Algae: Pond Powered Biofuels

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Special Thanks to:
Executive Summary

The US is the world’s largest energy consumer, which results in adverse effects on the climate, overdependence on foreign oil and economic uncertainties. To mitigate these harmful effects, biological alternatives to fossil fuel sources are being investigated. Biofuels today are primarily produced from first-generation feedstocks such as corn, sugarcane, soybeans and rapeseeds. Unfortunately, reliance on crop-based feedstocks has led to problems such as land depletion, continued fossil fuel usage, competition with food, and increased water use. Algae, on the other hand, are an appealing feedstock for next-generation biofuels because they can make use of natural or underutilized resources, can be produced domestically, consume carbon dioxide via photosynthesis and have the potential to displace fossil fuel usage in an environmentally sound manner. Therefore, finding ways to overcome the technical, economic, cultural and policy barriers to the use of algae for biofuels production presents a compelling opportunity for society.

Algae are simple unicellular organisms that produce carbohydrates, proteins and lipids as a result of photosynthesis. Sunlight, water, nutrients and arable land are the major requirements for growing algae. Thankfully, the water can be brackish or saline, thereby avoiding competition with freshwater resources, and the land can be non-arable, avoiding competition with food production. The products of algae growth can be used for many different fuels: lipids can be processed into chemical feedstocks, biodiesel or jet fuel; biomass can be fermented into ethanol, anaerobically digested to produce methane, or burned directly for power generation; or simply used as a carbon sink. Compared to terrestrial crops, algae utilize solar energy more efficiently and because they are not limited to one growth cycle per year, they can be harvested much more often.

Texas presents a unique opportunity for algae production because it contains the basic resources needed to grow algae in abundant quantities: Texas produces over 170 million metric tons of CO$_2$ annually (more than any other state, and ahead of all but 6 countries); contains abundant saline and brackish aquifers; receives abundant sunlight; and has an impressive knowledge base and technical expertise within the energy and refining industry. Additionally, as one of the largest producers of energy in the world, Texas has an incentive to produce the next generation of fuels. These qualities make Texas an interesting case study for the growth and production of algae for biofuel use on a large scale.

Algae as a biofuel feedstock have garnered much interest in the venture capital, investment, and research arenas with many companies, universities and laboratories leading research efforts. The rise in investments has increased yearly and is a promising sign that algae-based biofuels have the potential to contribute to our nation’s energy portfolio. Research areas include genetic modification of algal species for efficient sunlight utilization or producing specific hydrocarbon chains for direct processing into gasoline, diesel and jet fuel. Varying levels of success have been achieved by companies and research labs but none have succeeded in producing algae oil on a scale sufficient for meeting US transportation requirements. To understand the long-term planning and other issues, accurate and objective assessments are needed to assess the feasibility of algae growth.
**Intro/Need for Alternative Fuels**

The need for clean, economical and sustainable sources of energy is more important than ever. Our nation has prospered with cheap and abundant energy allowing for widespread industrialization in the last century providing high standards of living and economic prosperity. Fossil fuels have been at the center of these accomplishments but also represent many pressing problems our society faces: adverse economic effects due to increasing energy prices, environmental implications from the combustion of fossil fuels, and many foreign policy vulnerabilities for imported fuels. Energy has become increasingly more expensive in the last few years with a barrel of oil costing $70 in July 2007 rising to over $130 in July of 2008. [1] While oil has fallen to under $70 a barrel in Fall 2008, the uncertainty and fluctuation in fuel prices have had adverse effects on our economy and in many cases making our daily lives more expensive.

In addition to the economic implications, environmental concerns have been a major driver for the reformulation of our energy policy. Current energy sources for transportation are dominated by petroleum, which emits harmful pollutants and carbon dioxide into the atmosphere upon combustion. Consensus within the scientific and most of the political community is that emission of greenhouse gases from the combustion of fossil fuels is detrimental to the environment and results in worse air quality and alteration of global biological systems. Limiting the use of traditional fossil fuels in favor of biological sources has been proposed to reduce the amount of harmful greenhouse gases released into the atmosphere because biological sources take up carbon from the environment during photosynthesis, creating a closed carbon cycle.

The US is also highly dependent on foreign sources of petroleum, which raises the specter of national security implications from the oil trade. Over one-quarter of the world’s petroleum is consumed by the US, representing over 21 million barrels per day (MMBD). Of the 21 MMBD, over two-thirds are imported from foreign nations including Saudi Arabia, Iran, Venezuela, Russia, Canada and Mexico. In particular, revenue from oil exports to the US have helped Russia, Venezuela and Iran exercise leverage in foreign policy discussions by strengthening their economies and expanding their militaries and social programs. [2, 3] In the US, domestic fuel production has been proposed to provide energy security and independence from foreign producers. In that vein, domestically-produced biofuels have the potential to offset a portion of foreign oil imported into the US.

