

Biomass Utilization of Carbon

The Algorithm

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2. Executive Summary

The goal of this project was to address the environmental implications of an algae biomass system that sequesters carbon dioxide to produce economically valuable products (Oakey, 2016). The Algrithm, a company driven by reducing CO₂ emissions, chose a final product based upon the results of economic analyses that considered potential carbon capture and utilization incomes, as well as the value of diverse products under various commodity pricing constraints. Many algae-based bio-products were considered before narrowing in on a specific product that would encompass the volume of typical utility-scale electricity producing plants, a wide range of future carbon costs, and the scalability of the proposed carbon utilization process. Due to the economic viability of algal-based products in prominent industries, a full analysis has led to the selection of bio-surfactants, a widely applied, high-value product. Based on industrial standards and researched assumptions, the Algrithm's system could produce 11,400 lb_m/day of valuable lipids for further conversion into bio-surfactants. Through preliminary economic calculations, the Algrithm is projected to have an annual revenue of \$13.41 million with a 15-year net present value of \$9.54 million at a tax rate of 35% and an interest rate of 12% with an IRR of 16.7%. As the Algrithm moves forward with further research and evaluations, both the economics and the process unit operations will be developed conclusively and will be indicative of the potential success of environmentally-friendly, algae-based bio-surfactants.¹

3. Scope of Work

This design is to develop a carbon sequestration system using microalgae, and then process and produce a marketable end product from the cultivated algal biomass.

The constraints on this design include scientific and technical, production, practical, product and feedstock specification, safety, environmental, and economic constraints. Each of these categories can be broken down into more specific aspects of each constraint.

- Production Constraints
 - Purity of bio-surfactants—the final bio-surfactant product will need to meet customer and industry specifications in regard to purity. This will ensure that the final product performs satisfactorily and meets industry standards.
 - Byproducts—algae cake and byproducts from separators (to be determined with further chemical analysis) must be accounted for.
 - Waste (both water and chemicals)—all waste must be accounted for so that it can be tested against applicable EPA standards and regulatory specifications.
 - Tolerance percentage—tolerances must be set to allow an acceptable range for testable quality-related properties of the bio-surfactant product.
 - Marketability—the current market for bio-surfactants must be analyzed to determine demand and competitive pricing. The marketability of primary and byproducts may limit total sellable quantities. The prices of similar

¹ Traci Reusser

products currently on the market will constrain the price of the Algalrithm's products.

- Market size—Even the overall size of the market will have an effect on the Algalrithm's viability. The bio-surfactant market is projected to exceed \$2.6 billion by the year 2023 (Global Market Insights, 2017). This rapidly growing market for bio-surfactants will foster large-scale production, and allow the Algalrithm to grow to meet industry needs.
 - Feedstock limitations—the availability and costs of feedstock materials may limit overall output. If a feedstock is scarce or extremely costly, production could be significantly impacted.
 - Capital finance limitations—there will be a theoretical limit on the initial investment into the plant facilities and equipment. This limit must be based on payback period and economic analysis. The Algalrithm's ability to secure these initial funds may constrain production.
 - Labor force—the availability of a skilled, experienced labor force could also potentially limit production. Since carbon sequestration using algae in photobioreactors is not a common industrial practice, obtaining experienced professionals may be difficult to impossible. In this event, funds must be allocated for training for new employees to orient them to the photobioreactor and processing systems.
 - Time—growth rates have a high possibility of constraining production. If growth rates are too slow, there may be considerable downtime as the algae is cultivated, before it can be processed.
 - Ongoing budget—the availability of funds over time may constrain production. If the bio-surfactant market proves to be volatile, then downturns in the market may heavily affect the Algalrithm's income, which could result in scale backs or shutdowns on production.
- Practical Constraints
- Photobioreactor size—the reactors will have a practical size limit. The equipment must be large enough to minimize the overall number of photobioreactors, providing economies of scale. However, the equipment should not be so large that it results in huge sums of money expended for purchase and maintenance of custom-built reactors. Current industrial-scale photobioreactors will be used.
 - Heat exchanger size—there must also be a practical size limit on heat exchangers employed in the system. Heat exchangers that are too small will be inefficient, and heat exchangers that are too large may be much too costly and/or hazardous.
 - Available sunlight for photobioreactors—hours of daylight will constrain algae growth.
 - Overall Plant size—there will be a limited acreage available for the theoretical plant purchase. The current acreage being considered for plant construction is a 10 acre lot located in southeastern Colorado. Also, the utilities associated with the plant building(s) must be considered, and will likely increase with plant size.

- Product and Feedstock Specification Constraints
 - Purity of wastewater, byproducts, and final products—all products and byproducts must meet EPA, regulatory, and customer constraints and specifications. Bio-surfactant and soil amendment products must not be dangerously toxic or volatile.
- Safety Constraints
 - Worker safety—plant layout and unit operations must be designed and maintained so as to minimize risk to operators and other personnel. This must include any noise in the production area that may be loud enough to cause hearing loss to workers or visiting personnel. Hazardous materials such as dichloromethane must be monitored and controlled to be sure that workers are not exposed to damaging or dangerous conditions while working with these chemicals.
 - Consumer safety and health—the end-product must be approved by industry safety standards. Residual dichloromethane must be removed from products to render them safe for end-use.
 - Safety of the public—the Algalgorithm's facilities must meet all industrial coding and specifications to avoid any unexpected events that might endanger the public in the surrounding area. Also, noise emitted from the plant must be monitored and controlled if the plant is located in a populated area. CO₂ lines entering the facility must be monitored to ensure safe operating pressures.
 - Unit operation process control—a robust process control system must be developed to maintain stable, safe operating conditions.
 - Safe transportation of CO₂ and other chemicals—the Algalgorithm must work with CO₂ and chemical providers to ensure safe delivery of products.
- Environmental Constraints
 - Emissions – CO₂ and other emissions in general must meet EPA standards.
 - Wastewater control—wastewater treatment and disposal must meet EPA standards.
 - Other waste products—any other waste products must meet environmental and local regulations to ensure safe disposal.
- Economic Constraints
 - Realistic selling price for product/byproducts—the market for bio-surfactants will constrain the maximum selling price for our product.
 - Profitability of system—in order for the Algalgorithm to be viable, long-term profit must outweigh both the initial investment and operating costs.
 - Carbon tax estimation—this carbon tax must be estimated, using current taxes imposed by foreign countries as a metric.

- Fixed capital investment estimation—there will be only a limited amount of fixed capital investment that will be available for construction and start-up of the Algrithm facilities.²

4. Introduction

4.1 Background

Global carbon dioxide emissions have reached alarming levels. These emissions can be attributed to both human and natural sources. The natural emissions of carbon dioxide include decomposition, respiration, and ocean release; these emissions are in balance with carbon dioxide consumption from processes like photosynthesis. The human sources of emissions are generally attributed to the burning of fossil fuels such as natural gas, coal, and oil and can be lowered by social changes and legislation. The atmospheric CO₂ level as of October 2016 was 404.93 ppm, which is over 20 ppm higher than the October 2005 measurement of 380.29 ppm (NOAA, 2016).

The increase in emissions has proven to be of great interest for governments around the world. The *Accord de Paris*, a United Nations climate change agreement signed in April 2016 with implementation in 2020, details the goals of constraining global temperature rise to no more than 2°C, which corresponds roughly with 500 ppm (Clark, 2012). This task seems inherently simple, with a range of nearly 100 ppm for success, but due to the alarming rate at which CO₂ emissions are increasing and the long lifespan of CO₂ in the atmosphere, there is dire need for improvement. The agreement was signed by 193 members of the United Nations Framework Convention on Climate Change and expressively calls for mitigation and financial actions to be taken against greenhouse gas emissions.

Currently, there are several plans in place for reducing emissions that do not involve a tax on carbon dioxide emissions. The carbon tax, however, has implemented in countries across the globe as a means to encourage low-emitting systems. The details of a carbon tax are determined by the implementing country and offer room for variation. Of the fifteen countries with successful carbon taxes, the form of the tax ranges from including the tax in consumers' bills to directly taxing various types of emissions from CO₂-producing industrial plants. There are no standard prices on the carbon tax nor any guaranteed methods of implementation, leading many countries to look elsewhere to solve their emission issues.

An area of energy-based science that has appealed to researchers for its abilities to both produce energy-dense products and to reduce CO₂ emissions is the use of biomass. The general premise of this practice requires growth of a plant that sequesters CO₂ from the atmosphere and then converts it to biomass. The biomass produced can then be converted into various products through refining and chemical processing. The overall emissions of this system are considered to be carbon-neutral, as the carbon dioxide consumed by the plant is equal to that produced by the

² Catherine Brame

process. In ideal situations, this biomass utilization process could even be carbon-negative with more CO₂ being sequestered than produced.

As the globalized reaction towards CO₂ emission rates becomes more severe, the need for action grows rapidly. Countries are searching for methods to reduce their emissions, but the current implemented practices are not enough to efficiently reduce the carbon dioxide concentration in the atmosphere. Further steps must be taken to effectively minimize greenhouse gases. Algal biomass utilization of carbon is a potential answer to the emission-reduction questions for which countries have been searching.

This process is promising to countries and industries around the world. There are numerous options to produce biomass, making its possible applications impressive. One specific organism that produces a large content of biomass and is relatively simple to grow is microalgae.

There are many strains of microalgae that can be turned into biomass. Microalgae is enticing due to its minimal growth requirements and its ability to produce energy-dense lipids. There are minimal land requirements for microalgae growth; on an industrial scale it is typically grown in either an open-pond system, photobioreactor or a fermenter tank. The necessary growth elements for microalgae are an energy source of either sunlight or sugars, CO₂, and nutrient-rich water. The potential production of microalgae far outweighs the requirements, with *chlorella* strains of algae producing 28-32 % dry weight oil content, all of which can be utilized by various industries with lipid-based products (Demirbas, 2011).

Microalgae as a feedstock is an essential part of this product. Algal growth involves minimal land requirement; they have high growth rates and are tolerant to stressors. Growing algae sustainably, biomass development, characterization and cultivation systems requires a lot of consideration (Algae Biofuels).³

Algae can be grown sustainably by using non-arable land, non-potable water, waste water nutrients, waste carbon dioxide, sufficient sunlight or glucose source, and supporting infrastructure to access downstream processing operations. Algal biomass development involves fast growth rates, high oil content, various strains, breeding, and genetic engineering. Biomass characterization has many fundamental components, including lipids, starch, and proteins, which are comparable to plants. One useful strain is *chlorella* or a mixture of *chlorella* sub-species. *Chlorella* is the strain of algae that will be used to produce bio-surfactants and has been in current research involving their production.

Algal growth requires nutrients to grow in addition to a carbon and energy source. Nutrients include nitrogen, phosphates and other organic compounds (Abdel-Raouf, 2012). Nutrient sources need to be high in these compounds for optimal algae growth. Sources of nutrients being considered for this process include wastewater and food-waste. The nutrients that come from food-waste and wastewater, turn waste into a renewable resource used as a feedstock for our algae.

³ Katie Hopfensperger

Wastewater is often used in the cultivation of algal biomass (Pittman, 2011). Using wastewater is cost effective and requires low energy. Using wastewater would eliminate the initial wastewater treatment processes that many companies must use and pay for to prevent waste. Companies would instead send their wastewater that needs to be treated to the algae facility where it would be filtered and possibly pre-treated before being used as a nutrient source for the algae growth process.

Three types of wastewater were considered; agricultural, municipal and industrial. Currently, agricultural wastewater is most widely used for algae production, with 37.1 grams algae biomass per liter of wastewater with nitrogen and phosphorus contents (Pittman, 2011). However, algal growth depends on the nutrients present in the wastewater source. It must be high in nitrogen and phosphates, as well as organic compounds and low in toxic compounds. Agricultural wastewater, per research, is used for many different algae strains and has advantages because it is not high in toxins but is high in nitrogen and phosphates. Specifically pig wastewater in agriculture is advantageous because it is not high in toxins or other harmful chemicals like pesticides. The most common strain of algae used with agricultural wastewater is *chlorella* or a mixture of *chlorella*. *Chlorella* could also be used in industrial water if another water source was needed or used in addition to the agricultural wastewater.

Food-waste can be used as a feedstock or as an additional lipid source to produce biomass products. The content and composition of the food-waste lipids depends on the type of food waste used. The food-waste needs to be high in unsaturated and saturated fatty acids to be useful as an additional feedstock. This is a consideration that might affect the outcome of the final product and is discussed therein.⁴

4.2 Business Opportunity

The business opportunity of the Algalgorithm is largely attributed to microalgae's ability to sequester carbon dioxide. Algal biomass utilization of carbon is an environmentally friendly process that produces valuable and tailorable products. With growing global concern over CO₂ emissions, the Algalgorithm is marketable in many countries.

The United States has not yet introduced a carbon tax, but it has the potential to follow in the path of the European countries that have implemented the system. Should the U.S. join the movement against CO₂ emissions, the Algalgorithm's method of algal biomass utilization of carbon could be locally successful.

This system has the potential to earn favor with both the government and the industrial power plants around the country. A large source of marketability of the Algalgorithm is centered around the sequestration of carbon dioxide. The location of the utilization system would be near an industrial power plant with large CO₂ emissions. The selection of location is paramount, as the quantity of CO₂ from the power plant that can be consumed by the microalgae is directly related

⁴ Traci Reusser

to the tax amount paid by the industrial plant. The more CO₂ that the microalgae sequesters, the less taxable CO₂ is being emitted into the atmosphere by the industrial plant. The tax reductions received by these industrial power plants would be proportional to the income received by the Algalrithm from the power plant.

In addition to the environmental benefits of CO₂ sequestration, the ability to use wastewater as a nutrient source for microalgae factors into the theoretical success of the Algalrithm. For the microalgae to produce large quantities of biomass it requires nutrients containing nitrogen and phosphorus, which can commonly be found in wastewater. This biomass system can use wastewater from a nearby system—whether it be agricultural, municipal, or industrial—as a medium for algal growth. The microalgae will reside in an open pond, fermenter, or photobioreactor with the filtered wastewater until the nutrients have been consumed and the algae has reached peak growth. This method allows nearby wastewater-producers to eliminate sending their wastewater to a treatment facility and instead send it to the less expensive biomass system. Similar to the relationship of the carbon tax with the industrial plants, the wastewater treatment costs would be used as a basis for income from the nearby wastewater-producers. Additionally, this system leaves room for the Algalrithm to proceed with further treatment of the wastewater after the nutrients have been consumed should it prove to be economically viable.

Based on polls done by the Carbon Tax Center, there is an interest in carbon tax implementation in several states in the U.S. These states include, but are likely not limited to, Washington, New York, Vermont, Rhode Island, Massachusetts, and Colorado (Carbon Tax Center). Due to both its centralized location to wastewater producers and CO₂-producers and its potential for inexpensive shipping of lipid-based biomass products to manufacturing companies, Colorado is the optimal location for this biomass utilization process. A location in southeastern Colorado increases the business opportunity of the Algalrithm because the area caters to all of these necessary marketing facets.⁵

There are multiple for-sale locations within southeastern Colorado that are close to a carbon source, such as power plants or other industrial operations. Since carbon would likely be compressed and transported via pipelines, transportation costs can be minimized by selecting a location in close proximity to the source. Wastewater supply is another consideration when selecting plant location. With agriculture central to Colorado's economy, there are many agricultural wastewater options to choose from in the southeastern Colorado area. Ideally, this wastewater supply would also be close to the algae cultivation plant, further decreasing material transportation costs.

