USING ALGAE FOR NUTRIENT REMOVAL: FROM THEORETICAL UNDERSTANDING TO ENGINEERING DESIGN

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AGENDA

• Introduction

• Case Studies: Algae cultivation coupled with a wastewater treatment process
  • Fundamental research
  • Engineer design

• Conclusions
INTRODUCTION-ALGAE RESEARCH

Started as early as 50’s

Food, Biodiesel

Resources

• Carbon, Nitrogen, Phosphorus
• Water
• Other macronutrients/micronutrients

Control

pH, temperature, salinity, etc.
COMMERCIALIZATION HURDLES

• Economically: life cycle analyses
• Environmental impacts:
• Technically: process optimization, algae harvesting
• Resource availability (site specific)
• Climate (solar radiation, high temperature)
• Land
SUSTAINABLE APPROACH FROM ALGAE INDUSTRY

• CO₂ supply (coal fired power plant/other industrial source)

• N/P supply (wastewater) (nutrient recycle)

• Water (non-potable, non-agricultural water)
# PARADIGM SHIFT IN WASTEWATER INDUSTRY

<table>
<thead>
<tr>
<th>WASTES</th>
<th>VS.</th>
<th>RESOURCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant influent</td>
<td></td>
<td>Food (C, N, P)</td>
</tr>
<tr>
<td>Plant effluent</td>
<td></td>
<td>Food (C, N, P)</td>
</tr>
<tr>
<td>Biosolids</td>
<td></td>
<td>Energy</td>
</tr>
<tr>
<td>Incineration air emission</td>
<td></td>
<td>CO₂ (carbon sources)</td>
</tr>
<tr>
<td>Hydraulic jump</td>
<td></td>
<td>Energy</td>
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</tbody>
</table>
Algae cultivation coupled with a wastewater treatment process
WHY MICROALGAE?

• Consumes nutrient and carbon
• Grow faster (~3 times) than terrestrial biomass
• Microalgaed-derived biodiesel
  • Substantial amounts of triglycerols (TGA) (e.g., 10-50 % dry cell weight)

# MICROALGAE DIVERSITY

<table>
<thead>
<tr>
<th>Microalgae</th>
<th>Oil content (% dry wt.)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Botryococcus braunii</em></td>
<td>25-75</td>
</tr>
<tr>
<td><em>Chlorella sp.</em></td>
<td>28-32</td>
</tr>
<tr>
<td><em>Nitzschia sp.</em></td>
<td>45-47</td>
</tr>
<tr>
<td><em>Neochloris oleoabundans</em></td>
<td>35-54</td>
</tr>
</tbody>
</table>
**EXPERIMENTAL CONDITIONS**

- **Strain:** *Chlorella Vulgaris*
- **Open system** \( (pCO_2=0.037\%) \)
- **Mixing speed:** 125 rpm
- **Light Intensity:** 6500 K fluorescent lamp and 6000 lux (Photon flux: 100.8 \( \mu \text{mol/ m}^2\text{s}^{-1} \))
- **16-hr light/ 8-hr dark cycle**

**Wastewater 1**
- Initial cell density: Low (45 mg/L)
- No pH control

**Wastewater 2**
- Initial cell density: Medium (355 mg/L)
- Daily pH control by using CO2(g)
BATCH EXPERIMENT
# CHARACTERISTICS OF WASTEWATER SAMPLES

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Wastewater 1 (mg/L)</th>
<th>Wastewater 2 (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIC</td>
<td>50.2 ± 0.8</td>
<td>72.2 ± 1.8</td>
</tr>
<tr>
<td>Nitrogen (NH$_4^+$/NH$_3$)</td>
<td>8.1 ± 0.2</td>
<td>18.3 ± 0.5</td>
</tr>
<tr>
<td>Phosphorus (PO$_4^{3-}$)</td>
<td>1.9 ± 0.1</td>
<td>1.4 ± 0.1</td>
</tr>
<tr>
<td>pH</td>
<td>7.3 ± 0.1</td>
<td>7.9 ± 0.1</td>
</tr>
</tbody>
</table>
GROWTH OF C. VULGARIS WITH LOW INITIAL CELL DENSITY

- Lag-phase period for adaption: 24 hours
  - TIC was not reduced during the period
- Growth-phase
  - The cell density of C. vulgaris significantly increased
  - TIC sharply decreased until 72 hours
REMOVAL NITROGEN AND PHOSPHORUS