The dramatic rise in fuel costs over the past few years and concerns about climate effects have renewed a focus on alternative energy sources. In particular, policymakers continuously look to domestically produced biofuels to help minimize uncertainties in world oil markets and reduce impacts of climate change. In 2007 Congress passed the Energy Independence and Security Act (EISA 2007), which among other initiatives, provides a federal mandate to increase domestic biofuel production to 36 billion gallons by the year 2020. Of the 36 billion gallons, only 15 billion can come from traditional starch-based corn ethanol. The remaining 21 billion gallons are to be comprised of cellulosic ethanol and biodiesel from a number of advanced feedstocks, of which algae is one.
Interest in biofuels, and in particular algae, is not a new concept however. The Department of Energy’s National Renewable Energy Laboratory (NREL) in Golden, CO led an extensive program researching the use of algae for biofuels from 1978 to 1996. The program was disbanded, but with the recent rise in energy prices and concern about climate change and carbon emissions, there is a renewed interest in algae-based biofuels.

Why Algae?

Algae are an appealing feedstock because they possess many biological and technical attributes that help us overcome problems that are presented by many first generation biofuel feedstocks. Complaints about first-generation feedstocks include their requirements for vast fossil fuel inputs, water intensity, impact on soil erosion, net energy balance, limited harvesting frequency, requirements for arable land, competition with food, and incompatibility with existing infrastructure. Biofuels are currently produced from terrestrial crop feedstocks such as corn and sugarcane for ethanol and soybeans and palm plants for biodiesel. Biodiesel produced from soybeans and palm plants have intensive resource, nutrient and land requirements that undermine the ultimate goal of providing clean, sustainable and domestically produced sources of fuel. Relying solely on first generation feedstocks would require a significant amount of land to meet our current fuel consumption. Furthermore, concerns for counterproductive environmental effects have been raised recently over the destruction of CO₂ absorbing rainforests and wetlands in Brazil and Indonesia to plant sugarcane and palm plants for biofuel production.

By contrast, algae are more efficient at utilizing sunlight than terrestrial plants, [4] consume harmful pollutants, and have minimal resource requirements and do not compete with food or agriculture for precious resources. [5] Algae have higher growth rates than terrestrial plants, allowing a large quantity of biomass to be produced in a shorter amount of time in a smaller area. Algae growth rates of 10 to 50 g m⁻² d⁻¹ (grams of algal mass per square meter per day) have been published in the literature. [6] Compared to terrestrial plants such as corn and soy, algae have shorter harvest times because they can double their mass every 24 hours. [7] These short harvest times allow for much more efficient and rapid production of algae compared to corn or soy crops.

To illustrate the land requirements for biofuel crop production, yields of different oil producing crops can be examined, as shown in Table 1. The US consumes over 40 billion gallons of diesel fuel in one year and currently has over 587 million acres devoted to agricultural crop production. In order to replace this consumption with soybean-based biodiesel over 142% of our current cropland would be used. Higher oil content plants such as jatropha and palms fare better by requiring 34% and 11% of our current cropland, but are not necessarily compatible with our climate. As an improvement, microalgae with varying oil contents would require less than 6% of the amount of land used for crops.
Table 1. Typical land requirements of first generation biodiesel feedstocks to meet current US diesel fuel consumption (40 billion gallons per year). Yields and land data from: [8, 9].

<table>
<thead>
<tr>
<th>Crop</th>
<th>Oil yield (gal/acre-yr)</th>
<th>Land area needed (million acre)</th>
<th>Percent of existing US cropping area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>18</td>
<td>2,222</td>
<td>379%</td>
</tr>
<tr>
<td>Cotton</td>
<td>35</td>
<td>1,143</td>
<td>195%</td>
</tr>
<tr>
<td>Soybean</td>
<td>48</td>
<td>833</td>
<td>142%</td>
</tr>
<tr>
<td>Canola</td>
<td>127</td>
<td>315</td>
<td>54%</td>
</tr>
<tr>
<td>Jatropha</td>
<td>202</td>
<td>198</td>
<td>34%</td>
</tr>
<tr>
<td>Oil palm</td>
<td>635</td>
<td>63</td>
<td>11%</td>
</tr>
<tr>
<td>Microalgae (15% oil)</td>
<td>1,200</td>
<td>33</td>
<td>6%</td>
</tr>
<tr>
<td>Microalgae (50% oil)</td>
<td>10,000</td>
<td>4</td>
<td>1%</td>
</tr>
</tbody>
</table>

Because algae production systems will be in man-made structures and presumably located in the sunniest parts of the nation (the desert Southwest), marginal or underutilized land can be used to grow algae instead of competing with agricultural land or destroying forests for biofuel production. [10, 11]

Resource requirements for algae growth
One of the most compelling advantages of using algae as a biofuel feedstock is that the resource requirements are less intensive compared to other crops and plants. Algae require only a few basic resources to grow successfully: CO$_2$, water, sunlight and nutrients. Sunlight is normally abundant throughout most of the year and utilized more efficiently than terrestrial crops. CO$_2$ can be obtained in high concentrations from power plants and industrial processes, or at ambient concentrations from the atmosphere. Algae are less selective when choosing water sources to grow in than terrestrial crops such as corn or soybeans. Algae will grow in most water sources with varying pH levels from fresh drinking water, saline or brackish aquifers and wastewater effluent. [12] Brackish, or moderately salty water, is abundant and provides a suitable environment and resource for algae to grow in. It is this aspect that is especially appealing because the algae do not have to compete with agriculture, human, or other uses for fresh water supplies. Recent studies have shown that current biofuel production cause significant consumption of water resources. [13, 14] The water intensity of algae-based biofuels production should not be underestimated, but fortunately algae are not faced with massive irrigation or soil erosion issues that plague crop-based biofuel production.

