Optimisation of microalgae culture in the light changing conditions of solar production in photobioreactor

\[ \frac{\frac{\rho \Phi}{K_a \phi X}}{K_a + G} = \frac{\frac{J_{\text{sun}} M}{\nu_{\text{mix}} - K_r G X}}{K_r + G X} \]

Pr. Jeremy Pruvost - Université de Nantes
Laboratoire GEPEA (UMR-CNRS)
Plateforme AlgoSolis (UMS-CNRS)
Saint-Nazaire, France

Dr. Arnaud Artu - AlgoSource Technologies
Dr. Mariana Titica, Pr. Jack Legrand – GEPEA - Un. Nantes
Pr. C.Sihem Tebbani – CentraleSupélec - Un. Paris-Saclay
France
Closed PBR technology:
- Difficult to scale up for mass production on large land areas
- Involves more complex and expensive processes

But PBR technology:
- Allows providing the necessary controlled conditions to avoid external contamination, greatly increasing the number of species that can be cultivated,
- Allows providing (at least in theory) optimized growth conditions for the species in culture

Several industrial plants are nowadays using PBR technology (for new species, new products, higher performances and production robustness...)
But there is still a need to develop efficient approaches for an optimized and robust operation of solar PBR
Mains issues of solar PBR operation

In solar outdoor conditions, closed PBR technology suffer from several limitations inherent to their operating principles:

- Risk of biofilm formation on the PBR walls
- Oxygen accumulation in the culture
- Overheating of the culture (sunlight IR absorption)

Culture confinement induces:

- Can be (at least partly) solved with an appropriate engineering (PBR design, coupling to thermal regulation devices, mixing, materials..).
- If the case, light-use remains the limiting factor

But even the only optimization of the light-use in solar conditions is a challenge

→ Light changing conditions!

Pruvost et al., Biotech progress, 2013
Optimizing light attenuation conditions in PBR

An optimal biomass concentration exists, corresponding to an optimal dilution rate (or residence time)

Biomass productivity $P_x = \frac{C_x}{\tau_p} = C_x D$

Increasing biomass concentration decreases the light energy absorption rate

$\tau_p = \frac{V_R}{Q} = \frac{1}{D}$

$P_x \text{ max}$

$C_{x\text{opt}}$

$\tau_{p\text{ opt}}$

$<A>$

$\mu\text{mole}_{\text{net}}\text{g}^{-1}\text{s}^{-1}$
Optimizing light attenuation conditions in PBR

Chlorella v, PFD = 250μmoles/m².s

Unstable !

Kinetic regime
(light transmission - High photon absorption rates)

Full light absorption (Case A)

Luminostat regime (Case B)

Maximal biomass productivity $P_x$ ($kg.m⁻³.day⁻¹$)
Biomass productivity $P_x$ ($kg.m⁻³.day⁻¹$)
Biomass concentration $C_x$ ($kg.m⁻³$)

Working in low light attenuation conditions leads to unstable biological behavior (oversaturation) and because of the proximity of the maximal dilution rate, a culture washing will be highly possible

So, the full light absorption regime has to be preferred !

Takache et al., Biotechnology Progress, 2012.
Optimisation of light conversion in microalgal culture systems

The solar case
Light attenuation modeling

Allows determining the irradiance-field $G(z)$ in the culture depth $z$

Note: $G$ is a function of irradiation conditions, biomass concentration, microalgae radiative properties (i.e. absorption, scattering)

$$G(z) = G_{\text{col}}(z) + G_{\text{dif}}(z)$$  \hspace{1cm} \text{Two-flux model (solar case)}

$$G_{\text{col}}(z) = \frac{2}{\cos \theta} \frac{(1 + \alpha) \exp[-\delta_{\text{col}}(z - L)] - (1 - \alpha) \exp[\delta_{\text{col}}(z - L)]}{(1 + \alpha)^2 \exp[\delta_{\text{col}} L] - (1 - \alpha)^2 \exp[-\delta_{\text{col}} L]}$$

$$G_{\text{dif}}(z) = \frac{4}{1 + \alpha} \frac{(1 + \alpha) \exp[-\delta_{\text{dif}}(z - L)] - (1 - \alpha) \exp[\delta_{\text{dif}}(z - L)]}{(1 + \alpha)^2 \exp[\delta_{\text{dif}} L] - (1 - \alpha)^2 \exp[-\delta_{\text{dif}} L]}$$

Calculation of the local rate of photons absorption ($A(z)$)

$$A_\lambda(z) = E_{\alpha_\lambda} . G(z)$$

with $E_{\alpha_\lambda}$: Absorption cross section of the microalgal (function of pigment, size, shape...)

