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MICRO-ECOLOGICAL LIFE SUPPORT SYSTEM ALTERNATIVE

CREATING A CIRCULAR FUTURE

MODELING AND EXPERIMENTAL CAMPAIGN OF A NOVEL, COMPACT, THIN-TUBE PHOTOBIOREACTOR FOR HIGH VOLUMETRIC PRODUCTIVITY

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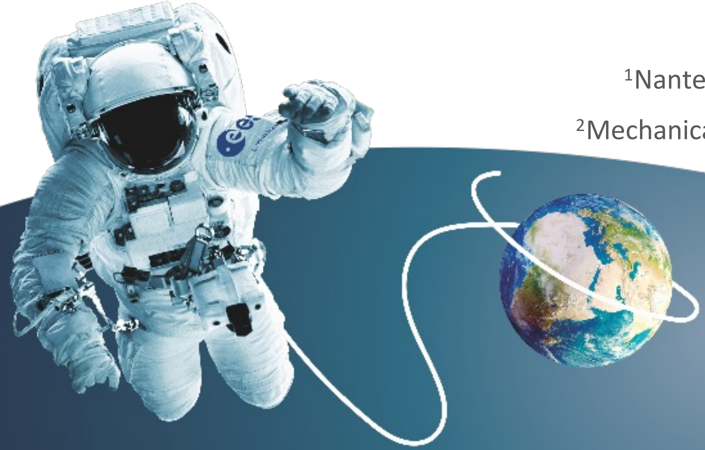

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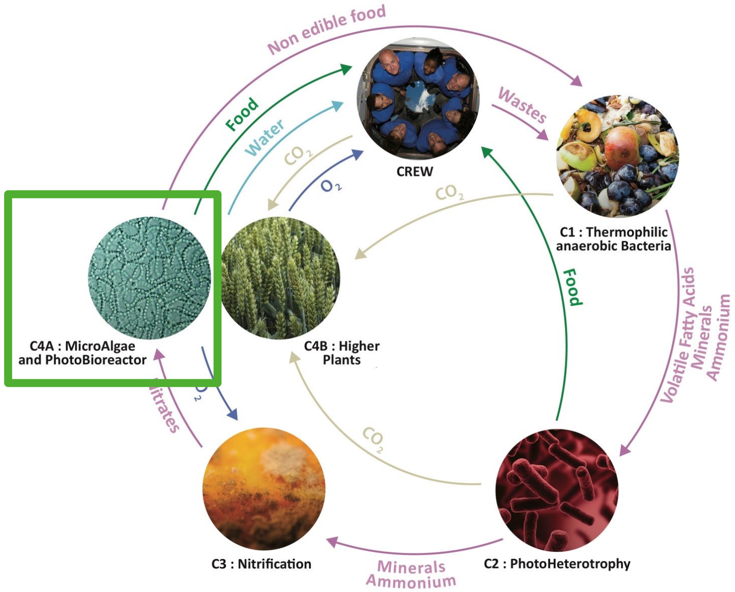
Context: MELiSSA Project



- Photosynthetic algae
  - Consume waste effluents
  - Produce biomass, O_2

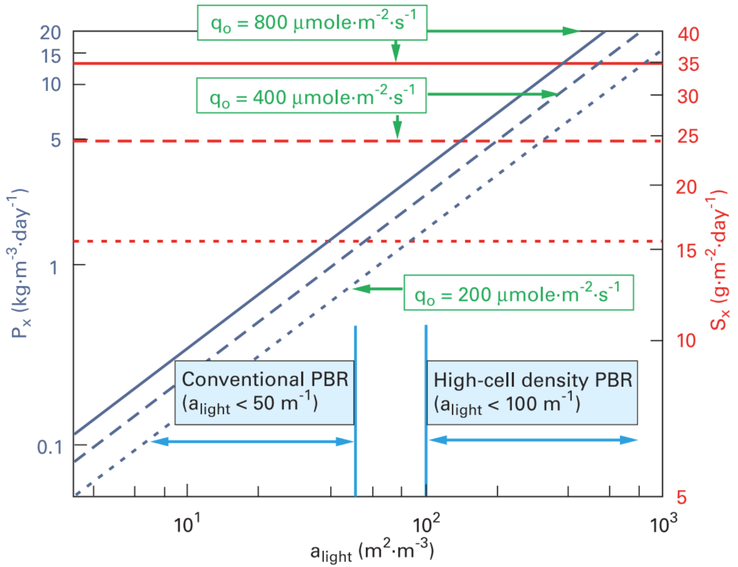
Context: Photobioreactors

- Intensified PBRs

$$a_{light} = \frac{illuminated\ surface\ area}{culture\ volume}$$

  - Large ratio of illuminated surface to culture volume, a_{light}

Context: Photobioreactors



Photobioreactor productivity as a function of illuminated surface-to-volume ratio for Chlamydomonas reinhardtii *under continuous operation in light-limited conditions*

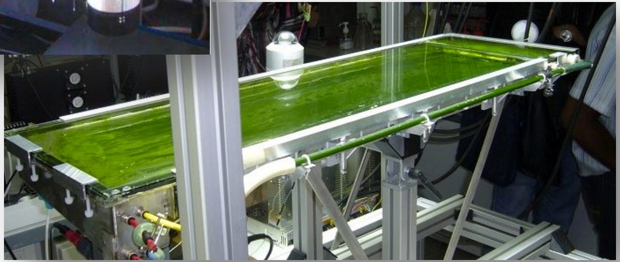
- Intensified PBRs

$$a_{light} = \frac{illuminated\ surface\ area}{culture\ volume}$$

  - Large ratio of illuminated surface to culture volume, a_{light}
  - High biomass concentration
  - High volumetric productivity