In order for the system to remain carbon negative, while maintaining quality and purity requirements, photobioreactors will be used as the method of cultivation. A photobioreactor system with an output of one ton per day utilizes an area of approximately 0.4 acres (Power Plant CCS). Literature sizing and electricity requirements for industrial-scale photobioreactors are shown in Table 1.

⁵ Katie Hopfensperger

Table 1. Sizing and electricity requirements for an algae system with an output of one ton per day (Power Plant CCS).

Price of algae system	\$619,000
Required area	0.4 acres
Required electricity	55 kW

The Algalgorithm's photobioreactors will produce an estimated eighteen tons per day of biomass. Using this information—in conjunction with the information provided in the literature for a one-ton production system—just over seven acres will be needed for the photobioreactor portion of the plant. After including the three acres needed for the bio-surfactant processing facility, approximately ten acres of land must be purchased to encompass all production and processing facilities. According to real estate advertisements, ten to fifteen acres of undeveloped land in southeastern Colorado costs between \$40,000 and \$60,000 (Land Watch, 2017). While surveying would be needed to select the best lot of land to purchase, the asking prices listed can be used as preliminary figures for initial land purchase, used in fixed capital investment calculations.⁶

4.3 Alternatives

Many algae based bio-products were considered before narrowing in on a specific product that would encompass the volume of typical utility-scale electricity producing plants, a wide range of future carbon costs, and the scalability of our proposed carbon utilization process. Micro-algae can be used to produce pharmaceuticals, bioplastics, biofuels, cosmetics, foods, fertilizer and animal feed.

4.3.1 Pharmaceuticals

An alternative to bio-surfactants originally considered for this project was the production of pharmaceuticals. Algae lipids are extremely rich in omega-3 fatty acid chains, in particular two important molecules; eicosapentaenoic acid (EPA) and docosahexanoic acid (DHA). The role of these lipids in the body is crucial; the three main categories of complex lipids are triglycerides, cholesterol esters, and phospholipids. They are composed of the fundamental building blocks of glycerol, cholesterol, and fatty acids (Staples, 1995). Lipids make up anywhere from 12-40 % of the human body based on fitness, and help with numerous regulatory, structural, and modulatory catabolic pathways in the body. Omega-3 fatty acids are regularly recommended for their overall health benefits. They are important for brain development and function, cardiovascular health, and cell structure and function. They help lower bad cholesterol in the body, as well as prevent the development of osteoporosis.

Algae is also one of the most effective and abundant sources of beta-1,3-glucan. Some specific strains of microalgae have the highest concentrations of beta glucan in the world. It aids the human immune system response, and helps fight cancer, disease, and infections (Miller, 2016).

⁶ Catherine Brame

The primary reason algal pharmaceuticals wouldn't be viable or realistic for this project, is the low recovery of pharmaceutical grade lipids from algae biomass. The production of growing, harvesting, and processing algae is extremely expensive, and anywhere between 7-30 % of the original biomass would be extracted and used for algal pharmaceuticals (D'Aquino, 2000). This would not be an economically viable process, and would never make profit in the real world.

Another reason this alternative was not pursued, is due to the expensive nature of the medicine and health care market. Many other cheaper materials, like krill and fish, are currently being used to create the same medicines, and cure the same things more effectively. Simply making pharmaceuticals from algae just because it is possible, isn't an economically realistic option in the present market (Moloughney, 2015).

Lastly, there is currently limited research into the large-scale production of algal pharmaceuticals. It would be difficult to perform a real-world economic analysis that could accurately depict this project. Since there is limited research that primarily focuses on lab scale productions, it's been chosen to forgo using algae lipids for pharmaceutical production.⁷

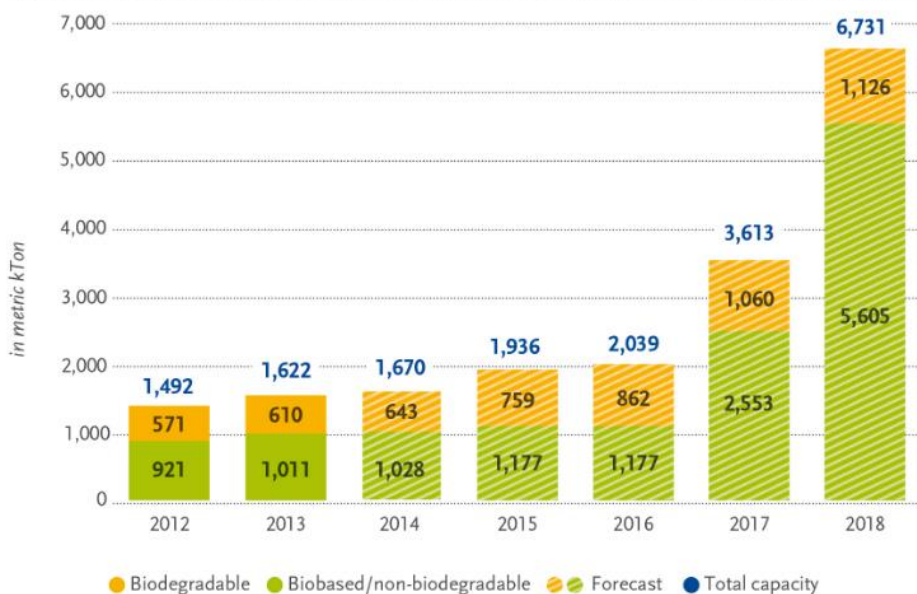
4.3.2 Bioplastics

Bioplastics were also evaluated as a possible product from the cultivated algae. Once cultivated and separated from its water source, the long-chain carbohydrates within the algal biomass can be processed using plastic extrusion technology to form bioplastic resin pellets (ALGIX Algae Bioplastics). These pellets can then be further processed to produce various bioplastic packaging and household products.

Bioplastics emerged as a potential product due to the rapid market growth for greener and more sustainable plastics. Currently, only 1% of global plastic production consists of bio-based plastics, but that number is projected to increase in coming years. Projected growth rates vary depending on the source, but estimates range from 20% to 100% annual market growth, with an average projected value of 6.1 million tons produced in the year 2021 (European Bioplastics, nova-Institute). Figure 1 shows this rapidly growing global production in the bioplastic sector.

⁷ Mary Uselmann

Global production capacities of bioplastics



Source: European Bioplastics, Institute for Bioplastics and Biocomposites, nova-Institute (2014)
 More information: www.bio-based.eu/markets and www.downloads.ifbb-hannover.de

Figure 1. Global bioplastic production (European Bioplastics). Values for years 2012 and 2013 are documented amounts, while years 2014 through 2018 are projected figures.

This growth is due to the increased demand for sustainable products, especially in plastic packaging. Packaging currently makes up the largest sector of bio-based plastic products, followed by consumer goods and automotive products (European Bioplastics, nova-Institute).

Despite the promising bioplastic market, the issues associated with algal bioplastic production outweighed the potential gains for this project's processes and business model. One concern associated with bioplastics is the limited shelf-life due to their biodegradable characteristics, which compromises their functionality as packaging and many consumer goods and automotive products. This is one of several arenas in which petroleum-derived plastics continue to outperform bioplastics. Carbonation retention in beverage packaging and plastic consistency are two more challenges that algal-based bioplastics struggle with compared to petroleum-based plastics.

Another challenge associated with algal-based bioplastics is production cost. Bioplastics continue to be costlier to manufacture than petroleum-based plastics. With this manufacturing cost, selling prices must be raised accordingly, rendering bioplastics a less appealing option for customers and consumers. Oil prices must reach approximately 70 \$/barrel before costs associated with plastic production break even (Tides Center/Environmental Health Strategy

Center). With current oil prices approximately 50 \$/barrel, bioplastics remain costlier to manufacture and more difficult to market than petroleum-based plastics.⁸

4.3.3 Biofuels

Another direction is to use algae as a biomass is to use it for biofuels, such as biodiesel, bioethanol, bio-butanol and hydrogen fuel. Each of these products require many factors to be considered, such as the nature of the algae, constituents and byproducts, environmental conditions of cultivation, genetically modified organisms, growth optimization, extraction, and heterotrophic algae respiration and fermentation. There are different cultivation processes, reactors and culture techniques that can be used for biofuels.

Biofuels are advantageous because they can be produced from multiple types of algal strains that can be grown in a variety of locations. Additionally, wastewater can be used in the algal cultivation process, and the algae used can sequester carbon dioxide. The disadvantages of producing biofuels from current bio-based sources are the human health risks, such as infection and exposure to allergies, toxins, carcinogens, antibiotics, enzymes, chemicals, and acidic and caustic materials. Some of these hazards are associated with algae based biofuels, and are still being research as indicated in literature. There are environmental risks, especially from using genetically modified organisms that could potentially enter the environment. There is also the disadvantage that every company involved in biofuel research has adapted its own process and each process contains different risks.

Per Environmental Science and Technology Review, “the majority of commercial growth processes of algae use varieties of open ponds” (Menetrez, 2012). Such facilities are located at lower latitudes. This is advantageous because the temperature, climate, and solar radiance are favorable.

Solazyme is a current biofuel production company that uses a heterotrophic method to produce a lipid byproduct for biodiesel (Menetrez, 2012). This biodiesel is used for jet fuel and opened its first commercial plant in 2010. Another company that produces a lipid-like petroleum is Sapphire Energy. They use an open pond method with carbon dioxide injection. Exxon has given millions of dollars to Synthetic Genomics, Inc. for the research and development of lipid-like petroleum. Bioethanol is being produced from a GMO form of algae using autotrophic method by Algenol Biofuels. Cellana produces many products, one of which is biofuels from algae using a photo bioreactor and parallel raceway ponds in an autotrophic process. Heliae Development, LLC has used many algae strains for jet biofuels. These are a few companies from the 21st century that are using algae as a feedstock for third generation biofuels. This is not a new process, but an evolving process that is being researched and developed by many companies.

The price of biofuel depends on the cost of petroleum, especially the production of biodiesel. As the cost of petroleum fluctuates, so does the price of biofuels. Most of the research and industrial use information already available on algae as a feedstock depend solely on biodiesel. Even with

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the research already available, the costs are still an estimate. With the cost of biofuels being more expensive than traditional fuels and they are already widely researched, a different source of algal biomass utilization was considered.⁹

4.3.4 Fertilizer

Most commercial fertilizers are synthetically produced with petroleum, but fertilizers can also be produced organically with algae. This is an environmentally friendly option, but these algal fertilizers do not typically function as well as the synthetically produced fertilizers. The nutrient (primarily nitrogen) content is much more variable in organically produced fertilizers, causing inconsistent effectivity and questionable reliability. It does have the benefit of contributing to lower input farming systems, which would be helpful for those in developing countries (Hongyuan Wang, 2015), but the production of algal bio-fertilizers still is yet to be conducted on an industrial scale (Runfa Wang, 2015), making it a difficult choice for this project.

There have been successful advances in improving the plant-growing properties of algae-based fertilizers, but this research has been primarily on lab-scale experiments. In addition, many larger-scale tests have been conducted using a blend of algae-based fertilizer and commercial fertilizer, so algae have yet to be used on a large scale as a stand-alone fertilizer.

4.3.5 Food

Microalgae's role within the food industry stems from the fact that the algal lipids are tailorable for high end products. In the food industry, microalgae lipids are used commonly for nutrient-based supplements and substitutes. The lipids strains can be incorporated into nutrient-rich, highly specified products like baby formulas and supplements. These baby formulas are marketed as high value due to their dense nutrient content and their organic nature, a quality that entices many consumers. It is for these similar reasons that microalgae lipids are also marketable as oil substitutes for baked goods. The concoctions produced from algal lipids allow for a healthier, organic ingredient to include when baking. These lipids have been tested to successfully produce various products like muffins, rolls, and breads. (Microalgae to Feed and Fuel the World: Food, Pharmaceutical, and Cosmetic Producers Are Tapping a New Green Resource).

Based on the high value products generated from algae within the food industry, microalgae in this industry would be successful. On the market, algae-based food products sell at higher rates than biofuels, but are generally less valuable than cosmetics. Their averages on the market are around \$2,500 per metric ton (Wijfells). The higher end supplements with a large overlap to the pharmaceutical industry, such as omega-3 supplements, have selling prices upwards of \$1.1 million per metric ton (Wijfells), making them both highly specified and largely successful. The Algrithm chose not to pursue algae-based food products due to the sterility and specificity needed to produce high value, marketable foods and supplements.

⁹ Traci Reusser

4.3.6 Cosmetics

Algae has large potential within the cosmetics industry. Both macro- and microalgae can produce lipids that have rejuvenating abilities for the body. These lipids can be incorporated into cosmetic products that target skin and hair. Creams and masks made from algae have shown to have antiaging effects on the face. These products can increase longevity of skin, while also offering layers of protection to prevent damages like dry, cracking skin or sunburns. In addition to the skin-related products formed from microalgae, there are also algal applications for hair products. Similar to the skin protection, algae offer anti-breakage and strengthening formulas for hair treatment. (Hui-min Wang, 2015).

In addition to the traditional hair and skin cosmetics, microalgae also play a role in the crossover between the cosmetics industry and the medical field: bio-lubricants. Using microalgae lipids to create lubricants allows for non-toxic, effective products that carry large implications for the future of medicine. The bio-lubricants currently created and tested are designed for prosthetic limbs. These bio-lubricants effectively reduce the friction caused by movement of the prosthetic limbs, making them viable and sustainable options compared to the current lubricants used in the medical field.

The cosmetics industry does show promise where microalgae products are concerned. With high value products, microalgae have the ability to cater to wealthier consumers. In general, the microalgae products in the cosmetics industry have market prices ranging from \$6,500-\$35,000 per metric ton (Wijfells). These prices are much larger than those of other algal products, due to specificity of the industry. Rather than pursue the production of these high-end products the Algrithm opted for the more widely applied product of bio-surfactants. Bio-surfactants do have a place in the cosmetics industry, however, as they are necessary ingredients for hand soaps and shampoos. This market choice allows the Algrithm to remain involved in the successful cosmetic industry without committing to producing specialized, high end products.¹⁰

4.4 Final Product

Bio-surfactants are surface-active agents made up of organic molecules that are amphiphilic, with both hydrophobic and hydrophilic groups (Paniagua-Michel, 2014). Surfactants are used in various products, such as soaps, detergents, emulsifiers, wetting agents and even foods.

Advantages of using algae-based bio-surfactants versus traditional petroleum surfactants are their biodegradable and eco-friendly qualities, as well as the absence of toxicity. Current bio-based surfactants are made from soybean, linseed, canola, sunflower, and rubberseed oils (Pleissner, 2014). By using algal biomass under heterotrophic or autotrophic conditions it would not only enable the formation of bio-based chemicals but reduce the use of food-based biomass. Algae-based bio-surfactants are biodegradable and do not accumulate in the environment which contributes to an eco-friendly product.

