Biodiesel from Algae

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Abstract

In this process design, biodiesel will be produced from a biomass source, algae. To reduce the harm done to the environment, this process utilizes sustainable raw materials and has a minimal carbon footprint. Via carbon fixation, algae produce lipids that are useful for producing biodiesel. Microalgae is specifically effective in the production of biofuel due to various properties making it a reliable renewable energy source. While there are several existing approaches to obtain biofuel from algae, the exact process described in this literature was chosen based upon its optimization of economic, logistical, and environmental considerations. A flowchart was created that goes into detail for the biodiesel production process that is cost effective and produces high quality biodiesel.

Objective

The objective of this process is to analyze the efficiency of biodiesel production from biomass (microalgae). Specifically, this process will produce 59,000 kg of biodiesel every 24 hours. Also critical in this process is the ability to have a positive return on investment and payback period that is comparable to the fuel production industry.

Introduction

History/Background

For decades, society has relied on fossil fuels to power transportation, homes, and other energy needs. With the finite and non-renewable nature of such fossil fuels, scarcity will one day become an irrefutable problem, and society will face a difficult issue to solve if too much time is wasted. This is true even ignoring the known negative impacts that fossil fuels have on ecosystems globally, including pollution and the overproduction of greenhouse gases. While consumers are starting the process of transitioning to electric cars in preference to the usual internal combustion engine vehicles, it is still important to consider how the electricity for such vehicles is being produced. The answer in many cases is fossil fuels, but with biodiesel that can be renewably and sustainably sourced, another green solution is offered in the name of preserving our planet and building a stronger future for generations to come.

The production of biodiesel spans decades, originally using vegetable oil from crops such as soybeans and the fats from animals as the main biomass or feedstock (Surriya et al., 2015). Though the use of oils from crops is very effective when producing biodiesel, there are some hinderances that delay production. One negative is the amount of time needed to grow and harvest crops and extract their oils. Another is the immense space required to grow and harvest the crops commonly used for biodiesel production. The U.S. alone has allocated 51.5 million acres of land to crops for producing biofuel (Merrill, 2021). Algae production, on the other hand, faces neither of these problems. Microalgae's ability to grow rapidly, abundantly, and at low cost make algae an ideal choice when sourcing biomass for biodiesel production. Using algae-specific bioreactors or raceway ponds, among other methods, algae can easily be grown in bulk without occupying large swaths of land that crops and livestock require (Sudip et al., 2012). Keeping the goal in mind of finding cleaner alternative ways to produce biodiesel, biodiesel production can thrive and grow into the industry it is today, serving as a potential substitute for the dwindling and environmentally damaging supply of fossil fuels that modern society currently relies on.

Relevance

Production of cheap, sustainable energy is a mainstay of the modern mindset. Geopolitical conflicts that occur around the globe often have motivations rooted in access to nonrenewable fuel resources, thus, renewable energy sources are exceptionally relevant. Algae-based biodiesel production is therefore rooted in algae's economical sustainability. Biodiesel from algae presents an opportunity to adhere to carbon-friendly energy practices without needing to abandon existing energy infrastructure (Alonso et al., 2010).

Algae based biodiesel's relevance to climate change is also pertinent. Research has shown that algae is capable of rapidly and efficiently sequestering carbon dioxide via photosynthesis, and this requires an acre of algae being able to sequester 2.7 tons of carbon dioxide per day (Anguselvi et al., 2019). Much of the wild algae that exists in nature has a habitat in our oceans, producing up to 70% of atmospheric oxygen via photosynthesis (Bourgougnon et al., 2021). The algal growth stage of the biodiesel production process described here carries the added benefit of carbon sequestration prior to harvesting algae for usage in biodiesel. Biodiesel's emission profile is also an improvement from traditional petrol-diesel, releasing fewer harmful chemicals and up to 70% less carbon monoxide (Surriya et al., 2015).
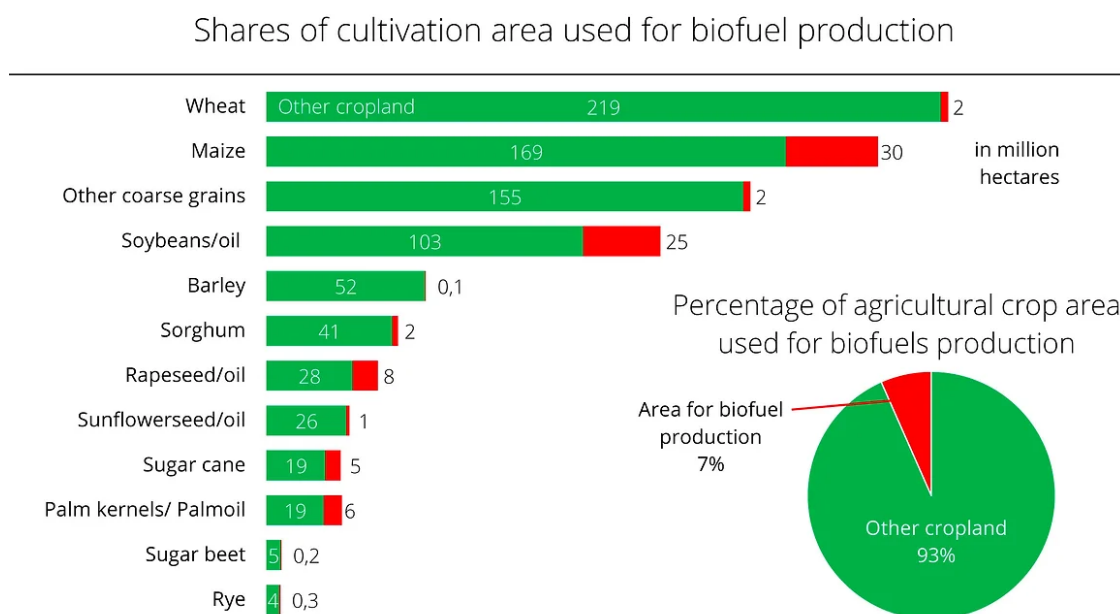

Figure 1. Amount of land used for different crops and amount of that land used for biofuel (Ufop, 2022)

Unlike other biomass sources like vegetable oil and animal fats, algae do not have to compete with common aspects of the biofuel industry such as the competition over agricultural land and other land uses (see Figure 1). Also, algae are extremely versatile as a biomass source. In our process, the lipids and fats of algae can be utilized to produce biodiesel. However, the remaining byproducts can still be used, as the leftover proteins and starches of algae can be applied to the development of bioethanol. Not only are the algae beneficial for production of biofuels, but the effects of using algae as a biomass source can result in cleaner wastewater. Typically, in wastewater treatments, algae are used as a natural filter for removing pollutants to improve water quality (Bhatt et al., 2014).

Process Considerations

Raw materials

A few ingredients are needed to produce the biofuel from the biomass. The first and most obvious question revolved around the specific definition of "biomass." The processes described throughout this case will begin with a specific type of microalgae that will serve as the primary transformative ingredient throughout and will be the foundation of the final biodiesel product. Additional chemicals will be necessary to the production of biodiesel, including but not limited to water, nitrogen dioxide, and phosphate. The machines and systems necessary to make the entire process work from start to finish will include a few different steps that will be elaborated further below. An algae pond will be necessary for the initial cultivation of algae at the beginning of each batch. Furthermore, pumps will be necessary throughout the process for logistical handling of various materials at the end of each process for transportation into the next step. A dewatering mechanism for the preparation of the initial stage of algae is also necessary. Other machines and mechanisms necessary for production will include at least one specific pretreatment method, an oil compressor, multiple separation mechanisms for a few key points throughout the process, a hydrolyzer, a fermenter, a distillery, and an esterification reactor. The order and quantities of these machines and set of initial ingredients will be specified in greater detail throughout the production summaries and unit operation procedures.

Production Summary

To begin the production of biodiesel derived from algae mass four main steps are required. This consists of pretreatment, implementation of platform chemicals, purification, and finally product finalization. The physical process of pretreatment consists of two main systems, mechanical and thermal treatment. Mechanical treatment utilizes milling to finely ground the algal cells into smaller matter where ultrasonication is done. Thermal treatment utilizes steam explosion, autoclaving, and freeze drying to prep the algae for conversion to biodiesel with oil extraction (Ghedini et al., 2021). Following the pretreatment of algae for biodiesel conversion, the introduction of platform chemicals is introduced. This process utilizes triglycerides and transesterification to treat the algae before decantation. Transesterification can be used for all algal types for biodiesel production and utilizes a catalyst which has three possible sub-classifications. These sub-classifications are homogeneous, biocatalyst, and heterogeneous transesterification. Homogeneous catalysts can utilize acid and base reactions to initiate a reaction and have an overall shorter reaction time which is better for large scale industrial production, but this will require a separation process due to saponification. Biocatalysts utilize an enzyme-based catalyst which causes an aqueous reaction. This process is expensive on an industrial scale but is very effective in product production (Ghedini et al., 2021). Lastly a heterogeneous catalyst can be used which also utilizes acid and base reactions but does not have saponification allowing for easier separation from the reaction products allowing for reusability of the catalyst. Additionally, this can utilize both liquid and solid catalyst allowing for the use of transesterification and esterification but causes (in both) extreme reactions thus reducing the product output and increases the cost of purchasing materials (Ghedini et al., 2021). The next step of the production system is purification. To start decantation, which is a simple process of washing the completed transesterification product to separate the glycerol and other biproducts from the biodiesel (Ghedini et al., 2021). These biproducts have their own uses and can be further refined or sold as raw products. After this subprocess of purification we have a separated

biofuel that can be pumped out ready to be used. This then carries into the product finalization where the derived biodiesel products can be sold accordingly.

