Progress and Perspectives of Large Scale Algae Biomass Harvesting: A Case Study at the ATP³ Testbed

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Introduction

Challenges in algae harvesting

Progress of large scale algae harvesting

- Algae harvesting using membrane filtration
- Algae harvesting using sedimentation and DAF
- Algae harvesting using centrifugation
- Techno-economic model analysis for large scale algae harvesting

Perspectives of large scale algae harvesting

- Influence of the algae cell surface properties and media characteristics on the algae harvesting using flotation
- Growth inhibition of culture media recycling
- Qualities of the harvested biomass
Production of Algae Biomass, Biofuels and Bioproducts

CO₂ → Nutrients → Sun → Water

Cultivation → Harvesting → Extraction/conversion → Biodiesel → Pharmaceutical/Nutraceutical Bioproducts
Challenges in Algae Harvesting

-Huge volume of water needs to be processed for one gallon biodiesel

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algae concentration (g L(^{-1}))</td>
<td>1</td>
</tr>
<tr>
<td>Oil content (%)</td>
<td>30%</td>
</tr>
<tr>
<td>Neutral lipid (%)</td>
<td>50%</td>
</tr>
<tr>
<td>Extract efficiency (%)</td>
<td>80%</td>
</tr>
<tr>
<td>Biodiesel density (g L(^{-1}))</td>
<td>900</td>
</tr>
<tr>
<td>Algae dry biomass (kg)</td>
<td>28.4</td>
</tr>
<tr>
<td>Water volume needed (L)</td>
<td>28,388</td>
</tr>
</tbody>
</table>

-Difficult to separate algae from water

- Similar density to water (1010 - 1030 kg m\(^{-3}\))
- Small size (2-50 µm diameters)
- Diversity of algal cell and culture medium characteristics
Algal Mass Cultivation at the ATP³ Testbed

1,500 L each

660 L each

15,000 L

100,000 L
Algae Harvesting and Dewater Technologies at the ATP³ Testbed

- Sedimentation
- Dissolved air flotation
- Membrane filtration
- Centrifugation
- Freeze dryer
Algae Harvesting using Membrane Filtration

Membrane algae harvesting unit (Litree)

Feed, concentrate and permeate collected for membrane harvesting

Membrane algae harvesting unit (Litree)

Pore size: ~10 nm
SEM Images of Clean and Fouled Membrane

Clean membrane

After algae cake layer buildup

Zhang et al. *Algal Research* 2013
Optimize Operation Conditions of Membrane Harvesting

Air assisted backwashing with air scouring

- Hollow fiber (inside out)
- Algae suspension in fiber
- Algae cake layer

Flux (L m\(^{-2}\) h\(^{-1}\)) vs. Time (min)

- Air assisted backwash with air scour
- Air assisted backwash without air scour

Flux (L m\(^{-2}\) h\(^{-1}\)) vs. Filtration time (min)

- 10 min
- 15 min
- 30 min
- 60 min

Flux (L m\(^{-2}\) h\(^{-1}\)) vs. NaClO (mg L\(^{-1}\))

- 0.17 m s\(^{-1}\)
- 0.09 m s\(^{-1}\)
- 0.01 m s\(^{-1}\)

Flux (L m\(^{-2}\) h\(^{-1}\)) vs. NaClO (mg L\(^{-1}\))

- 0
- 100
- 200
- 300
- 400
- 500

Zhang et al. *Bioresource Technology* 2010

Zhang et al. *Separation and Purification Technology* 2009
Production Scale Membrane Algae Harvesting

Membrane area: 30 m²
Permeate flow: 19 L/m² h
Biomass recovery: 85%
Solid content: 4-6%
Medium recycle: 90%

Membrane algae harvesting units (Litree)

Recycled culture media
Modeling of Membrane Algae Harvesting

\[ Q = \frac{A \Delta P}{\mu(R_m + R_c + R_p)} \]

\[ F = \frac{\pi}{6} d_p^3 \rho \frac{dv_p}{dt} = F_B + F_s + F_I - F_d \]

\[ \dot{J}_S = v_B + v_s + v_i \]

Zhang et al. *Bioresource Technology* 2010
Algae Harvesting using Sedimentation

Sedimentation algae harvesting unit (Integrated Engineers)

- Flow rate: 5-8 gpm
- Biomass recovery: 80%
- Solid content: <3%

Before Harvesting

Algae Concentrate

Effluent

Lamella

$\text{d}_p, \rho_p, N_p$

$\text{d}_f, \rho_f, v_f, N_f$
Algae Harvesting using Dissolved Air Flotation

DAF algae harvesting unit (World Water Works)