¹⁰ Katie Hopfensperger

Like any bio-based product and the alternative products the Algrithm considered, the market of bio-surfactants follows the trend of the petroleum market. However, bio-surfactants are a commodity and the desire for green products is ever increasing. Bio-surfactants will replace traditional petroleum based surfactants in the production of many everyday products increasing its viability.

The general process for the bio-surfactants, developed by Pleissner in “Plasticizer and Surfactant Formation from Food-Waste and Algal Biomass-Derived Lipids”, is shown in Figure 2. The algal biomass production shown here will require nutrients which can come from the food-waste hydrolysate and/or wastewater. The lipids from the algal biomass are extracted and undergo transesterification and epoxidation until the fatty acid methyl esters are formed, then, with glycerol, they produce bio-surfactants. This process is assuming the use of a fermenter under heterotrophic conditions. Heterotrophic conditions require an energy source versus an autotrophic process which requires sunlight. The energy source used in many lab-scale reactions is glucose, which is the feed source used along with food waste hydrolysate for their reaction.

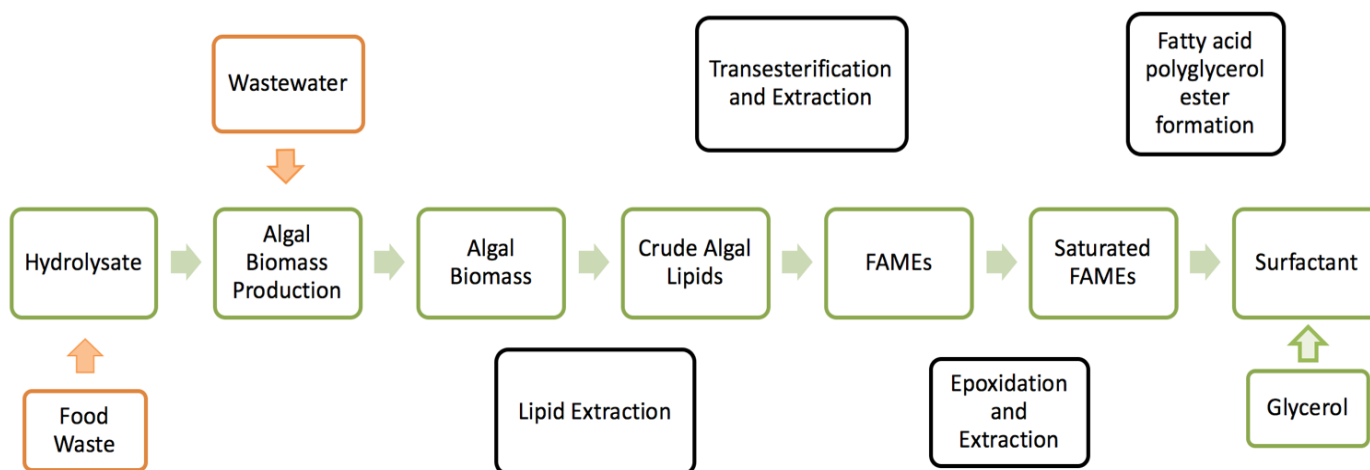


Figure 2. Bio-surfactant production from algal biomass with intermediate steps and considerations.

The chemical reaction mechanism for bio-surfactants produced from algal biomass is shown in Figure 3 (Pleissner, 2014). This process was developed by Pleissner and aspects of this process were adapted by the Algrithm. This process shows the algal biomass in a fermenter and in batch cultures with glucose, nitrogen, and phosphate at a temperature of 28°C and a pH of 6.5. The extraction of the crude algal lipids was performed using a continuous flow of carbon dioxide at 90°C and 450 bar for 1 hour. The lipids extracted were transesterified with methanol at 90°C to form fatty acid methyl esters (FAMES). The double bonds of the unsaturated FAMES were epoxidized. The unsaturated FAMES after epoxidation can be used to produce plasticizers which are used to improve flexibility and stability of polymers. The reaction was conducted at 60°C and was completed within 5 hours. Although plasticizers are not the main product they may be beneficial as an additional side product. The epoxidized and saturated FAMES then undergo transesterification with polyglycerol to form different FAMES that produce surfactants. The

polyglycerol was prepared in a side reaction by heating glycerol in the presence of NaOH for 2 hours at 140°C. The transesterification process was conducted at 70°C in a 1:1 (w/w) of FAMES mixture-to-polyglycerol and was performed for approximately 24 hours, after which no saturated and epoxidized FAMES were unreacted.

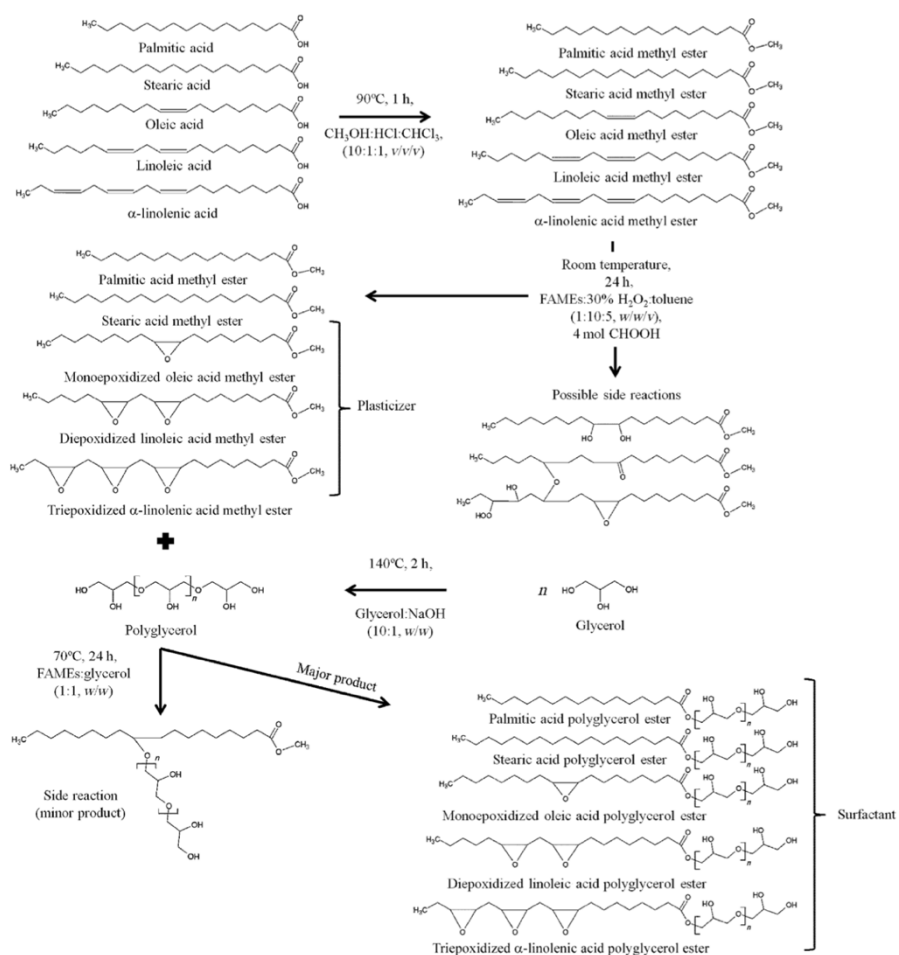


Figure 3. Schematic of bio-surfactant reaction mechanism. Methylation of the fatty acids from lipid extraction, epoxidation of unsaturated FAMES, and transesterification of saturated FAMES with polyglycerol (Pleissner, 2014).

This specific reaction has been produced on a lab scale using food-waste and lipid-rich solids. Research presented in “Plasticizer and Surfactant Formation from Food-Waste and Algal Biomass-Derived Lipids” indicates a possible side reaction after the methylation of the saturated and unsaturated FAMES (Pleissner, 2014). During epoxidation, the possible side reactions of hydroxylation, oxidation, oxygenation, and dimer formation can result in an unidentified side product. These could be attributed to either the chemicals H_2O_2 and acetic or octanic acid used during the epoxidation of the unsaturated FAMES or the reaction specifications, such as temperature and reaction time. Current research indicated that there were no hydroxyl groups present other than an unknown product. These side reactions and products are inconsistent with research and require further investigation to determine reaction specifications.

The final formation of bio-surfactants from a saturated and epoxidized FAMES mixture to polyglycerol also indicated possible side products. This reaction may require further chemical modifications to improve the quality of the bio-surfactants produced (Pleissner, 2014). This research indicated that the bio-surfactants produced could be used in shampoo and textile applications but there is further investigation needed to determine the exact properties and uses of the final product.

This reaction used food-waste lipids and feedstock to produce bio-surfactants. The mass balance for the food-waste and algal lipids is shown in Figure 4. The food-waste hydrolysate was generated by hydrolysis of carbohydrates and proteins using enzymes from fungus (Pleissner, 2014). The lipid-rich hydrolysis was separated from the hydrolysate and used as an alternative reaction, shown on the right side of Figure 4. The hydrolysate that was separated out from the lipid rich hydrolysis and the hydrolysate was used as a feedstock for the algal biomass production. This is an alternative approach to the wastewater nutrient source but could be used as an additional nutrient source to promote an environmentally and sustainable product.

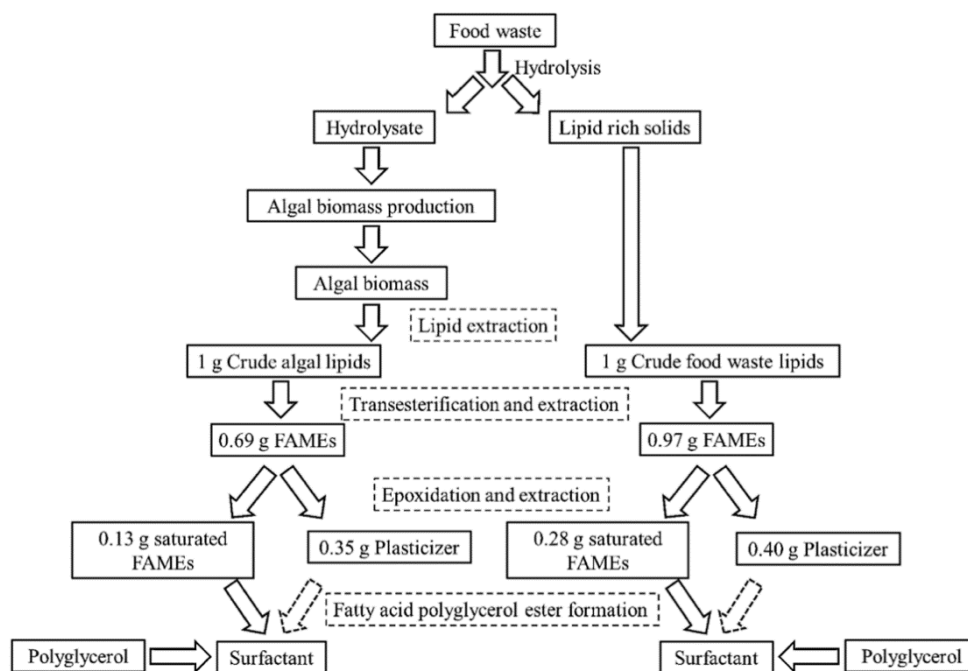


Figure 4. Lab scale mass balance of bio-surfactants from algal biomass (Pleissner, 2014).

The Algalrithm's process was based off of the process of algae to surfactants above with changes to meet the specifications and conditions of an industrial scale process. For the Algalrithm's process, algal biomass will be produced by cultivating algae with CO₂ and nutrients obtained from a wastewater source. The cultivation process will take place in a photobioreactor and will produce oxygen from the photosynthesis reaction occurring during the biomass production. The algal lipids will be extracted using a similar method as described in Figure's 2 and 3. First, the crude algal lipids will undergo transesterification with dichloromethane rather than chloroform. This change was made to avoid using chloroform as a solvent due to the hazards of chloroform and to reduce costs. The side reactions shown above may not be present in the scale up version of this process. In Pleissner's research, the side products varied from trial to trial and without

testing this process on a lab scale using the changes that the Algalrithm has implemented, the side reactions are unknown. For this process, they have been omitted, and it is assumed that during the process of algal lipids to bio-surfactants, all the lipids will form FAMES that will make up the composition of surfactants.¹¹

5. Base Case Description

5.1 Basics and Overall Design

The biomass process will begin with algae cultivation in photobioreactors (PBR). Carbon dioxide and wastewater (for nutrient purposes) will be fed to the PBRs with the initial algae batch. The algae will undergo photosynthesis to produce algal biomass and oxygen (O₂). The O₂ and excess CO₂ will be separated from the liquid biomass stream and vented to a gas phase separator. The CO₂ will be recycled back to the PBR to be used for cultivating algae. The liquid biomass will be sent to a press where the lipids will be extracted. The liquid slurry left after lipids are extracted is sent to a separator where water is removed and the algae cake is sold as a soil amendment side product. The lipids will be separated from the left over water that is present after pressing. Once water is removed, the pure lipids would then be sent to a series of reactors to undergo conversion to bio-surfactants.

The pure lipid stream will be sent into an esterification reactor. The ensuing reaction will convert the fatty acids into FAMES. Any unreacted reactant will be recycled or separated from the main product, and the FAMES will be sent into the second reactor to undergo epoxidation. Hydrogen peroxide and toluene will also be inserted to facilitate the epoxidation of the FAMES. After any side products and unreacted components have been removed, the epoxidized FAMES will undergo an addition reaction with polyglycerol in the third reactor. This is the final step in the reaction process, and will produce epoxidized fatty acid polyglycerol esters, which make up bio-surfactants.

Although part I of this process (algae to raw lipids) is modeled below, there are several aspects of the process that do not meet the realm of the Algalrithm's project and would need further consideration before implementation. These issues and concerns have been addressed within this section and in future work.

5.2 Chemistry and Separations

The chemistry of the final process had to be broken down into separate molecules in order to model the process in Aspen+. The chemistry of photosynthesis is important for this process, and is depicted in the photobioreactor (PBR). The inputs into the PBR consist of CO₂, wastewater, and algae. The most important source of energy for the reaction is sunlight, which couldn't be modeled in Aspen+. The reaction inside the PBR is described below in Equation 1:



¹¹ Traci Reusser

We modeled our Algae as “biomass” which consists of a ratio of carbon, nitrogen, oxygen, sulfur, phosphorus, and hydrogen, and we modeled the carbon chain after similar molecular structures of biomass found in literature (Davis, 2014).

The wavelengths of photons from the sun excite electrons and drive the reaction and growth of the microorganisms. CO₂ consumption is proportional to the microalgal growth rate, and carbon will make up about half of the dried algae biomass produced. The design approach of the PBR relies heavily on the hydrodynamic design that determines liquid circulation velocity in a continuous loop and gas separation in an airlift system – this means the CO₂ needs to be “bubbled in” to the PBR, causing constant movement of microorganisms, promoting their growth and exposure to sunlight (Espen, 2002). A picture of a large scale photobioreactor is shown below in Figure 5.



