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Algae bioreactor for biodiesel production

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Abstract. Biodiesel production and use are becoming more prevalent across North America and Europe as fueling stations become equipped with biodiesel pumps at a continually increasing rate. As petroleum reserves become depleted, the price of petroleum-based diesel will increase, while biodiesel prices are expected to decrease due to increased supply. Biodiesel is produced through transesterification of oils or fats and can be used in unmodified diesel engines. This makes biodiesel an ideal petroleum-based-diesel substitute as car manufacturers and consumers will not experience manufacturing cost changes. Algae are efficient for biodiesel production because they are about 50% by mass oil, which can be used to make biodiesel fuel. Algae can also grow in areas where other plants cannot be grown such as salt water or polluted areas. Additionally, algae grown near power plants will consume the emitted CO_2 and use it for photosynthesis. This article reports the results of a ***student capstone design project***, in which a small reactor for biodiesel production was built using a vertical design. It produced 1420 ml (48 fl. oz.) of algae, which resulted in a net production of 591 ml (20 fl. oz.) of lipid oil through refreezing the algae. We were able to produce 532 ml (18 fl. oz.) of biodiesel fuel in less than 11 weeks.

Key words. Biofuel Production, Biodiesel Fuel, Algae Bioreactor

1. Introduction

Renewable energy production has advanced immensely in the past few decades, but fossil fuels still supply 84% of the global energy [1]. Clearly, fossil fuels are not renewable resources. They pollute the air, contribute to *climate change*, and will one day run out. Our long-term goals should include relying entirely on renewable resources.

One way to decrease our dependence on fossil fuels is to produce biofuels from renewable sources such as algae. Algae provide many benefits, including the capture of carbon dioxide and production of lipids as well as nutritional supplements [2].

Most algae are unicellular organisms containing around 50% (by mass) lipids within their cellular structure. The oil derived from algae can be used to make biodiesel fuel. Algae can grow in areas where other plants cannot. Examples include salt water and contaminated areas. Additionally, algae remove CO_2 from the air and use it for photosynthesis. Biodiesel fuel is produced through transesterification of oils from algae or other fatty materials and can be used in unmodified diesel engines. This makes biodiesel an ideal petroleum-diesel substitute for diesel vehicles and aircraft.

Algal biomass is an anticipated attractive source for biofuel production mainly due to its potential to produce up to 10 times more oil per hectare than traditional biofuel crops [3]. Since algae thrive on excess carbon dioxide, potentially prime locations for growing algae for biofuels could be next to existing power plants.

Not only do algae have the ability to provide a renewable source of fuel, they themselves benefit the environment. Research has shown algae are responsible for a substantial portion of global oxygen production and carbon dioxide sequestration [4].

Electric vehicles are becoming more prevalent on the roads but millions of fossil fuel consuming vehicles still dominate the roadways and the fuel they use is not renewable. Furthermore, a great majority of aircraft will continue to burn fossil fuels for years to come. By attempting to use rapidly growing strains of algae and harvesting the oils naturally produced by the organism, it is possible to produce a continuous supply of eternally replenishable fuel. This will make the world a cleaner place as the algae grown are replenishable and absorb a large amount of carbon dioxide from the atmosphere during the cultivation process.

Production of algae-based biodiesel consists of six steps:

1. Growing the algae
2. Harvesting the algae
3. Dewatering the algae
4. Extraction of the oil from the algae
5. Conversion of the oil into biodiesel (transesterification)
6. Biodiesel purification process with water

Algae are a diverse group of aquatic organisms. Like other plant life, they use photosynthesis to convert energy from sunlight into various carbohydrates, proteins, and oils. The proteins produced can be a great source of nutrients for human consumption.

There are three main inputs vital to good algae growth: sunlight, carbon dioxide, and nutrients. Sunlight and carbon dioxide are ample in most outdoor settings, especially during summer months. While alternative methods of supplying carbon dioxide (active flow of carbon dioxide from a tank into an algae medium) can be used, algae can thrive by obtaining carbon dioxide passively from the surrounding air.

The nutrients most vital to algae growth are nitrogen and phosphorus; these are vital to the protein building process and allowing the algae to convert the energy from sunlight during photosynthesis. It is worth noting that phosphorus is typically the limiting reagent in the algae growing process.

Algae are also used as a nutritional supplement for human consumption. They can be found in powder form, added to plant based protein sources, baked goods, dressings and beverages. Algae are high in protein and a good source of other nutrients. The two most commonly consumed algae are *Arthrospira platensis* (spirulina) and *Chlorella*. Both of these species are unicellular green algae. People who consume plant-based foods are more likely to consume algae as an alternative protein source especially because of its high protein content.