- Lag-phase period:
  - Small reduction (12% for N and 16% for P)

- Growth-phase period:
  - Nitrogen and phosphorus were sharply decreased (80% for N and 75% for P)
Both equations with the determined parameters well represent the growth
GROWTH AND NITROGEN CONSUMPTION WITH MEDIUM INITIAL CELL DENSITY

- Biomass was growing until 36 hours
- Phosphorus was depleted within 12 hours
- Nitrogen was removed within 48 hours
- Initial nitrogen concentration in W2 was higher than that in the W1 sample and phosphorus became a limiting substrate
GROWTH KINETICS OF CHLORELLA VULGARIS

- $\mu_{\text{max}}$ (hr$^{-1}$) and $K_s$ (mg/L): 32.85 (hr$^{-1}$) and 0.99 (mg/L)
- The culture with a high initial cell density and pH control using CO$_2$ gas could accelerate simultaneous algal cell growth and residual nitrogen and phosphorus uptake.
- The determined Monod equation well represent the growth
TAKE HOME MESSAGE 1

• Technology works, but not efficient!

• Between nitrogen and phosphorus, either one could be a substrate limiting its growth.

• All nitrogen and phosphorus could be removed within 48 hours, compared with traditional BNR within 6-8 hours.
RESEARCH DIRECTIONS

• Design more efficient algae treatment systems for nutrient removal

• Translate this knowledge into engineering design
EXPERIMENTAL CONDITIONS

- Strain: *Chlorella Vulgaris*
- Open system (pCO$_2$=0.037%)
- Mixing speed: 125 rpm
- Light Intensity: 6500 K fluorescent lamp and 6000 lux (Photon flux: 100.8 µmol/ m$^{-2}$s$^{-1}$)
- 16-hr light/ 8-hr dark cycle
- Initial cell density: high: 1338 mg/L
- Daily pH control by using CO2(g)
GROWTH AND NITROGEN CONSUMPTION WITH HIGH INITIAL CELL DENSITY

- No lag phase
- Phosphorus was depleted within 4 hours
- Nitrogen was removed within 8 hours
TAKE HOME MESSAGE 2

• Initial Microalgae density plays an very important role for nutrient removal.

• Considering it from a concept of F:M ratios for activated sludge system, low F:M helps remove nutrient.

• Light will be a limiting factor when cell density is high.
RESEARCH DIRECTIONS

• Design more efficient algae treatment systems for nutrient removal

• Translate this knowledge into engineering design
MODEL SIMULATION
MODEL VALIDATION: DYNAMIC SIMULATION (MEDIUM CELL DENSITY)
MODEL VALIDATION: DYNAMIC SIMULATION (HIGH CELL DENSITY)

![Graph showing Algae Reactor biomass modeled and Algae Reactor Ammonia N modeled over time with Biomass concentration (mg/L) and Ammonia concentration (mg/L) axes. Red line for biomass modeled, blue line for ammonia modeled, black line for biomass concentration.]
### COMPARISON OF ALGAE BASED TREATMENT AND CONVENTIONAL METHOD BY MODEL SIMULATION

Note: effluent concentration, $\text{NH}_4 = 2\text{mg/L}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Algae based treatment</th>
<th>Conventional BNR method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor volume</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>Biomass</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>
SYNERGISTIC RELATIONSHIP BETWEEN NUTRIENT REMOVAL AND ALGAE GROWTH

Input
N: wastewater effluent
P: wastewater effluent
C: air emissions from power plant or WWTP incinerators
Water: recycled water
Sunlight: environment

Output
Improved water quality
Improved air quality
Biodiesel production
Neutral lipids is the source for biodiesel production
- Neutral lipids can be increased under nitrogen deprivation condition with a high concentration of dissolved inorganic carbon.
ALGAE CULTIVATION COUPLED WITH A WASTEWATER TREATMENT PROCESS AND POWER PLANTS
CONCLUSIONS

• Importance of integrating Science and Technology to solve environmental challenges

• Cost is a big driver to apply innovative technology

• Should consider more environmental drivers, such as renewable energy, GHG neutral

• More collaboration between utilities, engineering firms and research institutes.
Building a world of difference.
Together