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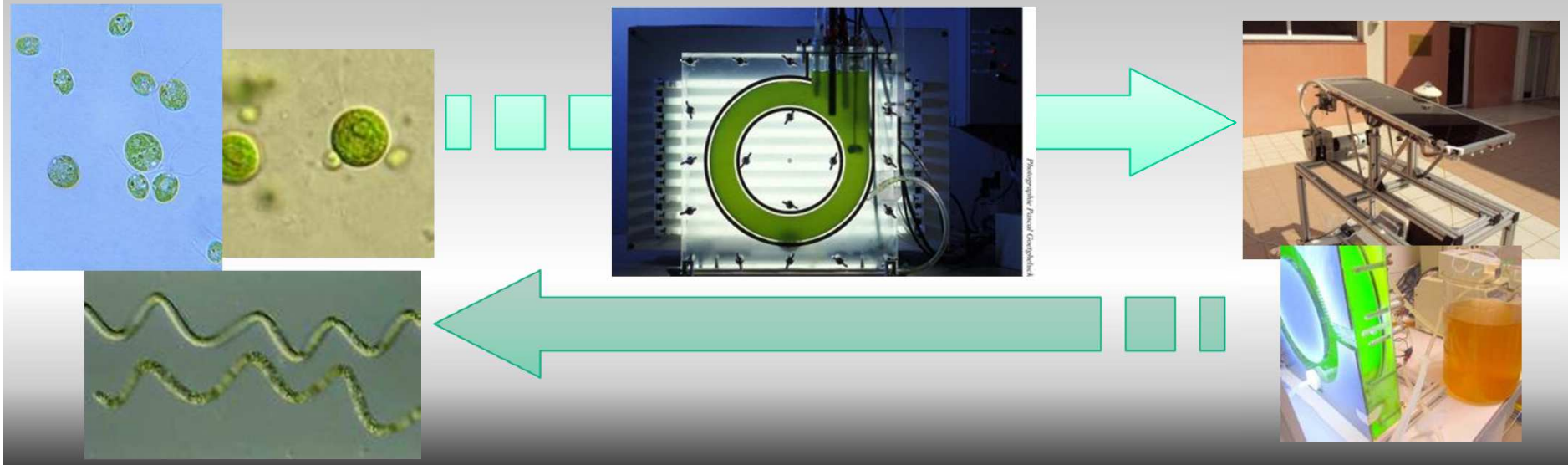
Some insights on photobioreaction engineering

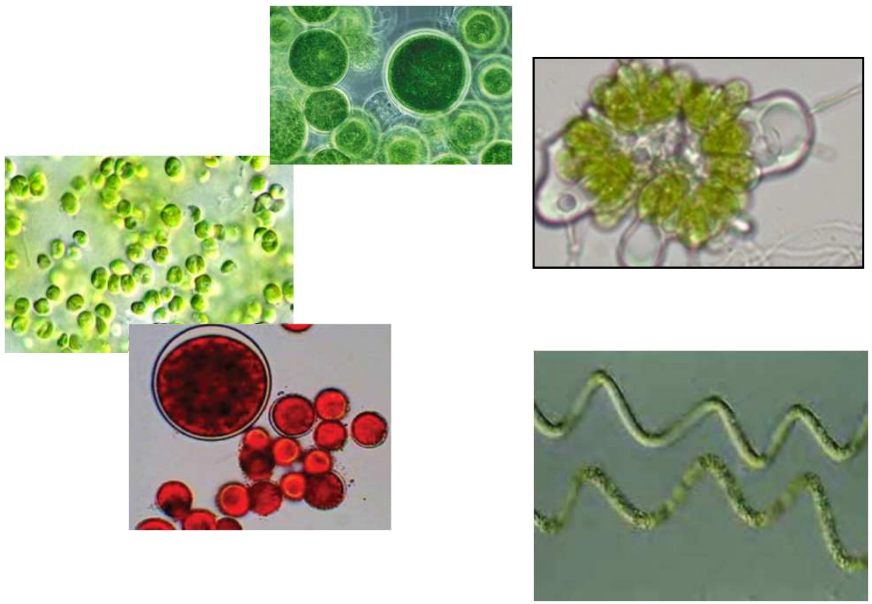


MELiSSA workshop – Lausanne – 8-9 June 2016

Industrial interests for microalgae

Microalgae: a new vegetable feedstock with high potential

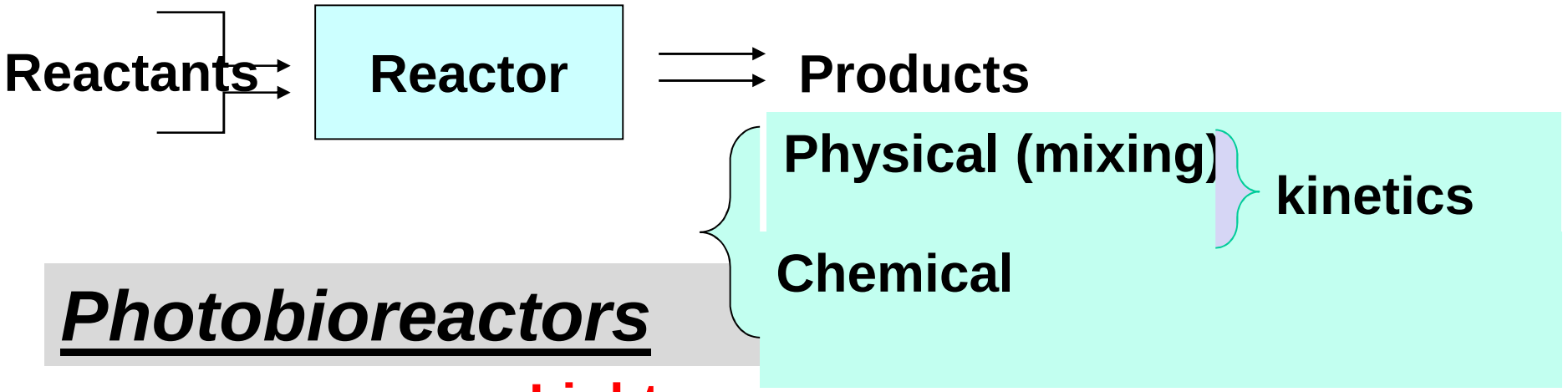
- **Composition**
  - **Proteins**
  - **Carbohydrates**
  - **Lipids**
  - **Specific metabolites: antioxidant, pigments, Polyunsaturated Fatty Acids, ExoPolySaccharides…**



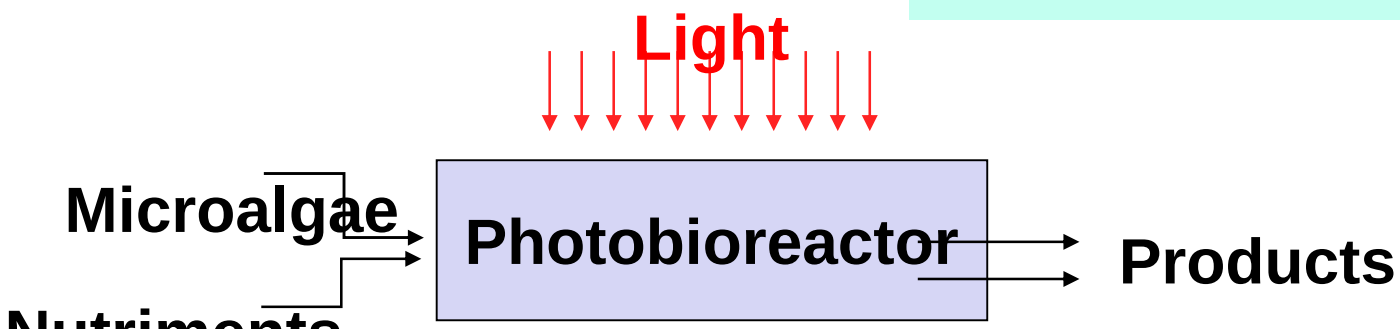
- **Application areas**
  - **Food**
  - **Feed**
  - **Food supplement**
  - **Biofuel production**
  - **Pharmaceutical**
  - **Cosmetics**