Efficient utilization of solar energy
Algae are more efficient at utilizing solar energy than higher order plants due to their unicellular structure and minimal competition between plant functions such as growing branches, stalks, leaves and other structures. [15] Higher solar energy utilization allows for a higher yield of usable biomass and lipids compared to higher order plants under similar conditions. Typical photosynthetic efficiencies, the amount of energy stored as biomass or lipids in the plant compared to the available energy, are on the order of 5-6% for algae, ~4% for sugar cane and ~1% for corn crops. [16] Higher photosynthetic efficiencies allow
for greater amounts of energy to be utilized and stored within the algae cell to be extracted later in the form of oil or biomass.

Natural CO$_2$ sequestration by algae
Algae, by virtue of photosynthesis, are adept at sequestering CO$_2$ or nitrogen oxides from the atmosphere.

When coal is burned to create electricity, carbon locked in the coal by plants and animals over millions of years is released into the atmosphere resulting in a net increase in the total amount of carbon. There is potential to effectively reduce the amount of carbon dioxide and nitrogen oxides released into the atmosphere from many stationary emitters by feeding the carbon-rich flue gas to the algae. [18-23] Algae are therefore able to fix approximately 1.8 kg of CO$_2$ fixed for every 1 kg of algae biomass produced. [7] Based on the literature, one can determine that approximately 40 ha of algae ponds are required to fix the carbon emitted from one MW of power generated from a coal plant. [24]

The carbon used to create lipids in the algae is still released into the atmosphere upon combustion of the fuel, but the overall amount of carbon has been used twice: once for energy production in a power plant and second to grow algae for transportation fuels. As carbon regulations are likely to be set in the future, using algae to consume CO$_2$ will become even more appealing.

Nutrient requirements for algae
Algae require smaller amounts of nutrients to grow compared to terrestrial, higher order plants because their simple cell structure. However, algae must be provided a wider array of nutrients because they lack the plant functions necessary to form organic compounds. [24] Higher order plants are able to form different compounds themselves and therefore require a smaller diversity of nutrients. Typical nutrient requirements for algae are nitrogen and phosphorus both of which traditionally come from fertilizers produced from fossil fuels for modern farming.

Benefits of wastewater treatment and algae growth
There is a unique opportunity to both treat wastewater and provide nutrients to algae using nutrient-rich effluent streams. Treated wastewater is rich in nitrogen and phosphorus, which if left to flow into waterways, can spawn unwanted algae blooms and result in eutrophication. [25] These nutrients can instead be utilized by algae, which provide the co-benefit of producing biofuels and removing nitrogen and phosphorus.

Oil Content and composition of algae
Algae can be oil-rich organisms. Oil content, the percentage of oil per weight of dry biomass, typically ranges from 20 to 50% depending on the species. [7] This oil is composed of many different types of lipids that can be processed easily into biodiesel, jet fuel or other chemicals. Algae species and their typical oil contents are presented in Table 2 below.
Table 2. Algae species and typical oil content. [7]

<table>
<thead>
<tr>
<th>Microalga</th>
<th>Oil Content (% dry weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Botryococcus braunii</td>
<td>25-75</td>
</tr>
<tr>
<td>Chlorella sp.</td>
<td>28-32</td>
</tr>
<tr>
<td>Crphtecodinium cohnii</td>
<td>20</td>
</tr>
<tr>
<td>Cylindrotheca sp.</td>
<td>16-37</td>
</tr>
<tr>
<td>Dunaliella primolecta</td>
<td>23</td>
</tr>
<tr>
<td>Isochrysis sp.</td>
<td>25-33</td>
</tr>
<tr>
<td>Monallanthus salina</td>
<td>&gt;20</td>
</tr>
<tr>
<td>Nannochloris sp.</td>
<td>20-35</td>
</tr>
<tr>
<td>Nannochloropsis sp.</td>
<td>31-68</td>
</tr>
<tr>
<td>Neochloris oleoabundans</td>
<td>35-54</td>
</tr>
<tr>
<td>Nitzschia sp.</td>
<td>45-47</td>
</tr>
<tr>
<td>Phaeodactylum tricornutum</td>
<td>20-30</td>
</tr>
<tr>
<td>Schiochytrium sp.</td>
<td>50-77</td>
</tr>
<tr>
<td>Tetraseknus sueica</td>
<td>15-23</td>
</tr>
</tbody>
</table>

Compared to terrestrial crops such as corn, soy or even palm plants, algae are far more oil-rich and offer a higher yield of oil per unit of land in a year. Table 3 lists several first generation biofuel crops with their oil yields (gallons/acre-year).