Context: Photobioreactors

DiCoFluV[1] volumetrically illuminated PBR (courtesy of Institut Pascal – UCA - France)



AlgoFilm[2] thin film PBR (GEPEA – NU - France)

- Intensified PBRs

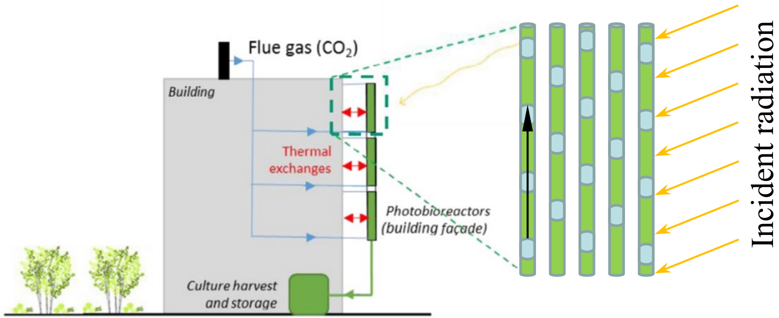
$$a_{light} = \frac{illuminated\ surface\ area}{culture\ volume}$$

  - Large ratio of illuminated surface to culture volume, a_{light}
  - High biomass concentration
  - High volumetric productivity

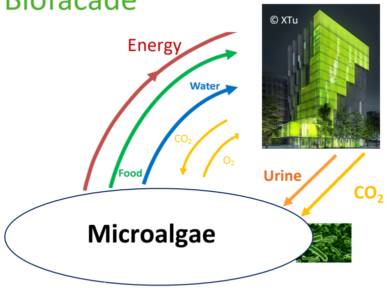
[1] J.-F. Cornet, *Chemical Engineering Science*. Vol. 65, pp. 985-98, 2010.
[2] J. Pruvost *et al.* *Algal Research*, vol. 21, pp. 120-137, 2017

Context: Terrestrial applications

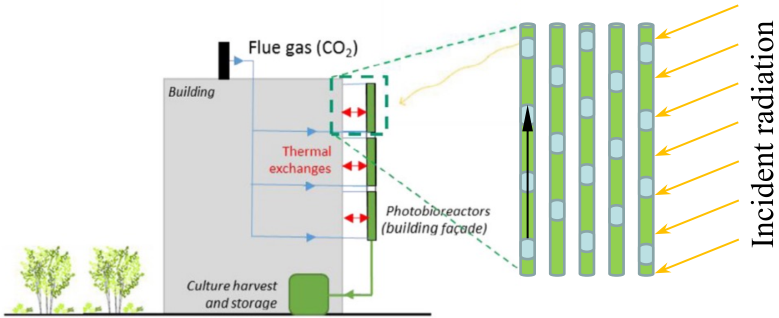
Biofaçades: Symbiosis between building waste and culture inputs



Biofacade

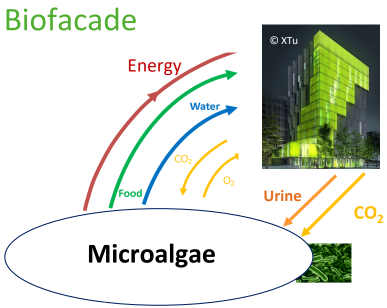


Context: Terrestrial applications

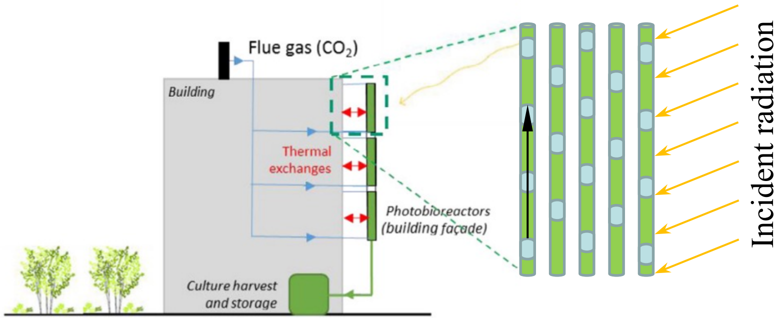


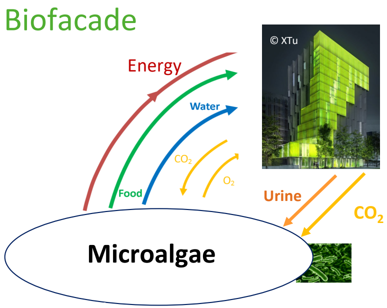
Biofaçades: Symbiosis between building waste and culture inputs

