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Technoeconomic Analysis of Algal Photobioreactors for Oil Production

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Presentation Outline

- Background
- Predicting lipid production from Algae
- Theoretical maximum lipid production
- Production estimates for bioreactors
- Inefficiencies of algal lipid production
- Economic considerations
- Conclusions

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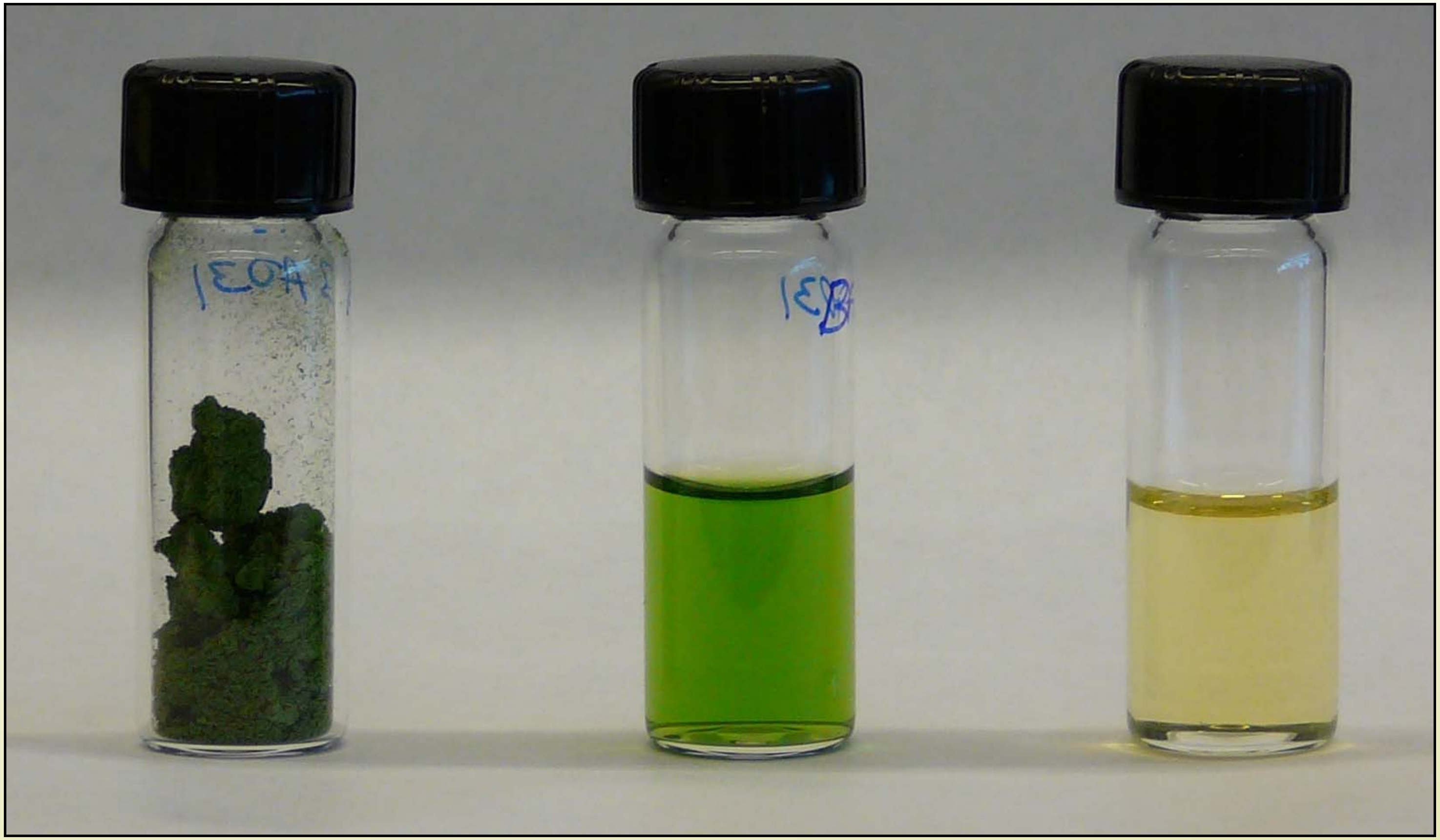
Algae to Biodiesel



Dried Algae

Algae Lipid Extract

Biodiesel

Algae: integrated solar collection, conversion, and storage system.

