Recent advances in downstream processing of microalgae

Robert W Lovitt
CSAR CCFP Cwater
College of Engineering
Swansea University
TOC

• Swansea activities in algae biotechnology
• Overview of DSP
CSAR - Centre for Sustainable Aquatic Research

- Multidisciplinary research team: Biologists, Engineers, Mathematicians and Physicists;
- 30 directly employed staff, together with 14 participating academic staff;
- Incorporates a RCUK *Large Research Facility* (controlled environment labs);
- New grant income 2008 to 2013: >£8m.
Areas of expertise at Swansea University

- **Mechanistic modelling** of algal physiology and biomass production systems;
- **Optimisation of biomass production** in photo-bioreactors;
- **Algal bioremediation technologies**: soluble nutrients (N&P); flue gases (C);
- **Downstream processing**: cell harvesting, disruption and fractionation using wide range of membrane and absorption processes;
- (Development and testing of value added products)
Production Facilities...
Large microalgal collection >40 species, regularly grow 8-10 species.

40 x 20 L carboys
20 x 100 L vertical bags
Algal Growth Laboratory

Port Talbot Steel works
9 million tons CO2
Ammonia
Minerals
Sewage works adjacent

- Containing: PBRs, gas blenders, gas distribution, HVAC and PBR gas extraction
Facility at Tata steelworks site, Port Talbot

- Algal Growth Laboratory (AGL) and Algal preparation laboratory (APL) installed at TATA steel
- 12x 80L reactors and 36X 20L carboys or flasks suitable for flue gas trials and culture adaptation experiments
- Preliminary trials on high concentration of CO₂ provided the basis for flue gas trials
CCFP, Engineering: DSP Facilities

- **Disruption**
  - Bead mills and High pressure cell homogeniser

- **Separations**
  - Wide range of membrane technology (MF, UF, NF, RO)
  - Lab to pilot scale
  - Portable pilot scale equipment
  - Absorption Process

- **Drying**
  - Freeze drying
  - Spray drying

- **Particle characterising technology**
  - Zeta potential
  - Mastersizer
  - PCS particles
  - Colloid characterization

200 L membrane harvesting

20 L membrane harvesting
Swansea Projects

• Bioalgeasorb – Bioremediation (waste treatment and thermal treatments)
• Shellplant – Shell fish fattening with algae
• Enalgea – Energy and bioremediation
• Accomplish – Flue gases
• Macrobiocrude – Seaweed hydrothermal treatment for oil
• Algal Biotechnology KTC – High value products and lighting systems
• Internally lit bioreactors – high value products
Economic Impacts of Microalgae production and processes

• Variable Product mix
  • valuable materials
  • waste valorisation
  • energy
• Process Integration
• Site specific biorefinery solutions
• iLUC
  • Potentially can avoid the problems of Land use change
So, how far can down the value chain can algae go?

- **Oils**
  - PUFA ≥ $1000 per kg
  - Fuel $1000 per tonne

- **Proteins**
  - Enzymes (100000/t)
  - Food ingredient ($2500/t)
  - Feed ($1500/tonne)

- **Carbohydrates**
  - Hydrocolloids ($10000/t)
  - Starch

- **Cells**
  - Nutrient supplements ($10,000/t)
  - Antioxidants ($100,000/t)
  - Pyrolytic oils and materials (?)

By combining these aspects in a biorefinery. Possible more viable solutions should result.

However, increased complexity requires increased costs and investment to make them work.
Key aspects of downstream processing

• Costs
  • Production cost and quality of biomass

• Key areas DSP costs
  • Reactors and DSP
  • Harvesting
  • Disruption
  • Fractionation
Composition dependent on culture

Bulk biochemical composition is highly variable and inducible. Dependent upon species, culture condition and growth stage.

*Nannochloropsis* sp. biochemical composition under different nitrogen regimes

- Nitrogen deprivation causes 2-fold increase in lipid content in *Nannochloropsis* sp. Corresponding decrease in protein. (Mayers, et al., In preparation)

- *Tetraselmis suecica* found to accumulate up to 50% carbs under N and P deprivation. (Bondioli, et al., 2012)

* Residual = DNA(1-3%), RNA (2-15%), minerals, salts (Geider & La Roche, 2002)
Algae composition

A triangular plot of the proportions of lipid, protein and carbohydrate content of algae, Williams and Laurens (2010).
Harvesting and downstream processing

• Cell Harvesting and Concentration
  • Speed important for high value materials
  • Final Concentration a key aspect
  • Application of membrane technology looks possible or combination with other systems

• Cell disruption
  • Required for easy extraction of materials
  • Perhaps still the most problematic area