Photobioreactor engineering

Chemical reactors



Photobioreactors



Physical (mixing, light transfer
Biological (metabolism)
} kinetics

Photosynthetic microorganisms cultivation

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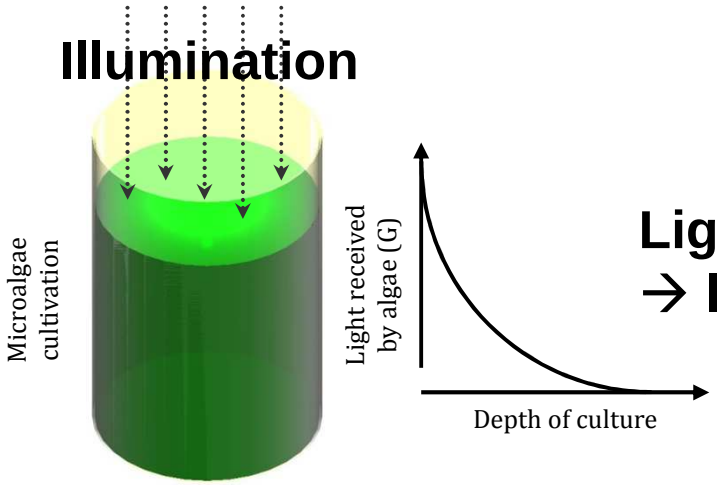
Photoautotrophic growth of *Chlamydomonas reinhardtii*

$$CO_2 + 0.593H_2O + 0.176\ NH_4^+ + 0.007\ SO_4^{2-} + 0.018\ PO_4^{3-}$$
$$\rightarrow CH_{1.781}O_{0.437}N_{0.176}S_{0.007}P_{0.018} + 0.086H^+ + 1.127\ O_2$$

Photosynthetic growth ⇒ **Needs light in addition to chemical nutrients**

Illumination



Light is absorbed in the culture volume
→ light is heterogeneoulsy distributed

Limiting growth factors

- ***Light***
- ***Dissolved carbon***
- ***Chemical nutrients***
- ***Physicochemical conditions (T,pH)***
- ***Bacterial contamination***

Aim of bioprocess engineering: control of growth limitations

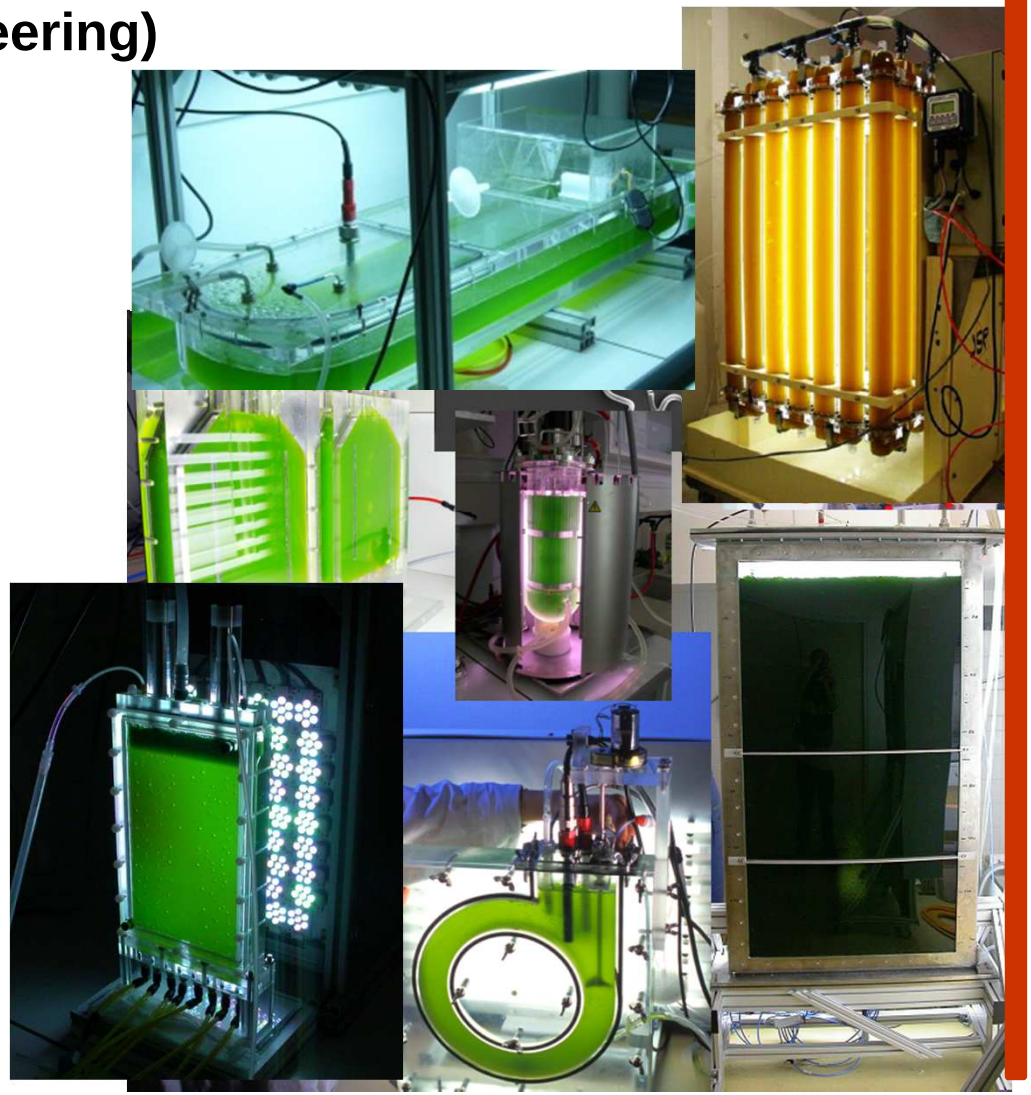
Modelling light-limited growth in photobioreactors

For maximal efficiency, photobioreactor are to be operated with physical limitation by light (light-limited growth model is thus the a basis in photobioreaction engineering)

Classification:

- **Artificial or solar light**
- **Closed or open systems**
- **Cylindrical tank, plan systems, tubular reactors**
- **Free or immobilised cells**
- **Mechanical agitation or airlift**

As a result, for a given geometry, photobioreactor efficiency is fully dependent on light supply



MODELING LIGHT-LIMITED GROWTH IN PHOTOBIOREACTOR

Mass balance on the photobioreactor

(1) $$\frac{dC_X}{dt} = \langle r_X \rangle - DC_X$$

CSTR
Key-term : $\langle r_x \rangle$ (biological production rate)

Radiative transfer modelling

Light availability is a function of light available (PFD), absorption and scattering by cells

(2) $$G_i = f'(q_o, Cx)$$

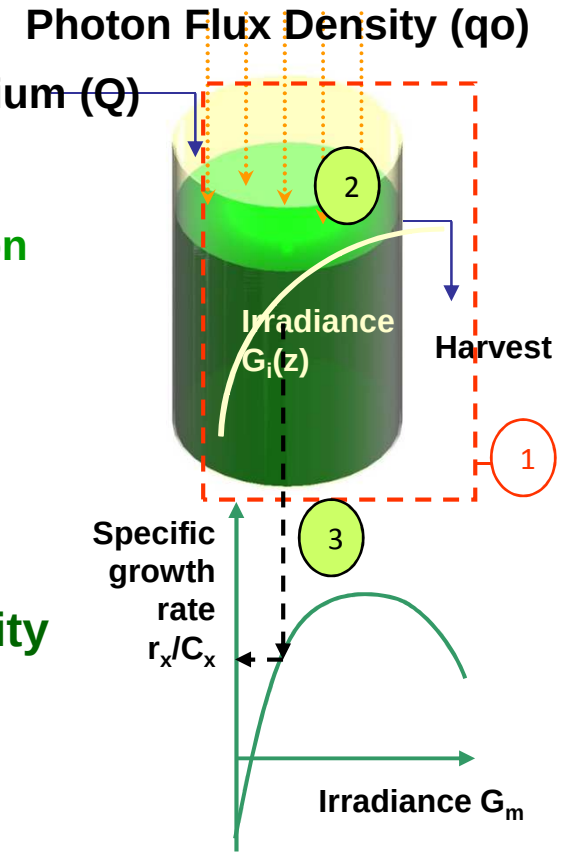
G_i: irradiance (inside culture)
q_0: incident photon flux density

Kinetic model of photosynthetic growth

(3) $$r_X = f(G_i, C_x)$$

Biomass production rate (rx) is related to light available inside the culture (local formulation). Needs to be integrated on reactor volume

$$\langle r_X \rangle = \frac{1}{Vr} \iiint_{Vr} r_X . dVr$$



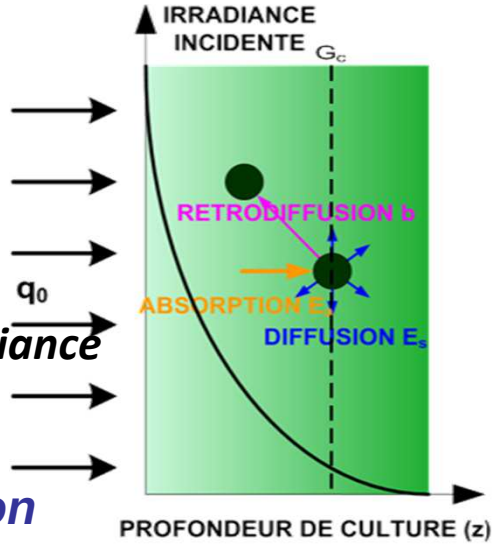
Dilution rate D = Q/Vr
Q : feeding flowrate
Vr : reactor volume
(t=1/D : residence time)