- Heavier structure → higher cost
  - Culture volume
  - Wall thickness



Context: Terrestrial applications

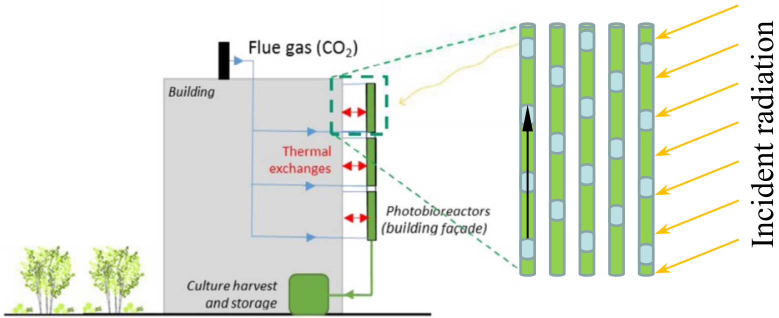


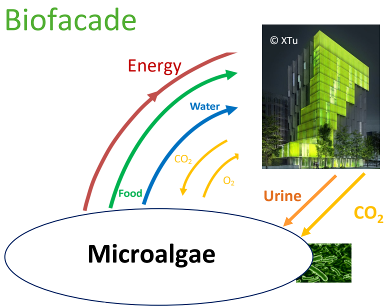


Biofaçades: Symbiosis between building waste and culture inputs

- Heavier structure → higher cost
  - Culture volume → intensification
  - Wall thickness

Context: Terrestrial applications





Biofaçades: Symbiosis between building waste and culture inputs

- Heavier structure → higher cost
  - Culture volume → intensification
  - Wall thickness → tubular design

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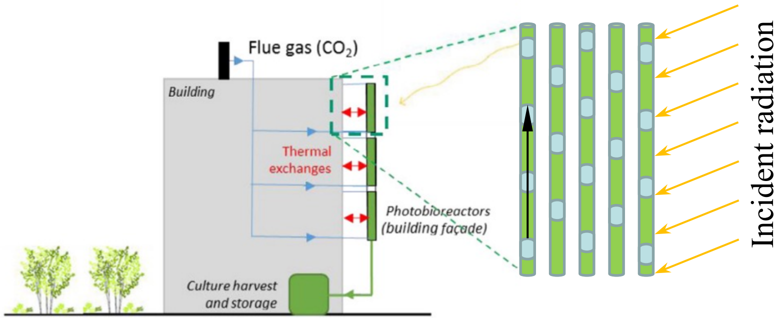
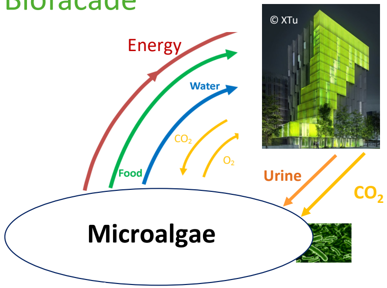




Biofaçades: Symbiosis between building waste and culture inputs

- Heavier structure → higher cost
  - Culture volume → intensification
  - Wall thickness → tubular design

THIN-TUBE PHOTOBIOREACTOR (diameter <1cm)

Outline

Objectives

1. Develop a comprehensive light transfer model for thin-tube photobioreactors to drive design decisions
2. Experimental proof-of-concept

Modeling approach

- Light transfer
- Growth kinetics

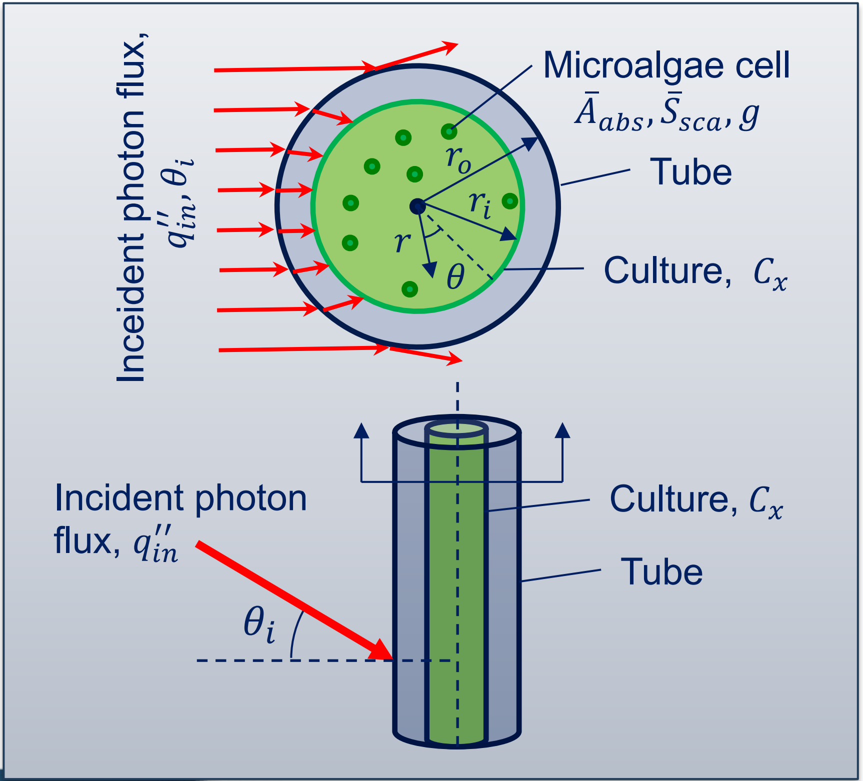
Simulation results

Experimental results

Modeling approach: Light transfer

Monte Carlo ray tracing

- Tracks many individual photons
- Models scattering and absorption:
  - Snell's law
  - Fresnel's equations