Algae Cultivation

The algae used in the creation of biodiesel will be sustainably sourced and renewed upon each batch of operation. This is to prevent the overharvesting of wild algae in oceans, which provide necessary oxygen to the atmosphere along with vital carbon and nitrogen fixation cycles that filter the air and work to maintain the delicate balance of the ecosystem. Having a dedicated process to the growth and regrowth of locally sourced algae also has the added benefit of reducing cost in the long term by decreasing logistical issues and the number of trips to the ocean necessary to maintain the biodiesel-worthy algae population. There are a few different methods available, including open pond, closed loop production, and closed tank.

The primary option for algal cultivation that was explored throughout this process is a method known as the open raceway pond (Lu & Chen, 2021), which involves an open-top water enclosure that algae is inoculated in made from relatively low-cost materials including cements and plastics. A paddle is used to circulate the water and encourage algal growth and overall cultivation.

It is also possible, and in many cases optimal, to use a closed tank system for algal cultivation. This way, it is easier to determine exactly how much algae to produce and it is possible to use such methods anywhere in the world. Obvious drawbacks include the cost of implementation, as well as limitations imposed by the amount of equipment possessed. By using the raceway pond, more algae can be produced at one time, and general maintenance tends to be easier. The raceway pond also has the benefit of being non-invasive to the environment. Regardless of how the algae is cultivated, the result tends to be about the same in terms of quantity of biofuel able to produce for a given volume of algae.

In a perfect world, there would be no external influences during the cultivation step in the process of obtaining the necessary algae, which serves as the biomass foundation that eventually leads to biofuel. This ideal system is known as a closed loop biorefinery (Venkata Mohan et al., 2020). While the raceway pond is both more accessible and often easier to implement depending on the local environment, the closed loops system ensuring a complete lack of contamination comes far closer to achieving a perfect first step in the production of biodiesel. However, the increased cost of a closed loop system compared to the open counterpart that is the raceway pond, lessens the advantage of the theoretical increase in productivity.

Pretreatments

Pretreatment is a vital part of converting algae into biodiesel. The sole purpose of pretreatment in this process is to cause cell disruption of the cell walls to access the lipids required for the process. A pretreatment step is extremely essential in guaranteeing that the algae will be exposed enough for further digestion or extraction of the biomass. Proper pretreatment techniques should be used when it comes to algae to ensure that the maximum amount of lipids is recovered to increase the total yield of biofuel (De Carvalho et al., 2020). When selecting a pretreatment, it is imperative that energy and yield are considered. Pretreatment usage in an excessive amount, or an insufficient amount of energy could possibly produce a small yield of lipids for biofuel. The key to a successful pretreatment is finding a pretreatment that will allow for most lipids to be extracted from the algae while maintaining a balanced energy input or

requirement. Along with the amount yielded and energy required, utilizing the best pretreatment would also benefit the process economically. Due to consuming the needed amount of energy to produce the most yield, the process becomes more cost efficient and can smoothly continue algae-based biodiesel production.

There are multiple routes to take when choosing a pretreatment. Most pretreatments can be separated by physical, chemical, biological, or physiochemical. Physical pretreatments involve the mechanical breakdown of the biomass, where the particle size of the microalgae is broken down and reduced into smaller particles. Physical pretreatments are usually high in energy requirements and not cost efficient. Chemical pretreatments of biomass are harsher as they sometime can involve toxic chemicals and substances in the process (Sharma et al., 2017). Chemical pretreatments are quick and in theory, cost effective. Conversely, the chemicals used in the process could possibly produce harmful byproducts, where extra maintenance will be required to recover the process and equipment. On the other hand, biological pretreatments are usually slower, manageable, and have a lower energy requirement. Biological pretreatments have various advantages such as being cost effective, requiring no harsh chemicals, and being environmentally friendly. In contrast to the advantages, biological pretreatments are not as innovative as other techniques due to a lack of technological progress (Sharma et al., 2017). Physicochemical pretreatments combine the methods and techniques of both physical and chemical pretreatments. Physicochemical pretreatments can precisely control the physical pretreatments and the lower energy requirement of chemical pretreatments. Therefore, when compared to physical or chemical pretreatments alone, physicochemical pretreatments are more cost-effective while being more efficient recovering more biomolecules (Sirohi et al., 2021).

However, an even better way to categorize the typical pretreatments specific to algae would be drying, thermochemical, cell disruption, and targeted fractionation (De Carvalho et al., 2020). Drying is a process that removes water from the algae in various techniques. Use of some of these techniques can have a huge impact on the biomass components and cell structure of the algae. Therefore, these effects will lead to trouble in the remainder of the process of the production of algae-based biodiesel. It is especially important in a process where lipids are being extracted, as the algae should be preserved while the water is secreted from the algae as much as possible. According to an analysis done of various microalgal pretreatments, the drying process could leave anywhere from 1% to 10% of water remaining causing lipid hydrolysis and effecting the later transesterification reaction (De Carvalho et al., 2020). Some of these drying techniques include solar heating, conduction, lyophilization, and convection. Thermochemical pretreatment uses heat and chemicals to convert microalgal biomass into energy and other products. Some thermochemical pretreatments involve much more dangerous processes such as hydrothermal liquefaction, pyrolysis, and combustion. The purpose of these thermochemical pretreatments is to break down the cell wall of the algae while the heat will dry out the water leaving behind biomass and lipids. Depending on the rates of the thermochemical pretreatment, the temperature, and the chemicals used, the yield of lipids to be extracted could vastly change. A great example of this is pyrolysis— a process where the biomass is heated up in the absence of oxygen or air to decompose into solids, liquids, and gases. Pyrolysis will heat up the algae to a temperature of 800ºC to 1000ºC using a large amount of energy; although pyrolysis will still produce more energy than consumed. In the study done on various microalgal pretreatments, slow pyrolysis, from 30-60 minutes, produced more liquids than fast pyrolysis (De Carvalho et al., 2020). Cell disruption is the method of destroying the cell walls or cell membranes of microalgae. Some of

the methods used in cell disruption include sonication, grinding, acid hydrolysis, and many more as this type of pretreatment could involve either mechanical, physical, or chemical techniques. When considering cell disruption as a pretreatment method, energy requirements and damage done to the microalgae should be deliberated heavily. Targeted fractionation, also known as solubilization, is a type of pretreatment that will dissolve components of the algae to be further processed later. Fractionation is an extremely slow step and useful for the development of nutritional bio-oils and food ingredients. Fractionation is not ideal to produce biodiesel since the process demands so many pretreatments for the pretreatments. Targeted fractionation is not worth the expense or energy to reduce the other components of the microalgal cell for lipid extraction.

Lipid Extraction

The hexane lipid extraction method is a widely used technique for lipid extraction from biological samples, including algae. After the algal oil sample has been homogenized and its cellular structure has been broken down to allow the release of lipids, it is ready to begin hexane extraction. Hexane is a non-polar solvent, meaning it has a high affinity for non-polar compounds like lipids. (Saini et al., 2021)

The sample is mixed with hexane, where it is agitated or stirred to facilitate the extraction process. Lipids dissolve in the hexane phase due to their non-polar nature (ScienceDirect). Other polar compounds, such as water-soluble molecules, remain in the aqueous phase. After sufficient mixing, the mixture is allowed to settle, resulting in the separation of the hexane phase containing the lipids and the aqueous phase. Once the phases have separated, the hexane phase containing the lipids is carefully separated from the aqueous phase. This separation can be done using techniques like pipetting or decanting. The hexane solvent is then evaporated from the lipid-containing phase, typically using techniques like rotary evaporation or a nitrogen blow-down. This leaves behind a lipid-rich residue for further steps.

The lipid residue may then be resuspended in a suitable solvent depending on the downstream application. Common solvents include chloroform, methanol, or a chloroform-methanol mixture (Saini et al., 2021). Finally, the isolated lipids can be analyzed using various techniques such as thin-layer chromatography (TLC), gas chromatography (GC), or mass spectrometry (MS) to characterize the lipid composition and quantity.

Transesterification and Catalyst classification

The transesterification of algae to biodiesel is done in two methods, the most common being a two-step process of lipid extraction. The first is when the algal structure is converted into biodiesel and the second method is a direct conversion process of algal using acid catalysts. From these processes, three main sub catalysts are utilized in the two-step process, homogeneous, heterogeneous, and bio transesterification. Each transesterification catalyst has pros and cons, with heterogeneous catalysts becoming more researched and utilized due to their greater efficiency in industrial scale usage.