(1) (2) (3) are solved to give biomass growth (Cx) with respect to radiation conditions

Radiative transfer modeling

$$(\Omega\cdot\nabla)\, I_\lambda(r,\Omega,t) = -(a_\lambda + s_\lambda)\, I_\lambda(r,\Omega,t) + \frac{s_\lambda}{4\pi}\iint_{4\pi} I_\lambda(r,\Omega',t)\, p_\lambda(\Omega,\Omega')\, \mathrm{d}\Omega'$$

Radiative Transfer Equation (*Chandrasekhar, 1960*): I=intensity or radiance

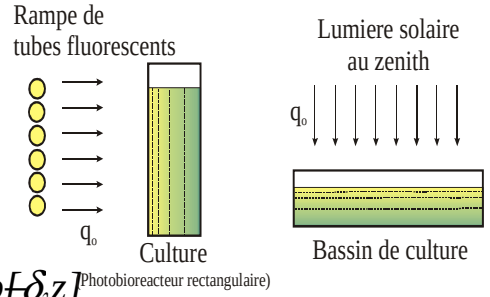


Two-Flux model + one-dimensional hypothesis

Ability to represent light scattering and absorption

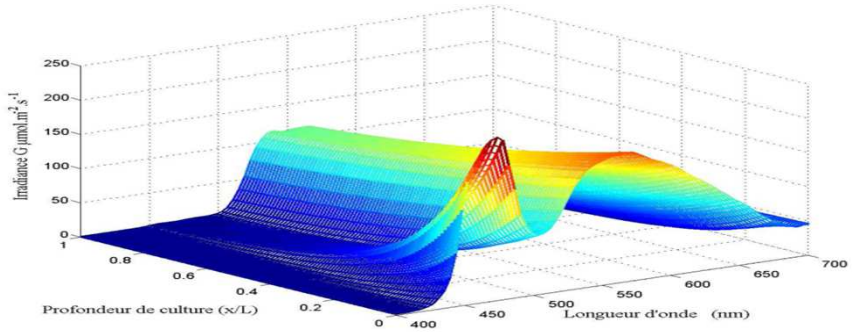
Analytical solution for most of the practical cases. For flat panel

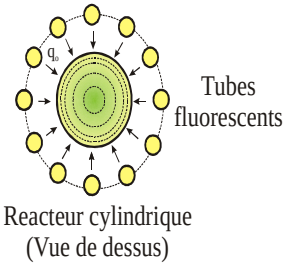
$$\frac{G_\lambda}{q_{0,\lambda}} = K\frac{[(1+\alpha_\lambda)\exp[-\delta_\lambda(z-L)]] - [(1-\alpha_\lambda)\exp[\delta_\lambda(z-L)]]}{(1+\alpha_\lambda)^2\exp(\delta_\lambda L) - (1-\alpha_\lambda)^2\exp(-\delta_\lambda L)} \quad \text{if } \rho_\lambda = 0$$



Flat panel PBR with reflecting back side

$$\frac{G_\lambda}{q_{0,\lambda}} = K\frac{[\rho_\lambda(1+\alpha_\lambda)\exp(-\delta_\lambda L) - (1-\alpha_\lambda)\exp(-\delta_\lambda L)]\exp[\delta_\lambda z] + [(1+\alpha_\lambda)\exp(\delta_\lambda L) - \rho_\lambda(1-\alpha_\lambda)\exp(\delta_\lambda L)]\exp[-\delta_\lambda z]}{(1+\alpha_\lambda)^2\exp(\delta_\lambda L) - (1-\alpha_\lambda)^2\exp(-\delta_\lambda L) + \rho_\lambda(1-\alpha_\lambda)^2[\exp(-\delta_\lambda L) - \exp(\delta_\lambda L)]}$$





Extension to the polychromatic light case

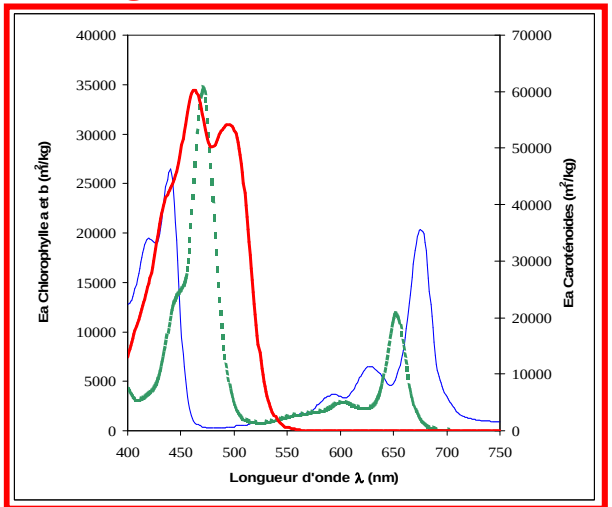
Radiative transfer modeling

Optical properties are a prerequisite to control light transfer in microalgae cultures

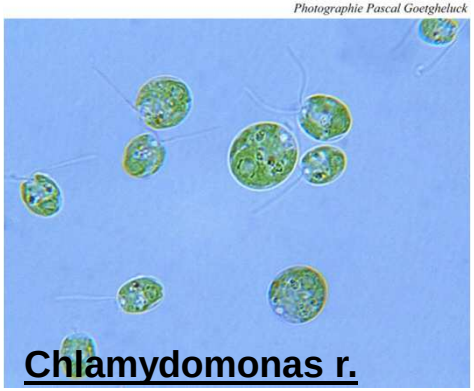
Optical properties are a function of:

Predictive determination of optical properties using Lorenz-Mie or anomal diffraction theory

•Pigments contents



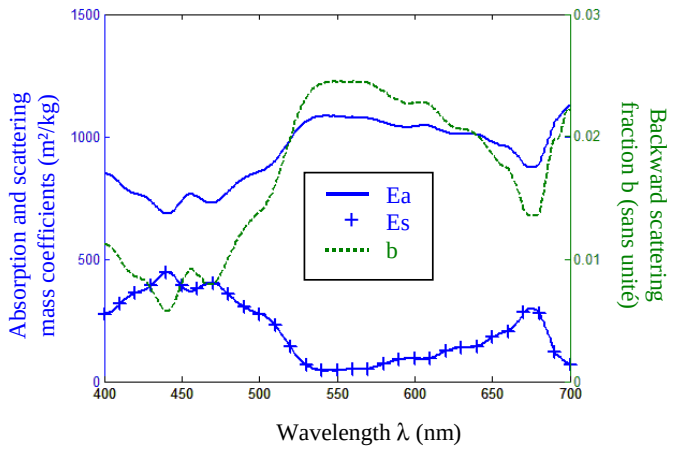
•Size and shape cells



Chlamydomonas r.

