ChEn5751 Biochemical Engineering
Microalgal Biodiesel Production – Culture

OVERVIEW

I. Overall Issues with Microalgal in relation to Culture and Cultivation Conditions

II. Microalgae Growth Requirements

III. Mass Cultivation of Algae:
   A. Open Ponds
   B. Enclosed System, Photobioreactors
   C. Heterotrophic Growth
   D. Growth at Municipal Sewage Plants
   E. Attached System, Algal Turf Scrubber

IV. Conclusions Recommendations
   A. Best Alternative
   B. Engineering Considerations
   C. Unresolved Issues
Advantages

1. Algae can double its volume Overnight

2. Unlike other biofuel feedstocks (e.g., soy, corn), it can be harvested day after day

3. Up to 50 percent of an alga’s body weight is comprised of oil, whereas oil-palm trees (currently the largest source of oil for biofuel) yield just 20 percent of their weight in oil

4. Yield of Algae oil versus other sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Gallons of Oil per Acre per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soy</td>
<td>50</td>
</tr>
<tr>
<td>Canola</td>
<td>150</td>
</tr>
<tr>
<td>Palm</td>
<td>650</td>
</tr>
<tr>
<td>Algae</td>
<td>10,000 (expected)</td>
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</tbody>
</table>
Issues

- **Commercialization of Algal biofuel production must overcome high costs** associated with production, harvesting, and preparation for traditional extraction and transesterification into fatty acid methyl esters.

- The reaction to make biodiesel, once the lipids from the algae are extracted, is the same as that used presently with vegetable oils. *Transesterification.*

- **Most methods used to extract the oil from algal biomass rely on a dry biomass product.** Regardless of the cultivation method of the algae, the cells must be dried before reaction.

- **Excess costs associated with biomass pretreatment** (removing the water from the cell) cause the feedstock costs to be the highest expense associated with biodiesel production.
Biomass Pretreatment – removing water from the cells

1. **Use Lypholization (freeze drying)** to ensure low homogenous moisture content in the cells
   - Li, Horsman et al. 2007, Li, Du et al; Refaat, Attia et al. 2008
   - Does not scale well at an industrial level due to its high cost and slow dehydration times.

2. **Flocculation** - Use **metal ions** (e.g., Fe$^{2+}$) in combination with cellulose or synthetic fibers to form **Aggregates**
   - Aggregates Settle due to size
   - Use belt, or belt filter press dewatering.
   - Cost constraints require separation and recovery of the flocculation chemicals for re-use
     - (R Putt, Auburn University), (Algae Research Proj Newcastle Univ)

3. **Industrial scale Oven drying** can lead to damage of lipid feedstock.

4. **Using temperatures low enough to protect the lipids** increases the drying time

5. **Other** methods, e.g., forced air drying, increase in the price
Biomass Pretreatment – removing water from the cells

5. Microalgal oil costs greatly exceed existing vegetable oils (e.g., soybean oil) because of:
   - Existing infrastructure is exclusively for terrestrial crops
   - Lack of investment in the culture of large scale microalgal aquatic organisms (Eriksen 2008).
1. Microalgae growth Requirements.
   - Light Source for photosynthesis – usually sunlight is used to minimize cost
   - Carbon dioxide, water, and inorganic salts.
   - The temperature between 15 and 30°C (~60-80 °F) for optimal growth (Li, Hu et al. 2007).

2. Some microalgae may be grown heterotrophically
   - Without light
   - Organic carbon source rather than CO₂

3. Growth medium must contain
   - Essential nutrients:
     - Nitrogen, phosphorus, iron,
     - Sometimes silicon (Grobbelaar 2004)

4. Algal cells must be continuously mixed
   to prevent biomass from settling (Molina, Fernandez et al. 1999)
5. Nutrients provided during daylight hours when algae reproducing.

