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Microalgae as a Feedstock for Biofuel Production

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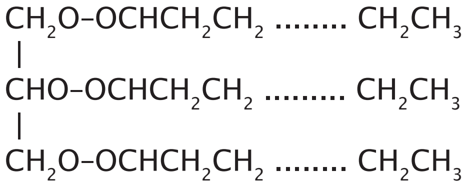
With energy prices reaching historical highs, biodiesel as an alternative fuel is increasingly attracting attention. Currently, biodiesel is made from a variety of feedstocks, including pure vegetable oils, waste cooking oils, and animal fat; however, the limited supply of these feedstocks impedes the further expansion of biodiesel production. Microalgae have long been recognized as potentially good sources for biofuel production because of their high oil content and rapid biomass production. In recent years, use of microalgae as an alternative biodiesel feedstock has gained renewed interest from researchers, entrepreneurs, and the general public. The objective of this publication is to introduce the basics of algal-biofuel production and the current status of this emerging biodiesel source.

Current Feedstock for Biodiesel Production

Biodiesel can be made from any oil/lipid source; the major components of these sources are tricylglycerol molecules (TAGs, figure 1). In general, biodiesel feedstock can be categorized into three groups:

1. Pure Vegetable Oil

The first group is pure oils derived from various crops and plants such as soybean, canola (rapeseed), corn, cottonseed, flax, sunflower, peanut, and palm. These are the most widely used feedstocks by commercial biodiesel producers. The oil composition from vegetable crops is pure; this cuts down on preprocessing steps and makes for a more consistent quality of biodiesel product. However, there is an obvious disadvantage for vegetable oils as the biodiesel feedstock: Wide-scale production of crops for biodiesel feedstock can cause an increase in worldwide food and commodity prices. Such a "food vs. fuels" debate has reached national attention when using vegetable oils for biodiesel production.



$$\begin{array}{l} \mathrm{CH_2O{-}OCHCH_2CH_2} \ldots\ldots\ldots \mathrm{CH_2CH_3} \\ | \\ \mathrm{CHO{-}OCHCH_2CH_2} \ldots\ldots\ldots \mathrm{CH_2CH_3} \\ | \\ \mathrm{CH_2O{-}OCHCH_2CH_2} \ldots\ldots\ldots \mathrm{CH_2CH_3} \end{array}$$

Figure 1. Molecular structure of tricylglycerols

2. Animal Fats

The second group of feedstock for biodiesel production is fats and tallow derived from animals. Compared to plant crops, these fats frequently offer an economic advantage because they are often priced favorably for conversion into biodiesel. Animal fat, however, has its own disadvantage when used for producing biodiesel. Because it contains high amounts of saturated fat, biodiesel made from this feedstock tends to gel, limiting widespread application of this type of fuel, particularly for winter-time use (Wen et al. 2006).

3. Waste Cooking Oils

The third group of biodiesel feedstock is comprised of recycled oil and grease from restaurants and food processing plants. The use of recycled oil and grease is often highlighted in the mainstream news because it utilizes waste products that can otherwise be disposal problems. However, recycled oils have many impurities that require preprocessing to ensure a biodiesel product of consistent quality. Preprocessing also makes the biodiesel production process more complicated and costly (Canakci and Van Gerpen 1999, 2001).

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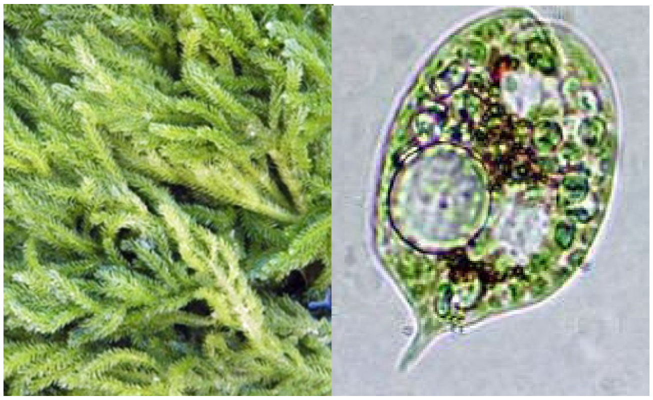
Background of Algae

Macroalgae vs. Microalgae

Algae are organisms that grow in aquatic environments and use light and carbon dioxide (CO_2) to create biomass. There are two classifications of algae: macroalgae and microalgae. Macroalgae are the large (measured in inches), multi-cellular algae often seen growing in ponds. These larger algae can grow in a variety of ways. The largest multi-cellular algae are called seaweed; an example is the giant kelp plant which can be more than 100 feet long. Microalgae, on the other hand, are tiny (measured in micrometers), unicellular algae that normally grow in suspension within a body of water.