Algae require very little to grow at an alarmingly fast rate. Being plant-based aquatic organisms, they utilize photosynthesis to grow. During this process the algae cells will absorb sunlight, carbon dioxide and other nutrients. Studies have shown that algae farms placed next to traditional power plants are great reducers of carbon dioxide. Having these two in close proximity reduces the carbon footprint of the power plant while the algae are growing. The process that takes place during photosynthesis is called sequestration. During the sequestration process, the carbon dioxide is broken down and the carbon element is kept in the algae. The oxygen is released into the water.

Summer is the best time for algae to grow due to the warmer temperatures. Algae have a higher growth rate when the temperature is between 15-27 °C (60-80 °F). Temperatures too cold or too hot could prevent algae from growing at an optimal rate. Growing algae indoors gives the grower the ability to control the temperature in order to keep the algae alive and growing at a suitable rate.

The production of oil from algae in this small-scale ***student capstone design project*** can be used as a basis for larger-scale production of lipid materials and biodiesel fuel. This study provides the experience needed for prototyping and getting estimates on production so that the algae growth and the oil produced can reach the best quality possible at a larger scale.

2. Algae Types

According to [5], algae are a diverse group of aquatic microorganisms capable of photosynthesis. They produce oxygen and are a source of food to aquatic life and used as a food supplement by some people. There are about of 7,000 species of green algae. They often exist in freshwater. They are mostly microscopic but some of them are multicellular. The cells of green algae are constructed mostly of cellulose (Fig. 1).

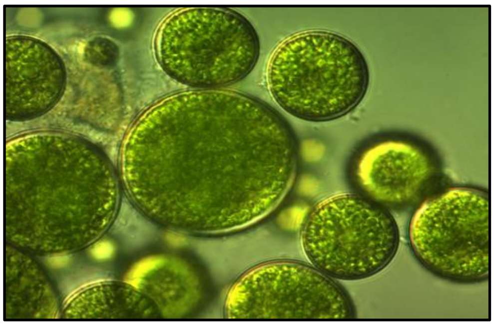

Fig. 1. Image of green algae [5]

Table I lists 14 algae subspecies and provides a range of oil content for each [6]. In the process of biodiesel production, a high algal oil content is desired, as it will result in the greatest yield.

Table I. Algae oil content by species [6]

Microalgae	Oil Content (% Dry Weight)
Microalgae Botryococcus braunii	25–75
Cylindrotheca sp.	16–37
Chlorella sp.	28–32
Crypthecodinium cohnii	20
Dunaliella primolecta	23
Isochrysis sp.	25-33
Monallanthus salina	>20
Nannochloris sp.	20-35
Nannochloropsis sp.	31-68
Neochloris oleoabundans	35-54
Nitzschia sp.	45-47
Phaeodactylum tricornutum	20-30
Schizochytrium sp.	50-77
Tetraselmis sueica	15-23

3. System Design

The bioreactor built for growing algae for the purpose of conversion into biodiesel fuel utilizes a vertical design. Three bins, stacked on a shelving unit serve as the growing area (Fig. 2). The top of each bin is open to allow CO_2 capture from the air for use in the photosynthesis process of the algae. Additionally, a drainage system was made by attaching a ball valve to the bottom of each bin. This allows the algae culture to be partially drained into the lower bins for both diluting and collecting the algae. The algae culture was started by filling the top tub with 34 litres (9 gallons) of pond water containing algae. At the start of each week, 59 ml (¼ cup) of garden liquid fertilizer was added to the culture to replenish lost nutrients in the system. Additionally, every other day, 5 ml (1 tsp) of potassium nutrients were added to the algae culture. After two weeks of growing, the algae culture was separated equally into the top and middle bin. Each bin was topped off with 15 litres (4 gallons) of clean water to dilute the algae culture so that it could continue to grow. After another two weeks, this process was repeated. The total growing period of the algae culture was 4 weeks, in which the final water volume was 95 litres (25 gallons).

Fig. 2. Finished bioreactor design

4. Algae Collection and Oil Separation

To make biodiesel, the oils contained in the algae needed to be separated from the algae membrane. The process for accomplishing this was follows. First, the algae were collected by draining the algae water through a cheesecloth filter (Fig. 3). This separated the algae from the water so that the oils could be extracted from the algae. This process yielded 1420 ml (48 fl. oz.) of algae. Next, the algae were run through a tomato processor (Fig. 4) to break down the cell walls, then run through a meat grinder (Fig. 5) to further break down the cell walls of the algae. This process created a paste that was then frozen and thawed multiple times over the course of five days.

Fig. 3. Cheesecloth used to separate the algae from the water

Fig. 4. Tomato processor used to make algae paste

Freezing and thawing the algae breaks down the algae paste enough to allow the oil to escape the algae. Finally, the oil was filtered from the remains of the algae to achieve as close to a pure oil as possible. However, due to filtering limitations, the oil yielded from this process was not free from algae contaminants (Fig. 6).

Fig. 5. Meat grinder used to create algae paste

Fig. 6. Oil yield after two days of freezing and thawing

5. Biodiesel Production

Algae biodiesel is typically made by mixing the algae oil with methanol and lye (sodium hydroxide) [7],[8]; however, we used isopropyl alcohol instead of methanol.