•Mean diameter : 4µm

•Shape : Tchebychev



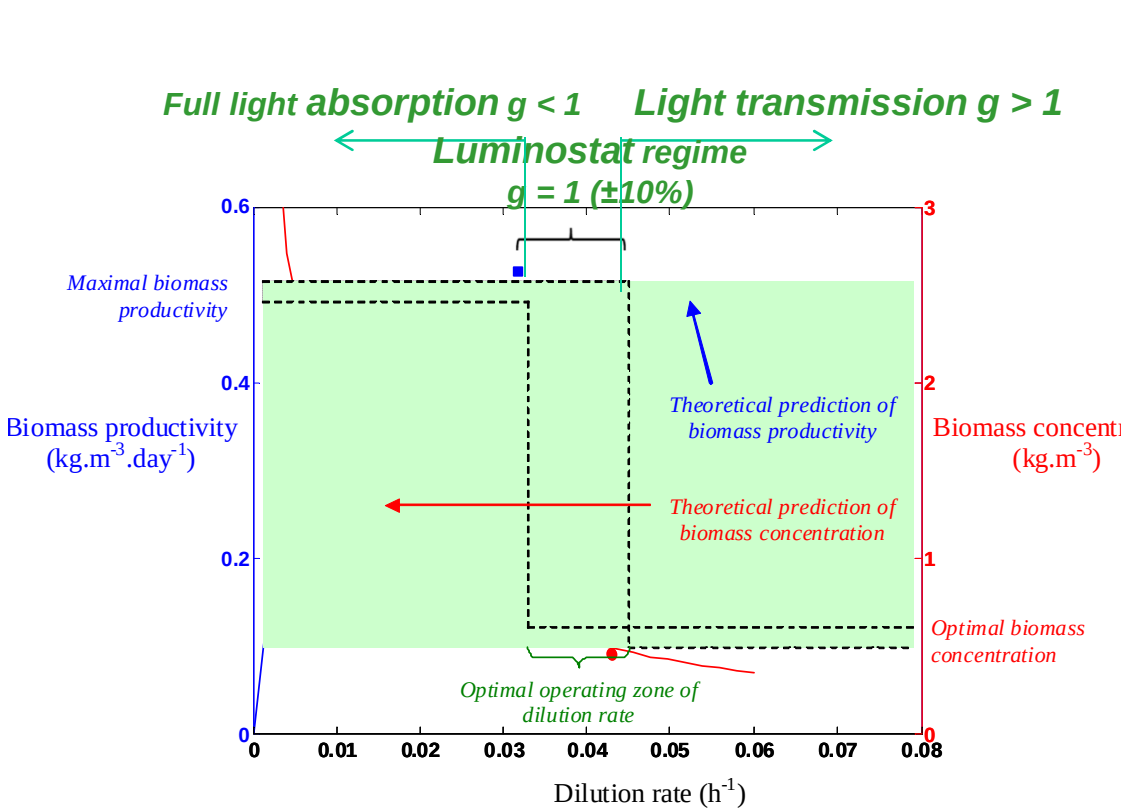
Interests:

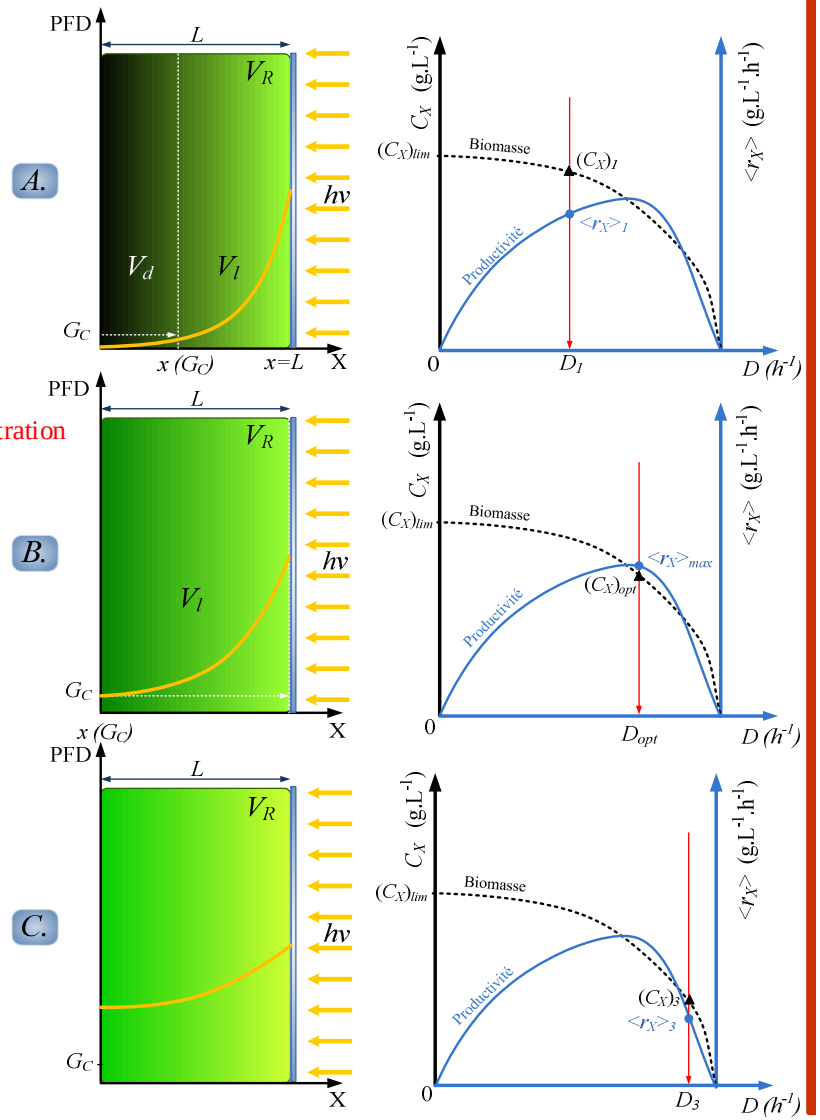
•The method can be applied to any species or mutant (various shapes, size, pigment contents)

*•Effect of pigment content variation can be considered (**pigment adaptation, pigment degradation due to mineral starvation**)*

Radiative transfer modeling

Understanding the role of light attenuation conditions





The role of illuminated fraction γ on biomass PBR productivity (γ =illuminated to total volume ratio)

Takache et al., Biotechnology Progress, 2012.

Kinetic modeling of photosynthetic growth

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In-depth approach with the aim to develop knowledge model

$$\mu = \mu_{max} \frac{G}{K_S + G}$$

Specific growth rate: usual equation (Monod type unstructured model)

$<r_x>=\mu X$

Predictive formulation

$$J_{O_2} = \left[\rho \overline{\varphi}'_{O_2} \mathcal{H} - \frac{J_{NADH_2}}{\upsilon_{NADH_2\text{-}O_2}} \times \frac{K_r}{K_r + G} \right] = \left[\rho_M \frac{K}{K+G} \overline{\varphi}'_{O_2} \mathcal{H} - \frac{J_{NADH_2}}{\upsilon_{NADH_2\text{-}O_2}} \times \frac{K_r}{K_r + G} \right]$$

JO2 Local specific rate of oxygen production (mole/kg/s)

A Specific local volumetric radiant power density absorbed

($A = \int E a G \lambda d\lambda$)

E_a Mass absorption coefficient

G Local spherical irradiance

K Half saturation constant for photosynthesis

K_r Saturation constant for respiration inhibition at light (obtained from JO2=0)

M_X C-molar mass for the biomass

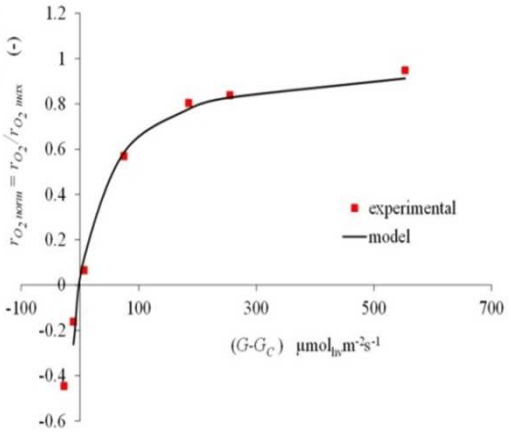
r_X Biomass volumetric growth rate (productivity)

$\overline{\varphi}'_{O_2}$ Energetic yield for photon conversion

r_M Maximum energetic yield for photon conversion

υ_{i-j} Oxygen mole quantum yield for the Z-scheme

Stoichiometric coefficient



Measurement of K by photosynthetic O2 production

Mean volumetric production (or consumption) rate <r> is deduced

$$<J_{O_2}> = \frac{1}{V_R} \iiint_{V_R} J_{O_2} \, dV$$

$$<r_X> = \frac{<J_{O_2}> C_X M_X}{\upsilon_{O_2-X}}$$

Fomulation based on measurable or predictible parameters

PBR engineering and sizing

General engineering formula for PBR productivity

$$< s_X >_{max} = (1 - f_d)\rho_M M_X \overline{\phi'_X} \frac{2\alpha}{1+\alpha} K \ln\left[1 + \frac{q_0}{K}\right]$$