In the process of using homogeneous transesterification production is relatively fast with a short reaction time due to its high reactivity. Consequently, this reaction is saponification due to the basic nature, thus requiring an extra separation process and filtration (Ghedini et al., 2021).

Overall, this has a high yield quickly but requires more processes adding production time and the materials have little reusability.

Heterogeneous transesterification is the main catalyst being developed and used due to its easier catalyst separation compared to the traditional homogeneous counterpart. This allows for reusability and lowers waste. Some of the disadvantages of this catalyst though are its smaller reaction scale requiring large and aggressive reactions reducing the overall yield requiring more additives which is costly (Ghedini et al., 2021). Overall though the heterogeneous catalyst pulls ahead in its total running cost due to the ease of separation and processing.

Finally, bio transesterification catalysts are being studied but are not in large scale usage due to their expensive scaling to industrial production. Research shows it is a very efficient catalyst for production of biodiesel without saponification, thus producing a pure form without the need for any further handling (Ghedini et al., 2021). This efficient catalyst also shines in its reaction activity allowing for low catalyst input and high product output. This also allows for the catalyst to be recovered and reused. Overall, though the initial cost outweighs the competitive cost of heterogeneous transesterification for industrial production. For the single step process or in-situ, a combination of lipid extraction and acid catalysts are suspended in controlled conditions in methanol allowing for shorter reaction times and less reagents (Ghedini et al., 2021). This though requires an extreme extraction and filtration method which is hazardous and requires many more sub processes costing more than the two-step method.

Separation of biodiesel from glycerol

Fats utilized in the transesterification process ultimately convert into biodiesel and glycerin. This poses a challenge in the process design since these two chemicals are mixed and must be separated to successfully obtain the true target product. Thus, a centrifugal unit procedure is employed to separate biodiesel from glycerol.
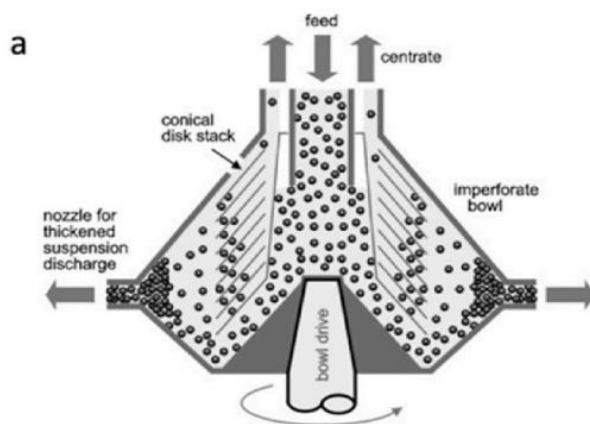
Figure 2. Schematic representation of a disk stack centrifuge, labeled and showing flow directions.

Two types of centrifuges are commonly utilized for this separation process, a disc stack centrifuge (see Figure 2) and a decanter centrifuge (see Figure 3). They differ in the methods utilized for discharging the intended biodiesel and waste matter such as glycerol. The disc stack centrifuge utilizes a fast-rotating disc bowl to create a high centrifugal force allowing for solids

to separate from the liquid mixture input to the system. For the decanter centrifuge it utilizes a similar method of centrifugal force utilizing a bowl but has an auger system that carries out particulates from the liquid mixture input. These both will discard the water taken out into an exit stream that can be further refined and.

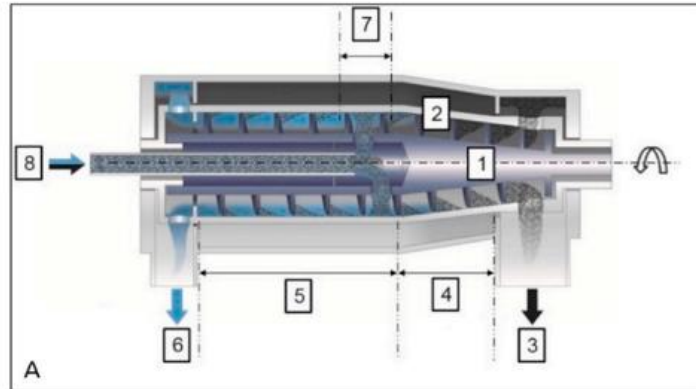Fig. 3. Schematic representation of a decanter centrifuge: 1. Bowl with openings for solid and liquid discharge, 2. Screw conveyor with feed inlet, 3. Solid discharge, 4. Drying zone or beach zone, 5. Clarifying zone or pond zone, 6. Liquid discharge, 7. Pitch, and 8. Feed.

Overall, biodiesel centrifuges can be an extremely efficient option for separation in a process system, especially when trying to obtain biofuel. This continuous process provides cheap operating costs, and the automation system prevents labor expenses. Most of these automated centrifuges have the ability to self-clean as well. Furthermore, it is a fast process with a high-quality output.

Polishing

After the biodiesel has been separated from glycerol, it must then be polished to improve biodiesel quality to comply with diesel quality standards. The aim of biodiesel polishing is the removal of residual glycerol, soaps, and remaining particulates. By improving the biodiesel quality, the economic value of the biodiesel increases, making this step critical to the economic viability of this process of producing biodiesel from algal biomass. Quality standards for biodiesel, such as the European (EN 14214) and the American (ASTM D6751) standards are quite stringent, as biodiesel falling outside of the range of these standards can cause damage to engine systems (Alhassan et al., 2020).
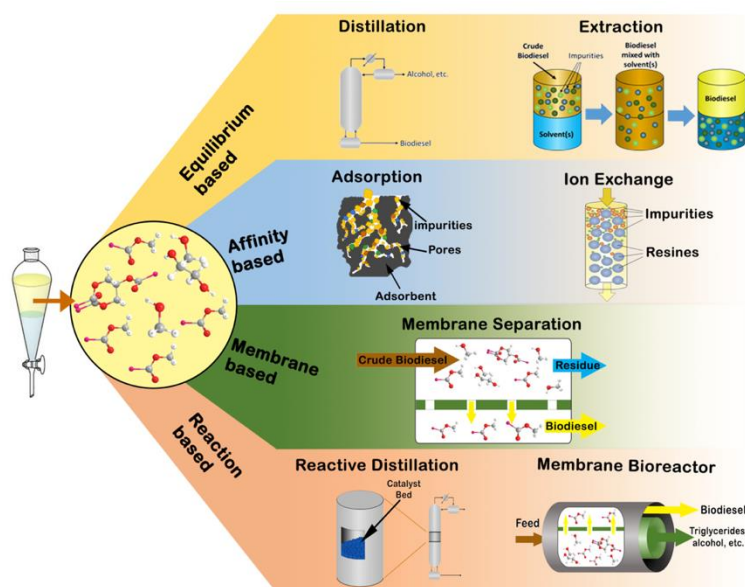
Fig.1. Biodiesel purification techniques classified based on the nature of the processes.

Figure 4. Common purification methodologies for biodiesel purification (Bateni et al., 2017)

The methodologies for biodiesel purification fall primarily into two categories: dry washing (the affinity and reaction-based approaches in Figure 4) and wet washing (equilibrium-based approaches in Figure 4). Membrane-based approaches can be used differently, i.e., with water or not, determining whether their usage is dry or wet. Wet washing is more commonly used, but dry washing has gained in popularity and efficacy in recent years (Alhassan et al., 2020). When considering which avenue of biodiesel polishing to pursue, cost and logistical feasibility were both highly considered to determine the approach with the smallest downside.

Wet Washing

Wet washing, as the name indicates, utilizes solvents, often water, to separate the solvent and biodiesel into two strata in an equilibrium-based separation. Salts can also be mixed into the water to capture free catalysts and glycerides to further improve purification (Lopez et al., 2008). Biodiesel and water do not dissolve in each other, thus, when wet washing is carried out using hydrophobic membranes, the addition of water allows glycerol to form aggregates that remain dissolved in the water without mixing with the biodiesel. These aggregates are large enough to be prevented from passing through the membrane, decreasing the amount of free glycerol present in the biodiesel to acceptable levels. However, this approach introduces significant membrane fouling (Alhassan et al., 2020). When approaching wet washing with microfiltration and ultrafiltration, a cross flow or dead-end filter approach yields differing outcomes. Microfiltration can remove glycerides and particulates to the degree required by the international standards but does so with an inefficiently low flux. Conversely, usage of ultrafiltration proves inconsistent in producing biodiesel that meets international glycerol content standards (Basha et al., 2013). A major downside of wet washing is the need to purify biodiesel wash wastewater before disposing of it, due to the presence of soaps, glycerides, and salts that cannot be processed in standard municipal water processing. This requirement yields added costs and steps in the purification process (Korbitz et al., 2008).