Mean rate of photons absorption ($\langle A \rangle$)

$$\langle A \rangle = \frac{1}{L} \int A(z) dz$$

Can be averaged over the PBR volume to obtain the mean rate of photons absorption

$$A(z) = \int_{\text{PAR}} A_\lambda(z) d\lambda$$

Can be averaged over the PAR to obtain the local value of the total rate of photons absorption
Experimental set-ups

Outdoor culture (AlgoSolis R&D facility)

Indoor culture (simulated diurnal conditions)

Chlorella vulgaris CCAP 211/19

Light-limited regime
pH=7.5
T=25°C

Simulation of day-night cycles with LED panels

Torus-shaped PBR

Flat panel (airlift) solar PBR

Flat panel (airlift) PBR

Torus-shaped PBR

$q_0 = 270 \mu\text{mol}_m^{-2}.s^{-1}$
(average yearly PFD in Nantes)

$PFD, q_0 (\mu\text{mol}_m^{-2}.s^{-1})$ vs $Time (h)$
**Prediction of pigment acclimation**

*Chlorella vulgaris* is well-known for its large capacity to adapt its pigment content to illumination conditions, which modifies light absorption conditions.

A large set of experiments was conducted: different PBR geometries, different PFD and operating conditions (i.e. dilution rate)...

![Image of pigments](image)

<table>
<thead>
<tr>
<th>MRPA, ⟨A⟩ (µmol_{hv}g^{-1}.s^{-1})</th>
<th>Pigment content, w_p (% C_X)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10%</td>
</tr>
<tr>
<td>5</td>
<td>8%</td>
</tr>
<tr>
<td>10</td>
<td>6%</td>
</tr>
<tr>
<td>15</td>
<td>4%</td>
</tr>
<tr>
<td>20</td>
<td>2%</td>
</tr>
<tr>
<td>25</td>
<td>0%</td>
</tr>
<tr>
<td>30</td>
<td>2%</td>
</tr>
<tr>
<td>35</td>
<td>4%</td>
</tr>
<tr>
<td>40</td>
<td>6%</td>
</tr>
<tr>
<td>45</td>
<td>8%</td>
</tr>
<tr>
<td>50</td>
<td>10%</td>
</tr>
</tbody>
</table>

The pigment content was found to be fully related to the mean rate of photon absorption (⟨A⟩).
Influence of harvesting strategies on light conversion

Continuous culture (permanent harvesting) was compared to semi-continuous culture (punctual harvesting)

Continuous culture (chemostat)

\[ D = \frac{Q_s}{V_R} \]
\[ Q_s = Q_e \]

Same illumination condition in both cases:
\[ \bar{q}_0 = 270 \, \mu\text{mol}_\text{h}^{-1}\text{m}^{-2}\text{s}^{-1} \]
and dilution rate \( D = 0.027\text{h}^{-1} \)
(Resistance time \( \tau_p = 37\text{h} - 65\% \) of daily renewal)

Semi-continuous culture
(repeated \( n \) times until periodic regime)

24h harvesting (continuous)

Batch growth

Dilution
Harvesting

\[ D = \frac{Q_s}{V_R} = \frac{V_s}{T_s \cdot V_R} \]

\( n \)
Influence of harvesting strategies on light conversion

- Semi-continuous mode leads to sharper time evolutions of biomass concentration, but also MRPA and pigment content.

- In semi-continuous mode, high MRPA values are achieved, due to the combination of both PFD increase (noon) and significant pigment decrease due to photoacclimation.
Influence of harvesting strategies on light conversion

At T=16h (6h after sunrise), growth rate is highly reduced, although high MRPA are achieved.