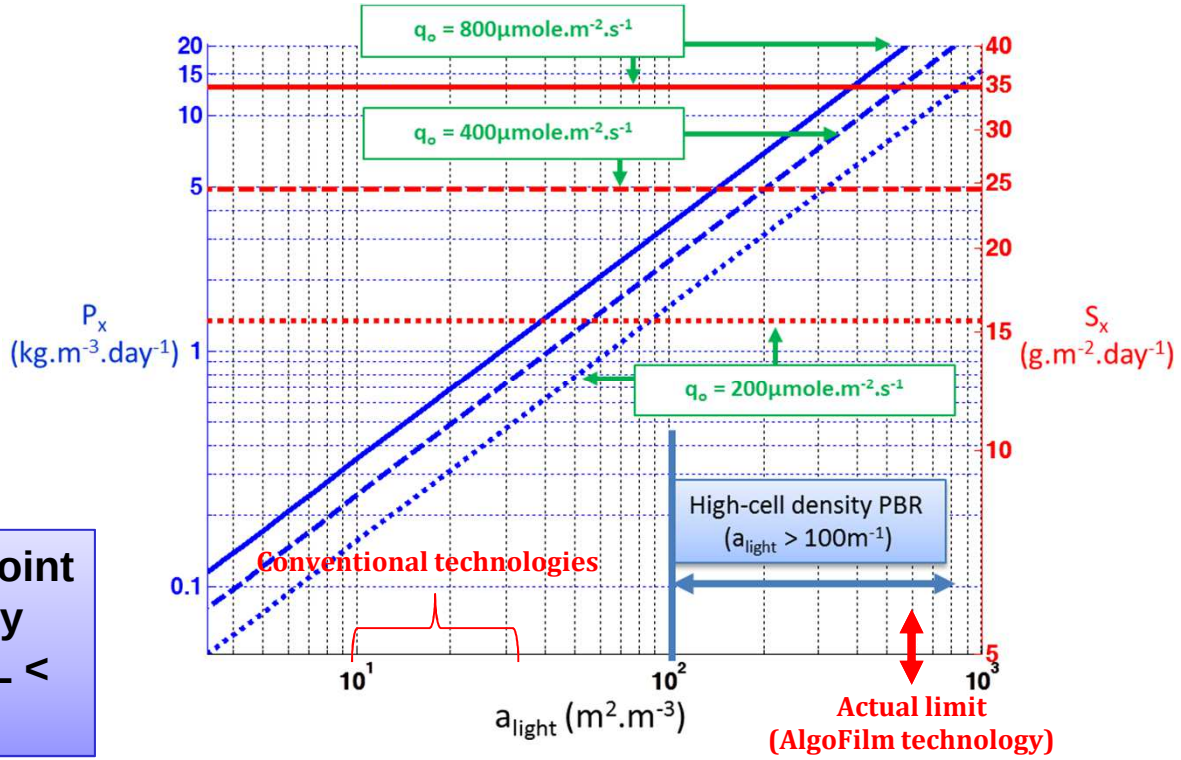
$$< r_X >_{max} = (1 - f_d)\rho_M M_X \overline{\phi'_X} \frac{2\alpha}{1+\alpha} a_{light} K \ln\left[1 + \frac{q_0}{K}\right]$$

3 engineering parameters
- **PFD (qo)**
- **Specific illuminated surface to volume ratio (a_{light} = S/V = 1/L)**
- **Non illuminated volume ($f_{d=}0$ for well-designed systems)**

Surface productivity of a given species is only a function of the PFD

Volumetric productivity can be increased by increasing PFD and/or specific illuminated to volume ratio (i.e. decreasing PBR depth):
Two-orders of magnitude can be covered with appropriate engineering !

The limit is from an engineering point of view → intensified PBR can only obtained with very thin systems (L < 1cm), ideally using high PFD



PBR engineering and sizing

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Examples of validation :
Cornet and Dussap, Biotech.Progress 2009

Engineering rules are actually available for PBR scaling

Table 2. Comparison Between Experimental Productivities Obtained in Very Different Kinds of Photobioreactors Cultivating *Arthrospira platensis* and the Simple Formula (Eq. 22)

Geometry of the reactor and lighting characteristics	Reactor type and working volume	Operating cultivation condition	Mean incident photon flux density (PAR) ($\mu mol_{hv}\ m^{-2}\ s^{-1}$)	Experimental observed productivity ($kg\ m^{-3}\ h^{-1}$)	Theoretical maximal productivity given by Eq. 22 ($kg\ m^{-3}\ h^{-1}$)	Deviation (%)
Rectangular, lightened by one side $a_{light} = 12.5\ m^{-1}$ ($f_d = 0$)	PBR 1, 4 L	Batch	40	$(1.6 \pm 0.2) \times 10^{-3}$	1.8×10^{-3}	+12
		Batch	50	$(2.1 \pm 0.2) \times 10^{-3}$	2.4×10^{-3}	+14
		Batch	85	$(3.2 \pm 0.2) \times 10^{-3}$	3.5×10^{-3}	+9
Cylindrical, lightened by one side $a_{light} = 12.5\ m^{-1}$ ($f_d = 0$)	PBR 2, 5 L	Batch	130	$(2.6 \pm 0.2) \times 10^{-3}$	2.8×10^{-3}	+8
		Batch	260	$(4.7 \pm 0.4) \times 10^{-3}$	4.9×10^{-3}	+4
		Batch	315	$(5.0 \pm 0.5) \times 10^{-3}$	5.4×10^{-3}	+8
		Batch	365	$(5.3 \pm 0.5) \times 10^{-3}$	5.9×10^{-3}	+13
		Batch	520	$(7.1 \pm 0.7) \times 10^{-3}$	7.4×10^{-3}	+4
		Batch	575	$(7.2 \pm 0.7) \times 10^{-3}$	7.8×10^{-3}	+8
		Batch	730	$(9.5 \pm 0.8) \times 10^{-3}$	8.9×10^{-3}	−6
		Batch	840	$(1.1 \pm 0.1) \times 10^{-2}$	9.6×10^{-3}	−4
		Continuous	630	$(8.0 \pm 0.7) \times 10^{-3}$	8.3×10^{-3}	+4
		Continuous	1045	$(1.2 \pm 0.1) \times 10^{-2}$	1.1×10^{-2}	−8
		Continuous	1570	$(1.3 \pm 0.1) \times 10^{-2}$	1.3×10^{-2}	0
Cylindrical, radially lightened $a_{light} = 25\ m^{-1}$ ($f_d = 0$)	PBR 3, 5 L	Batch	245	$(1.3 \pm 0.1) \times 10^{-2}$	1.4×10^{-2}	+8
		Batch	620	$(1.9 \pm 0.2) \times 10^{-2}$	2.2×10^{-2}	+15
		Batch	1095	$(2.7 \pm 0.1) \times 10^{-2}$	2.8×10^{-2}	+4
		Batch	1590	$(3.3 \pm 0.5) \times 10^{-2}$	3.2×10^{-2}	−3
Cylindrical, radially lightened $a_{light} = 40\ m^{-1}$ ($f_d = 0.48$)	PBR 4, 7 L	Continuous	235	$(1.0 \pm 0.1) \times 10^{-2}$	1.1×10^{-2}	+10
		Continuous	365	$(1.3 \pm 0.1) \times 10^{-2}$	1.4×10^{-2}	+7
		Continuous	625	$(1.7 \pm 0.2) \times 10^{-2}$	1.9×10^{-2}	+12
		Continuous	780	$(1.9 \pm 0.2) \times 10^{-2}$	2.1×10^{-2}	+10
Oblate cylinder, lightened by one side $a_{light} = 43.5\ m^{-1}$ ($f_d = 0$)	PBR 5, 0.106 L	Batch	65	$(8.9 \pm 0.1) \times 10^{-3}$	9.5×10^{-3}	+7
Cylindrical, radially lightened $a_{light} = 26.7\ m^{-1}$ ($f_d = 0.33$) (experimental results from Refs. 31,32)	PBR 6, 77 L	Batch	390	$(1.2 \pm 0.1) \times 10^{-2}$	1.3×10^{-2}	+8
		Continuous	525	$(1.4 \pm 0.2) \times 10^{-2}$	1.5×10^{-2}	+7
		Continuous	840	$(1.7 \pm 0.2) \times 10^{-2}$	1.8×10^{-2}	+6
Annular and cylindrical, radially lightened $a_{light} = 40\ m^{-1}$ ($f_d = 0$)	PBR 7, 6 L	Batch	190	$(2.2 \pm 0.2) \times 10^{-2}$	2.0×10^{-2}	−10
		Batch	340	$(3.1 \pm 0.3) \times 10^{-2}$	2.8×10^{-2}	−10
		Batch	530	$(4.1 \pm 0.3) \times 10^{-2}$	3.5×10^{-2}	−15
Rectangular, lightened by one side $a_{light} = 25\ m^{-1}$ ($f_d = 0$) (experimental results from Ref. 23)	PBR 8, 0.5 L	Batch and continuous	33	$(3.3 \pm 0.3) \times 10^{-3}$	3.5×10^{-3}	+6
		Continuous	135	$(1.1 \pm 0.1) \times 10^{-2}$	1.0×10^{-2}	−10

