The Power of Algae: Photobioreactor Design and Production Strategies for Biofuel Production

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The University of Arizona
Hybrid Solar and Electric Lighting System
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U.S. Department of Energy (DOE)

CO$_2$ Assimilation by Algae

David Bayless and Joel L. Cuello
Ohio University and The University of Arizona
Hybrid Solar and Electric Lighting System

- Solar collector
- Optical fiber cable
- Bioreactor
- Light emitting panel
- Flue gas injection
- Biomass
Hybrid Solar and Electric Lighting System
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Hybrid Solar and Electric Lighting System
Algae Growth Rates as Function of CO₂ Levels

- **Dry Weight (g/L)**
- **Number of days**

**Ambient CO₂**

**Elevated CO₂** (5% CO₂ supplemented)
CO₂ Assimilation by Algae

Carbon Assimilation (mgC/L day)

Light Conditions (µmol sec⁻¹ m⁻²)
Algae
Algae: Major Advantages

(1) renewable energy source

(2) potential for reduction of emissions from power plants

(3) much higher productivity than traditional fast-growing energy crops

(4) less area required than traditional crops when grown in photobioreactors
Algae: Major Advantages

(5) production in photobioreactors prevents potential degradation of soil and groundwater

(6) non-potable water can be used, aiding in wastewater treatment and utilizing non-productive areas

(7) production of economically valuable chemicals
Algae: Major Advantages

(8) Energy feedstock that does not compete with food or feed!
# Products from Microalgae

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Usage</th>
<th>Approx. Value ($/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astaxanthin</td>
<td>Salmon aquaculture, pigment</td>
<td>&gt;2500</td>
</tr>
<tr>
<td>β-carotene</td>
<td>Food supplement</td>
<td>&gt;500</td>
</tr>
<tr>
<td>Phycobiliproteins</td>
<td>Medical diagnostics</td>
<td>&gt;10,000</td>
</tr>
<tr>
<td></td>
<td>Food colors</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Health supplements</td>
<td>Dietary supplement</td>
<td>20-10</td>
</tr>
<tr>
<td>Xanthophyll</td>
<td>Chicken feeds</td>
<td>200-500</td>
</tr>
<tr>
<td></td>
<td>Fish feeds</td>
<td>1000</td>
</tr>
<tr>
<td>Plant</td>
<td>Biodiesel Yield (L/ha-yr)</td>
<td></td>
</tr>
<tr>
<td>------------------</td>
<td>----------------------------</td>
<td></td>
</tr>
<tr>
<td>Soybeans</td>
<td>446</td>
<td></td>
</tr>
<tr>
<td>Rapeseed</td>
<td>119</td>
<td></td>
</tr>
<tr>
<td>Mustard</td>
<td>1300</td>
<td></td>
</tr>
<tr>
<td>Jatropha</td>
<td>1892</td>
<td></td>
</tr>
<tr>
<td>Palm Oil</td>
<td>5950</td>
<td></td>
</tr>
<tr>
<td>Algae (Low)</td>
<td>45000</td>
<td></td>
</tr>
<tr>
<td>Algae (High)</td>
<td>137000</td>
<td></td>
</tr>
<tr>
<td>Ours (High)</td>
<td>132,300!</td>
<td></td>
</tr>
</tbody>
</table>
Which Algae do We Work with?

- Those accumulating hydrocarbons
- Those accumulating fatty acids
- Those accumulating starch
- Those producing hydrogen gas
Biofuel Production from Algae

- Species/Strain Selection
- Mass Production of Algae
- Harvesting
- Dewatering
- Product Extraction/Processing
Two Ways to Mass Produce Algae

Open Ponds

Photobioreactors
Open Pond System

- Water Nutrients
- Motorized paddle
- Algae
- Waste CO2
Photobioreactor Design
Photobioreactor

Controlled
Light
Nutrients
CO\textsubscript{2}
Mixing
Culture Density
pH
Temperature
Flow Rate
etc.

Algae
Photobioreactor Designs
Photobioreactor Design
Biofuel Production from Algae

Species/Strain Selection

Mass Production of Algae

Harvesting

Dewatering

Product Extraction/Processing
Hydrodynamic-Based Design of Algae Photobioreactors for Biofuel Production

Michael Mason, In-Bok Lee and Joel L. Cuello
The University of Arizona
B. braunii growth optimization

![Graph showing growth optimization of B. braunii with different conditions.