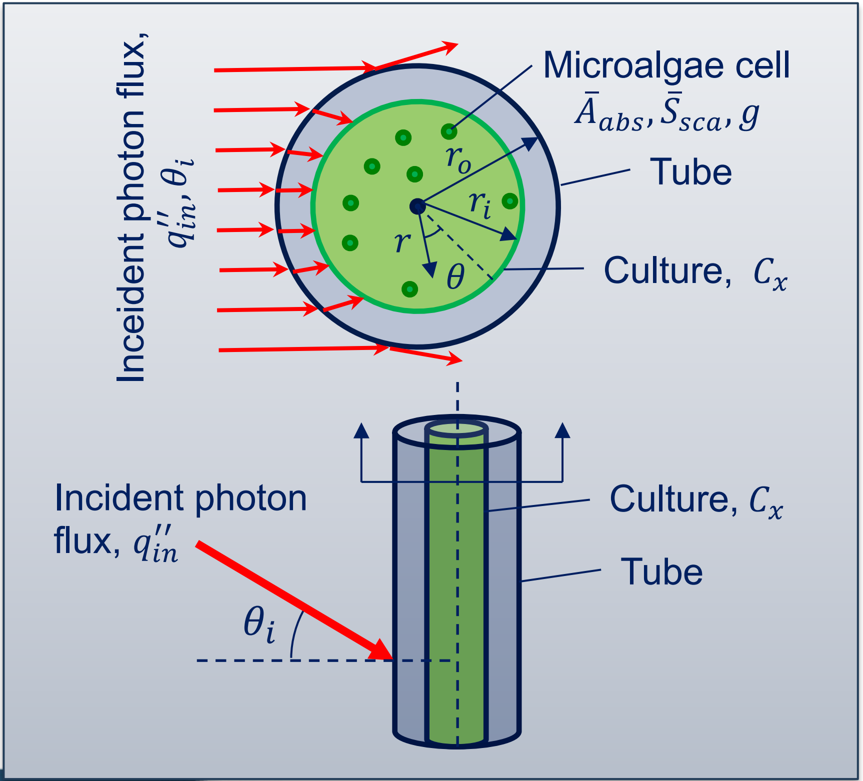


Modeling approach: Light transfer

Monte Carlo ray tracing

- Tracks many individual photons
- Models scattering and absorption:
  - Snell's law
  - Fresnel's equations

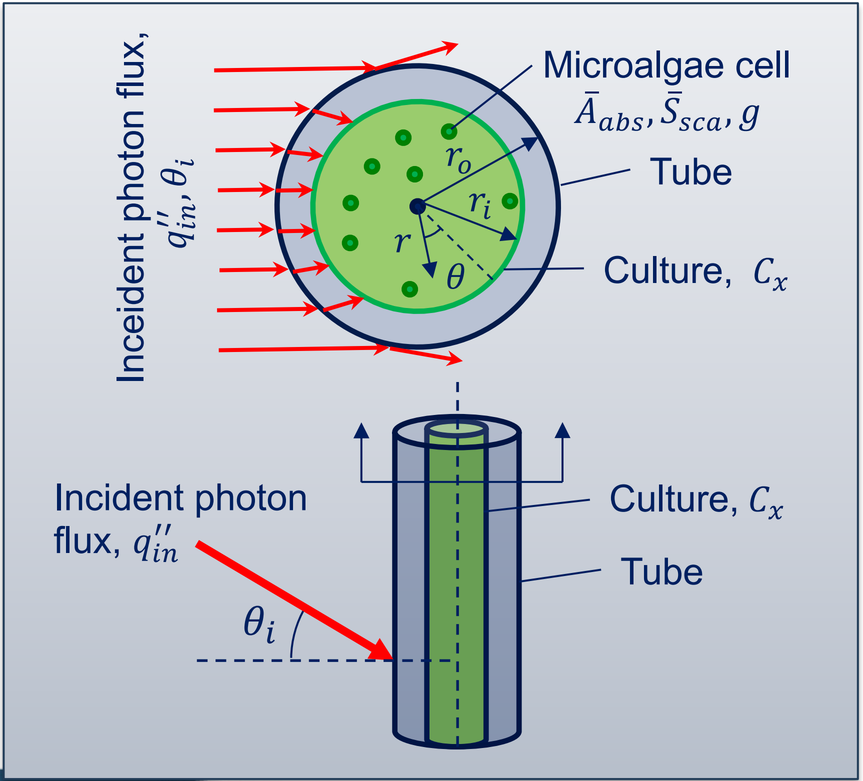
Output: Local rate of photon absorption, $\mathcal{A}(r,\theta)$ in $[\mu mol_{h\nu}/g/s]$



Modeling approach: Light transfer

Common assumptions:

- Negligible refraction effects
- Incident light is normal to tube
- Negligible culture scattering