Less than 15% deviation

Understanding and optimizing PBR technology

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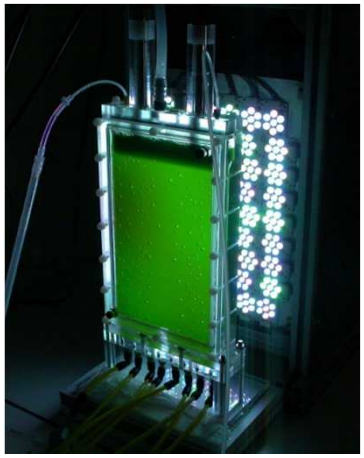
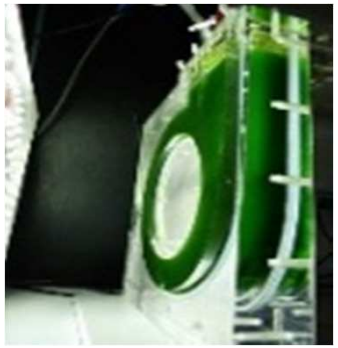
Investigation in fully-controlled PBR

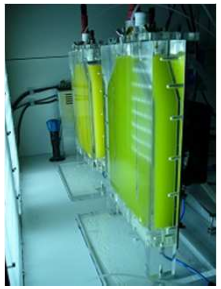


Flat panel PBR for simulated day/night cycles investigation

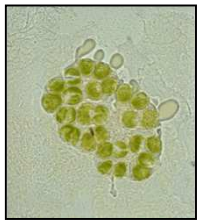


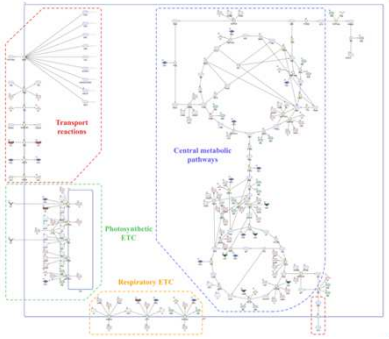
Torus PBR for in-depth investigation

Biological /metabolism studies

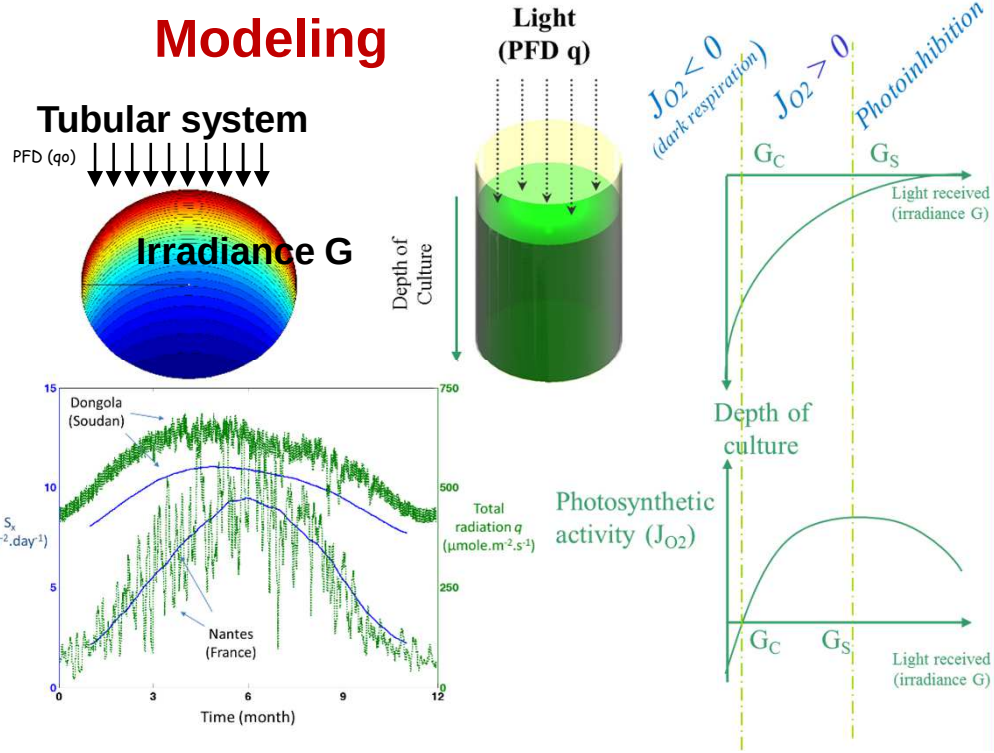


Investigation of light absorption conditions

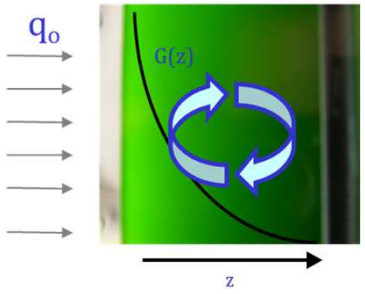




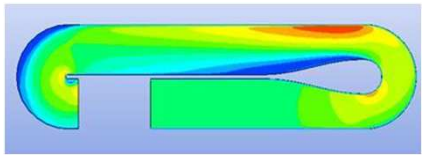
Modeling



Hydrodynamics/gas-liquid mass transfer/thermal optimisation



L/D cycles investigation

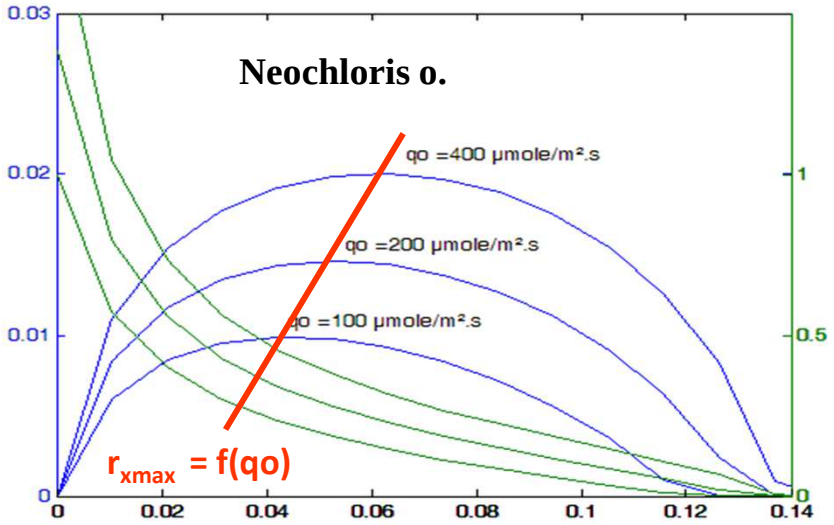


CFD for mixing optimisation in RW

Modelling light-limited growth in photobioreactors

For maximal efficiency, photobioreactor are designed and operated to be physically limited by light (light-limited growth model is thus the a basis in photobioreactor engineering)

Volumtric productivity r_x (g/l.h)



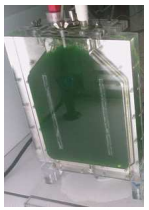
Biomass concentration X (g/l)

As a result, for a given geometry, photobioreactor efficiency is fully dependent on light supply: complex for solar technologies

Model-based PBR scaling

Scaling-up of biomass production

Scaling-up of biomass production



0.3m
(V_r = 1L)

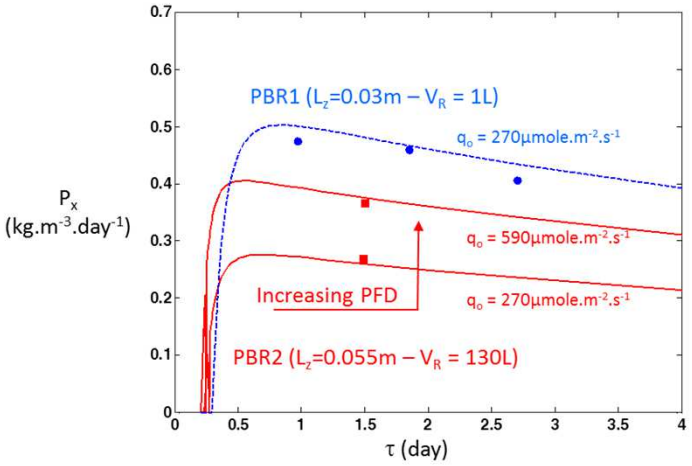
Airlift PBR
(lab-scale PBR)