Dry Washing

Dry washing foregoes usage of water in favor of adsorbents and ion exchange resins. The ion exchange adsorbents used for this process are commonly found in industrial processing plants (Chozhavendhan et al., 2021). Adsorption is the process of atoms and molecules adhering to a solid surface; the solid material that molecules are adhering to is referred to as the adsorbent. In the context of biodiesel purification, adsorbents take advantage of the chemical properties of waste present in unpurified biodiesel, namely glycerol, glycerides, and soap to remove them from the biodiesel. Ion exchange adsorbents have proven especially effective at removing glycerol and soaps from biodiesel, improving biodiesel quality standard adherence. Avoiding usage of water removes the need for additional wastewater handling, however, resins are generally limited in usage and are non-reusable (Bateni et al., 2017). This fact coupled with the relatively low cost of absorbents, as well as it being less energy, make dry washing an effective and economical process (Chozhavendhan et al., 2021).

Chosen Methods

Algae Cultivation

The cultivation of algae was done using a raceway pond. Assuming a 100% extent of reaction, the fermentation reaction contains reactants and products at the mass ratio displayed in Reaction 1. The heat conditions of the reaction involve a reference temperature of 25 degrees Celsius. The raceway pond in question has a maximum volume of 10000 cubic meters and a vessel volume of 9998.73 cubic meters. The depth is 0.2 meters, and the length and width are 707.06 meters and 70.71 meters respectively. The resulting surface area of each individual pond rounds to about 50000 square meters. The mass balances for this operation can be found in Tables A2 and A3 (streams Nutrients, CO2, S-103, and S-104).

$$174\,CO_2 + 2.5\,DAP + 44\,Nitrate + 58\,Water \rightarrow 100\,Biomass + 179\,Oxygen + 5.5\,Salts$$
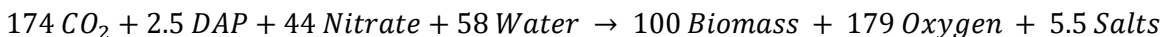
Reaction 1: Conversion of nutrients, water, and carbon dioxide to algal biomass, oxygen, and salts (Carmichael and Petrides, 2020)

Pretreatments

The method of pretreatment is a clarification unit to concentrate the algae and then break up the condensed algae to allow the oils to be recovered in the subsequent steps. The algae settle to the bottom of the tanks with the aid of the added flocculant. (Carmichael and Petrides, 2020). The mass balances for the clarification operation can be found in Tables A1 and A3 (streams S-106, S-107, S-108, S-109, and Flocculant).

The algae-rich stream exiting the clarification tank is then sent to the centrifuge, where it can then be concentrated from 5% biomass to 15% biomass (Carmichael and Petrides, 2020). The left-over supernatant stream from the centrifugation units is recycled back to the raceway ponds. When the concentrated biomass is sent to the sonicators, cell disruption occurs according to the mass coefficients in Reaction 2. Because the extent of cell disruption is 95%, for every 100kg of biomass that enters the sonicators, .95*26=24.7kg of TAG is released and available for further downstream processing (Carmichael and Petrides, 2020). The mass balances for the centrifugation operation can be found in Tables A1 and A2 (streams S-101, S-107, and S-110)

and the sonicator homogenization operation can be found in Tables A2 and A3 (streams S-110 and S-112).

$$100 \, Biomass \; \rightarrow \; 7 \, Ash + 42.2 \, Cell \, Debris + 0.8 \, NHP + 4 \, PL + 20 \, protein \; + \; 26 \, TAG$$
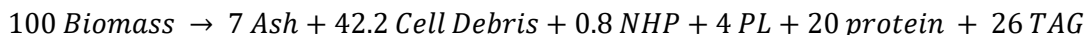
Reaction 2: Conversion of biomass to ash, cell debris, non-hydratable phospholipids (NHP), hydratable phospholipids (PL), and triacylglycerol (TAG) in homogenizing sonicator from (Carmichael and Petrides, 2020)

The sonicator output stream is then fed to a decanter to sit for 1.75 hours, splitting the output into a light lipid rich layer that is 98.8% TAG, and a heavy layer containing the rest of the products from the sonication reaction (Carmichael and Petrides, 2020). This method was chosen for its efficiency in producing TAG with respect to cost and time. The decanter operation mass balance can be found in Tables A3 and A4 (streams S-112, S-113, and S-114).

Lipid Extraction

Following the homogenization and decanting procedures, a hexane solvent is introduced into the process system where it is incorporated into a blending & storage unit with the oils containing the recovered product. Lipids and hexane are both non-polar in nature and, therefore, the lipids will dissolve in the hexane solvent. To facilitate this process at the industry level, the mixture is transferred from the blending unit to a centrifugation unit procedure. The centrifugation process results in the separation of the hexane-lipid mixture from the aqueous phase. Decanting this stream into an evaporation unit fully separates the two. Output of livestock feed is also developed from this procedure. By utilizing a rotary evaporation unit, a lipid-rich residue is produced that fuels the succeeding process systems and is used in transesterification. Mass balances for each operation can be found as follows: solvent mixing in tables A4, A5, and A6 (steams Hexane, S-115, S-114, and S-116); centrifugation in tables A4 and A5 (streams S-116, S-117, S-118, and Livestock Feed); and evaporation in tables A4 and A5 (streams S-117, S-125, and S-130).

Transesterification and Catalyst Classification

The transesterification process and selected catalyst for this process is a heterogenous transesterification. This process has become an industry standard for the insoluble nature of the heterogenous catalysts allowing for easy separation from liquid media. Overall, the process is reuseable and allows for a purer biodiesel in each batch allowing for higher product pricing and lowered operating costs due to less overall catalyst use. The downside of this process lies in its low reactivity which means each batch requires a larger amount of initial catalyst and decreases its yield efficiency, but for our goal of 60,000 kg of biodiesel a day while operating this form is adequate.

The implemented process for the transesterification step intakes flows from the homogenization and evaporation process and utilizes a saponification free reaction (see Figure 5), and it also separates to realize the biodiesel for further separation in an addition centrifuge step following. This process will also take out the glycerol, which can be sold separately for additional revenue.
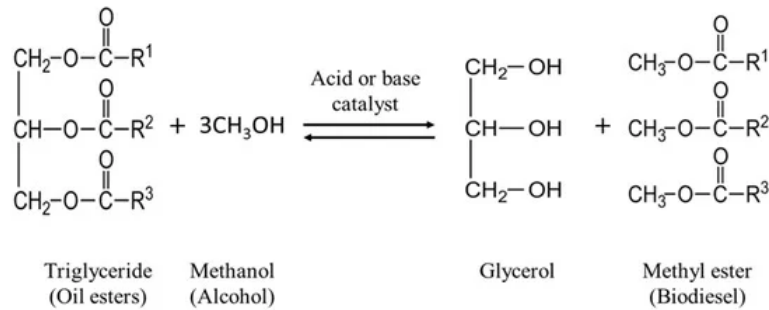
Figure 5 – Demonstration of the reaction utilizing catalyst in the transesterification process.

The catalyst selection can be altered if necessary for this process if further research determines a more effective mixture, as stated, "There are different catalysts used during the transesterification process (a) alkaline catalysts like potassium hydroxide, sodium hydroxide, and sodium methoxide, (b) acid catalysts like hydrochloric acid, sulfuric acid, and sulfonic acid phosphoric acid, (c) enzymatic catalyst like lipases and (d) inorganic heterogeneous catalyst like solid phase catalyst." (Yadav et al., 2022). Additionally, we can further classify the conversions shown in recent studies utilizing catalysts for biodiesel production for the proper ratio, "Baskar et al. [162] used zinc-doped calcium oxide as a catalyst for biodiesel production from castor oil. The experiment was carried out, and the maximum biodiesel conversion of 84.9% was obtained at a methanol-to-oil ratio of 10.5:1, a temperature of 57 °C, a time of 70 min, a catalyst concentration of 2.2%, and a green chemistry balance of 0.896." (Wang et al., 2023). The mass balance for the transesterification reaction can be found in tables A6 and A7 (streams S-120, CaOxide, S-123, and S-126).

Separation of Biodiesel from Glycerol

An appropriate centrifuge selection for the separation of biodiesel and glycerol is essential. Most algal production processes in industry employ a disc stack centrifuge, but decanter centrifuges are sometimes used as well. A decanter centrifuge is advantageous due to its ability to continuously process high flow rates. Decanter centrifuges are also typically easier to operate and are generally more energy efficient. A disc stack centrifuge has marginally better separation efficiency, however there is frequent downtime for cleaning (Ghazvini et al., 2022). A decanter centrifuge running at 7,000 RPM was chosen and modeled in SuperPro for this biodiesel production because of the benefits of continuous production and less downtime. The glycerol is expelled through the heavy phase outlet and the biodiesel remains in the center then exits. This centrifuge will provide an intense force that will successfully separate the denser glycerol from the biodiesel. The mixture of biodiesel and glycerol is fed into the centrifuge before undergoing up to 8,000 Gs of G-force operating at approximately 7,000 RPM. This high intensity centrifugal force causes the denser component of glycerol to discharge through the heavy-phase outlet while the less dense, biodiesel, remains in the center of the centrifuge and discharges through the biodiesel outlet tube. The two components can then be drawn off separately, with the biodiesel being further transferred to a polishing unit, and the glycerol can be further processed or disposed of. The mass balance for this centrifugation step can be found in Tables A6 and A8 (streams S-126, S-122, S-131, and Glycerol).