Table 3. Oil output of different biofuel feedstocks. [8]

<table>
<thead>
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<td>10,000</td>
</tr>
</tbody>
</table>

The main components of algae are carbohydrates, proteins, and lipids. [26] Of particular interest are the lipids, which can be processed into valuable fuel products such as biodiesel (through transesterification), jet fuel, and even traditional gasoline and diesel depending on the species. Lipids produced from algae contain saturated and polar lipids, which are suitable for use as a fuel feedstock and are contained in higher concentrations than other plants. [27]

Other uses for algal products
In addition to producing highly valuable lipids, algae can be used for alternative sources of power generation or animal feed. Once the algal biomass has been dried and the useful oils removed it is possible to burn the remaining biomass to provide a heat source for a small-scale power plant, much in the same way that coal or other woody biomass is burned to create heat and power. The biomass does not have to be combusted directly though. By anaerobically digesting the biomass, biogas (a combination of methane and carbon dioxide) can be produced and used as a substitute for natural gas. [28, 29] The resulting methane can either be combusted in a power plant to create electricity or used for home heating and cooking. Additionally, by burning the biomass directly or using the produced methane, an algae plant or farm could potentially power some of the production processes further reducing the environmental impact and cost by purchasing energy from fossil fuel-based plants. [7] The dry biomass can also be fermented to produce ethanol or used as animal feed. [30]

Algae as the original source of oil
Using algae as a source of fuel is not a new concept. A significant portion of the petroleum that is extracted from the ground today was deposited between 112 and 125 million years ago during the Early Cretaceous epoch. [31] Ocean-based organic material thrived in the volcanic and carbon-rich environment, which was then deposited on the seafloor to be compressed and stored for millions of years. The petroleum that we extract from the ground today is the result of millions of years of high temperatures and pressures from geologic forces transforming the organic matter into what we extract as petroleum today. By growing algae in ponds or reactors, we are trying to simulate the same procedure, but while avoiding the millions of years of processing.

Texas as a case study for large-scale algae-based biofuels production

Texas is a valuable case study for the production of algae for biofuels. The state contains abundant resources required for algae growth and is home to universities, researchers and decades of experience in the energy industry. Significant knowledge and expertise in refining and processing has been fostered by the oil and gas industry in Texas along with significant investments in infrastructure and capital required for large-scale energy production. In recent history, Texas has been positioned to lead on energy issues and because of that experience has the opportunity to lead in the next-generation of energy fuels. Texas also serves as a great case study that can later be expanded to larger regions such as the US because it contains many different climates, geographical locations, resources and challenges that are representative of broader locations. By analyzing and learning from Texas case studies, more informed decisions can be made when ramping up production and implementing biofuels on a larger scale.

Available Resources in Texas
The main resources required for sustainable algae growth are sunlight, CO₂, brackish or saline water, land and an assortment of nutrients. Texas contains all of these resources in significant amounts that provide an opportunity to grow algae for biofuels on a large scale. For example, Texas receives approximately 375 W/m² of solar energy annually, which is typical of southwestern states. [32] This average accounts for periods of lower and higher solar insolation (winter and summer, respectively) as well as variations
across the state: East Texas receives less sunlight than West Texas. As an illustration, solar insolation is depicted for the state in the following figures. Solar insolation variation averaged over a period of three years is depicted in Figure 1 for three geographical regions in the state along with a statewide distribution of average annual solar insolation in Figure 2.

![Average annual solar insolation at different locations in Texas](image)

**Figure 1.** Monthly variations of solar radiation at selected locations throughout Texas. Data obtained from [32]

![General location and relative intensity of annual solar radiation for Texas](image)

**Figure 2.** General location and relative intensity of annual solar radiation for Texas. [33]

**Water Resources in Texas**

In addition to freshwater streams and lakes, Texas has abundant water resources in the form of underground saline aquifers. Saline, or brackish, water is defined as having between 1,000 mg/L and
10,000 mg/L of total dissolved solids. As water makes its way into the ground and through geologic formations minerals and solids from rocks, soil and other materials dissolve into the water. The water then carries these new deposits with it until it is captured in an aquifer. Brackish water can be found in most of Texas’ 9 major and 21 minor aquifers totaling over 2.6 trillion gallons (8.5 million acre-feet). [34] Figure 3 depicts the locations of the major and minor aquifers in Texas. The major aquifers of Texas are depicted in the left diagram while the smaller, minor aquifers are shown on the right. Different colors correspond to individual aquifers.