<table>
<thead>
<tr>
<th>Flow rate</th>
<th>3-5 gpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass recovery</td>
<td>~75%</td>
</tr>
<tr>
<td>Solid content</td>
<td>6-8%</td>
</tr>
</tbody>
</table>
Algae Harvesting using Dissolved Air Flotation

Algae Concentration in the DAF Effluent

Dry weight in residual (g L⁻¹)

Time (min)

0 100 200 300 400 500 600 700

0.0
0.1
0.2
0.3

Algae Concentration in the DAF Effluent

Solid Contents of DAF Harvested Algae Biomass

Pond
Before screen
Final product

Solid content (%)

0.0
2.0
4.0
6.0
8.0
10.0

Biomass mass balance

Settled
13%
Penetrate screen
4%
Effluent
4%
Other
9%
Harvested
70%
Algae Harvesting using Dynamic Settler/Evodos Centrifuge

Evodos centrifuge

Separation Efficiency (%) vs. Flow rate (L/h)

- Scenedesmus sp., Pond
- Chlorella sp., Pond
- Nannochloropsis sp., Pond
- Nannochloropsis sp., PBR

Scenedesmus sp., Chlorella sp., Nannochloropsis sp.
Techno-economic Model Analysis for Large Scale Algae Harvesting

- Input algae characteristics
- Input goal, VRF or time
- Harvesting technologies & key parameters

Calculate efficiency, cost

Optimized harvesting process
## Summary of Algae Harvesting Technologies

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sedimentation</th>
<th>Dissolved Air flotation</th>
<th>Membrane Filtration</th>
<th>Centrifugation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process illustration</td>
<td><img src="image" alt="Process Illustration" /></td>
<td><img src="image" alt="Process Illustration" /></td>
<td><img src="image" alt="Process Illustration" /></td>
<td><img src="image" alt="Process Illustration" /></td>
</tr>
<tr>
<td>Concentration factor</td>
<td>&lt;15</td>
<td>10~30</td>
<td>5~20</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Separation efficiency</td>
<td>&gt;90%</td>
<td>&gt;85%</td>
<td>~100%</td>
<td>&gt;80%</td>
</tr>
<tr>
<td>Biomass recovery</td>
<td>~80%</td>
<td>~75%</td>
<td>~85%</td>
<td>~75%</td>
</tr>
<tr>
<td>Solid content of harvested biomass</td>
<td>&lt;3%</td>
<td>6-8%</td>
<td>4-6%</td>
<td>&gt;20%</td>
</tr>
<tr>
<td>Readiness of culture medium reuse</td>
<td>Need further treatment</td>
<td>Need further treatment</td>
<td>Ready to reuse</td>
<td>Need further treatment</td>
</tr>
<tr>
<td>Quality of algae biomass harvested</td>
<td>Coagulant contamination</td>
<td>Coagulant contamination</td>
<td>No contamination</td>
<td>No contamination Cells may break</td>
</tr>
</tbody>
</table>

*Based on the harvesting of Nannochloropsis sp, with a process flow of 500 L/h*
Perspectives of large scale algae harvesting
- 1) Factors Affecting DAF Algae Harvesting

**Influence of algal species**

- **Haematococcus sp.**
- **Scenedesmus sp.**
- **Chlorella sp.**

**Influence of growth phases**

- Exponential phase
- Stationary phase
- Declining phase

**Influence of coagulant**

- Chitosan
- $\text{Al}^{3+}$
- $\text{Fe}^{3+}$
- CTAB
Characterize Algal Cell Surface Functional Groups at Different Growth Phases of *Chlorella sp.*
Influence of Surface Functional Group on the Harvesting of *Chlorella sp.*

Zhang et al. *Bioresource Technology* 2012
Perspectives of large scale algae harvesting
- 2) Reduced Growth in the Recycled Media
Identification of Growth Inhibitors in the Recycled Media

[Graph showing absorbance vs. wavelength number in cm\(^{-1}\).]

[Graph showing response vs. molecular weight in Daltons.]
Perspectives of large scale algae harvesting

- 3) Quality of Harvested Biomass and Culture Media

**Separation Techniques:****

(a) DAF separated media

(b) DAF harvested biomass

(c) Biomass washed with 0.1 M HCl

**Graphs and Data:****

- Harvesting efficiency (%)

- Metal Concentration (mg L\(^{-1}\))

- Metal Content (mg g\(^{-1}\))

- Coagulant / Algae Dry Weight (mg g\(^{-1}\))
Summary

- Huge amount of water needs to be processed for algae harvesting. Economic and efficient algae harvesting consist of **volume reduction process** and **dewatering process**.
- **Algal strain**, **growth conditions**, and the **usages** of harvested biomass needs to be considered when select the harvesting method.
- **Qualities** of the harvested biomass, and **culture media recycling** needs to be considered.
- **Techno-economic model** helps to guide the selection of algal harvesting technologies.
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