequences to energy usage and effluent discharge, a structured LCA shows a clearly positive net environmental result. The project provides a record-low carbon footprint and thus justifies its contribution to climate-change care and the higher order of waste-to-energy principals, without causing the environmental deficits required in agricultural biofuel feedstocks.

VIII. Conclusion

The study was able to show the scientific, safety and economic viability of an industrial scale plant that is used in the processing of WCO as a source of biodiesel. The simulation of the process performed with help of Aspen HYSYS software proved to be highly efficient having the final FAME conversion rate of 97% and the mass flow rate of 1006 kg/hr that correlates with the benchmark reported in the scientific literature. This is a good conversion rate which justifies the operation parameters and unit operation which were selected and therefore validates the process design. Moreover, a comprehensive safety evaluation was implemented in the design phase of this plant by carrying out HAZOP study so as to address and eliminate the possible safety risks in the plant and provide a safe environment of operation. The project was economically feasible, and the profitability prospects of the project looked good considering the cost analyses of capital cost and operating cost. The analysis of the economy reveals results such as total fixed capital investment of $8,448,760 and overall investment of $10,138,512, robust return on investment (ROI) 32.3% and fast payback of 3 years after being operational. The total amount of production of the plant per year is estimated to be 8,260,560 liters, which would bring an annual net profit of the plant in the amount of $2,726,000. However, there are limitations in this study. The results of the simulation though supported by already known literature merits testing at the pilot level. The financial outlooks cling on the current economic situations, which by its necessity are susceptible to fluctuations. Their environmental review was limited to a life-cycle screening level examination and in-depth cradle-to-grave reviews are still to be done. Additionally, the scale-up challenges involving heat integration, uninterrupted catalyst recovery as well as decontaminating wastewater require additional academic research. With these crucial findings, there are some recommendations that can be made out of future study. First it would be recommended that more research is needed to deal with the use of new catalysts (the example of a nanocellulose-coated magnetite-strontium oxide catalyst which has been brought up in the

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introduction could have a high probability to inflict better yields and efficiency of the process). Second, a thorough life cycle assessment may be carried out to assess the overall impact on the environment of the plant on top of the initial considerations of sustainability. Finally, the possibility of utilizing binary hybrid feedstocks, such as mixing WCO with other oils, could be also studied in the future as the way to preserve the optimality of the production process and increase the scope of viable raw materials.

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