![Figure 3. Major and Minor aquifers in Texas.](image)

Other water sources available are process water from oil extraction and effluent from wastewater treatment plants. Wastewater is an untapped resource and is a potential source for water for algae growth because of its high nutrient concentration, which can be used directly by algae. Treated wastewater is currently released into local rivers or waterways after it has been processed at a facility. This water can lead to unwanted and uncontrolled algae or bacterial growth in rivers or waterways, which results in eutrophication and damage to ecosystems. Utilizing wastewater effluent as a source for algae production accomplishes the twin goals of producing biofuels while limiting the amount of fertilizers that are released into waterways. Texas contains many wastewater treatment plants that can provide algae producers with an excellent source of nutrients. Locations of wastewater treatment plants in Texas are shown in Figure 4 below.
Texas also contains CO$_2$ sources that can be used for algae growth. Ambient CO$_2$ can be used to grow algae but higher growth rates can be achieved by increasing the amount of CO$_2$ from atmospheric concentrations (0.036%) up to 10 to 15%, which are typical of coal and natural gas plant flue gases. [18] As of 2005, Texas contained 19 coal-fired power plants and 164 natural gas plants for a total of 170 and 96 million metric tons of CO$_2$ emissions, respectively. [37] A representation of CO$_2$ emissions in Texas is presented in Figure 5.

Figure 4. Wastewater treatment locations in Texas. [36]

Figure 5. Estimated percentage of CO$_2$ emissions in Texas by county. [38]

Algae production facilities would ideally be located in locations that balance the available resources: sunlight, water and CO$_2$ must be present in the area to grow algae economically. Ponds or reactors could potentially be sited next to power plants or wastewater treatment facilities to make use of those resources.
Texas Fuel Consumption
Texas also has an incentive to use sustainable, domestically produced fuel because it is one of the largest fuel consumers and CO₂ emitters in the world, ranking above many countries. Texas consumes almost 17 billion gallons of gasoline and diesel per year and emits nearly 192 million metric tons of CO₂ from transportation sources (2004 data). [39-41] Compared to the rest of the US, Texas is the largest consumer of petroleum and emitter of greenhouse gas pollutants. Texas has a unique opportunity to reduce its emission of CO₂ from power plant and transportation sources while producing valuable biofuels.

Energy Industry in Texas: Knowledge and Infrastructure
The potential for biofuels from algae and other next generation feedstocks provide Texas a unique opportunity to leapfrog other biofuels-producing states to lead in the next era of energy. Texas has been a prominent player in the energy industry since the discovery of the Spindletop oil field in Beaumont and subsequent discoveries along the Texas coastline and fields in the western regions of the state. Today Texas has over 26 refineries processing 7.4 million barrels per day [42] and the state has derived much of its growth and prosperity from petroleum resources and the petrochemical industry. A significant amount of knowledge, skill sets and expertise have been developed in over a century in the energy industry. Consequently, Texas has both abundant natural resources and a wealth of human talent available.

Major universities in the state have also benefited from oil discoveries with the creation of the Permanent University Fund (PUF) in 1876. One million acres of state land were originally set aside so that The University of Texas at Austin and Texas A&M University would receive revenues on land leases. Once oil was discovered, revenue from the PUF increased dramatically leading the PUF to be a primary source of funding for the universities. These universities, as well as others in the state, contribute to cutting edge research, development and achievements in the field of energy and the environment. Texas universities have benefited from petroleum oil in the past century and are poised to leverage these talents to propel itself into the next century and generation of energy.

Overview of Growth Methods
Algae are typically found growing in ponds, waterways, or other locations that receive sunlight, water and CO₂. Manmade production of algae tends to mimic the natural environments to achieve optimal growth conditions. Growth depends on many factors and can be optimized for temperature, [43] sunlight utilization, [44, 45] pH control, [46] fluid mechanics and more. Algae production systems can be organized into two distinct categories: open ponds and closed photobioreactors. Open ponds are simple expanses of water recessed into the ground with some mechanism to deliver CO₂ and nutrients with paddle wheels to circulate the algae broth. Closed photobioreactors are a broad category referring to systems that are enclosed and allowing more precise control over growth conditions and resource management. Table 4 presents a short comparison of open pond systems and closed photobioreactors. Each system has benefits and drawbacks with respect to optimal growth conditions. Brief overviews and discussions of both systems comprise the next two sections.
Table 4. Advantages and disadvantages of open and closed algae growth systems. [47, 48]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Open Pond</th>
<th>Closed Photobioreactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td>simple</td>
<td>more complicated - varies by design</td>
</tr>
<tr>
<td>Cost</td>
<td>cheaper to construct, operate</td>
<td>more expensive construction, operation</td>
</tr>
<tr>
<td>Typical Growth Rates (g/m2-day)</td>
<td>low: 10-25</td>
<td>variable: 1-500</td>
</tr>
<tr>
<td>Water losses</td>
<td>high</td>
<td>Low</td>
</tr>
<tr>
<td>Typical biomass concentration</td>
<td>low: 0.1-0.2 g/L</td>
<td>high: 2-8 g/L</td>
</tr>
<tr>
<td>Temperature Control</td>
<td>difficult</td>
<td>easily controlled</td>
</tr>
<tr>
<td>Species Control</td>
<td>difficult</td>
<td>Simple</td>
</tr>
<tr>
<td>Contamination</td>
<td>high risk</td>
<td>low risk</td>
</tr>
<tr>
<td>Light utilization</td>
<td>poor</td>
<td>very high</td>
</tr>
<tr>
<td>CO2 losses to atmosphere</td>
<td>high</td>
<td>almost none</td>
</tr>
<tr>
<td>Area requirements</td>
<td>large</td>
<td>Small</td>
</tr>
<tr>
<td>Depth/diameter of water</td>
<td>0.3 m</td>
<td>0.1 m</td>
</tr>
<tr>
<td>Surface:volume ratio (m2/m3)</td>
<td>~6</td>
<td>60-400</td>
</tr>
</tbody>
</table>