Macroalgae & Microalgae

Algae as a Bioenergy Source

Algae can also be used to generate energy in several ways. One of the most efficient ways is through utilization of the algal oils to produce biodiesel. Some algae can even produce hydrogen gas under specialized growth conditions. The biomass from algae can also be burned, similar to wood, to generate heat and electricity.

Algal biomass contains three main components: carbohydrates, proteins, and lipids/natural oils. Because the bulk of the natural oil made by microalgae is in the form of TAGs (figure 1)—which is the right kind of oil for producing biodiesel—microalgae are the exclusive focus in the algae-to-biofuel arena. Microalgae grow very quickly compared to terrestrial crops. They commonly double in size every 24 hours. During the peak growth phase, some microalgae can double every 3.5 hours (Chisti 2007). Oil content of microalgae is usually between 20 percent and 50 percent (dry weight, table 1), while some strains can reach as high as 80 percent (Metting 1996; Spolaore et al. 2006).

Table 1. Oil content of microalgae

Microalga	Oil content (% dry weight)
Botryococcus braunii	25–75
Chlorella sp.	28–32
Crypthecodinium cohnii	20
Cylindrotheca sp.	16–37
Nitzschia sp.	45–47
Phaeodactylum tricornutum	20–30
Schizochytrium sp.	50–77
Tetraselmis suecia	15–23

Source: Adapted from Chisti 2007

Compared with terrestrial crops—which take a season to grow and only contain a maximum of about 5 percent dry weight of oil—microalgae grow quickly and contain high oil content (Chisti 2007). This is why microalgae are the focus in the algae-to-biofuel arena. Table 2 lists the potential yields of oil produced by various crops and compares these values to oil yields from an open pond growing microalgae.

Table 2. Oil yields based on crop type

Crop	Oil yield (gallons/acre)
Corn	18
Soybeans	48
Canola	127
Jatropha	202
Coconut	287
Oil Palm	636
Microalgae[1]	6283–14641

Source: Adapted from Chisti 2007

[1] Oil content ranges from 30 percent to 70 percent of dry biomass

Other Uses of Algae

In addition to producing biofuel, algae can also be explored for a variety of other uses, such as fertilizer, pollution control, and human nutrition. Certain species of algae can be land-applied for use as an organic fertilizer, either in its raw or semi-decomposed form (Thomas 2002). Algae can be grown in ponds to collect fertilizer runoff from farms; the nutrient-rich algae can then be collected and reapplied as fertilizer, potentially reducing crop-production costs. In wastewater-treatment facilities, microalgae can be used to reduce the amount of toxic chemicals needed to clean and purify water. In addition, algae can also be used for reducing the emissions of CO_2 from power plants.

Seaweeds are often used as food—for people and for livestock. For example, it is often used in food preparation in Asia. Seaweed is rich in many vitamins, including A, B1, B2, B6, C, and niacin. Algae are also rich in iodine, potassium, iron, magnesium, and calcium (Mondragon and Mondragon 2003). Many types of algae are also rich in omega-3 fatty acids, and as such, are used as diet supplements and components of livestock feed.

The Synergy of Coal and Algae

One advantage of using algae biomass for biodiesel production is the potential mitigation of CO_2 emissions from power plants. Coal is, by far, the largest fossil-energy resource available in the world. About one-fourth of the world's coal reserves reside in the United States. Consumption of coal will continue to grow over the coming decades, both in the United States and the world. Through photosynthetic metabolism, microalgae absorb CO_2 and release oxygen. If an algae farm is built close to a power plant, CO_2 produced by the power plant could be utilized as a carbon source for algal growth, and the carbon emissions would be reduced by recycling waste CO_2 from power plants into clean-burning biodiesel.