Figure 5. An industrial size photobioreactor

The pH of the algae is extremely important to its growth as well. The chemical equilibria between inorganic carbon and the protons in water create a naturally buffering pH system inside the PBR. The algae should be maintained around a 7.0-8.1 pH range in order to provide optimal growth in a sterile environment. The bicarbonate ion, HCO⁻³, helps to maintain the system at a slightly basic pH. The reaction is described as follows:



In the light, algae perform photosynthetic carbon fixation, and the reaction shifts towards the left, and the pH increases. Conversely, algae perform respiration reactions in the dark, which produces CO₂, which shifts the reaction to the right, increasing the hydrogen protons and reducing the pH. In order to keep the pH constant and avoid intense pH shifts, CO₂ can be effectively resupplied when needed to control the pH. Alternatively, a small amount of acid could be supplied in the light reactions, and a base could be added during the dark reactions

(Espen, 2002). An innocent alkaline molecule typically added to water systems to raise pH is HCO^{-3} (Davis, 2014).

The flash drums, compressor and lipid separator column serve a similar purpose; to separate constituents in order to obtain a more pure, desirable product. The H_2O flash drum operates at approximately 200°C , which is plenty of heat to boil off the water, yet not harm the algae microorganisms (Oakey, 2017). The bottoms of this flash drum consist of practically pure biomass byproduct, which is a valuable and important source of revenue for the Algalrithm plant, as it can be sold as a soil amendment. The final flash drum, which gives the sellable lipid product operates at 200°C . Again, the lipid bottoms are dried and excess water containing nutrients is flashed off and recycled back as a wastewater stream into the PBR.

The oil press unit operation operates in Aspen+ as a compressor. By inputting a split fraction, the amount of lipids can be specified that will be produced from the total algae biomass, which is approximately 31% according to literature values. Once inputting that specification, Aspen+ modeled the compressor with a low heat duty of 25 BTU/hr to compress and squeeze the algae, which will separate the proteins and carbohydrates in the microorganisms. The heat duty needed may increase for a real world process, but for one compressor treating the amount of biomass specified in the model, this is the heat duty Aspen+ calculated. This operates the same way that an oil press does, and different strengths or types of compressors (such as piston, expellers, or screw configurations) could separate more or less lipid from the remaining biomass. For this particular strain of chlorella, the compressor will mechanically crush the algae to get an average of 31% original biomass as lipid surfactant (Davis, 2014). A picture of the algae lipid press is shown below in Figure 6.



Figure 6. Example of a mechanical algae press for lipid extraction

The unit operation reactor that models the lipid separation simulates the conversion of total biomass to lipid that happened during the compressor. Because the compressor doesn't allow the inclusion of a chemical conversion specification, this reactor was included to model the transformation of the original biomass to the final lipid product, which, in a real life process,

would separate naturally during the compressor. The separating reactor is essentially another way to model the oil crushing mechanics, where the energy dense lipids are separated from other excess components in algae.¹²

5.3 Assumptions and Approximations

The plant will encompass ten 1,000 m³ photobioreactors, estimating to be about 70% of our total fixed capital equipment cost. Approximately another 15% will encompass other equipment, including a compressor, dryer, and separators (Peters and Timmerhaus, 1991). The last 15% will account for installment and delivery factors, cost of land, and other technical aspects of the plant not currently accounted for (Myers, 2016).

Microalgae are characterized by potentially fast growth with the ability of high carbon fixation rates. One gram of microalgae will be able to sequester two grams of CO₂, and will grow at an average rate of 2 g/L*day. After the algae has been processed, dried, and compressed, approximately 31% of the original algal biomass will be extracted as sellable lipid product (Klassen, 2015). The other 69% will be a dried compressed algae cake comprised of proteins and carbohydrates, which will be sold as soil amendment. This produces an overall rate of production at 475 lb_m/hr of bio-surfactant ready to be sold. Assuming an 8000 hr/yr of total plant operation time, a yearly production rate of 3.8 MMlb_m/yr of surfactant will be produced. If our surfactant is sold at 98 c/lb_m, then a yearly revenue is estimated to be \$13.41 million.

Estimated costs of start-up materials needed for the plant consists of the one-time algae purchase, the plant construction costs, and the original cost of the land, which has been estimated in the start-up costs. Other materials initially needed for the plant include wastewater and CO₂, which we've assumed to be free, since we'll be obtaining wastewater from an agricultural wastewater treatment plant, and the CO₂ will be collected from an industrial source. Other variable costs include energy inputs such as electricity and steam, estimated to cost 4 c/kW and 900 c/Mlb_m respectively. Labor costs are assumed at four workers per shift, working for \$40/hr at 8000 hr/yr. Maintenance costs are estimated at 6% our total FCI, approximating a yearly expense cost of \$0.7 million (Myers, 2016).

In the Aspen+ modeled process, the photobioreactor is modeled as a single reactor for simplicity, but in reality, the system will consist of about 10 photobioreactors, which can be cycled through during the year, emptying them of algae and restarting the process in each of them again. The flash drum labeled CO2VAP is typically part of the photobioreactors in the real world, separating the CO₂ produced from the photosynthetic algae, and recycling it back through the process again. Photosynthesis is difficult to model in Aspen+, so the two processes are separated in order to depict an accurate reaction and separation that would occur. The rest of the plant is modeled the same as it would be in the real world. The heat duty, and mass flow rates have been

¹² Mary Uselmann

used to estimate the size of each unit operation, and therefore estimate the cost of each unit operation to predict the cost of the entire plant.

Startup costs and working capital are estimated as 10% and 20% the total installed FCI, respectively (Myers, 2016). Startup costs will include the purchase of algae the first year of production, which is estimated to be a one-time purchase.

Revenue from a carbon tax has not yet been included in the production cost analysis of the plant. Accurate theoretical values haven't been finalized yet. Once more research is performed, appropriate numbers will be included, and the annual revenue for the plant will increase. This will allow the surfactant to be sold at a cheaper, more marketable price, which will make the Algrithm's plant more profitable and competitive with the current bio-surfactant market.

5.4 Solution Procedure

The first step to developing a solution to the stated design problem was to analyze the potential end-products that could be produced from the algal biomass.

Once these products had been extensively investigated, and the most economically viable had been selected, cultivation systems were examined. Fermenters, open pond systems, and photobioreactors were compared and contrasted as potential cultivation systems. Fermenters originally emerged as an attractive option, since they had been used as large-scale algae production systems in some literature cases. However, after initial modeling, the CO₂ emissions associated with the glucose reaction in fermenters were revealed to be too great to confidently label the Algrithm as a carbon negative system. From this point, photobioreactors were selected as the next most economical and practical solution, since they allowed much greater product purity than open pond systems.¹³

The next step in developing the system was to model the system as a photobioreactor system, and to develop Aspen+ unit operations to represent more complicated processes such as photosynthesis and cell lysing. The comparison of different ways to extract the lipids from the algae biomass was researched, and it was decided that a mechanical press was the most environmental friendly and profitable choice. No chemicals need to be purchased, and no toxins need to be removed from our algal biomass before the final product is generated.

Finally, an economic analysis was conducted to ensure viability of the process and business model. This analysis involved multiple economic assumptions and a cash flow and cost production estimate report. Figure 7 shows the solution procedure used.

¹³ Mary Uselmann

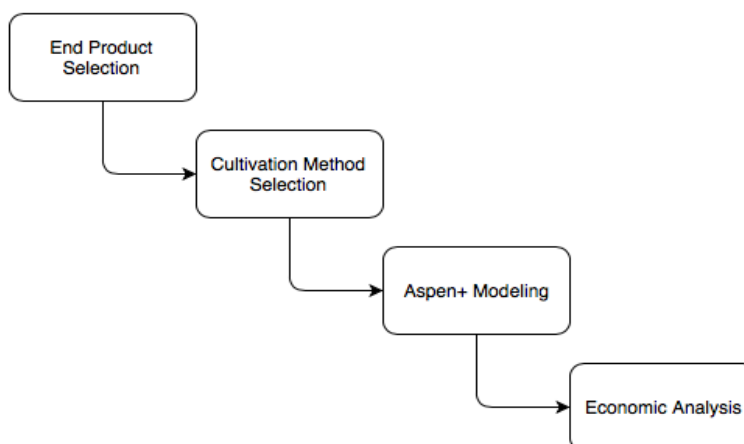


Figure 7. Method for solution procedure.

There will be more steps to take in order to finalize the Algrithm's processes and business projections, but the technique of using iterative, investigative problem solving will continue throughout the remainder of the project.¹⁴

5.5 Flowsheet

5.5.1 Algae Cultivation and Lipid Isolation

The algal lipid production process, Part I, is shown in Figure 8. Aspects of this design were simplified from the actual process to be able to model solid biomass production; and as mentioned, the model does not accurately represent the final product and purity nor the entire process. However, it is a preliminary process that has been modeled to the best of the Algrithm's capabilities of Aspen+ modeling for algal biomass systems. Due to Aspen+ and its inability to model photosynthesis, algal biomass and lipids, many aspects had to be simplified in order to model "biomass" in this process. This posed several issues because the actual make up of algal biomass had to be estimated using basic chemical components, and therefore could not accurately be separated in the system as it would in a real process. This would affect the yield of the final product of raw algal lipids. The purity of this system is also unknown due to the changes in the lab scale model process that had to be made to meet the specifications of this process. Without lab or pilot plant testing of this actual process, the actual yield and purity of the raw algal lipids in Part I is unknown.

Algae was modeled as a solid as an estimated component basis of N-Decane. N-Decane was chosen for its properties, but the components were adjusted to model a general algae species. In the future, the component break down of autotrophic chlorella algae will be modeled (Endo). The major components, carbon, nitrogen, hydrogen, oxygen, sulfur, and phosphorus, were used to make up algae in Aspen+ since algae is not a component that Aspen+ supports.

¹⁴ Catherine Brame

The inlet streams in the first part of the system consist of wastewater, carbon dioxide, and raw algae. Wastewater is used as the nutrient source for algae cultivation. In the actual process, a filter would be used to remove suspended solids from the wastewater before addition to the photobioreactor. Nutrients from the wastewater, nitrogen, phosphorus, and sulfur, are modeled as nitrogen gas, atomic sulfur and phosphoric acid in the wastewater stream, WW. Wastewater will enter the PBR with a flow of 500 lb/hr at 25C and 14.7 psia. The CO₂ stream will be sequestered from a nearby plant that produces CO₂. The CO₂ stream will be at 32C, 1200 psia at a mass flow of 2000 lb/hr. An initial algae batch, RAWALGAE, will be used to start the algae cultivation process. The algae inlet stream will be at a flow rate of 1000 lb/hr at 25C and 14.7 psia.

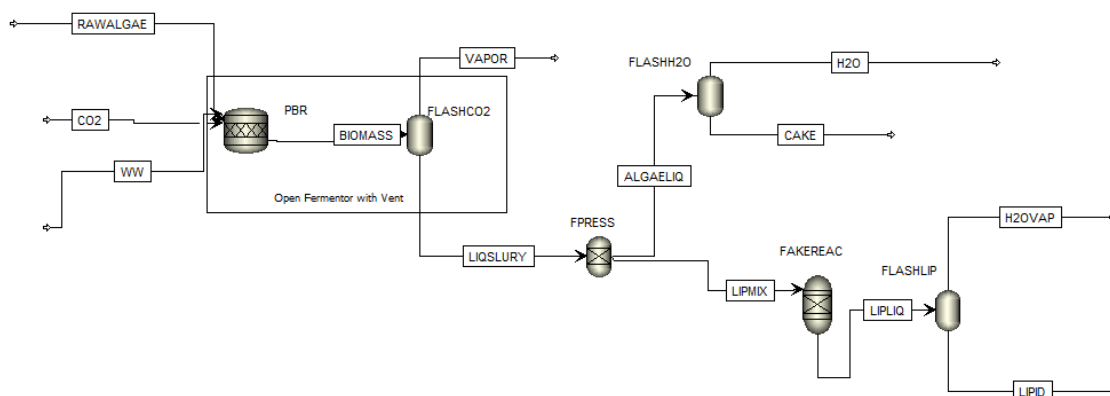


Figure 8. Aspen+ flowsheet diagram for Part I of bio-surfactant process, algae to lipids.

The cultivation process takes place in the photobioreactor. The photobioreactor, PBR, is shown attached with the separator, FLASHCO₂, to simulate a photobioreactor with a vent. This type of unit operation is not available in Aspen+, but can be modeled separately. An inlet mass flow was specified of 1,000 lb/hr of RAWALGAE, 500 lb/hr of WW, and 2,000 lb/hr CO₂ streams into the photobioreactor, PBR. The conditions of the PBR are shown in Table 2. Algae cultivation takes place in the PBR at atmospheric pressure. The photobioreactor is modeled as an RSTOIC reactor to be able to react algae to biomass. The reaction modeled is shown in Equation 1. Nitrogen, sulfur, and phosphoric acid are components of the RAWALGAE and WW stream. In the reaction it is assumed 85% conversion of CO₂.

Table 2. Photobioreactor conditions for algae cultivation process.

Outlet Temperature (F)	98.6
Outlet Pressure (psia)	14.7
Heat Duty (Btu/hr)	2305829.46
Net Heat Duty (Btu/hr)	2305829.46
Vapor Fraction	0.97

Once optimal growth has been reached, the algae biomass stream is sent to a separator, FLASHCO₂, where unreacted CO₂ and O₂ that was produced during photosynthesis is removed from the algal biomass stream, BIOMASS. This separator is a part of the photobioreactor that would be modeled in an actual system. The duty is specified as 0 Btu/hr and atmospheric pressure to remove H₂O and CO₂ vapor. Conditions for each of the separation units is shown in Table 3.

Table 3. Separator conditions for FLASHCO₂, FLASHH₂O, and FLASHLIP.

	FLASHCO₂	FLASHH₂O	FLASHLIP
Outlet Temperature (F)	98.6	392	392
Outlet Pressure (psia)	14.7	14.7	14.7
Heat Duty (Btu/hr)	0	157000.186	161397.493
Net Heat Duty (Btu/hr)	0	157000.186	161397.493
Vapor Fraction	0.97	0.61	0.99

After CO₂ and O₂ have been removed, the algae slurry, LIQSLURY, is sent to an oil press, FPRESS, to remove lipids from the algae biomass. Only 31% of the algae biomass is converted to lipids (Endo). The rest of the biomass, ALGAELIQ, is further treated.