Polishing

The final step of this process is dry washing the separated biodiesel to remove any remaining glycerol, glycerides, and soap. For this step, crude biodiesel is first fed into a fixed bed adsorber containing Purolite PD206 ion exchange resin (1-2 mm diameter), which beads with an adsorption capacity of 1.94 L/g for 2 hours (Atadashi, 2015). This initial flow-through step decreases levels of glycerol to 0.01% by weight, soap and glyceride levels to a negligible amount, and methanol content to around 1% (Atadashi, 2015). The resulting biodiesel from this step has sufficiently high quality to be sold at market rates.

After one batch of biodiesel purification, the Purolite PD206 beads must be cleansed of bound molecules in a flushing step to be used again. In the flush step, 3 BV of methanol is run through the adsorption column in two thirty-minute periods followed by a final non-standing flow-through rinse (Purolite 2023). The methanol from this step, containing small amounts of glycerol, salts, and soaps, can be routed for reuse in the transesterification process. These flow-through washing and flushing steps can be repeated using the same set of Purolite PD206 resin beads about 40 times before they must be replaced with new Purolite PD206 beads (Purolite, 2023). This adsorptive dry washing approach was chosen for its cost efficiency – no extra water removal steps are necessary using this method – and for its purification efficiency. The mass balance for the adsorption column step can be found in Tables A6, A7, and A8 (streams S-131, Methanol Stream 2, S-129, and Biodiesel).

Flowchart

The simple, complex, and SuperPro Designer process diagrams, seen in Figures 6, 7, and 8 demonstrate this process for producing biodiesel from algae in varying levels of detail. The simple diagram in Figure 6 displays each step of the process, denoted by rounded corner rectangles, and the raw materials added at relevant steps, represented by standard rectangles, with each blue arrow representing a materials stream. The complex diagram in Figure 7 includes the same information as the simple diagram, but also includes the amount of each material added in the process. The process described is continuous, so instead of giving materials used per batch, quantities are given in MT/hr to reflect the process's continual nature. Because this is a continuous process, there is also no relevance of displaying a Gantt chart. The final diagram, Figure 8, is the SuperPro Designer process diagram, with processes and stream labeled where relevant. This figure reflects each aspect of the chosen methods discussed above.
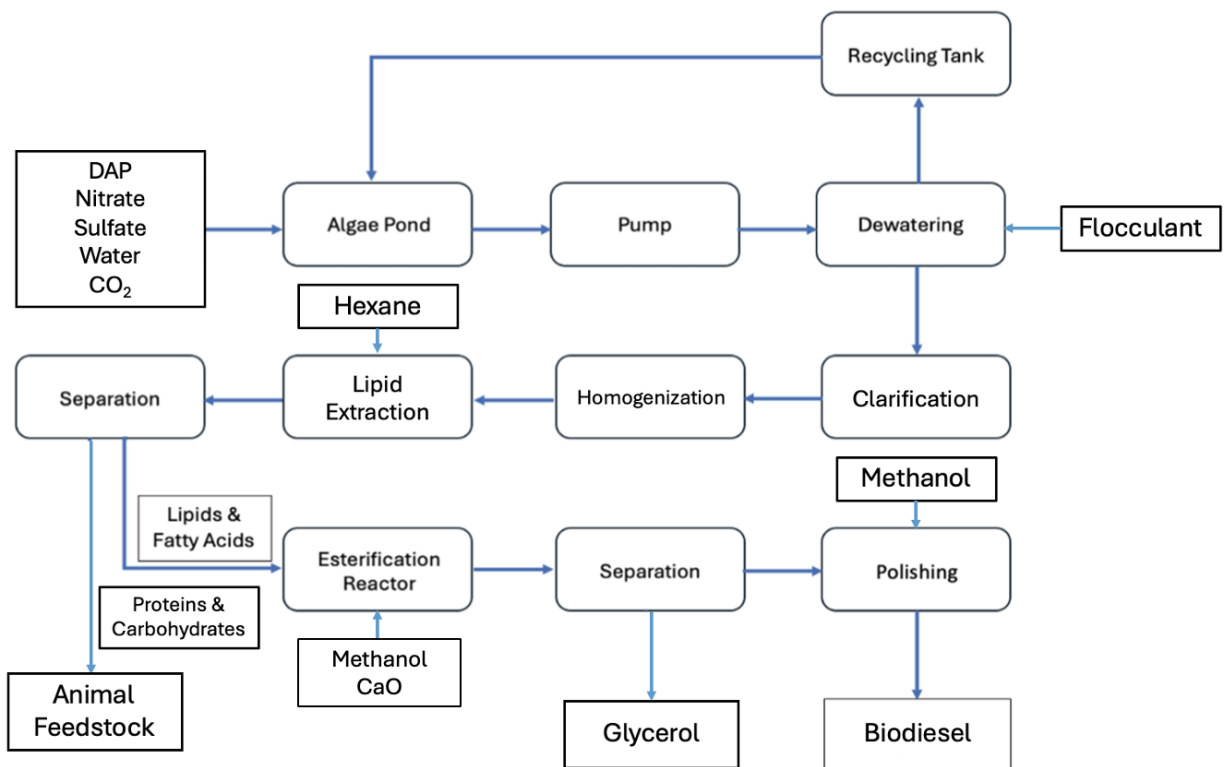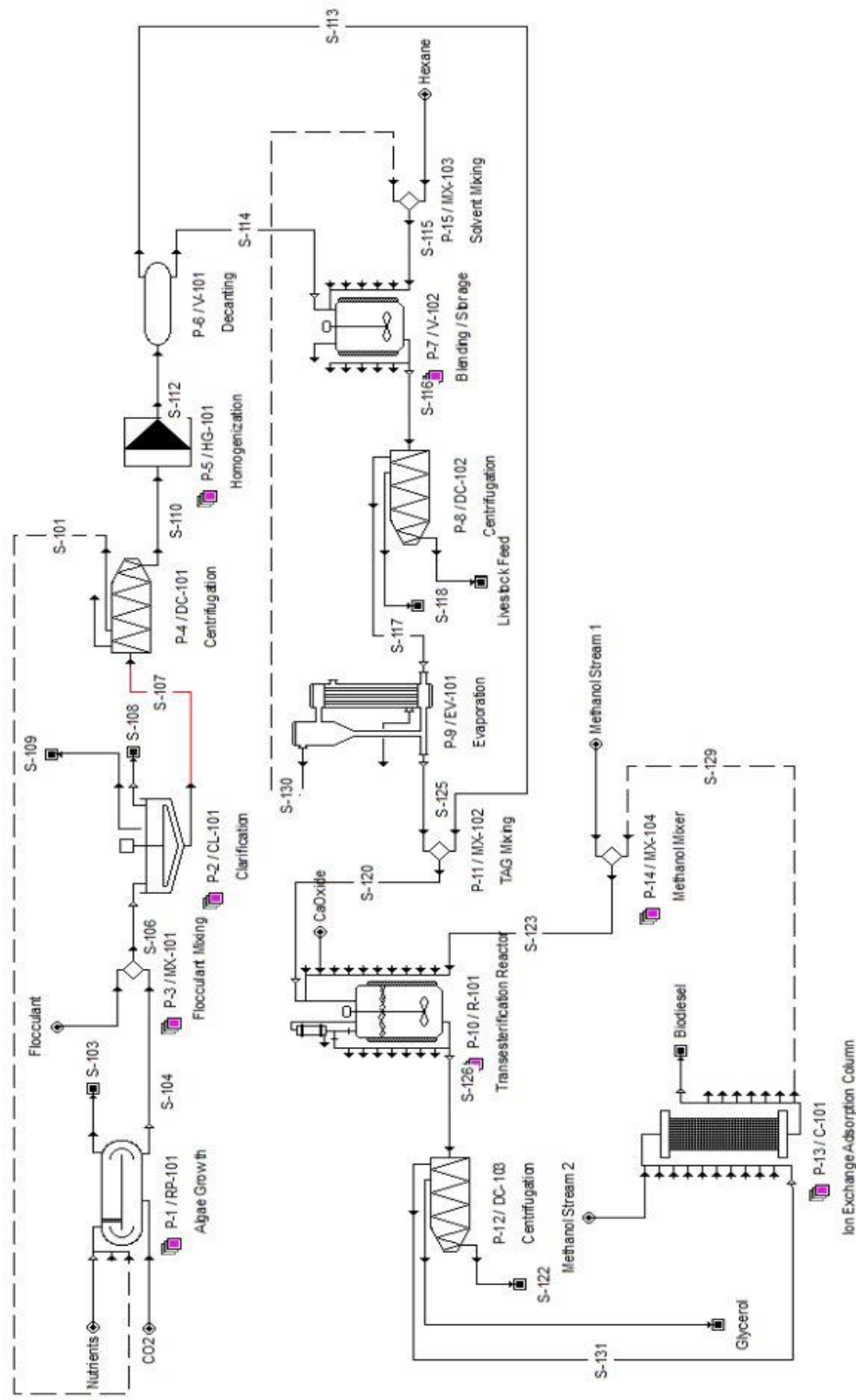
Figure 6 – Simple flowchart of the different processes involved in the production of biodiesel from algal biomass
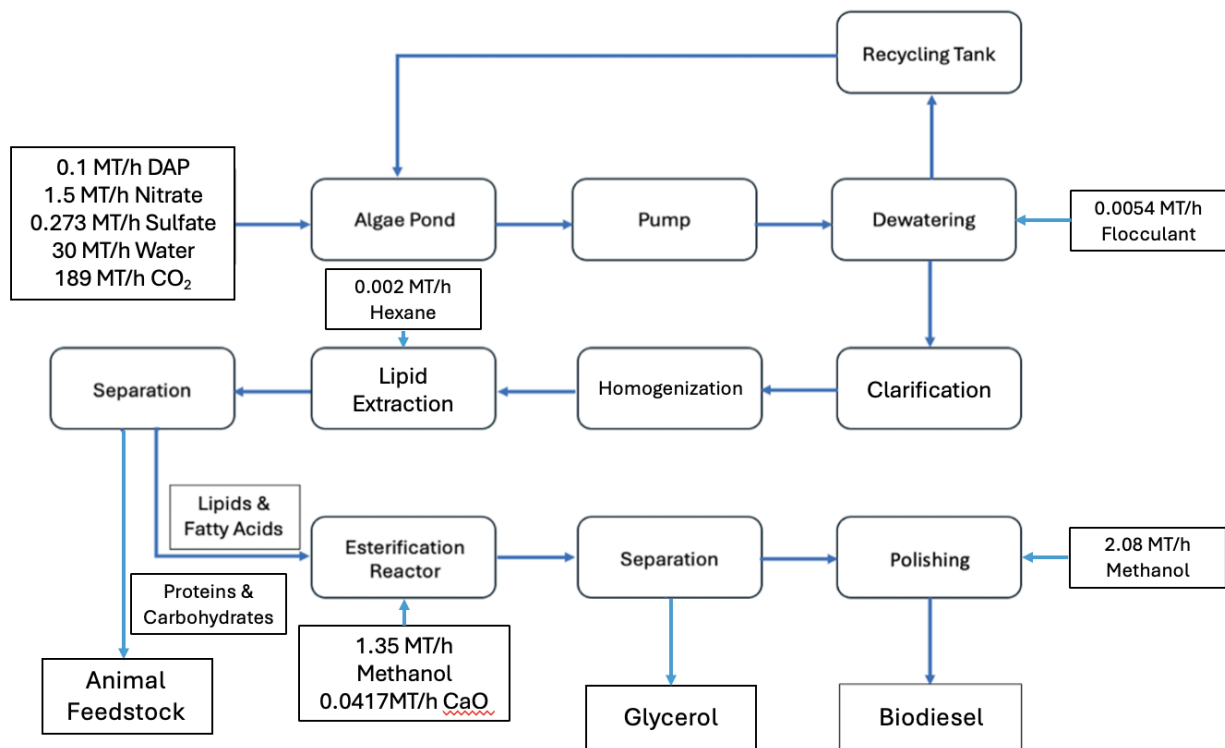
Figure 7 – Complex flowchart of the different processes involved in the production of biodiesel from algal biomass