Algae Mass-Cultivation Systems

Most microalgae are strictly photosynthetic, i.e., they need light and carbon dioxide as energy and carbon sources. This culture mode is usually called photoautotrophic. Some algae species, however, are capable of growing in darkness and of using organic carbons (such as glucose or acetate) as energy and carbon sources. This culture mode is termed heterotrophic. Due to high capital and operational costs, heterotrophic-algal culture is hard to justify for biodiesel production. In order to minimize costs, algal-biofuel production usually must rely on photoautotrophic-algal growth using sunlight as a free source of light—even though it lowers productivity due to daily and seasonal variations in the amount of light available.

Photoautotrophic microalgae require several things to grow. Because they are photosynthetic, they need a light source, carbon dioxide, water, and inorganic salts. The water temperature should be between 15°C and 30°C (approximately 60°F to 80°F) for optimal growth. The growth medium must contribute the inorganic elements that help make up the algal cell, such as nitrogen, phosphorus, iron, and sometimes silicon (Grobbelaar 2004). For large-scale production of microalgae, algal cells are continuously mixed to prevent the algal biomass from settling (Molina Grima et al. 1999), and nutrients are provided during daylight hours when the algae are reproducing. However, up to one-quarter of algal biomass produced during the day can be lost through respiration during the night (Chisti 2007).

There are a variety of photoautotrophic-based, microalgal culture systems. For example, the algae can be grown in suspension or attached on solid surface. Each system has its own advantages and disadvantages. Currently, suspend-based open ponds and enclosed photobioreactors are commonly used for algal-biofuel production. In general, an open pond is simply a series of outdoor "raceways," while a photobioreactor is a sophisticated reactor design that can be placed indoors (greenhouse) or outdoors. The details of the two systems are described below.

Open Ponds

Open ponds are the oldest and simplest systems for mass cultivation of microalgae. In this system, the shallow pond is usually about one-foot deep, and algae are cultured under conditions identical to their natural environment. The pond is designed in a raceway configuration, in which a paddlewheel circulates and mixes the algal cells and nutrients (figure 2). The raceways are typically made from poured concrete, or they are simply dug into the earth and lined with a plastic liner to prevent the ground from soaking up the liquid. Baffles in the channel guide the flow around the bends in order to minimize space.

The system is often operated in a continuous mode, i.e., the fresh feed (containing nutrients including nitrogen phosphorus and inorganic salts) is added in front of the paddlewheel, and algal broth is harvested behind the paddlewheel after it has circulated through the loop. Depending on the nutrients required by algal species, several sources of wastewater—such as dairy/swine lagoon effluent and municipal wastewater—can be used for algal culture. For some marine-type microalgae, seawater or water with high salinity can be used.

Open ponds

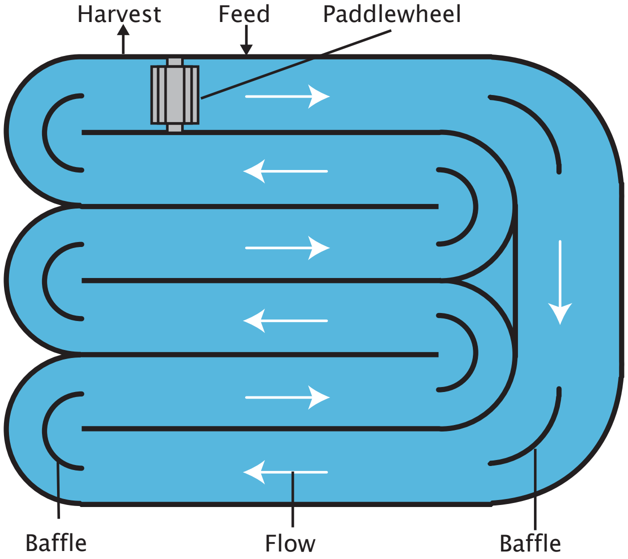


Figure 2. Open pond system

Although open ponds cost less to build and operate than enclosed photobioreactors, this culture system has its intrinsic disadvantages. Because they are open-air systems, they often experience a lot of water loss due to evaporation. Thus, open ponds do not allow microalgae to use carbon dioxide as efficiently, and biomass production is limited (Chisti 2007). Biomass productivity is also limited by contamination with unwanted algal species as well as organisms that feed on algae. In addition, optimal culture conditions are difficult to maintain in open ponds, and recovering the biomass from such a dilute culture is expensive (Molina Grima et al. 1999).