The algae liquid, ALGAELIQ, is sent to a separator to remove excess water and the algae cake left over will be sold as a byproduct. The byproduct is a soil amendment so further treatment of the algae cake will not be required as it would if it were to be used as animal feed. The removed water stream, H₂O, is a waste vapor stream. This process differs from the original preliminary process which used hexane to extract the algae cake. Hexane extraction was not used because it would require further treatment of the final product downstream and either recycling and/or disposal of the hexane after removal. Removal of hexane and disposing is a costly process and would require permitting to be discharging/removing and disposal of hexane from our system. Recycling would be the more viable option, however, the issue of still removing hexane downstream from the final product is costly itself and therefore this method was not chosen because of this. This also eliminates the evaporation unit to remove excess hexane from the pure lipid stream. Removing hexane from this process not only simplifies the process flow, but also removes any potential for having trace hexane in the lipid product that would be an impurity. Although hexane is not toxic, it poses other risks such as flammability if the concentrations are to be too high. For this process, large quantities of hexane would need to be used for the extraction process and would pose hazards to the system and workers due to its flammability. The cleanliness of our lipid stream is important so further treatment is not required after the lipids have been converted into bio-surfactants.

The lipid stream after the press, LIPMIX, is sent to a “fake” reactor, FAKEREAC, to change the solid algae biomass that was pressed to lipids into a liquid which best represents the lipid mix.

The FAKEREAC is specified as the same conditions of the press which is at 37C and 14.6 psia. After the solid to liquid conversion, the liquid lipids, LIPLIQ, is sent to a separator to remove excess water. The FLASHLIP is at 200C and 14.7 psia so that only water is removed from the liquid lipid mixture. This process is currently showing that nearly the entire LIPLIQ stream is vented from the separator. Before modeling the LIPMIX stream as a liquid stream rather than a solid stream, a flash unit was used to separate the water from the solid-liquid stream. In this process, only water was removed in the FLASHLIP as a vapor and the solid was all in the LIPID stream. Modeling the LIPMIX as a liquid stream rather than a solid stream has posed issues with using a separator. The Algalrithm has considered using a distillation tower rather than a separator in order to accurately separate the water liquid and lipid liquid streams, however, a flash tank should work due to the difference in boiling points of the lipids and water. The major issue is the modeling of the lipids in Aspen +, in which, the lipid stream does not completely depict actual lipids and therefore is resembling water more than it is lipids. This is a possible explanation as to why the lipids are being removed with water.

The final lipid stream will be sent to Part II of the bio-surfactant process, lipids to bio-surfactants. Currently, the lipid stream is showing very low amounts of lipids actually leaving the lipid stream and therefore is inaccurate. The actual stream would contain a much higher percentage of lipids that would proceed to Part II.

The stream results for Part I streams is shown in Table 4. Currently, this process shows that nearly all the lipids is vented in the FLASHLIP stream, meaning there is now lipid product. This is being assessed and a solution will be determined in the future. In liquid slurry, LIQSLURY, 1,534 lb/hr of biomass is produced after algae cultivation. We are carbon negative, producing 1,843 lb/hr of CO₂, which is less than the input at 2,000 lb/hr. The current process does not reflect oxygen production from the photosynthesis reaction. This is an issue because modeling photosynthesis in Aspen+ is not a common practice, the actual process requires sunlight and will produce oxygen that will be removed from the system. The Algalrithm is considering this process and different modeling aspects. All biomass enters the FPRESS and separation of the lipids and solid biomass occurs. There was 31% lipids pressed from the biomass, a flow of 1,058 lb/hr entered the ALGAELIQ stream and 475 lb/hr entered the LIPMIX stream. This stream was sent to the FAKEREAC where 100% of the LIPMIX solid is changed to liquid to represent actual lipids in the LIPLIQ stream. The LIPLIQ stream that enters the last separator, FLASHLIP, should only have water removed from the lipids, however, currently this is not the case. The current process shows that only 1.72 lb/hr of lipids is produced and that 474 lb/hr is vented as water vapor. This value is not reflective of the actual process. Approximately 31% of the biomass should be converted to lipids and only water should be removed in the last flash unit.

Table 4. Stream results in lb/hr for each unit operation in Part 1 of the algae to bio-surfactant.

	PBR			
Stream Results	ALGAE	CO2	WW	RAWALGAE

Mass Flows (lb/hr)	1000	2000	500	3499.991
NITROGEN	0	0	72.161	40.410
OXYGEN	0	0	0	0
SULFUR	0	0	82.600	0
H3PO4	0	0	252.428	15.146
WATER	0	0	92.812	66.828
GLUCOSE	0	0	0	0
CO2	0	2000	0	1843.151
BIOMASS	1000	0	0	1534.457
LIPID	0	0	0	0

Table 4. Stream results in lb/hr for each unit operation in Part 1 of the algae to bio-surfactant, continued.

	FLASHCO2			FPRESS		
Stream Results	RAWALGAE	CO2VAP	LIQSLURRY	LIQSLURRY	ALGAELIQ	LIPMIX
Mass Flows	3499.991	1926.950	1573.041	1573.041	1076.812	496.229
NITROGEN	40.410	40.408	0.0021	0.0021	0.0019	0.0002
OXYGEN	0	0	0	0	0	0
SULFUR	0	0	0	0	0	0
H3PO4	15.146	0.000	15.146	15.146	13.631	1.515
WATER	66.828	44.808	22.020	22.020	4.404	17.616
GLUCOSE	0	0	0	0	0	0
CO2	1843.151	1841.735	1.417	1.417	0.000	1.417
BIOMASS	1534.457	0.000	1534.457	1534.457	1058.775	475.682
LIPID	0	0	0	0	0	0

Table 4. Stream results in lb/hr for each unit operation in Part 1 of the algae to bio-surfactant, continued.

Stream Results	FLASHH2O			FAKEREAC		FLASHLIP		
	ALGAELIQ	CAKE	H2O	LIPMIX	LIPLIQ	LIPMIX	H2OVAP	LIPID
Mass Flows	1076.812	1072.593	4.219	496.229	496.229	496.229	492.987	3.242
NITROGEN	0.00193	2.87E-07	0.0019	0.0002	0.0002	0.0002	0.0002	3.29E-10
OXYGEN	0	0	0	0	0	0	0	0
SULFUR	0	0	0	0	0	0	0	0
H3PO4	13.631	13.631	3.20E-78	1.5146	1.5146	1.5146	3.61E-77	1.5146
WATER	4.404	0.187	4.217	17.616	17.616	17.616	17.608	0.008
GLUCOSE	0	0	0	0	0	0	0	0
CO2	0	0	0	1.417	1.417	1.417	1.417	9.26E-05
BIOMASS	1058.775	1058.775	0	475.682	0	475.682	0	0
LIPID	0	0	0	0	475.682	0	473.962	1.719

*Full stream tables can be found in the appendix.

As mentioned above, this process does not accurately represent the final yield and purity of the raw algal lipids that will be processed in Part II. The algal biomass is represented as chemical components and because of this, the actual properties of algal biomass and lipids are not properly represented. Since the properties are not accurately represented in Aspen+, the separation method of the water and algal lipids needs to be re-assessed in future work, as mentioned before, to obtain a better representation of the final algal lipids leaving Part I.¹⁵

5.5.2 Lipids to Bio-surfactants

The microalgae lipids that are separated and functional at the end of Part I of the biomass procedure move into Part II, as seen in Figure 9. The unit operations seen below represent preliminary methods for the fatty acid mixtures throughout the process. Each step in the procedure corresponds to a vital step within the reaction coordinate. Many of the exact unit operations will be tailored further during future work to accurately depict the reaction requirements in terms of both conditions and systems.

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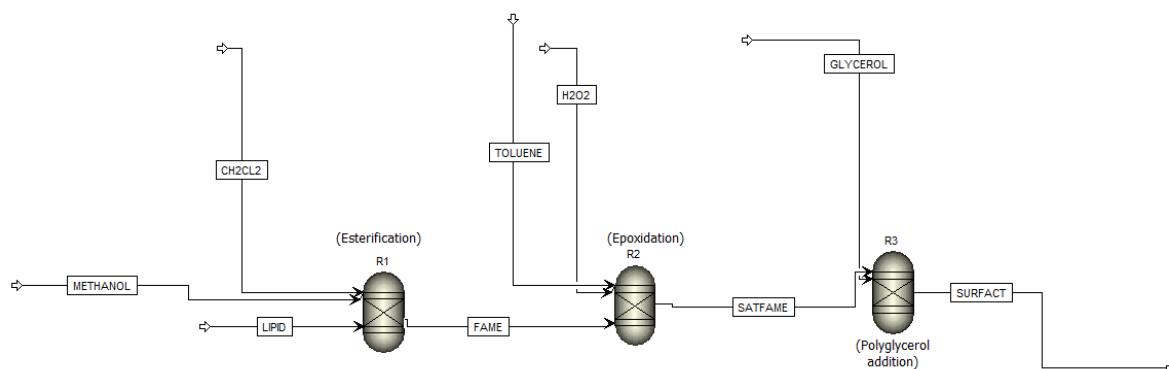


Figure 9. Preliminary Aspen+ flowsheet diagram for Part II of biomass process.

Part II of the biomass process begins with the pure lipids and pure dichloromethane entering a reactor, R1, modeled as a stoichiometric reactor. This reactor is the first substantial reaction of the conversion process: the esterification. The reaction between the methanol and the lipids produces FAMES; this reaction requires dichloromethane as a solvent in order to maintain conversion of lipids. If this esterification process results in unreacted reactant or undesired product, which is an unlikely possibility for the FAMES mixture desired, a separator unit can be included into the process design. This separator would remove the side-product before the mixture moves into the next reaction step.

The pure FAMES mixture coming from either R1 in Figure 5 or a separator unit following R1 will be sent to R2 for epoxidation. The epoxidation reaction requires an inlet feed of hydrogen peroxide; toluene will also be needed as a solvent to facilitate this step. Due to the possible variance in the FAME stream, the precise conditions of the hydrogen peroxide and toluene streams have not yet been determined. These conditions include, but are not limited to, mass or mole ratios to each other and to the FAMES, temperature, pressure, and the order in which they must be added to the mixture.

After the FAMES have undergone epoxidation, they will leave R2 as plasticizers, a potentially valuable byproduct the Algorithm could choose to pursue. This SATFAME stream product which will likely require a separator unit to isolate the plasticizers, should the Algorithm pursue plasticizers as a by-product. This separator unit would separate the saturated fames from the remaining undesired product by using their chemical and physical property differences. This process, much like the other mentioned, is entirely dependent on the conditions of the system and how much conversion each step of the reaction process can obtain.

The SATFAME (saturated FAMES) stream from the epoxidation reactor, R2, will then move into R3 to undergo polyglycerol addition. This addition step requires a polyglycerol stream, shown as GLYCEROL, to react with the plasticizers. The conditions of this reaction have not been determined, but the reaction could also result in a minor side product and the major product: bio-surfactants. The occurrence of a side product is unlikely due to the purity of this system, but should a minor product occur, another separator unit would be included following R3. This

separator unit, much like the other potential separator units in Part II of the design, will have operating conditions necessary to remove any excess side product. These conditions have not yet been determined, as the Algorithm is not anticipating side products for any of the three reactions in the processing of lipids to bio-surfactants. At this point in the process, following either R3 or a potential separator, the surfactant will be tested for purity. With the surfactant meeting purity standards, it will then be ready for either movement to manufacturing companies or alterations for specific products, a business decision which has yet to be determined.

Many of the conditions and unit operations of the biomass process turning microalgae into bio-surfactants are still up for consideration. As the Algorithm gathers more information from experts in the field, the current process will be updated to a detailed and conclusive process design flowsheet for both Part I and Part II of the biomass conversion.¹⁶

5.6 Base Case Discussion

It proved problematic and difficult to properly design and model our system in Aspen+. Designing a photosynthetic system, and inputting specifications of plant matter, molecular biomass make-up, and lipid extraction are not simple to model, and required a lot of knowledge in order to get the Aspen+ file to run properly.

In order to solve the problems posed by the program, the input streams had to be designed manually. The wastewater stream has molar specifications of phosphorus, nitrogen, and sulfur in order to model a real world wastewater stream that contained these trace nutrients necessary for algae to grow. The biomass constituent was modeled after biological make-ups of algae in literature.

Some of the unit operations had to be modeled differently in Aspen+ than they would actually be built in the real world process. In Aspen+, the photobioreactor and carbon dioxide flask tank are modeled as two separate processes. The photobioreactor in Aspen+ only allowed us to put in a reaction specification, but didn't allow the simultaneous separation of carbon dioxide given off from the photosynthetic algae. Therefore, it's modeled as two separate processes, when in the real world, the carbon dioxide and photobioreactor would be built and assembled together to create one unit operation.

Although it was difficult to model the Algorithm's plant in Aspen+, the final results are representative of the actual process and shouldn't be discarded.¹⁷

6. Design Alternatives

6.1 Cultivation Method

Three different cultivation methods comprise the majority of algal growth systems in industry. Differences in their location, regulation requirements, and necessary feeds determine which

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method is preferable in a given plant. Open air pond systems require the least regulation, while photobioreactors and fermentation tanks require more. However, with this increased regulation comes increased control of product composition and purity, as well as a more sterile growth process.

Open air pond systems can be in the form of natural bodies of water or manufactured shallow ponds/tanks, and are likely the most common system in commercial use today (Borowitzka, 1998). Algae is cultivated in a natural manner; the pool must simply be seeded with a strain of algae and then left to self-reproduce and grow given the naturally occurring resources in the environment. This method utilizes sunlight as the energy source for algae cultivation, and CO₂ as the source of carbon. The lack of purchased resources required for the process greatly reduces its cost. On the other hand, pond systems left open to the air are also more prone to collect debris and other matter in the water, which necessitates an additional filtration process.

Fermentation tanks (fermenters) are enclosed systems, and do not require large surface areas. Rather than capturing sunlight, fermenters use a heterotrophic cultivation process, and provide energy through sugars. A fermenter, like a photobioreactor, can be set to operate at a specific temperature, pH, etc. Fermenters have been widely used in various processes and are well understood. They can also produce algae of relatively high cell density, meaning they do not need to be as large as other cultivation tanks (Borowitzka, 1998). This decreases their capital cost as well as the cost of harvesting the algae. They are innately protected from outside factors that dictate the efficiency of other methods so greatly.

Fermenters were examined extensively as a design alternative. The ability to better control purity—as compared to an open pond system—and to decrease costs—as compared to photobioreactor systems—made fermenters an attractive early option for algae cultivation. However, after the fermenter system had been modeled using Aspen+, the issue of CO₂ generation became a clear roadblock. In a fermenter system, glucose must be added to the fermenter as an energy source in lieu of sunlight. Each mole of glucose then undergoes alcoholic fermentation, to produce two moles of ethanol and two moles of carbon dioxide, as shown in Figure 10.



Figure 10. Alcoholic fermentation reaction converting one mole of glucose into two moles of ethanol and two moles of carbon dioxide.

After analyzing the fermenter results of algae growth using Aspen+, it became clear that the carbon dioxide generated during the alcoholic fermentation of glucose was significant enough to push the Algalrithm's process into a carbon neutral, or even carbon positive, process. Since a carbon negative system is built into the Algalrithm's design problem statement, this result was deemed unacceptable, and it was decided to not move forward with a fermenter system.