Cost Analysis

The biodiesel industry is estimated to be worth around 32.9 billion dollars, and expanding to include fossil fuels and the oil industry as a whole elevates the value all the way up to upwards of 5 trillion dollars. The biodiesel industry is constantly growing with more being produced every year. With 1.6 billion gallons being produced by the US in 2022 and that number jumping to 4 billion in 2023 (U.S. Energy Information Administration, 2024). The proposed process under optimal conditions produces 2.17 metric tons of biodiesel per hour which translates to just under 6 million gallons per year which would mean that the proposed process would end up taking up well under 0.2% of the market even if there is no additional growth in the United States' biodiesel production. This also assumes that the proposed process only takes part in the United States biodiesel market and does not participate internationally. Simply put, there is no danger of oversaturation of the market as a result of the proposed process.

Raw materials contributing to the cost of initial investment include calcium oxide at $3.55 per kilo, diammonium phosphate at $772 per metric ton, flocculant at $1050 per metric ton, hexane at $0.40 per kilo, methanol at $0.24 per kilo, nitrate at $184 per metric ton, purolite PD206 at $825 per metric ton, and sulfate at $124 per metric ton. When calculated out, the annual cost for raw materials is estimated to be just over $8.6 million (see Figure 11). As far as equipment costs go, the unit cost for each of the raceway ponds was $189,000, and 8 units amounted to $1,512,000. 5 clarifiers for $1,143,000 each amounted to $5,715,000. 3 decanter centrifuges were purchased for $307,000 each. 10 homogenizers were purchased for 129,000 each for a total of 1,290,000. 2 blending tanks were bought for $457,000 each. A decanter tank and an evaporator were each purchased for $363,000 and $152,000 respectively. Two stirred reactors were bought for $1,043,000 each. Finally, 24 PBA chromatography columns were purchased for $849,000 totaling $20,376,000 for a total equipment investment of $41,661,000 (see Figure 10). The total cost when accounting for installation, process piping, instrumentation, insulation, electrical, buildings, yard improvement, auxiliary facilities, engineering, construction, contractor's fees, and contingency come out to an estimated $237,135,000. This number describes the first year including start-up fees and initial investments. Beyond the first year, the raw material cost does not change, and the most expensive item to consider involves facility-dependent costs at just under $45 million per year. The labor dependent costs are also estimated to be around just under $2 million annually, though it is important to consider that this number can increase depending on inflation and government intervention; however, assuming little fluctuation, the estimated annual costs come out to around $57,370,000.

1. EXECUTIVE SUMMARY (2024 prices)

Total Capital Investment	248,678,000 $
Capital Investment Charged to This Project	248,678,000 $
Operating Cost	57,116,000 $/yr
Main Revenue	29,233,000 $/yr
Other Revenues	21,342,241 $/yr
Total Revenues	50,576,000 $/yr
Batch Size	59,669.87 kg MP
Cost Basis Annual Rate	19,691,058 kg MP/yr
Unit Production Cost	2.90 $/kg MP
Net Unit Production Cost	2.90 $/kg MP
Unit Production Revenue	2.57 $/kg MP
Gross Margin	- 12.93 %
Return On Investment	6.38 %
Payback Time	15.68 years
IRR (After Taxes)	N/A
NPV (at 7.0% Interest)	- 129,866,000 $

MP = Total Flow of Stream 'Biodiesel'

Figure 9 – SuperPro Designer executive summary of detailed economic report.

2. MAJOR EQUIPMENT SPECIFICATION AND FOB COST (2024 prices)

Quantity/ Standby/ Staggered	Name	Description	Unit Cost ($)	Cost ($)
8 / 0 / 0	RP-101	Raceway Pond Vessel Volume = 9122.15 m3	192,000	1,536,000
5 / 0 / 0	CL-101	Clarifier Surface Area = 2203.31 m2	1,157,000	5,785,000
1 / 0 / 0	DC-101	Decanter Centrifuge Throughput = 3373165.72 L/h	307,000	307,000
10 / 0 / 0	HG-101	Homogenizer Rated Throughput = 19293.99 L/h	129,000	1,290,000
1 / 0 / 0	V-101	Decanter Tank Vessel Volume = 42546.28 L	362,000	362,000
2 / 0 / 0	V-102	Blending Tank Vessel Volume = 55377.24 L	456,000	912,000
1 / 0 / 0	DC-102	Decanter Centrifuge Throughput = 150329.29 L/h	307,000	307,000
1 / 0 / 0	EV-101	Evaporator Mean Heat Transfer Area = 9.81 m2	148,000	148,000
2 / 0 / 0	R-101	Stirred Reactor Vessel Volume = 28256.31 L	1,019,000	2,038,000
1 / 0 / 0	DC-103	Decanter Centrifuge Throughput = 20175.53 L/h	307,000	307,000
19 / 0 / 0	C-101	PBA Chromatography Column Column Volume = 634.82 L	859,000	16,321,000
		Unlisted Equipment		7,328,000
			TOTAL	36,641,000

Figure 10 – SuperPro Designer equipment cost summary.

5. MATERIALS COST - PROCESS SUMMARY

Bulk Material	Unit Cost ($)	Annual Amount		Annual Cost ($)	%
CaOxide	3.55	33,000	kg	117,150	1.45
Carb. Dioxide	0.00	1,512,047,371	kg	0	0.00
Diammonium Phos	772.00	792	MT	611,424	7.58
Flocculant	1,050.00	43	MT	45,045	0.56
Hexane	0.40	16,500	kg	6,600	0.08
Methanol	0.24	20,120,756	kg	4,828,981	59.89
Nitrate	184.00	11,880	MT	2,185,920	27.11
Sulfate	124.00	2,162	MT	268,108	3.33
Water	0.00	237,600,000	kg	0	0.00
TOTAL				8,063,228	100.00

Figure 11 – SuperPro Designer material cost summary.