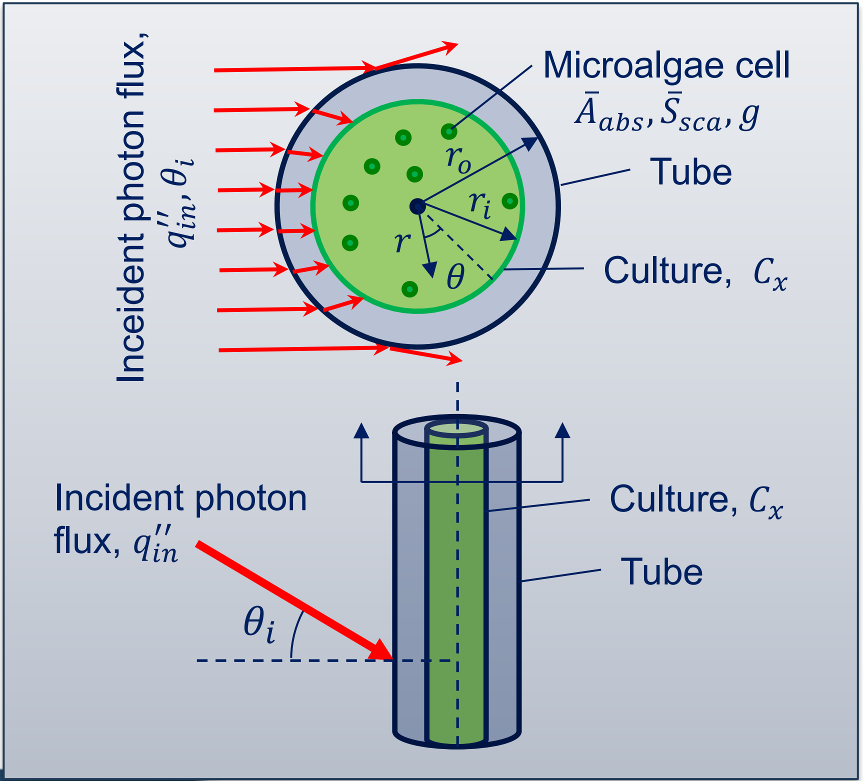


Modeling approach: Light transfer

Common assumptions:

- Negligible refraction effects
- Incident light is normal to tube
- Negligible culture scattering

MCRT method enables us to relax these assumptions



Modeling approach: Growth kinetics

Kinetic model growth model for *Chlorella vulgaris*[3] (issued from MELiSSA research on photosynthetic growth modeling)

- Culture is assumed to be light-limited
- Local rate of oxygen production, $J_{O_2}(r,\theta)$

$$J_{O_2}(r,\theta) = \rho_M \frac{K}{K+\mathcal{A}} \overline{\phi'_{O_2}} \mathcal{A} - \frac{J_{NADH_2}}{\nu_{NADH_2-O_2}} \frac{K_r}{K_r+\mathcal{A}}$$

Parameter	Value	Units
ρ_M	0.8	–
$J_{\mathrm{NADH_2}}$	2.8×10^{-3}	$\mathrm{mol_{NADH_2}\,kg_X^{-1}\,s^{-1}}$
$\nu_{\mathrm{O_2}-X}$	1.13	–
$\overline{\phi}'_{\mathrm{O_2}}$	1.1×10^{-7}	$\mathrm{mol_{O_2}\,\mu mol_{h\nu}^{-1}}$
M_X	0.024	$\mathrm{kg_X\,mol_C^{-1}}$
$\nu_{\mathrm{NADH_2-O_2}}$	2	–
K	40,000	$\mathrm{\mu mol_{h\nu}\,kg^{-1}\,s^{-1}}$
K_r	556.5	$\mathrm{\mu mol_{h\nu}\,kg^{-1}\,s^{-1}}$
$\mathcal{A}_c$	2800	$\mathrm{\mu mol_{h\nu}\,kg^{-1}\,s^{-1}}$

[3] H. Takache *et al. Biotechnology Progress*, vol. 28, pp. 681-692, 2016

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O$_2$ production

O$_2$ consumption (respiration)

Parameter	Value	Units
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- Culture is assumed to be light-limited
- Local rate of oxygen production, $J_{O_2}(r,\theta)$
- Average growth rate, $\bar{r}_x$

$$\bar{r}_x = \frac{\bar{J}_{O_2} C_x M_x}{\nu_{O_2-X}}$$

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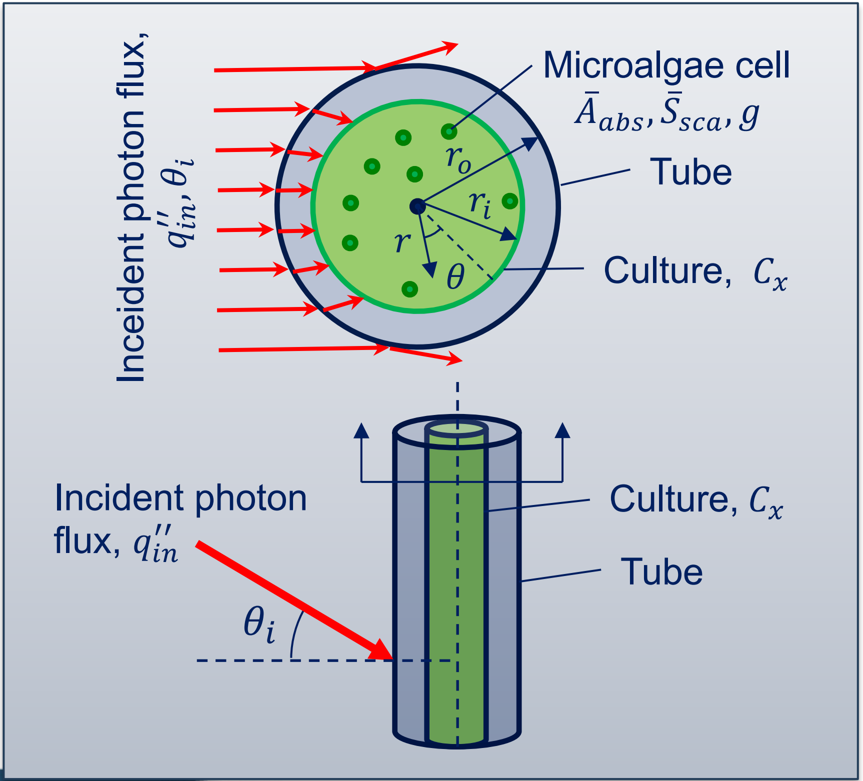
Simulation results: Impact of tube thickness

