Oval Glass Tube PBRs for Increased Light Absorption

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   - Static illumination (indoor)
   - Solar illumination (outdoor)

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You know SCHOTT, because you continuously come across us.
Glass Tubular Photobioreactors – SCHOTT Product Range
Goal

- Goal: Advantage of oval tubes vs. round tubes
Tube Geometries

2 tube geometries (equal circumference)

**Round**
- Diameter 65mm

**Oval**
- Elliptical, 82 mm x 41 mm (2:1)

Uniform cross sections along axis
Optical Setup

Angular dependence taken into account
Multiple internal reflexions, light guiding

Light intensity at depth $d$:

$$I(d) = I_0 \cdot e^{-\alpha d}$$

Choice: $\alpha = 1.15 \text{ cm}^{-1} \rightarrow 99 \%$ absorption in 40 mm

Only direct irradiation (no clouds), no scattering inside algae culture.

Damping by air-mass taken into account
Software

Ray tracing Software: ASAP 2009 (commercial)

- Run with one million parallel rays from one direction. Tube length = 1 m
- Conversion of result to power units with $P_{\text{in}} = 1000 \text{ W/m}^2$
- Output: Absorbed power in algae culture per 1 m tube

Mirrors at tube ends for "endless-tube"-simulation
Absorption in Round and Oval Tubes
Static Light Source (Indoor Situation)
Light Transmission into the Glass Tube (1/2)

- Geometrical width
- Photon Transfer
- Absorption = 1-Transmission loss

Bar chart showing:
- Exposed Area: 1.3
- Transfer: 1.02
- Absorbed fraction: 0.97
Light Transmission into the Glass Tube (2/2)

All effects considered (Part 1-3)
Oval tubes (m=2) absorb ~ 28% more light

Mostly: Geometrical effect

Oval tube volume ~ 82% of round tube

- Less water, pump energy saving
- Shorter optical path → higher culture concentrations
- Volumetric productivity increases by:
  \[ \frac{1.28}{0.82} \rightarrow +56\% \]
Experimental Verification at Heliae (Phoenix, AZ)

Setup: 500 l reactor, 2-side static fluorescence illumination, no shading among tubes.

Test with „real“ tubes with round ends

<table>
<thead>
<tr>
<th></th>
<th>Change (%)</th>
<th>Simulation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volumetric Productivity [g/(l*d)]</td>
<td>55.8</td>
<td>~ 56</td>
</tr>
<tr>
<td>Maximum dry weight concentration [g/l]</td>
<td>&gt; 25¹</td>
<td></td>
</tr>
<tr>
<td>Output [g/(tube*d)] (calculated from exp.)</td>
<td>39.9</td>
<td>~ 28</td>
</tr>
</tbody>
</table>

¹ stationary not reached
High Oval-Tube Light-Use For Production of High-Value Algae Ingredients

Definition of absorption densities

<table>
<thead>
<tr>
<th>Density</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>Brightest</td>
<td>20%</td>
</tr>
<tr>
<td>Intermediate</td>
<td>60%</td>
</tr>
<tr>
<td>Darkest</td>
<td>20%</td>
</tr>
</tbody>
</table>

More bright areas, less unproductive, dark space

→ Chance for light stressing of e.g. Haematococcus for higher-yield production of Astaxanthin
Year-Around Outdoor Simulation of Single Tube
4 Tube Configurations

<table>
<thead>
<tr>
<th>North-South: NS</th>
<th>round</th>
<th>Oval</th>
</tr>
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<tbody>
<tr>
<td>East-West: EW</td>
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</table>

NS

EW

\( \alpha = 0.85 \times \text{latitude (as PV)} \)
Choice of Latitude (4), Day (5) and Time (9)
e.g., 35°N (Winslow, AZ), June 21

Latitudes:
Phoenix 33.4°
Lisbon: 38.7°
Tel Aviv: 32.1°

Calculation of elevation and azimuth angles
→ Incident angle on tube

Then integration to obtain the daily absorbed energy
Absorbed Energy per Day and Year

Then integration to obtain the yearly absorbed energy

Simulation for 0°, 20°, 35°, 50°
Yearly Absorbed Energy at Different Latitudes

- **0°**
  - EW Round: 170 kWh
  - EW Oval tilt: 209 kWh
  - NS Round: 218 kWh
  - NS Oval: 231 kWh

- **20°**
  - EW Round: 167 kWh
  - EW Oval tilt: 205 kWh
  - NS Round: 206 kWh
  - NS Oval: 217 kWh

- **35°**
  - EW Round: 157 kWh
  - EW Oval tilt: 193 kWh
  - NS Round: 183 kWh
  - NS Oval: 188 kWh

- **50°**
  - EW Round: 138 kWh
  - EW Oval tilt: 170 kWh
  - NS Round: 150 kWh
  - NS Oval: 148 kWh
Round Tubes: NS better than EW

Normalization: Absorption = 100 % for 0° latitude, round tube, EW orientation
More Light Absorption with Oval Tubes

Absorbed Energy [norm]

Latitude [°]

NS, oval

EW, oval-tilt

32°
Performance Increase with Oval Tubes

Oval vs. EW round

Oval vs. NS round
Performance Increase with Oval Tubes

**Oval vs. EW round**

- **NS oval**
- **EW oval tilt**

**Absorption increase [%]**

**Latitude [°]**

0 10 20 30 40 50

**Oval vs. NS round**

- **NS, oval tilt**
- **EW oval tilt**

**Absorption increase [%]**

**Latitude [°]**

0 10 20 30 40 50
Outdoor Examination of Oval Tubes by Algae for Future, A4F, Portugal

Experimental Setting and Results
1000 l PBR in greenhouse, EW-orientation. Diatom strain, Summer 2015. 39°N.

Reactor was equipped consecutively with round and oval tubes. „Equal“ conditions.

Higher single tube absorption is (only) partially transferred to the PBR system.

<table>
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<tr>
<th></th>
<th>Change Exp. [%]</th>
<th>Simul. Single tube [%]</th>
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</thead>
<tbody>
<tr>
<td>Productivity per tube [g/day]</td>
<td>2.0</td>
<td>22.9</td>
</tr>
<tr>
<td>Maximum dry weight concentration [g/l]</td>
<td>42.4</td>
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Dry weight concentration strongly enhanced
Expectation: faster harvest more robust cultures
Summary

Indoor, artificial illumination
- Oval tubes lead to experimentally confirmed higher volumetric productivities (> 50 %), output increases by 28-40 %, peak algae concentrations > 25 %.
- Chance for higher-yield production of algae ingredients

Outdoor, solar illumination
- Single tube advantage is (only) partially transferred to system
- Higher peak concentrations (> 40 %). Short light paths provide chance for light stressing and a higher-yield production of algae ingredients.
- Smaller volumes (→ 10 % pump energy saving).
Thank you for your attention