Enclosed Photobioreactors

Enclosed photobioreactors have been employed to overcome the contamination and evaporation problems encountered in open ponds (Molina Grima et al. 1999). These systems are made of transparent materials and are generally placed outdoors for illumination by natural light. The cultivation vessels have a large surface area-to-volume ratio.

The most widely used photobioreactor is a tubular design, which has a number of clear transparent tubes, usually aligned with the sun's rays (figure 3). The tubes are generally less than 10 centimeters in diameter to maximize sunlight penetration. The medium broth is circulated through a pump to the tubes, where it is exposed to light for photosynthesis, and then back to a reservoir. A portion of the algae is usually harvested after it passes through the solar collection tubes, making continuous algal culture possible. In some photobioreactors, the tubes are coiled spirals to form what is known as a helical-tubular photobioreactor. These systems sometimes require artificial illumination, which adds to production costs, so this technology is only used for high-value products—not biodiesel feedstock. Either a mechanical pump or an airlift pump maintain a highly turbulent flow within the reactor, which prevents the algal biomass from settling (Chisti 2007).

Photobioreactors

The photosynthesis process generates oxygen. In an open raceway system, this is not a problem as the oxygen is simply returned to the atmosphere. However, in the closed photobioreactor, the oxygen levels will build up until they inhibit and poison the algae. The culture must periodically be returned to a degassing zone—an area where the algal broth is bubbled with air to remove the excess oxygen.

Also, the algae use carbon dioxide, which can cause carbon starvation and an increase in pH. Therefore, carbon dioxide must be fed into the system in order to successfully cultivate the microalgae on a large scale. Photobioreactors require cooling during daylight hours, and the temperature must be regulated in night hours as well. This may be done through heat exchangers located either in the tubes themselves or in the degassing column.

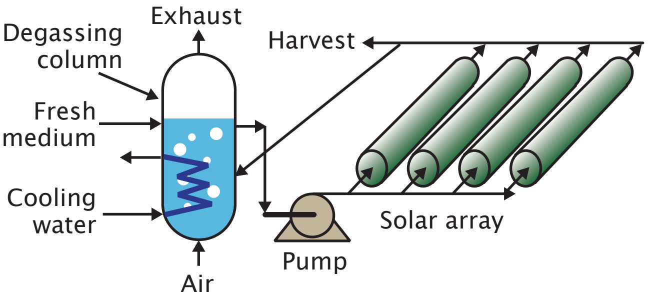


Figure 3. Schematic tubular photobioreactor

The advantages of enclosed photobioreactors are obvious. They can overcome the problems of contamination and evaporation encountered in open ponds (Molina Grima et al. 1999). The biomass productivity of photobioreactors can average 13 times more than that of a traditional raceway pond. Harvest of biomass from photobioreactors is less expensive than from raceway ponds, because the typical algal biomass is about 30 times as concentrated as the biomass found in raceways (Chisti 2007).

However, enclosed photobioreactors also have some disadvantages. For example, the reactors are difficult to scale up. Moreover, light limitation cannot be entirely overcome because light penetration is inversely proportional to the cell concentration. Attachment of cells to the tubes' walls may also prevent light penetration. Although enclosed systems can enhance biomass concentration, the growth of microalgae is still suboptimal due to variations in temperature and light intensity.

After growing in open ponds or photobioreactors, the microalgae biomass needs to be harvested for further processing. The commonly used harvest method is through gravity settlement or centrifuge. The oil from the biomass is extracted through solvent and further processed into biodiesel.

Research and Development of Algal–Biofuel Production

Algal-biofuel research originated in 1979, when the U.S. Department of Energy (DOE) initiated a research program called the Aquatic Species Program (ASP). The program was closed in 1995 due to a budget reduction. Over the 16-year project period, ASP pursued research in three major areas.

The first area was the study of the biological aspect of microalgae. It included screening and collecting a variety of algal species to access their potential for high oil production, investigating the physiology and biochemistry of the algae, and using molecular-biology and genetic-engineering techniques to enhance the oil yield.