• Cell fractionation
  • Fractionation not a problem (but lipid-protein emulsions are challenging), much technology is already developed for biotechnology and food industry
IGV biotech - Horizon photobioreactor
## Comparative Reactor Performance

<table>
<thead>
<tr>
<th></th>
<th>PBR*</th>
<th>Raceway*</th>
<th>IGV-Horizon**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual biomass (kg)</td>
<td>100,000</td>
<td>100,000</td>
<td>100,000</td>
</tr>
<tr>
<td>Volumetric productivity kg/m³/d</td>
<td>1.535</td>
<td>0.117</td>
<td></td>
</tr>
<tr>
<td>Areal productivity (kg/m²/day)</td>
<td>0.048</td>
<td>0.035</td>
<td>0.06</td>
</tr>
<tr>
<td>Biomass concentration (kg/m³)</td>
<td>4.00</td>
<td>0.14</td>
<td>40.00</td>
</tr>
<tr>
<td>Dilution rate (d⁻¹)</td>
<td>0.384</td>
<td>0.250</td>
<td></td>
</tr>
<tr>
<td>Area needed (m²)</td>
<td>5,681</td>
<td>7,828</td>
<td>4,566</td>
</tr>
<tr>
<td>Oil yield m³/ha</td>
<td>58.7</td>
<td>42.6</td>
<td></td>
</tr>
<tr>
<td>Annual CO₂ consumption kg</td>
<td>183,000</td>
<td>183,000</td>
<td>183,000</td>
</tr>
<tr>
<td>System geometry</td>
<td>132 parallel tubes/unit, 80 m long 0.06m diam</td>
<td>987 m² and 12 m wide 82 m long 0.30m deep</td>
<td></td>
</tr>
<tr>
<td>Number of Units</td>
<td>6</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Liquid kg/m²</td>
<td>75</td>
<td>300</td>
<td>6-7</td>
</tr>
</tbody>
</table>

*(Chisti, Biotech Adv 25, 294)*

**P Waldeck presentation**

Price of land, can have significant effect on costs
Harvesting technology

• Costs and quality
• Membrane technology is a good relatively cheap way of harvesting
Harvesting microalgae

Pilot-scale microalgae dewatering system

Temperature probe, pressure gauge and diaphragm valve

0.1 µm spiral wound PES membrane

200 L feed tank

2.4-8 m³/h centrifugal pump

Flow meter
Pilot-scale study – modelling and costs

General equation: \[ J = \frac{\Delta P}{(R_m + R_c)\mu} = \frac{1}{(R_m + R_c)\mu} \Delta P \]
where \( R_m \) and \( \mu \) are constant

Model validation

Concentration, g/L

\( J \), LMH

Batch 1
Batch 2
Batch 3

\( C_1, C_2, \ldots, C_n \)
Pilot-scale study – modelling and costs

Influence of the operating parameters: (A) Pressure, (B) Temperature, (C) Concentration and (D) Area

<table>
<thead>
<tr>
<th>Operating conditions</th>
<th>Baseline</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Ideal</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔP, bar</td>
<td>1.95</td>
<td>2.10</td>
<td>1.95</td>
<td>1.95</td>
<td>1.95</td>
<td>1.95</td>
</tr>
<tr>
<td>Area, m²</td>
<td>3.8</td>
<td>3.8</td>
<td>3.8</td>
<td>3.8</td>
<td>7.6</td>
<td>7.6</td>
</tr>
<tr>
<td>Initial concentration, g/L</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>293</td>
<td>293</td>
<td>303</td>
<td>293</td>
<td>293</td>
<td>283</td>
</tr>
<tr>
<td>Power, kWh/m³</td>
<td>2.23</td>
<td>2.07</td>
<td>1.72</td>
<td>2.68</td>
<td>1.08</td>
<td>1.74</td>
</tr>
<tr>
<td>Cost, $/kg</td>
<td>0.282</td>
<td>0.268</td>
<td>0.224</td>
<td>0.154</td>
<td>0.140</td>
<td>0.113</td>
</tr>
</tbody>
</table>

↑ ΔP = ↓ Time

↑ A = ↓ ↓ Time

↑ C = ↑ ↑ Time

↑ T = ↓ Time

Membrane area and initial biomass concentration significantly affect costs

Pump: 0.70 kWh and 57% efficient at a cost of US $ 0.129/kWh
Disruption technology

- Wet processing
- Dry processing
Cell Disruption

![Graph showing marine algal disruption as a function of disruption pressure (MPa). The graph plots the proportion disrupted against disruption pressure, with different symbols and lines representing different species.]
Technological challenges - Separations

Maintain the value of materials produced by efficient separations

Volumes now reduced by a factor of 100-200
Membrane Technology has a significant role to play
Oil droplet separation
Absorption (fluidised bed absorption technology)
Selective protein recovery

Effective fractionation to stabilized products for formulation and maximize value.