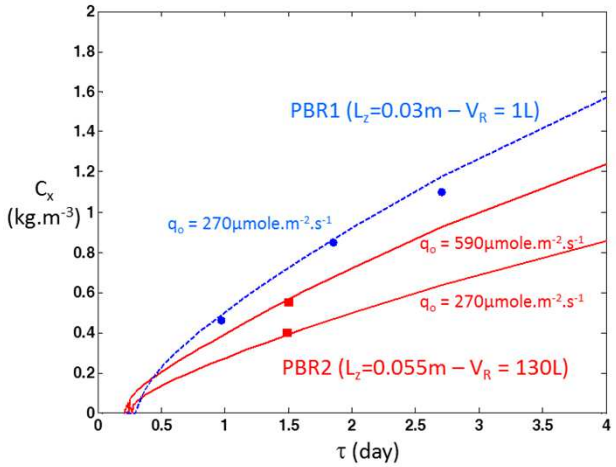
1.8m
(V_r = 130L)

Airlift PBR
(Pilote-scale PBR)

***Neochloris oleoabundans*:**
r_M = 0.8
ϕ= 1.83.10^{-9}kg/µmolehn^{-1}
K = 90µmole.m^{-2}.s^{-1}
a = 0.98

Prediction of biomass concentration and productivity as a function of PBR geometry (depth) and PFD : Maximal deviation of 15%

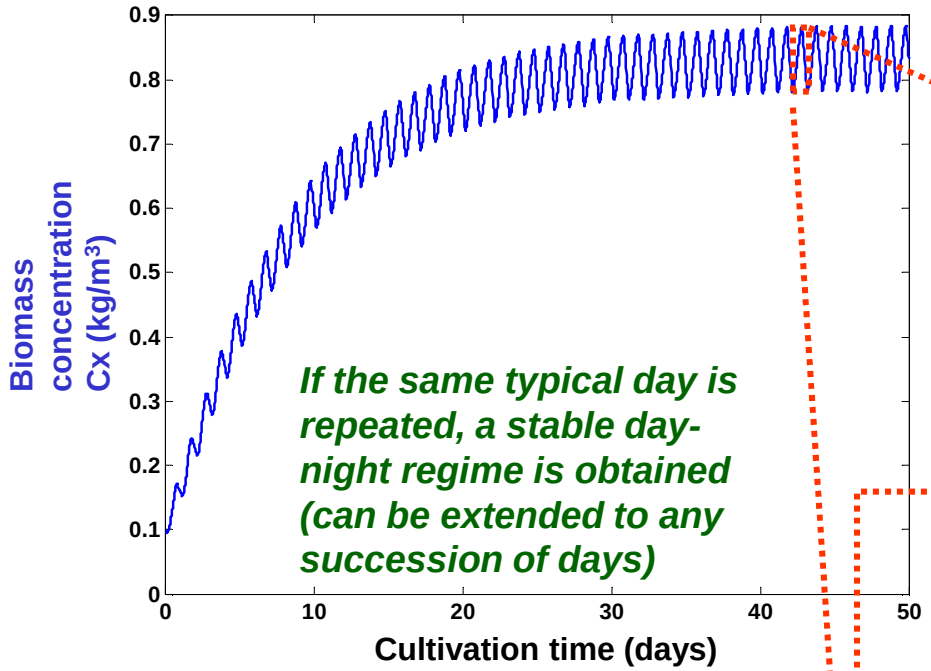




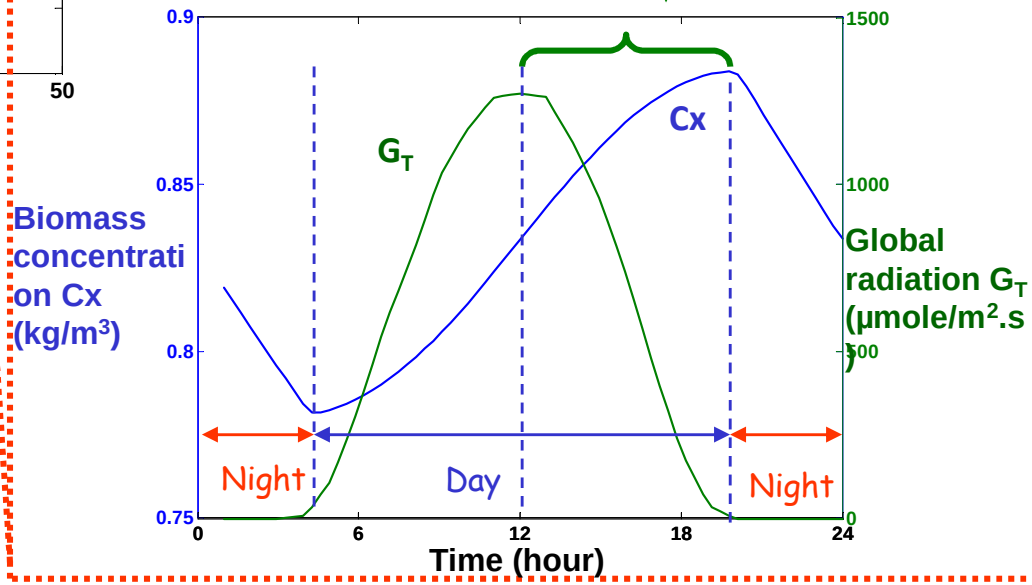
Engineering rules are actually available for PBR scaling

SOLAR PHOTOBIOREACTOR MODELING: Dynamic behavior of the process during day/night

Biomass growth during simulated day/night cycles



Delay between radiation and X evolution

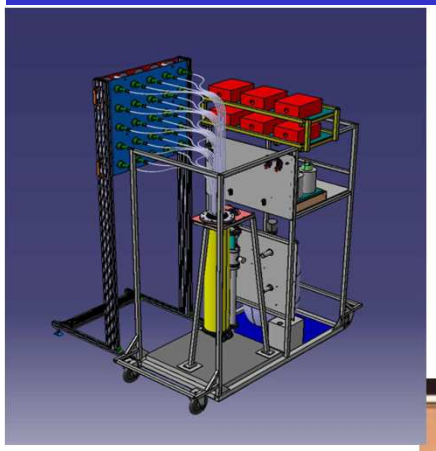


Dynamic evolution of biomass concentration

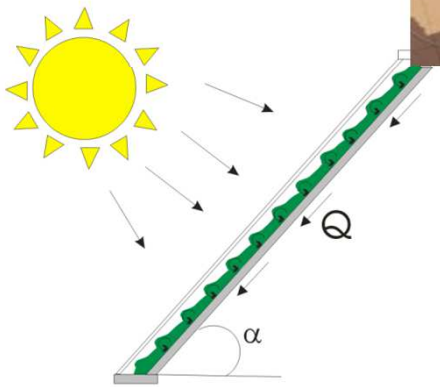
- Biomass growth all along the day
- Negative effect of night (biomass lost)