6. VARIOUS CONSUMABLES COST (2024 prices) - PROCESS SUMMARY

Consumable	Units Cost ($)	Annual Amount	Annual Cost ($)	%
Purolite PD206 Resin	7.80	26,287 gal	205,041	100.00
TOTAL			205,041	100.00

Figure 12 – SuperPro Designer consumable (adsorbent resin) cost summary.

H.	**Revenue/Savings Rates**	
	Biodiesel (Main Revenue)	17,187,669 kg /yr
	Glycerol (Revenue)	7,563.312 kg /yr
	Livestock Feed (Revenue)	93,918,929 kg /yr
I.	**Revenue/Savings Price**	
	Biodiesel (Main Revenue)	1.50 $/kg
	Glycerol (Revenue)	0.50 $/kg
	Livestock Feed (Revenue)	0.18 $/kg
J.	**Revenues/Savings**	
	Biodiesel (Main Revenue)	25,781.503 $/yr
	Glycerol (Revenue)	3,790,896 $/yr
	Livestock Feed (Revenue)	17,044,020 $/yr
1	Total Revenues	46,616,219 $/yr
2	Total Savings	0 $/yr

Figure 13 – SuperPro Designer yearly revenue profile.

While gross profits from the sale of biodiesel and streams S-124 and S-119 amount to just over $50 million (see Figure 9), subsidization from the government in their efforts to slowly implement biodiesels into the overall petroleum economy translates our annual net profits to $15,733,000. This means that there is an annual return on investment of 6.29% and overall profit will be achieved after 15.89 years. While this may, at first, seem like a long time to wait, fossil fuel-based oil companies can take up to 5.5 years to see profits and wait up to 17 years before peak production is reached (Lioudis, 2022). Our proposed process does not even account for the practice of mixing biodiesel with existing fossil fuels; a practice that could undoubtedly increase our overall profits - thus increasing return on investment and decreasing the wait time before seeing true profits. Our process also does not account for methods of producing biofuels from materials such as starches or carbohydrates but focuses solely on the production of biodiesel from green algae. Even without such practices, our process remains capable of turning a profit.

<u>Conclusion</u>

This biodiesel production process from algae successfully demonstrates that producing sustainable and economically favorable energy sources is feasible. Careful selection of instruments, methods, and reagents were essential for efficient, high yield biodiesel. Algae production and maintenance was also considered and enhanced. Unlike conventional methods such as fossil fuels, this biodiesel process is optimized for cost-effectiveness, logistical simplicity, and most importantly environmental caution. Using the provided flowchart and the detailed selection of methods, one can understand and formulate biodiesel from algae using our process. Overall, this process will eventually be profitable and is reasonable to invest in. However, when one investigates more lucrative energy investments like fossil fuel production processes, they may have higher interest in that sector. The future potential for a process like this

biodiesel production would need to be enhanced by energy conscious investors, or even government subsidy. Hopefully, further research can be done to lower costs or raise efficiencies to make it a more enticing investment opportunity.

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Appendices

Appendix A - Material and Streams Tables

Table A1: Biomass Flocculant Slurry (S-106), Post Clarification CO₂ (S-109), Clarified Sludge (S-107), Recycled Water (S-101)

Stream Name	S-106	S-109	S-107	S-101
Source	P-3	P-2	P-2	P-4
Destination	P-2	OUTPUT	P-4	P-1
Stream Properties				
Activity(U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	25.69	25.68	25.68	25.75
Pressure (bar)	1.01	1.01	1.01	1.01
Density(g/L)	39.76	1.79	994.77	994.43
Total Enthalpy (kW-h)	451,968.09	42,458.55	405,213.98	388,903.27
Specific Enthalpy (kcal/kg)	27.20	59.44	25.73	25.80
Heat Capacity (kcal/kg-°C)	0.96	0.20	1.00	1.00
Component Flowrates (kg/batch)				
Biomass	81,818.18	0.00	81,818.18	0.00
Carb. Dioxide	620,634.73	614,585.67	0.00	0.00
Diammonium Phos	354.55	0.00	354.55	0.00
Flocculant	130.00	0.00	130.00	0.00
Salts	4,500.00	0.00	4,500.00	0.00
Sulfate	35,530.15	0.00	35,175.76	33,887.24
Water	13,552,625.60	0.00	13,426,870.05	12,935,033.46
TOTAL (kg/batch)	14,295,598.21	614,585.67	13,548,848.53	12,968,920.70
TOTAL (L/batch)	359,551,858.03	342,428,139.86	13,620,023.17	13,041,538.63

Table A2: Initial Centrifuged Solids (S-110), Nutrients, CO₂, Raceway Pond Emissions (S-103)

Stream Name	S-110	Nutrients	CO2	S-103
Source	P-4	INPUT	INPUT	P-1
Destination	P-5	P-1	P-1	OUTPUT
Stream Properties				
Activity(U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	25.75	25.00	25.00	25.67
Pressure (bar)	1.01	1.01	1.01	1.01
Density(g/L)	1,001.91	994.70	1.80	1.74
Total Enthalpy (kW-h)	17,375.23	21,361.77	318,752.33	307,493.23
Specific Enthalpy (kcal/kg)	25.78	24.03	59.30	65.12
Heat Capacity (kcal/kg-°C)	1.00	0.96	0.20	0.21
Component Flowrates (kg/batch)				
Biomass	81,818.18	0.00	0.00	0.00
Carb. Dioxide	0.00	0.00	4,624,608.32	3,861,609.96
Diammonium Phos	354.55	2,400.00	0.00	0.00
Flocculant	130.00	0.00	0.00	0.00
Nitrate	0.00	36,000.00	0.00	0.00
Oxygen	0.00	0.00	0.00	146,454.55
Salts	4,500.00	0.00	0.00	0.00
Sulfate	1,288.52	6,552.00	0.00	0.00
Water	491,836.59	720,000.00	0.00	54,953.31
TOTAL (kg/batch)	579,927.83	764,952.00	4,624,608.32	4,063,017.82
TOTAL (L/batch)	578,820.84	769,024.50	2,570,826,119.09	2,338,493,643.23

Table A3: Algal Biomass (S-104), Flocculant, Homogenized Cellular Material (S-112), Decanted Light-Phase Lipids (S-113)

Stream Name	S-104	Flocculant	S-112	S-113
Source	P-1	INPUT	P-5	P-6
Destination	P-3	P-3	P-6	P-11
Stream Properties				
Activity(U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	25.69	25.00	18.00	18.00
Pressure (bar)	1.01	1.01	1.01	1.01
Density(g/L)	39.76	994.70	1,003.73	997.26
Total Enthalpy (kW-h)	451,964.30	3.79	11,770.48	431.64
Specific Enthalpy (kcal/kg)	27.20	25.11	17.46	18.10
Heat Capacity (kcal/kg-°C)	0.96	1.00	0.97	1.00
Component Flowrates (kg/batch)				
Ash	0.00	0.00	5,440.91	0.00
Biomass	81,818.18	0.00	4,090.91	0.00
Carb. Dioxide	620,634.73	0.00	0.00	0.00
Cell Debris	0.00	0.00	32,800.91	0.00
Diammonium Phos	354.55	0.00	354.55	0.00
Flocculant	0.00	130.00	130.00	0.00
Hydratable Phos	0.00	0.00	3,109.09	621.82
Non-Hydratable	0.00	0.00	621.82	248.73
Proteins	0.00	0.00	16,068.84	0.00
Salts	4,500.00	0.00	4,500.00	0.00
Sulfate	35,530.15	0.00	1,288.52	0.00
Triacylglycerol	0.00	0.00	19,885.70	19,646.33
Water	13,552,625.80	0.00	491,836.59	0.00
TOTAL (kg/batch)	14,295,463.21	130.00	579,927.83	20,516.88
TOTAL (L/batch)	359,552,936.43	130.69	577,772.75	20,573.34

Table A4: Decanted Heavy-Phase Layer (S-114), Solvent Mixer Output (S-116), Extracted Lipids (S-117), Centrifuge Wastewater (S-118)