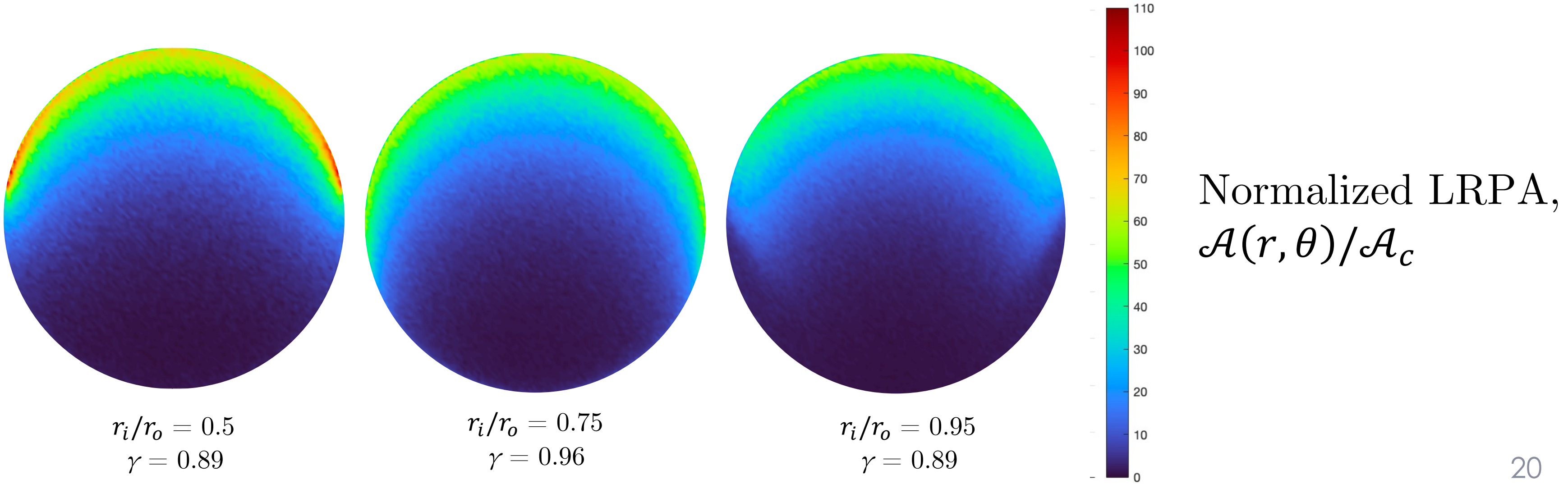
- Simulation parameters
  - Reactor
    - Inner radius: r_i = 1 cm
    - Incident photon flux: q''_{in} = 250 µmol/m^2/s
    - Incidence angle: θ_i = 0˚
  - Culture
    - Biomass concentration: C_x = 0.6 g/L
    - Absorption cross section: $\bar{A}_{abs}$ = 400 m^2/kg
    - Scattering cross section: $\bar{S}_{sca}$ = 4000 m^2/kg
    - Asymmetry factor: g = 0.974

Representative of *Chlorella vulgaris*



Simulation results: Impact of tube thickness

- Tube thickness can be optimized to improve average growth rate
  - Refraction through tube walls redirects light towards culture
  - Large tube thickness – Less concentrating effect
  - Small tube thickness – Smaller area to capture and redirect light



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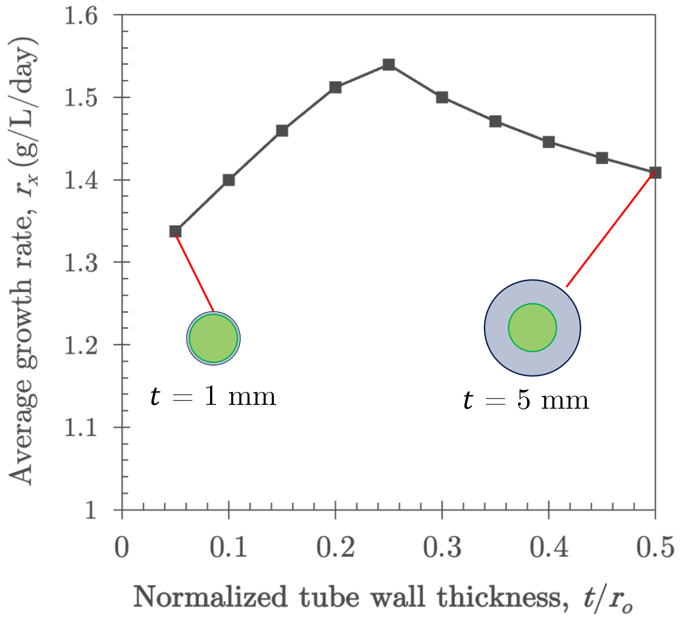
Representative of *Chlorella vulgaris*[4]



[4] R. Kandilian *et al.* *Journal of Quantitative Spectroscopy and Radiative Transfer*, vol. 175, pp. 30-45, 2016