Open Pond Reactors

Open pond reactors are the simplest growth system that can be built. Pond reactors are unsophisticated and consist of little more than a recess in the ground, sometimes lined with plastic, fashioned into a raceway pattern. Algae and nutrients are fed into the beginning of the raceway while paddlewheels help stir the broth and provide flow around the pond. A typical open pond reactor is shown in Figure 6 below.

![Figure 6. Raceway pond from Seambiotic in Israel. [49]](image)

Actual open ponds range in size of up to 1 hectare (1 hectare = 10,000 sq. m.) and volumes ranging from 100 liters to over 10 billion liters. [7, 50] Open ponds are the most common production facilities due to their simplicity, lower cost of construction and operation, which is very well understood. Open ponds are
used almost extensively in growing algae for nutritional supplements (Spirulina) and have been used for many years. Unfortunately open ponds are not without drawbacks. The simplicity of the systems leads to problems with controlling the growth environment and operating conditions delivering less than ideal algae yields. While ponds are more productive per acre of land than terrestrial crops, a significant amount of land must be used to grow algae in ponds.

Most ponds are open to the atmosphere, which allows unwanted or competing strains of algae with undesirable properties to enter the pond. These competing algae strains can potentially take over the pond rendering the harvest useless. Contamination by unwanted strains can be avoided by covering the ponds with a greenhouse or tarp, and even using pesticides to eliminate certain species of algae. CO₂ is usually delivered to the ponds through natural mass transfer from the atmosphere to the water. Since ambient CO₂ only composes 0.036% of the air, growth is typically limited by the amount of CO₂ that can be delivered into the water and subsequently to the algae cells. CO₂ can be bubbled through the water to increase the amount of dissolved gas, but unused CO₂ still escapes into the atmosphere. Other growth conditions such as temperature and pH are difficult to control as well. Temperature is difficult to maintain because of heat transfer to the environment and nutrient and oxygen production affect the pH of the water. Growth rates are generally lower for open ponds because sunlight energy is diminished below the water surface leaving algae cells at the bottom of the pond with little energy for growth. Mixing can be implemented to allow algae cells adequate exposure to photons, but mixing is not a full solution.

Closed Photobioreactors
While pond reactors are open to the atmosphere, closed photobioreactors are enclosed systems usually in the form of tubes or plates that contain the algae broth. They are more complicated than open pond systems but allow for much finer control over growth conditions and inputs in a more compact area. [48, 51] A tubular photobioreactor (shown in Figure 7) is one of the more common closed designs. Other designs include flat plate reactors, inclined plates, helical coils and combinations of different designs. Closed reactors are generally more expensive to construct and operate due to materials, pumps and control equipment required, but overall algae growth is higher compared to open systems because of greater control over the growth conditions and inputs.
Closed tubular or plate type photobioreactors tend to have smaller dimensions compared with open pond systems. Tube diameters are typically less than 0.1 meters and can be up to 80 meters long. [7] Some of the problems with growth in ponds are resolved when using a closed reactor. For example, complete control over temperature, pH, nutrient inputs and mixing is achievable using a closed system. This control allows growth conditions to be optimized and repeated consistently for maximum or desired yield. Unwanted algae strains are not a concern since the system is isolated from the outside environment. Higher concentrations of CO$_2$ can be delivered to the algae with less escaping to the atmosphere while unused CO$_2$ can be recaptured and reused. Because the depth of algae broth is reduced from 0.3 m to less than 0.1 m, fewer photons are attenuated in the broth allowing more algae cells to receive sunlight energy. [47, 52] Closed photobioreactors are usually not operated on large scales (many hectares) due to prohibitive costs and difficult operation and maintenance. In order for closed photobioreactors to be more prevalent, construction and operation costs must decrease. Cost aside, higher CO$_2$ concentration, temperature control and light availability allow closed photobioreactors higher growth rates than open ponds.