Solar PBR

DiCoFluv

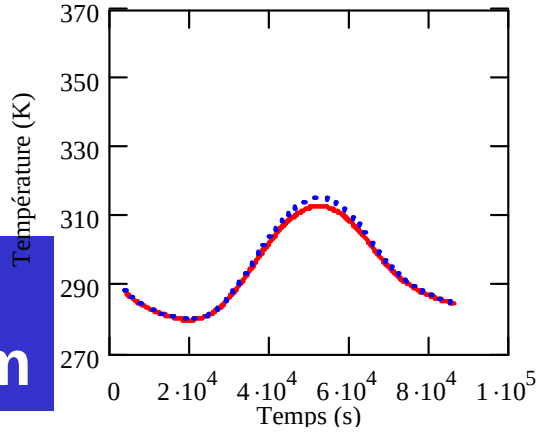


AlgoFilm

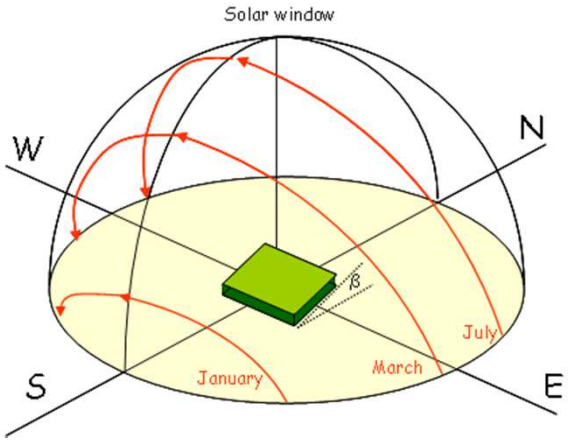


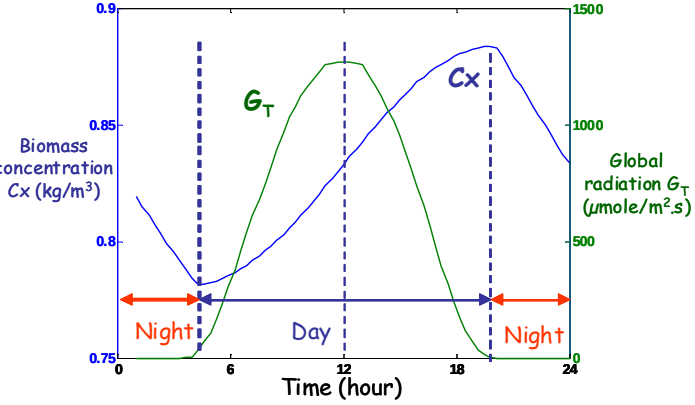
PBR conception: DiCoFluv & AlgoFilm

Passive thermal control



Models for solar PBR

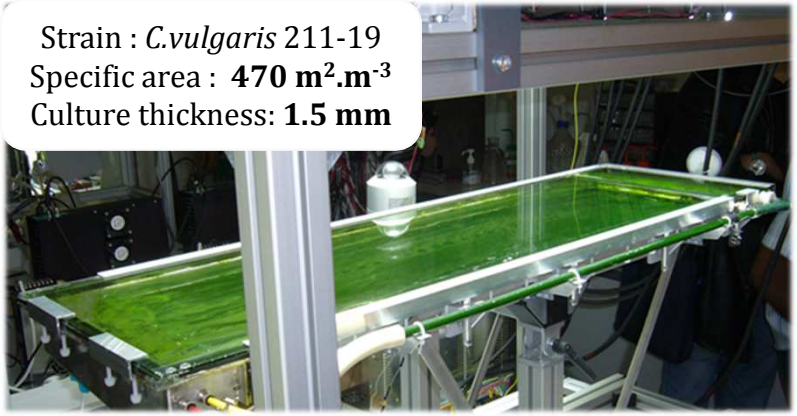


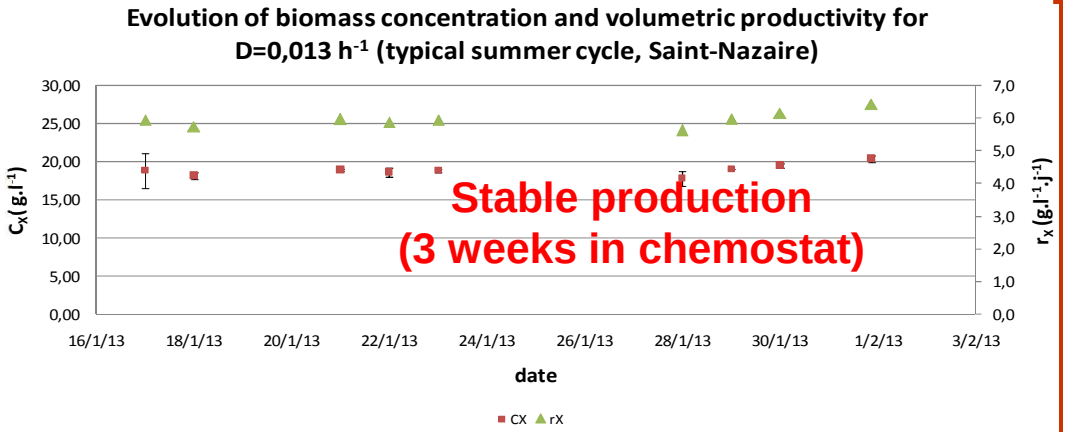


Day/light cycles behaviour

AlgoFilm solar technology

Strain : *C.vulgaris* 211-19
Specific area : **470 $m^2.m^{-3}$**
Culture thickness: **1.5 mm**





Productivity target (equator location)

$$< r_X >_{max} \cong 2 - 10 \ \text{kg.m}^{-3}_{liq}.\text{day}^{-1}$$

$$< s_X >_{max} \cong 16 - 28.10^{-3} \ \text{kg.m}^{-2}.\text{day}^{-1}$$

$$< s_X >_{max} \cong 60 - 100 \ \text{t.ha}^{-1}.\text{year}^{-1}$$

Maximal productivity achieved (15days cultivation) : 6.0 $kg.m^{-3}d^{-1}$

Expected from models (prior AlgoFilm development) : 5.5kg/m³.day

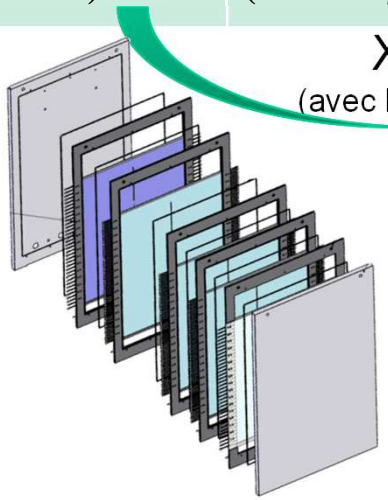
Technology	Volumetric productivity ($kg.m^{-3}.j^{-1}$)		Increase of volumetric productivity (with Algofilm technology)
Average radiation ($\mu mol_{hn}.m^{-2}.s^{-1}$)	430	270	
Raceway pond	~ 0,1	~ 0,07	~60-80
Conventional technology (a_{light}=20m^{-1})	~ 0,3 - 0,5	~ 0,2 – 0,35	~ 20
Algofilm (experimental results)	~ 6,1	~ 5,7	

Intermediate conception: « Filter-press » PBR

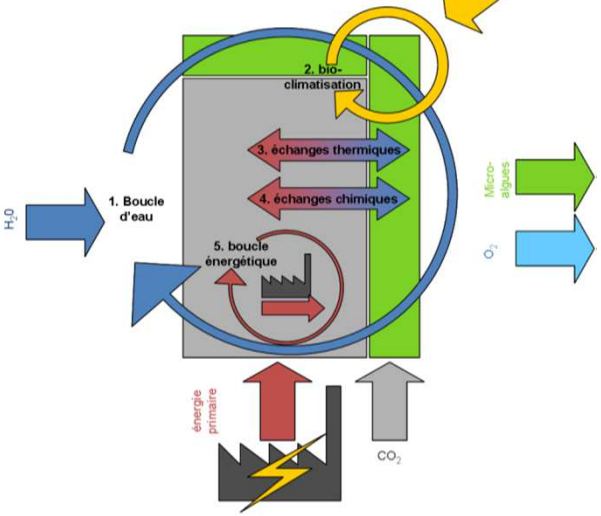
(Predictive models: GEPEA-IP)

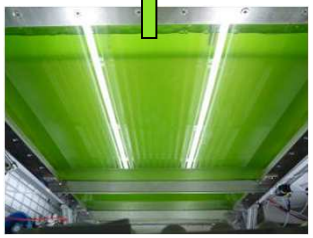
	Hector	PRIAM (Prototype)	PRIAM (Unité de production)
Volume	130litres	11.6litres	130litres (ou plus)
Surface éclairée	2.34m²	6m²	60m²
Surface spécifique éclairée	18m²/m3	515m²/m3 réel (666m²/m3 max)	515m²/m3 réel (666m²/m3 max)
Volume par unité de surface	55litres/m²	1.93litres/m²	1.93litres/m²
Performance maximale	0.4kg/m3/j (50g/j) (PFD = 500µmole/m²/s)	5.5kg/m3/j (60g/j) (PFD = 200µmole/m²/s)	5.5kg/m3/j (700g/j) (PFD = 200µmole/m²/s)

Hector (GEPEA)



Biofaçade project





Vertical PBR

Biofaçade pilot

Demonstrator

Optimisation and integration of PBR in the bulilding = symbiosis

ALGOSOLIS

MICOALGAE R&D PLATEFORM

Objectives

- ***Study in real conditions at industrial representative scale.***
- ***Development and optimisation of the different steps of the process***
- ***Microalgae production with industrial effluents (flue gas, wastewaters).***

INFRASTRUCTURE

- **Production surface: 1500m² (350m² on greenhouse)**
- **Biorefinery hall (240m²)**
- **Innoculation room and analytical laboratory (100m²)**

CULTURE PROCESS: 10 à 100m²

- **Closed raceways**
- **Intensified PBR**

HARVESTING PROCESS

- **Preconcentration/concentration systems**
- **Filtration and membrane separation**
- **Centrifuges**

BIOREFINERY

- **Cell disruption**
- **Extraction process**
- **Fractioning process**

BIOMASS CONDITIONING

- **Drying**
- **Lyophilation**
- **Congelation**

Concluding remarks

GEPEA
UMR CNRS 6144

In-depth control of PBR developed in the MELiSSA framework allows the set-up of knowledge models for:

- **PBR intensification**
- **New PBR conception**
- **Specific application: biofaçades**

Thank you for your attention

http://www.gepea.fr/