Simulation results: Impact of tube thickness

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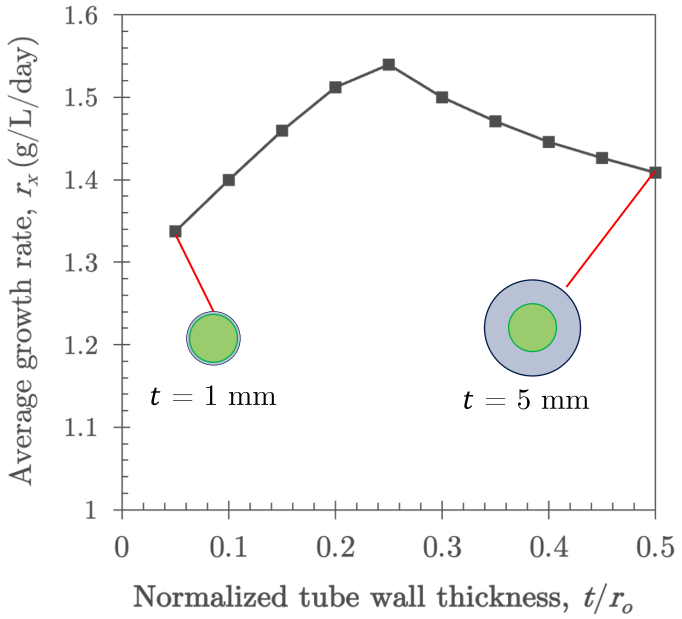
Representative of *Chlorella vulgaris*

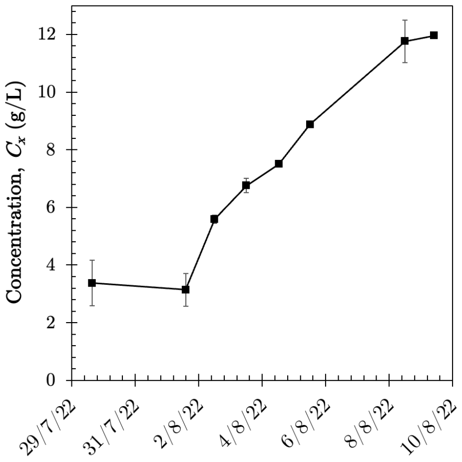
Up to **15%** decrease in average growth rate

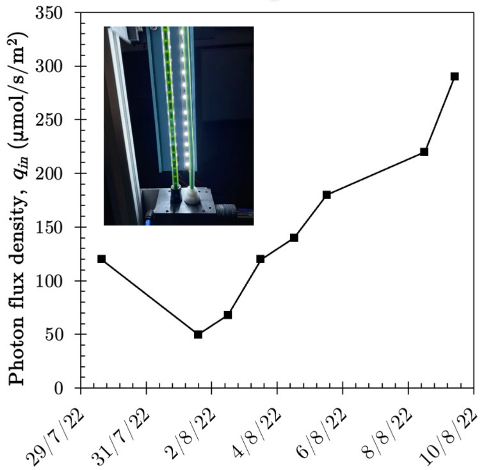


[4] R. Kandilian *et al.* *Journal of Quantitative Spectroscopy and Radiative Transfer*, vol. 175, pp. 30-45, 2016

Experimental results: Batch operation

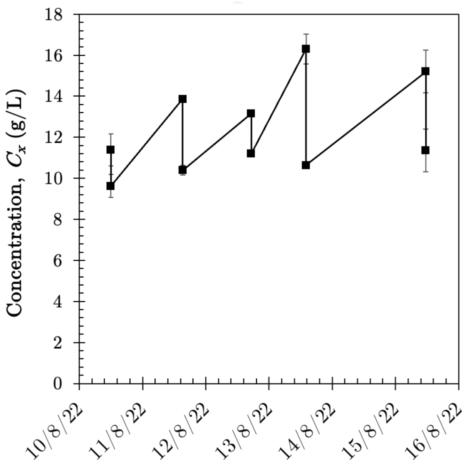
- PBR operation
  - Air/CO_2 bubbling
  - pH setpoint: 7.0
  - Incident photon flux, q''_{in} between 50 to 300 µmol/s/m^2
  - Nitrogen source: NH_4HCO_3
- PBR performance
  - Maximum concentration:
    - C_x = 12 g/L
  - Average growth rate:
    - $\bar{r}_x$ = 0.8 g/L/day

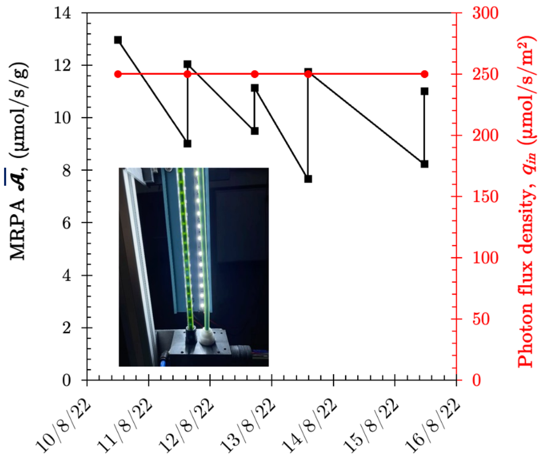




Experimental results: Continuous operation

- PBR operation
  - Injection of fresh culture medium once daily
  - pH setpoint: 7.0
  - Incident photon flux, q''_{in} = 250 μmol/s/m²
- PBR performance
  - Biomass concentration:
    - C_x = 10 – 16 g/L
  - Average productivity :
    - $\bar{r}_x$ = 3 g/L/day
    - $\bar{s}_x$ = 6 g/m²/day





Estimated mean rate of photon absorption

$$\bar{\mathcal{A}} = \frac{q''_{in} a_{light}}{C_x}$$

Conclusions

- Simulations
  - Tube wall thickness impacts growth rate
- Experiments
  - Current thin-tube PBR design can achieve high concentrations and growth rates

Future work

- Simulations
  - Include diffuse light in modeling
  - Investigate impact of angle of incidence
- Experiments
  - Operate reactor in continuous mode

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THANK YOU.