- Mix., CO₂, 200μmol
- Mix., no CO₂, 200μmol
- Mix., CO₂, 150μmol
- Mix., no CO₂, 150μmol
- No mix., CO₂, 200μmol
- No mix., no CO₂, 200μmol
- No mix., CO₂, 150μmol
- No mix., no CO₂, 150μmol

F.W. (g/L) vs. Time (days) with different conditions and CO₂ levels.](image-url)
Criteria for Algae Photobioreactors

Delivery of Light

Delivery of CO$_2$

Delivery of Nutrients

Optimal Culture density

Mixing/Hydrodynamic Conditions!!!
Design and Scale Up Strategy

Axial Dispersion Coefficient
Vessel Dispersion Number
Bodenstein Number
Reynold’s Number
Mixing Time

Identify and select set of hydrodynamic conditions that translate into optimal algae growth rate/productivity

Photobioreactor hydrodynamic conditions
Photobioreactor algae growth rate/productivity
Use of RTD to Determine Hydrodynamic Parameters

Determined Residence Time Distributions in 2 sizes of External Air-Lift Photobioreactor at 3 volumetric flow rates at coarse and fine bubble sizes.

Volume (4.4 L) of the small reactor whose diameter is 2 in is roughly half the volume (10.2 L) of the big reactor whose diameter is 3 in.
Example RTD Results for External Air-Lift

At Volumetric Flow Rate = 4.7 L/min with Coarse Bubbles (0.25” dia)

At 2 in diameter
RT = 55 s
Dispersion No. = 0.024
Bodenstein No. = 41.7
Reynold’s No. = 1961

At 3 in diameter
RT = 97 s
Dispersion No. = 0.058
Bodenstein No. = 17.4
Reynold’s No. = 1311
Mixing Time: Air-Lift

- Electrical Conductivity
- NaCl Injection
Mixing Time: Bubble Column

Air Flow Meter

NaCl Injection Port
Mixing Time: Bubble Column

Electrical Conductivity
Mixing Time Results

Control, 7 gpm, 25 vs. 50 cfh
Algae growth as function of hydrodynamic conditions
B. braunii growth optimization

- **F.W. (g/L)**
  - mix., CO2, 200umol
  - mix., no CO2, 200umol
  - mix., CO2, 150umol
  - mix., no CO2, 150umol
  - no mix., CO2, 200umol
  - no mix., no CO2, 200umol
  - no mix., CO2, 150umol
  - no mix., no CO2, 150umol

- **Time (days)**: 0, 2, 4, 6, 8, 10
Successful scale-up, higher productivity in photobioreactors
A Third Way to Mass Produce Algae
Algae Aquaculture

- Algae represent the largest aquaculture crop on a global basis

- Algae are a major component of diet in Asia
Goal

- Design microalgae production systems based on aquacultural growing systems
- Lower cost
- Small-scale and distributed production systems
- Realistic promotion of economic diversification in U.S. rural areas
Coupled Aquaculture and Hydroponics
Coupled Aquaculture Effluent and Algae
Aquaculture and Algae Biofuel
Integrated Algae/Fish-Feed Aquaculture

Biofuel

Fish Feed
Integrated Algae-Fish Aquaculture

Algae

Treated Water

Fish

Fish Feed

Algae Residues

Fish Waste/Water

Biofuel

Fish Body Residues

Fish Meat

Fish Feed

Algae Residues

Fish Waste/Water

Biofuel

Fish Body Residues

Fish Meat
Aquaculture and Algae Biofuels

Aquaculture producers are well-positioned to produce fish meat, fish/animal feed, and algae oil.
Production Strategies
Production Strategy:

Composite Lighting for Algae Biofuel Production
HYBRID SOLAR AND ELECTRIC LIGHTING (HYSEL) FOR SPACE LIFE SUPPORT

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The University of Arizona
National Aeronautics and Space Administration (NASA)

Grant No. NAG10-0255
Concentrator’s Spectral Output

![Graph showing spectral output](image)
HYSEL System -- LED

[Images of HYSEL System with LED lights and electrical wiring]
HYSEL System -- LED
HYSEL System’s Spectral Output

HYSEL - LED
HYSEL System -- XMH
HYSEL System -- XMH
HYSEL System’s Spectral Output

HYSEL - XMH
Lighting Profiles

PPF

30

322

3.9 hr

30

322

3.9 hr

0 24 24 48

30

194

9.5 hr

30

194

9.5 hr

0 24 24 48

HYSEL

HPS
Results - Dry Weight

- **Composite**
- **Conventional**

**DRY WEIGHT PER PLANT (g)**

**LIGHTING SYSTEM**
Results – Chlorophyll Content
Composite Lighting Applied to Algae

Takanori Hoshino and Joel L. Cuello
The University of Arizona
Composite Lighting Applied to Algae