Stream Name	S-114	S-116	S-117	S-118
Source	P-6	P-7	P-8	P-8
Destination	P-7	P-8	P-9	OUTPUT
Stream Properties				
Activity(U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	18.00	47.94	48.20	48.20
Pressure (bar)	1.01	0.08	0.08	0.08
Density(g/L)	1,003.97	988.43	918.52	988.03
Total Enthalpy (kW-h)	11,338.83	31,741.16	1,850.61	14,746.28
Specific Enthalpy (kcal/kg)	17.44	46.17	44.18	46.90
Heat Capacity (kcal/kg-°C)	0.97	0.96	0.91	0.97
Component Flowrates (kg/batch)				
Ash	5,440.91	5,440.91	0.00	0.00
Biomass	4,090.91	4,090.91	0.00	0.00
Cell Debris	32,800.91	32,800.91	0.00	0.00
Diammonium Phos	354.55	374.07	19.52	187.01
Flocculant	130.00	130.00	0.00	0.00
Hexane	0.00	4,950.00	4,900.00	0.00
Hydratable Phos	2,487.27	2,487.27	2,487.27	0.00
Non-Hydratable	373.09	373.09	373.09	0.00
Proteins	16,068.84	16,068.84	838.95	8,036.26
Salts	4,500.00	4,500.00	234.94	2,250.51
Sulfate	1,288.52	1,288.52	67.23	643.95
Triacylglycerol	39.37	39.37	39.37	0.00
Water	491,836.59	518,919.33	27,082.74	259,424.75
TOTAL (kg/batch)	559,410.95	591,463.22	36,043.12	270,542.49
TOTAL (L/batch)	557,199.41	598,389.23	39,240.51	273,820.32

Table A5: Livestock Feed, Reusable Hexane (S-130), Solvent-Free Lipids (S-125), Hexane

Stream Name	Livestock Feed	S-130	S-125	Hexane
Source	P-8	P-9	P-9	INPUT
Destination	OUTPUT	P-15	P-11	P-15
Stream Properties				
Activity(U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	48.20	40.00	40.00	25.00
Pressure (bar)	0.08	0.08	1.01	1.01
Density(g/L)	998.32	0.07	1,001.27	656.02
Total Enthalpy (kW-h)	15,304.39	20,401.54	151.41	0.79
Specific Enthalpy (kcal/kg)	46.26	548.52	32.24	13.52
Heat Capacity (kcal/kg-°C)	0.96	0.44	0.80	0.54
Component Flowrates (kg/batch)				
Ash	5,440.91	0.00	0.00	0.00
Biomass	4,090.91	0.00	0.00	0.00
Cell Debris	32,800.91	0.00	0.00	0.00
Diammonium Phos	167.40	19.52	0.00	0.00
Flocculant	130.00	0.00	0.00	0.00
Hexane	0.00	4,900.00	0.00	50.00
Hydratable Phos	0.00	0.00	2,487.27	0.00
Non-Hydratable	0.00	0.00	373.09	0.00
Proteins	7,193.64	0.00	838.95	0.00
Salts	2,014.54	0.00	234.94	0.00
Sulfate	576.43	0.00	67.23	0.00
Triacylglycerol	0.00	0.00	39.37	0.00
Water	232,223.45	27,082.74	0.00	0.00
TOTAL (kg/batch)	284,638.19	32,002.26	4,040.85	50.00
TOTAL (L/batch)	285,116.28	479,828,983.47	4,035.74	76.22

Table A6: Mixed Hexane Stream (S-115), TAG and Lipids (S-120), Esterified Products (S-126), Impure Biodiesel (S-131)

Stream Name	S-115	S-120	S-126	S-131
Source	P-15	P-11	P-10	P-12
Destination	P-7	P-10	P-12	P-13
Stream Properties				
Activity(U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	100.00	21.00	34.46	38.49
Pressure (bar)	0.08	1.01	1.01	1.01
Density(g/L)	0.06	997.91	929.90	877.52
Total Enthalpy (kW-h)	20,402.33	583.05	1,787.55	1,122.25
Specific Enthalpy (kcal/kg)	547.69	20.43	16.62	15.80
Heat Capacity (kcal/kg-°C)	0.49	0.97	0.48	0.41
Component Flowrates (kg/batch)				
BioDiesel	0.00	0.00	59,057.11	59,057.11
CaOxide	0.00	0.00	100.00	0.00
Diammonium Phos	19.52	0.00	0.00	0.00
Glycerol	0.00	0.00	19,685.81	1,078.78
Hexane	4,950.00	0.00	0.00	0.00
Hydratable Phos	0.00	3,109.09	3,109.11	170.38
Methanol	0.00	0.00	8,850.76	765.95
Non-Hydratable	0.00	621.82	621.82	34.08
Proteins	0.00	838.95	838.95	0.00
Salts	0.00	234.94	234.94	0.00
Sulfate	0.00	67.23	67.23	0.00
Triacylglycerol	0.00	19,685.70	0.00	0.00
Water	27,082.74	0.00	0.00	0.00
TOTAL (kg/batch)	32,052.26	24,557.73	92,565.73	61,106.30
TOTAL (L/batch)	540,117,852.75	24,609.16	99,544.24	69,635.03

Table A7: Reusable Methanol (S-129), Methanol Stream 1, Mixed Methanol (S-123), CaOxide

Stream Name	S-129	Methanol Stream 1	S-123	CaOxide
Source	P-13	INPUT	P-14	INPUT
Destination	P-14	P-14	P-10	P-10
Stream Properties				
Activity(U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	25.00	25.00	25.00	25.00
Pressure (bar)	1.01	1.01	1.01	1.01
Density(g/L)	789.62	789.61	789.61	2,900.00
Total Enthalpy (kW-h)	627.96	573.00	1,200.96	0.78
Specific Enthalpy (kcal/kg)	15.22	15.22	15.22	6.69
Heat Capacity (kcal/kg-°C)	0.61	0.61	0.61	0.27
Component Flowrates (kg/batch)				
CaOxide	0.00	0.00	0.00	100.00
Glycerol	0.11	0.00	0.11	0.00
Hydratable Phos	0.02	0.00	0.02	0.00
Methanol	35,507.88	32,400.00	67,907.88	0.00
Non-Hydratable	0.00	0.00	0.00	0.00
TOTAL (kg/batch)	35,508.00	32,400.00	67,908.00	100.00
TOTAL (L/batch)	44,968.74	41,032.70	86,001.44	34.48

Table A8: Glycerol, Solid Waste (S-122), Methanol Stream 2, Biodiesel

Stream Name	Glycerol	S-122	Methanol Stream 2	Biodiesel
Source	P-12	P-12	INPUT	P-13
Destination	OUTPUT	OUTPUT	P-13	OUTPUT
Stream Properties				
Activity(U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	38.49	38.49	25.00	38.49
Pressure (bar)	1.01	1.01	1.01	1.01
Density(g/L)	1,163.80	1,161.93	789.61	872.78
Total Enthalpy (kW-h)	677.47	7.81	627.96	1,081.13
Specific Enthalpy (kcal/kg)	24.36	11.56	15.22	15.59
Heat Capacity (kcal/kg-°C)	0.63	0.30	0.61	0.41
Component Flowrates (kg/batch)				
BioDiesel	0.00	0.00	0.00	59,057.11
CaOxide	0.00	100.00	0.00	0.00
Glycerol	18,607.02	0.00	0.00	0.00
Hydratable Phos	2,938.73	0.00	0.00	0.00
Methanol	1,148.92	0.00	35,507.88	612.76
Non-Hydratable	587.75	0.00	0.00	0.00
Proteins	474.64	354.16	0.00	0.00
Salts	132.92	99.18	0.00	0.00
Sulfate	38.01	28.36	0.00	0.00
TOTAL (kg/batch)	23,927.99	581.70	35,507.88	59,669.87
TOTAL (L/batch)	20,560.21	500.64	44,968.64	68,367.75

Table A9: Component Mass Balance Table

4. OVERALL COMPONENT BALANCE (kg/batch)

COMPONENT	INITIAL	INPUT	OUTPUT	FINAL	IN-OUT
Ash	0.00	0.00	5,440.91	0.00	-5,440.91
BioDiesel	0.00	0.00	59,057.11	0.00	-59,057.11
Biomass	0.00	0.00	4,090.91	0.00	-4,090.91
CaOxide	0.00	100.00	100.00	0.00	0.00
Carb. Dioxide	0.00	4,624,608.32	4,476,195.62	0.00	148,412.70
Cell Debris	0.00	0.00	32,800.91	0.00	-32,800.91
Diammonium Phos	0.00	2,400.00	354.41	0.00	2,045.59
Flocculant	0.00	130.00	130.00	0.00	0.00
Glycerol	0.00	0.00	18,607.02	1,078.67	-19,685.69
Hexane	0.00	50.00	0.00	0.00	50.00
Hydratable Phos	0.00	0.00	2,938.73	170.36	-3,109.09
Methanol	0.00	67,907.88	1,761.68	153.19	65,993.00
Nitrate	0.00	36,000.00	0.00	0.00	36,000.00
Non-Hydratable	0.00	0.00	587.75	34.07	-621.82
Oxygen	0.00	0.00	146,454.55	0.00	-146,454.55
Proteins	0.00	0.00	16,058.70	0.00	-16,058.70
Salts	0.00	0.00	4,497.16	0.00	-4,497.16
Sulfate	0.00	6,552.00	1,286.75	0.00	5,265.25
Water	0.00	720,000.00	546,601.52	0.00	173,398.48
TOTAL	0.00	5,457,748.20	5,316,963.72	1,436.30	139,348.18
				Overall Error:	2.553%