6. Up to 25% of the algal biomass produced during the day can be lost due to respiration during the night (Chisti 2007).

7. Cultivation Methods for Algae and Example Companies:
   - Open ponds, “high rate ponds” (HRP)
     20 grams per square meter per day
     (National Renewable Energy Laboratory, LiveFuels, GreenStar)
   - Enclosed systems, Photobioreactors
     (Mighty Algae, GreenFuel Technologies, Algae-Link)
   - Heterotrophic Growth Some species can also be grown very densely using heterotrophic growth (Borowitzka 1998).
     (Solazyme, Inc.)
   - Growing Algae at Municipal Sewage Treatment Plants
     (pilot plant in Norfolk, by Old Dominion University)
   - Attached systems: e.g., Algal Turf Scrubber (ATS) used to sequester nutrients (Craggs, Adey et al. 1995) or Remove Toxins
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OPEN PONDS / Raceways (HRP, 20 grams per square meter per day)

1. **Oldest and simplest systems** for mass cultivation of microalgae.
   - Shallow pond usually about 1 foot deep
   - Algae are cultured under conditions identical to natural environment.

2. The pond designed in a “raceway” or “track” configuration
   - Typically constructed from poured concrete, or
   - Dug into the earth and lined with a plastic to prevent loss of liquid.

3. **Mixing**
   - **Paddlewheel** provides circulation and mixing of the algal cells and nutrients
   - Baffles in the channel guide flow around bends, to minimize space and loss.
   - Alternately, In-ground **bubble columns** add CO₂ to the pond water, and pumps provide 10,000 gpm flowrates to circulate pond water eliminating expensive paddlewheels.

4. **Medium is added in front of the paddlewheel**

5. **Algal broth is harvested behind the paddlewheel,**
   after it has circulated through the loop.
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OPEN PONDS - OPEN Raceways

Schematic of a high rate pond (HRP), or paddlewheel raceway design
Seambiotic, Inc., Israel
Raceway/Paddle-wheel open-pond algae cultivation.
Growth fed by CO$_2$ flue-gas from a nearby IEC power plant.
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OPEN PONDS - OPEN Raceways

Kent Bio Energy’s Development Facility in Southern California
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OPEN PONDS - OPEN Raceways

1. Advantage
   - Cost less to build and operate than enclosed photobioreactors
   - High productivity (> 1,000 gallons per acre annually)
   - Production costs limited to around 20 cents per pound
   - Energy requirements very small versus \( \approx 6 \text{ Wh/g} \) energy content of algae

2. Disadvantages:
   - Water must be just the right temperature for algae to proliferate
   - Excessive water loss due to evaporation prevents efficient use of carbon dioxide. Atmospheric levels of \( \text{CO}_2 \) inadequate to spur exponential growth
   - Biomass production is limited (Christi 2007).
   - Contamination with invasive species, unwanted algal species, or organisms that feed on the algae
   - Optimal culture conditions difficult to maintain in open ponds
   - Recovering the biomass from a dilute cell yield of a few hundred ppm and concentrating them to 1-5 weight per cent for downstream processing is expensive (Molina, Fernandez et al. 1999).
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Closed photobioreactors

1. Great Diversity in Shape/Size. Two Broad Categories:
   - Use of natural light
   - Use of artificial illumination (Apt and Behrens 1999).

2. Enclosed Photobioreactor Design
   - Similar to conventional fermenters, but needs a supply of light and carbon dioxide.
   - Often tubular to enable greater light penetration.
   - Tubes, whether helical or straight, maximize surface area to volume ratio and let the algae grow as they circulate.
   - Oxygen scrubber to remove the gas from the system and expel it to the atmosphere. (Toxicity at high oxygen levels kill microalgae)
   - Other: triangular chambers made from sheets of polyethylene plastic – supplemental carbon dioxide bubbled through the system.
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Closed photobioreactors

Schematic of Tubular Enclosed Photobioreactor
Colorado's Solix Biofuels harvesting algae with a field of bioreactors - triangular chambers made from sheets of polyethylene plastic with supplemental carbon dioxide bubbled through the system. (inset)
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Closed photobioreactors

1. Advantages
   a. Avoid the problems of contamination and evaporation encountered in open ponds (Molina, Fernandez et al. 2000).
   b. Biomass productivity can be 13 times greater than raceway ponds on average (Chisti 2007).
   c. Harvest of biomass less expensive than that from a raceway pond, since the typical algal biomass is about 30 times as concentrated as the biomass found in raceways (Chisti 2007).