**Basics of the Algae Growth Process**

Production of algae is a straightforward process consisting of growing the algae by providing necessary inputs for photosynthesis, harvesting/dewatering and oil extraction. The fundamental mechanism governing algae growth is photosynthesis. It is in the photosynthesis process that light-driven reactions split water and assimilate carbon into the biomass. [53]. Energy in the form of photons is absorbed by the algae cells, which convert the inorganic compounds of CO$_2$ and H$_2$O into sugars and oxygen. The sugars are eventually converted into carbohydrates, starches, proteins and lipids within the algae cells. A diagram of the overall growth and harvesting process is presented in Figure 8.
In order to extract the valuable lipids from within the algae cells a series of steps must be undertaken to isolate the algae cells and oil. The traditional process begins by separating the algae biomass from the water broth in the dewatering stage using either centrifuges, filtration or flocculation techniques. Centrifuges collect biomass by spinning the algae-water broth so that water is flung away from the algae cells. Flocculation involves precipitating algae cells out of solution so that they can be removed out of solution. Once the algae cells have been collected the oil must be removed from the cells. There are multiple techniques for removing oil: solvent extraction or the mechanical method of squeezing the cells. Solvent extraction involves drying of the algae cells and then adding a solvent (typically n-hexane) to bind with the oil. The solvent-oil mixture can then be separated from the algae biomass. The solvent is then removed through another process so that only algae oil remains. Squeezing (or pressing) is simply a mechanical process that compresses the algae cells so that oil escapes from within the cell walls. Once the oil is removed it can be processed into biodiesel, jet fuel, ethanol, synthetic fuels or other chemicals.

Issues/Complications of Growing Algae

While algae have many potential benefits for the production of biofuels, CO₂ sequestration and more, there are many complications with growing algae reliably on a production scale. For example, the dewatering and oil extraction steps represent some of the more energy intensive processes in algae production. Dewatering algae cells is energy intensive, expensive and difficult to manage on a large scale. Removing the algae from the water broth is typically performed as a batch process, which limits the total amount of algae that can be processed. For example, centrifugation is considered too expensive and energy intensive to operate on a large scale, though it works reliably. In order to efficiently scale-up algae production lower cost and higher throughput methods must be developed. Researchers at The University of Texas’ Center for Electromechanics are currently working on removing oil directly from the algae cells suspended in broth using a high-voltage electrolysis process. Techniques like this have the potential to allow large volumes of algae broth to be processed economically and efficiently.

The entire life cycle of algae production must be taken into consideration when determining the net benefit to the environment and society. Using resources that would otherwise contribute to climate change or foul waterways are appealing incentives to grow algae. For example, nutrient sources must be chosen wisely so that environmental impacts are shifted towards other aspects of the production process. If the phosphorus and nitrogen used for growing algae come from fertilizer or fossil fuel sources the net environmental benefit is diminished.
In addition to sustainable selection of nutrient sources, the water impact of producing algae must not be overlooked. Growing any plant will require a substantial amount of water, but algae have the benefit of being able to grow in brackish water so the impact on potable water resources is lessened. Also, less water is lost producing algae than terrestrial crops; terrestrial crops incur significant losses from irrigation and runoff while algae ponds lose water mainly to evaporation. If algae are to be regarded as a sustainable fuel source water impacts must be considered and minimized.

Concerns have also been raised about excess algae and nutrient runoff from production facilities. Once algae are harvested and oil extracted, the water and remaining biomass must be disposed of. Excess water is normally recycled back to the ponds or tubes, but could be released into waterways. These actions might lead to problems similar to releasing treated wastewater into streams or rivers. The dead or crushed algae cells can also be dumped or disposed of in waterways. The idea for releasing green algae sludge into waterways could disrupt natural ecosystems and be met with resistance from the public. If the “waste” products of algae production are not recycled to grow more algae, care must be taken to minimize the effect their disposal has on the environment.

Temperature effects play an important role in algae growth with maximum growth occurring between 15°C and 25°C. [43] Thermal energy can be lost from the growth systems at night or in winter while temperatures can increase in the reactors due to high solar insolation. Regulating temperatures in growth systems is achieved more easily in photobioreactors because they are closed to the atmosphere but more difficult for open pond systems. An important example of temperature effects was noted in NREL’s Aquatic Species Program. Experimental ponds had been set up in Roswell, NM to test long term production of algae. The program was successful except that consistent growth rates could not be reproduced due to low temperatures during the night. [57] Problems controlling and maintaining temperature remains a barrier to algae growth at large-scales.

As it stands now, large-scale algae production for biofuels is cost-prohibitive and too expensive to compete with traditional fossil fuels, even with increasing prices. Several studies have investigated the economics of algae production and conclude that the current processes are too expensive to run on a large-scale and must be made more efficient. Algae oil has been estimated to cost approximately $10.60 per gallon while one of the cheapest sources of vegetable oil (palm oil) costs around $2 per gallon. [7] High costs of production can be attributed to difficulty in growing large amounts of biomass and the aforementioned hurdles in extracting the useful oils efficiently. As production and harvesting techniques mature, algae-based oil will become more cost-competitive with traditional fuels and other advanced feedstocks.

The technical feasibility of algae biofuels must also be investigated and addressed. Many different fuels and chemicals can be produced from algae including biodiesel, ethanol, jet fuel and synthetic fuels. These products must maintain compatibility with existing refining and transportation infrastructure. Infrastructure networks are expensive to build from the ground up so existing pipelines and refineries would ideally be utilized for processing and delivery of fuel. Algae-based fuels must also meet specific
ASTM standards for use in automobiles and aircrafts. Problems with combustion and flow properties and low temperatures are problems facing first-generation biofuels currently. To use bio-derived jet fuel, the cold flow properties must be maintained so that combustion processes are not affected at high altitudes.