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Bioreactor Options

Open Ponds

Advantages
- **Simple/cheap to construct**
- **Easier to operate & maintain**

Disadvantages *
- **poor light utilization**
- **difficulty controlling light and temperature**
- **contamination & evaporation**

*** greenhouses overcome some disadvantages**

Closed Photobioreactors

Advantages:
- ***Higher Productivity***
- **Less contamination, water use, & CO_2 losses**
- **Better light utilization & mixing**
- **Controlled culture conditions**

Disadvantages:
- **Cost/complexity**
- **Thermal management**
- **Oxygen accumulation**
- **Biofouling**
- **Cell damage by shear stress**
- **Deterioration of materials**

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Bioreactor Design Issues

- Variables affecting algae growth and lipid production
  - Irradiance levels, light-dark cycles,
  - CO_2 concentration,
  - temperature, pH, salinity,
  - nutrients
  - O_2 concentration
- Suspension versus Biofilm growth medium
- Scale-up
  - Gas (CO_2 & O_2) and nutrient management
  - Water management
  - Temperature management
- Performance models

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Algal Lipid Production

1. Microalgae, Sunlight, CO2, H2O, Nutrients produce mass

$$P_a = \frac{\tau \varepsilon_a \dot{E}_S}{E_a}$$

P_a	$kg/m^2\ yr$	*Microalgae production rate*
τ		*Efficiency of light transmission to microalgae*
ε_a		*Efficiency of conversion of incident sunlight to biomass in microalgae*
E_s	kW/m^2	*Solar irradiance*
E_a	kJ/g	*Energy content of microalgae*

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$$E_a \approx f_L E_L + f_P E_P + f_C E_C$$

E_a	*kJ/g*	***Energy content of microalgae (L = Lipids; P = Proteins; C = Carbohydrates)***
f_L		***Dry mass microalgae lipid content fraction***
f_P		***Dry mass microalgae protein content fraction***
f_C		***Dry mass microalgae carbohydrate content fraction***

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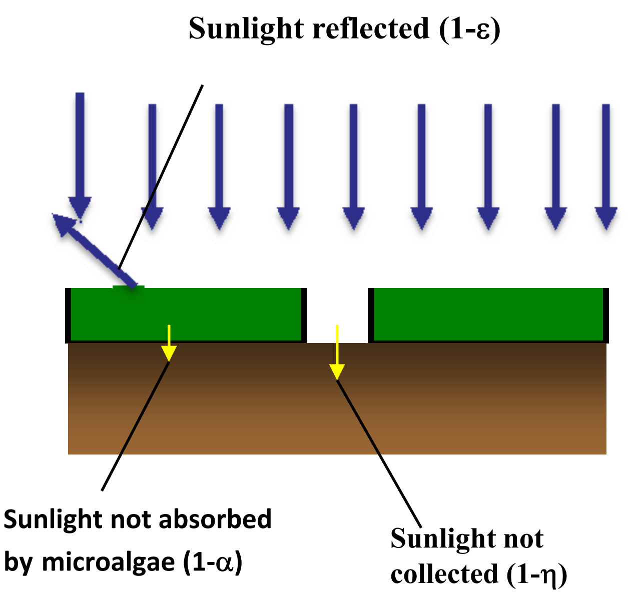
2. Transmission Efficiency of Sunlight to Microalgae

$$\tau = \varepsilon_{opt}\alpha\eta c_{PAR}$$



τ	*Efficiency of light transmission to microalgae*
ε_{opt}	*Optical light distribution efficiency*
α	*Light absorption coefficient of microalgae*
η	*Land use efficiency*
c_{PAR}	*Fraction of sunlight that is photosynthetically active radiation (PAR = 0.43)*