2. Disadvantages
   a. Variations in light and temperature (common in all photoautotrophic systems) can cause suboptimal growth of microalgae (Wen & Chen 2003)
   b. Scale-up very difficult and very expensive (Molina, Fernandez et al. 1999).
   c. Initial capital cost very high, due to complexity, and differences in design and construction (Eriksen 2008).
   d. Cost can be justified when producing a high value product (e.g., pharmaceutical), but a low value commodity, (e.g., fuel), might not recover initial construction costs in a reasonable time.
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Closed photobioreactors

2. Disadvantages (continued)
   
   e. Light Penetration
      (for both Enclosed Photobioreactors and Open Ponds)
      
      ▪ Light penetration is inversely proportional to cell density (Chen 1996) and decreases exponentially with penetration depth.
      
      ▪ Paradoxically, photobioreactors perform worse as they produce more.
      
      ▪ Attachment of cells to the tube walls may also prevent light penetration.

   f. Toxicity at High Oxygen Concentration Kills The Microalgae.
      
      ▪ Oxygen levels build up as the algae undergo respiration
      
      ▪ To mitigate, oxygen scrubbers are used to remove the gas from system
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Closed photobioreactors

GreenFuel Technologies, Cambridge, Mass.-based algae firm
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Heterotrophic culture systems

1. Growth Conditions
   ▪ Carbon from an organic carbon source in the medium, rather than through carbon dioxide (Chen 2006)
   ▪ Does not undergo photosynthesis, doesn’t require a light source.

2. Heterotrophic production of lipids by microalgae dependent on:
   ▪ Culture Age
   ▪ Media Nutrients
   ▪ Environmental Factors: Temperature, pH, And Salinity (Wen and Chen 2003).

3. Requirements for Microalgal Heterotrophic Production
   (Wen and Chen 2003)
   ▪ Ability to divide and metabolize in the dark;
   ▪ Ability to grow on inexpensive and easily sterilized media;
   ▪ Ability to adapt rapidly to the new environment (e.g., short or no lag-phase when inoculated to fresh media);
   ▪ Ability to withstand hydrodynamic stresses in fermenters and peripheral equipment.
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Heterotrophic culture systems

4. Advantages
   - Produce high levels of lipids and less protein than photosynthetic algae (Miao and Wu 2006).
   - Cells achieve higher cell density than in photoautotrophic growth (Vazhappilly and Chen 1998).
   - Cell density not limited by light inhibition as with the other growth methods.
   - In a Fermenter, can grow to a density of 150 g/L (Wu and Shi 2008).

5. Disadvantages
   - Not all species of microalgae can grow in heterotrophic culture. Best used in monocultures of a single alga species.
   - Requires extensive sterilization of media and equipment.
   - In medium rich with organic carbon sources (sugars or organic acids), algae can easily be out-competed by bacteria present in the medium (Skelton, Burkholder et al. 2008).
   - Expensive production - acceptable for high value products (e.g., pharmaceuticals) but not for a fuel or energy product (Schneider 2006).

6. Cost and complexity associated with a sterile process makes it unfeasible for large scale algae production for biofuel.
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Growing Algae at Municipal Sewage Treatment Plants

1. Nutrient-rich wastewater from agriculture, industry and municipal sewage piped to and purged at algae-growing stations. Biofuels produced

2. Plastic tanks on roofs of municipal Sewage Treatment Plants filled with treated sewage

3. Process:
   - Three days of growth in tanks
   - Algae scooped from container with fine-mesh bag
   - Air-dried until resemble a small cake
   - Blasted into a high-temperature converter, which captures the oils within the algae and creates biodiesel.

4. Projection: 200 gallons of biodiesel a day ($600,000 a year)
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Growing Algae at Municipal Sewage Treatment Plants

Pilot Algae biodiesel plant at Municipal Sewage Plant, Norfolk Virginia run by scientists at Old Dominion University, Virginia
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Growing Algae at Municipal Sewage Treatment Plants

5. Advantages:
   - Both micro- and macroalgae can be used for waste water treatment
   - Indigenous species can be used, so treatment does not have to be confined to avoid contamination
   - Can treat many types of contaminants. Great for removing Nitrogen (N) and Phosphorous (P)
   - Many years of research as a means of removing heavy metals from industrial wastewater sources
   - Current research focuses on new combinations of algal species and heavy metal samples (Gupta, Shrivastava et al, 2001).