Location and siting of algae facilities must also be taken into consideration. Ideally, algae production facilities would be located in close proximity to resources (areas with the most photons, power plants, aquifers or wastewater treatment plants, etc…) while minimizing transportation costs of algae-oil and biomass for further processing. In order to avoid competition with agricultural or other valuable uses algae “farms” could be located on marginal or under-utilized land. Public perception of large expanses of land covered with algae must be considered too. In order to displace and meet a significant percentage of our fuel consumption, land area equal to approximately 1 to 6% of our current agricultural crops would be required. There might be difficulty in convincing the public of the advantages of covering millions of acres with algae ponds or tubes.

Policy recommendations and regimes are also a challenging aspect of algae biofuels. EISA 2007 currently has provisions for advanced biofuel research and development, but future challenges to biofuel strategies must be anticipated. Water rights, algae biomass disposal and economic incentives will need to be decided to avoid complications. Also, the prospect of carbon regulation (either in the form of a carbon tax or cap-and-trade system) will impact algae biofuel production. By putting a price on carbon CO$_2$ would transform a waste product into a valuable resource that can be used to grow fuel, making the economics of algae production more attractive.

**Startups/Investments**

The Algae space has recently been scaling up very rapidly, with investments rising from $2 million four years ago to $260 million so far this year.

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There are many start-ups entering the market such as HR Biopetroleum, Petrosun, Solazyme, Greenfuel and Amyris, some of which have achieved commercial production. There is also the interesting trend of major Oil producers partnering with these startups to get their foot in the door of the algae opportunity. Shell partnered with HR Biopetroleum and Chevron has also made a deal with Solazyme. Jonathan Wolfson, CEO of Solazyme said about the deal, “"Building a relationship with Chevron Technology Ventures is an important step toward commercialization of Solazyme's technology which fits cleanly into Chevron's existing refining and fuels distribution infrastructure."

Of these Algae companies HR Biopetroleum is building a facility in Kona Hawaii, Valcent has one in El Paso, Texas, and PetroSun has built a plant in Rio Hondo, Texas.
The most interesting aspect of these various companies is that they span the technological gamut, from using growth ponds, to closed loop systems, using a carbon boost to using sugar as a boosting agent. The end products are as different as the methods they use: from algae for nutraceuticals to bio crude, and even 91 Octane bio gasoline from Sapphire.

Company Profiles

GreenFuels is a Cambridge Massachusetts based company that is developing a technology that utilizes exhaust gas emissions from power plants and industrial facilities to help grow their algae. First they scrub the emissions to remove some of the Nitrogen and Carbon compounds, then they feed it into their industrial scale algae farm, which can use untreated water resources. They have raised a large amount of Venture capital funding, and have installed their technology at various industrial and power plants globally.

Solazyme is a San Francisco based company that focuses using either cellulosic biomass or sugar to produce bio-oils for use in the: energy, pharmaceutical, industrial chemical and nutraceutical markets. Solazyme’s model is to gain licensing agreements for the production of their products. It has also raised significant venture capital financing.

Sapphire Energy is a San Diego based company that has raised over $100 million dollars from investors such as Bill Gates and was mentioned in Time Magazine’s “Best Inventions of 2008”. Sapphire seeks to produce 91 octane bio-gasoline, that can be used directly from the traditional fuel pump.

One company that is notable for being publicly traded and located in Texas is Valcent, which is part of Global Green Solutions (GGRN). They have built a test scale vertical bio-reactor in El Paso and are currently working to scale it up to industrial production. The self-contained nature of this system is interesting because it uses very little water, which holds great promise for growing algae in sunny but arid areas of Earth, such as El Paso.

Conclusion

Increasingly expensive and volatile prices for fossil fuel-based fuels and adverse environmental impacts are driving research for alternative sources of energy. Algae present a unique opportunity to produce necessary transportation fuels while mitigating the effects of its production and use on the environment. The US and Texas have many incentives to investigate the production of algae-based biofuels because of the vast economic, environmental and foreign policy benefits. Algae can make use of natural and underutilized resources, be produced domestically, reduce atmospheric carbon dioxide, reduce pollution in waterways and potentially displace fossil fuel usage in an environmentally sound manner.
While algae are a very promising feedstock, many challenges inhibit the production of large amounts of algae in an economic and sustainable manner. If algae are to be produced in quantities sufficient for displacing billions of gallons of petroleum fuels, efficient methods for growing algae in ponds or photobioreactors are needed to minimize resource, operation and maintenance costs. The harvesting, dewatering and oil extraction steps of the production process will need to become more efficient in order to handle large volumes of biomass and algae oil economically. Additionally, policy-makers will have to balance the need for cheap, clean and sustainable sources of energy while avoiding the complications and problems associated with first-generation fuels. Accurate and objective assessments will also be a vital resource in determining long-term planning and feasibility of growing algae for transportation fuels.

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49. Seambiotic.