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3. Solar Energy Capture Efficiency

$$\varepsilon_a = \varepsilon_{env}\varepsilon_{ph}u_p(1-r)$$

ε_a	***Efficiency of conversion of incident sunlight to biomass in microalgae***
ε_{env}	***Losses due to sub-optimal environmental conditions***
ε_{ph}	***Photosynthetic efficiency***
u_P	***Fraction of captured photons utilized by microalgae***
r	***Fraction of energy consumed by respiration in microalgae***

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4. Efficiency of Photon Utilization – Bush Equation

$$u_p = \begin{cases} \frac{I_S}{I_I}\left[\ln\left(\frac{I_I}{I_S}\right)+1\right] & I_I \geq I_S \\ 1 & I_I < I_S \end{cases}$$

u_P	*Fraction of captured photons utilized by microalgae*
I_I	*Photosynthetic photon flux density (PPFD) incident on microalgae, μ mole/m^2-s*
I_s	*Saturation PPFD of microalgae, μ mole/m^2-s*

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5. Lipids that can be Converted to Biodiesel

$$P_{CL} = \frac{f_{CL} P_a}{\rho_{CL}}$$

P_{CL}	L/m^2-yr	*Rate of production of lipids useable for biodiesel from microalgae*
f_{CL}		*Dry mass microalgae lipid content fraction useable for biodiesel* $< f_L$
P_a	kg/m^2-yr	*Microalgae production rate*
ρ_{CL}	g/L	*Density of lipids useable for conversion to biodiesel*

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Theoretical Maximum Production

$$P_{\mathrm{CL,max}} = 43\ \mathrm{L/m^2\text{-}yr}\quad (45{,}600\ \mathrm{gal/acre\text{-}yr})$$

Variables		Optimum Value
f_{CL}	***Dry mass microalgae lipid content fraction***	**0.60/0.72**
α	***Light absorption coefficient of microalgae***	**1**
τ	***Efficiency of light transmission to microalgae***	**0.40**
η	***Land use efficiency***	**0.98**
E_S	***Total Solar Irradiance***	**12,000 kJ/m^2-yr**
ε_a	***Efficiency of conversion of sunlight to chemical energy***	**0.22**
ε_{env}	***Losses due to sub-optimal environmental conditions***	**1.0**
ε_{ph}	***Photosynthetic efficiency***	**0.27**
ε_{opt}	***Optical light distribution efficiency***	***0.96***
E_L	***Energy content of lipids***	**38kJ/g**
$E_{P,,C}$	***Energy content of proteins and carbohydrates***	**17kJ/g**
I_s	***PAR saturation intensity***	**200 μmol/m^2-s**
I_I	***Intensity of light distributed inside the photobioreactor***	**200 μmol/m^2-s**

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Production Rates for open and closed Bioreactors

		Pond Bioreactors	*Concentrator Bioreactor*
P_{CL}	*gal/acre-yr*	**4,200**	**9,300**
E_s	*kW/m²-day*	**220**	**323**
u_P		**0.52**	**1.0**
τ		**0.32**	**0.20**
ε_a		**0.079**	**0.189**
f_{CL}		**0.51**	**0.51**