Photobioreactors are photoautotrophic systems, like an open pond, i.e. they also take advantage of sunlight as their energy source. They are not open to the air like traditional pond systems,

though, which gives the operator more control over the cultivation conditions. Certain species of algae require very specific conditions in order to grow, such as a high pH, a high temperature, or high nutrient content. Using a photobioreactor to grow algae would decrease the amount of contaminants aggregating in the system. A disadvantage arises in that both the capital cost and the operating cost increase when choosing a photobioreactor over an open pond or fermenter system. A tank which fully encloses the process water naturally costs more than a simple basin.¹⁸

6.2 Harvesting the Algae

Multiple processes have been found as viable methods for separating algae from the surrounding water. Thermal removal, via use of a heater or dryer, and mechanical removal, using a unit operation like a centrifuge, are two of the common water separation methods the Algalgorithm considered for the biomass process. Thermal removal of water is typically more expensive than mechanical removal, so mechanical processes are currently favored for separation. Two of the more predominant mechanical options are centrifuges and dissolved air flotation systems. Both can recover at least 70% of the microalgae in an algae-water mixture (Chen, 2011). Centrifuges make for a quick process, but the mechanics of the process are energy-intensive. This leads to the risk that it may rupture the algal cells prematurely. This may be further improved by adding a flocculation step before hand, which increases the particle sizes of the algae and ensures higher recovery (Grima, 2003).

Dissolved air flotation (DAF) is a process in which small air bubbles are created at the bottom of a tank. As the bubbles rise, they collect particulate matter suspended in the tank's solution. Microalgae has a low specific gravity, which makes DAF suitable to the conditions (Edzwald, 1993). DAF is generally not associated with a high capital cost, but there are frequently additional costs for the compression and bubbling of air required.

6.3 Oil Extraction

A simple method of extracting oil from algae is to use an oil press. Oil presses simply rupture the algal cells, and in so doing, typically yield 70-75% of the oil contained in the algae (Demirbas, 2011). This method is purely mechanical and therefore doesn't require any chemicals or other feeds. The process merely requires energy.

Solvent extraction takes advantage of the chemical properties of lipids. These lipids are soluble in organic solvents, so solvents like hexane can remove lipids from an organic mixture. Hexane has proven suitable for the process by consistently achieving oil recovery of over 99% (Topare, 2011). Hexane, being a relatively cheap commodity, allows for a viable process with the potential for further hexane recycling.

6.4 Continuous Flow vs. Batch Process

The entire process may be run continuously or as discrete, successive batches. Continuous flow systems are ideal for large production rates, i.e. over 1 MMlb_m/yr (Myers, 2016). It is generally the preferable method for this system because it saves time and energy with start-up and shut-

¹⁸ Catherine Brame

down of each of the consecutive unit operations. Some processes, however, necessitate a batch process system. If the production rate of the process is low, it is more economical, because processes with long reaction times or low-flow slurries normally operate more easily within a batch process (Myers, 2016). The algae growth and harvesting processes lend themselves more readily to batch processes, although they could also function in a semi-continuous process. The reactors at the tail end of the process are currently being considered as batch processes, but there is room for development into a continuous system should it be required for complete conversion into bio-surfactants.¹⁹

7. Permitting and Environmental Concerns

7.1 Environmental Issues

Environmental issues must be addressed when dealing with an industrial process. The process taking place at the industrial facility may pose environmental hazards to the surroundings. These environmental hazards must be considered to meet environmental standards that may be state or nationally regulated.

The Algalgorithm's scope is to sequester CO₂, which would be regulated if it was being produced from the process. The process was selected to use CO₂ from the production of other industrial processes to reduce the carbon footprint. Therefore, the process is carbon neutral. Excess CO₂ will be recycled back to the photobioreactor (PBR) to be further used for algae cultivation. There will be no CO₂ emissions from the production of algal biomass. Oxygen is produced during photosynthesis of algae in PBRs. The oxygen produced will have to be removed from the algal biomass after cultivation. This oxygen will be vented to the air but will not pose environmental hazards. By using excess CO₂ in a recycle stream back to the photobioreactor, the CO₂ would have to be separated using a gas separation process from the other vapors that are created during the cultivation process, such as oxygen.

Agricultural wastewater is being used as the nutrient source for algae cultivation. Agricultural wastewater was selected because of its low toxicity levels compared to industrial or municipal wastewater. The nutrients within the wastewater, nitrogen, phosphorus, and sulfur, are used for algal growth. The remaining wastewater is separated from the system using a separator. Additional wastewater processing will be necessary because all the other components of the wastewater do not react during algae cultivation and therefore will still be present in the water separated from the algae biomass. This wastewater will be sent to a wastewater treatment facility for further treatment. During the process, wastewater should not pose a hazard to the environment since it will be sent away to be treated further. If the water were to be discharged into a lake or other water resource without further treatment, a wastewater permit would be required by the federal Clean Water Act.

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During the reaction of lipids to produce bio-surfactants, there are no hazardous gas or liquid by-products or excess constituents that would require attention. The process of bio-surfactants requires caution to avoid environmental issues and is environmentally friendly. This differs from traditional surfactants. The lipid to bio-surfactant process is not modeled for this project, however, the reactants are assumed to fully react in the process to produce a final product of bio-surfactants.²⁰

7.2 Permits Needed

Potential chemicals and harmful products produced from the plant include carbon dioxide, oxygen gas, wastewater, nitrogen gas, and phosphoric acid. Once a material balance of the plant was conducted using the stream results from Aspen+, a conclusion was drawn that no permits are needed for the current process, since all potential harmful chemicals are recycled and needed for the growth of the algae in the photobioreactor, either in the wastewater or the CO₂ stream. However, it is highly unlikely waste permits won't be needed in the real world. Obtaining a waste permit for wastewater and an air pollution permit for any waste gases.

A net input of CO₂ into the plant was estimated to be about 2000 lb/hr, since the amount of algae input was 1000 lb/hr, and algae can soak up twice its weight in CO₂. The net output of CO₂ in our plant is 1841.7 lb/hr, which makes our process carbon negative. The CO₂ will be recycled back into the photobioreactors, and the leftover 156.8 lb/hr of CO₂ still needed will be taken from the industrial plant our process will be placed next to. The purpose of this project is the capture and sequestration of carbon dioxide using algal biomass, so it makes sense that this process is carbon negative. Industrial plants will need companies like the Algalgorithms in the future as a way to sequester their CO₂ emissions.

In order to model the process in Aspen+, nutrients like phosphorus, nitrogen, and sulfur that naturally occur in wastewater were modeled in molecules like H₃PO₄, H₂SO₄, and NH₃. Performing a material balance around the plant, the net output of phosphorus, sulfur, and nitrogen are negative, which means no permits need to be obtained for these nutrients. However, there is an excess of wastewater in the liquid slurry from the photobioreactor. This wastewater that is deficient in nutrients should not be recycled back to the system. Therefore, a wastewater discharging permit would be obtained to discharge wastewater. This wastewater would still be sent to a wastewater treatment facility after being removed from the liquid slurry because it would not be readily available to be discharged to open waters such as a lake or river.²¹

One permit that would be obtained is National Pollutant Discharge Elimination System (NPDES). This permit is obtained for industrial, municipal wastewaters that are discharged into bodies of water. The wastewater leaving the system must meet Environmental Protection Agency, EPA, water quality standards. The wastewater for this process would not meet the water quality standards, so instead of treating the water at our current facility before discharging

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to meet EPA water quality standards, the water is sent to a wastewater treatment facility in the region. The permit is still obtained because wastewater is being discharged from a point source, our facility, to a wastewater facility. Since the wastewater is from agricultural waste, such as pig agricultural waste, the wastewater leaving the facility will be able to be discharged into the combined sewer system to be further treated once it reaches the wastewater treatment facility.

For the state of Colorado where our facility will be located there will be additional permits required. Since no algae biomass system producing a bio-surfactant is currently located in Colorado, a similar permitting process was researched that is similar to oil/petroleum permitting since our bio-based surfactant would replace a traditional petroleum-based surfactant. One such permit for petroleum industrial facilities discharging water is the Discharges Associated with Produced-Water Treatment Facilities. This permit is for industrial facilities discharging wastewater to public water pipelines that lead to the wastewater facility (Department of Public Health and Environment). Since our facility is using municipal wastewater for our algae cultivation, we won't have associated hazards that some industrial facilities have when discharging wastewater.

An air pollution permit will need to be obtained for any air emissions from the facility. These air emissions could be from CO₂ and O₂, or emissions from energy requiring processes. It is not believed that the Algrithm's facility will be over the emissions limit requiring a Title V operating permit per the EPA. However, for the state of Colorado, a general air emission permit will need to be obtained for the start-up of the plant as well as a general air pollution permit for normal operating. Since more harmful air pollutants, such as those listed under Section 111 of the Federal Act (Regulation Number 6) are not an issue for this process, a source permitting air pollution permit is not required (Department of Public Health and Environment).

Therefore, the required permitting for this process would be for wastewater discharges as well as air pollution emissions.²²

7.3 Best Available Control Technology (BACT) Analysis

A BACT Analysis of our plant consists of a few important steps learned in lecture;

1. Identify all control technologies for reducing emissions.
2. Eliminate control technologies that are not ready for commercial application.
3. Rank remaining control options by control effectiveness.
4. Economic Analysis
5. Pick the most effective, reasonable BACT

However, because the purpose of this project is carbon capture utilization and storage, and currently no permits need to be obtained for this plant, a BACT analysis doesn't need to be

²² Traci Reusser

performed. If our plant does have minimal CO₂ emissions or other waste, the design of our plant already had the best available control technology in mind. The CO₂ produced is recycled back into the plant for the photosynthetic growth of the algae, as well as the wastewater containing essential nutrients such as phosphorus, nitrogen, and sulfurs. All output streams are recycled if they can be. Other companies that would be at risk for paying a carbon tax in the future, or are currently looking for ways to reduce their emissions of CO₂ or wastewater, would look at implementing a company like the Algalrithm's. This environmentally friendly process would capture and sequester their waste and emissions for them, and turn it into a biofuel, bioplastic, bio-surfactant, etc.²³

8. Safety and Risk Management

8.1 Safety Issues

The process of converting algae to bio-surfactants, described above as Part I and Part II of the base case design, has several safety issues related to the design. The unit operations themselves present risks in terms of operating conditions. The photobioreactor is the initiating unit operation of the process and it poses few risks. It is operated at inherently safe conditions with low-hazard inputs. As described above, the inputs into the reactor are wastewater, carbon dioxide, and *chlorella* microalgae. The Safety Data Sheet—SDS—information for all of the chemicals used in this process can be found in Appendix 15.7. Since the Algalrithm does not currently have composition information for the agricultural wastewater stream, the hazards associated with it are still to be determined. It is likely, however, that the nutrients and solids in the wastewater will pose little risk to workers given that no ingestion occurs. An SDS for water has been included in Appendix 15.7 for reference to the potential risks of the wastewater stream. The compressed carbon dioxide poses few inherent threats to workers, as it is non-flammable and only hazardous upon inhalation. Inhalation can be prevented by wearing respirators when working with the compressed carbon dioxide. An additional hazard associated with compressed carbon dioxide is that it can cause rupturing of tanks or cylinder under high temperatures, which will require extra caution and monitoring in the unit operations that require high operating temperatures.

The various flash tanks that follow the photobioreactor, FLASHH₂O, FLASHCO₂, and FLASHLIP, pose the greatest hazard to safety, as they are run at high temperatures and are used to remove volatile compounds. The specific hazards are discussed in the HAZOP analysis conducted by the Algalrithm, but the general hazards are associated with potentials for explosions or leakage of high temperature, volatile materials. Should the flash tanks stray from normal operating procedures, it would introduce risks to the equipment and the personnel nearby any of the unstable systems. These hazards are dangerous enough that the system would likely require immediate shutdown in order to prevent severe consequences.

Due to the semi-batch nature of the system and the algae growth reaction in the photobioreactor, this system has fewer associated safety issues than many industrial plants. The nature of the process allows control of each unit operation with the ability to halt the process in order to initiate shutdown of a malfunctioning unit operation. This allows the Algalrithm to protect its equipment and workers by maintaining control of Part I of the process design. There are various

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chemicals being used throughout the process that may have inherent warnings and dangers, which can be further detailed in their specific Safety Data Sheets (Appendix 15.7).

Part II of the process design has chemicals with more severe dangers and warning than those used in Part I of the process. Dichloromethane, the esterification component that reacts with the pure lipid stream, is an irritant that can target the central nervous system along with other organs (Appendix 15.7). Methanol and toluene are the most hazardous chemicals used in the process. If a malfunction occurred in R1 or R2, workers would be exposed to a chemicals that are flammable, irritants, toxic, and fatal upon ingestion. Much like toluene, hydrogen peroxide is also flammable and an irritant with acute toxicity levels. Glycerol, the necessary reactant for the polyglycerol addition in R3, has risks that are similar to those of dicholoromethane. Due to the nature of converting lipids to bio-surfactants, the use of these dangerous chemicals could not be avoided. There are unfortunate safety risks associated with this system, but ensuring that all employees of the Algalrithm are informed and trained on dealing with harsh chemicals mitigates many of the potential safety hazards of this design.

8.2 HAZOP Analysis

A hazard and operability study (HAZOP) was conducted by the Algalrithm for the base case design of the algae-to-surfactant system. Although many of the precise operating procedures and process instrumentation has yet to be finalized, a generalized list of problems and their associated risks was compiled. These potential problems and hazards in the operating procedure were used to identify not only the risks to personnel, but also the risks the system equipment. The completed HAZOP analysis used the guide words listed in Table 5 (Hazard and Operability Study). The HAZOP document, found in Appendix 15.8 was completed using Microsoft Excel to list the hazards associated with each unit operation in the algae-to-lipid process.

Table 5. HAZOP guide words.

Guide Word	Meaning
NO or NOT	None of the intent is achieved
MORE	Quantitative increase (larger than intended value)
LESS	Quantitative decrease (smaller than intended value)
AS WELL AS	Qualitative modification/increase
PART OF	Qualitative modification/decrease
REVERSE	Logical opposite of intent
OTHER THAN	Complete substitution
EARLY	Relative to the clock time
LATE	Relative to the clock time
BEFORE	Relating to order of sequence
AFTER	Relating to order of sequence

Since the Algalrithm decided on a semi-batch system as opposed to a continuous process, the last five guide words in Table 5 were included to describe the operational hazards associated with time or sequence problems. Due to the complexity of Part II of the base case design, only a brief HAZOP was performed. Further analyses of these hazards associated with Part II will be compiled as the Algalrithm moves forward with the bio-surfactant system.

Based on the HAZOP analysis of our Part I design, our system has several potential risks and hazards associated with it. The overall intent of this portion of our system is to complete the process of algae to lipids successfully while under normal operating conditions. These conditions vary with specific unit operations, which is to be expected with the various purposes of our unit operations. The majority of this process, however, is run at atmospheric pressure and 37°C.

