Maximal photosynthetic efficiency of microalgae in photobioreactors and the minimal requirement for gas transfer

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What’s determining PE outdoors?

- Light intensity
- Temperature
- Oxygen partial pressure
- Carbon dioxide partial pressure
- pH
- Nutrients

Low controllability

High controllability
Biomass growth

- Sunlight driven production of carbohydrates:
  \[ CO_2 + H_2O \rightarrow CH_2O + O_2 \]
  \[ 10 \text{ h} \]

- Carbohydrates yield biomass:
  \[ 1.18 \, CH_2O + 0.12 \, NH_4^+ \rightarrow CH_{1.78}O_{0.36}N_{0.12} + 0.18 \, CO_2 + 0.47 \, H_2O + 0.12 \, H^+ \]

- Taken together:
  \[ CO_2 + 0.71 \, H_2O + 0.12 \, NH_4^+ \rightarrow CH_{1.78}O_{0.36}N_{0.12} + 1.18 \, O_2 + 0.12 \, H^+ \]
  \[ 11.8 \text{ h} \]
Theoretical maximal photosynthetic efficiency (PE)

<table>
<thead>
<tr>
<th>N-source</th>
<th>( QR_{CO2} ) mol Cmol(^{-1} )</th>
<th>( Y_{x,E} ) g mol(^{-1} )</th>
<th>( PE_{PAR} ) % PAR</th>
<th>( PE ) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO(_3^–)</td>
<td>14.2</td>
<td>1.50</td>
<td>19</td>
<td>8</td>
</tr>
<tr>
<td>NH(_4^+)</td>
<td>11.8</td>
<td>1.80</td>
<td>21</td>
<td>9</td>
</tr>
<tr>
<td>No nitrogen*</td>
<td>10</td>
<td>1.96</td>
<td>21</td>
<td>9</td>
</tr>
</tbody>
</table>

* Hypothetical situation of biomass solely accumulating carbohydrates (CH2O)\(_n\)
Light use efficiency in practice

\[ r_{ph,abs} = r_{ph,\mu} + r_{ph,m} + r_{ph,heat} \]

\[ r_{ph,abs} = \int_{400}^{700} a_\lambda \cdot PFD_\lambda \cdot d\lambda \]

\[ r_{ph,\mu} = \frac{1}{QY} \cdot Y_{O2,x} \cdot \mu \]

\[ r_{ph,m} = \text{constant} \]

\[ r_{ph,heat} \]
PE in SLP panel photobioreactors?

**Short light-path**

**Turbulence**

<table>
<thead>
<tr>
<th>Species</th>
<th>$I$ (μmol m$^{-2}$s$^{-1}$)</th>
<th>Light path (cm)</th>
<th>$Y_{x,E}$ (g mol$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical maximum ⇒</td>
<td></td>
<td></td>
<td>1.50</td>
</tr>
<tr>
<td><em>Spirulina</em></td>
<td>1800</td>
<td>2.6</td>
<td>1.42</td>
</tr>
<tr>
<td><em>Spirulina</em></td>
<td>2x1050</td>
<td>1.4</td>
<td>1.62</td>
</tr>
<tr>
<td><em>Chlorococcum</em></td>
<td>2x1000</td>
<td>1.0</td>
<td>0.53</td>
</tr>
<tr>
<td><em>Nannochloropsis</em></td>
<td>2000</td>
<td>1.0</td>
<td>0.37</td>
</tr>
</tbody>
</table>
WUR-BPE research focused on...

- High PE at high light intensity PFD by:
  - Short light path
  - Turbulent mixing
  - High biomass density
Panel reactors and saturating light, 950 \( \mu \text{mol m}^{-2} \text{ s}^{-1} \)

\[ Y_{x,E} = 0.7 \text{ g mol}^{-1} \]

\[ \text{PE} = 4 \% \]

\( \text{Dunaliella tertiolecta} \)

1, 2 and 3 cm Light path
Panel reactors and saturating light, 950 $\mu$mol m$^{-2}$ s$^{-1}$

1, 2 and 3 cm Light path

$Y_{X,E} = 0.7$ g mol$^{-1}$

PE = 4 %

Chlorella sorokiniana
Spinning Tube-in-Tube photobioreactor

- *Chlorella sorokiniana*
- 1 cm light path, variable mixing
- 1500 micromoles m\(^{-2}\) s\(^{-1}\)
Over-saturating light, 1500 μmol m$^{-2}$ s$^{-1}$

$Y_{x,E} = 0.7$ g mol$^{-1}$

PE = 4 %
Over-over saturating light

- *Chlorella sorokiniana*
- 1.4 cm panel reactor
- Variable dilution rate
- 2100 $\mu$mol m$^{-2}$ s$^{-1}$
Over-saturating light, 2100 μmol m⁻² s⁻¹

Yₓ,E = 1.0 g mol⁻¹

PE = 5 %
Conclusions photosynthetic efficiency

- PE of 4% possible under high PFD
- Biomass concentration 1 - 10 g L\(^{-1}\)
- High mixing does not help much…?
- …and takes too much energy!
High PE?... Light dilution!