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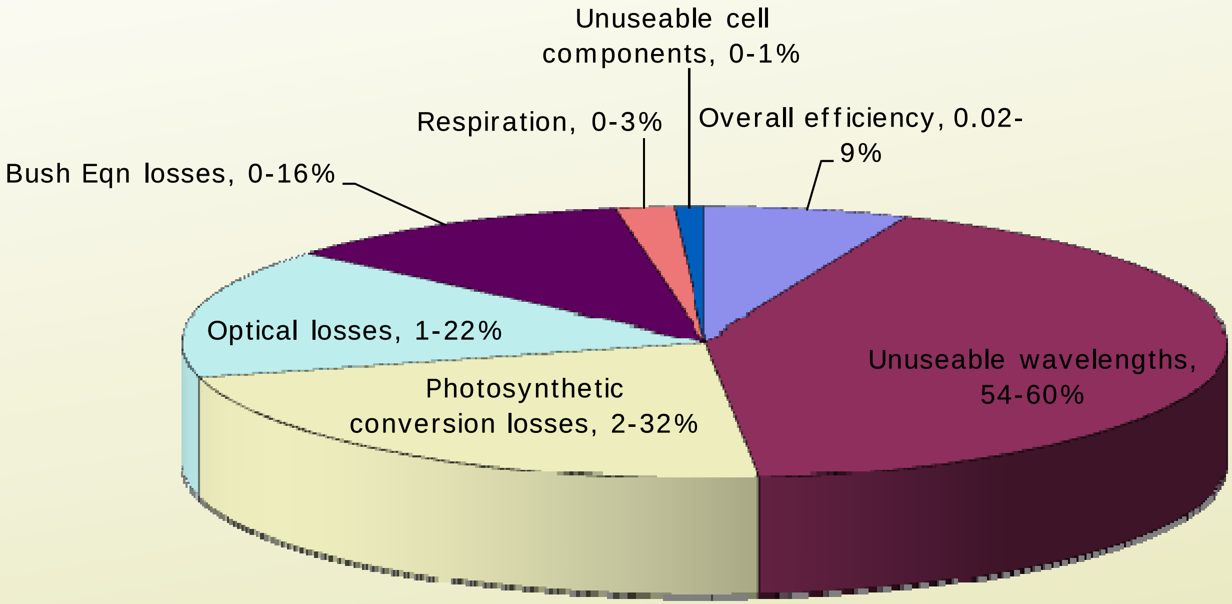
Efficiency of biodiesel from microalgae



~50 - 90% of the losses are due to biological limitations in how efficiently sunlight is used.

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Products from Microalgae

Chemical	Usage	Approx Value ($/kg)
Phycobiliproteins	Medical Diagnostics	> 10,000
Astaxanthin	Food supplement: human, animal, aquaculture	> 2,500
Xanthophyll	Fish Feeds	~1,000
Beta-carotene	Food Supplement	> 500
Health Supplements	Dietary Supplements	~10
Biofuels	Energy	1.0 <

A production facility that produces higher value products along with lipids for fuel should be evaluated.

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Economic Considerations

If a photobioreactor were built with a capital cost, *C*, to be recovered in *t* years, with an annual rate of return *i*, the required annual payment, *Q*, would be:

$$Q = \frac{Ci(1+i)^t}{(1+i)^t - 1}$$

Q must be less than or equal to the revenue from the photobioreactor minus the expenses:

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$$Q \le \left(\frac{V_{CL} f_{CL}}{\rho_{CL}} + \sum_i f_i V_i + \sum_i S_i - \sum_i M_i \right) P_a - \sum_i A_i$$

Q	***\$/m²-yr***	***Revenue from photobioreactor***
V_{CL}	***\$/L***	***Value of biodiesel feedstock (lipids)***
f_{CL}		***Dry mass microalgae lipid content fraction useable for biodiesel***
f_i		***Dry mass microalgae content fraction for product i***
ρ_L	***kg/L***	***Density of microalgae lipids***
V_i	***\$/kg***	***Value of non-lipid microalgae mass for product i***
ΣS_i	***\$/kg***	***Value of services provided***
M_i	***\$/kg***	***Per-kg cost of production***
P_a	***kg/m²-yr***	***Microalgae production rate***
ΣA_i	***\$/m²-yr***	***Annual operation costs***

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Example Annual Revenue

$$Q \leq \left(\frac{V_{CL} f_{CL}}{\rho_{CL}} + (1 - f_{CL}) V_a + S - M \right) P_a - A$$