As discussed in the base case design, the system begins with algae, carbon dioxide, and wastewater streams entering a photobioreactor (PBR). The intent for this reactor is to operate at a temperature of 37°C and a pressure of 14.7 psia. The HAZOP table, Table 6A and Table 6B, describes all of the potential hazards associated with operating condition deviations. Due to the restricted growth curve of microalgae, a runaway reaction is nearly impossible, but the system still faces risks in regards to the carbon dioxide and wastewater inlet streams. The carbon dioxide stream, should the input be MORE than intended (i.e. high flow), it could potentially cause the reactor to burst. On the other hand, LESS flow than intended could cause the reactor to implode. Both of these hazards pose risks to not only the integrity of the equipment, but also any personnel located near the reactor during a malfunction.

Table 6A. HAZOP analysis for photobioreactor (PBR) in Part I of process design

PBR						
Parameter/Guide Word	More	Less	None	Reverse	As well as	Part of
Flow	high flow	low flow	no flow	reverse flow	deviating concentration	contamination
Pressure	high pressure	low pressure	vacuum		delta P	
Temp	high temp	low temp				
Level	high level	low level	no level		different level	
Time	too long/too late	too short/too soon	sequence step skipped	backwards	missing actions	extra actions
Agitation	fast mixing	slow mixing	no mixing			
Reaction	fast reaction	slow reaction	no reaction			
Start-up/Shut Down	too fast	too slow			actions missed	
Draining/venting	too long	too short	none		deviating pressure	wrong timing
Inertising	high pressure	low pressure	none			contamination
Utility Failure			failure			
DCS Failure			failure			

Table 6B. HAZOP analysis for photobioreactor (PBR) in Part I of process design continued

PBR					
Parameter/Guide Word	Other than	Early	Late	Before	After
Flow	deviating material	too soon	too late	premature	delayed
Pressure	explosion				
Temp					
Level					
Time	wrong time				
Agitation					
Reaction	unwanted reaction				
Start-up/Shut Down	wrong recipe		late shutdown		delayed shutdown
Draining/venting					
Inertising	wrong material				
Utility Failure					
DCS Failure					

There are also several risks associated with the start-up and shutdown of the several photobioreactors. Should the reactors start-up or shutdown at a different time than intended (EARLY or LATE), the production of algae may be smaller than anticipated. Early start-up would attempt to begin the conversion of algae to biomass without the proper nutrients. Late start-up would decrease the amount of algae growing, because the algae would have less time to cultivate before the reactor was scheduled to be emptied. The risks associated with start-up or shutdown out of sequence (BEFORE or AFTER) are similar to those associated with early or late start-up or shutdown. If the reactor began start-up before the other systems began, the system could be halted until the following flash tank (FLASHCO₂) was available, due to the semi-batch nature of this system; similarly, starting-up after the other unit operations would just require the system to be halted. Both of these scenarios would result in a lower lipid production for that day. If the reactor began shutdown before the rest of the system, it would ultimately decrease the amount of algae going through the system during the last run-through; shutting down after the other operations would not affect the rest of the system as long as there was no excess algae or nutrients in the reactor.

In addition to the hazards associated with flows in and out of the photobioreactor, there are also potential risks due to the temperatures of the system. If the temperature were higher than it should be, the health of the algae could be compromised, leading to underproduction of biomass. In the extreme case where the temperature could rise to hazardous levels, the reactor could be dangerous for personnel to touch, and the temperature could even reduce the integrity of the reactor; this is unlikely, though, due to the low operating temperature of the reactor. The risks associated with the photobioreactor can be reduced by using a robust control system that monitors flowrates, temperatures, pressures, liquid levels, and carefully initiates start-up and

shutdown procedures. Overall, the sequential and timing risks of the photobioreactor impact the production and economics of the system more than the safety of equipment and personnel.

The flash tank (FLASHCO₂), joined with the photobioreactor, separates carbon dioxide and oxygen from the useable algae stream in the PBR. This separator is a continuation of the photobioreactor and has intent to run at the same conditions (37°C and 14.7 psia). The flash tank was designed to be adiabatic, which reduces the risks and hazards associated with it; the HAZOP analysis for this tank can be seen in Table 7A and Table 7B. The flow, temperature, and sequencing of the separator pose the same risks as those in the photobioreactor, since the flash tank is combined with the reactor. In the case of pressure buildup and temperatures rising, this flash tank does pose a risk for explosion, which could harm both personnel and equipment. These risks will be heavily monitored by using control sensors and systems.

Table 7A. HAZOP analysis for flash tank (FLASHCO₂) in Part I of process designed

FLASHCO₂					
Parameter/Guide Word	More	Less	None	Reverse	As well as
Flow	high flow	low flow	no flow	reverse flow	deviating concentration
Pressure	high pressure	low pressure	vacuum		delta P
Temp	high temp	low temp			
Level	high level	low level	no level		different level
Time	too long/too late	too short/too soon	sequence step skipped	backwards	missing actions
Agitation	fast mixing	slow mixing	no mixing		
Reaction	fast reaction	slow reaction	no reaction		
Start-up/Shut Down	too fast	too slow			actions missed
Draining/venting	too long	too short	none		deviating pressure
Inertising	high pressure	low pressure	none		
Utility Failure			failure		
DCS Failure			failure		

Table 7B. HAZOP analysis for flash tank (FLASHCO₂) in Part I of process designed continued

FLASHCO₂						
Parameter/Guide Word	Part of	Other than	Early	Late	Before	After
Flow	contamination	deviating material	too soon	too late	premature	delayed
Pressure		explosion				
Temp						
Level						
Time	extra actions	wrong time				
Agitation						
Reaction		unwanted reaction				
Start-up/Shut Down		wrong recipe		late shutdown		delayed shutdown
Draining/venting	wrong timing					
Inertising	contamination	wrong material				
Utility Failure						
DCS Failure						

Following the flash tank is the oil press used to separate lipids from the algae membranes. This unit operation poses few risks to personnel and equipment, as its intent is to run with a heat duty of 25 btu/hr, with no changes in pressure, temperature or composition. The most severe HAZOP characteristic associated with the oil press is if the flow into the press is MORE, which could potentially damage the oil press. In addition to damage to the oil press, deviations from the intended flow would likely have an adverse effect on the production of the system.

The undesired algae slurry that leaves the oil press is then sent to the FLASHH₂O separator that is used to dry the slurry. The intent of this flash tank is to vaporize water at 200°C and 14.7 psia. In order to accomplish this intent, the separator has a net heat duty of 157,000 Btu/hr. It is due to the intent of the separator that many of the risks occur. Much like the photobioreactor and the flash tank, the effectiveness of FLASHH₂O relies on the flows in and out of the separator. Too much flow could cause the separator to explode, while too little flow would likely lead to an excessively heated separator. Early or late start-up and shutdown of the system must be monitored using a precise control system, as this flash tank is operated at higher temperatures than the majority of the process. In the case of the flash tank getting too hot, there are potential safety and equipment risks, more severe than those in FLASHCO₂.

The final unit operation in Part I of the design process is the FLASHLIP flash tank. This separator has the same intent as FLASHH₂O, but has a higher net heat duty of 161,000 Btu/hr. The intent of this reactor poses the same threats as those associated with FLASHH₂O, potentially effecting both personnel and equipment. Since this separator yields the final product of Part I, the pure algae lipid, any consequences of risks are more severe for this unit operation than for the other units in Part I. Should this separator malfunction, it has the potential to ruin the

end product of the Part I process, which would severely affect the Algalgorithm's production for a short time period, due to the semi-batch nature of this process.

A large majority of the potential hazards and risks of the Algalgorithm's system are caused by intent within the Part II of the process design. As explained in the base case design for Part II of the system, the Algalgorithm was unable to model this portion of the system using Aspen+. Based off the preliminary design of Part II, this portion of the system used hazardous chemicals like dichloromethane, toluene, hydrogen peroxide, and glycerol. The SDSs for these chemical compounds are found in Appendix 15.7 and are the primary references for the HAZOP analysis.

All three reactors, R1, R2, and R3, have similar risks associated with them. Since the reactors have not been thoroughly modeled, the operating conditions of each reactor cannot be determined. It is likely R1, R2, and R3 would be run at temperatures of 90°C, 140°C, and 70°C respectively and at atmospheric pressure. Of these operating conditions, R2 poses the most risks due to its higher temperature. The hazards associated with toluene for both equipment and personnel in addition to the high temperatures present explosion and leakage risks for equipment and personal injury to workers. Aside from the severe conditions of R2, many of these reactors' risks are like those of the photobioreactor in terms of operating condition changes and sequential alterations.

In addition to the photobioreactor's risks detailed above, these three reactors have unique risks due to the various chemicals being used. As described above, the chemicals used in the Part II of the process can have many adverse effects. The chemicals can cause corrosion to the system and can be especially harmful to workers should a leak or explosion occur. All of the chemicals used in this portion of the process have the potential to cause serious damage to exposed workers, which make them a large risk in this HAZOP analysis. The safety of the workers can be protected by incorporating the proper control and monitoring systems in order to ensure that the system is running under normal operating conditions.²⁴

9. Economics

In order to perform an accurate preliminary economic analysis, some realistic assumptions were made. The plant will include approximately ten 1,000 m³ photobioreactors. At about ten meters in length, this will make the plant roughly the size of a football field. After modeling the process in Aspen+, and performing extensive research, we've concluded about 1000 lb_m/hr of biomass would be produced, and about 475 lb_m/hr lipid will be produced (Doucha, 2011). Similarly, in depth research into the extraction of algal lipids allows an accurate conclusion of about 31% of the original algae biomass to be processed into a sellable lipid surfactant. This would make the total bio-surfactant production rate to be about 475 lb_m/hr, with an extra 1058 lb_m/hr of excess algae cake that can be sold as a soil additive.

Table 8 below summarizes other expense costs approximated for the plant. A complete cost production report that includes variable, utility, and other miscellaneous costs can be found in the appendix.

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Table 8. Equipment cost summary

Equipment	ISBL FOB Cost
Photobioreactors	5.13 MM\$
CO2 Flash Drum	\$7,000
Compressor	\$6,000
H2O Flash Drum	\$8,000
Separator	\$20,000
Lipid Flash Drum	\$15,000
Pumps/Other vessels	\$50,000
Total ISBL FOB	5.23 MM\$

A total inside battery limit (ISBL) can be calculated from the ISBL FOB (freight on board) number from above. After delivery, installation, outside battery limit costs, and scale up factors are included, a total fixed capital investment (FCI) is concluded below in Table 9 (Peters and Timmerhaus, 1991).

Table 9. Fixed capital investment (MM\$)

Installed ISBL	29.0
Installed OSBL	1.0
Total Installed FCI	30.0

After approximating about \$30 million for our FCI, an extra \$1.45 million will need to be added the first year of plant operation for initial start-up costs. In order to make the process economically viable and profitable, the surfactant product will need to be sold at approximately 98 c/lb_m. This projects our annual revenue to be about \$13.41 million/yr. The net present value (NPV) of the project was projected out 15 years into the future, where the plant will be worth about \$9.54 million. The internal rate of return (IRR) is then estimated to be about 16.7%. Table 10 below summarizes the cash flow analysis of the project. A full cash flow table can be found in the appendix.

Table 10. Economics Summary (\$MM)

Fixed Capital Investment	30.0
Start-Up Costs	1.12
Annual Revenue	13.41
Net Present Value (r = 12%)	9.54
Internal Rate of Return	16.7%
Pay Back Period (yrs)	4.7
Minimum Acceptable Rate of Return	12%

- Does not include revenue from carbon tax

Revenue from a carbon tax will be implemented in the future. Currently, it is difficult to estimate a realistic carbon taxation price for the U.S, especially in light of current events and the elect of the new President of the United States. Further research will be conducted, and a realistic carbon tax can be input into our cash flow analysis of the plant, furthering the profitability and economic success of our process.

An economics sensitivities table is shown below in Table 11. It shows the large variance the Algrithm could potentially sell their surfactant at, as well as if the FCI was increased by 25%, or if the byproduct revenue was sold for approximately 50% less than what it's estimated at.

Table 11. Economics Sensitivity Analysis

Case	FCI MM\$	Surfactant Price (\$/lb)	Annual Revenue MM\$	NPV15 MM\$	IRR %
Base Case	30	0.98	13.4	9.5	16.70%
-40 c/lb surfactant	30	0.58	7	3.36	14%
+25% FCI	37	0.98	7.9	2.44	13%
-40 c/lb byproduct revenue	30	0.98	4	-9	6.60%

If the final surfactant product was sold for 40 c/lb less (in the case of impurities, or trying to be more competitive in the market), the IRR% would be 14%, and the NPV would still be 3.36 MM\$, keeping our process economically viable. The byproduct is currently being sold as a soil amendment at 85 c/lb, as shown in the cost production sheet below, Figure 11. In the extreme case our by-product was sold at 45 c/lb, approximately 50%, then our IRR% would be reduced to 6.6%, and the NPV would be a -9 MM\$. This however is shown as an example as an extreme case, and the Algrithm doesn't estimate the necessity to have to sell the by-product at such a cheap cost.

Table 12 below summarizes the final stream results for the final product of our plant.

Table 12. Mass flows of inlet and outlet streams

Stream Results		CO₂	WW	Algae	Byproduct	Lipid
Mass Flows	lb/hr	2000	500.00	3499.99	1072.59	492.99
CARBON	lb/hr	0	0.00	0.00	0.00	0.00

HYDROGEN	lb/hr	0	0.00	0.00	0.00	0.00
NITROGEN	lb/hr	0	72.16	40.41	0.00	0.00
OXYGEN	lb/hr	0	0.00	0.00	0.00	0.00
SULFUR	lb/hr	0	82.60	0.00	0.00	0.00
H3PO4	lb/hr	0	252.43	15.15	13.63	0.00
HEXANE	lb/hr	0	0.00	0.00	0.00	0.00
ETHANOL	lb/hr	0	0.00	0.00	0.00	0.00
WATER	lb/hr	0	92.81	66.83	0.19	17.61
GLUCOSE	lb/hr	0	0.00	0.00	0.00	0.00
CO2	lb/hr	2000	0.00	1843.15	0.00	1.42
BIOMASS	lb/hr	0	0.00	1534.46	1058.78	0.00
SULFU-01	lb/hr	0	0.00	0.00	0.00	0.00
NITRI-01	lb/hr	0	0.00	0.00	0.00	0.00
LIPID	lb/hr	0	0.00	0.00	0.00	473.96

The CO₂, wastewater (WW), and algae are all streams that are initially at the beginning of our plant that go into our photobioreactor (after initial start-up of the plant, majority of that algae will be recycled). The byproduct column is the dried algae cake coming off our H₂O flash drum which will be sold as a soil amendment, and the lipid column is our final lipid bio-surfactant. With the outlet flows of these products, we've estimated the cost to which the soil amendment and bio-surfactant must be sold for, which would make our plant economically profitable, and also competitive with the current bio-surfactant and fertilizer market. Selling our bio-surfactant at 98 c/lb is fairly competitive with other plastic markets, which currently on the market to sell anywhere between 0.51 - 200 c/lb (Chang, 2014). Our soil amendment, if sold at about 85 c/lb is very competitive with the market, as other companies sell there's anywhere between 0.5 - 3 \$/lb, depending on the chemical or additive used in the brand of soil amendment (Chang, 2014).