To convert the algae oil obtained from the system described above to biodiesel, the oil was mixed with isopropyl alcohol and lye. For 591 ml (20 fl. oz.) of algae oil, 5 grams of lye and 296 ml (10 fl. oz.) of isopropyl alcohol were used. The mixture was stirred for ten minutes to allow the fat from the oil to separate from the glycerin which settles at the bottom of the mixture. This forms a thick clump of fat and any leftover algae that remained in the oil (Fig. 7).

Fig. 7. Biodiesel produced

6. Results

After four weeks of growing the algae, a total yield of 1420 ml (48 fl. oz.) of algae was obtained. The amount of oil extracted out of the collected algae was 591 ml (20 fl. oz.). Typically, algae contain 50% oil by mass. We obtained 42% oil by volume. This can be improved by using more efficient methods for oil extraction. One such method could be to compress the algae oil out of the algae. We yielded 532 ml (18 fl. oz.) of biodiesel from the oil, which equates to a 90% biodiesel yield. Losses result from the fat separating out of the oil and accumulating at the bottom of the mixture. Additionally, the leftover algae membranes that made it through the oil filtering process mixed with the fat, and contributed to the losses as well as the green coloring.

7. The System Cost

The total budget allocated to this ***student capstone design project*** was USD 400. The team was able to design a system which used approximately USD 280 of the budget for resources and components such as water bottles, shelving, CO_2 supply, PVC piping, tubing, and an algae culture growth kit for the initial design. Due to design changes and unforeseen complications with the algae culture growth kit, the team effectively retrofitted the initial system and its components for a final system that cost approximately USD 140 to produce. Components used for the final design incorporated shelving, totes, PVC piping, ratchet straps, and lye water. Areas of improvement for the system include keeping large particulates out of the system with covers or screens for the totes. Another design improvement that could be made to the system would be to devise a way to integrate the biodiesel production process into the algae growth system.

8. Safety Considerations

Converting lipid material to biodiesel is often accomplished by using methanol, also known as methyl alcohol (or alternatively isopropyl alcohol), and lye (sodium hydroxide, NaOH).

The oil is first heated to 54-60 °C (130-140 °F). Next, the methanol and lye are mixed to form a meth-oxide solution. Caution must be exercised during this step, as this mixing is an exothermic process. If the compounds are mixed too quickly, and the boiling point of methanol, 64 ° C (148 °F), is exceeded, a violent explosion can occur.

Once the lye is dissolved in methanol, the meth-oxide solution can be added to the heated oil while stirring continuously. This combination causes transesterification - a process by which “the oil and methanol crosscut one another’s chemical bonds to form new chemical bonds.” When this is complete, two compounds result: biodiesel, and glycerol.

The solution is then left to settle for a period of about 24 hours, during which the biodiesel and glycerol separate owing to their different densities. One or the other can then be removed from the container.

Before use in a combustion engine, the biodiesel must be washed and filtered until its concentration reaches B100 (100% biodiesel). This is roughly the same process that would be used in a large-scale biodiesel operation. The only difference is that specialized equipment would be used to efficiently heat, mix, and separate the various compounds in much larger quantities.

Methanol is a volatile and flammable liquid with a distinctive alcoholic odor. Ingesting as little as 10 ml of pure methanol can cause permanent blindness by destruction of the optic nerve. Thirty ml is potentially fatal.

Lye is a caustic substance. It is able to burn or corrode organic tissue. It can damage exposed skin and cause burns, blindness, and even death when consumed.

For these reasons, the process of transesterification should only be carried out with extreme caution while wearing an approved lab coat, goggles and gloves.

9. Conclusions

The system designed provides a zero-emission solution for growing algae and converting its lipid materials into biodiesel fuel. This system could further benefit the environment if it is placed next to industrial plants that emit high levels of CO_2, which the algae use for their chemical processes. Consequently, the carbon footprint of these industrial plants will be reduced.

The vertical design of the system used is an efficient use of space for algae growth. Despite this, an algae pond dug into the ground would likely allow large amounts of algae to be grown for less cost. This would need to be explored in a follow up project to determine the most cost-efficient bioreactor design. Further, implementing an automated feeding, collection, and oil extraction system would decrease the time needed to produce the biodiesel by reducing inefficiencies due to human input. An automated system would likely allow algae biodiesel to be produced for much less cost in the long run. Such a system would require much less human labor which should result in cheaper prices after the initial investment of the automated system has been recouped.

The current cost of biodiesel derived from algae is much higher than traditional petro-diesel derived from petroleum. A study conducted by Auburn University found the average cost of biodiesel to be USD 33/gallon (7.67 €/litre) in California, far above the current cost of traditional petro-diesel [9].

This student design project was carried out during summer in Flint, Michigan. Implementing a similar project outdoors is not recommended during cold and cloudy seasons.

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