Many traditional approaches available (good biochemical/food process engineering)
Oil-Protein separation key problem
Effective process modeling

• Effect of genetic engineering
  • Because the variability of the natural environment engineered organisms are at a disadvantage to wild type organisms
    • Inducible flocculation ?
    • Inducible cell lysis ?
Algae Biorefinary
Algae Utilisation schemes

• Parallels with the dairy industry
  • Contents of algae cells can be considered as a milk

• Agriculture – Aquaculture refineries possible
  • Aquaculture needs PUFA and protein, make a lot of wastes
  • Chicken and pig farming could be well suited to this application

• Fuels and chemicals
  • Over hyped area but feasible when the technology is established
Multi-stage-stage biorefinery fractionation process using low energy ball mills. (Steve Skill, PML)

Harvest

Growth Media Recycle

Passive settling

Ball Mill 1

Passive settling

Ball Mill 2

Passive settling

14% solids

Extra-cellular Extract

Sunscreen
Anti-inflammatory
Anti-oxidants (Anti-ageing)

Lysate

Anti-oxidants
Carotenoids
Natural colours

Further Fractionation

(Crossflow filtration)

Protein

Hair Care
Fractionation of microalgae

Cell disruptor

Microfiltration

Ultrafiltration

Recycle (concentrate)

Permeate

Undisrupted cells

Disrupted cells

Freeze-dryer
Fractionation of microalgae
Fractionation of microalgae

DF strategies to increase purity

<table>
<thead>
<tr>
<th>Concentration (mg/L)</th>
<th>Protein</th>
<th>Carbohydrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Sep 1</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>DF 1</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>DF 2</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>DF 3</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Purity (%)
Regional economics, demands, resources - all play a role in the best strategy and spectrum of products to be produced.
Integration of AD with algal production

Food Waste etc. → AD → Engine → Power

O₂

CO₂, Heat,

AD filtration → MF Nutrient → PBR → MF Algae harvesting

Fine solids

Water

Cell debris

Dewatered course solid → Compost

N and P minerals

Protein recovery → Protein Feed → Power

Export Options
Tentative DSP Scheme for High Value Products

Key to unit operations

- **DF** = Diafiltration
- **MF** = Microfiltration
- **UF** = Ultrafiltration
- **NF** = Nanofiltration
- **RO** = Reverse osmosis
- **C** = Centrifugation
- **SCC** = Supercritical CO2
- **IL** = Ionic liquids
- **SO** = Salting out
- **ppt** = precipitation

Products for formulation

- Functional protein
- Cosmetic peptide 1
- medical carbohydrate 1
- Purified HUFA
- Nutrient oil/fat
- Carotenoids
- Cosmetic peptide 2
- Medical carbohydrate 2

Development of scalable high resolution separations

Nutrients formulation → PB Reactor

- Water
  - harvesting
  - Cell pre-treatment
  - Cell disruption
  - Solvent extraction
    - Oil/carotenoids
    - Enzyme(s)
    - RO water
    - Carbohydrate fraction
    - Carbohydrate fractionation
    - insol proteins & carbohydrate
      - ppt
      - SO
    - Protein hydrolysate
    - Protein conc
      - soluble
      - MF
    - Carbohydrate conc
      - OIL
      - RO water
      - Protein hydrolysate
      - Carbohydrate fraction
      - Enzyme(s)
      - RO water

- RO water
  - IL
  - CO2
  - CHP
  - Anaerobic digestion

- UF/spray dry
  - Enzyme(s)
  - NF/RO
Conclusions

• A massive multidisciplinary effort is required
  • More knowledge on the chemical biology of algae

• A holistic approach gives flexibility
  • Several problems can be solved simultaneously - energy, food and materials

• The future using all the tools available requires us to turn toward closed systems
  • genetic engineering
    • Not just product formation also processing aids
    • Light sensing and product formation
  • optimized environmental conditions
  • Novel process technology
Future Prospects

• Where are we at?
  • reliable large scale systems yet to be proved

• Fully integrated systems need to be developed
  • Based on high value materials but with the potential to produce bulk energy products
  • Key unit operations need to be proved

• Internally lit reactors as energy transformation systems to produce carbon materials
  • High degree of process control, very stable environments
  • Optimised process conditions
  • Basis of improved starter cultures