In order to size all of our equipment, heat duties and mass flows for each unit operation were analyzed, in order to size, scale, and estimate the production cost for our plant. Below in Table 12 is a summary for the net heat duties mass flows for each unit operation.

Table 13. Sizing of unit operations using heat duty and mass flow rates

Unit Operation	Heat Duty (Btu/hr)	Mass Flow (lb/hr)
Photobioreactor	2305829	3499.99
CO₂ Flash Drum	0	3499.991
Compressor	25.31043	1573.04
H₂O Flash Drum	157000.186	1076.81
Lipid Separator	-430529	496.22
Lipid Flash Drum	161397.5	496.22

Based off these heat duties and mass flows, the unit operations were sized using the Peters and Timmerhaus textbook, Process Design and Economics for Chemical Engineering.

A preview of the cost production estimate report is shown below in Figure 11. A full interactive excel file can be found in the Appendix 15.2.

Production Cost Estimate Report							
Evaluator	Mary Uselmann						NOTE: MM ==> million
Product Name	Surfactants		Location	UWYO			
Process Name	2016						
Nameplate Production	4 MMBE/yr	8000	hr/yr	Operating Factor	475	lb/hr	
ISBL (installed)	29.01 MM\$						product
OSBL (installed)	1.00 MM\$			Start-Up Costs	1.12	MM\$	
Total FCI (installed)	30.01 MM\$			Working Capital	2.24	MM\$	
Product and Revenue							
	Unit	Unit Price			Revenue	c/lb	
Surfactant polyethers	lb	98.00	c/lb		13.41	353.00	
Raw Materials							
	Unit	Unit Price		Consumption per		c/lb	
Wastewater, CO2	lb	0.00	c/lb	0.2105	lb/lb product	0.0000	0.00
CO2	lb	0.00	c/lb	0.8105	lb/lb product	0.0000	0.00
Gross Cost of Raw Materials						0.00	0.00
Byproducts							
Cake - Soil Additives	lb	85.00	c/lb	3.0000	lb/lb product	9.6300	255.00
Wastewater	lb	0.00	c/lb	0.0000	lb/lb product	0.0000	0.00
	lb	0.00	c/lb	0.0000	lb/lb product	0.0000	0.00
Total Byproduct Credits						9.63	255.00
Net Cost of Raw Materials (NRM)						0.00	-255.00
Catalysts and Chemicals							
	unit	c/unit		unit/lb product		0.00	0.00
None	lb	0.00	c/lb	106.95	lb/lb product	0.0000	0.00
			c/l		/lb product	0.00	0.00
Total Catalysts and Chemicals						0.00	0.00
Utilities							
Electricity	Kw	4	c/Kw	1.5928	Kw/lb product	0.2421	6.37
Steam	Mlb	900	c/Mlb	0.0023	Mlb/lb product	0.0792	2.08
		0	c/l	0.0000	/lb product	0.0000	0.00
Total Utilities						0.32	8.46
Miscellaneous Variable Costs							
Misc name	unit	c/unit		unit/lb product		0.00	0.00
			c/l	/lb product		0.00	0.00
Total Misc. Variable						0.00	0.00
Total Variable Costs (VC)							
						0.32	-246.54
Fixed Costs							
				Basis			
Labor (basis: 8000 hr/yr * 1.6)	4	men/shift @	40	\$/hr +	0	MM\$/yr	2.24
Maintenance	4%	% ISBL +	2%	% OSBL +	0	MM\$/yr	1.18
Miscellaneous Fixed Costs					1	MM\$/yr	1.00
Total Fixed Costs (FC)						4.42	116.39

Figure 11. Production cost estimate report

The picture summarizes many important parts of our process, including startup costs, working capital, total installed FCI, and annual revenue. It also shows costs coming from our byproducts, miscellaneous costs, variable costs, and utilities cost (Myers, 2016).²⁵

10. Global Impacts

The Algorithm's process of converting algae biomass into surfactants has the potential impact the world in several positive ways. The algae growth process requires carbon dioxide, which will be sequestered from one of the nearly 6,000 industrial companies in Colorado. Although the carbon dioxide taken from the industrial plant will need to be compressed and transferred to the Algorithm's processing plant, the relationship between the Algorithm and the industrial plant is

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nearly effortless. With the potential for expensive carbon taxes, industrial companies will seek methods for lowering the carbon dioxide emissions; the Algrithm has the answer. The industrial plant will have to pay the Algrithm to sequester the carbon dioxide, but the charge will ultimately be much less than what they would pay for a carbon tax. This incentivizes industrial companies to seek creative alternatives to emitting carbon dioxide, as it is financially beneficial for companies wishing to avoid further taxation. Upon the Algrithm's start-up, the system will only benefit the local southern Colorado area, as reduced carbon emissions will only be in the processing plant's area. Should the Algrithm's process of sequestering carbon dioxide be as successful as anticipated, however, it has the potential to start a global trend of using biomass to create common products, which can ultimately reduce carbon emissions around the world.²⁶

Another global impact is utilizing wastewater for algae cultivation. We will be using agricultural wastewater from nearby farms as the nutrient source for the growth of algae. The reason for this is to eliminate waste from the environment. Local farms will be able to dispose of agricultural wastewater without having to worry about what they are disposing of or without having to obtain a permit to release their wastewater into bodies of water, such as rivers or lakes. This is environmentally friendly because wastewater generally contains excess nutrients that can cause dead zones if too much accumulates in a body of water. Wastewater is cost effective and requires low energy. In a wastewater treatment plant, the wastewater would be treated and nutrients would be removed, by utilizing wastewater in the production of algal lipids, the initial wastewater treatment process would be eliminated.²⁷

In addition to the potential environmental and industrial benefits, the Algrithm's process also appeals to many consumers that seek bio-based products. Using algae biomass to create surfactants offers consumers a natural-based product that was created using fewer harsh chemicals than typical industrial products. With society's current interest in returning to natural, healthy roots for products, systems like the Algrithm's will thrive in the public's eye. Positive feedback from consumers gives the Algrithm the chance to expand into other industries in order to drive industrial products towards bio-based processes. In addition to the public's opinion about natural products, using a biomass system has a smaller carbon footprint than many petroleum based products. The environment, and the public, not only benefit from the Algrithm's carbon-negative process, but they also benefit from the reduced environmental impacts from what little carbon dioxide is being emitted by the algae processing system.

Although it is likely that the success of the Algrithm will drive competitors towards the similar biomass processes, it will ultimately benefit the environment, which gives this system the potential to positively change the world's emissions of carbon dioxide. One benefit of the algae processing system that will benefit the Algrithm in the case of competitors is the ability to tailor algae lipids and systems to create products that could apply for many different industries. At this point in time, the Algrithm is only planning to create surfactants and soil amendments, but microalgae has applications in several industries, allowing for the Algrithm's expansion.

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²⁷ Traci Reusser

Due to the overall environmentally-friendly implications of the Algalrithm's system and the guaranteed purity of the surfactant product, there are very few ethical issues associated with this process. The largest question of ethics stems from the Algalrithm charging industrial companies to sequester their carbon dioxide. It may seem that a company like the Algalrithm that is driven by the desire to improve upon the environment should not seek financial incentives for their actions. This is not the case, however, as the Algalrithm is merely seeking to implement a commerce system in which both parties are financially benefitted; this ultimately ensures that the Algalrithm will have a small source of income to help increase operations and ensure the success of the bio-surfactant product.²⁸

11. Conclusion and Recommendations

This project revolved around the central goal of carbon sequestration using algae. Rising carbon concentration in the atmosphere has caused many countries and corporations to be more aware of their carbon emissions, and to begin to take measure to decrease or attempt to counteract these high-volume emissions. From this general problem statement of utilizing algae to sequester carbon dioxide from the atmosphere or directly from emission sources, the Algalrithm was born. In order to develop a more well-rounded process, various end products to potentially be used from the cultivated algae biomass were examined. Products examined included pharmaceuticals, bioplastics, biofuels, fertilizer, food, and cosmetics. Once economic and process constraints had been identified for each possible product, bio-surfactants emerged as the most viable and economical solution.

Constraints for the design as a whole were then identified. The Algalrithm's constraints included scientific and technical, production, practical, product and feedstock specification, safety, environmental, and economic constraints. Each of these constraint categories were then broken down further to identify specific aspects and influences that may limit production or economic viability. Once these constraints had been identified, the remainder of the design could be modified and built around these constraints to better the Algalrithm's chance of economic success, longevity, and stability.

The current process plan for the bio-surfactant process begins with cultivating a strain of *Chlorella* in photobioreactors, using the sequestered carbon as a feedstock for the algal blooms. These algae can then be harvested, dried, and sent through an oil press to extract the lipids used to produce the final bio-surfactant product. This design could be verified first with laboratory trials, then by constructing a pilot plant, and then moving into larger scale production.

The preliminary economic analysis conducted—using bio-surfactants as the product—projects a positive net present value of approximately \$9.54 million after fifteen years of operation. Continued economic analyses will be necessary to increase accuracy of economic forecasts, but this preliminary value provides the incentive to move forward with the process of carbon sequestration using algae from which bio-surfactants will be produced and sold. Given the IRR

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of 16.7%, it is recommended that this business model be further developed, as this falls above the cutoff of 12% for an acceptable IRR (Peters and Timmerhaus, 1991).

12. Future Work

Next steps for the Algrithm include improved photosynthesis modeling, selecting a carbon tax based on those already in use, more detailed molecular and physical property analysis of the end-product bio-surfactant, further process specifications, and continued, in-depth development of the current economic analysis—both internal and external.

In the current Aspen+ model, the process is represented with biomass as the only product stream, despite the inevitable oxygen stream that will result from a photosynthetic reaction. Figure 12 shows the photosynthetic reaction in question.

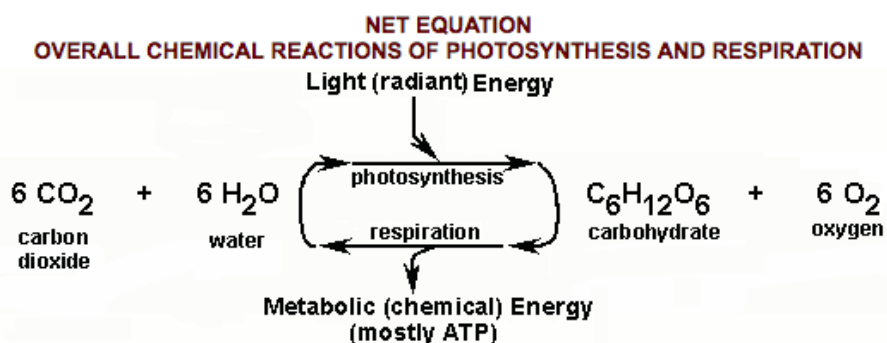


Figure 12. Chemical reaction behind photosynthesis.

Since Aspen+ does not have photosynthesis reactions built into its operations, the reaction has to be manually built using multiple assumptions and calculations to create an "equivalent" reaction. This equivalent reaction is still under development, and will need to be modified to include the oxygen stream exiting the photobioreactor.

Furthermore, the biomass component modeled in Aspen+ must be refined to ensure greater accuracy. The current formula being used is an estimation of biomass content using available literature. The current formula includes only carbon, oxygen, nitrogen, sulfur, and phosphorous. This formula may be altered to model different strains of algae, or even to model the current strain more precisely.

Several potential carbon tax situations may also be developed. While multiple countries do currently utilize a carbon tax, the United States does not yet employ any such taxes. In order to increase the Algrithm's to economic success using carbon sequestration, there must be some form of income generated by through the utilization of other facilities' carbon emissions. While it is impossible to pinpoint exactly what form or rate of carbon tax the United States government may enact in the future, educated guesses can be made, using other countries' existing carbon taxes as models for the United States' theoretical future carbon tax.

As of 2013, fifteen countries had implemented some form of carbon tax, including Australia, Ireland, Chile, Sweden, Finland, Great Britain, New Zealand, and France. While some of these nations have since repealed or abandoned their legislation, the effectiveness of lowering emissions the tax has been apparent in almost all instances. In order to satisfy carbon tax legislation, many high-emission facilities must employ high cost systems to reduce their carbon emissions, or even decrease output. The Algalgorithm, however, would provide a cost-competitive option that would offer affordable carbon sequestration to these high-emission facilities. In order to calculate a realistic income that the Algalgorithm could expect to see from this sequestration process, a carbon tax has to be assumed. Moving forward, one or more situations could be examined economically, using other countries' existing carbon taxes as models. These potential incomes could then be factored into the Algalgorithm's cash flow analysis, and the potential increase in profitability could be estimated.

A detailed molecular and physical property analysis will also be key in assuring the viability of the Algalgorithm. An in-depth understanding of how the final bio-surfactant product will behave in various conditions, and in combination with other constituents, is necessary to ensure a safe and effective end-use product. Specific manufacturers will be targeted to sell the final bio-surfactants produced by the Algalgorithm based off of the compounds' purities as well as the nature of any impurities present in the post-production product. Such considerations will also include any impurities present in the wastewater used to cultivate the algae, to ensure that there are no dangerous toxins in the final product. Any methods of processing or packaging must be examined to ensure that no harmful chemicals are being introduced to the algae lipids or cake that could create an unsatisfactory or even dangerous end product.

While an initial economic analysis has been conducted, it will need to be updated and refined over the remainder of the project. This economic analysis must be well-rounded to ensure the long-term success of the Algalgorithm. The energy balances must be maintained to ensure the accuracy of duties associated with each unit operation involved in the processes. This, along with market prices for utilities, serves as a base case utility cost for the Algalgorithm facility. Overall plant utilities can then be added to the base operation costs.

Raw material and byproduct costing is another economic component to be further analyzed. This research will contribute to existing cash flows and net present value calculations. Soil amendments are currently being investigated as the most likely byproduct produced from the algae cake left over after oil extraction, but this product must be accurately costed and examined for marketability to be verified as procedurally and economically viable.

Finally, a thorough analysis of the current and future market for bio-surfactants, byproducts, and carbon sequestration must be conducted to determine the longevity and viability of the Algalgorithm business model. The susceptibility of the surfactant market to changing oil prices results in an ever fluctuating market, and uncertain forecasts. However, bio-surfactants' promise of a less toxic and more environmentally friendly alternative may help to decouple them from the

ever volatile market. An analysis will include forecasts regarding bio-surfactant and byproduct markets, and projected carbon tax revenues as a function of time.²⁹

13. Acknowledgements

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15. Appendix

15.1 Database

Database file with overall information attached as a separate file.

15.2 Economics

Economic Excel Spreadsheet attached as a separate file.

15.3 Flowsheet

Aspen + bkp and inp files attached in a separate folder.

15.4 Meeting Minutes

Meeting Minutes attached as a separate file.

15.5 Paper Resources

All journals, papers, and book sections used for research and information are attached as a separate file.

15.6 Website Resources

All website screen shots are compiled into a file with references.

15.7 Safety Data Sheets

All safety data sheets, SDS, are compiled into a separate file.

15.8 Hazard and Operability Study, HAZOP

All HAZOPs are compiled into a separate file.