A quick pigment acclimation occurs (5 to 2.7%), reducing MRPA which leads to more favorable growth conditions.
Determination of critical light-regimes

Analysis of the light absorption profile for $T=16$ h ($q_0 = 730 \text{ \mu mol}_{hv}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)

Continuous mode leads to too high RPA values for effective photosynthetic conversion (86% of the culture volume received a rate of photons absorption $A$ higher than $20 \text{ \mu mol}_{hv}\cdot\text{g}^{-1}\cdot\text{s}^{-1}$)

Semi-continuous mode leads to too high RPA values for effective photosynthetic conversion (86% of the culture volume received a rate of photons absorption $A$ higher than $20 \text{ \mu mol}_{hv}\cdot\text{g}^{-1}\cdot\text{s}^{-1}$)
Guidelines for solar PBR operation

Case study: Flat Panel PBR ($L_z=3$cm), *C. vulgaris*

Rational guidelines can be set for optimal operation of solar PBR, by determining the range of biomass concentrations for:

- **Reduced effect of negative effect of dark volume** (i.e. then maximizing biomass productivity)
- **Reduced risk of biological drift induced by too large rates of photon absorption** (i.e. loss of productivity due to photoinhibition)
Optimisation of light conversion in microalgal culture systems

Towards optimized advanced-controlled strategies
The objective of the optimization was to determine the dilution rate maximizing the biomass production under solar conditions, while keeping low the risk of biological drift which could be induced by too large rates of photon absorption.

**Optimization Problem Statement**

- continuous or semi-continuous operation
- dilution rate maximizing daily biomass production (Crit1)

\[
\text{Crit1} = \max_{D(t)} \int_0^T D(t)X(t)\,dt \\
(T=24 \text{ hours})
\]

- Low risk of culture drift due to too large values of the rate of photons absorption (Crit2)

\[
\text{Crit2: } RPA(L) < 20 \, \mu\text{mol}_\text{hn}.\text{g}^{-1}.\text{s}^{-1}
\]

In semicontinuous conditions, dilution rate is calculated every hour during the day. Additional constraint: \(X(0) = X(24)\).
Model based optimization of PBR operation under fluctuating light conditions

<table>
<thead>
<tr>
<th>4 scenarios are presented:</th>
<th>Daily biomass production $\int_0^{24} D(t)X(t)dt$ (kg X/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• No optimization (reference case)</td>
<td>0.056</td>
</tr>
<tr>
<td>• Typical dilution rate value (30% renewal per day, i.e. D=0.0125 h⁻¹)</td>
<td></td>
</tr>
<tr>
<td>• Crit 1: biomass production optimization</td>
<td>0.165</td>
</tr>
<tr>
<td>• Optimized constant dilution rate value (80% renewal per day, i.e. D=0.035 h⁻¹)</td>
<td></td>
</tr>
<tr>
<td>• Crit 1: biomass production optimization</td>
<td>0.23</td>
</tr>
<tr>
<td>• Semicontinuous operation</td>
<td></td>
</tr>
<tr>
<td>Harvesting 2 hours before sunset (biomass concentration 0.56g/l)</td>
<td></td>
</tr>
<tr>
<td>D=0.37 h⁻¹ during one hour (X(0) = X(24) = 0.3 g/L)</td>
<td></td>
</tr>
<tr>
<td>• Crit 1 (biomass production optimization) +Crit2 (low risk of culture drift)</td>
<td>0.12</td>
</tr>
<tr>
<td>• Semicontinuous operation</td>
<td></td>
</tr>
<tr>
<td>Harvesting 4 hours before sunset (biomass concentration 0.8g/l)</td>
<td></td>
</tr>
<tr>
<td>D=0.14 h⁻¹ during one hour (X(0) = X(24) = 0.6 g/L)</td>
<td></td>
</tr>
</tbody>
</table>

The harvesting strategies can be dynamically adjusted to optimize biomass production while keeping the production process in an stable operating range (productivity-robustness compromise)
Conclusion

Radiative (light) transfer modeling allows determining the light regimes which occur in solar culture systems.

The rate of photons absorption (RPA) revealed a key quantitative value to represent relevant features of solar PBR operation, like the pigment acclimation and culture response to light received and its attenuation in the culture volume.

Calculation of the RPA allows setting optimized control strategies for solar PBR, maximizing biomass productivity while keeping the culture process within a stable operating range (i.e. productivity-robustness compromise).

Efforts have to be pursued at both biological (i.e. photosynthetic response to high and dynamic light) and bioprocess (i.e. advanced control-command of solar PBR) levels.

The approach has to be extended to intensified solar PBR and other relevant features of solar PBR, such as temperature control and thermal regulation optimization.
Thank you for your attention

New International Master Degree (Univ. Nantes) Opening in Sept. 2017!

master-mbe@univ-nantes.fr

CONTACT
Jeremy PRUVOST
algosolis@univ-nantes.fr
www.algosolis.com
Model based optimization of PBR operation under fluctuating light conditions