6. Disadvantage:
   - Lower treatment capability of algae in cold weather (unable to treat waste water) or with subdued light conditions when using living algae
   - Algal photosynthesis and productivity slow down in cold weather or when there is a lower light intensity and sub-optimal temperature range for growth (Wang, Qi, et al. 2004)
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Attached Culture Systems - Algae Turf Scrubbers

1. Keeps the algae in place and bring the nutrients to it, rather than
   suspending the microalgae in a culture media

2. Process:
   - Water washed over the algae at short time intervals, alternating with full
     exposure to sunlight. Algae remove Nitrogen and Phosphorus from water.
     - Overcomes light inhibition problems while delivering maximum load of nutrients
       and gases to the algae (Adey and Goertemiller 1987).

3. Applications
   - Often employed to treat river water. A small ATS, treating 1 acre of river water
     for any N, P, and heavy metal pollution can produce 140 kg/day of dry biomass
     (Algaeturfscrubber.com, 2009).
   - Tested to treat manure effluent (Mulbry, Kondrad et al. 2008, Pizarro, Mulbry et
     al. 2006, Craggs, Adey et al. 1995)
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Attached Culture Systems - Algae Turf Scrubbers

Algal Turf Scrubber takes polluted water from a creek and processes it through plastic mats, where algae remove phosphorus and nitrogen from the water.

The Algae is then harvested for use as compost, fuel or cattle feed.
Attached Culture Systems - Algae Turf Scrubbers

1. Advantages:
   - Productive and Efficient
   - Ability to harvest the algae on its substrate, rather than filtering it out of media
   - Easy to Scale up (e.g. Hydromentia, Inc. Florida has implemented 1,440-acre ATS facility to treat river water, 3 billion gallons per day

2. Disadvantages:
   - ATS systems have only been used to cultivate macroalgae
   - Total lipid production low when algal colony consists of macroalgae. Also, access to excess nitrogen reduces lipid production (Sheehan et al 1998)
   - Using ATS systems to simultaneously treat wastewater and produce lipids for biofuels represents a Recent development and has not been explored extensively (Mulbry, Kondrdard et al. 2008).
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Conclusions / Recommendations

1. Best Alternative: Open Pond Algae Cultivation
   - High productivity (> 1,000 gallons per acre annually)
   - Ability to use land not suitable for row crops
   - Most cost and energy effective means of production for algal biofuels
   - Production costs constrained to approximately 20 cents per pound

2. Engineering Considerations of Open-Pond Algae Farming
   - Front end process which provides the nutrients, and high rate ponds (20 grams per square meter per day)
   - Back end process which harvests the algae and produces a liquid transportation fuel.
   - Large scale algae farming requires concentrated carbon dioxide from carbon capture, because algae are 50% carbon and air-to-pond transport of atmospheric carbon dioxide insufficient for high-rate ponds.
   - Small scale algae farming could employ animal waste as a source of nutrients via anaerobic digesters
   - In-ground bubble columns could efficiently supply CO₂ to the pond water, and their pumps could provide 10,000 gpm flowrates needed to circulate pond water in 5 acre ponds, thereby eliminating expensive paddlewheels.
Unresolved Issues

1. Harvesting micro-algae, at pond concentrations of a few hundred ppm, and concentrating to 1-5 weight per cent for downstream processing

2. Pretreatment of Biomass

4. Carbon Cycle - Conversion of the algal biomass to fuels feedstocks

   a. Lipids for bio-diesel production.

   b. Anaerobic digestion of entire algal biomass to methane, with the carbon dioxide co-product returned to the ponds via bubble columns.

      Methane purified for injection in natural gas pipelines, or liquefied to LNG for truck transport.

   Mass Balance: Carbon dioxide IN (photosynthesis) \( \approx \) Methane OUT (anaerobic digestion)