Conventional

Dark Period
12 hours per day
PPF average (During Light Period)
200 µmol m\(^{-2}\) s\(^{-1}\)

Composite

Dark Period
0 hours per day
PPF average (During Light Period)
100 µmol m\(^{-2}\) s\(^{-1}\)

Chlamydomonas reinhardtii
# Composite Lighting Applied to Algae

<table>
<thead>
<tr>
<th></th>
<th>Nutrition</th>
<th>Light Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Photoautotrophic</td>
<td>12 hours: 200 µ mol m⁻² s⁻¹</td>
</tr>
<tr>
<td></td>
<td>With 5% CO₂ provided</td>
<td>12 hours: Dark</td>
</tr>
<tr>
<td>Composite Lighting</td>
<td>Photoautotrophic</td>
<td>12 hours: 175µ mol m⁻² s⁻¹</td>
</tr>
<tr>
<td></td>
<td>With 5% CO₂ provided</td>
<td>12 hours: 25 µ mol m⁻² s⁻¹</td>
</tr>
</tbody>
</table>
Results - Chlamydomonas

**Dry Cell Weight (g DCW L$^{-1}$ suspension)**

- Cont
- Nutrient Limitation

- 26%

- 50 - 250 hours
  - $y = 0.0061x - 0.0223$
  - $y = 0.0047x - 0.0085$

- Bars: Standard Deviation with N = 5

- Time (hour)
Results - Chlamydomonas

Starch Content (%: g glucose/g CDW)

Bars: Standard Deviation with N = 5

Nutrient Limitation

63%

Time (hour)
Conclusion

For a fixed quantity of light energy, Composite Lighting resulted in significantly greater algae growth compared with that for Conventional Lighting.
Conclusion

Equal moles of photons do not necessarily result in equal growth in green algae
Growth of Algae in Wastewater

Sara Kuwahara and Joel L. Cuello
The University of Arizona
Growth of Algae in Wastewater
## Algae Wastewater Treatments

<table>
<thead>
<tr>
<th>Nutrients (mg/L)</th>
<th>Reclaimed water</th>
<th>Reclaimed water + 50% P and 50% N</th>
<th>Diluted 50% modified Chu-13</th>
<th>Reclaimed water + 100% P and 100% N</th>
<th>Modified Chu-13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>E</td>
</tr>
<tr>
<td>Calcium</td>
<td>48.70</td>
<td>48.70</td>
<td>14.976</td>
<td>8.70</td>
<td>29.952</td>
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<tr>
<td>Carbon</td>
<td>218.00</td>
<td>218.00</td>
<td>21.696</td>
<td>218.00</td>
<td>43.392</td>
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<tr>
<td>Chloride</td>
<td>90.00</td>
<td>90.00</td>
<td>13.263</td>
<td>90.00</td>
<td>26.525</td>
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<tr>
<td>Magnesium</td>
<td>7.80</td>
<td>7.80</td>
<td>9.859</td>
<td>7.80</td>
<td>19.718</td>
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<tr>
<td>Nitrogen</td>
<td>20.60</td>
<td>25.632</td>
<td>25.632</td>
<td>51.263</td>
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<tr>
<td>Phosphate</td>
<td>12.00</td>
<td>12.0</td>
<td>7.112</td>
<td>14.224</td>
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<tr>
<td>Sodium</td>
<td>116.00</td>
<td>142.00</td>
<td>0.000</td>
<td>116.00</td>
<td>116.00</td>
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<tr>
<td>Sulfate</td>
<td>106.00</td>
<td>106.00</td>
<td>25.229</td>
<td>106.00</td>
<td>50.459</td>
</tr>
</tbody>
</table>
Growth of Algae in Wastewater
Growth of Algae in Wastewater

Dry Weight (dry g/ g dry starting weight)

Time (hour)

control
100% sw

Average A
Average B
Average C
Average D
Average E
Growth of Algae in Wastewater

Total Chlorophyll (g/L)

- Average A
- Average B
- Average C
- Average D
- Average E

100% sw
control
Growth of Algae in Wastewater

Total Nitrate (mg/L)

Time (hours)

Total nitrate (mg/L)

Average A
Average B
Average C
Average D
Average E
Growth of Algae in Wastewater

Total Organic Phosphate (mg/L)

Time (hours)
Hydrogen Gas Production from Algae

Takanori Hoshino and Joel L. Cuello
The University of Arizona
Acknowledgments
Acknowledgments