Q		Revenue from photobioreactor
V_{CL}	\$2-\$4 / gal	Value of lipids produced
f_{CL}	0.51	Lipid content of microalgae
ρ_L	0.88 kg/L	Density of microalgae lipids
V_a	\$0-\$0.05/kg	Value of non-lipid microalgae mass
S	\$0.2 - \$0.6/L	Value of services provided
M	\$0.1 - \$0.3/L	Per-kg cost of production
P_a	kg/m2-yr	Production rate of microalgae
A	10%-20% Q	Annual operation costs

S	=	Heavy metals removal
		Carbon sequestration
		Wastewater Treatment
M	=	Upstream processing
		Supplemental nutrients
		Downstream processing
		Packaging and shipping
		Waste disposal
A	=	Labor
		Electricity
		Heating
		Maintenance

V_a, *S*, *M*, and *A* are currently not well known, thus accurate revenue predictions are difficult to make.

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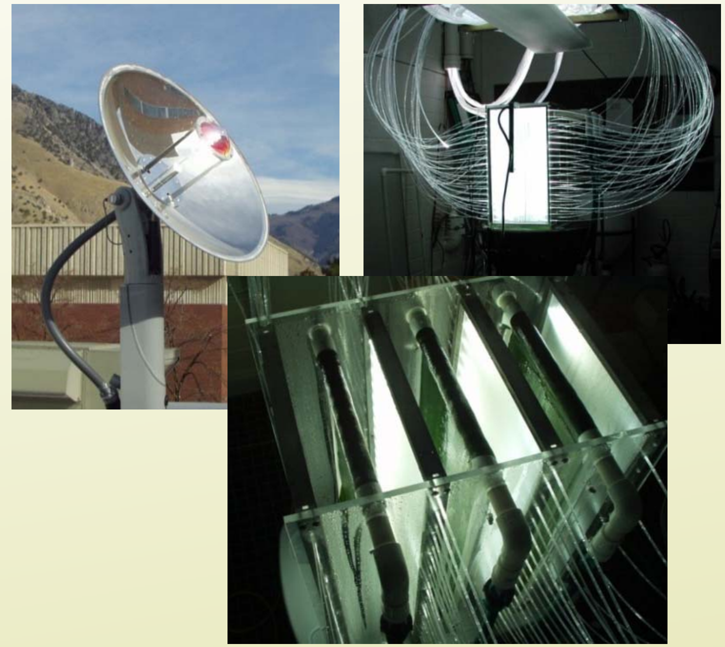
Projected Revenue from Microalgae

Pond Bioreactors

- Lipid Annual Production
  P_{CL} = 4,200 gal/acre-yr
- Gross Annual Revenue
  Q = $10,500 – 22,500 /acre-yr

Concentrator Bioreactor



- Lipid Annual Production
  P_{CL} = 9,300 gal/acre-yr
- Gross Annual Revenue
  Q = $23.200 – 49,600/acre-yr

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Conclusions

- The use of sunlight to produce biodiesel using microalgae can only be expected to operate with efficiencies of at most 9%, and likely much less.
- 50-90% of the inefficiencies can be attributed to biological limits to the efficiency at which sunlight can be used.
- most significant improvements can be made by minimizing optical losses (maximizing the solar energy received by the algae) and minimizing light over-saturation of the microalgae.
- **At very most, 43L/m^2-yr of biodiesel can be expected from microalgae in the U.S**

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Conclusions

- **Biodiesel may not be the primary source of income**
  - ✓ Other products from microalgae – pharmaceuticals, pigments, etc.
  - ✓ Photobioreactor provides services – nutrient removal, water purification, etc.
  - ✓ Petroleum fuel additive
  - ✓ Electricity generation from otherwise wasted infrared energy
    - ✓ 395 W/m^2 of PAR, 495 W/m^2 of infrared
    - ✓ At 15% conversion efficiency and \$0.05/kWh, electricity generation would add \$16/m^2-year
  - ✓ Process heat from IR energy

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Thank You

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