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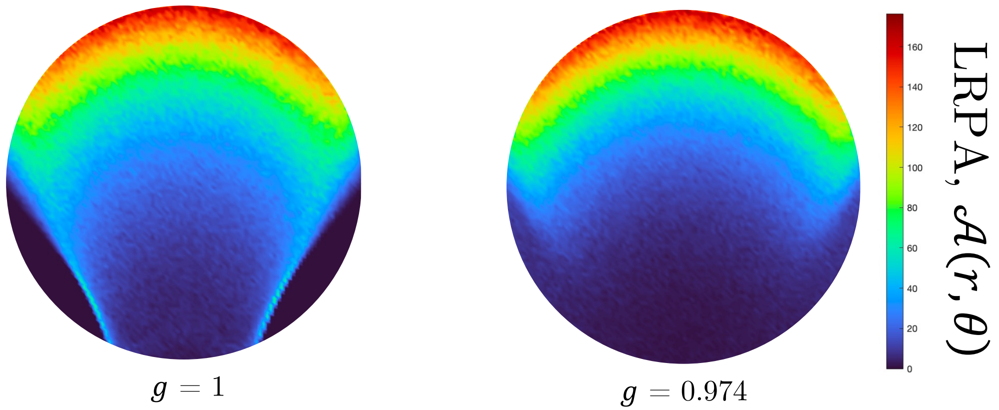
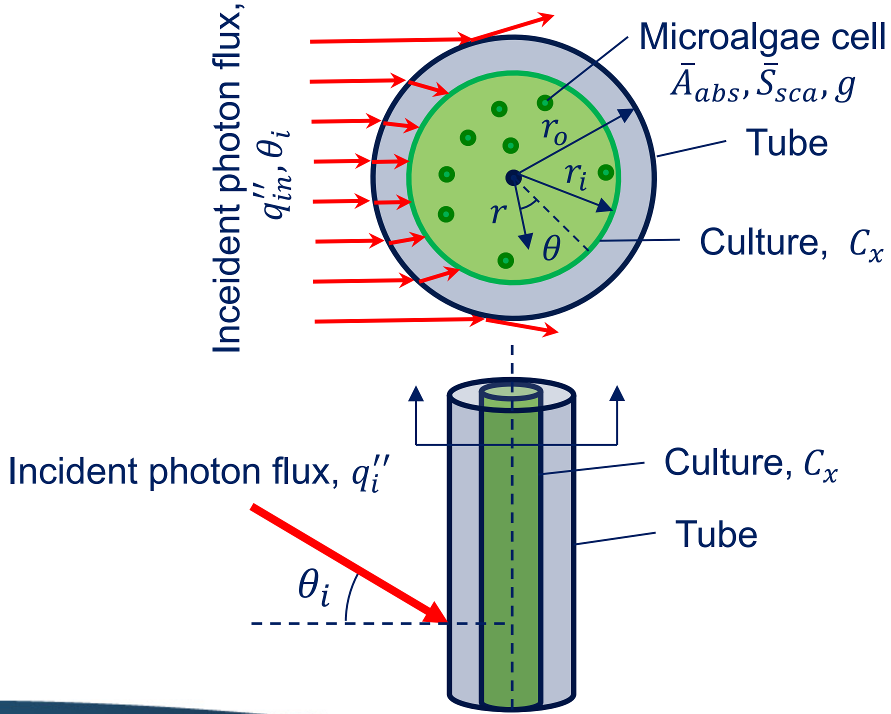
Simulation results: Impact of scattering by microalgae

- Microalgae are primarily forward scattering
  - Asymmetry factor $g \approx 1$
  - Small deviations in g can impact LRPA due to large scattering cross-section



Modeling approach: Light transfer

- Assumptions:
  - General
    - Optically smooth interfaces
    - PAR averaged optical properties
    - Negligible wave effects
  - Incident light
    - Collimated
    - Diffuse light neglected
  - Culture
    - Homogeneous
    - Constant absorption cross-section



Kinetic growth model terms

$$J_{O_2}(r,\theta) = \left[\rho_M \frac{K}{K+\mathcal{A}} \overline{\phi'_{O_2}} \mathcal{A} - \frac{J_{NADH_2}}{\nu_{NADH_2-O_2}} \frac{K_r}{K_r+\mathcal{A}}\right]$$

- ρ_M - maximum energy yield for photon conversion
- K- half-saturation constant for photosynthesis
- K_r - saturation constant describing inhibition of respiration in light
- $\overline{\phi'_{O_2}}$ - mole O_2 quantum yield for the Z scheme of photosynthesis
- J_{NADH_2} - specific rate of cofactor regeneration on the respiratory chain
- $\nu_{NADH_2-O_2}$- stoichiometric coefficient of cofactor regeneration on the respiratory chain

$$\bar{r_x} = \frac{\bar{J}_{O_2} C_x M_x}{\nu_{O_2-X}}$$

- M_x - C-molar mass for the biomass
- ν_{O_2-X} - oxygen production stoichiometric coefficient

Medium composition: Modified Sueoka[4]

Name	Formula	g/L
Ammonium Bicarbonate	NH_4HCO_3	7.279
Magnesium Sulfate Heptahydrate	$MgSO_4, 7H_2O$	0.809
Calcium Chloride Dihydrate	$CaCl_2, 2H_2O$	0.110
Potassium phosphate	KH_2PO_4	0.342
Dipotassium phosphate	K_2HPO_4	0.657
Hutner's Solution	-	1.500