- Go vertical and reduce light
- Combine with short light path systems
  - High biomass density

\[ I_r = I_\perp \cdot \cos \beta \]
PE at moderate light intensity

\[ Y_{x,E} = 1.1 \text{ g mol}^{-1} \]

570 micromoles m\(^{-2}\) s\(^{-1}\)

PE = 6 %
Outlook

- A Photosynthetic efficiency of 7% seems to be within reach for closed photobioreactors…
  - When corrected for night biomass loss 6% is a reasonable target for real life

- What will it cost…?
  Materials / construction
Mixing/gassing for CO₂ and O₂ transfer

- Gassing needs to be minimized, but:
  - CO₂ and O₂ transfer capacity must meet demands
  - Sedimentation must be prevented

- Important for any system, closed PBRs and open ponds!

- What is the energy requirement?
Gas transfer: a calculation example

Width 0.01 m

5 rows / m

0.5 m
Flue gas 10% v/v CO₂

Exhaust 1% v/v CO₂

Recirculation 1% ≈ v/v CO₂

3414 m³ h⁻¹ ha⁻¹

11.6 kW ha⁻¹

PFD_{surface} = 400 \mu mol m⁻² s⁻¹

QR = 18.7 hν / CO₂

PE = 6 %

Biomass production: 771 mol BioC h⁻¹ ha⁻¹

≈ 18.5 kg h⁻¹ ha⁻¹

125 kW ha⁻¹

Creation of transfer area!

186 m³ h⁻¹ ha⁻¹

Flue gas 10% v/v CO₂
CO$_2$ transfer rate (CTR) and gas flow rate

\[
CTR = k_{l,CO2} \cdot a \cdot (C_{CO2,interface} - C_{CO2,bulk}) \quad [\text{mol CO}_2 \text{ m}^{-3} \text{ s}^{-1}]
\]

\[
k_{l,CO2} \cdot a = 0.96 \cdot k_{l,O2} \cdot a = 0.96 \cdot 0.32 \cdot v_{gs}^{0.7}
\]

- $PFD$
- $QR_{CO2}$
- $V_r$
- $A_r$

25 °C, pure water, pH 7

0.35 mM CO$_2$ $\cong$ 1% v/v CO$_2$  
0.1 mM CO$_2$

Bubble column  
Coalescing, non-viscous  
bubble diameter $\approx$ 6 mm

Superficial gas velocity
Conclusions gas transfer

- Liquid mixing and CO$_2$ supply can be combined
- O$_2$ can be removed too
  - O$_2$ will accumulate to $\approx$ 2 times air saturation
- Amount of energy is needed equivalent to 10% of sunlight energy fixed inside the biomass
  - independent of photosynthetic efficiency or light input
  - Also algal ponds need to be gassed
Acknowledgments

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- Maria Cuaresma
Thank you for your attention

www.bpe.wur.nl
www.wetsus.nl

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Biomass growth versus lipid accumulation

\[
\text{CO}_2 + 0.71 \text{H}_2\text{O} + 0.12 \text{NH}_4^+ \rightarrow \text{CH}_{1.78}\text{O}_{0.36}\text{N}_{0.12} + 1.18 \text{O}_2 + 0.12 \text{H}^+ 
\]

11.8 h

50% w/w fatty acid (C\text{16}) accumulation/excretion:
\[
\text{CO}_2 + 0.88 \text{H}_2\text{O} + 0.05 \text{NH}_4^+ \rightarrow \text{CH}_{1.91}\text{O}_{0.23}\text{N}_{0.05} + 1.32 \text{O}_2 + 0.05 \text{H}^+ 
\]

13.2 h

\[
\text{CO}_2 + 0.95 \text{H}_2\text{O} + 0.12 \text{NO}_3^- \rightarrow \text{CH}_{1.78}\text{O}_{0.36}\text{N}_{0.12} + 1.42 \text{O}_2 + 0.12 \text{OH}^- 
\]

14.2 h

50% w/w fatty acid (C\text{16}) accumulation/excretion:
\[
\text{CO}_2 + 0.98 \text{H}_2\text{O} + 0.05 \text{NO}_3^- \rightarrow \text{CH}_{1.91}\text{O}_{0.23}\text{N}_{0.05} + 1.43 \text{O}_2 + 0.05 \text{OH}^- 
\]

14.3 h