The second research area was the development of algal mass-production systems. Several demonstration culture systems located in California, Hawaii, and New Mexico were conducted during the project period. However, in these outdoor systems, it was difficult to maintain the algal-oil production capacity originally obtained in the laboratory scale, and researchers encountered a severe contamination of undesirable native species. It should be noted that DOE suggested open ponds as the major system for algal-biofuel production because of their relative low cost. The cost of enclosed photobioreactors was still prohibitive due to capital and maintenance costs, particularly for production of biofuels.

The third research area was analysis of the resource availability, including land, water, and CO_2 resources. DOE concluded that there were significant amounts of land, water, and CO_2 to support the algal-biofuel technology. In summary, after 16 years of research, DOE concluded that algal-biofuel production was still too expensive to be commercialized in the near future. In its research, three factors limited commercial algal production: the difficulty of maintaining desirable species in the culture system, the low yield of algal oil, and the high cost of harvesting the algal biomass.

In recent years, with energy prices reaching historic highs, algal-biofuel production has gained renewed interest. Both university research groups and start-up businesses are researching and developing new methods to improve algal-process efficiency, with a final goal of commercial algal-biofuel production. The research and development efforts can be categorized into several areas:

1. Increasing oil content of existing strains or selecting new strains with high oil content;
2. Increasing the growth rate of algae;
3. Developing robust algal-growing systems in either open-air or enclosed environments;
4. Developing co-products other than oil;
5. Using algae in bioremediation; and
6. Developing an efficient oil-extraction method.

One way to achieve these goals is to genetically and metabolically alter algal species. The other way is to develop new growth technologies or to improve existing ones so that the same goals listed above are met.

However, it should be noted that this new wave of interest has yet to result in a significant breakthrough.

Economics of Algal-Biofuel Production

The production cost of algal oil depends on many factors, such as yield of biomass from the culture system, oil content, scale of production systems, and cost of recovering oil from algal biomass. Currently, algal-oil production is still far more expensive than petroleum-diesel fuels. For example, Chisti (2007) estimated the production cost of algae oil from a photobioreactor with an annual production capacity of 10,000 tons per year. Assuming the oil content of the algae to be approximately 30 percent, the author determined a production cost of \$2.80 per liter (\$10.50 per gallon) of algal oil. This estimation did not include costs of converting algal oil to biodiesel, distribution and marketing costs for biodiesel, and taxes. At the same time, the petroleum-diesel price in Virginia was \$3.80 to \$4.50 per gallon.

Whether algal oil can be an economic source for biofuel in the future is still highly dependent on the petroleum-oil price. Chisti (2007) used the following equation to estimate the cost of algal oil where it can be a competitive substitute for petroleum diesel:

$$C_{\text{algal oil}} = 25.9 \times 10^{-3}\, C_{\text{petroleum}}$$

where: C_{algal} oil is the price of
microalgal oil in dollars per
gallon and
$C_{\text{petroleum}}$ is the price of crude oil
in dollars per barrel

This equation assumes that algal oil has roughly 80 percent of the caloric energy value of crude petroleum. For example, with petroleum priced at \$100 per barrel, algal oil should cost no more than \$2.59 per gallon in order to be competitive with petroleum diesel.

Algal Biofuel in the Near Future

Algal biofuel is an ideal biofuel candidate which eventually could replace petroleum-based fuel due to several advantages, such as high oil content, high production, less land, etc. Currently, algal-biofuel production is still too expensive to be commercialized. Due to the static cost associated with oil extraction and biodiesel processing and the variability of algal-biomass production, future cost-saving efforts for algal-oil production should focus on the production method of the oil-rich algae itself. This needs to be approached through enhancing algal biology (in terms of biomass yield and oil content) and culture-system engineering. In addition, using all aspects of the microalgae for producing value-added products besides algal fuel—such as in an integrated biorefinery—is an appealing way to lower the cost of algal-biofuel production. Indeed, microalgae contain a large percentage of oil, with the remaining parts consisting of large quantities of proteins, carbohydrates, and other nutrients (Spolaore et al. 2006). This makes the residue after oil extraction attractive for use as animal feed or in other value-added products.

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